FROM ATOMS TO QUARKS AND BEYOND: A HISTORICAL PANORAMA

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Abstract: The inward bound path of discovery unravelling the mysteries of matter and the forces that hold it together has culminated at the end of the twentieth century, in a theory of the Fundamental Forces of Nature based on Nonabelian Gauge Fields, called the Standard Model of High Energy Physics. In this article we trace the historical development of the ideas and the experimental discoveries on which this theory is based. This involves the following components: quantum field theory and quantum electrodynamics, weak interactions and parity violation, strong interactions and quarks, nonabelian gauge fields and spontaneous symmetry breaking. We develop these different strands of history and weave them together. We also mark significant Indian contributions wherever possible. Finally we have a glimpse at future developments, in particular quantum gravity and string theory. An Appendix on more Indian contributions is added at the end.

Plan of the article

1. Scope
2. HEP before and after the Standard Model
3. Future of HEP
4. Present Status in India and Suggestions for Future
5. Some Reflections on the Panorama of HEP
6. Appendix: More Indian contributions
0.1 Scope

The earlier part of the 20th Century was marked by two revolutions that rocked the Foundations of Physics.

1. Quantum Mechanics & 2. Relativity

Quantum Mechanics became the basis for understanding Atoms, and then, coupled with Special Relativity, Quantum Mechanics provided the framework for understanding the Atomic Nucleus and what lies inside.

INWARD BOUND

| Atoms | Nuclei | Nucleons | Quarks | ? |
|-------|--------|----------|--------|---|
| $10^{-8}$ cm | $10^{-12}$ cm | $10^{-13}$ cm | $10^{-17}$ cm |

This inward bound path of discovery unraveling the mysteries of matter and the forces holding it together – at deeper and ever deeper levels – has culminated, at the end of the 20th century, in the theory of Fundamental Forces based on Nonabelian Gauge Fields, for which we have given a rather prosaic name:

THE STANDARD MODEL OF HIGH ENERGY PHYSICS

But, this is not the end of the road. More on that, later. Thus, what is called High energy physics (HEP) is just the continuation of the era of discoveries that saw the discovery of the electron, the discovery of radioactivity and X rays, the discovery of the nucleus and the neutron and the discovery of cosmic rays and the positron.

These discoveries went hand in hand with the development of Quantum Mechanics, Relativity and Quantum Field Theory. For, without the conceptual advances made in these theoretical developments, the above experimental discoveries could not have been assimilated into the framework of Physics.

So, the present-day HEP must be regarded as the successor to Nuclear Physics, which in turn was the successor to Atomic Physics:

Atomic Physics $\rightarrow$ Nuclear Physics $\rightarrow$ High Energy Physics
HEP is the front end or cutting edge of the human intellect advancing into the unknown territory in its inward bound journey. This 100-year-long history must be viewed together, to get a true picture of HEP. It is within this broad framework that we must place any particular contribution or the totality of Indian contributions, for a proper perspective. Viewed in this light, it is perfectly natural to include the great Indian contributions made in the earlier part of the 20th century. If Bose, Raman & Saha were alive and young today, they would be doing HEP. So, I start with their contributions . . .

1. M N Saha’s (1923) theory of thermal ionization played a crucial role in the elucidation of stellar spectra and thus was of fundamental importance for the progress of Astrophysics. (Saha’s (1936) reinterpretation of Dirac’s quantization condition for monopoles, in terms of angular momentum quantization, was very original and its importance is now recognized.)

2. S N Bose (1924) discovered Quantum Statistics even before the discovery of Quantum Mechanics by Heisenberg & Schrödinger one year later. Logically pursued, Bose’s discovery by itself would have led to Quantum Mechanics. But, History went differently. QM was discovered soon (in fact, too soon) and the flood gates were open. This was unfortunate for India. This may be called Missed Opportunity I.

3. C V Raman (1928) discovered the inelastic scattering of photon on bound electrons and thus took the concept of photon one step higher. Raman effect is a fundamental experimental discovery that has not been surpassed or even equalled in its importance and impact even after 70 years by any other experiment done in this country.

4. S Chandrasekhar (1932) applied relativistic quantum mechanics to the interior of stars. He calculated the degeneracy pressure (or Pauli pressure) of a relativistic electron gas and thus initiated our understanding of the gravitational collapse of stars.

5. H J Bhabha’s (1935) calculation of $e^+e^-$ scattering was one of the earliest nontrivial applications of Dirac equation to a process in which Dirac’s hole theory played a crucial role. This was done even before a full-fledged Quantum Field Theory existed.
0.2 HEP before and after the Standard Model

0.2.1 QED

\[ L = -\frac{1}{4} (\partial_\mu A_\nu - \partial_\nu A_\mu)^2 - \bar{\psi} \gamma^\mu (i\partial_\mu - e A_\mu) \psi - m \bar{\psi} \psi \]

Planck (1900) : Quantization of radiation energy
Einstein (1905) : Photon
Bose (1924) : Photons as identical particles
\{ Bose and Einstein (1926), Fermi and Dirac (1926) \} : Quantum Statistics
Dirac (1927) : lays the foundations for QED by introduction of \( a, a^+ \) for photons
\[ [a, a^+] = 1 \] (bosons)
Jordan & Wigner (1928) : \( \{b, b^+\} = 1 \) (fermions)
Compton (1925), Raman (1928) : photon scatters like particle
Dirac (1928) : Relativistic Eq. for electron
Anderson (1932) : Discovery of \( e^+ \)
Bhabha (1935) : \( e^+ e^- \) scattering
Kramers (1947) : The idea of renormalization
Lamb & Retherford (1947) : Exptl discovery of Lamb shift
Bethe (1947) : First calculation of Lamb shift using renormalization
\{ Feynman, Schwinger, Tomonoga, Dyson \} (1946 – 50) : Covariant Formalism, Perturbation Series for S matrix, Feynman Diagrams, QED emerges as a renormalizable QFT.

The development of Quantum Electrodynamics (QED) is concurrent with the development of Quantum Field Theory (QFT), which has been the basic language of HEP, at least so far.

QED is characterised by the Lagrangian density given in the box above and the various milestones in its development are tabulated below that. We now describe them in more detail.
The history of QED originates with the concept of the photon. Following Planck’s epochal discovery in 1900 that the experimentally observed black-body radiation required quantization of radiation energy, Einstein introduced the concept of photon in 1905. But it took many years and the formulation of quantum mechanics itself in 1923-24 by Heisenberg and Schrödinger before Dirac could lay the foundation of QED and QFT in 1927, by introducing the annihilation and creation operators $a$ and $a^*$ for photons satisfying commutation relations. The work of Bose and Einstein as well as that of Fermi and Dirac led to the recognition that there are are two fundamentally different types of quantization and correspondingly particles or quanta come in two varieties, namely bosons and fermions. It was Dirac who clarified the situation and thus unified both kinds of quantum statistics. All this was in 1926. In 1928, Jordan and Wigner introduced the annihilation and creation operators for fermions such as electrons satisfying anticommutation relations, thus completing the picture.

Compton’s (1925) and Raman’s (1928) discoveries that photon scatters like a particle both from free and bound electrons took the concept of the photon a step further.

The next milestones were Dirac’s discovery of the relativistic wave equation for the electron in 1928 and Carl Anderson’s discovery of the positron in 1932. The concept of the antiparticle emerged as a law of nature that was a necessary consequence of relativistic quantum mechanics. Bhabha (1935) showed that the scattering of electron and positron could be calculated correctly and systematically within the framework of Dirac equation.

Modern QED starts with renormalization. The idea of renormalization was due to Kramers, but the breakthrough came from the experimental discovery of Lamb shift (1947) which provided the impetus for the first calculation of this effect by Bethe (1947) using the idea of renormalization. Through the seminal work of Feynman, Schwinger, Tomonoga and Dyson, QED emerged as a covariant, local and renormalizable QFT, capable of precise calculations within the perturbative framework. Precision experiments on Lamb shifts and $g-2$ of electron and muon soon proved QED to be one of the most successful and precise theories ever constructed.

Here one must refer to S N Gupta’s contribution (1950). It was Gupta who first constructed a manifestly relativistic formulation of QED. Before him, QED was formulated in Coulomb gauge which lacked manifest relativistic invariance. Gupta showed how to do QED in the covariant Lorentz gauge in a consistent way by using indefinite metric.

It may be worthwhile to pause and look back at the earlier decades before QED was proved to be a correct theory. Both because of the intrinsic divergence disease of the theory and of the supposed incapability of the theory to explain the higher energy phenomena in the realm of cosmic rays, it was widely expected that QED will fail. Heitler’s well-known book on “Quantum Theory of Radiation” provides good evidence for this part of history. Succeeding editions of the book estimated the demise of QED at higher and higher energies. That demise never came. QED is still alive and kicking although incorporated in a bigger
framework, namely the Standard Model of High Energy Physics. There is perhaps a moral in this story—the widely prophesied demise of the Standard Model also might never come!

0.2.2 Weak Interactions

Becquerel (1896) : Radioactivity ($\alpha, \beta, \gamma$)

Pauli (1930) : "Neutrino"

Fermi (1934) : Theory of $\beta$-decay: $L_{int} = \frac{G_F}{\sqrt{2}} \bar{p} \gamma_\mu n \bar{e} \gamma^\mu \nu + h.c.$

Lee, Yang, Wu (1956) : Parity Revolution

Sudarshan & Marshak (1957) : V-A Form

Feynman & Gell-Mann (1957) : Universal current $\times$ current theory

The story of weak interactions starts with Henri Becquerel’s discovery of radioactivity in 1896 and its subsequent classification into alpha, beta and gamma decays of the nucleus. But the real understanding of beta-decay in the sense we know it now came only after Enrico Fermi invented a physical mechanism for the beta-decay process.

The basic ingredient for Fermi’s theory had been provided by Wolfgang Pauli. To solve the puzzle of the continuous energy spectrum of the electrons emitted in the beta-decay of the nuclei, Pauli had suggested that along with the electron, an almost massless particle also was emitted. Fermi succeeded in incorporating Pauli’s suggestion and thus was born the theory of weak interactions. Fermi also named Pauli’s particle as neutrino.

Drawing an analogy with QED where the basic interaction is the emission of a photon by an electron, Fermi pictured the weak interaction responsible for the beta-decay of the neutron as the emission of an electron-neutrino pair, the neutron converting itself into a proton in the process.

This theory of weak interactions proposed by Fermi purely on an intuitive basis in 1934 stood the ground for almost 40 years until it was replaced by Standard Model. However an important amendment to Fermi’s theory came in 1956. This was the discovery of parity violation in weak interactions by Lee, Yang and Wu. But Fermi theory survived even this fundamental revolution and the only modification was to replace the vector interaction by an equal mixture of vector (V) and axial vector (A) interaction. This is the V-A form proposed by Sudarshan and Marshak and others.

During 1947-55, many new particles such as muons, pions, kaons and hyperons were discovered and all of them were found to decay by weak interactions. In fact parity revolution itself was triggered by the famous tau-theta puzzle in the decays of the kaons which was the culmination of the masterly phase-space plot analysis of the three-pion decay mode.
of the kaon by Dalitz. The field of weak interactions thus got enriched by a multitude of phenomena, of which nuclear beta-decay is just one. Weak interaction is indeed a universal property of all fundamental particles.

Remarkably enough, all the weak phenomena, namely the weak decays of all the particles could be incorporated in a straight-forward generalization of the original Fermi interaction. This was achieved by Feynman and Gell-Mann (1957) in the form of the current $x$ current interaction:

$$L_{int} = \frac{G_F}{2\sqrt{2}} (J^+ \mu^- J^- \mu^+ + J^- \mu^- J^+ \mu^+)$$

$$J^+ \mu^- = \frac{1}{2} \bar{u} \gamma_\mu (1 - \gamma_5) d + \frac{1}{2} \bar{\nu} \gamma_\mu (1 - \gamma_5) e + \ldots$$

$$J^- \mu^- = \frac{1}{2} \bar{d} \gamma_\mu (1 - \gamma_5) u + \frac{1}{2} \bar{\epsilon} \gamma_\mu (1 - \gamma_5) \nu + \ldots$$

A fundamental experimental discovery - the discovery of CP violation was made by Fitch and Cronin in 1964, in the weak decays of neutral kaons. This asymmetry in the basic laws of nature and its ramifications in Cosmology are current topics of research.

The story of weak interactions is not complete without due recognition of the neutrino, especially because of more recent developments to be described later.

Pauli proposed the neutrino in 1930. Although because of the success of Fermi’s theory based on neutrino emission in explaining quantitatively all the experimental data on nuclear beta decays, there was hardly any doubt (at least in theorists’ minds) that neutrinos existed, a direct detection of the neutrino came only in 1956. This achievement was due to Cowan and Reines who succeeded in detecting the antineutrinos produced from fission fragments in nuclear reactors.

Subsequently, it became possible to detect the neutrinos from the decays of pions and kaons produced in high-energy accelerators. It is by using the accelerator-produced neutrinos that the important experiment proving $\nu_\mu$ not to be the same as $\nu_e$ was done.

Further, even neutrinos produced by cosmic rays were detected. The underground laboratory (of TIFR) at the deep mines of the Kolar Gold Fields was one of the first to detect cosmic-ray produced neutrinos. This was in 1965.
0.2.3 Strong Interactions

Yukawa (1934)
Heisenberg; Isospin Symmetry
Powel, Occialini . . .: Discovery of \( \pi \) (1947)
\( \Delta \) resonance: Fermi (1952)
Chew-Low Theory: (1954)
Discovery of Strangeness: Gell-Mann & Nishijima (1955)
Resonances (1957-65)
S-matrix Theory (1957-62): G.F. Chew
\( SU(3) \): \{ Sakata, Gell-Mann, Neeman (1961) \\
Discovery of \( \Omega^- \) (1964) \}
Quarks: Gell-Mann, Zweig (1964)
Current algebra, PCAC, Chiral symmetry (1965-70)
Scaling in DIS and partons: Bjorken, Feynman (1967)
SLAC expts: Taylor, Friedman, Kendal (1967)
Discovery of Asymptotic Freedom of NAGT & Birth of QCD (1973)

Strong interactions proved a harder nut to crack. After the discovery of the neutron and the recognition of the strong nuclear force of range 10 Fermi, Yukawa (1934) propounded his famous theory of exchange of a meson of mass about 100 MeV as the mechanism of this short-range strong interaction. Thus Dirac’s quantization of the electromagnetic field in 1927 which was the birth of QFT, inspired the creation of the QFT of weak interactions by Fermi and strong interactions by Yukawa, within the space of another 7 years.

However there was a period of confusion. The disentanglement of the strongly interacting pion (the Yukawa meson) from the weakly interacting muon took many years and it was finally resolved only in 1947 when Powel and Occialini unambiguously discovered the pi-mu decay chain. The discovery of muon is of great importance since the modern puzzle of the "generations" starts from the muon.

The next important milestone was the invention of the notion of "isospin" by Heisenberg in 1935 (?), motivated by the equality of the pp, pn and nm forces. This is the forerunner of all the internal symmetries that came later and that play such a fundamental role in present-day Standard Model. Although Yukawa made a successful prediction of the pion on the basis of a QFT for strong interaction, further progress was stalled because the interaction was too strong to be treated by perturbative methods. The impetus provided by the nucleon-pion resonance Delta (1238) (discovered by Fermi and Herbert Anderson in 1954) led to the partially successful Chew-Low theory that helped to understand the Delta
resonance. Historically this theory was important since it was the forerunner of the bootstrap model for hadrons. The 60’s were the golden age of hadrons. Hundreds of them were discovered and under the influence of this deluge of particles, QFT was declared dead and an alternate philosophy called S-matrix theory was proposed, its chief proponent being G F Chew. Many important ideas were developed under its banner: dispersion relations, Regge poles, bootstrap, nuclear democracy etc. Ultimately this proved to be a dead end. And a different line of attack spearheaded by Gell-Mann proved more successful. Starting with SU(3), this led to current algebra, and then to quarks, which finally led, via scaling in deep inelastic lepton-hadron collisions and asymptotic freedom to Quantum Chromodynamics (QCD). So, back to QFT even for strong interactions. However one must not conclude the S-matrix approach was a complete failure. Although it was a failure for hadrons, it is this approach that gave birth to String Theory! More about that later.

We now turn to a somewhat more detailed version of the tortuous history of the discovery of quarks as the constituents of the hadron.

Let us start with Heisenberg’s isospin symmetry which is based on the SU(2) group. The strange behaviour of the kaons and hyperons discovered in cosmic rays (strong production rates and weak decay rates) in the 50’s led to the discovery of a new quantum number strangeness by Gell-Mann and Nishijima in 1955. This is the first new hadronic “flavour” to be discovered— to use the modern parlance. Sakata and his collaborators invented the SU(3) group symmetry underlying all the hadrons. This was a consequence of their speculation that all the hadrons (strange as well as nonstrange) were composed of three basic hadrons p,n and $\lambda$ (the strange baryon). A more elegant and highly successful classification of all the hadrons under Sakata’s SU(3) was achieved by Gell-Mann and Neeman in 1961 when they realised that p,n and $\lambda$ together with 5 other baryons belonged to the octet representation (The Eightfold Way) of SU(3) rather than the triplet as originally proposed in the Sakata model. The discovery of $\Omega^-$ in 1964 confirmed the eightfold way and the SU(3) symmetry.

But then the following question arose. Eventhough p,n and $\lambda$ were not a triplet, SU(3) group has a triplet, which is the fundamental representation of SU(3). Where are they? Here one must describe an event that occurred in Bangalore in August 1961. The first TIFR Summer School in Theoretical Particle Physics was held in the Indian Institute of Science Campus at Bangalore. Dalitz and Gell-Mann were the lecturers. Apart from graduate students, senior physicists like H J Bhabha, M G K Menon and S N Biswas were also in the audience. Gell-Mann lectured on SU(3) and the Eightfold Way, fresh from the anvil, even before they were published. During one of the lectures, Dalitz questioned him about the triplets. Why is he ignoring them? Gell-Mann managed to evade it, inspite of Dalitz’s repeated questioning. If Gell-Mann had answered the question directly, quarks would have been born in Bangalore in 1961 instead of having to wait for another three years. If any of the other Indian participants had succeeded answering, we would have got the quarks and this would have been a major Indian contribution. This is the Missed Opportunity II.

Gell-Mann and Zweig independantly proposed the idea of quarks in 1964, but it took many years before quarks emerged as physical entities. Gell-Mann himself was tentative
in his proposal; the title of his published paper was "A schematic model for hadrons". He took the point of view that quarks are only mathematical. The three quarks $u,d,s$ replaced $p,n,\lambda$ of Sakata as the fundamental triplet of SU(3) and all the hadrons are to be regarded as composites made of quarks and antiquarks.

The chief reason for the reluctance to accept quarks as constituents of hadrons was the prevalent S-matrix philosophy at that time. The idea of some strongly interacting particles being more elementary than others was repugnant to the whole scheme of nuclear democracy. G F Chew in a lecture at The Tata Institute of Fundamental Research, Bombay in 1967 (?) even claimed to be able to prove that because of relativity and quantum mechanics no constituent more elementary than the nucleon and other hadrons was possible.

Inspite of this quark-phobia there were a few bold souls that took the idea of physical quarks as constituents of hadrons seriously and worked out the consequences. One may mention the names of A N Mitra, G Morpurgo and R H Dalitz among others. In particular Dalitz who was the rapporteur for the Berkeley conference in 1965 (?) (one of the famous Rochester series which later became the the Biennial International Conference in High Energy Physics), instead of reporting the spin-parity determination for the recently discovered hadronic resonances, as he traditionally did with consummate skill and thoroughness, surprised everybody by reporting how all the spin-parity as well as other quantum numbers of the hadrons agreed beautifully with the quark model.

However, although hadronic spectroscopy did give strong evidence for the correctness of the quark hypothesis and the constituent quark model, there was no clinching evidence for its correctness.

Meanwhile, Gell-Mann’s current algebra programme of exploiting mathematical quarks to abstract the properties of the weak and electromagnetic currents of the hadrons paid dividends. Coupled with the notion of PCAC (Partially Conserved Axial Current), current algebra supplied a temporary theoretical framework for the study of hadrons.

Quark model got a big boost when SU(6) symmetry was discovered by Gursey,Radicati,Sakita and others. Since each of the three spin-1/2 quarks has two spin states, there are a total of six states and SU(6) symmetry follows if one ignores spin-dependant forces between the quarks. The success of SU(6) brought quarks nearer to physical reality.

But a very serious contradiction developed soon. This is the conflict of the apparent total symmetry of the three-quark wave function in the baryonic ground state with the antisymmetry requirement of Fermi-Dirac statistics. As a simple example, consider the doubly charged Delta(1238) which is a spin-3/2 baryon made of three u quarks. The wave function of the three u quarks in the ground state contains a symmetric spatial part corresponding to zero relative orbital angular momenta and a symmetric spin part corresponding to total spin 3/2.

There was good phenomenological support for the assumption of symmetric spatial part.
SU(6) symmetry assigned both the spin-1/2 octet baryons and the spin-3/2 decimet baryons to a single 56-dimensional representation. Hence Delta (1238) and the nucleon must have the same spatial part of the quark wave function. If this spatial wave function were not symmetric, it would have nodes corresponding to higher relative orbital angular momenta for the quarks and such a node in the spatial wave function would have been seen in the form factor of the proton. This argument developed by A N Mitra and R Majumdar ruled out the nodes and hence favoured the symmetrical spatial wave function.

But then the total wave function of the three quarks is symmetric under the interchange of space and spin variables, thus violating the antisymmetry requirement of the wave function of the three identical fermions (uuu). Antisymmetry was restored by the invention of a new quantum number, called "colour", which is three-valued, and the assignment of an antisymmetric colour wave function for the three bound quarks. For, the total wave function is now a product of space, spin and colour parts and the total is antisymmetric. Greenberg played an important role in the solution of this statistics problem, although his original proposal was that quarks were parafermions of rank three. It was Nambu who suggested the idea of a three-valued quantum number, which was later called colour by Gell-Mann.

Quarks became "real" only after two important experimental discoveries that came later—scaling in deep inelastic scattering (in late 60’s) and \( \psi \), the bound state of charm quark \( c \) and antiquark \( \bar{c} \) in 1974. Most of the sceptics started believing in the reality of quarks only after these developments.

The ultimate triumph of quarks has a parallel in the history of atoms. There were sceptics who did not believe in the reality of atoms—Mach, Ostwald and others. Boltzman waged a heroic fight against their conservative notions, but the battle was won only after Perrin verified Einstein’s formula for Brownian motion based on the reality of atoms.

### 0.2.4 Summary of HEP before the Standard Model (before circa 1971)

Putting together the ideas of subsections (2.1)-(2.3), we have

\[
L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{e} \left[ i\gamma_\mu \left( \partial^\mu - ieA^\mu \right) - m_e \right] e + i\bar{\nu}_e \gamma_\mu \partial^\mu \nu_e + \bar{\mu} \left[ i\gamma_\lambda \left( \partial^\lambda - ieA^\lambda \right) - m_\mu \right] \mu + i\bar{\nu}_\mu \gamma_\lambda \partial^\lambda \nu_\mu + \bar{u} \left[ i\gamma_\mu \left( \partial^\mu + \frac{2}{3} ieA^\mu \right) - m_u \right] u + \bar{d} \left[ i\gamma_\mu \left( \partial^\mu - \frac{i}{3} eA^\mu \right) - m_d \right] d + \bar{s} \left[ i\gamma_\mu \left( \partial^\mu - \frac{1}{3} ieA^\mu \right) - m_s \right] s + \frac{G_F}{2\sqrt{2}} \left( J^+_\mu J^-_\mu + J^-_\mu J^+_\mu \right)
\]
+ strong interactions among quarks whose nature was not known.

where,

\[ J^\lambda_\lambda = \frac{1}{2} \bar{e}_\lambda \gamma(1 - \gamma_5) \nu e + \frac{1}{2} \bar{\mu}_\lambda \gamma(1 - \gamma_5) \nu \mu + \frac{1}{2} (\bar{d} \cos \theta_c + \bar{s} \sin \theta_c) \gamma(1 - \gamma_5) u \]

\[ J^\lambda_+ = (J^-_\lambda)^\dagger \]

and

\[ \sin \theta_c \approx 0.22. \]

Here we have the Lagrangian density describing the electromagnetic and weak interactions of the three quarks \( u, d, s \) and the four leptons \( e, \mu, \nu_e, \nu_\mu \). The existence of these quarks as the constituents of the hadrons had been inferred from hadron spectroscopy through a clever guess. However nobody knew the form of the strong interaction among the quarks which is responsible for binding them into hadrons. So, it is left unspecified. The weak current \( J^\lambda_- \) has been written in term of the Cabibbo-rotated quarks, in order to incorporate the weak decays of the strange hadrons. CP violation was experimentally known, but not understood theoretically.

### 0.2.5 Brief History of The Standard Model

| Theory | Experiment |
|--------|------------|
| 1954   | Nonabelian gauge fields |
| 1964   | Higgs mechanism |
| 1967   | EW Theory |
| 1971   | Renormalizability of EW Theory |
| 1973   | Asymptotic freedom → QCD |
| 1974   | Charm |
| 1975   | \( \tau \)-lepton |
| 1977   | Beauty |
| 1978   | polarized \( e d \) expt |
| 1979   | 3 jets |
| 1983   | W,Z Bosons |
| 1994   | Top |
| 1998   | \( \nu \) mass |

The major events which culminated in the construction of the Standard Model are shown in this table in chronological order. Using nonabelian gauge theory with Higgs mechanism, the Electroweak (EW) theory was already constructed in 1967, although it attracted the attention of most theorists only after another 4 years, when it was shown to be renormalizable. The discovery of asymptotic freedom of nonabelian gauge theory and the birth of QCD in 1973 were the final inputs that led to the full standard model.
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On the experimental side, the discovery of scaling in Deep Inelastic Scattering (DIS) which led to the asymptotically free QCD and the discovery of the neutral current which helped to confirm the EW theory can be regarded as crucial experiments. To this list, one may add the polarized electron deuteron experiment which showed that SU(2) x U(1) is the correct group for EW theory, the discovery of gluonic jets in $e^+e^-$ annihilation confirming QCD and the discovery of W and Z in 1983 that established the EW theory. The experimental discoveries of charm, $\tau$, beauty and top were also fundamental for the concrete 3-generation SM, with cancellation of anomalies and CP violation incorporated (although the last feature was theoretically discovered by Kobayashi and Maskawa in 1974 itself).

However note the blank after 1973 on the theoretical side. Theoretical physicists have been working even after 1973 and experiments also are being done. But the tragic fact is that none of the bright ideas proposed by theorists in the past 30 years has received any experimental support. On the other side, experiments have only been confirming the theoretical structure completed in 1973. None of the experiments done since 1975 has made any independent discovery (except the discovery of neutrino mass). If this continues for long, it will be too bad for the future of HEP. I shall come back to this point later.

### 0.2.6 Brief Physics Behind the History

First about the electroweak sector. The idea of using the beautiful Yang-Mills nonabelian gauge field theory to construct weak interactions is an old one, but it was Glashow who identified SU(2)xU(1) as the correct gauge group for an electroweak theory. However the stumbling block was the masslessness of the gauge quanta which would contradict the short range of weak interactions. So the gauge symmetry had to be broken. Although the idea of spontaneous breakdown of symmetry (SBS) was around, Goldstone’s theorem which predicted the existence of a massless scalar boson (the Nambu-Goldstone boson) as the consequence of SBS prevented the application of SBS to construct any physically relevant model. Thus, apparently one had to choose between the devil (massless gauge boson) and the deep sea (massless scalar boson). It was Higgs who showed that this is not correct; there is no Goldstone theorem if the symmetry that is spontaneously broken is a gauge symmetry. The devil drinks up the deep sea and becomes a regular massive gauge boson. This is called Higgs mechanism. By combining SU(2)xU(1) Yang-Mills gauge theory with Higgs mechanism Weinberg and Salam independently constructed the successful electroweak theory.

At this point one could ask why SBS? Why not break the gauge symmetry explicitly? The answer is renormalizability. Although the original Yang-Mills theory with massless gauge fields is renormalizable, Yang-Mills theory with massive gauge bosons and with explicit breaking of the symmetry is nonrenormalizable. Gerard t’Hooft and Veltman proved that the renormalizability of the original Y-M theory is not lost if the gauge bosons acquire masses through SBS.

There was one further problem - the problem of chiral anomalies originally discovered by Adler, Bell and Jackiw before the advent of the standard model. These anomalies would make the electroweak theory nonrenormalizable unless they are cancelled suitably. This is what happens; the leptonic and the quark anomalies cancel each other.

Fermi’s theory of weak interactions was not renormalizable and construction of a renor-
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malizable theory of weak interactions had remained as one of the fundamental problems in HEP. The SU(2)xU(1) gauge theory with SBS solved that problem.

The electroweak theory based on SU(2)xU(1) gauge group links weak and electromagnetic interactions together. Here a remark on this unification is in order. Apart from any aesthetic or other considerations, there is an important physical reason for linking weak and electromagnetic interactions. It is possible to construct a renormalizable theory of weak interactions alone. But since such a theory would necessarily contain charged vector bosons (as a part of the gauge boson multiplet), one has to have a meaningful theory for these electrically charged vector bosons. It has been known for a long time that the theory of the charged vector bosons (spin 1 particles) is afflicted with many diseases. All these problems are neatly solved, once the charged vector bosons and the photon (along with another neutral massive vector boson in the case of SU(2)xU(1)) are combined into the gauge multiplet. It is the gauge symmetry that cures the diseases.

In electroweak theory, Maxwell’s laws of electromagnetism have been incorporated into a more general system of laws which unify electrodynamics with weak interactions. The implications of this fundamental unification are yet to be fully understood or realized. There is no doubt that the consequences of this unification will be as profound and far-reaching as Faraday’s unification of electricity and magnetism and of Maxwell’s unification of electrodynamics with optics.

Let us next go to QCD. Why QCD? What is the reason for believing QCD to be the theory of strong interactions?

As already mentioned in Sec 2.3, for a time physicists had given up QFT as a useful approach for understanding strong interactions and taken to the S-matrix approach. So what caused the resurgence of QFT in strong interaction physics and what is the reason for going for this particular nonabelian gauge field theory based on SU(3), which is QCD?

The reason came from an experiment, the so-called deep inelastic scattering (DIS) of electrons on the nucleon, in which the virtual photon of large momentum-transfer-squared $q^2$ emitted by the electron probes the structure of the nucleon. It was found that, as observed by the high $q^2$ probe, the nucleon behaves as if it were composed of free, point-like constituents (called partons by Feynman). The electron scatters off each parton, elastically and incoherently. The incoherent sum of all parton cross-sections gave a very good description of the experimental results. It was a remarkable discovery that such a complicated process in which many hadrons are produced in the final state could be described in such a simple fashion. This discovery was originally made at SLAC with electron scattering and later similar results were found also for the DIS of neutrinos on nucleon at CERN.

This phenomenon has a rather close resemblance to Rutherford’s famous alpha particle scattering experiments which led to the discovery of the nucleus inside the atom. Thomson’s spread-out atomic model would lead to soft scattering (i.e. small scattering angles) only. Experimentally, Rutherford and collaborators found hard scattering (large scattering angles), thus showing the presence of “point-nucleus” inside the atom. In the same way, in DIS, even for large $q^2$ (i.e. large scattering angle), scattering was observed to take place, in contrast to what would be expected for a spread-out nucleon. This led to the discovery of point-like constituents deep inside the nucleon.

More detailed study of the experimental data revealed that these partons are in fact quarks; they seemed to have the same spins and charges as expected for quarks.
Attention should now be turned to the adjective 'free'. In addition to being point-like, the quark-partons behave as if they are free. If they were interacting, the free-parton model for DIS would not have worked.

Now the quarks are bound by tremendous attractive forces to make up the nucleon. So the interaction between quarks should really be superstrong. And yet, when observed through high $q^2$ probes, this superstrong interaction weakens to such an extent that the quarks behave as free particles.

This was a mystery. On the other hand, this provided an important clue about the nature of the strong interaction itself. One could now say that any candidate theory of strong interactions should satisfy this property, namely it should tend to a free field theory at high $q^2$. Is there any such theory?

In QFT, it is the renormalization group which provides the required technique to answer this question. By using renormalization group one can define a momentum-dependent coupling constant, also called running coupling constant. So what we need is a theory in which this coupling constant goes to zero for large momenta. Such a theory is called asymptotically free, i.e. it tends to a free field theory for asymptotic momenta.

To cut the long story short, it was soon discovered that none of the conventional field theories such as $\phi^4$, Yukawa interaction $\bar{\psi}\psi\phi$ or QED $\bar{\psi}\gamma_{\mu}\psi A_{\mu}$ is asymptotically free. Of all the renormalizable quantum field theories, only nonabelian gauge theory was found to possess the unique distinction of being asymptotically free. The characteristic nonlinearity of Y-M fields, in particular the cubic vertex is the essential ingredient that makes the theory asymptotically free.

So, asymptotically free YM theory emerged as the only choice for a theory of strong interactions. Since the colour degree of freedom with three colours was already there (see Sec 2.3), the gauge group was taken as SU(3) acting on the 3 colours and QCD was born.

Let us next look at the matter sector. All the nucleons are made of u and d quarks. With electrons to go around the nuclei, all the atoms can be made. Even the weak interactions are included once the $\nu_e$ is given. Hence with the quartet made up of a doublet of quarks and a doublet of leptons ($u, d, \nu_e, e$), apparently the whole Universe can be made. But if the Universe started as a fireball as is claimed in the Big Bang model of cosmology, it would have started with equal amount of matter and antimatter, whereas the present-day Universe seems to be made entirely of matter. Sakharov speculated that this asymmetry between matter and antimatter could have been created later during the evolution of the Universe. One of the necessary conditions for this is CP violation which certainly exists in HEP. But does the SM have it? Yes, if the above matter quartet is repeated atleast twice more. This was the theoretical discovery made by Kobayashi and Maskawa. CP violation arises from the complex coupling constants, but often the phases can be absorbed into the definition of the fields. All the phases cannot be absorbed, if there exist atleast three quartets. That is why we have, in addition, ($c, s, \nu_{\mu}, \mu$) and ($t, b, \nu_{\tau}, \tau$). Together these are now called the three generations of fermions and all of them have been experimentally proved to exist.
The complete Lagrangian of the Standard Model is given by

$$\mathcal{L} = -\frac{1}{4} \left( \partial_\mu G^i_\nu - \partial_\nu G^i_\mu - g_3 f^{ijk} G^j_\mu G^k_\nu \right)^2$$

$$-\frac{1}{4} \left( \partial_\mu W^a_\nu - \partial_\nu W^a_\mu - g_2 \epsilon^{abc} W^b_\mu W^c_\nu \right)^2 - \frac{1}{4} \left( \partial_\mu B_\nu - \partial_\nu B_\mu \right)^2$$

$$- \sum_n \bar{q}_n L \gamma^\mu \left( \partial_\mu + ig_3 \frac{\lambda^i}{2} G^i_\mu + ig_2 \frac{\tau^a}{2} W^a_\mu + i \frac{g_1}{6} B_\mu \right) q_n L$$

$$- \sum_n \bar{u}_n R \gamma^\mu \left( \partial_\mu + ig_3 \frac{\lambda^i}{2} G^i_\mu + i \frac{g_2}{3} \tau^a B_\mu \right) u_n R$$

$$- \sum_n \bar{d}_n R \gamma^\mu \left( \partial_\mu + ig_3 \frac{\lambda^i}{2} G^i_\mu - i \frac{g_1}{3} B_\mu \right) d_n R$$

$$- \sum_n \bar{l}_n L \gamma^\mu \left( \partial_\mu + ig_2 \frac{\tau^a}{2} W^a_\mu - i \frac{g_1}{2} B_\mu \right) l_n L$$

$$- \sum_n \bar{e}_n R \gamma^\mu \left( \partial_\mu - ig_1 B_\mu \right) e_n R$$

$$+ \left| \left( \partial_\mu + ig_2 \frac{\tau^a}{2} W^a_\mu - i \frac{g_1}{2} B_\mu \right) \phi \right|^2 - \lambda (\phi^+ \phi - v^2)^2$$

$$- \sum_{m,n} \left( \Gamma^u_{mn} \bar{q}_m L \phi^+ u_n R + \Gamma^d_{mn} \bar{q}_m L \phi d_n R + \Gamma^c_{mn} \bar{l}_m L \phi c_n R + h.c. \right)$$

The first three terms describe the pure gauge field part of the SU(3)xSU(2)xU(1) non-abelian gauge theory. The next group of terms describes the fermions. The left-handed SU(2) doublet quark of the nth generation (n=1,2,3) is denoted by \(q_n L\) and the corresponding right-handed singlets are denoted by \(u_n R\) and \(d_n R\). For the leptons, \(l_{nL}\) is the doublet while \(e_{nR}\) is the singlet.

The last group of terms describes the Higgs field and its interactions with itself, with the gauge bosons and with the fermions which are respectively responsible for spontaneous symmetry breaking, generation of W and Z masses and generation of masses for the quarks and leptons. The \(\Gamma\)'s are complex numbers and hence lead to CP violation.

**Standard Model** is the basis of all that is known in HEP. Although it is believed that SM is only an effective low energy description and it is to be replaced by something beyond, so far SM has resisted all attempts at overthrowing it. All the precision tests performed so far are in beautiful agreement with SM. All the experimental signals that seem to signal its overthrow, disappear in about 6 months – 1 year, except one signal, namely the signal that neutrino has mass. Neutrino is the only particle, a part of which, its right-hand part \(\nu_R\), has zero quantum number and so it is not acted on by the SM group : \(SU(3) \times SU(2) \times U(1)\). So, \(\nu_R\) is banished from SM and as a consequence, the mass of neutrino within SM is zero.
That is why $\nu$ having a mass is regarded as a signal beyond SM.

Note the almost complete absence of Indian contribution. (Of course Salam’s name is there, as a major contributor to the construction of the $SU(2) \times U(1)$ electroweak theory. We shall eschew parochialism and include him since he is from the subcontinent.) Let me give a little bit of my side of the story here. I was aware of the beauty of Yang-Mills (YM) theory from the time of Sakurai’s famous Annals of Physics paper of 1960 and I realized the importance of YM theory to weak interaction ever since I listened to Veltman in the Varenna School in 1964 where he stressed the conservation of weak currents. When Weinberg’s paper with the quaint title ”A model of Leptons” came out in Physical Review Letters in 1967, I was immediately convinced that this was the correct theory for weak interactions and began to work on it. I still missed the boat completely because I was too muddle-headed and stupid. Instead of trying to renormalize the divergences away (which we now know to be the right thing, after ’t Hooft showed it in 1971), I was trying to generate the strong interactions from the divergences. I was too ambitious and missed the real thing.

Mine was a double failure. Since I was very familiar with partons, scaling and the quark-model sum rules that the DIS structure functions were found to obey, I was fully aware of the serious problem that was staring at everybody’s face, namely, how to reconcile the free-quark behavior exhibited by the DIS structure functions with the superstrong interactions of quarks inside the hadrons. The techniques that were subsequently used to effect the reconciliation were also known to me. In fact I was giving a series of lectures on Wilson’s RG ideas and the Callan-Symanzik $\beta$ function at TIFR, when the preprints of Politzer and Gross-Wilczek proving asymptotic freedom in YM theory came out.

So, I failed on both fronts: on both the two most important QFT discoveries of the latter part of the 20th century - namely renormalizability of YM theory with SSB and asymptotic freedom of YM theory - both of which being the essential theoretical inputs in the construction of the SM of HEP. This is Missed Opportunity III.

Forgetting about myself, it was a collective failure of the Indian High Energy Physicists. By that time we had strong theory groups in the country and we should have made significant contributions in the construction of SM, but we did not. In my opinion, this is a glaring failure and we cannot forgive ourselves for it.

The author apologises for the above intrusion of his personal story. There is no other way of conveying the flavour and excitement of the discoveries of the early 70’s and there may be lessons to be learnt in this story of failures.

0.2.8 Discovery of Neutrino Mass

Neutrino mass was discovered in 1998 through neutrino oscillations by the SuperKamioka group in Japan. This discovery was made in the study of cosmic-ray produced neutrinos, called atmospheric neutrinos. Inspite of the fact that the Indian group was a pioneer in
atmospheric neutrino physics being the first to detect the atmospheric neutrinos in the KGF mines in 1965, we lost the initiative and missed the chance to make this fundamental discovery. This is **Missed Opportunity IV**.

Indications for neutrino oscillations and neutrino mass came first as early as 1970 from the pioneering solar neutrino experiments of Davis et al in USA which were later corroborated by many other solar neutrino experiments. But the clinching evidence that solved the solar neutrino problem in terms of neutrino oscillations had to wait until 2002 when the Sudbury Neutrino Observatory could detect the solar neutrinos through both the neutral-current as well as the charged-current modes.

### 0.3 Future of HEP

Standard Model is not the end of the story. There are too many loopholes in it. First of all, there are many interesting questions and unsolved problems within SM:

- Higgs and symmetry breaking
- QCD and Confinement
- CP and its violation
- Neutrinos and their masses and mixings

The celebrated Higgs mechanism that breaks the SU(2)xU(1) gauge symmetry and gives masses to all the elementary particles according to our present understanding of the SM comes with a price. A massive scalar boson called Higgs boson has to exist but it has not been seen experimentally inspite of intensive search. Maybe it will be seen in the LHC (Large Hadron Collider) that is being built at CERN. Until it is seen, our understanding of the electroweak sector of the SM will remain incomplete.

In the QCD sector, colour confinement has not yet been proved. Asymptotic freedom of QCD and its implied weakness of the QCD coupling for large momenta led to the recognition of QCD as the theory of strong interactions. But its complement, namely the strong QCD coupling for small momenta necessitates nonperturbative understanding of QCD. That is a tall order, for our understanding of QFT has not progressed beyond perturbation theory. Remember all the low energy hadronic physics falls into this regime of small momentum transfer and hence strong coupling and QCD has contributed precious little to this physics. Inspite of enormous work done (lattice QCD and fast computers) our understanding of the fundamental mechanism of confinement remains incomplete. One is tempted to repeat the Churchillian remark: "In no other field has so much effort been wasted towards so little effect."

Although CP violation exists in the SM with 3 generations of fermions, its confrontation with experiments is not complete. Such a confrontation is in progress through experiments in the "B factories". There is a serious problem with QCD because of the strong CP violation that it predicts. This problem is not yet solved.

As already mentioned, the discovery of neutrino mass requires us to go beyond SM, but we do not know the precise direction to take. An attractive possibility is the "see-saw"
mechanism that naturally explains the smallness of the neutrino mass simultaneously linking
the tiny neutrino mass to superheavy mass scales and to physics beyond SM. Hence the name:
see-saw. This mechanism requires the neutrino to be a Majorana fermion for which particle
is the same as antiparticle (in contrast to a Dirac fermion). The only experimental test for
the Majorana nature of the neutrino is the observation of neutrinoless double beta decay for
which no definitive evidence has been established so far.

The solution of these problems sets the agenda of HEP for the immediate future.

However, the biggest loophole in SM is the omission of gravitation, the most important
force of nature. Hence, it is now recognized that quantum gravity (QG) is the next frontier
of HEP, and that the true fundamental scale of physics is the Planck energy $10^{19}$ Gev, which
is the scale of QG.

We are now probing the region with energy $\leq 10^3$ GeV. One can see the vastness of
the domain one has to cover before QG is incorporated into physics. In their attempts to
probe this domain of $10^3 - 10^{19}$ Gev, theoretical physicists have invented many ideas such
as supersymmetry and hidden dimensions and based on these ideas, they have constructed
many beautiful theories, the best among them being the string theory, which may turn out
to be the correct theory of QG.

**String Theory**

String theory is the high-energy-physicist’s first successful attempt to construct a relativistic quantum field theory which is finite even after including gravitation. This was the reason for all the excitement and fuss when it first hit the headlines in 1984. For the first time in history we are glimpsing at a solution to an age-old problem, namely the problem of constructing a quantum theory of gravity. So far, any attempted theory of gravity was afflicted with the worst divergence diseases known in quantum field theory - much worse than the divergences in QED, QCD and electroweak dynamics all of which were renormalizable divergences. Quantum gravity is not renormalizable. String theory solves the problem by a nonlocal generalization of the usual local quantum field theory based on point particles. A point particle is replaced by a one-dimensional object known as a string (either a open or closed string), with a length of the order of the Planck length ($10^{-33}$ cm).

Here a brief history of string theory is in order. String theory was born in attempts to construct the hadronic S-matrix. Starting with Veneziano’s discovery (1968) of a formula for the hadronic scattering amplitude which had both Regge behaviour and crossing symmetry the S-matrix approach reached its pinnacle in the construction of the dual model. However, ironically enough, just at that juncture, Nambu (1969) identified the spectrum of the dual model with the vibrations of a string and the S-matrix approach was soon abandoned in favour of a canonical dynamical formalism for the string.

Remarkable discoveries followed soon: supersymmetry (in two dimensions) was discovered in the attempt to include fermionic excitations in the string spectrum (Ramond 1971, Neveu and Schwarz 1971). Goddard, Goldstone, Rebbi and Thorn discovered in 1973 that a consistent relativistic quantum dynamics for the string required the number of space-time dimensions to be 26 and Gliozzi, Scherk and Olive showed that the same for a supersymmetric string required 10 dimensions. The point-particle limit of the open string theory was found to yield Yang-Mills gauge theory while the same limit of the closed string theory yielded gravitation (Neveu and Scherk 1972, Yoneya 1974).
In the hadronic context the above discoveries were regarded either as irrelevant or bizarre (especially the unseen higher dimensions). Because of these "troubles", the popularity of the strings waned after about 1974. An additional and important reason for the loss of interest in strings as a description for hadrons was the discovery of QCD which emerged as the basic theory of hadrons.

Meanwhile, motivated by the discovery of the connection of strings to gauge and gravitational fields in the point-particle limit, Scherk and Schwarz in 1974 proposed to liberate string theory from its original restricted hadronic context and apply the theory to the whole world and that liberated string theory from all the "troubles". All they had to do was to change the string length from $10^{-13}$ to $10^{-33}$ cm.

In 1984 Green and Schwarz discovered that chiral and gravitational anomalies cancel in the open superstring theory in 10 dimensions if the gauge group is SO(32) or E8E8. The discovery of this miraculous cancellation marked the start of the string revolution.

For local field theories there already exists the beautiful Kaluza-Klein idea of unification in which both 4-dimensional gauge forces and 4-dimensional gravity are derived from higher dimensional ($d$ larger than 4) gravity. The string-analogue of this phenomenon is the "heterotic string" discovered by Gross, Harvey, Martinec and Rohm in 1985, wherein open strings with Yang-Mills internal indices as well as pure gravity type closed strings can both be derived from pure gravity-type higher-dimensional closed strings. The construction of the heterotic string is a high-point of the ingenuity of theoretical physicists. Whether Nature utilizes them is yet to be seen.

Including the heterotic and the original open and closed strings there are now five string theories that are anomaly-free and consistent. But all of them live in 10 dimensions. How do we go from 10 to 4 dimensions? By compactification of 6 of the dimensions. How do we go from 10 to 4 dimensions? By compactification of 6 of the dimensions. But there are thousands of ways of doing this. Which is the correct way? Nobody knows for sure.

After the second string revolution of 94-96 initiated by Edward Witten, Ashoke Sen and others that led to breakthroughs such as the discovery of duality linking all the consistent string theories, string theory has become extraordinarily rich. It has metamorphosed into M theory and it now includes in its domain not only strings, but also membranes and multidimensional branes.

But, Physics is not theory alone. Even beautiful theories have to be confronted with experiments and either confirmed or thrown out. Here we encounter a serious crisis facing HEP. In the next 10-25 years, new accelerator facilities with higher energies such as the LHC ($\sim 10^4$ Gev) or the Linear Electron Collider will be built so that the prospects for HEP in the immediate future appear to be bright. Beyond that period, the accelerator route seems to be closed because known acceleration methods cannot take us beyond about $10^5$ GeV. It is here that one turns to hints of new physics from Cosmology, Astroparticle Physics and Nonaccelerator particle physics. However, these must be regarded as only our first and preliminary attack on the unknown frontier. These are only hints. Physicists cannot remain satisfied with hints and indirect attacks on the superhigh energy frontier.

**To sum up the situation:** There are many interesting fundamental theories taking us to the Planck scale and even beyond, but unless the experimental barrier is crossed, these will remain only as Metaphysical Theories. It follows that,

- either, new ideas of acceleration have to be discovered,
or, there will be an end to HEP by about 2020 AD.

Some of the ideas being pursued are laser beat-wave method, plasma wake field accelerator, laser-driven grating linac, inverse free electron laser, inverse Cerenkov acceleration etc. What we need, are a hundred crazy ideas. May be, one of them will work!

By an optimistic extrapolation of the growth of accelerator technology in the past 60 years, one can show that $10^{19}$ GeV can be reached before the end of the 21st century. (See my Calcutta talks)\(^1\) But, this is possible only if newer methods and newer technologies are continuously invented.

Another Way Out

In the past three years, another revolutionary idea is being-tried – namely to bring down Planck scale from $10^{19}$ GeV to $10^3$ GeV. This is the so called TeV scale gravity which uses large (sub-mm) extra dimensions. (If we cannot go up to the mountain top why not ask the mountain top to come down?) One version of this idea which is popular is due to Randall and Sundrum.

This is a very interesting field, with a bewildering variety of worlds that theorists can construct, as a scan of recent hep-net will show.

Is Nature so kind and considerate to us, that it would have brought down the Planck scale for our sake? Only Future can tell.

But, if this turns out to be correct, then Quantum Gravity and String Theory are not some distant theories relevant at $10^{19}$ GeV, but they are immediately relevant at $10^3 - 10^5$ GeV. So, it becomes even more urgent to understand String Theories and assimilate them into Physics!

Preons

A brief look at the history of atoms, nucleons and then quarks would suggest that preons must be the next natural step. There may exist in Nature a never-ending layered structure.

As we already mentioned, in the hey-days of S-matrix and bootstrap philosophy in the early 60’s, it was even proposed that perhaps the end of the road was in sight and that no more constituent structure beyond the hadrons was possible. But the subsequent development of physics has shown this to be wrong. We now believe that hadrons are made of quarks. Are quarks, in turn, made of preons?

Many preonic models have been proposed but none is as yet required by experimental data. Down to a distance scale of $10^{-17}$ cm, quarks and leptons behave like point particles. Nevertheless, Nature might have already chosen one preonic model and future experiments might reveal it!

0.4 Status of HEP in India and Suggestions for the Future

Theory : There is extensive activity in HEP theory in the country, spread over TIFR, PRL, IMSc, SINF, IOP, HRI, IISc, Delhi University, Panjab University, BHU, NEHU, Gauhati

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\(^1\)Perspectives in High Energy Physics, Proceedings of the VIII HEP Symposium, Calcutta (1986), p 399; The Future of HEP, Particle Phenomenology in the 90’s, World Scientific (1992), p1
From Atoms to Quarks and Beyond: A historical panorama

University, Hyderabad University, Cochin University, Viswabharati, Calcutta University, Jadavpur University, Rajasthan University and a few other centres. Research is done in almost all the areas in the field (see Appendix). Theoretical HEP continues to attract the best students and as a consequence its future in the country appears bright. However, it must be mentioned that this important national resource is being underutilized. Well-trained HEP theorists are ideally suited to teach any of the basic components of Physics such as QM, Relativity, QFT, Gravitation and Cosmology, Many Body Theory, Statistical Mechanics, and Advanced Mathematical Physics since all these ingredients go to make up the present-day HEP Theory. Right now, most of these bright young theoretical physicists are seeking placement in the Research Institutions. Ways must be found so that a larger fraction of them can be absorbed in the Universities. Even if just one of them joins each of the 200 Universities in the country, there will be a qualitative improvement in physics teaching throughout the country. But, this will not happen unless the young theoreticians gain a broad perspective and train themselves for teaching-cum research careers. Simultaneously, the electronic communication facilities linking the Universities among themselves and with the Research Institutions must improve. This will solve the frustrating isolation problem which all the University Departments face.

Experiments:

Many Indian groups from National Laboratories as well as Universities (TIFR, VECC, IOP, Delhi, Panjab, Jammu and Rajasthan Universities) have been participating in 3 major international collaboration expts:

- $L3$ expt on $e^+e^-$ collisions at LEP (CERN)
- $D$ zero expt on $\bar{p}p$ collisions at the Tevatron (Fermilab)
- Heavy-ion collision expts at CERN and BNL

As a result of the above experience, the Indian groups are well poised to take advantage of the next generation of colliders such as LHC and Linear Collider. Already the Indian groups have joined the CMS and ALICE? international collaboration at LHC. It is also appropriate to mention here that Indian engineers and physicists have contributed towards the construction of LHC itself.

Thus, the only experimental program that is pursued sofar in the country is the participation of Indian groups in international accelerator-based experiments. This is inevitable at the present stage, because of the nature of present-day HEP experiments that involve accelerators, detectors, experimental groups and financial resources that are all gigantic in magnitude.

While our participation in international collaborations must continue with full vigor, at the same time, for a balanced growth of experimental HEP, we must have in-house activities also. Construction of an accelerator in India, in a suitable energy range which may be initially 10-20 GeV and its utilization for research as well as student-training will provide this missing link.

In view of the importance of underground laboratories in $\nu$ physics, monopole search, $p$ decay etc, the closure of the deep mines at KGF is a serious loss. It is planned to revive underground neutrino experiments in India. A multi-institutional neutrino collaboration
has been formed with the objective of creating the India-based Neutrino Observatory (INO) at a suitable site.

Finally, as pointed out in the last section, known methods of acceleration cannot take us beyond tens of TeV. Hence in order to ensure the continuing vigor of HEP in the 21st century, it is absolutely essential to discover new principles of acceleration. Here lies an opportunity that our country should not miss! I have been repeatedly emphasizing for the past 20 years that we must form a small group of young people whose mission shall be to discover new methods of acceleration.\footnote{IPR is already initiating research in this area and CAT is training young scientists in accelerator technology through SERC Schools.}

To sum up, a 4-way program for the future of experimental HEP in this country is suggested.

1. A vigorous participation of Indian groups in international experiments, accelerator-based as well as nonaccelerator-based.

2. Construction of an accelerator in this country.

3. Creation of an underground laboratory for nonaccelerator particle physics, especially neutrino physics.

4. A programme for the search for new methods of acceleration that can take HEP beyond the TeV energies.

\section*{0.5 Some Reflections on the Panorama of HEP}

\textbf{Twists and Turns of History}

First we reflect on some of the interesting twists and turns through which HEP has evolved over the years. There may be important lessons for the future in the past history.

One of the strange things in the history of HEP is what happened to internal symmetries such as isospin, strangeness, SU(3), baryon number and lepton number all of which were beloved quantum numbers of particle physicists. Since all these played major roles in the early history of particle physics, one would have thought these would be the building blocks on which the edifice of HEP would be erected.

But this is not what happened. Once the SM was in place, all these old symmetries lost their fundamental significance. The empirical importance of isospin (SU(2)) and the old flavour SU(3) is now understood to be merely due to the smallness of the u,d,s quark masses. The really fundamental internal symmetry forming the basis of all the HEP interactions through the gauge principle is the symmetry SU(3)xSU(2)xU(1) acting on an entirely different space! While SU(3) acts on colour space which has nothing to do with the old flavour space, SU(2) still has some connection with the old isospin but acts on the left handed parts of the quarks u and d and acts on heavy quarks as well as on leptons in contrast to the old isospin.

It is this twist and turn that converted pre-SM particle physics into post-SM HEP.

Another related twist and turn is the story of the triplet: the original Sakata triplet gave way to the quark triplet \((u,d,s)\) and finally to the colour triplet \((q_1,q_2,q_3)\)!
The interplay between the history of weak and strong interactions is also full of twists and turns. Yang-Mills theory was originally used by Sakurai to construct the theory of strong interactions through the old isospin symmetry and the old hypercharge and baryon number quantum numbers. But the more successful application of Y-M theory was in the construction of the electroweak theory which lay in the future, for that required the understanding of spontaneous breaking of symmetry (SBS). And SBS itself was first discovered in the context of strong interactions, namely the broken chiral symmetry with pion as the pseudo Nambu-Goldstone boson.

Chiral symmetry itself originates from the near-masslessness of the u and d quarks which is the origin of the old isospin too, as was already mentioned above.

Finally the cycle was completed by constructing the Y-M theory of strong interactions with colour SU(3) and without SBS!

Yet another twist and turn, followed by a fantastic jump, is the story of the string: hadronic string (at $10^{-13}$ cm) gave rise to the fundamental string (at $10^{-33}$ cm), with a jump by 20 orders of magnitude.

The story of baryon number B and lepton number L is even stranger. The conservation of B that is so basic for the stability of all matter is not an essential part of SM at all! Corresponding U(1) is not contained in the gauge group of SM. Conservation of B turns out to be an accidental consequence of the particle content of the SM. For, with the usual particle content of the SM (gauge bosons, quarks, leptons and the Higgs doublet) there is no way of writing a B-violating or L-violating renormalizable interaction. That is the reason why most of the attempts at going beyond the SM, such as GUT, SUSY or giving mass to neutrinos, all of which involve adding new particles, end up violating B or L or both.

**A meta-theorem on Higgs**

Scalar bosons have become the theoretician’s tool in building models. Whether one wants to build models going beyond SM or wants to explain some perceived discrepancy of experimental data with SM, one creates a new scalar sector and invokes the Higgs mechanism for SBS. Here is a theorem: One can construct a scalar sector to solve any problem in HEP! Consequently, hundreds or thousands of models have been constructed in the last 25 years, many with a similar number of scalar bosons. But not even a single one (even the original one required in the electroweak theory) has been seen experimentally! It is a great irony of Nature that, while QFT of the scalars is the simplest to teach and that is the way it is usually taught, none has been observed. Is there a fundamental problem with elementary scalars?

**Is there a Balmer formula?**

In the SM, all the 12 fermion masses are arbitrary parameters fixed only by experiment. Perhaps one has to extend SM to include a theory of generations for understanding the pattern of the fermion masses. Enormous amount of theoretical work has been done to attack this problem, but there is no memorable result.

However, in 1982, Yoshio Koide found a remarkable empirical relation:

$$m_e + m_\mu + m_\tau = \frac{2}{3} (\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2$$

which is satisfied to an accuracy of 1 part in $10^5$. There does not exist any other relation of comparable accuracy in all of HEP (except of course the precision results calculated from...
QED and Electroweak theory). But, to this day nobody has succeeded in deriving the Koide relation from any theory. Is this the much-needed Balmer formula which can serve as the guide post for discovering the correct theory of generations and thus going beyond the SM?

**A critique of strings**

String theory does not offer solutions to any known problem in HEP, such as the generation puzzle, the CP problem, the Higgs problem etc, nor does it give any clue to the various parameters of the standard model. This may require the correct choice of the six-dimensional compact manifold. It may be that if we know the correct six-dimensional potato with all its warts and holes, the theory will determine all the masses of the quarks and leptons and all the parameters of the standard model. But this is a tall order! The discovery of the correct 6-dim manifold may require more mathematics than what physicists know. It almost amounts to saying that if you put in all of mathematics, all of physics will come out.

So we must grant strings have not done anything for HEP (atleast not sofar). Hence the real motivation for strings at the present stage lies elsewhere - infact it lies in Quantum Gravity. Gravity must be incorporated into the rest of physics. It is intolerable to have one world where gravity is ignored and quantum mechanics reigns supreme and another world where gravity cannot be ignored but use of quantum mechanics leads to meaningless divergent results.

Strings are welcome even as a free invention of the human mind, since it broadens our horizons and allows us to go beyond the shackles of point particles and local quantum field theories based on them. Now we know that string theory includes membranes and branes of higher dimensions too. So one can imagine a relativistic quantum system consisting of a mind-boggling variety of interacting extended objects living in nine space dimensions and one time dimension. Many of these extended objects are analogous to the solitons in local quantum field theories.

Although M theory now links all the consistent string theories through duality, there is still no unique string theory as was once claimed. In effect, there exist an infinite number of theories since the number of vacuum states in string theory or M theory is almost infinite. But this is not a catastrophe! For, the number of consistent local quantum field theories is also infinite. For instance there is an infinite number of consistent nonabelian gauge theories based on the infinite number of available Lie groups. That has not prevented progress in local quantum field theory and its application to HEP. Experiment and observation allowed us to make a choice and that is how Standard Model was constructed. That is the way physics has progressed sofar and there is no reason to expect anything different in the future.

**What about cosmology?**

If current ideas in Cosmology and Astrophysics are correct, then early universe provides us with a HEP laboratory where particle energies were not limited by any manmade restrictions. So it is believed by many that all our theories of HEP can be tested by appealing to events in the early universe.

There is no doubt that the era of "precision cosmology" has dawned with the measurement of CMBR anisotropy whose accuracy is awe-inspiring. It is claimed that an accurate determination of the parameters of the evolutionary model of the universe is possible. We seem to have come a long way from Landau’s dictum: "Astrophysicists are often wrong but seldom in doubt." However it is rather worrying that cosmologists are not able to balance both sides of Einstein’s equation. The right-hand-side needs 25 times more energy and mat-
ter than what we see! Such a huge chunk of mysterious "dark energy and dark matter" seems too much to swallow. If it stays, it will be one of the greatest discoveries.

In any case, we know of only one universe and the events presumably occurred only once, that too, quite a long time ago. Modern Science owes its existence to the advent of repeatable experiments under controlled conditions whereas History provides only a single sequence of events. History cannot be a substitute for Science. Cosmology cannot provide crucial and definitive tests for fundamental theories of Physics. On the other hand, laws of physics inferred from and tested in laboratory experiments can and must be applied to the study of the history of the universe. In other words, the only healthy traffic between HEP and cosmology is a one-way-traffic: HEP $\rightarrow$ Cosmology

**New Technologies?**

All modern technology is based on electrodynamics. We now know that electrodynamics does not stand alone; it is only part of the unified electroweak dynamics. What are the deeper implications of the electroweak unification? Will there be a technology based on electroweak dynamics? Our understanding of QCD is at an even more primitive stage, because of colour confinement. But chromodynamics will be mastered and chromodynamic technology also will come.

As compared to electrodynamics, our understanding of SM is at a very preliminary stage, perhaps comparable to the study of electricity by rubbing amber on wool or glass on cat’s fur! Electromagnetism is just one of the 12 forces contained in the SM which is based on 12 gauge bosons. One can envisage a stage when all the forces of SM will be released and put to work. That will be SM technology.

**New Principles of Acceleration?**

We have already stressed the importance of discovering new principles of acceleration. There is no future for HEP without it. Supergravity, Higher Dimensions, String Theory and M Theory are likely to fade away as Metaphysics if there is no direct experimental support. Planck energy must be attained in the laboratory. After all, there is no Law of Nature (such as the Second Law of Thermodynamics) that forbids this. If there is such a Law, one must prove it.

All accelerators are based on electrodynamics. There will come a day when accelerators would be based on SM technology.

**Why do all this?**

What is the aim of the Inward Bound Journey? Why should we delve into deeper regions of space-time? Why should we push the frontier of HEP to higher and higher energies?

The real justification is the expectation that we will reach the boundaries of validity of our present view of the physical universe based on our present conceptual framework of space-time (namely relativity) and our present understanding of dynamics (namely quantum mechanics).
0.6 Appendix: More Indian contributions

The following Appendix is presented with apologies for any omissions for which the author takes the blame.

Seminal and well-known contributions by Indian physicists have already been mentioned in the main story of the historical panorama. Many more contributions have been relegated to this Appendix, chiefly because their inclusion there would have affected the flow and flavour of the main narrative. Also, attention must be drawn to the negative comments in Sec 2.5 about HEP in the last 30 years which apply to all the world-wide work of the relevant period including that by Indian physicists mentioned in this Appendix.

Before Standard Model:

The importance of Bhabha scattering (the scattering of positron on electron) in the development of QED was mentioned in Secs 1 and 2. Bhabha’s formula is nowadays routinely used to calibrate the beams at the electron-positron colliders. Bhabha’s analysis of cosmic rays and his identification of the penetrating component as being due to a “heavy electron” with mass around 100 times that of the electron was a brilliant piece of cosmic ray phenomenology. This is the particle which we now call the “muon”.

Bhabha-Heitler theory of cosmic ray showers is well-known. Their theory of electromagnetic shower development initiated by a high-energy electron or photon cascading through bremsstrahlung, pair production and pair annihilation has become standard textbook stuff.

The discovery of the V-A form of weak interactions by Sudarshan and Marshak (see Sec 2.2) was a significant milestone in the history of HEP.

Regge poles were mentioned in Sec 2.3. These are poles of the S matrix in the complex angular momentum plane and played an important role in the S matrix theory of strong interactions. B M Udgaonkar derived the basic formulae for the high-energy behaviour of hadronic cross sections in the s-channel that is controled by the Regge poles in the t-channel. V Singh studied the Regge poles in the exactly soluble case of Coulomb scattering. Deser, Gilbert and Sudarshan wrote down a useful integral representation for the three-point function. S M Roy derived the basic integral equations satisfied by pion-pion scattering from analyticity, crossing symmetry and unitarity. These, known as Roy equations, are now used in combination with chiral symmetry, to confront with experimental data.

In the days of flavour SU(3) symmetry, the Gell-mann - Okubo mass formula based on the octet property of SU(3) breaking was an important ingredient. Based on the same octet assumption, V Gupta and V Singh produced a sum rule for the decay widths of the baryon decuplet. When SU(3) got enlarged to SU(6) as discussed in Sec 2.3, M A ? Beg and V Singh obtained the SU(6) mass formula. One must also mention the work of Mitra and Ross who used Galilean invariance for understanding the “enhanced” heavy meson modes (like N-eta) of hadronic decays.

R H Dalitz and G Rajasekaran showed that a pole in the S matrix is in general followed by a retinue of poles in the complex energy Riemann sheet. This discovery of “shadow poles” not only removed a serious obstacle to the application of broken symmetry to particle physics but also leads to a reformulation of a basic tenet of the S matrix theory.

In the early days of the quark model the possibility of “molecular hadrons” namely
composites of the $qqq$ and $\bar{q}q$ states was envisaged by Rajasekaran who also formulated an empirical test for their identification. This topic has become important in the current context of excitement over possible existence of pentaquarks, tetraquarks and other multiquark hadronic states.

Then came current algebra (see Sec 2.3) and again there were many Indian contributions. The soft pion relation for K form factor due to V S Mathur, S Okubo, L K Pandit and others, the pi pi mass difference calculation due to Tapas Das, S Okubo and others, the pi-N scattering length formula due to A P Balachandran and others and the discovery of a fixed pole in the virtual Compton scattering on proton due to S R Choudhury, V Gupta, R Rajaraman and Rajasekaran are some of these. Early work of T Pradhan on what came to be known later as Schwinger term in the current density algebra must be mentioned.

P K Kabir made substantial contributions to our understanding of CP violation. His book "The CP Puzzle" became a standard resource on this topic.

Towards Standard Model:

The confinement of massless Yang-Mills quanta was conjectured by Rajasekaran even before the advent of QCD. The very first calculation showing the cancellation of divergences in the radiative correction to muon decay in SU(2)xU(1) gauge theory also was done by him.

The first model-independent analysis of the neutral current weak interaction data was performed by Rajasekaran and K V L Sarma. Their equations, subsequently called "Master Equations" by J J Sakurai, played a crucial role in pinning down the coupling constants of the interaction as was demonstrated by Sakurai and L K Schgal.

Are quarks fractionally charged? The remarkable properties of broken-colour QCD with integrally-charged quarks were discovered by Rajasekaran and P Roy as well as J C Pati and Abdus Salam. Subsequently, S D Rindani, Rajasekaran and many others tested the viability of this non-standard QCD in a variety of "jet" experiments. These studies have uncovered one loop-hole after another in the experimental tests usually cited in support of the standard QCD with fractionally-charged quarks.

Within Standard Model:

V Soni discovered the existence of quasi-stable solitonic configurations in electroweak theory, which came to be known as "sphalerons" and play a crucial role in the electroweak baryogenesis. A P Balachandran rediscovered the old "Skyrmions" and brought it within the context of the modern chiral Lagrangians and this led to Witten’s important work on this subject. R Rajaraman wrote an excellent book on solitons.

Within QCD the problem of colour confinement and the calculation of hadronic properties remain hard nuts to crack. R Anishetty and H Sharatchandra converted QCD into its dual form which offers fresh insights into the problem. Following a different lead based on Bethe-Salpeter formalism Anishetty has been able to make progress into the mesonic sector. Harindranath et al have attacked the problem using light-cone approach.

In Sec 3 we had referred to the strong CP problem. In a critical reappraisal of the problem H Banerjee, D Chatterjee and P Mitra have questioned whether such a problem exists.

QGP formation in high temperature QCD has been shown in the lattice version of QCD. R Gavai and Sourendu Gupta have made substantial contribution to this study. Bikash Sinha
made important proposals in the search for signals of QGP formation in heavy-ion collisions. On the other hand C P Singh foresaw the many obstacles that interpretation of heavy-ion experiments would face in revealing QGP.

Neutrino Physics:

A very significant contribution to neutrino physics was made by R Cowisk in 1972 when he along with McLelland obtained an upper bound on the sum of neutrino masses using the early astrophysical data and the big bang model of cosmology. R N Mohapatra is one of the originators of the idea of see-saw for the tiny mass of the neutrino. S Pakvasa is one of the early physicists to recognize the importance of atmospheric neutrinos for the study of oscillations. When neutrino oscillations were indicated by many experiments, one of the complete analyses of both solar and atmospheric neutrinos within a realistic three-neutrino framework was made by M V N Murthy, M Narayan, G Rajasekaran and S Uma Sankar. This group was the first to include the null results from the CHOOZ reactor within the three-neutrino framework and thus obtain a bound on the important mixing angle theta13, and also show that the solar and atmospheric neutrino problems were approximately decoupled. This decoupling led to a considerable simplification of all the subsequent phenomenological analyses of the solar, atmospheric, reactor and accelerator neutrinos. A recent up-to-date analysis is due to S Choubey, S Goswamy, D P Roy, and Amitava Raychoudhuri.

Beyond Standard Model:

What is the next step after the successful establishment of the Standard Model based on SU(3)xSU(2)xU(1)? Grand Unified Theories (GUT) unifying quarks and leptons and also unifying electroweak and QCD through a semisimple Lie group SU(5), SO(10) or E6 with a single unified coupling constant was considered as a possible next step. But the very first model unifying quarks and leptons (albeit not based on a semisimple group) was the SU(4)xSU(2)xSU(2) model proposed by J C Pati and A Salam and extensively studied by Pati and R N Mohapatra especially in the context of the left-right symmetric models. The group-theoretic work of M L Mehta and Pramod Srivastava proved very useful in the construction of anomaly-free gauge models.

An important consequence of GUT is baryon number violation and proton decay, although this has not yet been observed experimentally. Here one must refer to the theoretical work of A N Mitra and Ramanathan who showed that a correct normalization of the proton’s Bethe-Salpeter amplitude increased its lifetime by a factor of 100! This normalization was based on quadratic charge conservation a la DIS (which has a topological similarity to the Feynman diagram of proton decay), instead of the more usual linear charge conservation.

The wide disparity between the scale of the electroweak symmetry breaking in the SM and the scale of the GUT symmetry breaking, called the problem of hierarchy, can be solved by invoking supersymmetry. This important discovery is due to R Kaul and P Majumdar. N D Hari Dass etal proved a no-go theorem for the de Sitter compactification of higher dimensional theories.

Superstring theory could be the correct theory incorporating Quantum Gravity and the Standard Model in one unifying framework. Ashoke Sen made an important contribution to the second string revolution that involved the discovery of duality symmetries linking all the
consistent string theories. The alternative nonperturbative approach to Quantum Gravity called Loop Quantum Gravity was pioneered by Abhay Ashtekar.

A large number of Indian physicists have been involved in the construction of models that go beyond the SM as well as in deriving the phenomenological consequences of such models that could provide evidence for them in the upcoming colliders. Further, there is a strong Indian group of String Theorists who have made a mark in the international scene by their outstanding contributions. Both these classes of contributions, going respectively by the names of phenomenology and formal theory, form a substantial part of present-day HEP activity in India as well as internationally, but have to await future experiments for their substantiation. (This is the blank space alluded to in Sec 2.5.)

General:

Following the footsteps of Dirac whose relativistic wave equation describes all the fermions in the Standard Model, many high-spin equations were written down in the literature (including some by Bhabha), but they were all afflicted by various kinds of diseases. We have already mentioned the case of charged spin 1 particles whose problems were solved only by including them into the Yang-Mills gauge multiplet. The problems of spin 3/2 particles were solved by S D Rindani and M Sivakumar through Kaluza-Klein theory. Supergravity also can solve this problem. Thus the higher symmetries of Yang-Mills, Kaluza-Klein or Supergravity are necessary for consistent higher-spin interactions. Nature loves higher symmetries.

Inspite of the fact that parastatistics for quarks was abandoned with the advent of QCD there exists the possibility of new forms of statistics for newer degrees of freedom that may open up when deeper regions of space-time are probed with higher and higher energy machines. For instance Strominger has speculated that quantum blackholes obey "infinite statistics". A K Mishra and G Rajasekaran discovered an elegant algebra describing a new form of statistics called "orthostatistics" that combines infinite statistics with Fermi-Dirac or Bose-Einstein statistics. S Chaturvedi solved the problem of calculating the partition functions for parastatistics which remained an open problem for a long time.

Experiments:

In the early days of experimental particle physics M G K Menon along with others in the Bristol Group discovered many of the decay modes of K mesons during their studies of the interactions of cosmic rays in nuclear emulsion. Lokanathan and Steinberger determined the branching ratio of pions decaying into electrons and neutrinos and this played a crucial role in the formulation of $V - A$ theory. The TIFR cosmic ray group pioneered many cosmic ray experiments. As already pointed out in Sec 2, they were the first to detect atmospheric neutrinos in the deep mines of Kolar Gold Fields in 1965.

Other outstanding experiments of fundamental significance are the search for proton decay in the KGF experiment, the search for axion in the nuclear reactor experiment at Trombay and the search for the fifth force using torsion balance (by R Cowsik, N Krishnan and Unnikrishnan), although none of these searches going on world-wide have yielded positive results so far.

Among the major international experiments in which the Indian groups have participated
are the precision tests at LEP that established the standard model as a renormalizable QFT, the discovery of the top quark at the Tevatron and the Heavy Ion Collision experiments at CERN and Brookhaven searching for Quark Gluon Plasma.

The first two-in-one experiment BOREX using Boron 12 to detect solar neutrinos via charged current and neutral current modes simultaneously and thus establish neutrino oscillations if they exist was proposed by S Pakvasa and R Raghavan, but this experiment did not materialise. Instead, a similar experiment using deuterium in heavy water proposed by H Chen did materialize and this was the experiment of Sudbury Neutrino Observatory which successfully solved the solar neutrino problem.

A unique low-energy solar neutrino experiment BOREXINO which will focus on the monochromatic Be neutrino lines was proposed and led by R Raghavan.

Retrospect:

Inspite of the above Indian contributions one must admit the remarkable absence of great Indian contributions in the recent history of HEP. Why have we come down? Where are the equivalents of Bose and Raman in the present-day HEP? There may be sociological reasons for this, but this is not the place to go into them.

Is it possible that India throws up great names only when Physics goes through revolutionary development as in the beginning of the 20th century? If so, the next revolution which may come in the 21st century must be eagerly watched! Remember that the solution of the Quantum Gravity problem and/or the formulation of String Theory is still incomplete. They may usher in the next revolution in Physics and may involve great contributions from India. There are already signs of this, in the quality of Indian contributions to String Theory and Quantum Gravity. We shall close with this optimistic remark.