Hundred years of Fundamental Physics and a Crisis

G. Rajasekaran

Institute of Mathematical Sciences, Chennai
&
Chennai Mathematical Institute

Abstract

One hundred years of Fundamental Physics have culminated in a theory called the Standard Model of High Energy Physics. This theory is now known to be the basis of almost ALL OF KNOWN PHYSICS except gravity. Although the discovery of the HIGGS BOSON in 2012 has established this theory, gravitational force has been left out. The energy scale of quantum gravity, known as the Planck Scale, is 16 orders of magnitude higher than the presently accessible TeV energies. This is a Crisis in Fundamental Physics that can be met only by the discovery of new principles of acceleration. The talk will highlight this theme.

Hundred years of Fundamental Physics

- The earlier part of the 20^{th} 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, the MICROCOSM.

- At the beginning of the 20^{th} century, the quest for the understanding of the atom, topped the agenda of fundamental physics. This quest successively led to the unravelling of the nucleus and then to the nucleon (the proton or the neutron). Now we know that the nucleon itself is made of three quarks.

- This is the level to which we have descended at the end of the 20^{th} century. The depth (or the distance scale) probed thus far is 10^{-17}cm.

INWARD BOUND

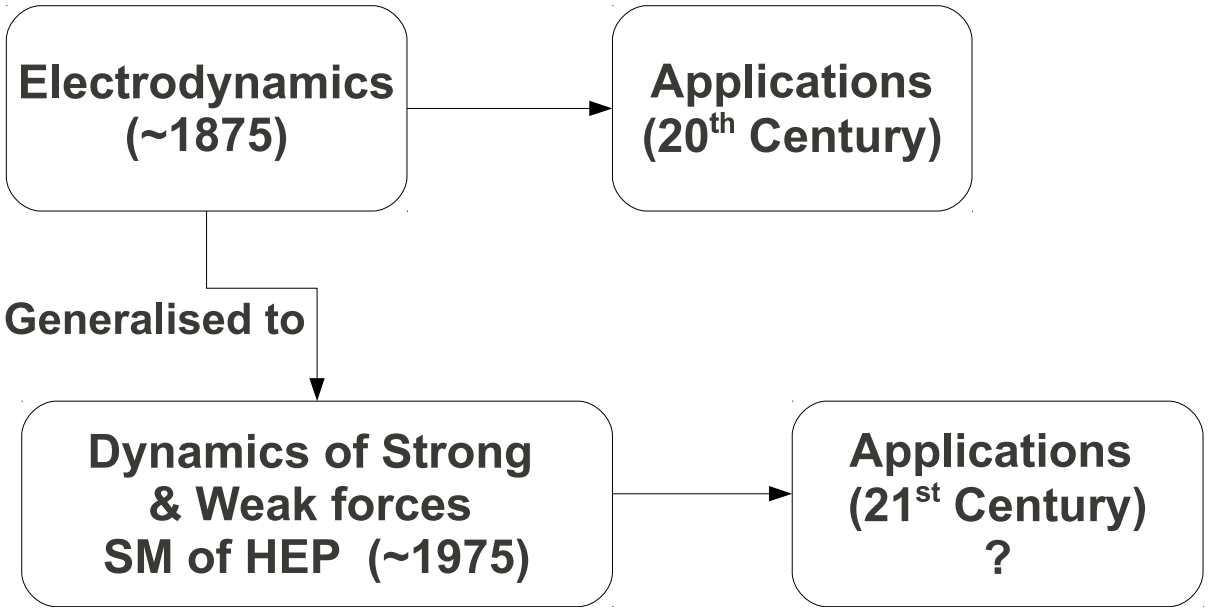
Atoms	$\longrightarrow$	Nuclei	$\longrightarrow$	Nucleons	$\longrightarrow$	Quarks	$\longrightarrow$	?
10^{-8}cm		10^{-12}cm		10^{-13}cm		10^{-17}cm		

- This inward bound path of discovery unravelling the mysteries of matter and the forces holding it together - at deeper and ever deeper levels - has culminated, at the end of the 20^{th} century, in the theory of Fundamental Forces based on Non abelian Gauge Fields, for which we have given a rather prosaic name

THE STANDARD MODEL OF HIGH ENERGY PHYSICS

- In this theory, the strong forces operating within the nuclei and within the nucleons, as well as the weak forces that were revealed through the discovery of radioactivity 100 years ago are understood to be generalizations of the

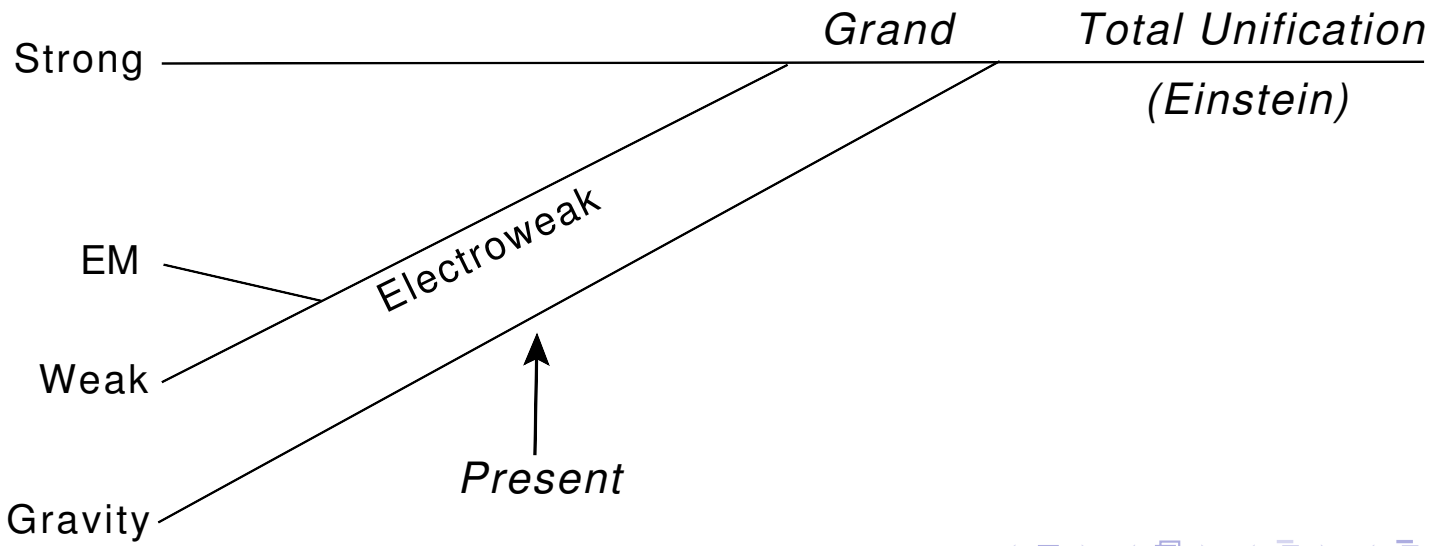
ELECTRODYNAMICS OF FARADAY & MAXWELL



- The 20^{th} century owes a lot to the Faraday - Maxwell Electrodynamics, for, the applications of electrodynamic technology (starting with wireless, ...) have become a part of modern life.
- Equally profound applications will follow, once the technologies of the strong and weak forces are mastered!

The four fundamental forces of Nature

Force	Strength	Range
Strong	1	10^{-13} cm
EM	$\frac{1}{137}$	∞
Weak	$10^{-5}/m_p^2$	$< 10^{-14}$cm
Gravity	$10^{-40}/m_p^2$	∞



Laws of Electrodynamics

$$\vec{\nabla} \cdot \vec{E} = 4\pi\rho$$ Oersted

$$\vec{\nabla} \times \vec{E} + \frac{1}{c}\frac{\partial \vec{B}}{\partial t} = 0$$ Ampere

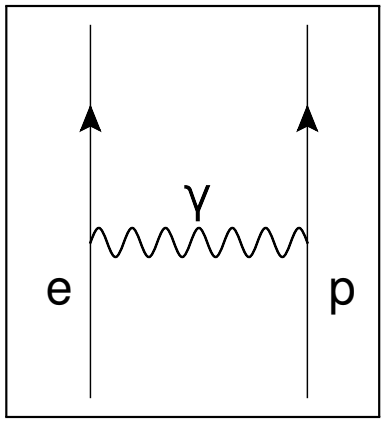
$$\vec{\nabla} \cdot \vec{B} = 0$$ Faraday

$$\vec{\nabla} \times \vec{B} - \frac{1}{c}\frac{\partial \vec{E}}{\partial t} = \frac{4\pi}{c}\vec{j}$$ Maxwell

Hertz

- Relativity (Special)
- Quantum Mechanics
- Quantum Field Theory

$\Longrightarrow$



(Feynman Diagram)

STANDARD MODEL OF HIGH ENERGY PHYSICS

$$= \boxed{\text{ELECTROWEAK DYNAMICS}}$$

(based on $SU(2) \otimes U(1)$)

$$\oplus$$

$$\boxed{\text{QUANTUM CHROMODYNAMICS}}$$

(based on $SU(3)$)

Laws of Electroweak Dynamics

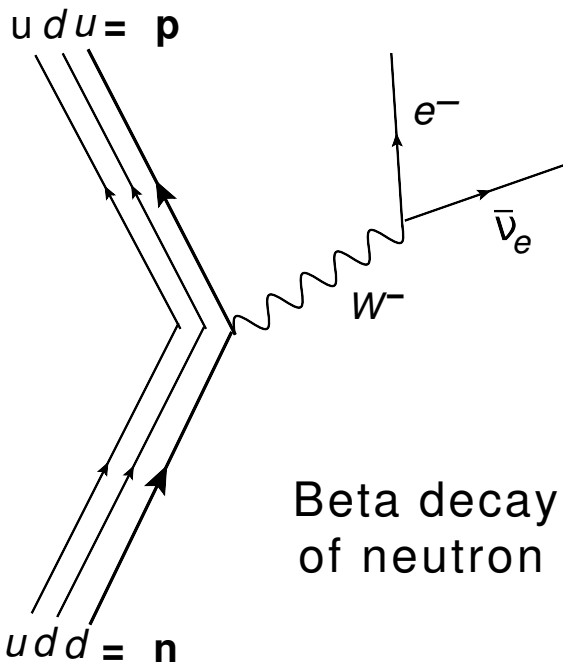
$$(\vec{E}_i, \vec{B}_i): \quad i = 1,\ 2,\ 3,\ 4$$
$$\gamma, W^+, W^-, Z$$

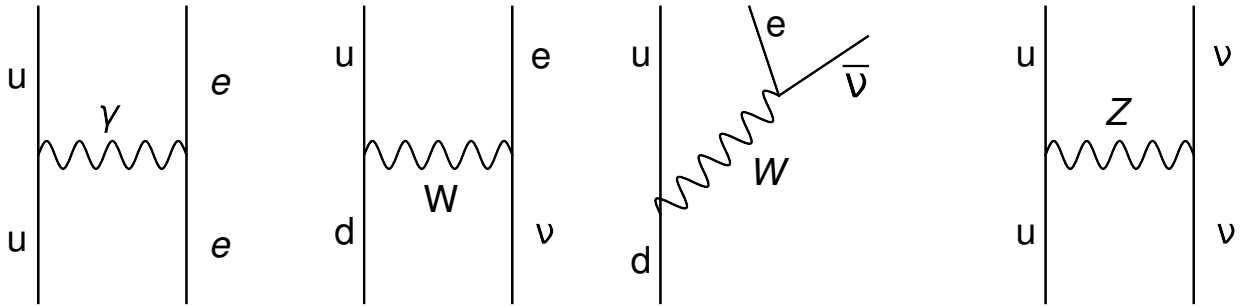
$$\vec{\nabla} \cdot \vec{E}_i + \ldots = 4\pi\rho_i$$

$$\vec{\nabla} \times \vec{E}_i + \frac{1}{c}\frac{\partial \vec{B}_i}{\partial t} + \ldots = 0$$

$$\vec{\nabla} \cdot \vec{B}_i + \ldots = 0$$

$$\vec{\nabla} \times \vec{B}_i - \frac{1}{c}\frac{\partial \vec{E}_i}{\partial t} + \ldots = \frac{4\pi}{c}\vec{j}_i$$





Laws of Quantum Chromodynamics (QCD)

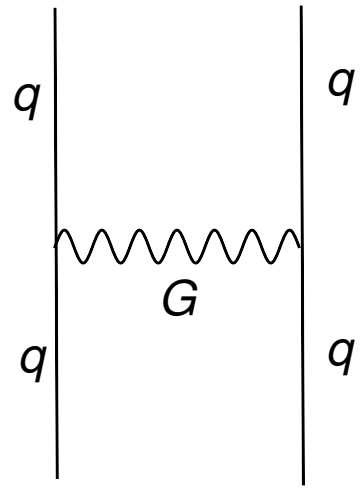
$(\vec{E}_\alpha, \vec{B}_\alpha): \quad \alpha = 1, 2, ..., 8: \quad$ 8 Gluons G_α

$$\vec{\nabla} \cdot \vec{E}_\alpha + ... = 4\pi\rho_\alpha$$

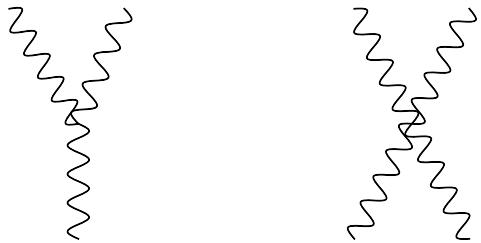
$$\vec{\nabla} \times \vec{E}_\alpha + \frac{1}{c}\frac{\partial \vec{B}_\alpha}{\partial t} + ... = 0$$

$$\vec{\nabla} \cdot \vec{B}_\alpha + ... = 0$$

$$\vec{\nabla} \times \vec{B}_\alpha - \frac{1}{c}\frac{\partial \vec{E}_\alpha}{\partial t} + ... = 4\pi\vec{j}_\alpha$$

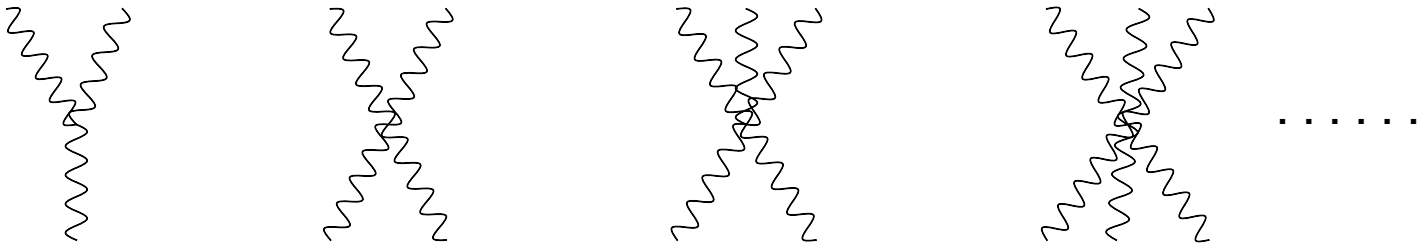


Nonabelian gauge fields
(Yang – Mills fields)



CONFINEMENT?

Gravity



. . . . . .

Field Sector

Bosons

(Bose-Einstein Statistics)

Spin: $0, 1, 2, ...$

γ

W^+, W^-, Z

$G_\alpha : \quad \alpha = 1, ..., 8$

H

$g_{\mu\nu}$

Particle Sector

Fermions

(Fermi-Dirac Statistics)

Spin: $\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, ...$

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

p $\sim$ uud
n $\sim$ ddu

$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$

$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$

Standard Model of HEP ($SU(3) \otimes SU(2) \otimes U(1)$ gauge theory)

$$
\begin{aligned}
\mathcal{L} &= -\frac{1}{4}\left(\partial_\mu G^i_\nu - \partial_\nu G^i_\mu - g_3 f^{ijk} G^j_\mu G^k_\nu\right)^2 - \frac{1}{4}\left(\partial_\mu B_\nu - \partial_\nu B_\mu\right)^2 \\
&- \frac{1}{4}\left(\partial_\mu W^a_\nu - \partial_\nu W^a_\mu - g_2\, \varepsilon^{abc}\, W^b_\mu\, W^c_\nu\right)^2 \\
&- \sum_n \bar{q}_{nL}\gamma^\mu\left(\partial_\mu + i g_3 \frac{\lambda^i}{2} G^i_\mu + i\frac{g_2\tau^a}{2} W^a_\mu + i\frac{g_1}{6} B_\mu\right) q_{nL} \\
&- \sum_n \bar{u}_{nR}\gamma^\mu\left(\partial_\mu + i g_3 \frac{\lambda^i}{2} G^i_\mu + i\frac{2}{3} g_1 B_\mu\right) u_{nR} \\
&- \sum_n \bar{d}_{nR}\gamma^\mu\left(\partial_\mu + i g_3 \frac{\lambda^i}{2} G^i_\mu - i\frac{g_1}{3} B_\mu\right) d_{nR} \\
&- \sum_n \bar{l}_{nL}\gamma^\mu\left(\partial_\mu + i\frac{g_2\tau^a}{2} W^a_\mu - i\frac{g_1}{2} B_\mu\right) l_{nL} - \lambda(\phi^\dagger\phi - v^2)^2 \\
&+ \left|\left(\partial_\mu + i g_2 \frac{\tau^a}{2} W^a_\mu + i\frac{g_1}{2} B_\mu\right)\phi\right|^2 - \sum_n \bar{e}_{nR}\gamma^\mu\left(\partial_\mu - i g_1 B_\mu\right) e_{nR} \\
&- \sum_{m,n}\left(\Gamma^u_{mn}\bar{q}_{mL}\,\phi^c\,u_{nR} + \Gamma^d_{mn}\bar{q}_{mL}\,\phi\,d_{nR} + \Gamma^e_{mn}\bar{l}_{mL}\,\phi\,e_{nR} + h.c.\right)
\end{aligned}
$$

$$\boxed{\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}\begin{pmatrix}u_\alpha\\ d_\alpha\end{pmatrix};\ \mathsf{n}=1}$$

$$\Downarrow$$

$$\boxed{\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L\begin{pmatrix}u_\alpha\\ d_\alpha\end{pmatrix}_L \quad e^-_R \quad u_{\alpha R} \quad d_{\alpha R};\quad \alpha=1,2,3}$$

$$\boxed{\begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}\begin{pmatrix}c_\alpha\\ s_\alpha\end{pmatrix};\ \mathsf{n}=2} \qquad \boxed{\begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}\begin{pmatrix}t_\alpha\\ b_\alpha\end{pmatrix};\ \mathsf{n}=3}$$

- SM was constructed by theorists more than 40 years ago. Experimenters verified each component of this theory in the next 40 years, except for one component, the Higgs boson. This last missing piece was discovered only in 2012 and that was big news.
- SM has emerged as the STANDARD THEORY describing Nature.
- Where do we go from here?
- Remember the SM is a theory of only three fundamental interactions. The 4th one, gravitational force is missing in SM.

Quantum Gravity

- It is a deep irony of Nature that the twin revolutions of quantum & relativity that powered the conceptual advances of the 20^{th} century and that underlie all the subsequent scientific developments, have a basic incompatibility between them. The marriage between quantum mechanics and relativity has not been possible.

- By relativity, here we mean general relativity since special relativity has already been combined with quantum mechanics leading to quantum field theory which has been used in constructing SM.

- Gravity which gets subsumed into the very fabric of space & time in Einstein's General Relativity has resisted all attempts at being combined with the quantum world.

- Hence, Quantum gravity has become the most fundamental problem of physics.
- The most successful attempt to construct Quantum Gravity is String Theory.
- Actually, String Theory offers much more than a quantum theory of gravity. It provides a quantum theory of all the other forces too. In other words, it can incorporate the SM of HEP also, within a unifying framework that includes gravity.

String Theory

- In string theory, a point particle is replaced by a one-dimensional object called string as the fundamental entity. Its length is about 10^{-33} cm which is the length scale of any theory of quantum gravity including string theory. The various vibrational modes of the string correspond to the elementary particles.
- String theory automatically contains quantum gravity and that is its special beauty.
- However that is bought at a price. It works only if the number of space dimensions is 9 and including time it is 10. Where are the extra six dimensions? They are curled up to form space bubbles at distance scales of the same 10^{-33} cm!
- Both the string and the extra curled-up dimensions will be revealed only when when we can access such length scales.
- So, has String Theory solved the problem of Quantum Gravity? Yes, perhaps. But how do we know?

The Crisis

- Where is the experimental support for String Theory?
- Remember it took 40 years to verify the Standard Model as the correct theory of Nature.
- That required the construction of particle accelerators and particle colliders of higher and higher energy ultimately culminating in the construction of the Large Hadron Collider (LHC)at CERN Geneva reaching energies in the TeV region.
- This machine is a behomath. It has a circumference of 28 Km and its construction took 20,000 physicists and engineers working for 20 years.
- In relativistic quantum mechanics there is an inverse relationship between the length scale and the energy required to probe it.

$$E \sim \frac{1}{L}$$

- Remember I said (at the beginning of my talk) that we have descended down to a length scale of 10^{-17} cm. To probe this, we needed the TeV energies of LHC.
- So, to probe the length scale of Quantum Gravity 10^{-33} cm, we need 16 orders more energy, 10^{16} TeV.
- This is the energy required to experimentally test String Theory or any theory of Quantum Gravity.
- Most people think this is not possible.
- This is the Crisis in Fundamental Physics.
- Galileo had decreed

  "Laws of Physics are written in the language of Mathematics, but those Laws can be proved or disproved only by Experiments."

- For 400 years, Physics has progressed only by following the path decreed by Galileo.
- If we give up this path now, that will be the end of Fundamental Physics.
- In that case, all the beautiful theories that we build for Quantum Gravity will remain as mere metaphysics.
- What is the way out?

- Cosmology: If current ideas in Cosmology and Astrophysics are correct, then early universe provides us with a HEP laboratory where particle energies were almost unlimited. So it is believed by many among us that all our theories of HEP can be tested by appealing to events in the early universe. At the risk of getting a flak from many of my respected colleagues, I would like to strike a note of caution.

- There is no doubt that the era of "precision cosmology" dawned with the measurement of CMBR anisotropies whose accuracy is awe-inspiring. First, COBE, then WMAP and now Planck are creating waves. We seem to have come a long way from Landau's dictum:

  "Astrophysicists are often wrong but seldom in doubt".

- However 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 controllable 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 universe and its history. In other words the only healthy traffic between HEP and cosmology is a one-way traffic:

$$\text{HEP} \longrightarrow \text{Cosmology.}$$

- We have to make a direct attack on the High Energy Frontier.
- Instead of merely scaling up the sizes of the accelerating machines, we must discover new Principles of Particle Acceleration.
- Either, new principles of acceleration have to be discovered, or, there will be an end to HEP by about 2040.
- This conclusion has nothing to do with Quantum Gravity or Planck energy (10^{16} TeV).

Growth of Accelerator Energies

- Growth of accelerator energies over the past 80 years has been phenomenal.
- The energy has been increasing by a factor 10 every 6 years.
- I interpret this exponential growth as an optimistic sign for the future of fundamental physics.
- So, if the same growth can be maintained, 16 powers of 10 can be reached in 96 years.
- But this is possible only if new principles of acceleration and newer technologies are continuously invented.
- What are the new principles of acceleration? I will give one example.

New Principles of Particle Acceleration

- In the last 30 years, many ideas on laser-plasma acceleration are being pursued.
- Using laser excitation of plasma wakefields, electrons have been successfully accelerated to 1 GeV in 1 cm (compared to kilometre-size conventional accelerators to get similar energies).
- So table-top accelerators are perhaps not far way.
- Maybe this will lead to breakthroughs that will help us to cross the superhigh energy barrier.
- What we need are a hundred crazy ideas. Maybe one of them will work!
- Maybe the breakthrough will come from one of you, especially the students. This is an excellent opportunity and challenge for experimentally oriented students.

The 10-dimensional World and Mathematics

- Strings live in a 10 dimensional world having 6 compact space dimensions in addition to our familiar 4- dimensional space-time.
- What is the shape of this 6-dim compact manifold?
- Some time ago string theorists found that Calabi-Yao manifold (which had been earlier discovered by these two mathematicians) is a good choice.
- It maybe that if we know the correct six-dimensional potato with all its warts and holes string theory will determine the properties of all the dozens of elementary particles and even Standard Model will follow.
- We now know that in addition to the one-dimensional strings String Theory automatically contains two-dimensional membranes and in fact branes of higher dimensions too.

- String Theory is the relativistic quantum dynamics of a mind-boggling variety of interacting extended objects (chairs, tables...) living in a 10-dimensional world. It has rich mathematics and physics. Its richness is continuously being discovered.
- No wonder String Theory is so difficult.
- But it will be mastered through Mathematics.
- String Theory requires the creation of new mathematics.
- ALL of Great Mathematics may have to be used in gaining control of String Theory.

- String Theory is the top candidate for a correct theory of quantum gravity, which is the next frontier in fundamental physics, after the spectacular success of the standard model of high energy physics.
- However string theory is so complex that it requires all the mathematics that is yet to be created.
- So this is the ideal area for ambitious students who are mathematically oriented.

Symmetry Breaking and Higgs

- Remember the vast disparity between EM and weak force as regards their ranges; one is of infinite range and the other is short ranged. How does EW unification cope with this breakdown of the EW Symmetry that is intrinsic to unification?
- This is achieved by a Spontaneous Breakdown of Symmetry (SBS) engineered by the celebrated Higgs mechanism which keeps photon massless while raising the masses of W & Z to finite values.
- Thus Weak interaction gets a finite range ($\sim 10^{-15}$cm). The experimental discovery of W and Z with the masses (80 and 91 GeV) predicted by the EW theory was a great triumph for the theory. That happened in 1982.

- The idea of SBS in HEP originates from Nambu although he applied it in a different context. But the stumbling block was the Goldstone Theorem. This predicted the existence of a massless spin-zero boson (called Nambu-Goldstone boson) as the consequence of SBS and prevented the application of SBS to construct any physically correct theory, since such a massless boson is not observed.

- Thus apparently one had to choose between the devil (massless W boson) and the deep sea (the Nambu-Goldstone boson).

- It was Higgs who, in 1964, showed that this is not correct. He showed that there is no Goldstone Theorem, if the symmetry that is broken is a gauge symmetry. The devil drinks up the deep sea and comes out as a regular massive spin one gauge boson. No massless spin zero boson (N. G. boson) is left.

- This is called Higgs mechanism. Many others (especially Kibble) have contributed to this.

- Earlier, Glashow had identified the correct version $(SU(2) \otimes U(1))$ of the Yang-Mills theory for the electroweak unification. By combining that with Higgs mechanism, Weinberg & Salam independently constructed the EW part of SM in 1967.

- There is a bonus. Higgs mechanism postulates the existence of a universal all-pervading field called the Higgs field and this field which gives masses to W and Z also gives masses to all the fermions of the particle sector, except to the neutrinos. Thus, in particular, the masses of the quarks and electron come from the Higgs field.

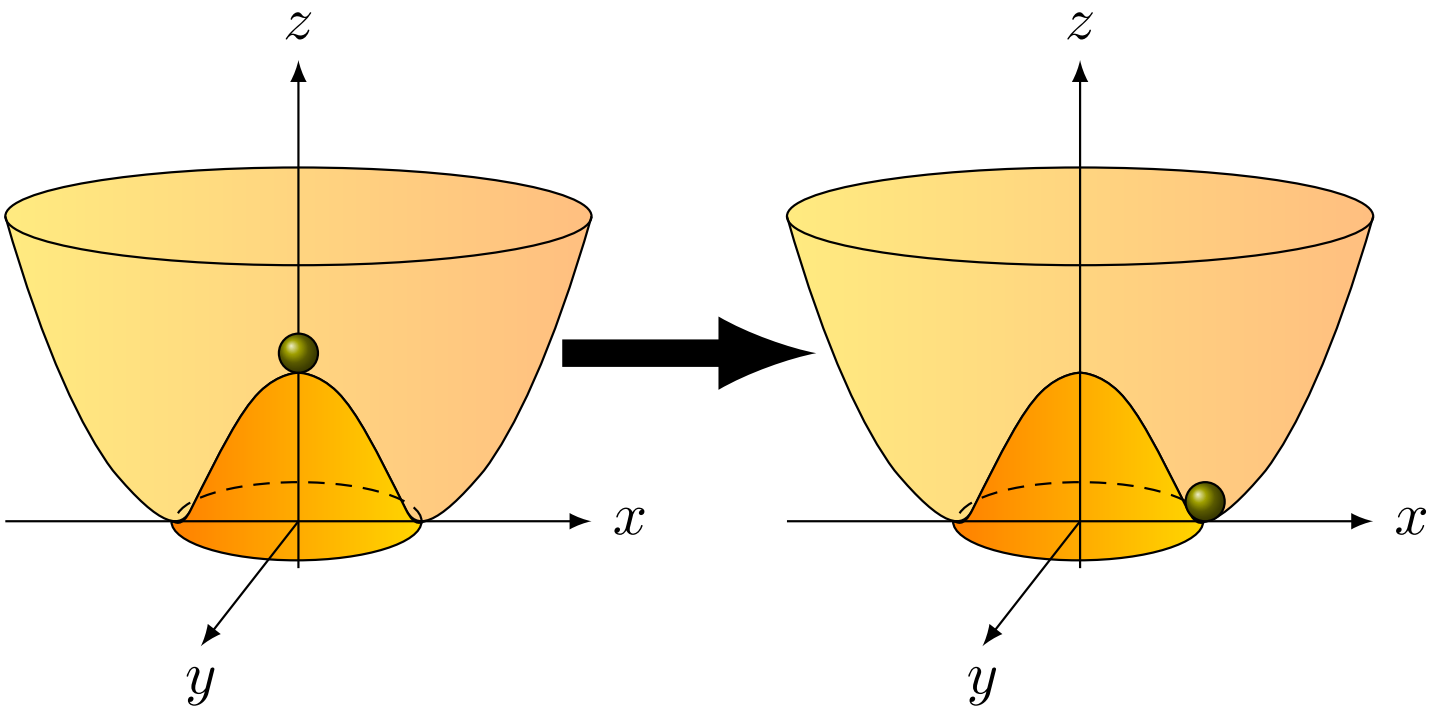
- But there is an important by product of the Higgs mechanism: a massive spin zero boson, called Higgs boson, must exist as a relic of the original Higgs field.

- High energy physicists searching for it in all the earlier particle accelerators had failed to find it.

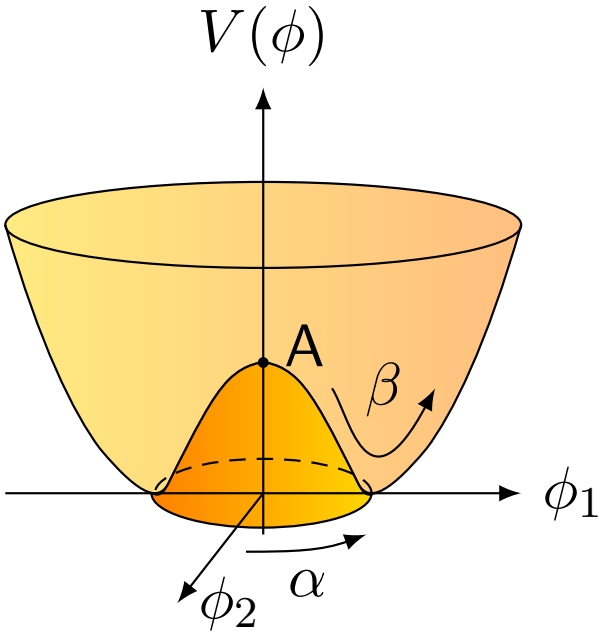
- So the discovery of the Higgs boson in 2012 at a mass of 125 GeV, at the gigantic particle collider, called LARGE HADRON COLLIDER (LHC) at CERN, Geneva, has been welcomed by everybody.

- In the last 4 decades, experimenters have succeeded in confirming every component of the full SM with three generations of the fermions.
- Higgs boson remained as the only missing piece.
- So, with its discovery, SM has emerged as the STANDARD THEORY describing Nature.
- This is a great scientific, engineering and technological achievement.

Spontaneous Breakdown of Symmetry (A Tutorial)



Consider a simple mechanical example: a ball placed on the top of a hill of circular cross section surrounded by a circular valley. This system has a circular symmetry, but the ball is in an unstable equilibrium and will roll down into the bottom of the valley where it will reach a point of stable equilibrium. The ball could have come to any point along the circular bottom of the valley, but once it has done it, the circular symmetry is broken.



α : massless mode (N G boson)
β : massive mode (Higgs boson)

Replace the hill and valley problem with a problem of field theory. This is Goldstone's model of the scalar field which has two components ϕ_1 and ϕ_2. The quanta of the scalar field have spin zero and hence are bosons. The potential energy V of the field system as a function of the field components is chosen to be exactly like in the mechanical system and has circular symmetry in the field space. It has a maximum energy at point A where ϕ_1 and ϕ_2 are zero and a minimum along a circle.

- It is wrong to choose the maximum of the potential (point A) as the ground state of the field system although the field is zero at that point since it is a state of unstable equilibrium. We can choose any one point along the circle of minimum of V, as the ground state of the system; however, once we choose it, the circular symmetry is broken. This is the mechanism of spontaneous breakdown of symmetry.
- An important consequence follows. Since it does not cost any energy to move around the circular trough of minimum potential, there exists a massless particle (the α mode). Movement along a direction normal to this circle (the β mode) costs positive potential energy and this corresponds to the massive particle. The massless mode is called the Nambu-Goldstone boson and this result is called the Goldstone Theorem (proved by Goldstone, Salam & Weinberg) which states that SBS of any continuous symmetry results in the existence of the spin zero massless N. G. boson.

- By the addition of a massless spin one gauge boson to the Goldstone model (thus elevating the original circular symmetry to a gauge symmetry), Higgs showed that the massless spin zero boson is eaten up by the massless spin one boson and as a result, the massless spin one boson becomes massive and the massless spin zero boson disappears. This is the Higgs mechanism. The massive spin zero boson (the β mode) however exists and this is the Higgs boson which was eagerly searched for, and presumably discovered now.

- Note that in the ground state, the field is not zero, but is equal to the radius of the circle of minimum potential. This is the universal Higgs field existing everywhere, that gives mass to all the particles.

Beyond Standard Model

- Neutrinos:
  Neutrinos are massless in the SM. As already mentioned, Higgs mechanism does not give mass to neutrions. About 15 years ago, experimenters discovered that neutrinos do have tiny masses and this has been hailed as a great discovery since this may show us how to go beyond SM. Neutrinos may be the portal to go beyond SM and that is the importance of the

  India-based Neutrino Observatory (INO)

  which is about to come up in Tamil Nadu.

Dark Matter:

Astronomers have discovered that most of the matter in the Universe is not the kind we know. It is called dark matter since it does not emit, absorb or scatter light. Although this discovery has been made already, nobody knows what this dark matter is and only physicists can discover that. A dark matter experiment also will be mounted in the INO cavern (suitably extended).

Other things?

- In the last 4 decades after the SM was constructed, theoreticians have not been idle but have constructed many theories that go beyond the SM. Of these, grand unification (already mentioned) is one. Another is Supersymmetry: postulates the existence of a boson corresponding to every known fermion and vice versa. This is a very elegant symmetry that leads to a better QFT than the one on which SM has been built. But, if it is right, we have to discover a whole new world of particles equalling our known world; remember we took a 100 years to discover the known particles starting with the electron.

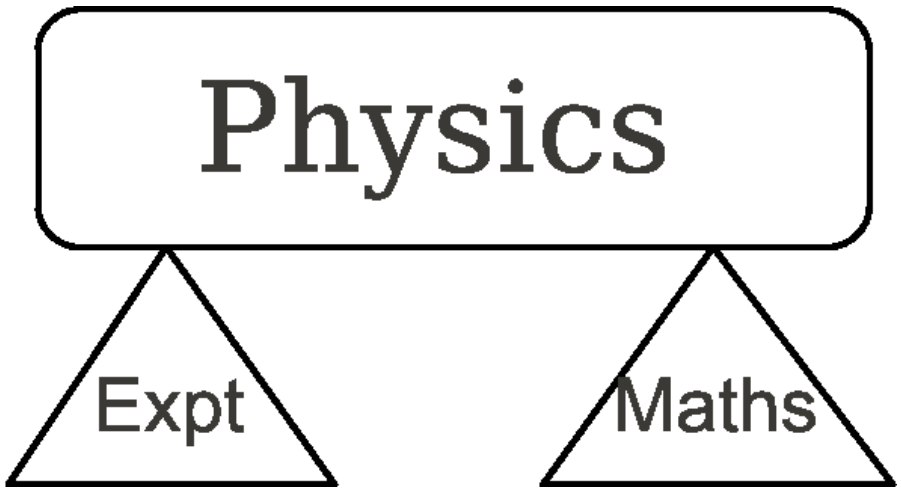
- There are many more theoretical speculations apart from grand unification and supersymmetry. But none of them has seen an iota of experimental support so far, even in the LHC. However LHC will have many more years of operation; let us hope new things will be discovered.

Quantum Gravity

- The biggest loophole in SM is that gravity has been left out. The most successful attempt to construct quantum gravity is the String Theory, but it is still an incomplete theory. So, Quantum Gravity is the next frontier and the journey continues.

Nobel Prizes for the Standard Model

1979:	Glashow, Salam & Weinberg	Construction of the Electroweak theory
1984:	Rubbia & Van der Meer	Discovery of W & Z bosons
1990:	Friedman, Kendall & Taylor	"Observation" of quarks inside the proton
1999:	't Hooft & Veltman	Proof of renormalizability of electroweak theory
2004:	Gross, Politzer & Wilczek	Asymptotic freedom of YM theory (QCD)
2008:	Nambu Kobayashi & Maskawa	Spontaneous breaking of symmetry Matter-antimatter asymmetry
2013:	Englert & Higgs	Higgs mechanism



- Laws of Nature are written in the language of Mathematics. ("God is a Mathematician")
- The Laws can be discovered only through Experiments.