Theoretical scenarios for 10^3 GeV to 10^{19} GeV

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Basic dogmas of particle physics are reviewed. Some of their implications beyond the standard model are explored. Higgs sector of the standard model of electroweak interactions is the weakest link in the model. Elementary Higgs field makes the model 'unnatural' beyond about 10^3 GeV. Supersymmetry provides the most attractive framework wherein this problem can be addressed. This new symmetry, relating fermions and bosons, is expected to be operative at about 10^3 GeV. In addition, grand unification of the fundamental interactions can be studied consistently only within a supersymmetric formulation. Inclusion of gravity with other interactions leads to supergravity theories, which should emerge as a low energy description of a more fundamental theory, the string-theory. Supersymmetry again is an essential feature of such a theory. Quantum gravity, with its characteristic scale of 10^{19} GeV, may well be described by a superstring theory.

TODAY, particle physics involves six quarks and six leptons as the fundamental constituents of all matter. It was only last year that the sixth quark, the 'top', was discovered. The quarks come in three-somes, the three colours. The quarks and leptons experience four types of basic forces, electromagnetic, weak nuclear, strong nuclear and gravitational. The electromagnetic and weak forces are described by the model of Glashow, Salam and Weinberg[1–3], while the strong interactions experienced by the quarks are believed to be governed by Quantum Chromodynamics (QCD). These together form the Standard Model of particle physics. Einstein's general theory of relativity provides an excellent description of the gravitational forces at large distances. However, short distance picture of gravity, where quantum effects become relevant is still puzzling. In this sense, quantum gravity is the least understood of all the basic forces of Nature.

The present theoretical understanding of the fundamental constituents and the forces experienced by them is governed by four guiding principles or dogmas: (i) Gauge principle, (ii) Renormalizibility (or finiteness for theories with gravity), (iii) Naturalness principle, and (iv) Unification of the fundamental forces of Nature. We shall review these ideas in the following.

Gauge dogma

Every fundamental force has an underlying gauge principle. The oldest known gauge principle is that of electromagnetic interaction. The physical consequence of this principle is that this force is carried by a spin one massless vector gauge quantum, the photon, with an underlying gauge group $U(1)$. Two other fundamental interactions, the weak and strong nuclear forces are also governed by gauge theories. In the successful unified picture of electromagnetic and weak interactions due to Glashow, Salam and Weinberg[1–3], we have a gauge theory of four spin 1 gauge quanta. One of these is massless and is identified with the photon. Other three are massive, two charged $W_\mu^\mp$ and one neutral Z_μ^0. These mediate weak nuclear forces. The underlying gauge group of this theory is $SU_L(2) \times U_Y(1)$ which is spontaneously broken down to an electromagnetic $U(1)$. Discovery of these gauge bosons, $W^\pm$ and Z^0 in 1983, a major event in the history of science, confirmed the now thirty-year-old electroweak theory.

The strong nuclear force which holds the quarks together in a proton or neutron is described in terms of eight spin one gauge bosons, the gluons, corresponding to a gauge theory based on colour group $SU_C(3)$.

The gravitational interaction, usually thought of in terms of geometric properties of space-time, is also compatible with the gauge dogma[4,5]. This force is mediated by a postulated spin two massless field, the graviton. Experimental discovery of this gauge particle is an outstanding problem. Whereas non-gravitational forces are described by the gauge theories of internal symmetry groups, the gravitational interaction is governed by the gauge theory of space–time symmetries. In this sense gravity is somewhat different.

Principle of renormalizability

All the known non-gravitational fundamental forces of nature are described by renormalizable quantum gauge field theories. These theories combine the building blocks of modern physics, special theory of relativity, quantum and gauge principles. Quantum field theories are generically plagued with infinities. In renormalizable field theories, there is a systematic way of absorbing these infinities into redefinition of the fields and parameters, leaving behind only finite values for them. Unfortunately, this is not true for quantum theory of gravity. The root of the problem is that, unlike other quantum gauge field theories, description of gravity necessarily, involves a dimensionful coupling constant, Newtons gravitational constant. This makes one-loop or higher divergences in this theory to have a functional form other than that of the quantum action. Therefore, the usual prescription of absorbing these infinities back into the original quantum action by rescaling the parameters and fields is not available. In fact the gravitational quantum field theories may in general never be perturbatively renormalizable.

There are only two extreme options for the gravitational field theories: either the infinities of the S-matrix cannot be removed at all, or the infinities on their own are altogether absent. Thus, an acceptable quantum theory of gravity should be finite on its own – there should be some inner mechanism such that the divergences cancel. Some symmetry may provide such a mechanism. Obviously, finiteness of the S-matrix is a stronger constraint than renormalizability. But, it appears that quantum gravity has to choose a more miraculous way of existing other than the soft option of renormalizability that other interactions adopt.

Naturalness dogma

According to this dogma, existence of a small parameter in Nature cannot be an accident, there must be an associated symmetry. This is best formulated as follows:

't Hooft's doctrine of naturalness: At any energy scale μ, a set of physical parameters, $\alpha_i(\mu)$ may be small, if and only if in the limit $\alpha_i(\mu) \to 0$, the system has an enhanced symmetry[6].

The weakly broken symmetry ensures that the smallness of the parameter is stable against perturbative influences. An example of a perfectly natural theory is quantum electrodynamics. The electromagnetic coupling α, the electron mass m_e, the muon mass m_μ, etc. can all be independently small. The smallness of m_e (or m_μ) is protected by the fact that, in the limit $m_e \to 0$ (or $m_\mu \to 0$), we have an additional symmetry corresponding to the separate conservation of the left- and right-handed electron-like leptons. All corrections to the electron mass due to the quantum fluctuations are small, proportional to m_e itself. Also, $\alpha \to 0$ enhances symmetry; it implies no interaction; hence the particle number of each type is conserved.

On the other hand, field theories with elementary scalar fields are not natural. There is no approximate symmetry that protects the smallness of the scalar mass. Electroweak theory has an elementary scalar field in its Higgs sector. This provides masses to the weak gauge bosons $W^{\pm}$, Z^0 through the so-called Higgs mechanism breaking the electroweak gauge group $SU(2) \times U(1)$ to the electromagnetic $U(1)$ at about 100 GeV. This ensures the renormalizability of such a theory of massive non-abelian gauge bosons. Though Higgs particle is central to our present understanding of structure of matter, yet it has stayed completely elusive. Experimental discovery of this particle is a major outstanding problem of present times. That is why Leon Lederman has nicknamed it as 'the God Particle'[7]. Being an essential part of the standard model, at the same time it renders the electroweak theory 'unnatural'. That is, the 100 GeV scale of this theory is no longer stable under perturbative quantum corrections. For definiteness, the correction to Higgs mass m_H due to quantum fluctuations of a size characterized by a scale Λ is

$$\delta m_H^2 \propto \alpha \Lambda^2,$$

say, at one loop level. Corrections to the masses of weak gauge bosons $W^{\pm}$ and Z^0 are also of the same order. This is because these gauge bosons acquire masses through spontaneous symmetry breaking whose scale is controlled by the Higgs mass. Thus, if $m_H \sim 100$ GeV, and $\alpha \sim \frac{1}{100}$, and if we wish that the Higgs mass does not receive large corrections, $\delta m_H \sim m_H$, we have:

$$\Lambda^2 \sim \frac{\delta m_H^2}{\alpha} = \frac{(100\ \text{GeV})^2}{1/100} = (1000\ \text{GeV})^2$$
$$\Lambda \sim 10^3\ \text{GeV} = 1\ \text{TeV}.$$

Naturalness of the electroweak theory breaks down at this scale. If there were no new mass scales, or equivalently no new physics beyond 1 TeV, there was no problem. But that is not so. In general there is no reason to believe that there is no new heavy particle, or new interaction with characteristic scales > 0(1) TeV. In particular, we already know, there is a physical scale, 10^{19} GeV associated with quantum gravity. Thus, natural scale of the electroweak theory, as it stands today, is not 100 GeV but 10^{19} GeV! It is an immediate and serious problem. However, what this hints at is only that there has to be some new physics at and beyond 10^3 GeV so that the standard model with its characteristic scale of 100 GeV becomes natural.

One framework for addressing this problem is to think of the scalar Higgs, not as an elementary particle but, as a fermion–antifermion composite, much in the same way as a pion is made of a quark and an antiquark. This is what is called the technicolour option[8–11]. Technicolour is the name given to the new postulated QCD-type force, again a gauge interaction, that would keep these new fermions, techniquarks together in the Higgs particle.

Thus, if we were to probe the Higgs particle with energies greater than 10^3 GeV, we would see it not as an elementary scalar particle, but as a techniquark and a techni-antiquark. Since theories with only fermions and gauge fields are natural like the electrodynamics, now there is no naturalness problem. The condensation of techniquarks results in the masses for weak gauge bosons $W^{\pm}$ and Z^0. This still does not solve the problem of masses for the quark and lepton. For that a new gauge interaction, the extended technicolour is introduced. The extended technicolour gauge bosons with masses of the order of 10–100 TeV connect the ordinary quarks and leptons with the techniquarks. This provides a mechanism for the masses of quarks and leptons. However, there are some serious phenomenological difficulties with this scenario. The difficulties include the non-observation of large flavour changing neutral current effects, heavier Higgs particle, absence of large anomalous contributions to the $Zb\bar{b}$ vertex and large contributions to S, T and U parameters[10–12].

Another perhaps more attractive framework for addressing the naturalness problem of the electroweak theory is supersymmetric[13–17]. This option retains the elementarity of the scalar field. In a supersymmetric theory, the naturalness violating effects due to bosonic and fermionic quantum fluctuations cancel against each other. Since this cancellation has to operate at all orders of perturbation, we need a symmetry which relates the bosonic effects to fermionic effects. That is what supersymmetry does: it relates bosonic and fermionic degrees of freedom.

Supersymmetry[18–20] requires that bosons and fermions come in families. For example, the photon has a superpartner, a neutral fermion, the photino; the electron is accompanied by a scalar partner, the selectron; quarks have scalar partners, squarks; the weak gauge bosons, $W^{\pm}$ and Z have fermionic partners, the wino and zino, etc. Similarly, if we are studying gravity, spin 2 graviton has a superpartner, a spin 3/2 fermion, so-called gravitino.

Exact supersymmetry would imply that all the properties except the spin of particles in a supermultiplet are the same. Thus, the masses and couplings of superpartners would be exactly equal. This, however, is not borne out in Nature, otherwise we would have already seen, say, the selectron, a scalar electron with the same mass and charge as the electron. Hence supersymmetry must be broken so that the superpartners are heavy enough to have been beyond any detection so far. This breakdown should be such that the basic reason for introducing supersymmetry, namely the naturalness problem, does not get out of hand again. In fact the cancellation between the bosonic and fermionic quantum fluctuations need not be exact, it should be only up to the naturalness breakdown scale of the standard model:

$$m^2_{\text{sparticle}} - m^2_{\text{particle}} \leq (10^3 \text{ GeV})^2 .$$

Thus what is required is only a TeV scale supersymmetry. Then, the masses of the particles would be less than one TeV. Present and next generation colliders may, therefore, be able to discover supersymmetry.

The minimal supersymmetric extension of the standard model consists of adding supersymmetric partners to the field content of the standard model. For anomaly-free extension, it also contains two Higgs doublets instead of one. All renormalizable supersymmetric interactions consistent with various global conservation properties are included. In addition, the most general soft-supersymmetry breaking terms (with mass parameters associated with them of the order 1 TeV or below to meet the naturalness constraint) are added.

Besides, the compelling naturalness arguments developed in early eighties[13–17], there are other reasons that have emerged since then in support of supersymmetry[12,21]. Some of these are:

(i) Phenomenologically, a major development hinting at supersymmetry is the beautiful quantitative agreement of precision measurements of the low-energy electroweak coupling constants with the predictions of supersymmetric unified theories. Non-supersymmetric alternative extensions of the standard model have difficulties in this regard.

(ii) Unification of electroweak and strong nuclear forces is possible only in supersymmetric framework; the three coupling constants tend to meet in a point as we go up in the energy scale only in the minimally supersymmetric standard model. We shall return to this point again later.

(iii) There are cosmological implications of supersymmetry. For example, in the minimal supersymmetric standard model, there is a light supersymmetric particle (LSP) which has qualitatively neutrino-like properties. This would be a satisfactory candidate for cold dark matter.

These positive hints are surely tantalizing. Are these mere coincidences? Are there somewhat more definite ways in which we would know if TeV scale supersymmetry is indeed relevant or otherwise? Two possible ways are:

(a) As mentioned above, in supersymmetric extensions of the standard model, there are more than one Higgs doublet. For the lightest Higgs particle, there are rigorous upper bounds, independent of the detailed assumptions, in these models. This is not so in the non-supersymmetric standard model. The numerical value for this bound in minimal supersymmetric standard model is about 150 GeV. For more complicated models (with broken R-parity), this value may go up to 175 GeV. Thus, if no Higgs particle is seen experimentally up to about this upper limit, it is a signal that TeV supersymmetry may not be operative in Nature.

(b) Minimal supersymmetric extension generically tends to reduce the value of quantum corrected parameters, such as couplings, towards the classical (tree) values as compared to those in the non-supersymmetric theory. This is due to the approximate Bose–Fermi cancellations in the loop effects. Thus, in the more detailed experimental precision tests, if the values of the low energy electroweak couplings tend to deviate systematically from the non-supersymmetric theoretical values towards the tree values, this would be a strong hint of minimal supersymmetry.

In the end, only experimental discovery of the superpartners will be the complete vindication of the supersymmetric ideas.

Unification dogma

The oldest example of unification is Maxwell's theory of electromagnetism which provides a combined description of electricity and magnetism. $SU_L(2) \times U_Y(1)$ electroweak theory is a mixed theory of electromagnetic and weak forces. There have been various attempts at developing unified theories of electroweak forces and strong nuclear forces[22,23]. The most popular one is where three groups of the standard model, $SU_C(3) \times SU_L(2) \times U_Y(1)$ are embedded in a larger group, $SU(5)$. All these attempts at grand unifications imply new mass scales much above 1 TeV. As we have argued earlier, mass scales above 1 TeV make the standard model scale perturbatively unstable. It is, therefore, clear that the unification of these three basic forces can be achieved consistently only in a supersymmetric framework. Further, as alluded to earlier, there is a remarkable property associated with the running coupling constants of the minimal supersymmetric extension of the standard model. The three coupling constants α_1, α_2, α_3 associated with the gauge groups $U(1) \times SU(2) \times SU(3)$ respectively evolve with the energy in such a way as to meet at a point only in the minimal supersymmetric standard model and not in the non-supersymmetric standard model[24]. The meeting point occurs at $\mu = 2 \times 10^{16}$ GeV. It is a clear hint of unification at about 10^{16} GeV in the supersymmetric case. Above this scale, all the three interactions are the same and are governed by a single coupling constant corresponding to gauge group $SU(5)$.

In this $SU(5)$ unification, the quarks and leptons are members of one family. The differences which are seen between quarks and leptons are to be viewed as the low-energy phenomena obtained by spontaneous breakdown of the larger $SU(5)$ symmetry to the smaller $U(1) \times SU(2) \times SU(3)$ symmetry at the unification scale of about 10^{16} GeV. In this scenario, there are gauge interactions between the quarks and leptons mediated by new gauge fields, the lepto-quark gauge bosons of $SU(5)$. These new gauge bosons are very heavy, with masses given by the unification scale with the result that the new interactions are very weak. One important implication of these new interactions is that proton in these models is not completely stable. Its lifetime is large but finite, $\tau_{\text{susy}} \sim 10^{35}$–$10^{39}$ years in the supersymmetric $SU(5)$ theory, as compared to $\tau_{\text{non-susy}} \sim 10^{27}$–$10^{31}$ years in the nonsupersymmetric $SU(5)$ model. Experimental limits for proton lifetime are $\tau_{\text{expt}} > 10^{32}$ years, clearly in contradiction with non-supersymmetric model, but consistent with the supersymmetric version. This is satisfying from the supersymmetric point of view. It need not have been so. This surely is not evidence for supersymmetry, but, if the proton lifetime had not worked out to be long enough, it would have been a clear evidence against minimal supersymmetric $SU(5)$ unification.

The unification scale for the three interactions, the electromagnetic, weak and strong, $\mu \sim 10^{16}$ GeV is only three orders of magnitude away from the scale of quantum gravity, $\mu_{\text{Planck}} \sim 10^{19}$ GeV, at which the quantum features of gravity become relevant. It may as well be that we should be thinking of unification of all the forces, including gravity, at the same time. Here again supersymmetry offers an advantage. So far we had been discussing supersymmetry which holds in the same way everywhere in space–time, the global supersymmetry. We could also think of supersymmetry which holds independently at every point of space–time, the so-called local supersymmetry. Gravity is automatically included in such theories. These theories are called supergravity theories. Here spin 2 transverse graviton has a partner, spin 3/2 gravitino. Supersymmetric matter can also be added to these theories. Recall we want a good quantum theory of gravity to be finite. Unfortunately, supergravity theories still are not satisfactory from this point of view. Thus we can think of supergravity theories only as effective low energy theories. As we go up in the energy scale up to the Planck scale, the supergravity theories would have to be replaced by some other fundamental theory which would have to be finite. There do exist candidates for such a theory. These are the superstring theories.

In a string theory[25], the elementary entities are not point particles, but tiny linearly extended objects of the size of Planck length, 10^{-33} cm. Strings can be of two types: open strings and closed strings. Ordinary matter like electrons, quarks, photon, gluons, etc. and their superpartners are described by an open superstring. Graviton and its superpartner gravitino are identified with a closed superstring. This identification respects the basic interaction properties of these particles, namely all types of matter experience the gravitational forces, but graviton does not experience the non-gravitational forces. This property is reflected in the fact

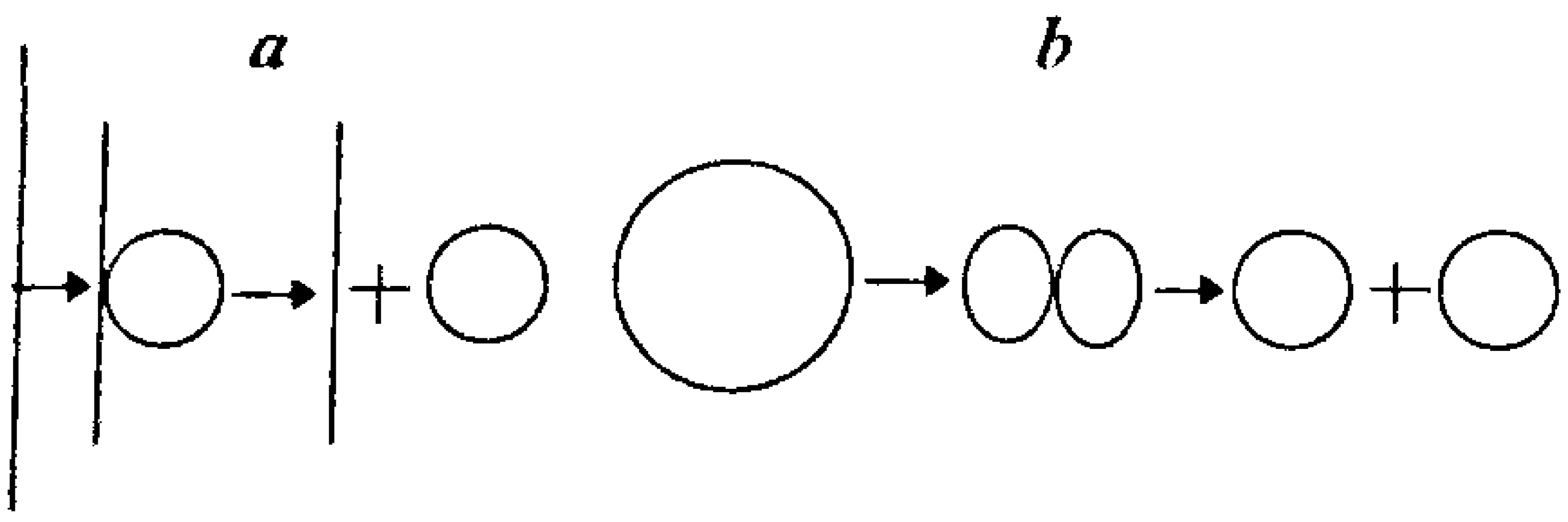

Figure 1a, b. An open string emits an open string and a closed string but a closed string emits only closed strings.

that an open string can emit a closed string as in Figure 1 *a*, but a closed string can emit only a closed string, not an open string, as in Figure 1 *b*.

This picture is indeed encouraging. In fact it does turn out that a closed string does have a spin 2 massless excitation to be identified as the transverse graviton, and open string does have massless spin 1 excitations which are identified with transverse vector gauge bosons.

Some of the features of the string theories are[25]:

(i) This is a framework where all the fundamental forces, including gravity, are unified. It also unifies the matter (quarks and leptons) with mediators of the basic forces (gauge fields), as all these are supposed to be excitations of the same string. That is why sometimes, the string theory is pompously advertised as the *Theory of Everything*.

(ii) Superstring theory provides a *consistent* and *finite* theory of quantum gravity. It is for the first time that principles of general theory of relativity and quantum physics have been consistently married.

(iii) Even if, in the end, it does not turn out to be a completely satisfactory description of Nature, it does provide a theoretically rich testing ground for important conceptual issues of quantum gravity, particularly those related to the fate of black holes.

(iv) Supersymmetry is essential for this theory. Without supersymmetry, string theory is not consistent; it has a tachyon in its spectrum and also it does not provide a finite theory of gravity.

The superstring theory is also beset with difficulties. One problem is that there are several versions of the theory with no clear indication at present as to which of them is preferred by Nature. There is no understanding of the mechanism of supersymmetry breaking both in the supersymmetric field theories as well as in the superstring theories. These issues are expected to be related to the non-perturbative behaviour of these theories. There have been some recent developments which have allowed significant progress in this direction. A lot of circumstantial evidence is emerging for an electric-magnetic type of duality in these theories which relates any string theory at strong coupling to another string theory at weak coupling[26–28]. This may point towards the fact that there is only one fundamental theory of which the various superstring theories are only the asymptotic limits.

Though superstring theory provides a rich and conceptually deep framework, a major difficulty with it is that there is at present no easy way to test whether it is a correct description of Nature. Experimentally-useful effects of strings would occur typically at 10^{19} GeV. There is a huge gap between the present and near future experimentally reachable energy of 10^3 GeV and the Planck scale of 10^{19} GeV where the stringy features manifest. How can this gap be bridged or substantially narrowed?

Summary

We have explored the four dogmas of theoretical high energy physics, namely gauge principle, renormalizability (or finiteness for gravity), naturalness and unification. The requirement that the standard model be natural beyond 1 TeV leads to the extraordinary conclusion that Nature should be supersymmetric at that scale. This is experimentally interesting, because it implies possible supersymmetric particles just around the corner from the energies being explored at present. Discovery of supersymmetry is one of the foremost tasks of the machines of the next two decades. Supersymmetry, if discovered, will open up a whole variety of new particles and phenomena to be studied and analysed. This will influence profoundly the kind of physics that will be done in the 21st century. Supersymmetry may even have implications for cosmology.

Requiring a finite quantum theory of gravity and grand unification of all the four fundamental forces leads us to the speculative, but theoretically rich and conceptually challenging framework of superstrings. Supergravity theory would be only a low energy (at energies $\ll 10^{19}$ GeV) effective theory of such a superstring theory. While TeV supersymmetry will perhaps be discovered experimentally in the next decade or so, let us hope that some evidence, even if cloudy, for stringy ideas may also emerge early in the 21st century.

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New ideas on acceleration to Planckian energies

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A plasma can sustain electric fields that are many thousands of times stronger than those of the most powerful present-day conventional particle accelerators. Plasma-based accelerators thus offer exciting new possibilities and point towards superhigh energies in the future – a promising first step towards Planckian energies.

THE primary motivation for building particle accelerators of ever-increasing energy has come from high energy physics. Starting from the thirties when cyclotron accelerators generating energies of a million electron volts (MeV) provided the necessary tools to study nuclear reactions in the laboratory, the modern day synchrotrons and linear accelerators of up to trillion electron volts (TeV) are helping us probe the fundamental forces of nature and understand the conditions of the early universe. They provide the only controlled and direct means of testing theoretical models, such as the standard model, and explore questions and problems beyond the realm of these models. Unfortunately, the conventional accelerator technology is approaching practical limits and cannot take us to the energy range of interest to high energy physics in the near and long-term future. What are these energies? In the near term, the interest lies in the 10 TeV–100 TeV range where deviations from the standard model can be tested. And in the long term if quantum gravity, the ultimate frontier of high energy physics has to be explored, then one must attain Planckian energies which are of the order of 10^{19} GeV. Conventional accelerators certainly cannot take us there. Infact, the operating principle on which the present-day accelerators are based is about half a century old and one has more or less reached the limits of technology here. Basically these accelerators use strong magnetic fields to guide particles which are propelled by strong electric fields created in vacuum by RF sources. The guide field cannot be raised substantially since they will exceed the structural forces of the magnetic materials used and the electric field strengths are likewise limited by material breakdown limits. The maximum electric field one can obtain is about 1 MV/cm, i.e. 100 MV/m. Thus, to accelerate particles to 10 TeV, one needs to construct an accelerator that is about 100 km in length. The enormous capital costs and the engineering complexities involved in building such devices considerably diminish their future viability. The cancellation of the Superconducting Supercollider (SSC) is a telling example of the kind of fate that can befall such devices. It also underscores the need to come up with new ideas and look for alternative schemes.

Fortunately, plasma particle acceleration, a new technology that has made rapid advances in the past few years, offers a promising alternative. A plasma is a state of matter which is at a temperature where all the atoms are completely ionized. Such a state has overall charge neutrality but local imbalances in charges can give rise to large longitudinal electric fields. These fields, which cause the plasma electrons to oscillate back and forth around the massive ions – the so-called plasma oscillations – can be effectively used for particle acceleration.