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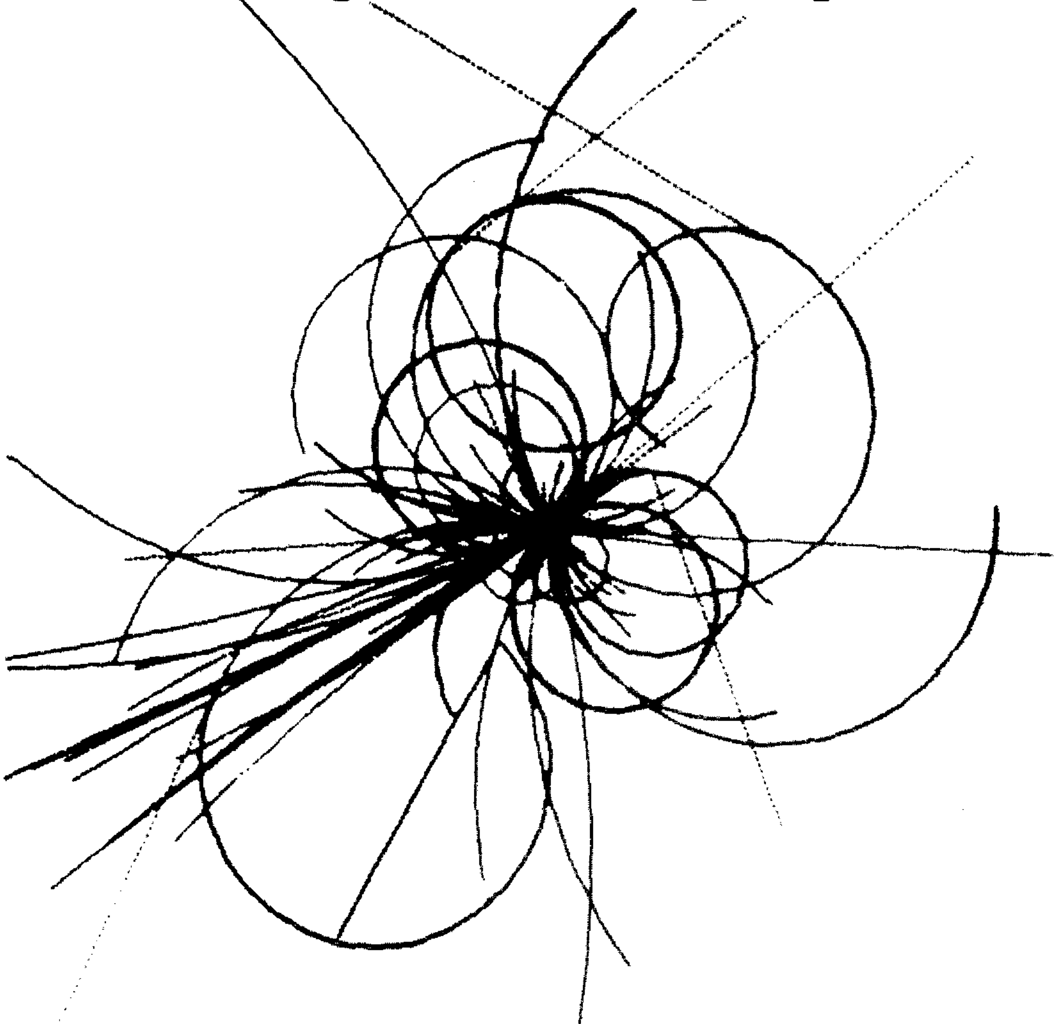
The Superconducting Super Collider



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Chris Quigg
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*Lecture given November 16, 1987, at Collège de France, Paris, as "La Physique à 40 TeV au Supercollisionneur Proton-Proton" in the 1987 Bernard Gregory Lecture Series.

†Operated by Universities Research Association, Inc., for the United States Department of Energy.

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Over the past two decades, the age-old struggle to describe and comprehend the nature of elementary particles and forces has been rewarded by a radically new and simple picture of Nature. This progress has, in large measure, been stimulated by experimental results from particle accelerators, instruments of the kind given to us by Bernard Gregory and his colleagues. We have learned that all matter in its diverse forms is assembled from a few building blocks called quarks and leptons. All known natural phenomena can be described in terms of a few fundamental forces acting among these basic constituents. The new insights embodied in the Standard Model of elementary-particle physics not only provide a framework for describing and understanding the world around us, but also elucidate the first instants after the creation of the universe.

However, as our conception of matter has become better established, we have become increasingly aware of its shortcomings. Although the Standard Model represents a great step toward a complete understanding of the structure of matter, the 1970s brought not only multifarious experimental support for that theoretical framework, but also the realization that it is incomplete. We do not believe that within the energy range now available there can be enough clues for us to piece together a comprehensive theory of the nature of matter. This conviction—together with our awareness of the value of exploration, our appreciation of the countless instances when unexpected, puzzling, and illuminating new observations have come out of accelerator experiments—motivates our quest for higher energies.

My first order of business will be to summarize the microscopic description of matter to which we have come in the past twenty years. I will review the evidence for quarks and leptons as fundamental constituents and explain the strategy of gauge theories of the fundamental interactions. Next, I will discuss questions the Standard Model raises but cannot answer. We can define a frontier where our current understanding ceases to make sense, where the clues that will lead us to a more satisfying description of Nature will have to be found. That frontier lies at energies of about 10^{12} electron volts for collisions among the fundamental constituents. The instrument of choice for reaching this new energy scale is a high-energy, high-luminosity, proton-proton collider. I will conclude by summarizing the status of the American project known as the Superconducting Super Collider, or SSC.

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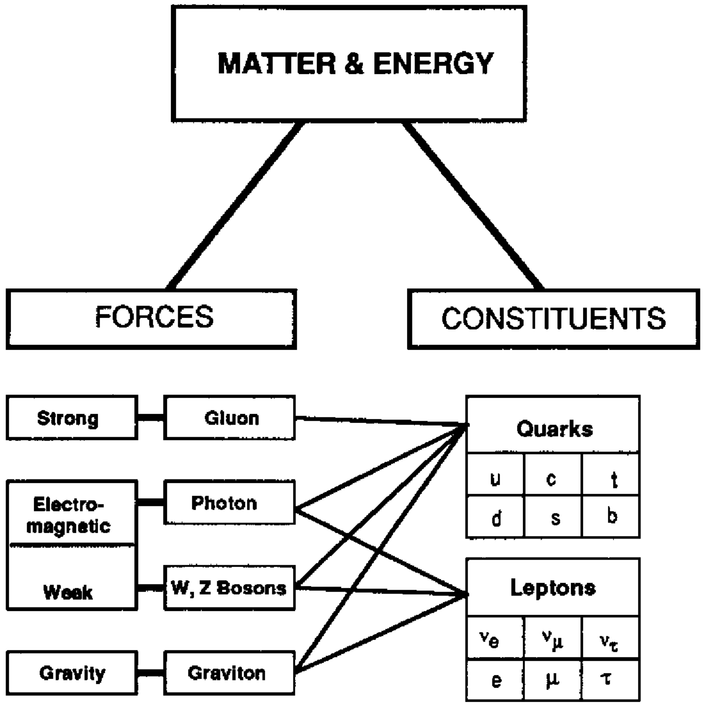


Figure 1: The Standard Model of Elementary-Particle Physics.

Where We Stand

The Standard Model, shown schematically in Figure 1, has emerged from the identification of leptons and quarks as fundamental constituents and the development of gauge theories of the strong, weak, and electromagnetic interactions. Because gauge theories provide a common mathematical framework, we see before us the prospect of a unification of these three interactions and the hope of a simpler and more comprehensive description of Nature.

The leptons experience weak and electromagnetic—but not strong—interactions. We know of six species: the electron, muon, and tau, all electrically charged, and their neutral partners, the neutrinos. The interactions of the electron neutrino and muon neutrino have been observed directly. We know a great deal about the interactions and properties of the tau neutrino and know that it must be a sequential neutrino, distinct from the electron neutrino and antineutrino or the muon neutrino and antineutrino. However, no experiment has been carried out in which a beam of tau neutrinos is produced, penetrates a large column of matter, and interacts in a target to produce a tau. This "three-neutrino experiment" would provide the final demonstration that the tau neutrino exists, but the outcome is not in doubt.

All the leptons are spin-$\frac{1}{2}$, pointlike, Dirac particles, structureless at the current limits of our resolution, about 10^{-16} cm. Much is known about their static properties such as magnetic moments and masses. It is noteworthy that the leptons fall into weak-interaction families

$$\binom{\nu_e}{e}_L, \quad \binom{\nu_\mu}{\mu}_L, \quad \text{and} \quad \binom{\nu_\tau}{\tau}_L \quad , \tag{1}$$

where the subscript L signals that the charged-current interaction is left-handed.

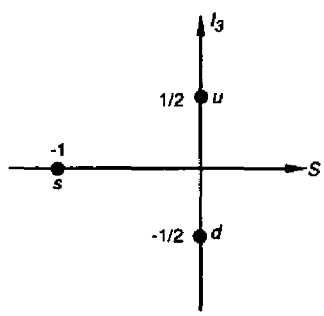
The other great class of particles we can study in the laboratory consists of the hadrons, which participate in the strong as well as the weak interactions. There are many hundreds of species, including the proton, neutron, pion, kaon, and Δ-resonance. The hadrons comprise both fermions, which have half-integral spins, and bosons, which have integral spins. All are composite, with sizes on the order of 10^{-13} cm in radius. The hadrons may be exceedingly stable, like the proton, whose lifetime of more than 10^{31} years considerably exceeds the age of the universe, or quite ephemeral, like the Δ, whose lifetime is about 10^{-24} second.

Order is brought to this diverse collection of strongly interacting particles by the idea that hadrons are made up of quarks, which, like the leptons, are spin-$\frac{1}{2}$, pointlike particles, smaller than about 10^{-16} cm in radius. Unlike the leptons, the quarks are not seen directly in the laboratory. It is therefore valuable to spend a few moments recalling the variety of experimental evidence that supports the quark model of the hadrons.

Why We Believe in Quarks

The original motivation for the quark model came from the spectroscopy of the strongly interacting particles developed in the early 1960s. The unitary symmetry group *SU(3)* was found to be a good classification symmetry for the hadrons then known. In contrast to the experience with the rotation group for angular momentum, or with *SU(2)* for isospin, it was observed that only a few of the low-lying representations of *SU(3)* were populated with hadrons. The mesons, hadrons of integer spin like the pion, appeared in families of one or eight members, but not of three, or six, or twenty-seven. The baryons, particles of half-integer spin like the proton, appeared only in families of one, eight, or ten members.

This pattern can be reproduced if we say that the hadrons are built up out of a fundamental triplet of quarks, an isospin doublet called up and down, and an isoscalar strange quark that carries –1 unit of strangeness:



If we make the rule that mesons are composed of a quark and antiquark, $(q\bar{q})$, then according to the arithmetic of *SU(3)*, $\mathbf{3} \otimes \mathbf{3}^* = \mathbf{1} \oplus \mathbf{8}$, so that mesons should occur in one- and eight-member families. Similarly, if baryons are composed of three quarks, (qqq), then the rules of *SU(3)* yield $\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{1} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{10}$, so that baryons should occur in one-, eight-, and ten-member families. It remains to be understood why quarks have only been observed in these combinations.

The first evidence that quarks are real, rather than merely mnemonic devices, came from experiments carried out in the late 1960s at the Stanford Linear Accelerator Center. A beam of high-energy electrons is scattered from a target, as shown in Figure 2. You observe the direction and momentum of the scattered electron and, if you wish, observe something about the recoil

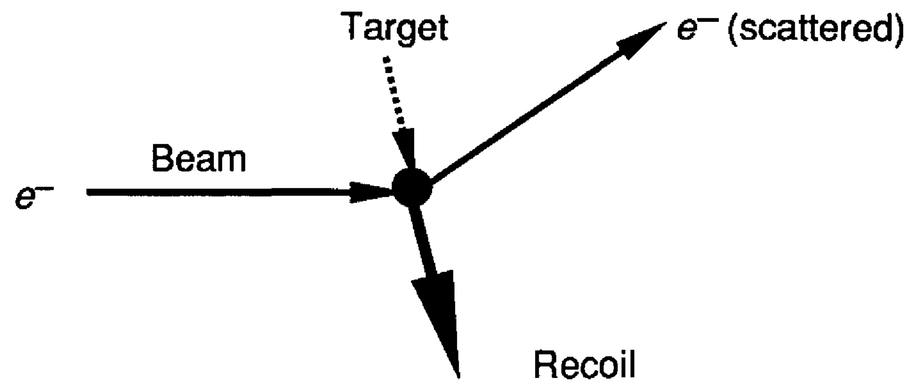


Figure 2: Kinematics of electron scattering.

particle or particles. The goal of the experiment is to measure the cross section as a function of the angle and energy of the scattered electron and to understand what that reveals about the internal structure of the target.

To appreciate the significance of the SLAC experiment it is useful to look at its historical antecedent. Take as a target a carbon nucleus, scatter electrons from it, and require that the carbon nucleus remain intact after the collision. In this way we are studying the reaction

$$\text{electron} + \text{carbon nucleus} \rightarrow \text{electron} + \text{carbon nucleus}. \tag{2}$$

If you hit the carbon nucleus very hard, it is likely to fly apart, because it is a loosely bound collection of protons and neutrons (or perhaps of alpha particles). By requiring that the nucleus remain intact you are selecting a very rare occurrence. The rate at which this elastic scattering process occurs decreases rapidly as the momentum transferred to the target increases. This is illustrated in Figure 3(a).

On the other hand, if you relax the constraint that the carbon nucleus remain intact and simply observe the scattered electron without regard to the details of the recoil system, then you find that the cross section is almost independent of how sharp a blow is delivered. This is indicated by the broken line in Figure 3(a). We interpret this constant cross section as evidence that the electrons are being scattered from small charged objects within the nucleus, constituents that are structureless at this resolution. Those are the protons, as may be verified by examining the debris from the shattered carbon nucleus.

It is a natural step to repeat these measurements with the proton as target and with beams of increasing energy. The results are indicated in Figure 3(b), where the scale of momentum transfer has been increased by two orders of magnitude. When inspected at this much higher resolution, the proton no longer behaves like a point particle. The structure of the proton is reflected in the fact that the rate for the reaction

$$\text{electron} + \text{proton} \rightarrow \text{electron} + \text{proton} \tag{3}$$

falls off rapidly. The proton tends to become excited or to produce new particles when hit hard.

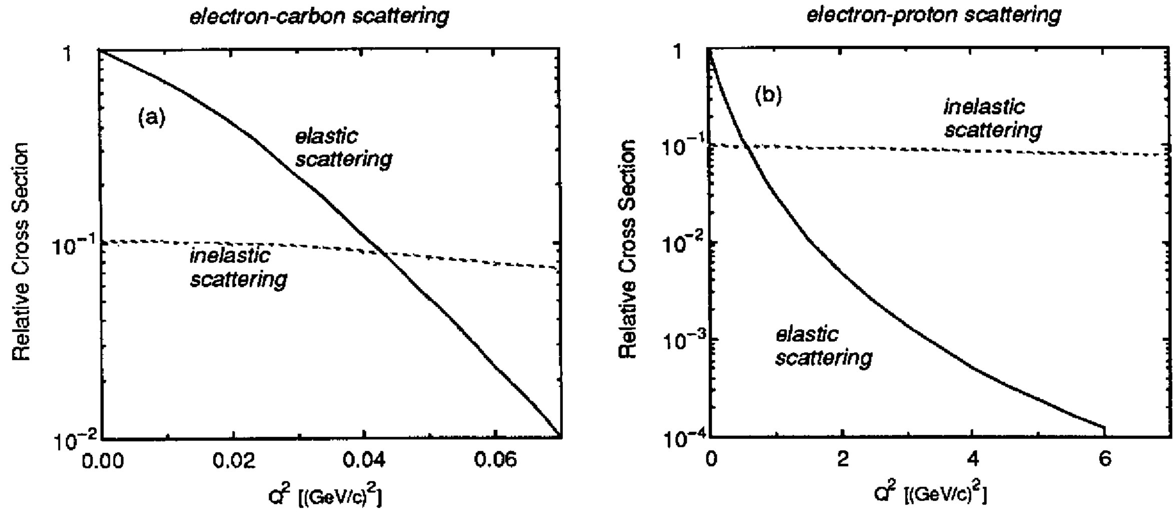


Figure 3: Elastic and inelastic cross sections for (a) electron-carbon scattering; (b) electron-proton scattering.

If we relax the constraint that the proton survive the collision intact, we find that, just as for the scattering of an electron from a nucleus, there is a contribution to the "inelastic" cross section that is essentially independent of how hard the proton is hit. Just as we inferred from the earlier experiments with nuclear targets the presence of charged, structureless objects—the protons—within the nucleus, it is tempting to conclude that there are charged, structureless objects within the proton itself. This role is naturally played by the quarks.

Unlike the protons within the nucleus, the quarks within a proton cannot readily be liberated. Our knowledge of the properties of quarks, like our belief in the physical reality of quarks itself, therefore rests on indirect evidence. What can be said about the properties of the quarks?

- From the observation that there are three quarks in a baryon we conclude that each quark has baryon number 1/3.

- The quark charges are given by the Gell-Mann–Nishijima formula as

$$Q = I_3 + \tfrac{1}{2}(B+S) = \begin{cases} 2/3 & u \\ -1/3 & d \\ -1/3 & s \end{cases} , \tag{4}$$

where B denotes baryon number and S strangeness. These assignments can be tested in several ways. We can note at once that they reproduce the charges (2,1,0,–1) of the baryons. Another test is to look at the decay rates for spin-one particles made of a quark and an antiquark, the so-called vector mesons. These particles decay (rarely) into electron-positron pairs. In the quark model, this decay occurs when the quark and the antiquark annihilate into a virtual photon that subsequently disintegrates, according to the laws of quantum electrodynamics, into the electron-positron pair. The rate at which this leptonic decay occurs is proportional to two parameters: the square of the electric charge carried by the quark and antiquark, and the probability for the quark and the antiquark to get together and annihilate, measured by the square of the bound-state wave function at zero separation, $|\psi(0)|^2$. Taking the wave functions

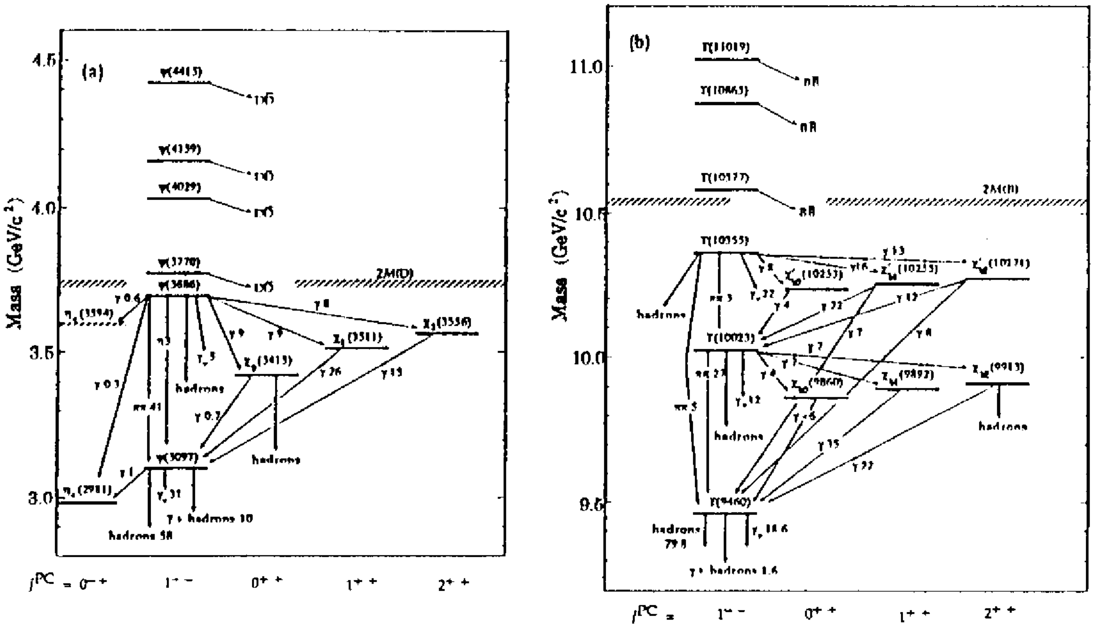


Figure 4: (a) The charmonium states (first observed in 1974);
(b) the upsilon family (first observed in 1977).

to be similar for all the light vector mesons, ρ, ω, and ϕ, we may test the charge assignments of the quarks that make them up by comparing the leptonic decay rates. The relative rates are just as expected.

• Quarks have spin-$\frac{1}{2}$. The multiplet structure of the hadrons exhibits precisely the pattern given by the quark model. For the mesons, the order of levels follows the sequence

$$J^{PC} = \underset{L=0}{0^{-+}\ 1^{--}} \quad \underset{L=1}{0^{++}\ 1^{+-}\ 2^{++}} \quad \cdots \, . \tag{5}$$

This pattern is evident for the "light mesons" made up of up, down, and strange quarks, but it is exhibited most clearly by the bound states of two heavy quarks. I show in Figure 4(a) the spectrum of states composed of a charmed quark and antiquark; the states composed of the fifth quark, called bottom or beauty, and its antiquark are shown in Figure 4(b). The order of levels is just what we expect for bound states of a spin-$\frac{1}{2}$ particle and antiparticle. The analysis of baryon spectra is more involved. It can be summarized in the statement that the $SU(6) = SU(3)_{flavor} \otimes SU(2)_{spin}$ classification of baryons, which hangs upon the spin-$\frac{1}{2}$ nature of the quarks, is highly successful.

Independent evidence for the spin of the quarks—and for the reality of the quarks—comes from the reaction

$$\text{electron} + \text{positron} \to \text{hadrons (mostly pions)} \ . \tag{6}$$

In the quark-parton model, the electron and positron annihilate into a virtual photon that disintegrates according to the rules of quantum electrodynamics into a quark-antiquark pair. The quark and antiquark are not observed directly. They materialize, by a process not yet completely understood, as hadrons collimated along the directions of the quark and antiquark. The resulting two-jet events are commonplace at high energies; one is shown in Figure 5. The colliding beams are perpendicular to the plane of the page and the projection shown is an end-on view

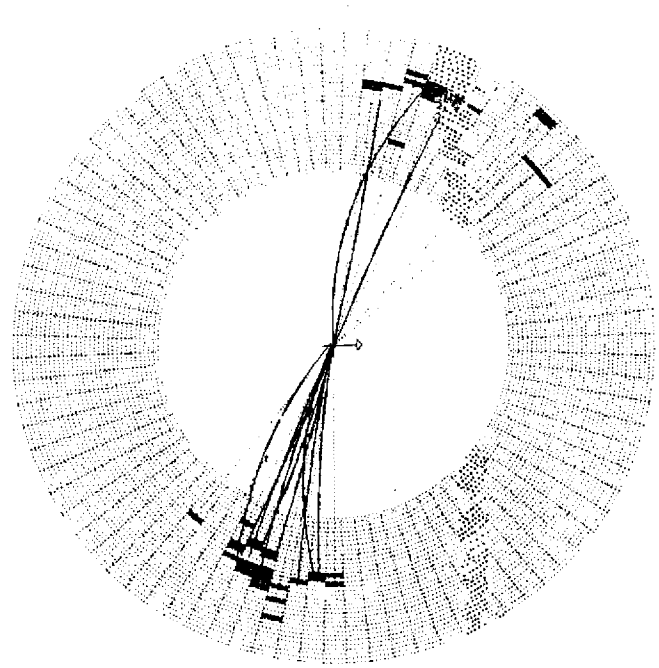


Figure 5: A two-jet event produced in 30-GeV electron-positron annihilations in the JADE Detector at the PETRA storage ring in Hamburg.

of the cylindrical detector, about two meters in diameter. Charged particles are indicated by their curved tracks in a solenoidal magnetic field, and neutrals are detected by the deposition of energy in the calorimeter cells. The trajectories of neutrals are reconstructed as dotted lines. With this indication that the directions of the quark and the antiquark in the semifinal state may be inferred from the jet directions, we may interpret the angular distribution of the jets with respect to the beam axis as the angular distribution of the quark-antiquark pair. The measured distributions are given by

$$\frac{dN}{d(\cos\theta)} \propto 1 + \cos^2\theta \,, \tag{7}$$

characteristic of the decay of the $J^P = 1^-$ photon into a pair of spin-$\frac{1}{2}$ particles.

This summarizes some of the evidence for the existence of quarks and for their detailed properties. The quark model reproduces much of what we know about the spectrum and interactions of hadrons, but in the form we have described so far it is not completely consistent. In building models of physical phenomena, it has paid off through the years to respect the grand principles that have great force and wide applicability. One such is the Pauli exclusion principle, which is a reliable guide to the construction of the periodic table of the elements. We can derive the exclusion principle, or more precisely the spin-statistics connection, from quantum field theory, so it should apply to quarks as well as to electrons.

The problem is that, for particles such as the Δ^{++} and the Ω^-, the quark model does not respect the Pauli principle. The Δ^{++}, for example, is a pion-nucleon resonance with a mass of about 1232 MeV/c^2. In the quark model it is a uuu state with spin = 3/2 and isospin = 3/2, a member of the ground-state supermultiplet in which all pairs of quarks are in relative s-waves.

Thus it is apparently a symmetric state of three identical fermions. Unless we are prepared to suspend the rules of quantum mechanics or to give up the quark model, it is necessary to invoke a new, three-valued, hidden degree of freedom in terms of which the Δ^{++} wave function may be antisymmetrized. This new degree of freedom is called color, and quarks are given the labels red, green, and blue. Any hadron will therefore be colorless: a baryon will be a color-singlet mixture of red, green, and blue quarks, and a meson will be a color-singlet mixture of red-antired, green-antigreen, and blue-antiblue quark-antiquark pairs.

Described in this way, the introduction of color seems arbitrary and artificial. However, a number of observables are sensitive to the number of distinct quark species. Subsequent measurements of these quantities have given strong support to the color hypothesis, which has become the foundation of our understanding of the strong interaction.

We have already seen that the cross section for the inclusive production of hadrons in electron-positron annihilations is described by the elementary process

$$\text{electron} + \text{positron} \rightarrow \text{quark} + \text{antiquark} \ , \tag{8}$$

where the quark and antiquark materialize with unit probability into the observed hadron jets. At a particular energy, the ratio

$$R \equiv \frac{\sigma(e^+ e^- \rightarrow \text{hadrons})}{\sigma(e^+ e^- \rightarrow \mu^+ \mu^-)} \tag{9}$$

is then simply given as

$$R = \sum_{\text{flavors}} e_q^2 \ . \tag{10}$$

At the highest energies explored, pairs of up, down, strange, charmed, and bottom quarks are kinematically accessible. In the absence of hadronic color we would therefore expect

$$R = e_u^2 + e_d^2 + e_s^2 + e_c^2 + e_b^2 = \frac{11}{9} \ , \tag{11}$$

but if each quark flavor exists in three distinct colors, we should have

$$R = 3(e_u^2 + e_d^2 + e_s^2 + e_c^2 + e_b^2) = \frac{11}{3} \ . \tag{12}$$

The colored-quark prediction is in excellent agreement with the data summarized in Figure 6. These data show, by the way, that the mass of the top quark (whose existence is required for the consistency of the electroweak theory and implied by the characteristics of b-quark decay) must exceed about 26 GeV/c^2. Proton-antiproton collider experiments extend the lower bound to about 40 GeV/c^2.

This completes our survey of the fundamental constituents. Let us now turn our attention to the fundamental interactions and to the gauge theories that describe them.

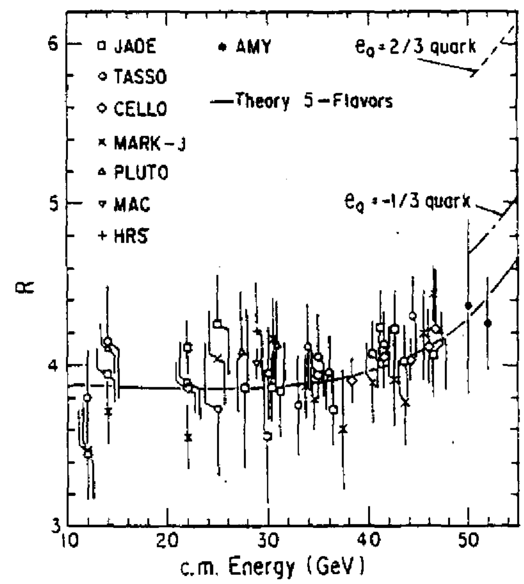


Figure 6: The ratio $R \equiv \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$.

Gauge Theories of the Fundamental Interactions

Quantum electrodynamics is in many ways the very model of a successful physical theory. It is renormalizable, calculable in perturbation theory, and in good agreement with experiment. The nine-digit accord between calculation and measurement for the gyromagnetic ratio of the muon sets a standard for other theories to equal. QED has now been subsumed in the Weinberg-Salam theory of the weak and electromagnetic interactions. Though tested only at the level of a few percent—the onset of sensitivity to loop corrections—the electroweak theory has many experimental successes: the prediction of neutral weak currents and charm, and the prediction of the existence and properties of the intermediate bosons $W^\pm$ and Z^0 found in the proton-antiproton collider experiments at CERN in 1983. At the level on which we have been able to test it, the electroweak theory provides a quantitative description of all electroweak phenomena.

The theory of the strong interactions, called quantum chromodynamics, is based on the color symmetry of the quarks. It provides insight into the systematics of hadron structure and hadronic interactions, and it predicted the existence of gluons, the carriers of the strong force. Because the strong interactions are, in most circumstances, strong, it has not yet been possible to derive from QCD many precise, testable predictions. A few quantitative successes, in which experiment agrees with theoretical predictions reliable within a few tens of percent, are known in the regime in which perturbation theory applies.

This is not the place to treat comprehensively theories of the fundamental interactions. However, it is appropriate to review the strategy for formulating a gauge theory, and to summarize the basic hypotheses that underlie our understanding of the strong, weak, and electromagnetic interactions.

Building a gauge theory is easier done than said. I shall first outline the steps and then carry out the construction of a theory in a simple example. First, we recognize conservation laws, or, equivalently, we notice symmetries in Nature, and build equations of physics that respect the symmetries in question. Having accomplished that, we try to impose the symmetry in a stricter form. When the new requirement is imposed, the equations of physics from which we began will have to be modified to accommodate the stricter form of the symmetry. This can be done in a mathematically consistent way only by introducing new interactions and new particles to carry those interactions.

To see what this outline means, suppose that we knew the Schrödinger equation, but not the laws of electrodynamics. Would it be possible to derive Maxwell's equations from a symmetry principle? The answer is yes! It is instructive to trace the steps in detail.

A quantum-mechanical state is described by a complex Schrödinger wave function $\psi(x)$. Quantum-mechanical observables involve inner products—expectation values of Hermitian operators—of the form

$$\langle O \rangle = \int \psi^* O \psi \,, \tag{13}$$

which are unchanged by a global phase rotation:

$$\psi(x) \to e^{i\theta}\psi(x) \ . \tag{14}$$

In other words, the absolute phase of the wave function cannot be measured and is a matter of convention. Relative phases between wave functions, as measured in interference experiments, are unaffected by such a global rotation. To emphasize the role of symmetry, we may say that ordinary quantum mechanics is invariant if we change our convention for zero phase uniformly everywhere in space. This is illustrated in Figure 7. Let each arrow represent the convention for a complex number with zero phase, i.e., a real number, at different positions in space—say at each seat in the lecture hall. With all its arrows pointing to the right (east), Figure 7(a) indicates the convention we have been trained to consider natural. A new convention for zero phase, directed toward the southeast, is displayed in Figure 7(b). What we have just seen is that the predictions of quantum mechanics do not depend on the orientation of the arrows.

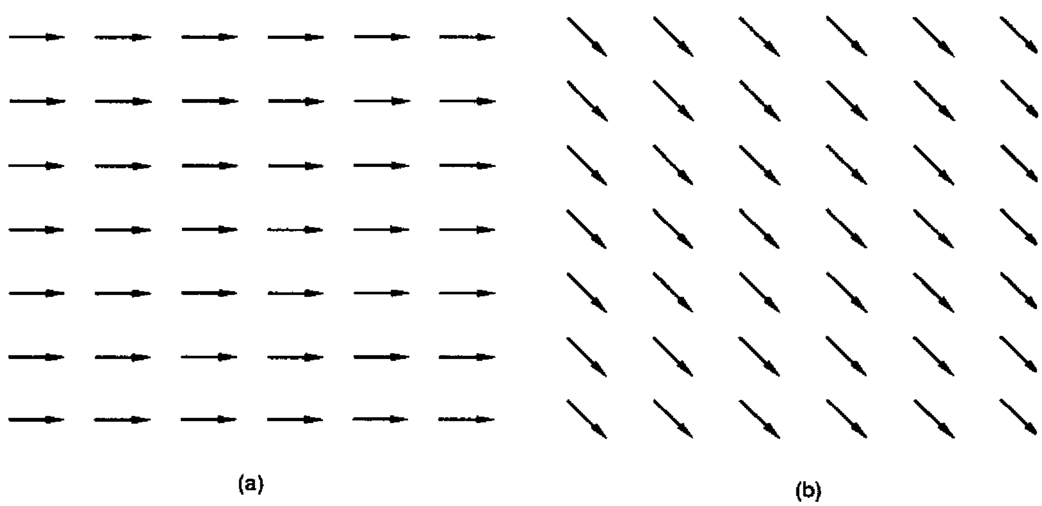


Figure 7: Arrows represent the convention for a complex number of zero phase at different points in space. (a) Original convention for zero phase; (b) new convention for zero phase.

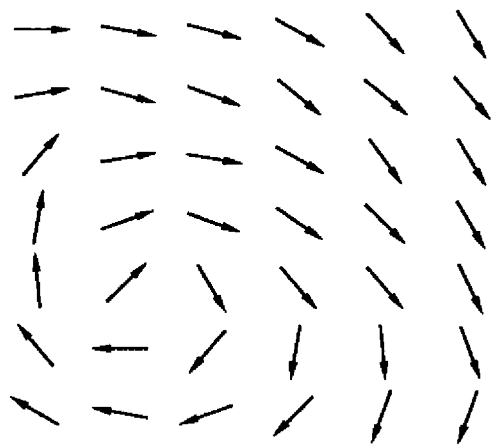


Figure 8: Arrows indicate a different convention for a complex number of zero phase at each point in space.

This raises the question: Are we free to choose one phase convention in Paris and another in Geneva, or indeed a different convention at each point in space, as indicated in Figure 8? Differently stated, can quantum mechanics be formulated to be invariant under local (position-dependent) phase rotations

$$\psi(x) \to \psi'(x) = e^{i\alpha(x)}\psi(x) \ ? \tag{15}$$

We shall see that this can be accomplished, but at the price of introducing an interaction. In this example we shall construct that interaction to be electromagnetism.

Quantum mechanical equations of motion, such as the Schrödinger equation, always involve derivatives of the wave function ψ, as do many observables involving energy and momentum. Under local phase rotations, derivatives transform as

$$\nabla\psi(x) \to e^{i\,\alpha(x)}\left[\nabla\psi(x) + i\,(\nabla\alpha(x))\psi(x)\right] \ , \tag{16}$$

which involves more than a mere phase change. The additional gradient-of-phase term spoils local phase invariance. Local phase invariance may be achieved, however, if the equations of motion and the observables involving derivatives are modified by the introduction of the electromagnetic field $\mathbf{A}(x)$. If the gradient is everywhere replaced by the gauge-covariant derivative

$$\mathcal{D} \equiv \nabla - i\,e\,\mathbf{A} \ , \tag{17}$$

where e is the charge in natural units of the particle described by $\psi(x)$ and the field $\mathbf{A}(x)$ transforms under local phase rotations as

$$\mathbf{A}(x) \to \mathbf{A}'(x) \equiv \mathbf{A}(x) + \frac{1}{e}\nabla\alpha(x) \ , \tag{18}$$

it is easily verified that under local phase rotations

$$\mathcal{D}\,\psi(x) \rightarrow e^{i\alpha(x)}\mathcal{D}\,\psi(x) \ . \tag{19}$$

Consequently, quantities such as $\psi^*\mathcal{D}\,\psi$ are invariant under local phase transformations. The required transformation law for the electromagnetic vector potential is precisely the form of a gauge transformation in electrodynamics. Moreover, the gauge-covariant derivative corresponds to the familiar replacement $p \rightarrow p - e\,\mathbf{A}$ for the momentum of a charged particle in the presence of an electromagnetic field. Thus the form of the coupling $(\mathcal{D}\,\psi)$ between the electromagnetic field and matter is suggested by local phase invariance.

Let us summarize the general consequences of the symmetry approach to interactions. Through Noether's Theorem, a (continuous) global symmetry implies (and frequently is recognized because of) the existence of a conserved current, the electromagnetic current in our example. A local gauge symmetry requires, in addition, the introduction of a massless vector gauge field A and prescribes the form of the interaction between matter and the gauge field in the form known as minimal coupling. Electromagnetism, or QED, is the gauge theory based on the group of phase transformations, i.e., on the Abelian group *U(1)*. The generalization to non-Abelian symmetries can be made, so that the construction of a gauge theory can be carried out for any continuous symmetry.

Quantum Chromodynamics

The simplest non-Abelian theory to describe, though regrettably not to solve, is the theory of strong interactions based on color symmetry. QCD is motivated by the observation that color is what distinguishes the quarks from the leptons. Since quarks experience the strong interactions but leptons do not, it is natural to regard color as a strong-interaction charge and to take the symmetry among red, green, and blue quarks as a local gauge symmetry. The unitary symmetry group *SU(3)* is an apt choice for the color symmetry because, having a complex fundamental representation, it makes a distinction between quarks and antiquarks. We would not want to construct a theory in which the existence of quark-antiquark bound states, the mesons, would imply that there should be quark-quark bound states, which are not observed.

With the choice of $SU(3)_{color}$ as the gauge group, the quark-antiquark interaction is mediated by vector gluons, which transform as an octet under the color symmetry. If physical states must be colorless, which would explain why free mesons and baryons exist but free quarks have not been observed, free gluons will not be seen. Our evidence for the existence of gluons, like that for the existence of quarks, is therefore indirect. It is basically of two sorts. First, energy-momentum sum rules in lepton-nucleon scattering indicate that the partons that interact electromagnetically or weakly, namely the quarks, carry only about half the momentum of a nucleon. Something else, electrically neutral and inert with respect to the weak interactions, must carry the remainder. This is a role for which the gluons are ideally suited. Second, at center-of-momentum energies exceeding about 17 GeV, a fraction of hadronic events produced in electron-positron annihilations display a three-jet structure instead of the familiar two-jet ($e^+e^- \rightarrow q\bar{q}$) structure. A typical event of this type is shown in Figure 9. This is interpreted as evidence for the process

$$e^+e^- \rightarrow q\bar{q} + \text{gluon}\,, \tag{20}$$

in which the gluon is radiated from the outgoing quark in a hadronic analog of electromagnetic bremsstrahlung.

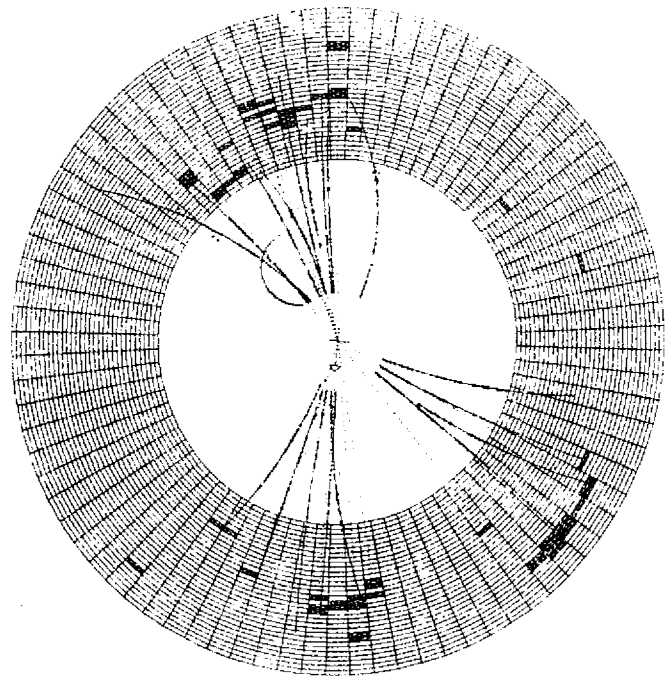


Figure 9: Three-jet event observed in the reaction $e^+e^- \rightarrow$ hadrons at 31 GeV, in the JADE detector at PETRA.

Electroweak Theory

The construction of the electroweak theory is somewhat more involved, so I shall describe it only very schematically. We begin from the observation that the leptons (electrons, muons, taus, and their neutrinos) seem to live in distinct families

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \quad \text{and} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \quad . \tag{21}$$

The familiar weak interactions change one family member into another but do not cross family lines. This suggests using the weak-isospin symmetry among neutral and charged leptons (or among up-like and down-like quarks) together with a phase invariance, as in electromagnetism, for the gauge symmetry. A theory can be constructed along these lines using the gauge group $SU(2)_L \otimes U(1)_Y$, where Y denotes the weak hypercharge. The resulting force particles are the photon and the two charged intermediate bosons W^+ and W^-, all of which are expected from the classical phenomenology of the weak and electromagnetic interactions, plus a new, neutral intermediate boson, the Z^0.

Although the $SU(2)_L \otimes U(1)_Y$ gauge theory contains the familiar charged weak current, it cannot describe the weak interactions without an important modification. It has been known for many years from the absence of pronounced form-factor effects in β–decay that the weak interactions are of very short range. The gauge bosons that mediate the weak interaction cannot be massless, for massless particles mediate forces of infinite range. How can the requirement that the intermediate bosons be massive be reconciled with the appealing constraint of local gauge invariance, which leads naturally to massless gauge bosons?

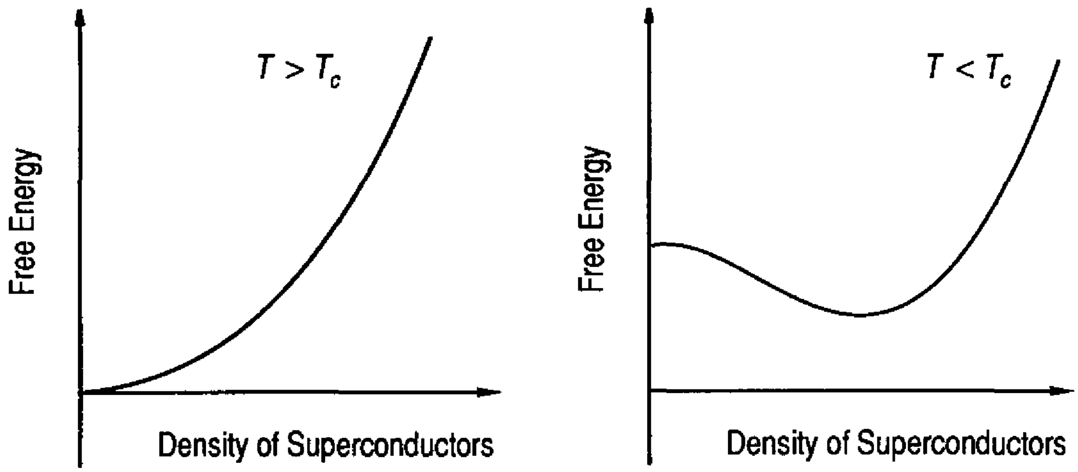


Figure 10: Ginzburg-Landau description of the superconducting phase transition.

The answer lies in the phenomenon of spontaneous symmetry breaking, whereby a physical system need not manifest all the symmetries of the interaction that gives rise to it. The most familiar example of a spontaneously broken symmetry is the spontaneous magnetization of soft iron. Electromagnetism is symmetric under spatial rotations; there is no preferred direction in space. This rotation-invariance is manifested by the fact that a lump of warm iron looks the same from all directions. If we regard the piece of iron as a collection of microscopic magnets, the micromagnets are in disorder, pointing randomly in all directions. However, when cooled below the Curie temperature, iron magnetizes spontaneously. The magnetic interaction among the micromagnets overcomes thermal agitation and causes an alignment: the selection of a preferred axis. Now, only rotations about the axis of magnetization leave the lump of iron unchanged in appearance. The full rotation-invariance of electromagnetism is hidden, or spontaneously broken. The hidden symmetry can be recovered by repeating the thermal cycle many times. Each time the iron is cooled, it will magnetize spontaneously, but each time along a different direction. The fact that every direction is equally probable shows that the underlying interaction—electromagnetism—does not have a preferred direction, and so is rotation-invariant.

The most apt analogy for the hiding of the electroweak symmetry is found in superconductivity. In the Ginzburg-Landau description of the superconducting phase transition, a superconducting material is regarded as a collection of two kinds of charge carriers: normal resistive conductors and superconductors. Above the critical temperature for the onset of superconductivity, T_c, the free energy of the substance is supposed to be an increasing function of the density of superconductors. The state of minimum energy, the vacuum state, then corresponds to a purely resistive flow, with no superconductors active. Below the critical temperature, the free energy is minimum when the density of superconductors is nonzero. These two cases are illustrated in Figure 10. If we now consider the behavior of the free energy in an applied magnetic field, we find that, below the critical temperature, the photon acquires a mass within the superconducting material. This is the origin in the Ginzburg-Landau model of the Meissner effect, the exclusion of a magnetic field from a superconductor. More to the point, for our purposes, it shows how a symmetry-hiding phase transition can lead to a massive gauge boson.

To give masses to the intermediate bosons of the weak interaction, we take advantage of a relativistic generalization of the Ginzburg-Landau phase transition known as the Higgs mechanism. We introduce elementary auxiliary scalar fields, with gauge-invariant interactions among themselves and with the fermions and gauge bosons of the electroweak theory. We then arrange their self-interactions so that the vacuum state corresponds to a broken-symmetry solution. As a result, the W and Z bosons acquire masses, as auxiliary scalars assume the role of the missing third (longitudinal) degrees of freedom of what had been massless gauge bosons. The quarks and leptons acquire masses as well, from their Yukawa interactions with the scalars. Finally, there remains as a vestige of the spontaneous breaking of the gauge symmetry a massive, spin-zero particle, the Higgs boson.

The principal consequences of electroweak unification are these: (i) The strengths of the weak and electromagnetic interactions become equal at short distances. (ii) The couplings of the Z^0 to matter are prescribed. (iii) The masses of the gauge bosons $W^{\pm}$ and Z^0 are predicted. It is remarkable that the resulting theory has been tested at distances ranging from about 10^{-16} cm to about 4×10^{10} cm, especially when we consider that classical electrodynamics has its roots in the tabletop experiments that gave us Coulomb's law. These basic ideas were modified in response to the quantum effects observed in atomic experiments. High-energy physics experiments continued the extension toward still shorter distances and both inspired and tested the unification of the weak and electromagnetic interactions. At distances longer than the scale of common experience, electrodynamics—in the form of the statement that the photon is massless—has been tested in measurements of the magnetic fields of the planets. With additional dynamical assumptions, the observed stability of the Magellanic clouds provides evidence that the photon is massless over distances of about 10^{22} cm.

Unification of the Fundamental Interactions

The theories that describe the fundamental interactions have a number of central elements in common. All are renormalizable field theories, calculable in perturbation theory. All are based on symmetry principles, which suggests the prospect of further unification. In fact, a hint that unification of the strong and electroweak interactions may be required comes from the electroweak theory itself. Applied only to leptons, or only to quarks, the electroweak theory is not mathematically self-consistent: triangle anomalies destroy the renormalizability of the theory. A self-consistent theory requires, for each weak-isospin doublet of leptons, a color-triplet weak-isospin doublet of quarks. The idea that quarks and leptons both are required suggests that they may be related, a notion encouraged by the similarity of their properties. This, in turn, suggests that there should be extended families of quarks and leptons and, in consequence, symmetries that may transform quarks into leptons.

A second hint that the strong, weak, and electromagnetic interactions might be unified arises from the calculated evolution of the coupling constants shown in Figure 11. Coupling constants in quantum field theory depend on the momentum scale at which they are defined. The QCD (strong interaction) coupling decreases at high momentum scales, or short distances. This is the celebrated property of asymptotic freedom, which implies the reliability of perturbation theory in short-distance strong-interaction processes. The couplings associated with weak isospin and the weak-hypercharge phase symmetry also evolve. It is highly suggestive that the three couplings, which differ considerably in strength in low-energy phenomena, evolve toward a common value at an energy near 10^{15} GeV.

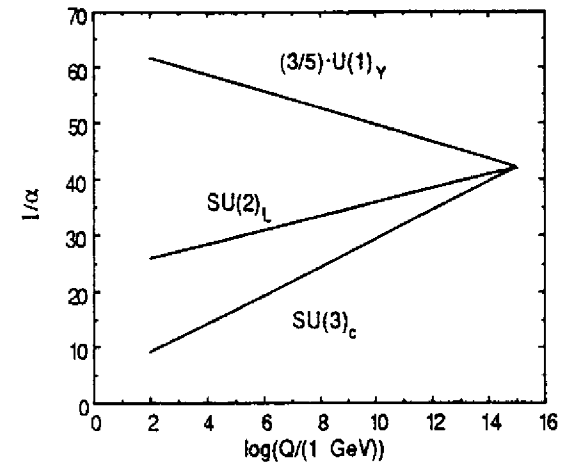


Figure 11: Evolution of the running coupling constants in leading logarithmic approximation in the *SU(5)* model. Three fermion generations are assumed.

As we have noted in the introduction to our discussion of the gauge theories of the fundamental interactions, different theories have survived different degrees of confrontation with experiment. QED has been tested most rigorously, while tests of unified theories of the strong, weak, and electromagnetic interactions remain largely at the level of "yes-or-no" questions. However, it is very important that for the theories that make up the Standard Model—the $SU(3)_{color} \otimes SU(2)_L \otimes U(1)_Y$ gauge theory of the strong, weak, and electromagnetic interactions involving three generations of color-triplet quarks ($u, d, s, c, b, [t]$) and color-singlet leptons ($e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau$)—there are no experimental embarrassments. No reliable data contradict the underpinnings or disagree with a credible prediction. Many predictions await sharpening or detailed experimental tests.

How Far We Have to Go

The Standard Model has an appealing simplicity and an impressive generality. The picture at which we have arrived has a pleasing degree of coherence and holds the promise of deeper understanding—in the form of a further unification of the interactions—still to come. This is an accomplishment deserving great respect, but if we have come impressively far in the past two decades, we still have far to go. The very success of the $SU(3)_{color} \otimes SU(2)_L \otimes U(1)_Y$ model prompts new questions: Why does it work? Can it be complete? Where will it fail? As we shall see, the Standard Model itself hints that the frontier of our ignorance lies at about 1 TeV for collisions among the fundamental constituents. In more general terms, the success of the Standard Model suggests that a significant step beyond present-day energies is needed to see breakdowns of our current understanding.

Beyond these generalities, there are many specific questions that the Standard Model raises but cannot answer.

• Although the Higgs mechanism shows how masses could be given to the quarks and leptons, the Standard Model offers no particular insight into the pattern of fermion masses or into the mixing angles that describe transitions that cross quark family lines.

• We have evidence from the requirement that the electroweak theory be anomaly-free, hence renormalizable, that quarks and leptons must occur together in generations. The idea of generations is supported by the explanation of the equality of proton and positron charges in unified theories, but we do not know why generations repeat or how many there are.

• These issues may be summarized in the complaint that there is too much arbitrariness in the Standard Model, a surfeit of parameters. How many parameters is too many?

	3	coupling parameters (α_s, α_{EM}, $\sin^2\theta_W$)
	6	quark masses
	3	Cabibbo-Kobayashi-Maskawa angles
	1	CP-violating phase
	2	parameters of the Higgs potential
	3	charged-lepton masses
	1	vacuum phase
for a total of	19	arbitrary parameters.

The situation is not improved by the unification of the strong, weak, and electromagnetic interactions. Unification imposes constraints among some parameters, but new parameters arise to describe the spontaneous breakdown of the unifying group into $SU(3)_{color}\otimes SU(2)_L\otimes U(1)_Y$.

• CP violation is parametrized, but not explained, by the Standard Model.

• Gravitation is omitted.

• The most serious structural problem is associated with the scalar, or Higgs, sector of the electroweak theory. The scalar sector is responsible for breaking the $SU(2)_L\otimes U(1)_Y$ electroweak symmetry down to $U(1)_{EM}$. Yet the dynamical nature of the spontaneous symmetry breaking is the least understood aspect of the theory. Indeed, the instability of the masses of elementary scalars in interacting field theory gives reason to suspect that the model may, in the end, be inconsistent. At a more operational level, the masses of the $W^\pm$ and Z^0 are specified by the theory, but the mass of the Higgs boson is constrained only to lie in the range

$$7\ \mathrm{GeV}/c^2 \lesssim M_H \lesssim 1\ \mathrm{TeV}/c^2 \ . \qquad (22)$$

The lower bound is strictly valid only in the simplest version of the Standard Model with one elementary Higgs doublet, and it depends upon the mass of the top quark. The upper bound is reasonably model-independent. If the Higgs boson mass exceeds 1 TeV/c^2, weak interactions must become strong on the TeV scale.

The problem of the scalar sector is exacerbated in unified theories of the strong, weak, and electromagnetic interactions. Several families of Higgs bosons are required to accomplish the breakdown from the unifying group G to the low-energy $SU(3)_{color}\otimes U(1)_{EM}$ symmetry we observe. Moreover, the breaking of the "electronuclear" symmetry must occur in two steps,

$$G \to SU(3)_{color}\otimes SU(2)_L\otimes U(1)_Y \qquad (23)$$

and

$$SU(3)_{color} \otimes SU(2)_L \otimes U(1)_Y \rightarrow SU(3)_{color} \otimes U(1)_{EM} \quad , \tag{24}$$

at scales separated by many orders of magnitude.

• The large number of quarks and leptons makes it natural to ask whether these fermionic constituents are truly elementary or composites of some more fundamental building block.

• Finally, we may ask what is the origin of the gauge symmetries themselves, why are the weak interactions left-handed, and whether there are new fundamental interactions to be discovered.

This list has inspired imaginative conjectures departing in many directions from the Standard Model paradigm. These have important implications that cannot yet be tested. Although theoretical speculation and synthesis is valuable and necessary, we cannot long advance without new observations. The experimental clues needed to answer our questions can come from several sources, including experiments at high-energy accelerators, experiments at low-energy accelerators and nuclear reactors, nonaccelerator experiments, and deductions from astrophysical observations.

The low-energy and passive experiments provide indirect access to high mass scales through their sensitivity to rare processes. However, according to our present knowledge of particle physics and our past experience, there is no substitute for experiments that probe directly at high energies. Satisfying responses to our complaints about the Standard Model will require experiments at the highest-energy accelerators.

The Next Step

Many of the questions we must confront are beyond the reach of accelerators in operation or under construction. Progress toward a more comprehensive understanding of the nature of matter will depend upon our ability to study phenomena at higher energies, or, equivalently, on shorter scales of distance. What energies must we reach, and what sort of new instruments will be required?

Illuminating the physics of electroweak symmetry breaking is perhaps the most sharply posed assignment for the next generation of accelerators. Unitarity arguments have shown us that new phenomena are to be found in the weak interactions at energies not much larger than 1 TeV for collisions among the fundamental constituents. The same scale is selected by the conjectural extensions to the Standard Model that offer potentially more satisfying descriptions of the scalar sector and thereby of the mechanism for spontaneous symmetry breaking.

One of these ideas involves introducing a complete new set of elementary particles that differ by one-half unit in spin from the known quarks, leptons, and gauge bosons. These new particles are consequences of a postulated supersymmetry, which relates particles of integral and half-integral spin. Supersymmetry would stabilize the mass of the Higgs boson at a value below 1 TeV/c^2 and would require the masses of the supersymmetric partners of the known particles to have masses less than about 1 TeV/c^2. No experimental evidence for superpartners has yet been found.

A second possible solution to the Higgs problem is based on the idea that the Higgs boson is not an elementary particle at all, but is in reality a composite object made up of elementary constituents analogous to the quarks and leptons. This scheme is reminiscent of the Bardeen-Cooper-Schrieffer theory of superconductivity, just as the Standard Model resembles the Ginzburg-Landau description. Although they would resemble the usual quarks and leptons, the new constituents would be subject to a new type of strong interaction, often called technicolor, which would confine them within about 10^{-17} cm. Such new forces could yield new phenomena as rich and diverse as the conventional strong interactions, but on an energy scale a thousand times greater—around 1 TeV. The new phenomena would include a rich spectrum of (technicolor-singlet) bound states, akin to the known hadrons. Again, there is no experimental evidence yet for these particles.

Both general arguments, such as unitarity considerations, and specific conjectures for resolutions to the problem of the scalar sector select 1 TeV as an energy scale on which new phenomena crucial to our understanding of the fundamental interactions must occur. The dynamical origin of electroweak symmetry breaking is but one of the important issues that define the frontier of elementary particle physics. Because of its immediacy and fundamental importance, this issue helps set the requirements for future accelerators and detectors. Of course, when designing an instrument that will serve our field for a quarter of a century or more, we must ensure that the new device will open a large new territory to investigation.

Either an electron-positron collider with beams of 1–3 TeV or a superconducting proton-(anti)proton collider with beams of about 5–20 TeV would allow an exploration of the TeV regime for hard collisions. The higher beam energy required for protons simply reflects the fact that the proton's energy is shared among its quark and gluon constituents. That partitioning of energy among the constituents has been thoroughly studied in experiments on deeply inelastic scattering of leptons from nucleons, so the rate of collisions among constituents of various energies may be calculated with some confidence. Any accelerator to explore the 1-TeV scale must make available a high collision rate, because the hard-scattering (pointlike) cross sections of central interest scale as ${E_{cm}}^{-2}$.

The scientific opportunities presented by both the electron-positron and proton-(anti)proton alternatives are attractive and somewhat complementary. The hadron machine reaches to higher energy and provides a wider variety of constituent collisions, which allow for a greater diversity of phenomena. The simple initial state of the electron-positron machine represents a considerable measurement advantage. However, experiments at the CERN and Fermilab proton-antiproton colliders show that hard collisions at very high energies are relatively easy to identify. Because the essential technology is in hand for the hadron collider, it is the instrument of choice for the first exploration of the TeV regime. Multi-TeV hadron colliders are under active study in the Soviet Union (UNK), in Western Europe (LHC), and in the United States (SSC).

The Superconducting Super Collider

The high-energy physics community in the United States has embarked on the design and eventual construction of a high-energy, high-luminosity, superconducting proton-proton collider to explore the 1-TeV scale. The SSC will produce collisions of 20-TeV proton beams at a luminosity of up to 10^{33} $cm^{-2}sec^{-1}$, yielding more than 10^8 interactions per second.

Superconducting magnets are chosen for two reasons. First, they make possible confining fields three times as strong as those available with conventional iron magnets. More important, the electrical power requirements for a superconducting machine are far smaller than for a conventional accelerator. A conventional version of the SSC would consume 4 GW of electrical power; the SSC's average consumption will be about forty times smaller.

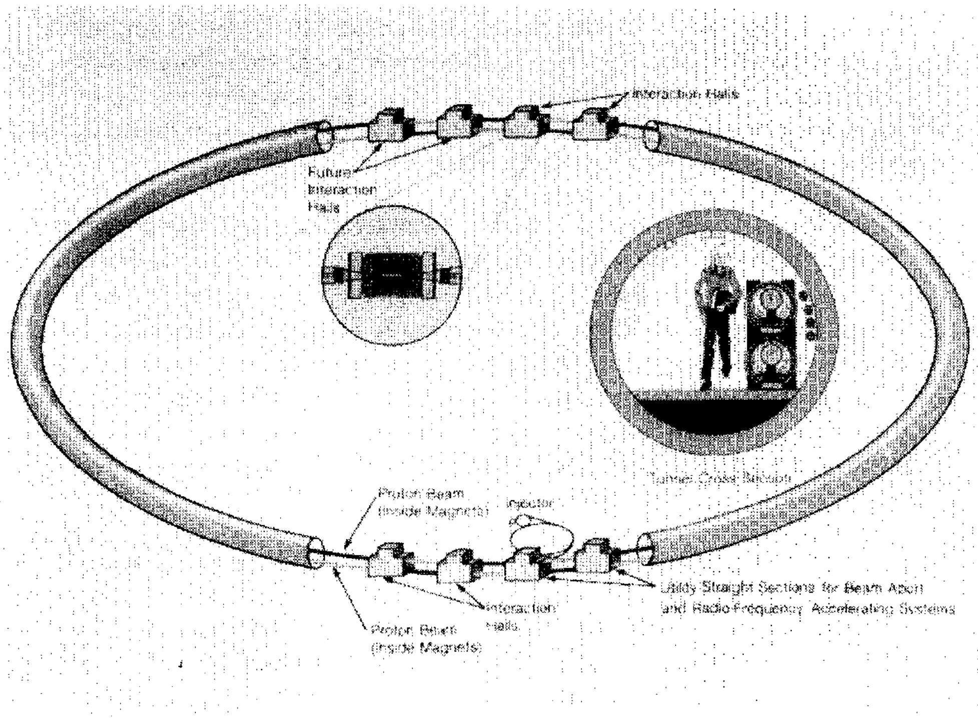


Figure 12: Collider ring layout envisaged in the SSC Conceptual Design Report.

Even with the more intense fields made possible by superconducting magnets, the SSC will be an instrument of impressive size. In the engineering units appropriate to the problem, the bending radius is related to beam momentum and confining field by

$$\rho = \left(\frac{10}{3}\text{km}\right) \cdot \left(\frac{p}{\text{TeV}/c}\right) \Big/ \left(\frac{B}{\text{tesla}}\right) . \tag{25}$$

For a 20-TeV/c beam in a confining field of 6.6 T, the SSC design field, the implied radius of curvature is $\rho \approx 10$ km. With allowance for the straight sections accommodating experimental areas, acceleration gear, etc., the circumference of the SSC will be about 84 km.

The proposed layout of the Supercollider is shown in Figure 12. Interaction halls cluster on the two gently curved sides of the collider ring. In this perspective the near cluster incorporates the injector complex, the radio-frequency accelerating system, beam absorbers, and two of the six interaction halls. The far cluster adds four more interaction halls, two of which are reserved for development after research begins. The schematic enlargement of an interaction hall shows a detector surrounding the point at which two beams collide; the cross section to the right shows the position of the two superconducting magnet rings in the tunnel. The two independent rings for the proton beams will sit one atop the other, 70 cm apart.

The superconducting magnets essential for guiding the protons around the rings are made of two coils arranged to approximate a cosθ current distribution. The inner coil has an inside diameter of 4 cm. The coils are wound of cable made from composite strands containing thousands of filaments—each about 6μm in diameter—of a niobium-titanium alloy embedded in a copper matrix. Interlocking stainless steel or aluminum collars surrounded by an iron yoke hold the cables in place. This 17-meter-long package, called the "cold mass," is sealed in its own cryostat, where it can be maintained at an operating temperature of 4.35 K. The 3840 dipole magnets in each collider ring have a peak operating field of 6.6 teslas, which corresponds to a current of 6504 amperes. Figure 13 shows a cross section of the SSC dipole.

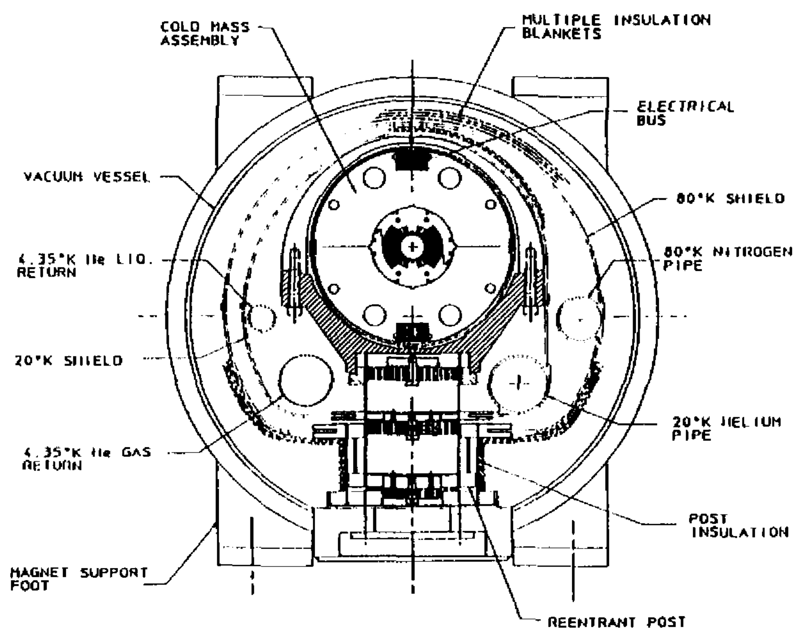


Figure 13: Cross section of the 6.6-tesla superconducting dipole magnet for the SSC.

Substantial increases in the current-carrying capacity of superconducting cable have resulted from a collaboration among industry, university researchers, and the U.S. national laboratories focused on the development of improved superconductor for the SSC. The SSC specification for the critical current density in niobium-titanium strand, J_c = 2750 A/mm^2 at 4.2 K and 5 T, represents a 50 percent improvement over the conductor used in the Tevatron. Material meeting this demanding specification is now routinely received in production quantities.

When might the SSC be in operation? An important milestone was passed in March 1986, when the SSC Central Design Group completed a Conceptual Design Report for the SSC. Every major system had been thought through, and a detailed cost estimate had been made. Because a location has not been selected for the Supercollider, the Conceptual Design was not adapted for any specific site. During the summer of 1986, the Department of Energy and independent experts validated the cost and technical feasibility of the machine described in the Conceptual Design Report. President Reagan endorsed the SSC as a national goal in January 1987. In April of that year, the Department of Energy began a site search that has led to a short list of seven "Best Qualified Sites" in the states of Arizona, Colorado, Illinois, Michigan, North Carolina, Tennessee, and Texas. The Department of

Energy intends to designate a preferred site in November 1988. From the time the site is available, sometime in 1989, it will take about seven and a half years to build the machine. We hope to commence experimentation with the SSC by 1996.

We believe that the SSC can foster a new level of international cooperation in particle physics. As a frontier research instrument, the Supercollider will certainly attract to its experimental program many of the best particle physicists from around the world. This, is of course, traditional in our field, but we may hope for more: active international collaborations established early enough to allow significant foreign participation in the design and construction of the SSC and its detectors, and not just in the performance of experiments.

The advances of the past decade have brought us tantalizingly close to a profound new conception of the most basic constituents of matter and their interactions. The simpler and more comprehensive understanding we have gained organizes current knowledge and locates the horizon of particle physics at energies of trillions of electron volts, and the horizon of cosmology at about a millionth of a billionth of a second after the moment of creation. Important answers will be found with the Supercollider: from it we await new discoveries about the unification of the forces of nature and the patterns of the fundamental constituents of matter.

Acknowledgments

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