Particle Physics in the Twenty-First Century

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Deputy Director for Operations
Superconducting Super Collider Central Design Group
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Elsewhere in this volume, Alvin Trivelpiece discusses the need for scientists like me to market science. So you can judge my credentials, I would like to begin by relating the basis of my understanding of marketing. Recently, I was in Paris where I realized a boyhood dream of being taken into the heart of the French establishment. I went for an interview at one of the great news magazines in France, housed in a small, elegant nineteenth-century office building about 20 yards from the Arc de Triomphe, and was admitted to the editorial offices. We began by discussing the TEVATRON, the SSC, and the meaning of life. Since this was France and it was Friday night, after the formal interview the journalist who was in charge took me to a tiny restaurant around the corner. It was one of those nice little places with six tables covered with starched tablecloths and run by a very warm woman of a certain age who serves in a solicitous fashion the kind of food that Grandmother would have served you if Grandmother happened to be one of the great chefs of Lyon. In the course of a magnificent dinner, which went on for three hours, the journalist, a woman of about my age, and I continued our discussion of science and life. I explained why Leon Lederman was a great man and said all the other things that I was supposed to say. We started talking about the differences between science writing and journalism in the United States and France, and we talked about the training of science writers, Watergate, and the Greenpeace affair. By the time we had finished all that, it was dessert. In the middle of a spectacular Tarte Tatin, she leaned across the table, looked deeply into my eyes, and said, "I'd do anything for a story."

Under my breath I whispered, "Be still my heart. (This must be what Leon means by marketing.)"
Fortunately, she noticed my discomfort immediately and said, "But you're not a story."

With that introduction, on to particle physics in the twenty-first century.

**Elementary Particle Physics**

What is elementary particle physics? It's the science devoted to searching for the ultimate constituents of matter and the interactions among them. We try to answer timeless questions such as, What is the world made of? How does the world work? (God will come at the very end of this talk; I promise I will get to God.) The way in which we go about this search is really common to all of the rest of science. We try to discover a reason for this and a reason for that which seem to be unrelated. But we also try to understand laws, hopefully simple and small in number, which apply generally in different times, different places, and different circumstances. The hope is to take laws learned in one place and apply them elsewhere, both for understanding things better but also, of course, for the possibility of eventually putting that knowledge to productive use.

**Fig. 1.** Goals of elementary particle physics.

The framework in which we labor, shown in Fig. 1, is one that you can't derive from any basic principles, but it is one that has served well for thousands of years. This is to imagine that there are some group of ultimate constituents of all matter and to try to identify those. By those ultimate constituents we mean...
now, and have historically meant, little things that make up everything else and which themselves have no internal structure and are indivisible. We can talk about them as the little nuggets that build up everything else. According to this scheme, having identified those constituents we next try to identify the forces by which they interact and work together to make up all the phenomena that we see in the Universe. So the fundamental questions are, what are these basic constituents of all matter and energy, and what are the fundamental forces between them?

Fig. 2. "Man and the four elements," woodcut by Hans Weiditz accompanying a 1532 German edition of Petrarch (1304-1374), The Mirror of Consolation.

The idea that this framework should be useful has been with us for a long time. There is the ancient notion of the four constituents of earth, air, fire, and water. A view of these constituents is shown in this magnificent sixteenth-century woodcut (Fig. 2). There, earth, air, fire, and water interact by means of two forces called love and strife. With our funny names for the quarks - charm, beauty, truth, and so forth - we are just following a hallowed historic tradition of making up silly names for profound concepts. This illustrates not only that the
idea of basic constituents is old, but that the identity of those constituents has changed over the years as we have been able to look more deeply into the structure of matter. We now think it is a little quaint to talk about earth, air, fire, and water as the basic constituents. While the identity of those constituents has changed over time, the idea that fundamental constituents should be a good way of organizing things has persisted.

One of the other things that has changed since early times is that the work of physicists used to be represented in books that came with covers like the one shown in Fig. 3, an etching from a seventeenth-century edition of Lucretius's book, *On the Nature of Things*. I'm hopeful that in the era of desktop publishing we will be able to get back to this sort of format so that our work is taken as seriously as it should be. For those of you lacking in classical education, I hasten to point out that the title doesn't imply it's a sex book.

*Fig. 3. Frontispiece, De Rerum Natura of Lucretius (J. Tonson, London, 1712).*
That is the basic framework. What do we make of it now? It's frequently written in newspapers and claimed by my colleagues that a grand synthesis of natural law is at hand and that we are on the threshold of a complete new understanding of everything. Humility forces me to note that this may not be the first time in history that scientists have made such claims, so it is interesting to examine the basis for the current assertions. I think the claims are not completely frivolous. Whether or not the picture we now have really is close to a final understanding of at least some level of nature, what we now know and the questions we are able to ask will form a lasting part of some enduring understanding of at least a segment of nature.

The reasons that one can be somewhat confident on this point have to do with developments over the last 20 years in particle physics which we can classify as the emergence of the Standard Model. This is the single unified picture which gives us a language for discussing all the phenomena we see about us, and for organizing that information and trying to understand it. This Standard Model has a couple of basic facets. One of them is recognizing what are the elementary particles, at least for the current generation of scientists. Instead of earth, air, fire, and water, they are particles called leptons and quarks. It is finding things which seem - at the current limits of our resolution - to be elementary, indivisible objects that gives us one starting point.

The other important development is the formulation of a mathematical expression for the forces of nature. These are called gauge theories of the strong, weak, and electromagnetic interactions. Without going into the details of these theories, they all have in common the idea that by observing symmetries in nature, by doing experiments and recognizing patterns, we can then follow our nose within this mathematical framework and write down theories which are self-consistent and even true, and which describe a wide range of phenomena. Having a common mathematical expression for different interactions, we are able to see the prospect of unifying these three interactions and the promise of being able to bring them together with gravitation.

In a discussion like this, it's very easy to give too much credit to theorists because their ideas are simple and can be explained in an elegant way. I feel it is important, particularly in a place like Fermilab, to explain why a theorist spends time here and what is the relationship of theory to the rest of the world. One of
the points that I hope this audience is aware of, but certainly the people who write my children's school books are not, is that there is an essential interplay between theory and experiment and the availability of new technology. Put differently, there is a relation between discovery of new phenomena, understanding or insight into those phenomena, and new tools that enable us to make progress. In our own field, the history of accelerator and detector technology precisely parallels and, if you want, leads the development of the more abstract intellectual content of the subject. Whenever we can measure things more precisely or look under a rock where nobody has been able to look before, we have the potential for new discovery. From those new discoveries often come insights. Having made those discoveries we can then use them for calibrations or to invent new tools.

That sort of interplay, illustrated in Fig. 4, between the existence of these three branches of the science enterprise and the importance of each in sustaining the others is, I think, under appreciated. In my children's school books, which I read on occasion when I need to get my blood pressure up, you find that the last person in the history of science who built an instrument and then used it for a scientific discovery was Mr. Leeuwenhoek, who in the sixteenth century took two magnifying glasses and put them together to make a microscope and learned from that exercise the structure of the onion cell. After that, I guess technology
became too complicated to be explained in the school books, and so you find that Mr. X. or Ms. Y got this or that idea and that was that. This slights the process of experimentation and also the essential role played by the availability of new tools to do experimentation.

There are lots of examples in fields other than particle physics. For example, the whole business of molecular biology emanates from the discovery that certain enzymes like to take a bite out of DNA molecules at a certain point. Having made that discovery, one tries to understand it and does more experimentation to see what it means, and you find that there are other enzymes that like to take bites out of other pieces of DNA molecules. Having done that allows you to invent a new technology not only for a growth industry like genetic engineering, but also for doing more experiments. Now you can take apart and put back together these molecules that govern the structure of life. In the course of doing that, substituting this for that, adding this piece here, cutting out that piece there, you develop some insights into the nature of the genetic code and what it means for us. This interplay of instruments, experiments, and theory is something which needs to be emphasized.

It is annoying when people, either academics convinced of the purity of their research or people who do technology and are convinced that the rest of us are just frittering away our time and the taxpayers' money, try to make strong cases either that technology is the stepchild of fundamental discovery and it just comes dragging along later, or that fundamental discovery follows 25 years after technological innovation. Both of them nourish each other and are essential to each other.

Back to science. It has been known since the 1930s that within this framework of forces and constituents one could identify (Fig. 5, page 22) four forces of nature which are responsible for everything we know. That is one of the simplifications and generalizations that physics is good at, and in fact, one of the great triumphs. Instead of dealing with the force of the wind, the force of lightning, the force of friction, and other such things, one for each situation that we encounter, we can interpret everything that goes on around us as the result of the action, either singly or in concert, of the strong, electromagnetic, weak, and gravitational interactions. The strong interaction is responsible for binding protons and neutrons together in nuclei, electromagnetism for light, microwave
ovens, and television, weak interactions for radioactivity, and gravitation for the motions of the stars and planets. That recognition didn’t occur until the 1930s. While the electromagnetic and gravitational interactions were known before, the strong and weak phenomena were discovered in the thirties.

At that time, the fundamental constituents appeared to be the proton and neutron (the constituents of the nucleus), the electron, and by circumstantial evidence, something called the neutrino. The moment at which they were thought to be fundamental constituents didn’t last very long because a lengthy series of experiments showed that there were lots of other things equally fundamental looking. Furthermore, if you looked inside a proton you found that there were gears, and wheels, and sponge foam, and stuff like that. On close inspection, the proton is seen to be a big, squishy object, not at all something you can’t excite, shake, and break apart.

I now slight 50 years of experimental physics and give you the answer. The answer, which has become clear to us only in the last 15 or 20 years, is that at the current limits of resolution which correspond to distances of about $10^{-16}$ cen-
timeters (very small), the fundamental indivisible-looking things are a bunch of particles called quarks which have names like up, down, charm, strange, top, and bottom, or truth and beauty if you like, and corresponding things called leptons which are relatives of the electron called the electron and its neutrino, the muon and its neutrino, the tau and its neutrino. The distinction between these two classes of particles is that the leptons experience gravitational, weak, and electromagnetic interactions whereas the quarks, in addition, experience the strong interaction. Figure 6 shows the situation before modern analysis is brought to bear on the forces. We just know that the forces are there. Our ancestors in the 1930s made this invention and we find that it is indeed satisfactory to describe what goes on around us.

**MATTER & ENERGY**

**FORCES**

**CONSTITUENTS**

- **Strong**
  - **Quarks**
    - u
    - c
    - t
    - d
    - s
    - b

- **Electromagnetic**
  - **Leptons**
    - e
    - μ
    - τ
    - ν_e
    - ν_μ
    - ν_τ

- **Weak**

- **Gravity**

*Fig. 6. Progress toward the Standard Model.*

The progress toward understanding the forces, which has culminated in the last 15 or 20 years, but which began in the 1920s, is to have a framework in which we can analyze the interactions between quarks and leptons. I'll summarize that very schematically, so you have some notion of how we do it and the interplay between a grand principle and experimentation and observation.
The first step is to do experiments and to recognize some pattern or symmetry of nature. If you then give a mathematical expression to your theory of the forces, the equations of physics, which tell how we get from here to there, have to embody or reflect this symmetry. You then decide to be so impressed with symmetry that you try to impose it on the equations in a stricter form and find that the equations of physics that you would naively write down don't respect the symmetry in a stricter form. However, they can be modified to accommodate the stronger symmetry requirements at the price of changing the consequences of your theory. The changed consequences are that you can only accommodate the symmetry in the stricter form if you introduce specific interactions between the particles and, to carry those interactions, specific particles to mediate them.

The idea that you can have some grand scheme like this, a recipe or a great principle, in order to guide your search for theories is very important. It is terribly easy to make up theories. What's not easy is to make up theories that aren't automatically wrong. So if you find a grand principle which restricts your search for theories to those that have a chance of being right, you are far ahead of the game. Having done that, we arrive at what is called the Standard Model (Fig. 7).

**THE STANDARD MODEL**

![Diagram of the Standard Model of Particle Physics](image)

*Fig. 7. The Standard Model of Particle Physics.*
On the one side we have the fundamental constituents, the quarks and leptons. Notice that these fundamental constituents are represented as little bricks since they are the fundamental building blocks that make up all matter. The forces are on the other side. Our understanding of the forces has now given us a common understanding of the weak and electromagnetic interaction. That's fun, because it's fewer fundamental forces and also repeats history. Electricity, represented by lightning, and magnetism, represented by a compass needle, seem very different, but the great triumph of experiments through the nineteenth century and theory in the 1860s was to recognize that they are two facets of the same interaction. We have been able to do that almost completely again for the weak and electromagnetic interactions.

In addition to that, we now recognize the carriers or messengers of these interactions: the gluon (because it glues quarks together) for the strong interaction, the photon for electromagnetism, intermediate bosons for the weak interactions, and we guess that there may be something called the graviton for gravity. Having a similar mathematical expression for all of these, we may be able to go further and reduce them to one grand principle instead of a few.

**Experiments in the Twenty-First Century**

So that is a little bit about where we stand and very little about how we got there. I'd now like to say just a few words about how we think we know these things, namely by doing experiments. The chapter by Sadoulet answers the questions about everything I have left out. Our brief as particle physicists is to try to find the most basic constituents and the most fundamental forces. This is impelled by a belief that if you deal with simpler and smaller systems, you will discover rules of more general application that you can then combine to describe large and complex systems. We try to look at the structure of matter on finer and finer scales. We do this by making our "microscopes," which are the combination of particle accelerators and detectors.

My colleagues who do experiments do, to a certain approximation, one single experiment, as shown in Fig. 8 (page 26). This single experiment consists of a couple of elements. First, there is a beam of particles which we prepare with loving care in the accelerator. This beam hits a target, which we also prepare with loving care in the experimental areas. Products stream out of this interac-
tion of the beam and target. For TEVATRON collisions, 50 to 100 particles are not uncommon. Then, standing over here to one side holding a tin cup, is the experimental physicist who catches the products and says, "Yes, one came here and one came there."

The Experiment

![Diagram]

Fig. 8. The Experiment.

There are lots of variations on this experiment. First of all, detectors are complicated because if many particles are coming out, it doesn't do just to stand off to the side with one large tin cup and say, "Yes, something happened." Instead, you need to know that this particle went here and identify what type of particle it was, while this particle went there and it was a different sort. You try to characterize as best you can everything that happened in the collision. That is the complexity of detector systems about which I'll say a little bit more later.

There is an infinite variety of experiments. You can change the beam, you can change the target, you can change the conditions. There are also people who try to cut corners. Some of my colleagues are so incredibly lazy that they leave out the beam and just have a target. These are people who build large plastic bottles full of distilled water and wait for a proton to decay and wink at them. That leaves out the beam. There are other types who only have a beam and leave out the target, studying the decays of particles in the initial beam. These are also lazy people. But finally, there is a third class who leave out both beam and target, and those are called theorists.
What are the goals of a detector system? Ideally, all of the characteristics of all of the particles produced in an event are measured. This means large, angular coverage, because particles come out in many different directions. It also implies high spatial resolution to characterize the tracks as well as possible. At the same time, it is important to identify the particle characteristics, to know that this is a pion, that's a muon, and this is an electron. A very important aspect, which will become more important as we move towards the SSC, is to try to extract the events of interest for the particular investigation you're doing from the routine background of things that go on all the time, that you've studied before, and that on that particular day you don't care about, except to monitor the performance of your detector. How to make the selection is of considerable importance.

In the SSC environment, we expect to have 100 million interactions per second taking place. All of them will be complicated and give rise to a couple of hundred particles. The speed at which you can hope to record these events on some medium like magnetic tape or a laser disk is about 1 to 10 interactions per second. That means a decision must be made very quickly. "Very quickly" means to begin in the space of 15 nanoseconds, or roughly the time between one interaction and the next. In other words, you've got to begin deciding how to reduce 100 million interactions per second to the 1 to 10 interactions per second that are particularly notable and worth recording. That is a reduction by a factor of 10 million on line. This must be done quickly without throwing away anything important. That's a great challenge to our ingenuity and to putting remote intelligence on the detectors. You have to do this while keeping the costs of construction, operation, and data reduction within reasonable bounds. These reasonable bounds apply not only to the money involved, but also to other parameters - intangibles like the lifetime of graduate students. You must be able to analyze these events while you still remember why you're doing it.

Sadoulet's chapter also discusses detectors, but I'd just like to emphasize the different scales involved in these projects. There are many different skills required to make these detectors and many different scales on which they operate. Figure 9 (page 28) shows a particular experiment, an Italian-American collaboration working in the Proton Laboratory at Fermilab. There is a lot of heavy equipment consisting of magnets and drift chambers, which requires know-
Fig. 9. A typical experiment in particle physics: Fermilab Experiment 687.

Fig. 10. Silicon microstrip detector in the E-687 apparatus.
ledge of things as diverse as mechanical engineering and track finding. The whole experiment is about 100 feet long. The heart of the detector, where the interactions take place, is in a locked room lined with copper. Only the Italians have the key to it. Inside it looks like the Treasure Room at the Vatican Museum. One of their contributions to the experiment is a magnificent silicon microstrip detector (Fig. 10). Notice the electronic cables coming out of the device and the foil covering. This device can give extremely precise position resolution information for the tracks just after the interactions take place. You can see we are dealing with things which are on the finest scale we know how to make while also embedding them in these gigantic monsters which weigh hundreds of tons.

The Unity of Science

If you look back over the progress in particle physics over the last 25 years, you can search for common threads in the progress we have made, especially in theory. If you do this objectively, you find that the common thread is that we have shamelessly ripped-off ideas from people who do condensed-matter or solid-state physics.

Let me give you some examples. I want to show not only that theorists are willing to exploit other people's ideas, but that the mathematical techniques and constructs discovered in one place are frequently of value elsewhere. For instance, an early phenomenological description of the transition from the superconducting to the normal phase was a parametrization given by Ginzburg and Landau. They said, more or less, let's suppose that the free energy of a superconducting substance may depend upon the density of the superconducting charge carriers in the medium in two possible ways: Above some temperature in the normal phase, the more superconducting charge carriers you have, the more energy it costs you, as shown in Fig. 11 (page 30). This is an unfavorable situation. The vacuum state of the Universe, the state of lowest energy, corresponds to no superconductors, i.e., to a normal resistive substance. But, they said, let us suppose that in the superconducting phase below a certain temperature, the free energy behaves as shown by the solid curve in Fig. 11. Out at the minimum there is a finite density of superconducting charge carriers. That will then be the state in which your system finds itself. If you write this down in the
form of equations, you are able to derive the Meissner effect and other properties of superconductors, and get some understanding of why a superconducting material behaves as it does.

\[ \text{Density of Superconducting Charge Carriers} \]

\[ \text{Free Energy} \]

**Fig. 11. Ginzburg-Landau description of the superconducting phase transition.**

In particle physics we make a relativistic generalization of the Ginzburg-Landau parametrization called the Abelian Higgs model. By building on this insight from superconductivity, this model shows us how to incorporate the notion of symmetry breaking into one of the gauge theories of the basic interactions. This style of argument is the foundation of the standard electroweak theory in particle physics.

You may know that, in the realm of superconductivity, there is something which is better, more complete, more microscopic, more predictive, than the Ginzburg-Landau theory. That is the Bardeen-Cooper-Schrieffer, or BCS, theory of superconductivity which aids understanding of the basis of superconducting behavior. In that theory the Ginzburg-Landau order parameter, the density of superconducting charge carriers, is identified as the quantum mechanical wave function of Cooper pairs of electrons. These are bound states of pairs of electrons which are held together by the electromagnetic interaction itself. It's the behavior of the substance as a function of temperature with respect to those pairs that yields superconductivity, and of course, all the consequences found by Ginzburg and Landau.
In high-energy physics our current aspirations to go beyond the Standard Model are a lot like the aspirations in the early days of superconductivity: to go beyond a description and to be able to predict features without sticking in arbitrary assumptions. What we would like to do is to replace our borrowed Ginzburg-Landau theory with something with which we can calculate and which has more predictive power. What we do in that case is to replace the thing called the Higgs boson with a bound state of fundamental particles like the bound states of electrons, the Cooper pairs in the BCS theory.

To be as economical as the BCS theory, you might first imagine making a quark-antiquark bound state held together by the strong or color force. If you follow that through, you find that, mathematically, it could do a lot of what needs to be done except that it doesn’t agree with the way the world is. So, keeping the same idea, one can introduce new constituents not yet seen and assume that they are bound together by some new super-strong force whose properties one can describe (we call this the technicolor force because it’s like the color force). Following your nose through the BCS theory, you can derive models in which, if we could only solve them completely, we would be able to predict all the properties of the standard electroweak theory. These are called technicolor models. Understanding whether they have anything to do with the world we live in is one of the early goals of the SSC.

What does all of this have to do with high-temperature superconductivity? This spring I called all my postdocs together and said, "The implications for high-energy physicists in the twenty-first century are extremely clear. The first thing that you have to do as your homework problem for tonight is to identify the correct theory of high-temperature superconductors." Since they’re smart kids, I was sure they’d do it quickly. Having done that, we could then follow in the glorious tradition of the Ginzburg-Landau theory and the BCS theory and rip it off.

The Motivations for Twenty-First-Century Physics

What is it that we think we need to know? What motivates us to go into the twenty-first century asking for larger and more powerful facilities? The existing Standard Model has a certain elegance. To the extent that we are able to test it by doing experiments and calculations, it describes very well everything we see in the world around us. Having a model that is that successful, you are prompted
to ask a series of new questions. First, is it reasonable that the model should work? Does it really hang together internally or are there little things swept under the rug which look like chinks in its armor? Could the model possibly be complete? Can you imagine that that is all there is to the world, or must there be other things to make it a better and more predictive theory? And finally, if you are not convinced that it's the end of the road, you can ask the theory itself where it will fail. At what point, at what energy, at what scale of distances does it cease to make sense? Where will new things happen?

Having looked within the Standard Model, we have known for about 10 years that at energies for collisions among fundamental constituents of about 1 TeV, the Standard Model ceases to make sense. It can't be the complete story. Something new must happen there. The problem for us is that theorists, being inventive people, can think of lots of ways new things might happen. There is no way to know, without doing experiments and making observations, which, if any, of these is the right path to follow. That is a specific motivation for taking a step into a particular energy regime. At the same time, there is a more general argument, which is that things are going along so swimmingly that it seems likely that it is necessary to take a significant step beyond where we are now in order to see breakdowns of the current theory and to go beyond it.

What are the kinds of things that we'd like to know? We can identify a fair number of questions that the Standard Model and our current understanding raise but can't answer. One of these is, what determines the basic properties of quarks and leptons, their masses, and their electric charges? It's very nice to have identified a set of particles which seem for the moment to be indivisible and out of which everything else could be made. But instead of simply describing how the world is put together using them, how much more satisfying it would be if we were able to prescribe what their properties are and to understand why there seem to be six quarks and six leptons. Are there more? How many of them are there? What other properties do they have? What does it mean? A purely personal point of view: We are made of up and down quarks and electrons, and so it's not obvious why all those other things have to be around. It is probable that there is some reason for that; it would be wonderful to understand it.
If we look into the Standard Model itself, our description of the weak and electromagnetic interactions tells us that you can't have a theory of the world based only on quarks or only on leptons. In order for the theory to make sense mathematically, there has to be a family of quarks for each family of leptons. This is a strong suggestion that quarks and leptons are really related to one another. We'd like to verify that they are related to one another and understand how they are related and what this relation means.

We can also ask whether quarks and leptons are the last step in finding basic building blocks or whether we are going to discover, upon closer inspection, that they have internal structure as did atoms, nuclei, and protons. There is no experimental evidence, other than history, that quarks and leptons are not fundamental. But the motivation for thinking that they might not be fundamental is that the number of them, six quarks and six leptons, which may grow as we do more experiments, is coming perilously close to the number of fingers and toes of a single theoretical physicist. It's sort of the boundary at which we can keep track of things, so you might imagine that quarks and leptons are really composite systems made of a few other things.

Another question goes to the heart of much of the discussion of the first round of experiments for the SSC. The influence of gravitation and electromagnetism are both felt at astronomical distances. On the other hand, the weak and strong forces are effective only on the subatomic scale; for the strong force, distances of about $10^{-13}$ centimeters or less, for the weak force about $10^{-15}$ centimeters or less. What is responsible for these differences? For the strong forces, we have a fairly good idea that it's the very strength of the force which is responsible for essentially screening it off past a certain distance. We may even be able to test that idea by computer simulation. For the weak force, our understanding is at the level of the Ginzburg-Landau theory of superconductivity, and we need to go beyond that. The electroweak theory has been verified by direct measurements of phenomena ranging from $10^{-16}$ centimeters all the way out to $10^5$ kilometers.

Motivated by the common mathematical framework for the different theories of interactions, we can ask whether there really is an underlying unity among all the fundamental forces. In the course of doing this, and also out of humility, we can ask whether there might not be undiscovered fundamental forces. We found
that in putting together electromagnetism and the weak interaction, we were forced to invent a new kind of radioactivity, mediated by the Z boson, which has been discovered in experiments and so was a triumph for this style of argument. If we now put together the strong, weak, and electromagnetic interactions of gravitation, new sorts of interactions will be forced upon us; it would be interesting to find out what those consequences are and what they are doing.

Finally, you can ask whether there are new kinds of matter which are not composed only of quarks and leptons.

So our situation is this: The success of the Standard Model, the fact that we can discuss a whole realm of phenomena, leads us to try to go beyond it and to learn more.

**The Superconducting Super Collider**

The instrument that we have chosen to take us beyond current energies so that we can make experimental investigations at higher energies or shorter distances is the Superconducting Super Collider. The SSC is a superconducting proton-proton collider with an energy, determined by the physics goals we want to achieve, of 20 TeV per beam, and a collision rate, also determined by physics goals, of about 100 million interactions per second. That is the instrument of choice because we know how to build it. We are limited, in building accelerators, to stable charged particles, electrons and protons, and so the number of combinations that one can think about is rather small. A proton-proton collider is the only one that we know how to build on this energy scale.

What is the magic of 20 TeV per beam? Anytime you take a step into the unknown, you have the possibility for discovery. But when asking for a facility to serve the scientific community for a quarter of a century or so, at a significant burden on the taxpayers, we want to try to choose wisely a machine that will at least answer the questions we can pose today. Many of those questions have to do with really understanding the relationship between the weak and electromagnetic interactions and reducing the number of apparently arbitrary parameters we have to specify to have a theory of the world. Four years ago, my colleagues and I studied the prospects for supercollider physics in depth and found that the energy and interaction rate planned for the SSC would allow a thorough investigation of the questions we know how to pose today. If we were to reduce the
beam energy by a factor of four, to about 5 TeV, we would not have the same confidence, both for reasons of energy threshold and also because the lower the energy, the higher the interaction rate needed to get interesting numbers of high-energy collisions of quarks and gluons. Over the past few years, many workshops and summer studies have been held both here and in Europe on this topic, and countless trees have sacrificed their lives to publish the proceedings. The general conclusion on both sides of the Atlantic is that the SSC parameters are indeed well matched to the scientific issues we need to pursue. Table I summarizes some of the basic characteristics of the SSC.

Superconducting magnets are chosen for two reasons. One is the high field strength which allows us to make the device relatively small. The second reason is low power consumption. There's a famous Fermilab legend, even a true legend, that when the energy of the Fermilab accelerator was doubled by going from normal magnets to superconducting magnets, the power consumption was

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<th>Table I.</th>
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<td><strong>SSC parameters</strong></td>
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<td>Interaction rate:</td>
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<td></td>
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<tr>
<td>Superconducting magnet type:</td>
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<tr>
<td>Dipole magnetic field:</td>
</tr>
<tr>
<td>Magnetic radius of curvature:</td>
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<tr>
<td>Number of dipoles:</td>
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<tr>
<td>Dipole length:</td>
</tr>
<tr>
<td>Number of quadrupoles:</td>
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<tr>
<td>Vacuum chamber ID:</td>
</tr>
<tr>
<td>Residual pressure in beam tube:</td>
</tr>
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cut by a factor of three. This was very important in light of the fact that Commonwealth Edison was raising the power bill by a factor of three at the same time. Fermilab didn't save any money, but it was possible to do better physics and more physics at the same time.

The high field-strength argument for the magnets is as follows: With magnetized iron one can reach a field of about 2 tesla. With niobium-titanium superconductor, the Fermilab TEVATRON operates at about twice that field, and the SSC prototypes operate at about three times that field. Given current fabrication techniques, it is thinkable to go up to perhaps 10 tesla. This feeds immediately into the implied size of a proton synchrotron because there is a connection between the radius of the machine, the momentum of the beams, and the magnetic field. In the appropriate engineering units for this problem, the radius is two miles times the momentum measured in TeV divided by the magnetic field in tesla. If we choose 20 TeV at 5 tesla, just to pick round numbers, this means a radius of eight miles. With allowance for straight sections in which to do acceleration and experiments, the SSC will have a circumference of about 52 miles. The SSC's first mission is to explore the scale of energies of about 1 TeV for collisions between the fundamental constituents.

To show the scale of the Supercollider, I show in Fig. 12 the accelerator overlaid on a satellite photo of Washington, D.C. Obviously this is not one of the original 35 candidate sites, but the illustration shows two things. One is that the size of this scientific device is very large and we have to be prudent in planning for it. Second, the ring roughly follows Interstate 495, the Washington Beltway. This shows that the SSC really is something on the scale of human constructions that are routinely handled, and something we can contemplate doing.

There are lots of challenges associated with building and operating an SSC, and some of us are beginning to devote parts of our lives to seeing that it happens. Elsewhere in this volume, Peter Limon addresses some of the challenges in building and operating magnets for the SSC. The complexity of the detectors and the challenges presented by trying to make online selections from large numbers of events is also discussed by Tom Nash in the Roundtable later in this monograph.
But, you remind, you didn’t say anything about God. Leon Lederman promised that I was going to give a scintillating discussion in which I would reveal the secrets of the Universe, the theory of everything, the Meaning of Life, and the nature of God. The way God comes in is this: It is true that God answers all our prayers, even Leon’s, but She usually says no.