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Revolutions and Revelations

Chris Quigg

Fermi National Accelerator Laboratory,
P.O. Box 500, Batavia, Illinois, USA 60510

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1 Introduction

1.1 Vienna Tales

It is a great pleasure to be back in Vienna, among friends, and in these splendid surroundings of the Academy of Sciences. Vienna is the birthplace of my scientific grandfather, Viki Weisskopf, and some years ago I had the good fortune to spend a month as Schrödinger Professor in the Institute for Theoretical Physics on Boltzmanngasse.

I'd like to begin by telling you a lesson in Viennese culture that I learned during my appointment at the University. One fine day toward the end of my stay, my hosts dispatched me to the bank with a very official-looking piece of paper that I could exchange for my Schrödinger stipend, a stack of Schilling notes in various denominations. In those pre-Euro days, it seemed straightforward to peer into a nation's cultural self-identity by examining the faces on the banknotes. Imagine my delight when I found Mozart on the 5000-Schilling note, and my rapture when I discovered my own Schrödinger on the 1000-Schilling note. Knowing from daily commerce that Freud was only on the 50-Schilling note, I thought to myself, "What a civilized country! Austrians really must have their priorities straight: Music! Physics!"

I fairly sprinted back to the Institute for Theoretical Physics to share my new cultural insight. Now, Alfred Bartl is a very gentle man, but when I told him what I had just learned about the Austrian soul, he looked at me for a long moment with great pity. Then he said, in a patient soothing tone, "Don't you understand . . . no Austrian has ever seen a Mozart or a Schrödinger — but Freud is everwhere!"

Perhaps I did over-interpret the faces of Mozart and Schrödinger on the old Schilling notes, but there is no doubt that Vienna is one of the great sites of our patrimony as particle physicists. Not far from here, in the meadows of the Prater, Victor Hess launched the famous balloon flights during which—measuring how the conductivity of the atmosphere varies with altitude—he discovered the cosmic radiation [1]. At the Radium Institute, Marietta Blau made enhancements to the sensitivity of photographic emulsions that led, in 1937, to the observation of "stars," the many-body disintegration of nuclei under the impact of cosmic rays [2]. And let us not neglect Wolfgang Pauli, whose theoretical insights and spooky perturbations on experimental apparatus are the stuff of legend [3]. Vienna's scientific heritage is as rich as its musical, artistic, and literary past, and it provides an inspiring setting for our discussions of the future of particle physics and the exciting prospects for the Large Hadron Collider.

Our confidence in a vibrant future grows out of the accomplishments of the recent past, so let us take a moment to assess some of the contributions that set the scene for the LHC's era of exploration.

1.2 A Decade of Discovery Past

We particle physicists are impatient and ambitious people, and so we tend to regard the decade just past as one of consolidation, as opposed to stunning breakthroughs. But a look at the headlines of the past ten years gives us a very impressive list of discoveries. ¶ The electroweak theory has been elevated from a very promising description to a *law of nature.* This achievement is truly the work of many hands; it has involved experiments at the Z^0 pole, the study of e^+e^-, $\bar{p}p$, and νN interactions, and supremely precise measurements such as the determination of $(g-2)_\mu$. ¶ Electroweak experiments have observed what we may reasonably interpret as the influence of the Higgs boson in the vacuum. ¶ Experiments using neutrinos generated by cosmic-ray interactions in the atmosphere, by nuclear fusion in the Sun, and by nuclear fission in reactors, have established neutrino flavor oscillations: $\nu_\mu \to \nu_\tau$ and $\nu_e \to \nu_\mu/\nu_\tau$. ¶ Aided by experiments on heavy quarks, studies of Z^0, investigations of high-energy $\bar{p}p$, νN, and ep collisions, and by developments in lattice field theory, we have made remarkable strides in understanding quantum chromodynamics as the theory of the strong interactions. ¶ The top quark, a remarkable apparently elementary fermion with the mass of an osmium atom, was discovered in $\bar{p}p$ collisions. ¶ Direct $\mathcal{CP}$ violation has been observed in $K \to \pi\pi$ decay. ¶ Experiments at asymmetric-energy $e^+e^- \to B\bar{B}$ factories have established that B^0-meson decays do not respect $\mathcal{CP}$ invariance. ¶ The study of type-Ia supernovae and detailed thermal maps of the cosmic microwave background reveal that we live in a flat universe dominated by dark matter and energy. ¶ A "three-neutrino" experiment has detected the interactions of tau neutrinos. ¶ Many experiments, mainly those at the highest-energy colliders, indicate that quarks and leptons are structureless on the 1-TeV scale.

We have learned an impressive amount in ten years, and I find quite striking the diversity of experimental and observational approaches that have brought us new knowledge, as well as the richness of the interplay between theory and experiment. Let us turn now to the way the quark–lepton–gauge-symmetry revolution has taught us to view the world.

1.3 How the world is made

Our picture of matter is based on the recognition of a set of pointlike constituents: the quarks,

$$\begin{pmatrix} u \\ d \end{pmatrix}_{\mathrm{L}} \quad \begin{pmatrix} c \\ s \end{pmatrix}_{\mathrm{L}} \quad \begin{pmatrix} t \\ b \end{pmatrix}_{\mathrm{L}} , \tag{1}$$

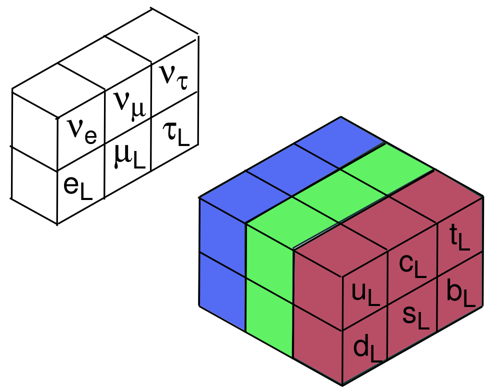

Fig. 1. The left-handed doublets of quarks and leptons that inspire the structure of the electroweak theory.

and the leptons,

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_{\mathrm{L}} \qquad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_{\mathrm{L}} \qquad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_{\mathrm{L}} , \tag{2}$$

as depicted in Figure 1, plus a few fundamental forces derived from gauge symmetries. The quarks are influenced by the strong interaction, and so carry *color*, the strong-interaction charge, whereas the leptons do not feel the strong interaction, and are colorless. By pointlike, we understand that the quarks and leptons show no evidence of internal structure at the current limit of our resolution, ($r \lesssim 10^{-18}$ m).

The notion that the quarks and leptons are elementary—structureless and indivisible—is necessarily provisional. *Elementarity* is one of the aspects of our picture of matter that we test ever more stringently as we improve the resolution with which we can examine the quarks and leptons. For the moment, the world's most powerful microscope is the Tevatron Collider at Fermilab, where collisions of 980-GeV protons with 980-GeV antiprotons are studied in the CDF and DØ detectors. The most spectacular collision recorded so far, which is to say the closest look humans have ever had at anything, is the CDF two-jet event shown in Figure 2. This event almost certainly corresponds to the collision of a quark from the proton with an antiquark from the antiproton. Remarkably, 70% of the energy carried into the collision by proton and antiproton emerges perpendicular to the incident beams. At a given transverse energy $E_\perp$, we may roughly estimate the resolution as $r \approx (\hbar c)/E_\perp \approx 2 \times 10^{-19}$ TeV m$/E_\perp$. [1]) Imagine what the LHC will bring!

Looking a little more closely at the constituents of matter, we find that our world is not as neat as the simple cartoon vision of Figure 1. The left-handed and right-handed fermions behave very differently under the influence of the charged-current weak interactions. A more complete picture is given in Figure 3. [This figure represents the way we looked at the world before the discovery of neutrino oscillations that require neutrino mass and almost surely imply the existence of right-handed

[1]) See "Searches for Quark and Lepton Compositeness" in Ref. [5] for a more detailed discussion.

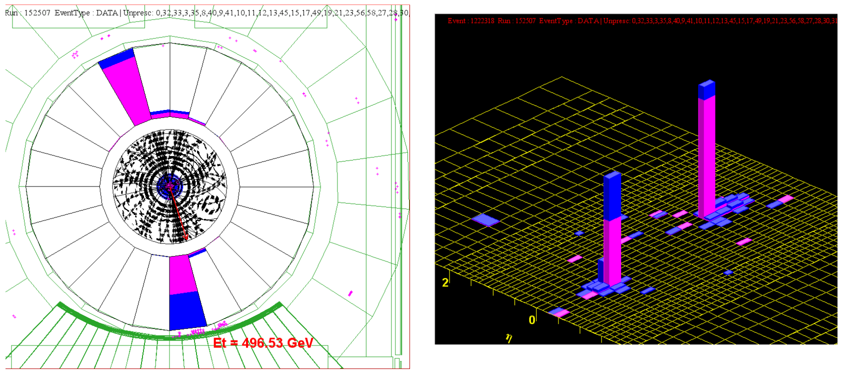

Fig. 2. A Tevatron Collider event with 1364 GeV of transverse energy, recorded in the CDF detector. The left panel shows an end view of the detector, with tracking chambers at the center and calorimeter segments at medium and large radii. The right panel shows the Lego™ plot of energy deposited in cells of the cylindrical detector, unrolled. See Ref. [4].

neutrinos.] Neutrinos aside, the striking fact is the asymmetry between left-handed fermion doublets and right-handed fermion singlets manifested in *parity violation* in the charged-current weak interactions. What does this distinction mean?

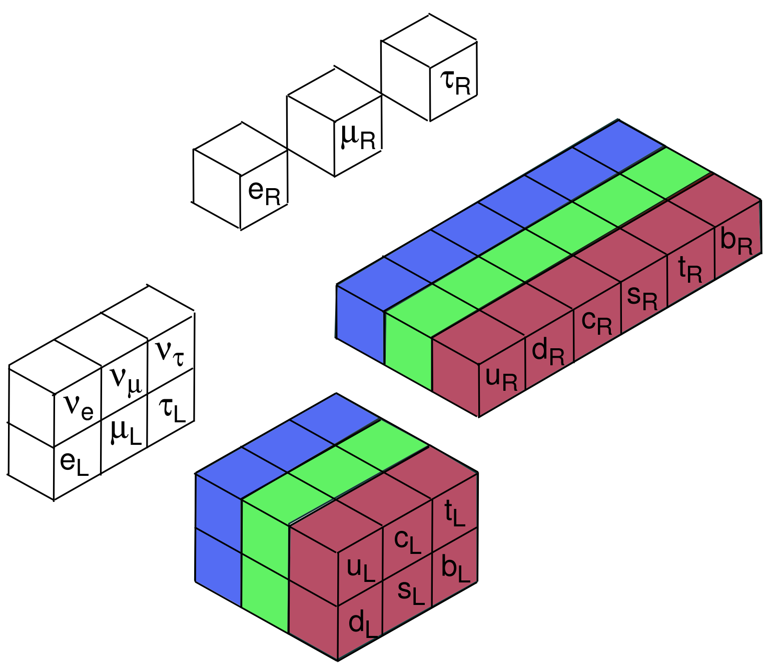

Fig. 3. The left-handed doublets and right-handed singlets of quarks and leptons.

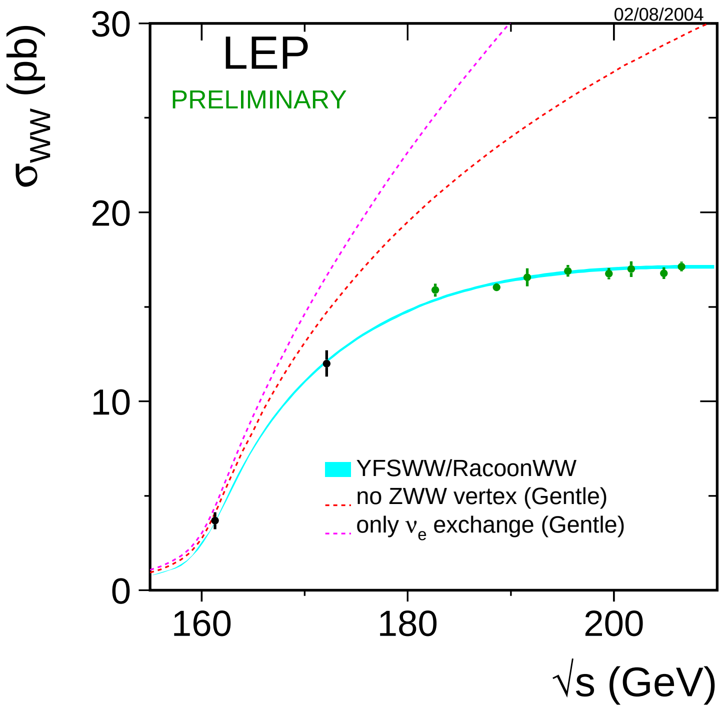

Fig. 4. Cross section for the reaction $e^+e^- \to W^+W^-$ measured by the four LEP experiments, together with the full electroweak-theory simulation and the cross sections that would result from ν-exchange alone and from $(\nu+\gamma)$-exchange [6].

A remarkable achievement of recent experiments is the clear test of the gauge symmetry, or group-theory structure, of the electroweak theory, in the reaction $e^+e^- \to W^+W^-$. Neglecting the electron mass, this reaction is described by three Feynman diagrams that correspond to t-channel neutrino exchange and s-channel photon and Z^0 exchange. The LEP measurements in Figure 4 agree well with the predictions of electroweak-theory Monte Carlo generators, which predict a benign high-energy behavior. If the Z-exchange contribution is omitted (middle dashed line) or if both the γ- and Z-exchange contributions are omitted (upper dashed line), the calculated cross section grows unacceptably with energy—and disagrees with the measurements. The gauge cancellation in the $J = 1$ partial-wave amplitude is thus observed.

The comparison between the electroweak theory and a considerable universe of data is shown in Figure 5 where the pull, or difference between the global fit and measured value in units of standard deviations, is shown for eighteen observables [6]. The distribution of pulls for this fit, due to the LEP Electroweak Working Group,

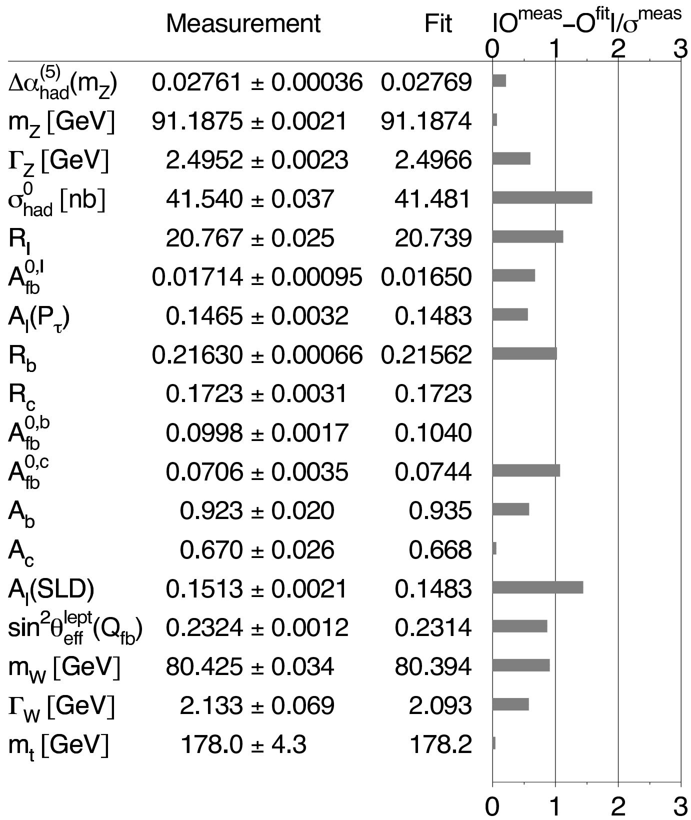

Fig. 5. Precision electroweak measurements and the pulls they exert on a global fit to the standard model, from Ref. [6].

is not noticeably different from a normal distribution, and only one measurement differs from the fit by as much as about two standard deviations [7]. It is from fits of the kind represented here that we learn that the standard-model interpretation of the data favors a light Higgs boson.

While testing the consistency of the theory, precision measurements also give us indications of the values of unknown parameters; these indications, in turn, set up new tests of the theoretical framework. A notable example is the time evolution of the top-quark mass favored by simultaneous fits to many electroweak observables, which I show in Figure 6. Higher-order processes involving virtual top quarks are an important element in quantum corrections to the electroweak theory's predictions the makes for many observables, and so each measurement is, in effect, an indirect measurement of the top-quark mass. The success of these indirect determinations in pointing to a heavy top-quark mass encourages us to believe that we should put some stock in similar indications of a light Higgs-boson mass. The current accord between direct and indirect determinations of the top mass is shown in the last entry of Figure 5.

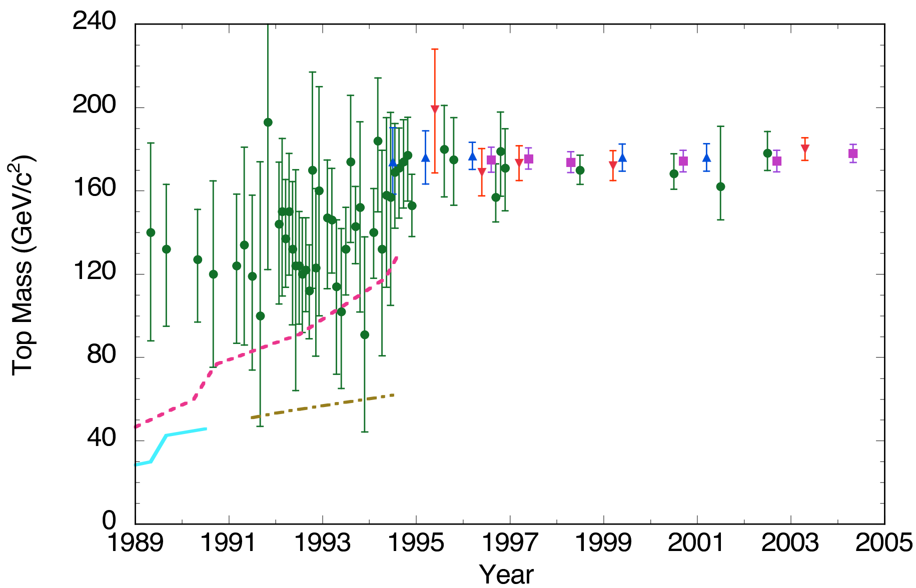

Fig. 6. Indirect determinations of the top-quark mass from fits to electroweak observables (open circles) and 95% confidence-level lower bounds on the top-quark mass inferred from direct searches in e^+e^- annihilations (solid line) and in $\bar{p}p$ collisions, assuming that standard decay modes dominate (broken line). An indirect lower bound, derived from the W-boson width inferred from $\bar{p}p \rightarrow (W \text{ or } Z) +$ anything, is shown as the dot-dashed line. Direct measurements of m_t by the CDF (triangles) and DØ (inverted triangles) Collaborations are shown at the time of initial evidence, discovery claim, and at the conclusion of Run 1. The world averages from direct observations are shown as squares. For sources of data, see Ref. [5]. (From Ref. [8].)

These are just a few indications of the quantitative successes of the electroweak theory, which is only one component of the standard-model edifice. They serve as token reminders of the strong foundation on which our hopes for future progress rest. In what follows, I want to very briefly point to five areas in which I believe we can anticipate truly revolutionary progress over the next decade or two.[2)]

2 Revolution: Understanding the Everyday

The first revolution will be led by the LHC over the next decade. That is the problem of understanding the everyday, the stuff of the world around us. It pertains to basic questions: Why are there atoms? Why is there chemistry? Why are stable structures possible? Knowing the answers to those questions may even give us an insight into What makes life possible?

[2)] A more extensive discussion is to be found in my lecture at the SLAC Summer Institute [9].

Those are the general questions that we are seeking to answer when we look for the origin of electroweak symmetry breaking. I think that the best way to make the connection is to consider what the world would be like if there were nothing like the Higgs mechanism for electroweak symmetry breaking. First, it's clear that quarks and leptons would remain massless, because mass terms are not permitted if the electroweak symmetry remains manifest.[3)] We've done nothing to the strong interaction, so QCD would still confine the (massless) color-triplet quarks into color-singlet hadrons, with very little change in the masses of those stable structures. In particular, the nucleon mass would be essentially unchanged, but the proton would outweigh the neutron because the down quark now does not outweigh the up quark, and that change will have its own consequences.

Even in the absence of a Higgs mechanism, the electroweak symmetry is broken by QCD. As we approach low energy from above, the chiral symmetry that treated the massless left-handed and right-handed quarks as separate objects is broken. The resulting communication between the left-handed and right-handed worlds engenders a breaking of the electroweak symmetry. It's not a satisfactory theory of our world because the scale of electroweak symmetry breaking is measured by the pseudoscalar decay constant of the pion, so the amount of mass acquired by the W and Z is set by f_π, not by what we know to be the electroweak scale: it is off by a factor of 2500.

But the fact is that QCD breaks the electroweak symmetry, so the world without a Higgs mechanism—but with strong-coupling QCD—is a world in which the $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ becomes $\mathrm{U(1)_{em}}$. Because the weak bosons have masses, the weak-isospin force, which we might have taken to be a confining force in the absence of symmetry breaking, is not confining. Beta decay is very rapid, because the gauge bosons are very light. The lightest nucleus is therefore one neutron; *there is no hydrogen atom.* It is likely that some light elements, such as helium, would be created in the first minutes after the big bang. Because the electron is massless, the Bohr radius of the atom is infinite, so there is nothing we would recognize as an atom, there is no chemistry as we know it, there are no stable composite structures like the solids and liquids we know.

Look how very different the world would be, if it were not for the mechanism of electroweak symmetry breaking whose inner workings we intend to explore and understand at the LHC. What we are really trying to get at, when we look for the source of electroweak symmetry breaking, is why we don't live in a world so different, why we live in the world we do. I think that's a glorious question. It's one of the deepest questions that human beings have ever tried to engage, and *you* will answer this question.

What could the answer be? The agent of electroweak symmetry breaking represents a novel fundamental interaction at an energy of a few hundred GeV. We do not know what that force is. It could be the Higgs mechanism of the standard model (or a supersymmetric standard model), which is built in analogy to the

[3)] I assume for this discussion that all the trappings of the Higgs mechanism, including Yukawa couplings for the fermions, are absent.

Ginzburg–Landau description of superconductivity. Maybe it is a new gauge force, perhaps operating on as yet unknown constituents. It could even be that there is some truly emergent description of the electroweak phase transition, a residual force that arises from the strong dynamics among the weak gauge bosons [10]. We know that if we take the mass of the Higgs boson to very large values, beyond a TeV in the Lagrangian of the electroweak theory, the scattering among gauge bosons becomes strong, in the sense that $\pi\pi$ scattering becomes strong on the GeV scale. Resonances form among pairs of gauge bosons, multiple production of gauge bosons becomes commonplace, and that resonant behavior could be what hides the electroweak symmetry. A new thought is that electroweak symmetry breaking is the echo of extra spacetime dimensions [11]. We don't know, and we intend to find out during the next decade which path nature has taken.

One very important step toward understanding the new force is to find the Higgs boson and to learn its properties. I've said before in public, and I say again here, that the Higgs boson will be discovered whether it exists or not. The precise technical meaning of my assurance is this. There will be (almost surely) a spin-zero object that has effectively more or less the interactions of the standard-model Higgs boson, whether it is an elementary particle that we put into to the theory or something that emerges from the theory. Such an object is required to make the electroweak theory behave well at high energies, once electroweak symmetry is hidden. You will find it, and that will be the start of something big [12].

3 Revolution: The Meaning of Identity

The second revolutionary theme is one that I suspect will take much longer to define and achieve; it has to do with the tantalizing question of "What makes a top quark a top quark, an electron an electron, and a neutrino a neutrino? What distinguishes these objects?" In more operational terms, we may ask, "What determines the masses and mixings of the quarks and leptons?" It is not enough to answer, "The Higgs mechanism," because the fermion masses are a very enigmatic element of the electroweak theory. Indeed, *all fermion masses, starting with the electron mass, are evidence for physics beyond the standard model!* Once the electroweak symmetry is broken, our theory permits—welcomes—fermion masses, but the values of the masses are set by the famous, and apparently arbitary, Yukawa couplings of the Higgs boson to the fermions. Nothing in the electroweak theory is ever going to prescribe those couplings. It is not that the calculation is technically challenging; there is no calculation.

The exciting prospect, then, is that quark and lepton masses, mixing angles, and $\mathcal{CP}$-violating phases put us in contact with physics beyond the standard model. The challenge for us is to construct what the big question really is. We know very well what measurements we would like to make in B physics, charm and strange physics, and neutrino physics—which elements of the mixing matrices we would like to fill in and which relationships we would like to test. Perhaps we will find that these don't fit the framework in which we view them, and that will give us some insight into the new physics. But if our standard-model framework passes every test, the new physics will still be there, and we need to understand how to get at it. There is a role here for the LHC, to be sure.

We may find new phenomena that suggest the origin of some or all of the quark and lepton masses.[4] And it might just be that we haven't grasped a latent pattern in the masses because we're not seeing the whole picture yet. Perhaps it will take discovering a new kind of matter—superpartners, or something entirely different—and seeing the spectrum of those new particles before it all begins to make sense. I do think it important that we consider the quarks and leptons together, to learn whether neutrino mass truly stands apart, and whether a common analysis can bring new insights.

I also believe that this question will, in the end, have revolutionary impact, once we understand what the question is. So it is up to all of us—not just to LHC*b*, not just to the flavor-physics groups in ATLAS, CMS, and ALICE—to pay attention to the problem of identity, and to learn how to frame the question. Lifting the veil of electroweak symmetry breaking will be a big step, but I cannot guarantee that it will suffice.

Until now, our best hope for finding simple relations among quark and lepton masses has come from unified theories of the strong, weak, and electromagnetic interactions. Those theories are the focus of our next topic.

4 Revolution: The Unity of Quarks & Leptons

The quarks and leptons have many attributes in common. All are spin-$\frac{1}{2}$ particles, structureless at our current limits of resolution, and the six quarks seem paired with the six leptons. But could we have a world made only of quarks, which respond to the strong interaction, or only of leptons, which do not? If the known quarks and leptons were unrelated sets that matched by chance, how could we account for the remarkable neutrality (to 1 part in 10^{22}) of ordinary matter? It seems unreasonable to us that the surpassing balance between the proton charge and the electron charge could be mere coincidence. Thus we are led to imagine quarks and leptons as members of an extended family, and from that hypothesis flows the full story of unified theories.[5]

Once we assign color-triplet quarks and color-singlet leptons to the same unified-theory multiplet, it is a natural implication that protons should decay, mediated by quark–lepton transformations. That natural implication might not be unavoidable, because we don't know which quarks go with which leptons. The traditional pairings: up and down with the electron and its neutrino, etc., are based only on tradition—the order in which we encountered the particles. For all we know *experimentally,* the first generation of quarks might go with the third generation of leptons. If we can find evidence for proton decay, we shall have definitive proof of

[4]) Perhaps lepton flavor violation will emerge as an important clue.

[5]) In less down-to-earth terms, we require matched pairs of quarks and leptons in order that the electroweak theory be free of anomalies, and so make sense up to high energies in the presence of quantum corrections.

the connection between quarks and leptons and gain information on which quarks should be associated with which leptons. Supersymmetric unified theories offer an attractive target of a proton lifetime only one or two orders of magnitude away from the current lower bound. Our challenge is to design the massive, low-background, finite-cost detector to push the sensitivity by a factor of 100.

A characteristic prediction of unified theories is coupling-constant unification, the statement that at some high-energy scale, the apparently independent couplings we observe in our low-energy world all have a common value. To test a candidate unified theory, we evolve the measured low-energy values up to high energies—which entails some assumptions about the spectrum of particles between here and there—and see whether the values coincide somewhere. That's a familiar, and valuable, exercise that has given us a hint of TeV-scale supersymmetry. But another way to view the same system of equations is to imagine that, on some happy day in the future, a theory might tell us the unification scale and the value there of the unified coupling constant. Then the differing values we see at low energy for the U(1) associated with weak hypercharge, the SU(2) associated with weak isospin, and the SU(3) associated with color come about because of the different evolution given by the different gauge groups and the particle spectrum. In this sense, we can understand why the strong interaction becomes strong on a certain scale.

There is a parallel to the running of coupling constants in the running of particle masses. Perhaps the pattern of quark and lepton masses looks weird—pattern*less*—to us because we measure the masses at low scales, and not at the high scale where the values are set. At the appropriate high scale, the pattern might be rational—literally!—given by symmetry factors of some sort. According to our current spotty interpretation, the masses and mixing angles arise together, so any such exercise must confront plenty of constraints.

It seems to me that one of our urgent goals should be to understand how we can establish the unity between quarks and leptons, and how we would follow up the discovery of quark–lepton transitions.

5 Revolution: Gravity Rejoins Particle Physics Rejoins Gravity . . .

For good reason, particle physicists normally neglect the influence of gravity on particle collisions or decays. If we estimate the rate for a representative process, such as kaon decay into a pion plus a graviton, it's easy to see that the emission of a graviton is suppressed by M_K/M_{Planck}. The Planck mass ($M_{\text{Planck}} \equiv (\hbar c/G_{\text{Newton}})^{1/2} \approx 1.22 \times 10^{19}$ GeV) is a big number because Newton's constant is small in the appropriate units. A dimensional estimate for the branching fraction is $B(K \to \pi G) \approx (M_K/M_{\text{Planck}})^2 \approx 10^{-38}$. It will be a long time before the single-event sensitivity of any experiment reaches this level!

One realm in which gravity has not been far from our thoughts involves the problem of separating the electroweak scale from higher scales. The electroweak scale is not the only one we recognize as significant: the Newtonian theory of gravity points to the Planck scale, and there may be a unification scale for strong, weak, and electromagnetic interactions; for all we know, there are intermediate scales, where flavor properties are determined and masses are set. The essence of the hierarchy problem, as it is called, is this: We know that the Higgs-boson mass must be less than a TeV, but the scalar mass communicates quantum-mechanically with the other scales that may range all the way up to 10^{19} GeV. How do we keep the Higgs-boson mass from being polluted by the higher scales?

Our response, for twenty-five years or so, has been to seek to extend the standard model, to temper the influence of distant mass scales. Supersymmetry, which balances fermion loops against boson loops, is one richly elaborated example [13, 14], and the notion that the Higgs boson may be composite is another. Now a new approach is under investigation, spurred by the recognition that we have investigated the electroweak theory and the rest of the standard model up to about 1 TeV, but we have tested the inverse-square law of gravity only up to energies of 10 meV (yes, *milli*-electron volts)! We have turned the question around to ask why the Planck scale is so much bigger than the electroweak scale, rather than why the electroweak scale is so low. In other words, why is gravity so weak? We'll see some consequences of posing the problem this way in the following Section.

Gravity has also weighed on the minds of electroweak insiders for three decades. In the electroweak theory, all of space is pervaded by a vacuum energy density that turns out to be really large. The contribution of the Higgs field's vacuum expectation value to the energy density of the universe is $\varrho_H \equiv M_H^2 v^2/8$, where M_H is the Higgs-boson mass and $v \approx 246$ GeV is the scale of electroweak symmetry breaking. A vacuum energy density corresponds to a cosmological constant $\Lambda = (8\pi G_{\mathrm{Newton}}/c^4)\varrho_{\mathsf{vac}}$ in Einstein's equations. We've known for a very long time that there is not much of a cosmological constant, that the vacuum energy has to less than about $\varrho_{\mathrm{vac}} \lesssim 10^{-46}$ GeV^4, a very little number. It corresponds to ≈ 10 MeV/ℓ or 10^{-29} g cm^{-3}.

But if we use the current lower limit on the Higgs-boson mass, $M_H \gtrsim 114$ GeV, to estimate the vacuum energy in the electroweak theory, we find $\varrho_H \gtrsim 10^8$ GeV^4. That is wrong by no less than fifty-four orders of magnitude! This mismatch has given many of us a chronic dull headache for about thirty years. In the simplest terms, the question is, "Why is empty space so nearly massless?" A new wrinkle to the vacuum energy puzzle is the evidence for a nonzero cosmological constant, respecting the bounds cited a moment ago. That discovery recasts the problem in two important ways. First, instead of looking for a principle that would forbid a cosmological constant, perhaps a symmetry principle that would set it exactly to zero, now we have to explain a tiny cosmological constant! Second, from the point of view of the dialogue among observation and experiment and theory, now it looks as if we have access to some new stuff whose properties we can measure. Maybe that will give us the clue that we need to solve this old problem.

6 Revolution: A New Conception of Spacetime

Asking why gravity is so weak has given rise to new thinking, part of it connected with a new conception of spacetime. What is our evidence that spacetime is really three-plus-one dimensional? How well do we know that there are not other, extra, dimensions? What must be the character of those extra dimensions, and the character of our ability to investigate them, for them to have escaped our notice? How can we attack the question of extra dimensions experimentally?

I will just call attention to a few examples of how physics might be changed if additional dimensions have eluded detection.

Perhaps, in contrast to the strong and electroweak gauge forces, gravity can propagate in all dimensions, including those we haven't perceived, because it is universal. When we inspect the world on small enough scales, we will see gravity leaking into the extra dimensions. Then by Gauss's law, the gravitational force will not be an inverse-square law, but will be proportional to $1/r^{2+n}$, where n is the number of extra dimensions. That would mean that, as we extrapolate to smaller distances, or higher energies, gravity will not follow the Newtonian form forever, as we conventionally suppose. On small scales, gravity will evolve more rapidly; its strength will grow faster, and so it might rejoin the other forces at a much lower energy than the Planck scale we have traditionally assumed. That could change our perception of the hierarchy problem entirely.

Perhaps extra dimensions offer a new way to try to understand the dramatic hierarchy of fermion masses, ranging from 1 for the top quark, in natural units of the Higgs field's vacuum expectation value, to a few $\times 10^{-6}$ for the electron, and so on. If gravity is intrinsically strong but spread out into many dimensions, tiny black holes might be formed in high-energy collisions, and we might just be able to detect the exchange or emission of Kałuza–Klein towers of gravitons at the LHC [15, 16]. While gravity is generally negligible in particle-physics processes at low energies, it has been present in our consciousness for years in the vacuum energy problem and the hierarchy problem of the electroweak theory. Perhaps now gravity is presenting itself as an opportunity—one that is here to stay!

7 Envisioning Particles and Interactions

I have been concerned for some time with the prevailing narrow view of the goals of our science. It distresses me to read in the popular press that the sole purpose of the LHC is to find—to check off, if you will—the Higgs boson, the holy grail (at least for this month) of particle physics. I am troubled still more when the shorthand of the Higgs search narrows the discourse within our own community. In response, I have begun to evolve a visual metaphor—the double simplex—for what we know, for what we hope might be true, and for the open questions raised by our current understanding. I have a deep respect for mathematics as a refiner's fire, but I believe that we should be able to explain the essence of our ideas in languages other than equations. I interpolated a brief animated overview [17] of the double simplex at this point in my lecture. For a preliminary exposition in a pedagogical setting, see Ref. [18]. I am at work on more complete explanation of the aims of particle physics through the metaphor of the double simplex.

8 Observations, Opportunities, Concerns

Before concluding, I would like to offer some remarks in the spirit of Jos Engelen's message [19] to "friendly laboratories."

To CERN: Keep your focus on the LHC to make it a glorious success—*soon!* You carry the hopes and dreams of us all.

To CERN and ECFA and EPS: Please find ways to welcome others into Europlanning. The Summer Study on the Future of Particle Physics held at Snowmass in 2001 was immeasurably strengthened and enriched by the participation of more than two hundred colleagues from outside the United States. We need to do more, in all regions, to draw enlightenment and support—and even hard questions—from our colleagues around the world.

To all the rulers of the particle physics universe: We thrive on competition, but hyperunilateralism will be our common undoing. We all have a stake in a healthy *world* program.

To the LHC community: Respect the Tevatron, hope for some vigorous competition, and learn from the Tevatron experience [20].

To all of us: We have an obligation to involve more people in the adventure of our science, our trust in experiment over authority, and our shared belief in the power of reason and the importance of doubt. We celebrate the many nations represented in the LHC collaborations, but I draw your attention to the vast blank expanses on the CMS and ATLAS collaboration maps. Those parts of the world need our ideas and our technical expertise, too; and we need to engage the people of those parts in the scientific enterprise.

To the LHC community: How will we actually do physics at the LHC? Can everyone who wants to participate be accommodated at CERN? What would be required for people to participate effectively at regional analysis centers? (Of the centers? of CERN? of the experiments?)

To all of us: How can we advance the commissioning of the Right Linear Collider? Must we execute projects in sequence? Can we optimize scientific return by executing in parallel, through cooperation and global networks? How can we best take advantage of the multitude of the scientifc opportunities before us [21]?

9 The Road Ahead

The Large Hadron Collider will lead us into real golden age of exploration and discovery. I look forward to a wonderful flowering of experimental particle physics, and of theory that engages with experiment. ¶ We will make a thorough exploration of the 1-TeV energy scale; search for, find, and study the Higgs boson or its equivalent; and probe the mechanism that hides electroweak symmetry. ¶ We will continue to challenge the standard model's attribution of $\mathcal{CP}$ violation to a phase in the quark mixing matrix, in experiments that examine B decays and rare decays—or mixing—of strange and charmed particles. ¶ New accelerator-generated neutrino beams, together with reactor experiments and the continued study of neutrinos from natural sources, will consolidate our understanding of neutrino mixing. Double-beta-decay searches may confirm the Majorana nature of neutrinos. ¶ The top quark will become an important window into the nature of electroweak symmetry breaking, rather than a mere object of experimental desire. Single-top production and the top quark's coupling to the Higgs sector will be informative. ¶ The study of new phases of matter, especially through heavy-ion collisions, and renewed attention to hadronic physics will deepen our appreciation for the richness of QCD, and might even bring new ideas to the realm of electroweak symmetry breaking. ¶ Planned discoveries and programmatic surveys have their (important!) place, but exploration breaks the mold of established ideas and can recast our list of urgent questions overnight. Among the objectives we have already prepared in great theoretical detail are extra dimensions, new strong dynamics, supersymmetry, and new forces and constituents. Any one of these would give us a new continent to explore. ¶ Proton decay remains the most promising path to establish the existence of extended families that contain both quarks and leptons. A vast new underground detector will be required to push the sensitivity frontier. ¶ We will learn much more about the composition of the universe, perhaps establishing the nature of some of the dark matter. Observations of type Ia supernovae, the cosmic microwave background, and the large-scale structure of the universe will extend our knowledge of the fossil record. Underground searches may give evidence of relic dark matter. Collider experiments will establish the character of dark-matter candidates and will make possible a more enlightened reading of the fossil record.

You who have been preparing the LHC experiments know that none of this will be easy. We have miles to go before the beams cross, the detectors record events, and we begin to decipher the messages they contain. At the same time, we are taking such a great step into the unknown—including the 1-TeV scale where we know many treasures are hidden—that I believe the flood of amazing results will come quickly, while we are still learning how to listen to our detectors [22]. It is a glorious prospect; how lucky we are to be part of it!

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