Inventory and Outlook of High Energy Physics

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I have kept very close to the content and style of the talk as it was delivered. You may access the associated PowerPoint presentation through a link at [http://www.ichep02.nl/MainPages/PlenaryProgram.html](http://www.ichep02.nl/MainPages/PlenaryProgram.html)

John Wheeler’s description of the progression from graduate student to professor as being the passage from knowing everything about nothing to knowing nothing about everything carries over with obvious (and inessential) modifications to the progression from talks at parallel sessions to the conference summary. I feel especially daunted here, after listening to a series of beautiful plenary talks that have already summarized their subject areas, so that I’m reduced to providing a summary of the second order. In order to supply at least a small amount of value added, I’ll try to frame the new developments actually reported at the Conference within the broader context of contemporary physics, and also to indicate a few directions that I feel are important and promising, but which did not get emphasized during the Conference.

1. The Standard Model

1.1. QCD

Very near half of the parallel sessions, 23 out of 48, centered around the strong interaction and QCD. This concentration reflects an enormous wealth of intriguing phenomena. We’ve been shown that even questions that have been pursued for a long time, ranging from low-energy spectroscopy and the search for exotics to high-energy reaction dynamics and the emerging new phenomenology of diffractive dissociation at high energy, are far from being exhausted. Still, progress in the mature areas of strong interaction physics tends to be incremental, and its description is necessarily complex, so I won’t devote anything like equal time to reviewing them. Instead, I’ll content myself with a few general observations about QCD.

The discovery that the basic degrees of freedom in the strong interaction (quarks and gluons) are entirely different from the apparent ones (mesons and baryons), and the development of techniques, both theoretical and experimental, to work with these degrees of freedom, is a wonderful triumph of empirical investigation and intellectual analysis – one of the greatest ever, I think. Concealed beneath a complex and bewildering array of phenomena, profoundly simple and mathematically precise principles of symmetry (nonabelian gauge invariance) and dynamics (local quantum field theory) are found to be running the show.

No brief summary can do justice to this story, but most of you are familiar with its main outlines, and Figure 1 will serve both as icon and mnemonic. In it the results of dozens of experiments of different characters performed at a variety of mass scales, together comprising many thousands of independent measurements, are compared with the theoretical calculation of the running coupling, which contains exactly one adjustable parameter. The quality of the agreement speaks quite well for itself, of course, but two amplifications are appropriate.

First, you will notice that the alternative theoretical curves, based on different values of the adjustable parameter, focus to the right, at high energy, where most of the data is. The parameter is usually taken to be $\Lambda_{QCD}$, roughly speaking the mass or inverse distance scale at which the QCD coupling becomes of order unity. On very
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Figure 1. Running of the coupling in QCD. It exhibits the uniformly successful application of a theory containing only a single continuous parameter to describe a tremendous variety of experimental measurements performed over a wide range of energies. Many of the calculations must be carried to several orders of perturbation theory to achieve adequate accuracy. Especially noteworthy is the “lattice gauge theory” point, which is fully non-perturbative.

On general heuristic grounds we should expect $\Lambda_{\text{QCD}}$ to be associated with characteristic physical phenomena like the inverse of the geometric radius of hadrons, as defined by high-energy total cross-sections, or the transverse momentum ‘cutoff’ observed for particle production in high-energy scattering. The equivalent energy scales are a little fuzzy to define, but they surely lie in the range 150–250 MeV. Not coincidentally, these values parameterize the limiting curves in Figure 1, which bracket the data. The point I want to reinforce is that if we regard this range of values for $\Lambda_{\text{QCD}}$ as given, the theoretical predictions at high energy are essentially unique. They contain no adjustable parameters whatsoever!

Second, I want to call your attention especially to the theoretical point labelled “heavy quarkonia-lattice”. All the other theoretical points are based on calculations using what are usually called “perturbative methods”. Actually, these calculations usually employ sophisticated renormalization group arguments and factorization techniques, besides including at least one and usually two orders in virtual loops, so the name hardly does them justice. In any case the “perturbative” calculations in themselves represent a tour de force of quantum field theory, and they provide overwhelming, tangible evidence for the quark-gluon description of strong interactions in general and the existence of jets – tangible incarnations of the quarks and gluons, which quite literally track their energy-momentum – in particular. But the lattice calculations go yet deeper. They are based directly on the fundamental degrees of freedom and algorithmic definition of the theory, with no approximations at all aside from practical ones imposed by finite computer resources. By way of contrast, the corresponding calculations in QED, or even standard model electroweak theory, are impossible in principle – those theories lack nonperturbative definition, and don’t provide adequate foundations for completely honest calculations! So it is very reassuring, and gratifying, that the lattice calculations agree with the perturbative ones, and with experiment. Indeed the power of full, nonperturbative implementation of the theory to determine $\Lambda_{\text{QCD}}$ quantitatively already competes with that of traditional perturbative methods, and it waxes steadily.

While stringent testing of the principles of QCD remains an important activity, the main focus of research in the field has long since moved from verification to application. An ironic consequence of asymptotic freedom is that extreme conditions of matter become amenable to reasonably straightforward theoretical analysis, while great ingenuity (or extremes of patience and computer power) is needed to use the theory in tamer circumstances. Thus first-principles QCD enables us to make accurate predictions for jets at large transverse momentum in ultra-high energy collisions, providing the essential foundation for designing signatures and estimating backgrounds for experiments at the energy frontier, while ordi-
nary nuclear physics remains mostly out of reach.

On the other hand, recently there has been great progress in studying what might be called extreme nuclear physics – understanding the behavior of hadronic matter in highly excited states.

One limit of great interest is that of high temperature $T$, with zero net baryon number density, or small chemical potential $\mu$. According to theory, this is the form of matter that dominated the Universe during the earliest moments of the Big Bang. Intuitively we might expect that energetic quarks, antiquarks, and gluons are liberated, and propagate quasi-freely, at asymptotically high temperatures. And this is basically what happens; but to leave it at that would constitute criminal neglect. The high $T$, small $\mu$ regime of QCD is susceptible to direct simulation using Monte Carlo techniques. From this work it emerges that the transition from the energy density characteristic of a pion gas, with 3 degrees of freedom, to nearly that of free quarks and gluons – 52 degrees of freedom! – occurs in a narrow range of temperatures around $T_c \sim 150–200$ MeV. There is no true phase transition, but a rapid crossover from a state of matter that would be considered “obviously hadronic” to one best described starting with quasi-free quarks and gluons, i.e., the famous quark-gluon plasma. Although it has been known for several years, I still find this precocious approach to the quark-gluon plasma amazing, since on the low-temperature side one is not much past a dilute gas. On the other hand the pressure lags somewhat behind, and approaches closely to the energy density only at $T \sim 600–800$ MeV (whereas of course for free massless particles they’d be equal). A longstanding fundamental challenge has been to understand the origin of this discrepancy analytically; it now appears that this challenge is being met.

Experimental work in heavy ion collisions is going great guns, as we’ve heard. There is good evidence for elliptic flow, which can be interpreted as a manifestation of pressure, which implies multiple scattering. When this is analyzed quantitatively, it provides pretty convincing circumstantial evidence that something approaching thermal equilibrium is established, at a temperature well above the predicted crossover. An important goal for the near future is to gather direct evidence for ultra-high temperatures in the initial fireball, by capturing prompt photons and dileptons. Perhaps the most dramatic experimental discovery so far in this field is the opaqueness of the fireball. This leaves its signature in monojets: high transverse momentum jets lacking a balancing jet in the opposite hemisphere. The opacity seems too large to be ascribed to quasi-free quarks and gluons, and may be telling us something important about the effective degrees of freedom activated in hadronic wavefunctions. It will be interesting to see how the result reported in this paragraph gets reconciled with the result reported in preceding one!

Another lively frontier is the opposite limit, large $\mu$ and small $T$. This is relevant to the description of ultra-dense cold matter, as might be found in the interior of compact stars. By adapting techniques from the theory of superconductivity we can construct a weak-coupling but nonperturbative description of the ground state and low-energy excitations of three-quark matter at asymptotically high densities. In this remarkable color-flavor locked state confinement and spontaneous chiral symmetry breaking, dynamical properties of QCD that are often regarded as difficult and mysterious can be derived rigorously and understood simply. At subasymptotic densities we lose rigorous control, and several more complicated alternatives have been proposed. These include interesting inhomogeneous and quasi-crystalline states, some incorporating meson condensates. Unfortunately both laboratory and numerical experiments in this domain are impractical. Compact stars do not reveal their inner secrets easily, but technique in experimental astrophysics is in a state of perpetual revolution, and we might be able to discern the effects of exotic states in their mass-radius relations, cooling curves, and/or the gravitational radiation they emit at creation or in violent collisions.

1.2. Electroweak

Although not traditional, I think it is useful and natural to discuss the electroweak sector of the
standard model as two separate theories, which are on a very different conceptual footing and only loosely connected. Here I refer not to the two gauge symmetries $SU(2) \times U(1)$, which are birds of a feather, but rather to two parts of the theory that really are radically different, namely the piece describing gauge field interactions and the piece describing Higgs field interactions. (Note that every interaction of the standard model involves one or the other!)

The interactions of the gauge bosons are governed by a very tight theory, derived from the profound and beautiful principle of local symmetry. All the properties of the gauge bosons, and thus of the interactions they mediate, must be derived from just three continuous parameters: $g_2$ and $g_1$, and the magnitude of the symmetry-breaking condensate, which generates their mass. (To be completely correct I should qualify this. Within the minimal standard model, strictly interpreted, it is consistent to vary the strength with which other fields couple to the $U(1)$ factor continuously. That is to say, charge quantization is not an automatic consequence of the gauge symmetry of the standard model. This flaw is mitigated by demanding anomaly cancellation, and removed in unified gauge theories.) Of course, these three parameters must describe many more than three independent kinds of measurements. Their success in doing so, especially after the rigorous quantitative work of the LEP era, is truly remarkable. It is displayed in Figure 2. As always, there are marginal misfits at the edge of experimental and theoretical uncertainties, but no really convincing discrepancy has emerged, despite much effort. This impressive fit places very severe constraints on ideas that ascribe electroweak symmetry breaking to the influence of a new strongly interacting sector (technicolor), and exerts considerable pressure on models where extra dimensions (“TeV gravity”, “brane worlds”) or complicated Higgs sectors (“little Higgs”) are invoked in this regard.

In his Autobiographical Notes Einstein describes the two sides of his gravitational field equation $R_{\mu \nu} - \frac{1}{2} g_{\mu \nu} R = T_{\mu \nu}$ as constructions of gold and of wood. His point, of course, is that the description of gravity in terms of space-time curvature is profound and conceptually based, whereas in his day the description of the energy-momentum of matter was by comparison ramshackle and essentially phenomenological. Were he with us today, I think Einstein might be willing to say that QCD and the gauge sector of electroweak theory are built from noble metals.

Not so the Higgs sector. Within the standard electroweak model, in its minimal form, it is the interactions of quarks and leptons with the Higgs field – to be precise, the interactions of matter with the Higgs condensate – that are responsible for their masses and weak mixing angles, including CP violation. But there is no deep principle in play. The theory allows – and the phenomenology requires! – a large number of independent parameters to describe these masses and mixings. It is a ramshackle structure, and we should certainly aspire to raze it to the ground and replace it with something much better.

Though ramshackle, the standard model description of masses and mixings is proving to be amazingly fruitful and durable. Using it,
Kobayashi and Maskawa anticipated the existence of a third generation, so as to provide a mechanism to accommodate the observed phenomenon of CP violation. The third generation promptly appeared. Major experimental tests reported at this Conference, and other recent work on CP violation and weak mixing angles, have failed to bring it down. I'll discuss this further below.

2. Completing the Standard Model: The Higgs Particle

The ultimate support for the ramshackle part of the standard model – the wooden girders, so to speak, around which it hangs – is the Higgs field. Its independent physical quantum, the Higgs particle itself today remains the only major ingredient of the Standard Model that has eluded direct observation. (To be sure, the longitudinal parts of the W and Z bosons devolve from components of the Higgs doublet!) From the study of radiative corrections to electroweak parameters, as indicated in Figure 2, one can infer limits on the Higgs particle mass. These limits assume, of course, that no additional unknown particles are contributing significantly. The limits are displayed in a more expansive format in Figure 3.

It is quite impressive and significant how well the mass is boxed in. This makes the challenge facing the Fermilab Tevatron, in searching for this particle, very tangible and concrete. That challenge is made graphic in Figure 4.

I'd like to take this opportunity to complain about an often repeated, but nonetheless quite misleading, bit of hype to the effect that finding the Higgs particle will explain The Origin of Mass. First of all, the honest story of the true origin of most of the mass of matter is extremely beautiful, and we ought to be very proud of it and make it better known. Most of the mass in ordinary matter comes from its constituent protons and neutrons. These in turn are built from nearly massless quarks and strictly massless gluons. The mass of protons and neutrons arises from the pure energy of QCD dynamics, according to \( m = E/c^2 \). We have calculated it, with quite respectable accuracy, based on a theory that contains no continuous parameters whatsoever. To my mind this ranks among the very greatest achievements in all of science. Second, as mentioned above, the Higgs mechanism does not provide an even remotely satisfactory account of masses and mixings; rather, these are accommodated using many continuous parameters unconstrained by theory. What the Higgs mechanism really explains is not the origin of mass, but the breaking of electroweak symmetry. Through it we learn that empty space is a sort of exotic superconductor. This accurate representation of its nature is more challenging to explain, but ultimately more profound and beautiful (not to mention true) than the usual vulgarization.

With the opening of the LHC, the Higgs particle will become a much easier target. If low-energy supersymmetry is valid, there will be several scalar “Higgs particles”, including at least one charged and two additional neutral species. Sorting all this out will be a rich and exciting enterprise, as suggested by Figure 5.
terest of its target, the search for the Higgs particle involves some pretty points in quantum field theory dynamics. Uniquely, its primary coupling to ordinary matter is entirely nonclassical; it communicates through a virtual top loop to gluons! Its primary production mechanism in hadronic collisions is through gluon fusion. This brings special interest to the determination of gluon distribution functions, since they figure directly into anticipating the production rate, and interpreting it once measured. Also, since the Higgs particle has vacuum quantum numbers it can be produced with rapidity gaps \[10\]. This will open a new chapter in the ongoing saga of diffractive scattering, which has been especially refreshed through recent discoveries at HERA.

3. Unification and Supersymmetry

3.1. (Only Slightly In-)Direct Evidence

Because the standard model is so successful, and provides a close approximation to the last word on Nature’s inner workings, we are obliged take its shortcomings very seriously. Consider Figure 6, which displays the bare-bones core of the standard model, specifically the transformation properties of the lightest quarks and leptons under the gauge groups \(SU(3) \times SU(2) \times U(1)\). Left-handed fields are used exclusively, so we employ charge conjugation \(u^c\) to get the right-handed \(u\) quark into the game, through its (left-handed) conjugate. \(SU(3)\) acts horizontally, \(SU(2)\) acts vertically, and the hypercharge \(U(1)\) assignments are indicated by subscripts. Two shortcomings hit the eye. First, the particles fall into five disconnected pieces. Second, there is no evident rhyme or reason to the hypercharge assignments. They are simply chosen to accommodate experiment. Along the same lines, the gauge symmetry falls apart into three independent pieces.

These shortcomings can be overcome, in a way I find compelling, by building upon the concepts of the standard model itself.

3.1.1. Unification of Multiplets

The gauge symmetry \(SU(3) \times SU(2) \times U(1)\) and the observed fermions fit snugly into an \(SU(5)\) unification. Using a simple breaking scheme (condensate in the adjoint 24 representation), and starting with fermions in the antisymmetric tensor 10 and vector 5 representations, we arrive at precisely the gauge groups and fermion multiplets of the standard model, including the hypercharge assignments. This is a highly non-trivial coincidence. Since it cuts the number of
multiplets down from five to two, and uniquely fixes the hypercharge assignments, this unification achieves substantial esthetic gains over its starting point. Still more beautiful is the possibility of unification afforded by the slightly larger group $SO(10)$. Now the fermions all fit into a single spinor $16$ representation. This is a particularly elegant representation, with remarkable properties, as indicated in Figure 7. The components of the spinor representation can be specified by their transformation properties under the diagonal $SO(2) \times SO(2) \times SO(2) \times SO(2) \times SO(2)$. These have the physical interpretation of being the values of five color charges. All possible combinations of charges $\pm \frac{1}{2}$ are allowed, subject to the constraint that the number of $+\frac{1}{2}$ charges is even. From these abstract mathematical rules, the multiplet structure of a complete family in the standard model falls out automatically, matching the pattern observed in Nature. In particular, the hypercharges are uniquely predicted from the strong and weak charges, according to the simple formula

$$Y = -\frac{1}{6}(B + R + G) + \frac{1}{4}(P + O).$$

The spinor $16$ contains, in addition to the fermions of the standard model, an additional particle $N$. $N$ is a singlet under $SU(3) \times SU(2) \times U(1)$, and so it has none of the standard gauge interactions with matter. Its “non-observation” does not pose immediate problems. Indeed it plays a major constructive role in the theory of neutrino masses.

### 3.1.2. Unification of Couplings

Unified gauge symmetry requires universal gauge coupling strength. This does not hold, of course, in the standard model. The $SU(3)$ coupling is observed to be larger than the $SU(2)$ coupling, which in turn is larger than the $U(1)$ coupling.

Fortunately, as we have seen in Figure 6, a great lesson from QCD is that coupling constants evolve with energy. The same sorts of calculations that give us asymptotic freedom in the strong interaction allow us to evolve, theoretically, the effective couplings up to high energy, or equivalently short distance, scales. If the gauge part of the standard model derives from a larger gauge symmetry, spontaneously broken at a unique large energy scale, we should expect that these couplings meet at a point. For in their evo-
olution from high to low energies, the couplings only started to diverge after the big symmetry was broken.

If we evolve the couplings up to high energy using only the particles of the minimal standard model, we get the result shown in top part of Figure 8. Notice that to a good approximation the inverse couplings are predicted to run logarithmically, so the running generates straight lines in this log plot. The width of the lines indicates the experimental uncertainties, post LEP. It is a remarkable near-miss, but a miss nonetheless. One can try to repair this small discrepancy in any number of ways, using various slight perturbations on the minimal model. In the absence of any powerful guiding principle, however, such fixes lack conviction.

Instead of tinkering with the standard model, let us consider the apparently drastic, but independently motivated, idea that supersymmetry is broken only at relatively low (≲ TeV) energies. This modifies the running of the couplings, because there are more virtual particles to consider, in a way that is easy to compute. Though it involves a vast extension of the minimal standard model (more than twice the particles!), low-energy supersymmetry has a surprisingly small, and remarkably salutary, effect on the unification of couplings calculation. If we extend the standard model in the most economical way to include low-energy supersymmetry, we find the result shown in the bottom part of Figure 8. The unification now works much better, quantitatively. This is an extremely encouraging result, both for unification and for low-energy supersymmetry.

The quantitative success of the unification of couplings calculation (with low-energy supersymmetry) is undeniable. How seriously should we take it?

At the most formal level, the unification of couplings is an over-constrained fit of three measured quantities – α₁(Mₚ), α₂(Mₚ), α₃(Mₚ) – to two theoretical parameters, the scale of unification and the strength of coupling at unification. Given the precision of the measurements, it is remarkable that an adequate fit is obtained.

But simply saying that one number falls into place does not do justice to the state of affairs, because many other things, besides failure to satisfy this one numerical constraint, could have gone wrong. If the couplings had met at too small an energy scale, we would have difficulties with rapid proton decay. If they had met at a significantly larger a mass scale, at or above the Planck scale, we would have had to worry about quantum gravity corrections. The actual scale at which they meet, not far on a logarithmic scale, but still significantly below, the Planck scale, is uniquely acceptable. Similarly, if the unified coupling were
much larger we could not trust the perturbative calculation.

To me, the unification of multiplets and the unification of couplings are the crown jewels in an inventory of physics beyond the standard model. Together, they make a powerful *prima facie* case for the elements that went into their derivation: unified gauge symmetry, for the unification of multiplets; renormalizable quantum field theory, operating smoothly up to near-Planckian scales, for the proper logarithmic running of couplings; and low-energy supersymmetry, for detailed numerical success. Nowadays, in the context of string theory, we know – or, rather, we have incomplete suggestions about – many alternative ways that the low-energy $SU(3) \times SU(2) \times U(1)$ symmetry of the standard model might emerge from constructions that involve neither effective unified gauge field theories nor symmetry breaking through condensates. Of course there is no necessary contradiction, since early reduction to an effective unified gauge field theory also still remains a viable option. Along this line, perhaps we should take the striking success of the “oldies but goodies” I’ve just recalled as indications that in searching for string-based models of Nature, we should look with favor upon those that reduce to something like an effective supersymmetric $SO(10)$ renormalizable gauge field theory, or a recognizably broken version thereof, just below the Planck scale. At least we can say that other schemes have some coincidences to explain.

### 3.2. Additional Evidence,
**For the Sympathetic**

The unification of couplings calculation is unique in its *quantitative* success, but in addition there are several impressive *qualitative* points in favor of low-energy supersymmetry.

The most profound concerns stabilization of the electroweak scale. In the minimal standard model, and in a generic extension of it, radiative corrections to the Higgs field mass parameter, which governs the scale of electroweak symmetry breaking, are quadratically divergent. In order that these corrections not dwarf the final value we need, the cut-off must be imposed at $\lesssim 1$ TeV. But we would like to contemplate physics at much higher scales, and did so with striking success in the unification of couplings calculation, so it is preferable to have these corrections cancel. By balancing off virtual bosons and fermions, supersymmetry accomplishes this cancellation. Supersymmetry effectively broken at $\lesssim 1$ TeV will protect the electroweak scale adequately.

Other mechanisms have been proposed to generate or stabilize the electroweak symmetry breaking scale. But, as I mentioned previously, they tend to leave nontrivial footprints in the form of radiative corrections, and there is little sign of deviations from the standard model in precision electroweak measurements. Another important advantage of low-energy supersymmetry is that the radiative corrections it generates are generally small. Figure 9 displays this feature.

![Figure 9](image-url)

**Figure 9.** Modification of the precision electroweak parameters in models incorporating low-energy supersymmetry. Because these models contain several parameters that relevant, but currently undetermined, a sampling of results from typical models in the allowed space is displayed, as the solid blob. The important point is that the corrections to the standard model are generically small, and lie comfortably within existing experimental limits.

Furthermore, standard model fits to precision measurements require a low value for the Higgs mass, near (or below!) existing experimental lim-
its. In the standard model itself, there is no reason to favor such a value. But in its extension to incorporate low-energy supersymmetry, the Higgs mass is tied to the $W$ and $Z$ masses, and it must be light.

3.3. Where It Takes Us

Unless all these indications are part of an elaborate, cruel jest on the part of the Creator, we can look forward to a golden age of discovery. New quantum dimensions of superspace will open up, inhabited by weird doppelgangers of the familiar fundamental particles.

Both the strength and the weakness of the unification of couplings calculation is its robustness. Because the inverse couplings run logarithmically, factor-of-few reshiftlings in the mass spectrum of the contributing particles tend to induce only small changes in this calculation. That feature, of course, is what allows us to abstract a general success for low-energy supersymmetry and unification, which is fairly insensitive both to the actual spectrum of supersymmetric particles and to the details of unified symmetry breaking. The other side of the coin is the implication that this success does not provide much resolving power for those details.

The mechanism of supersymmetry breaking is still up for grabs, with several proposals under active consideration. They lead to mass spectra with quite distinctive patterns, as displayed in Figure 10. These mechanisms could encode, respectively, the first tangible influence of quantum gravity in subatomic physics (gravity mediation) the existence of new strongly interacting sectors (gauge mediation), dynamics from small curled-up extra spatial dimensions (anomaly and gaugino mediation), or combinations of these. Exciting stuff!

Low-energy supersymmetry provides excellent candidates for the dark matter that cosmology seems to demand. The density of dark matter produced depends on poorly conditioned details of the model but, as displayed in Figure 11, there is a healthy swath of parameter space where it roughly matches what the cosmologists want. Also indicated in this Figure are some of the many experimental approaches to identifying dark matter. Finally, I should own up to the dark side of low-energy supersymmetry. It offers many new potential sources of flavor and CP violation, including baryon number violation. Some of these are associated with low-dimension operators, so that _a priori_ they are sensitive to physics at high mass scales, where exotic effects of quantum gravity and exchange of the new particles associated with unification are unsuppressed. Nature does not seem to avail Herself of these possibilities, at least not that we’ve seen so far. So special mechanisms and symmetries must be postulated, to keep the basic ideas of low-energy supersymmetry and unification phenomenologically viable. Possibilities have been suggested, so it’s not an outright contradiction (for example, gauge mediation cleanly suppresses the potential flavor and CP violation), but we need more complete and convincing ideas. Interpreting things optimistically, this is a relatively poorly explored area which makes close contact with some of the most fundamental aspects of supersymmetry, unification, and string theory, so major new theoretical insights might still be plausibly expected. And several concrete estimates suggest that positive experimental dis-
Figure 11. Dependence of supersymmetric dark matter production on two of the standard parameters for low-energy supersymmetry breaking. In the light blue (or light gray!) band, the lightest $R$-odd particle supplies all or most of the density required by astronomical observations. Also indicated are expected sensitivities of various experimental probes. For a full explanation, see [11].

Coveries lie just ahead in electric dipole moments, $\mu - e$ conversion processes, and proton decay.

4. Segue

Now I need to shift gears, and discuss recent progress in a few areas where experiments are supplying us with wonderful results, but results that we can’t yet do justice to theoretically. At this point, a joke is in order.

A man walks into a bar, takes a seat on the next-to-last stool, and spends the evening chatting up the empty stool next to him, being charming and flirtatious, as if there were a beautiful woman in that empty seat. The next night, same story. And the next night, same story again. Finally the bartender can’t take it any more. She asks, “Why do you keep talking to that empty stool as if there were a beautiful woman in it?”

The man answers, “I’m a theoretical physicist. I’m hoping that a beautiful woman will tunnel in from an extra dimension and materialize on that stool. Then I’ll seem very clever indeed, and I’ll have the inside track with her.”

“That’s ridiculous,” says the bartender.

“Plenty of very attractive women come to this bar all the time. You’re reasonably presentable, and extremely articulate; if you applied your charm on one of them, she might be interested in you.”

“Oh come on,” he replies, “how likely is that?”

5. Results in Flavor Physics

5.1. CP Violation

This is a vast and intricate subject, with a lot of relevant data gushing in right now from BABAR and BELLE on $B$ meson physics, as well as final results from heroic, decades-long programs at CERN and Fermilab measuring $\epsilon'/\epsilon$. Fortunately for me the results and their interpretation were beautifully reviewed at this Conference by Yosi Nir [12], and I don’t have much to add. Perhaps the most eloquent thing for me to do is simply to display Figure 12. The delicate relations of the unitarity triangle, which are overconstrained by the data, appear to be well obeyed. The dominant source of CP violation in the $B$ and $K$ systems thus appears, on the face of it, to derive from an irremovable complex phase appearing in the mixing matrix for 3 quarks, just as Kobayashi and Maskawa proposed. The intrinsic phase is not small; the relative smallness of CP violation in the $K$ meson system, which for many years is all we’ve had to look at, is because this system is fairly well insulated from goings on in the heavy quark sectors.

Of course, more complete and accurate measurements may still reveal subtle deviations from this picture, but for now the ramshackle flavor structure of the minimal standard model is holding up.

Before leaving the subject, I’d like to express my admiration for the beauty of this physics. In Figures 13 and 14, lifted from Nir, you see how the relative phases between very different sorts of amplitudes interfere to govern various kinds of physical processes, and the intricacy of the resulting formulas. This complex of ideas and measurements could be used as the basis of a course in fundamental quantum mechanics – and provides an extremely impressive demonstration, in an extremely exotic setting, of how well it works!
Figure 12. Unitarity triangles, derived from orthogonality relations in the 3-family Cabibbo-Kobayashi-Maskawa unitary mixing matrix. If this framework is adequate to describe the processes measured, the various allowed bands must overlap, thus marking out a consistent, allowed region for the underlying parameters. So far, they do. For more details, see [12].

Through familiarity we can easily lapse into taking that for granted, but it is an extraordinary fact.

5.2. Neutrino Oscillations
This is another vast and intricate subject on which there has been dramatic progress recently.

We've just heard a nice summary of the experimental situation, and there are many reviews available, so again my main duty is simply to recall the appropriate image, shown as Figure 15 [13]. The existence of neutrino oscillations, with large mixing angles, is secure. Neutral current results from the SNO collaboration, coming in slightly after the Conference, confirmed that the Sun is putting out its full share of neutrinos, and the long-standing deficit of electron neutrinos observed in charged currents is mostly, and presumably entirely, due to oscillations. The various solar neutrino experiments all appear to be fit very well to the so-called large mixing angle, or LMA, solution.

Within the framework of electroweak $SU(2) \times U(1)$, neutrino masses can be accommodated by means of a nonrenormalizable interaction

$$\Delta L = \frac{1}{M} \phi l \phi^\dagger l$$

where $l$ is the lepton doublet and $\phi$ the Higgs doublet. With $\phi$ replaced by its vacuum expectation value $v$, this becomes a Majorana neutrino mass of magnitude $v^2/M$. With $M$ of order $10^{15} - 10^{16}$ GeV, this is about right. That mass scale is equal to what appears in the unification of couplings as the scale at which unification symmetry breaks.

There is a simple, concrete dynamical mechanism for generating neutrino masses which ex-
5.3. What Does It All Mean?

So what does it all mean? That’s a rather embarrassing question, I’m afraid.

We’ve learned a few important lessons. The ramshackle part of the standard model holds up amazingly well. CP violation in the quark sector is not intrinsically small. There is a pronounced mass hierarchy for quarks, with small mixing, and (probably) a significant mass hierarchy for neutrinos, with large mixing. The magnitude of neutrino masses roughly accords with expectations from unified gauge theories.

The biggest issues, however, remain the obvious ones, and they remain unresolved. Why is there repetition of families? Why are there three? Why is there such a spread in quark and lepton masses? There is a factor of roughly 10^{-6} between the electron mass and the top quark mass, a tiny number that begs for a qualitative explanation, but we have only vague speculations about its origin. Can we infer profound symmetries, or profound dynamical principles, from the study of flavor? Or will it remain, indefinitely, a spectacularly abstruse branch of natural history?

Some familiar facts seem especially clear and significant. Masses, like couplings, evolve with energy scale, and the observed ratio m_b/m_τ is at least roughly consistent with equality at the unification scale. Although for historical reasons we usually speak of the t quark as being extraordinarily heavy, there are good reasons to consider m_t as the most reasonable of quark masses. Indeed, a wide range of masses at the unification scale focus down to roughly the observed value of m_t at accessible energies.

A sophisticated and possibly important effort in model-building is directed toward forging links between the pattern of masses and mixings and the one hand and gauge unification on the other [14]. The light Higgs doublet (or doublets), whose vacuum expectation value generates the masses and mixing, can descend from a combination of irreducible representations of the unified symmetry. Those representations have different restrictions on interfamily couplings, e.g., symmetry or antisymmetry in the family indices; and within a family, different ratios for their contributions to quark versus lepton mass matrices. By using all
the data, and looking for patterns, we can start to construct a genealogy.

This quest ties up with the question of why the light Higgs doublet of electroweak theory is badly split from its unified partners \[15\]. Those partners must be extremely heavy, as otherwise they would mediate unacceptably large contributions to proton decay. There are fairly simple mechanisms that explain, or at least naturally accommodate, this splitting; as one might expect from the heuristic, bottom-up argument about stabilizing the electroweak scale, one thing these mechanisms have in common is that they rely heavily on special properties of supersymmetric theories.

Since in these schemes quark and lepton mixings are intimately related, one might suspect that tension arises between the smallness of quark mixings and the largeness of lepton mixings revealed in neutrino oscillations. There is no conflict, but one is led along these lines in surprisingly specific directions, involving so-called “lopsided” mass matrices \[14\]. A generic prediction of this framework is that the mixing observed in atmospheric neutrino oscillations will not be accurately maximal.

A seemingly very different approach attempts to forge links between the geometry of small folded up extra dimensions and the observed pattern of masses and mixings. Some ideas here are that fermions in different families live at different places in the extra dimensions (e.g., that they are localized on orbifold singularities), that the Higgs field has different amplitudes at these places, which accounts for their different masses, and that overlap of their wavefunctions determines the mixings. Some attractive, reasonably economical models have been constructed along these lines \[16\].

Of course, even successful model-building and pattern-matching of this kind will not satisfy our hunger for deep insight into the physical world. We want to know what big ideas are in play, why things are the way they are. What principles determine which unified symmetry multiplets condense, and which combinations stay light to become the electroweak Higgs doublets? What dynamics determines the shape of the extra dimensions, and where the fermions live? Is there a useful notion of symmetry among the families, and if so how is it broken, and how could we tell? By answering questions of this order we might bring the subject to an appropriate, higher level.

To sum up: despite much hard and extremely impressive work, and some significant progress, our understanding of fermion masses and mixings remains superficial at best; we are still at the level of pattern-gathering, similar to where we were in strong and weak interaction physics in the early 1960s (or maybe the 1910s?). Fortunately, there are real prospects for gathering important new information, and observing fundamentally new phenomena, soon. Many avenues are ripe for exploration: electric dipole moments, charged lepton number violation, baryon number violation, and rare decays in $K$ and in $B$ physics. On the theoretical side, we desperately need more powerful, sharply testable ideas.

6. Cosmic Connections

6.1. Challenges from Cosmology

Measurements of cosmological parameters have improved dramatically in recent years, primarily due to measurements of cosmic microwave background anisotropies and supernova redshift surveys. The supernova part of this is summarized in Figure 16, taken from Marc Kamionkowski’s excellent review here.

All the measurements seem to converge upon a simple, but unexpected and challenging picture. The answer is sufficiently weird that we might be led to rethink the foundations, but for now Einstein’s general relativity and the Friedmann-Robertson-Walker model of a homogeneous and isotropic expanding universe, with today’s structure emerging from the growth of small perturbations early by gravitational instability, form at least an adequate descriptive framework, which I’ll adopt. The universe is observed to be very nearly spatially flat, and accelerating. Spatial flatness is correlated with a critical value of the average mass density, $\rho_c = 3H^2/8\pi G$, with $H$ the Hubble expansion parameter. In units where the critical density is 1, ordinary (baryonic) matter contributes about $\rho_B \sim 0.03$, some unknown pressureless ‘dark matter’ contributes $\rho_d \sim 0.3$, and
some negative-pressure ‘dark energy’ contributes $\rho_d \sim 0.7$, with $p_d \approx -\rho_d$.

Plausible candidates for the dark matter include a quasi-stable particle served up by low-energy supersymmetry – the lightest particle with negative $R$-parity, where $R = (-1)^{B+L+2s}$ is 1 for all standard-model particles and $-1$ for their superpartners – and the axion, to be discussed below. There are important, vigorous searches underway to pin down these possibilities.

The properties of the dark energy are consistent with its deriving from a cosmological term. Depending on whether we put this on the left-hand side of Einstein’s equation together with the curvature, or on the right-hand side together with the energy-momentum tensor, we can think of it either as a modification of the basic equations of gravity or as a peculiar form of matter. However regarded, its actual value is difficult to reconcile with other aspects of our understanding of Nature.

On the one hand, its value seems absurdly small. Our best-established theories in the standard model require that empty space is permeated with condensates – at the very least a condensate for spontaneous chiral symmetry breaking in QCD, and another for electroweak symmetry breaking. Naive estimates of the contribution of these condensates to the energy yield values about 60 orders of magnitude larger than the observed value. And condensates associated with supersymmetry breaking should be, and unified symmetry breaking could be, even heavier. But gravity, which is universal, seems to blithely ignore all this structure, as well as energy that might be associated with zero-point motion of quantum fields.

On the other hand, its actual non-zero value seems weirdly coincidental. Why should the weight of empty space, which presumably ought to be determined by local physics, have anything to do with the density of (dark) matter? If it really is a cosmological term, this is a coincidence that will not stand the test of time, since the matter density gets diluted by the expansion of the Universe while the cosmological term abides; nor was it true in the very early Universe. It is very suspicious to label as coincidence a quantitative correlation that happens to be true in every case we actually measure it – even if, as here, the number of such cases is one. Maybe it indicates a flaw in the foundations.

To me, this is the biggest mystery in physical science. It makes a mockery of claims that we have a “Theory of Everything” or a “consistent theory of quantum gravity”. Everything – but not including most of the mass of the Universe? Consistent – but not with one of the most fundamental qualitative features of gravity in Nature?

Putting these deep concerns aside, the emerging picture is strikingly consistent with expectations from inflationary models. A period of rapid inflation in the early universe can very naturally explain its flatness. Detailed models, coming in several varieties (slow-roll, chaotic, eternal, hybrid, etc.) also suggest a mechanism for generating the fluctuations that seed structure formation that is consistent with information emerging from the measurement of microwave background.
anisotropies. At present the tests are quite weak, but they could be greatly strengthened by future measurements of polarization.

Assuming that some simple inflationary model survives rigorous testing, we shall be faced with a big theoretical challenge. Essentially all current models are based on postulating the existence and properties of “inflation” fields *ad hoc* – and, of course, extrapolating the cosmological term back in time naively. On the face of it they all involve fine-tuning, invoking small couplings to explain the drawn-out period of inflation and the smallness of fluctuations. It would be very satisfying to identify appropriate fields based on considerations of fundamental physics. Alternatively, we might be required to find mechanisms that achieve the existing successes, which are basically qualitative, in a different way.

6.2. Cosmic Rays

High-energy cosmic rays are interesting for many reasons, of course, in astrophysics. They extend to higher energies than will be available at accelerators in the foreseeable future, so it is important to watch for lessons they might contain about fundamental physics. A new generation of powerful detectors, prominently including the Auger array, should soon bring the study of this domain to a new level. These matters were nicely reviewed by Tom Gaisser.

For many years the most striking anomaly in the field has concerned the most energetic cosmic rays. This is the existence of significant numbers of events with primary energy above about $10^{11}$ GeV, the so-called GZK cutoff. Conventional particles – protons, photons, and nuclei – above this energy have a hard time propagating over cosmic distances, so one expects the spectrum of cosmic ray primaries to decrease sharply just below this energy. It has appeared that this was not the case, that the spectrum held up or even rose. This has inspired several proposals for exotic particle-physics sources, which I won’t describe in detail here except to say that all have serious problems.

Recent recalibrations, displayed in Figure 17, now cast some doubt on the existence of the anomaly. It is too soon to tell how this situation will resolve itself – Auger should give decisive experimental results – but it is a bit of news worth noting.

7. An Ultralight Sector?

Many ideas suggest the possible existence of a new sector of physics, consisting of very weakly interacting, ultra-light or even massless spin-0 particles. These have various names, including axions, familons, modulons, vadrons (a new one; see below), and dilatons. Aside from the dilaton, which is a special case, they are associated with spontaneous symmetry breaking, essentially as the Nambu-Goldstone bosons of various possible broken symmetries. The axion is the best motivated and best developed, so I’ll focus on it as representative.
7.1. Recollections of Axions

Given its extensive symmetry and the tight structure of relativistic quantum field theory, the definition of QCD only requires, and only permits, a very restricted set of parameters. These consist of the coupling constant and the quark masses, which we’ve already discussed, and one more – the so-called $\theta$ parameter. Physical results depend periodically upon $\theta$, so that effectively it can take values between $\pm \pi$. We don’t know the actual value of the $\theta$ parameter, but only a limit, $|\theta| \lesssim 10^{-9}$. Values outside this small range are excluded by experimental results, principally the tight bound on the electric dipole moment of the neutron. The discrete symmetries P and T are violated by $\theta$ unless $\theta \equiv 0 \mod \pi$. Since there are P- and T-violating interactions in the world, the $\theta$ parameter cannot be put to zero by any strict symmetry assumption. So its smallness is a challenge to understand.

The effective value of $\theta$ will be affected by dynamics, and in particular by condensations (spontaneous symmetry breaking). Peccei and Quinn discovered that if one imposed a certain asymptotic symmetry, and if that symmetry were spontaneously broken, then an effective value $\theta \approx 0$ would be obtained. Weinberg and I explained that the approach $\theta \to 0$ could be understood as a relaxation process, wherein a very light collective field, corresponding quite directly to $\theta$, settled down to its minimum energy state. This is the axion field, and its quanta are called axions.

The phenomenology of axions is essentially controlled by one parameter, $F$. $F$ has dimensions of mass. It is the scale at which Peccei-Quinn symmetry breaks. More specifically, there is some scalar field $\phi$ that carries Peccei-Quinn charge and acquires a vacuum expectation value of order $F$. (If there are several condensates, the one with the largest vacuum expectation value dominates.) The potential for $|\phi|$ can be complicated and might involve very high-scale physics, but the essence of Peccei-Quinn symmetry is to posit that the classical Lagrangian is independent of the phase of $\phi$, so that the only way in which that phase affects the theory is to modulate the effective value of the $\theta$ term, in the form $\theta_{\text{eff.}} = \theta_{\text{bare}} + \arg \phi$. Then we identify the axion field $a$ according to $\langle \phi \rangle \equiv F e^{i a/F} e^{-i \theta_{\text{bare}}}$, so $\theta_{\text{eff.}} = a/F$. This insures canonical normalization of the kinetic energy for $a$.

In a crude approximation, imagining weak coupling, the potential for $a$ arises from instanton and anti-instanton contribution, and takes the form $\frac{1}{2}(1 - \cos \theta_{\text{eff.}}) \times e^{-8 \pi^2/g^2 \Lambda_{\text{QCD}}^4}$. So the energy density controlled by the axion field is $e^{-8 \pi^2/g^2 \Lambda_{\text{QCD}}^4}$. The potential is minimized at $\theta_{\text{eff.}} = 0$, which solves the problem we started with. The mass$^2$ of the axion is $e^{-8 \pi^2/g^2 \Lambda_{\text{QCD}}^4}/F^2$. Its interactions with matter also scale with $\Lambda_{\text{QCD}}/F$. The failure of search experiments, so far, together with astrophysical limits, constrain $F \gtrsim 10^9$ GeV.

Now let us consider the cosmological implications. Peccei-Quinn symmetry is unbroken at temperatures $T \gg F$. When this symmetry breaks the initial value of the phase, that is $e^{ia/F}$, is random beyond the then-current horizon scale. One can analyze the fate of these fluctuations by solving the equations for a scalar field in an expanding Universe.

The main general results are as follows. There is an effective cosmic viscosity, which keeps the field frozen so long as the Hubble parameter $H \equiv R/R \gg m$, where $R$ is the expansion factor. In the opposite limit $H \ll m$ the field undergoes lightly damped oscillations, which result in an energy density that decays as $\rho \propto 1/R^3$. Which is to say, a comoving volume contains a fixed mass. The field can be regarded as a gas of nonrelativistic particles (in a coherent state). There is some additional damping at intermediate stages. Roughly speaking we may say that the axion field, or any scalar field in a classical regime, behaves as an effective cosmological term for $H \gg m$ and as cold dark matter for $H \ll m$. Inhomogeneous perturbations are frozen in while their length-scale exceeds $1/H$, the scale of the apparent horizon, then get damped.

If we ignore the possibility of inflation, then there is a unique result for the cosmic axion den-$^1$

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$^1$I am putting a standard integer-valued parameter, not discussed here, $N = 1$, and slighting several other inessential technicalities.
sity, given the microscopic model. The criterion $H \lesssim m$ is satisfied for $T \sim \sqrt{\frac{M_{\text{Planck}}}{F_{\Lambda_{\text{QCD}}}}}$. At this point the horizon-volume contains many horizon-volumes from the Peccei-Quinn scale, but it is still very small, and contains only a negligible amount of energy, by current cosmological standards. Thus in comparing to current observations, it is appropriate to average over the starting amplitude $a/F$ statistically. The result of this calculation is usually quoted in the form $\rho_{\text{axion}}/\rho_{\text{critical}} \approx F/(10^{12} \text{ GeV})$, where $\rho_{\text{critical}}$ is the critical density to make a spatially flat Universe, which is also very nearly the actual density. Ongoing, heroic experiments are approaching a crucial test of this dark matter candidate, as shown in Figure 18.

Figure 18. Experiments to search for a cosmic axion background. They are approaching sensitivities such that the hypothesis that axions contribute significantly to the dark energy will be tested.

In the derivation of this form the measured value of the baryon-to-photon ratio density at present has been used. This is adequate for comparing to reality, but is inappropriate for our coming theoretical exercise. If we don’t fix the baryon-to-photon ratio, but instead demand spatial flatness, as suggested by inflation, then what happens for $F > 10^{12} \text{ GeV}$ is that the baryon density is smaller than what we observe.

If inflation occurs before the Peccei-Quinn transition, this analysis remains valid. But if inflation occurs after the transition, things are quite different.

### 7.2. Undetermined Universe and the Anthropic Principle

If inflation occurs after the transition, then the patches where $a$ is approximately homogeneous get magnified to enormous size. Each one is far larger than the presently observable Universe. The observable Universe no longer contains a fair statistical sample of $a/F$, but some particular “accidental” value. Of course there is a still larger structure, which Martin Rees calls the Multiverse, over which it varies. Now if $F > 10^{12} \text{ GeV}$, we could yet be consistent with cosmological constraints on the axion density, so long as the amplitude satisfies $(a/F)^2 \lesssim F/(10^{12} \text{ GeV})$. The actual value of $a/F$, which controls a crucial regularity of the observable Universe, is contingent in a very strong sense – in fact, it is different “elsewhere”. In this very precise and specific sense, then, the laws of physics are not unique.

Within this scenario, the anthropic principle is correct and appropriate. Regions with large values of $a/F$, so that axions by far dominate baryons, seem pretty clearly to be inhospitable for the development of complex structures. The axions themselves are weakly interacting and essentially dissipationless, and they dilute the baryons, so that these too stay dispersed. In principle laboratory experiments could discover axions with $F > 10^{12} \text{ GeV}$. Then we would conclude that the vast bulk of the Multiverse was inhospitable to intelligent life, and we would be forced to appeal to the anthropic principle to understand the anomalously modest axion density in our Universe.

### 7.3. Coupling Nonuniqueness? – The Cosmological Term

Ratcheting up the level of speculation one notch further, we can consider the hypothesis that this is the only source of the observed nonvanishing cosmological term. To avoid confusion, let me call the axion variant that appears here the *vadron*, in homage to Darth Vader (Lord of the Dark Force). I’ll use the symbols $v$, $F_v$, etc. with the obvious meaning.
Several attractive consequences follow.

- The magnitude of the residual cosmological term is again of the general form \\
  \( \frac{1}{2}(v/F_v)^2 e^{-8\pi^2/9^2 \Lambda_v^4} \) for \( v/F_v \ll 1 \), then saturating, but now with \( g_v \) and \( \Lambda_v \) no longer tied to QCD. This could fit the observed value, for example, with \( v/F_v \sim 1 \), \( \Lambda_v \sim M_{\text{Planck}} \), and \( \alpha_v \sim 0.01 \).

- The freezing criterion \( H \gtrsim m \) translates into \( F_v \gtrsim M_{\text{Planck}} \). If this condition holds by a wide margin, then the value of the effective cosmological term will remain stuck on a time-scale of order \( 27H^{-1}(H/m)^4 \), considerably longer than the current lifetime of the Universe. If \( F_v \) is comparable to or less than \( M_{\text{Planck}} \), significant conversion of the effective cosmological term controlled by \( v \) into matter is occurring presently.

- In any case, such conversion will occur eventually. Thus we might be able to maintain the possibility that a fundamental explanation will fix the asymptotic value of the cosmological term at zero.

- With larger values of \( \alpha_v \) and smaller values of \( v/F_v \), we realize an anthropic scenario, as discussed above, but now for dark energy instead of dark matter.

7.4. Experiments!

Speculation is fun (and I hope you’ll forgive my indulgence) but to me the interest of an idea about Nature reaches a different level when its truth can be tested by observation. Lacking that discipline, we are in grave danger of saying things that are not merely wrong, but strictly meaningless (Hume). Fortunately, the idea of an ultra-light sector does suggest several different kinds of concrete experiments. I have already mentioned the axion search. There is also the possibility of searching for new quasi-macroscopic forces, both spin-independent (scalar coupling) and spin-dependent (pseudoscalar coupling), or “dipolar”, involving CP-violating cross-terms. Another possible signature is the time-variation of physical constants, which might be mimicked by interaction with a slowly varying cosmic background field. Pursuit of such heterodox experiments is difficult and risky, in the sense that negative results are not unlikely, but this pursuit is of absolutely fundamental importance.

8. The Glory of Precision

The most profound guiding principle of physics is that it is possible to construct a precise quantitative description of basic physical phenomena. (Nowadays it is PC to add, what should go without saying, that in complex situations completely precise description may not be practical.) The special mission of high-energy physics – perhaps its defining characteristic, more than high energy as such – is to put this principle to the test ruthlessly, at the most extreme limits of accurate calculation and controlled measurement that we can attain. It’s both our glory and our burden that we can care passionately about the existence of particles and effects that emerge only from one-in-a-trillion collisions at ultra-sophisticated, ultra-expensive accelerators, and worry over part-in-a-trillion discrepancies between ultra-refined theory and ultra-delicate experiments.

Two contemporary examples must be mentioned here.

Figure 19 illustrates how the value of experimental work on CP violation and flavor physics could be enhanced by using the full power of QCD in its nonperturbative realization to calculate precise predictions for weak interaction matrix elements. It is not an isolated case. There is a general principle at work: Even if your ultimate ambition is to find deviations from the standard model, it’s good strategy, both scientifically and economically, to figure out as precisely as possible what it is that the standard model predicts.

We’ve just been treated to a description of new experimental results of unprecedented accuracy for the anomalous magnetic moment of the muon. Here is the number:

\[ a_\mu \equiv \frac{g - 2}{2} = 11 659 204.7(5) \times 10^{-10} \]

It is an extraordinary achievement in experimental physics, the fruit of remarkable courage, perseverance, and ingenuity. Hats off! With another year of running time the precision, which cur-
Figure 19. The unitarity triangle, again, together with an indication of how the power of the measurements could be enhanced by achievable improvements in the theoretical estimation of operator matrix elements in QCD.

rently is limited by statistics, could be improved by a factor of two or more.

We should not let memory of some recent pratfalls besmirch, even for a moment, another magnificent story on the theory side. Nowhere else in all of science are such intricate calculations, involving concepts so remote from mundane experience, both possible and necessary to do justice to experimental results. Five loops of QED! Two loops of electroweak processes! Dispersion relations, precise low-energy experiments, and clever use of chiral symmetry for the virtual strong interaction effects! The result of all this is at once impressive, frustrating, and tantalizing. Depending upon whether one estimates hadronic vacuum polarization based on $e^+e^-$ annihilation or $\tau$ decay, the discrepancy between theory and experiment is $3.0\,\sigma$ or $1.9\,\sigma$. Presumably the difference between these estimates, which cannot represent real physics, will be straightened out in coming months, possibly with an assist from lattice gauge theory. With achievable improvements in experiment and theory, conceivably we could find ourselves looking at a $5\,\sigma$ effect by the next Lepton-Photon get-together.

It’s not irrelevant to note that the anomalous moment of the muon has long been recognized as an especially sensitive diagnostic for low-energy supersymmetry. Of course, by itself even a convincing discrepancy between experiment and the standard model prediction of $g - 2$ cannot rule low-energy supersymmetry in, nor would the absence of such a discrepancy rule it out. But if and when low-energy supersymmetry is discovered, the value of $g - 2$ will provide a very significant piece of information concerning how the new sector communicates with ordinary matter.

As we speak there are serious questions as to whether there will be adequate funding available to exploit the existing opportunities, both in numerical QCD and in experimental $g - 2$. In my opinion, failure to exploit these opportunities would be a tragic waste. We must strive harder, as a community, to convey the glory of precision.

9. No Conclusion

Breathe easy, there won’t be a summary of the third order. I would, however, like to add one final observation. The overwhelming impression I take away from this Conference is that brilliant work by many people has resulted in an extraordinarily precise, profound description of the physical world. This description incorporates on the one hand the vast body of knowledge and technique quite inadequately labelled the standard model, enlarged to accommodate neutrino masses; and on the other hand big bang cosmology, enlarged to include the circle of ideas and observations around inflation. But all this progress should not mark an end. Rather it allows us to ask – that’s easy enough! – and (more impressive) to take meaningful, concrete stabs at answering some truly awesome questions. Do all the fundamental interactions derive from a single underlying principle? What is the quantum symmetry of space-time? To what extent are the laws of physics uniquely determined? Why is there any (baryonic) matter at all? What makes the dark matter? Why is there so little dark energy, com-
pared to what it “should” be? Why is there so much, compared to everything else in the Universe? These are not merely popularizations or vulgarizations but genuine, if schematic, descriptions of a few of our ongoing explorations.

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