

Perspectives and Questions: Toward an Expansive Agenda for Particle Physics

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Global celebration greeted the 2012 discovery at CERN’s Large Hadron Collider of a particle that matches the textbook description of the Higgs boson. That achievement validated a remarkable chain of theoretical reasoning that combined the prescriptive notion of electroweak gauge symmetry with a simple, but *ad hoc*, embodiment of spontaneous symmetry breaking. It was made possible by generational triumphs of accelerator art and experimental technique, and by human resourcefulness and collaboration on a global scale, all sustained by the enlightened support of many governments and institutions.

Some imagine that, once the keystone of the standard model of particle physics has been set, our subject is over. Others worry that we may be at an impasse because no comparable wonders have appeared, leaving us without well-defined clues to a more complete paradigm. I am neither so readily satisfied nor so easily discouraged: we have so much more to learn! This essay surveys many questions that, taken together, constitute an inspiring array of opportunities to enhance our understanding of the physical world.

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I. PROLOGUE

A. Anticipations of a New World

Before experiments¹ began at the Large Hadron Collider, we were confident that a thorough exploration of the 1-TeV scale would reveal the mechanism of electroweak symmetry breaking. We had reason to suspect that in this same energy range we might discover (WIMP, weakly interacting massive particle) dark matter candidates, superpartners, or evidence for new strong dynamics related to dynamical electroweak symmetry breaking. And why not new constituents or new gauge bosons, representing new forces of Nature?

Looking ahead, I was encouraged by these words of Cecil Frank Powell, a pioneer of the photographic emulsion method that revealed the pion (Powell, 1969?):

“When [the emulsions exposed on the Pic du Midi] were recovered and developed in Bristol it was immediately apparent that a whole new world had been revealed. . . . It was as if, suddenly, we had broken into a walled orchard, where protected trees had flourished and all kinds of exotic fruits had ripened in great profusion.”

¹ The LHC detectors (Froidevaux and Sphicas, 2006) and upgrades planned for the (high-luminosity) HL-LHC (Campana *et al.*, 2016) represent the greatest complexity and performance yet achieved. The developments in computing needed to keep pace are detailed in (Elvira *et al.*, 2022).

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Some optimists asserted that a mere eight minutes of LHC experimentation would establish the existence of supersymmetric particles. That sort of exuberance—imprudent at the time—invites ridicule in retrospect. In the event, we have reaped “only” the epochal discovery of the 125-GeV Higgs boson (Aad *et al.*, 2012; Chatrchyan *et al.*, 2012)².

While it is true that we have found no other new terms in the Lagrangian of the universe, each negative search offers fresh guidance for theory. And if we broaden our view of discovery just a little, we find that the LHC has indeed revealed exotic fruits in great profusion, in the form of seventy-nine new hadrons (Koppenburg, 2025), a good number expressing body plans³ beyond the classic meson ($q\bar{q}$) and baryon (qqq) configurations.

Progress in particle physics is by no means confined to experimentation at the highest energies. Our subject is continually nourished by news from exquisitely precise measurements, experiments using found beams from natural sources, and a widening spectrum of astrophysical and cosmological observations. Synthesizing all this information is a fascinating challenge for contemporary research.

In this essay, I survey the frontiers of particle physics by posing a multitude of questions. The general message is that the openings for progress are many and broadly distributed. Each question could merit an essay of its own, but I have adopted the format of lists, not fully documenting the questions. The references are schematic; I trust that a curious reader will be able to enrich them⁴.

My goals are to encourage colleagues (myself included) to think broadly and originally about our common future. I hope that readers will consider the opportunities I catalogue, to make their own lists—and perhaps to order them and set personal and community priorities, conscious of the advantages of diversity and of scale diversity in experimental undertakings. It would please me if the list that follows served as incentive for a graduate seminar. An open-ended assignment could be to choose a question, flesh it out, investigate, report, refine the question, and even act on it.

B. Questions Our Forebears Pondered

A revealing way to assess the progress in particle physics over the past six decades is to consider the Problems of High-Energy Physics cited in the (Fermi) National Accelerator Laboratory Design Report (Cole *et al.*, 1968):

Which, if any, of the particles that have so far been discovered, is, in fact, elementary, and is there any validity in the concept of “elementary” particles?

What new particles can be made at energies that have not yet been reached? Is there some set of building blocks that is still more fundamental than the neutron and the proton?

Is there a law that correctly predicts the existence and nature of all the particles, and if so, what is that law?

Will the characteristics of some of the very short-lived particles appear to be different when they are produced at such higher velocities that they no longer spend their entire lives within the strong influence of the particle from which they are produced?

Do new symmetries appear or old ones disappear for high momentum-transfer events?

What is the connection, if any, of electromagnetism and strong interactions?

Do the laws of electromagnetic radiation, which are now known to hold over an enormous range of lengths and frequencies, continue to hold in the wavelength domain characteristic of the subnuclear particles?

What is the connection between the weak interaction that is associated with the massless neutrino and the strong one that acts between neutron and proton?

Is there some new particle underlying the action of the “weak” forces, just as, in the case of the nuclear force, there are mesons, and, in the case of the electromagnetic force, there are photons? If there is not, why not?

In more technical terms: Is local field theory valid? A failure in locality may imply a failure in our concept of space. What are the fields relevant to a correct local field theory? What are the form factors of the particles? What exactly is the explanation of the electromagnetic mass difference? Do “weak” interactions become strong at sufficiently small distances? Is the Pomeranchuk theorem⁵ true? Do the total

² On a recent visit to the Museo Galileo in Florence, I came upon these effusive words from one Ludovico (Antonio) Muratori (1672–1750): “God has truly reserved to our own day the discovery of an incredibly amazing phenomenon. I am referring to electricity.” Should we not in turn temper our laudable impatience a little and celebrate the fact that Nature has reserved to our day the discovery of a most wondrous phenomenon, the agent of electroweak symmetry breaking?

³ This term from morphology and comparative anatomy encompasses both tabulating constituents and identifying substructures.

⁴ Two essential resources are the Snowmass 2021 Report (Butler *et al.*, 2023) and the *Physics Briefing Book: Input for the 2026 update of the European Strategy for Particle Physics* (de Blas, 2025).

⁵ Let a and b label hadron species. The inference that differences of the ab , $\bar{a}b$, $a\bar{b}$, and $\bar{a}\bar{b}$ total cross sections should vanish at high energies is due to (Pomeranchuk, 1958).

cross sections become constant at high energy?
Will new symmetries appear, or old ones disappear, at higher energy?

Young physicists in particular may be a bit astonished by how little our colleagues knew in 1968 of what we consider textbook material. But consider how much more they knew than the pioneers of a half century before, and be prepared to be chastened by how quaint and incomplete our current knowledge will seem a few decades hence! While some of the questions are challenging to decrypt, overall they exhibit a great deal of insight into the kind of issues that might matter. Indeed, several remain relevant in our time.

C. Context

Let us set our point of departure: the evolving standard model of particle physics circa 2025. We have established a set of building blocks, spin- $\frac{1}{2}$ constituents that appear pointlike at the current limit of our resolution, $r \lesssim 10^{-18}$ m. These are arrayed in Figure 1 to exhibit their family relationships.

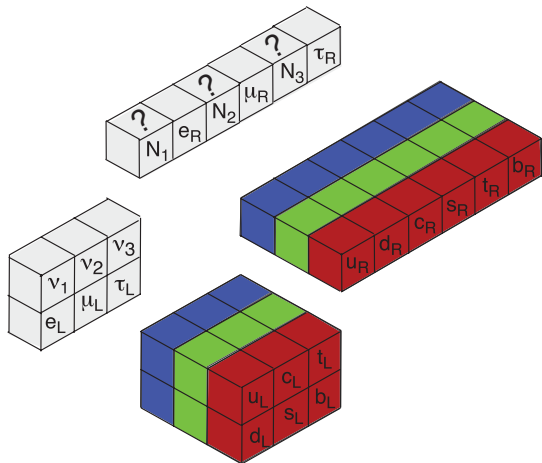


FIG. 1 A schematic representation of the quarks and leptons, the fundamental constituents of the standard model of particle physics. The color-triplet quarks are painted red, green, and blue; the left-handed weak-isospin doublets are indicated by the stacked pairs. Interactions are governed by $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetry, spontaneously broken to $SU(3)_c \otimes U(1)_{em}$.

Six quarks (up, down, charm, strange, top, and bottom) are color triplets that experience the strong interaction described by quantum chromodynamics (QCD), generated by the color gauge group $SU(3)_c$. The left-handed quarks experience the charged-current weak interaction; they form weak-isospin doublets that are roughly aligned with the mass eigenstates: (u, d) , (c, s) , (t, b) . On current evidence, the right-handed quarks are weak-isospin singlets.

Six color-singlet left-handed leptons ($\nu_e, e, \nu_\mu, \mu, \nu_\tau, \tau$) form weak-isospin doublets in which the flavor eigenstates are perfectly aligned. In the figure, I have labeled the neutrinos as mass eigenstates (ν_1, ν_2, ν_3), to match the labeling of the quarks. We infer the likely existence of right-handed neutrinos (here labeled N_1, N_2, N_3) from the discovery that neutrinos have (very tiny) masses. The ? signal that we have not yet established that the right-handed neutrinos exist, nor characterized them in detail.

In addition to the color and left-handed weak isospin family symmetries, there is a weak-hypercharge phase symmetry, so that the interactions that rule the nanonoworld⁶ are derived from a $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetry, that is hidden, or spontaneously broken, to $SU(3)_c \otimes U(1)_{em}$. The placement of quarks and leptons in Figure 1 makes it visually tempting to join the quark and lepton multiplets together to form extended quark-lepton families, with lepton number as a fourth color (Pati and Salam, 1974).

To build a theory out of these observations, we lay out a small set of Guiding Principles. We take Nature to be reliable, not capricious. We adopt Poincaré-invariant Relativistic Quantum Field Theory, embodying local causality and unitarity as a productive mathematical framework, disciplined by the constraints of symmetries and conservation laws (via Noether’s theorems); and the notion of hidden symmetries. A generation ago, Renormalizability would have been taken as a *sine qua non*. Now we are comfortable with the notion of effective field theories (Weinberg, 2021), in which we identify the important degrees of freedom for each scale of energy or resolution.

To this general framework, I would add these working hypotheses:

- ☐ Minkowski spacetime (except where gravity is strong),
- ☐ constancy in time of the fundamental constants such as $\hbar, c, G_N, m_e, \alpha, \dots$,
- ☐ pointlike quark and lepton constituents with sharply defined masses,
- ☐ gauge symmetry as the typical origin of interactions.

The product \mathcal{CPT} of the discrete symmetries, charge conjugation \mathcal{C} , parity \mathcal{P} , and time reversal \mathcal{T} , is an exact symmetry of any local and Lorentz-invariant quantum field theory with a positive-definite Hermitian Hamiltonian that preserves microcausality (Streater and Wightman, 1964). All observations to date indicate that the strong and electromagnetic interactions respect charge conjugation, parity, and time reversal invariance separately, but the weak interactions do not⁷.

⁶ The distance scale around 10^{-18} m might properly be called the attoworld, I use *nanonano* to emphasize how far we have come from the atomic scale.

⁷ For a review of tests of conservation laws for discrete spacetime (and other symmetries), see A. Pich and M. Ramsey-Musolf, “Tests of Conservation Laws,” in (Navas et al., 2024).

D. How to Progress?

To advance our understanding, we will need to explore regions of the unknown and to probe unanswered questions. It is the role of all of us, and an obligation of theorists in particular, to try to divine where the secrets are hidden. We must seek out soft spots in our current understanding, especially where the stories we tell are *unprincipled*, by which I mean not (yet) founded on sound principles.

Think, for example of *Supersymmetry*, a beautiful and rich idea. As soon as we try to apply it to our world, we must add a new element, such as R -parity, to ensure a measure of proton stability. Then, if we want to put supersymmetry forward as a solution to naturalness, we must solve the so-called μ problem, to make it relevant on the 1-TeV scale. Generically, supersymmetric theories imply flavor-changing neutral currents that are not observed, so we must find a mechanism that controls those. These issues do not mean that supersymmetry cannot be a valid extension of the standard model, but that we have not yet established principles that will make it so.

Similarly, *Big-Bang Cosmology* is indicated by a wealth of observations. Once we consider the idea of a hot, dense early universe, we must add a concept (usually taken to be inflation) to account for the exquisite flatness and uniformity of the universe and other features. As we learn more of the composition of the universe over time, it seems that we must add dark matter and dark energy, and perhaps other ingredients. All of which is to say that our impressive “standard cosmology” is still a work in progress—which is not a bad thing.

And let us confess that we do not know what, if anything, establishes the particle content and the gauge groups of the standard model of particle physics.

The first set of questions explores our Guiding Principles and Working Hypotheses, for they must not pass unchallenged.

1. Is Lorentz invariance exact⁸?
2. Are Nature’s laws the same at all times and places (accessible to us)?
3. What is the domain of validity of local quantum field theory?
4. What would it mean for causality to be violated?
5. Is \mathcal{CPT} a good symmetry?
6. Are there novel sources of \mathcal{C} , \mathcal{P} , \mathcal{T} , and \mathcal{CP} violation? Can we find evidence for \mathcal{P} and \mathcal{CP} -violating permanent electric dipole moments?

⁸ For compendia of tests of Lorentz invariance, see (Kostelecky and Russell, 2011) and (Liberati, 2013)

7. Do quarks and leptons show signs of compositeness? Are they made of more elementary constituents?
8. Can we find evidence for states with indefinite mass (beyond ordinary unstable resonances), such as unparticles or mass-varying neutrinos?
9. Are there supplemental spacetime dimensions?
10. Do any of the fundamental constants vary with time?

II. BEYOND THE HIGGS-BOSON DISCOVERY

The discovery of the Higgs boson by the ATLAS (Aad *et al.*, 2012) and CMS (Chatrchyan *et al.*, 2012) Collaborations working at the LHC is a landmark for our understanding of Nature and a remarkable achievement of many people—especially the experimenters and accelerator builders whose extended effort made the discovery happen⁹. We can say of the new, unstable particle with mass $M_H = 125.20 \pm 0.11$ GeV (Navas *et al.*, 2024) that the evidence is developing as it would for a textbook Higgs boson of the standard electroweak theory (Aad *et al.*, 2022, 2024; CMS Collaboration, 2025; Salam *et al.*, 2022; Tumasyan *et al.*, 2022). Its observed decays into W^+W^- and ZZ implicate $H(125)$ as an agent of electroweak symmetry breaking¹⁰. The W -boson mass (through the factor $1/M_W^4$) controls β -decay rates and energy production in the Sun. The putative Higgs boson decays to $\gamma\gamma$ at approximately the expected rate. It is dominantly spin-parity $J^P = 0^+$. Evidence for the $Ht\bar{t}$ coupling from the dominant production mechanism, gluon fusion through a top-quark loop, and from the observation of $t\bar{t}H$ production, imply that the Higgs field plays a role in the generation of fermion masses. That implication is supported by the observation of decays into $\tau^+\tau^-$, $b\bar{b}$, and lately $\mu^+\mu^-$, at close to the expected rates.

The LHC experiments are sensitive to the gluon-fusion and vector-boson-fusion production mechanisms, associated production of a Higgs boson plus an electroweak gauge boson, and $Ht\bar{t}$ or Htq production. At the current precision, the observed yields, which measure production cross section times branching ratios, are in line with standard-model expectations. We have found no evidence yet for charged or neutral companions to $H(125)$, and no suggestion of new strong dynamics. Although there is no

⁹ My before-and-after articles, (Quigg, 2009) and (Quigg, 2015), provide some intellectual history, reviews of theoretical contributions, and context.

¹⁰ In a *Gedanken* world lacking a Higgs mechanism, Quantum Chromodynamics breaks the electroweak symmetry $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{\text{em}}$, but induces only a tiny $M_W \approx 28$ MeV (Quigg and Shrock, 2009).

direct measurement of the Higgs-boson width, deft analysis of interference effects plausibly yields a value of the width close to the standard-model expectation.

This already impressive dossier indicates that the prospecting (or search-and-discovery) phase is over, and that we have advanced to a painstaking forensic investigation. What remains to be learned? Ever more quantitative studies within the framework of effective field theory will play a leading role (Dawson *et al.*, 2019). It is important to test whether the Higgs field is also a giver of mass to the lighter quarks and to the electron. Finding all these decay modes at the expected rates is an important branch point for theories of the fermion masses: it could rule against some pictures in which the source of light-fermion masses is quantum effects tied to the heavy fermions. Verifying the standard-model $H \rightarrow \mu^+\mu^-$ coupling raises interest in a $\mu^+\mu^- \rightarrow H$ factory. Some studies indicate that a muon collider’s beam-momentum spread might be fine enough to permit mapping out the H line shape, which would be a most impressive feat.

Establishing the origin of the electron’s mass occupies a special place in our quest to understand the nature of matter. The electron mass sets the scale of atomic energy levels ($\propto m_e c^2 \alpha^2$ in a Coulomb potential). It also governs the Bohr radius, and so the size and integrity of atoms, prerequisites to valence bonding. If I ruled the world, I would award the Nobel Prize in Chemistry to whoever shows that the Higgs field is responsible. This is no easy task: the $H \rightarrow e^+e^-$ branching fraction is only about five parts per billion. FCC-ee enthusiasts express hope that the formation reaction $e^+e^- \rightarrow H$ might be in reach, but we are far from knowing that it could be done.

The mass difference between up and down quarks determines whether protons or neutrons are stable against β -decay. The role of the Higgs field in setting these masses is not yet established.

The LHC experiments access several production channels and many decay modes; they will provide much additional precise information. But it would be advantageous to have a second look through the reaction $e^+e^- \rightarrow HZ$. If a high-luminosity e^+e^- Higgs factory were to drop out of the sky tomorrow, the line of users would be very long. Although that marvelous event will not happen, several ambitious proposals are in view. Their particular assets include the ability to determine absolute branching fractions and to measure directly the total width of the Higgs boson, and graceful access to decay channels such as $H \rightarrow c\bar{c}$. Important complementary information could be gleaned in other operating modes: Tera- Z for both precision tests and discovery, a WW threshold scan, and studies at $t\bar{t}$ threshold. A more comprehensive set of precise measurements, from the LHC, HL-LHC, and future machines, will enable us to make ever more incisive tests of the standard model as a quantum field theory, and to reflect on the implications of $M_H \approx 125$ GeV.

I close this section with a list of questions about elec-

troweak symmetry breaking and the Higgs sector that we must answer to approach a final verdict about how closely $H(125)$ matches the textbook Higgs boson.

11. Is $H(125)$ the only member of its clan? Might there be others—charged or neutral—at higher or lower masses?
12. Does $H(125)$ fully account for electroweak symmetry breaking? Does it match standard-model branching fractions to gauge bosons? In greater depth, are the absolute couplings to W and Z as expected in the standard model?
13. Is the Higgs field the only source of charged fermion masses? Are all the fermion couplings proportional to fermion masses?
14. Can we find evidence for flavor-changing decays of $H(125)$?
15. What can we learn from the rare decays $H \rightarrow \Upsilon\gamma$ and $H \rightarrow J/\psi\gamma$, and the comparison to the $H \rightarrow b\bar{b}, c\bar{c}$ decay rates?
16. What accounts for the immense range of fermion masses?
17. How can we detect $H \rightarrow e^+e^-$?
18. What role does the Higgs field play in generating neutrino masses?
19. Can we establish or tightly constrain decays to new particles? Does $H(125)$ act as a portal to hidden (dark or subliminal) sectors?
20. How convincingly can we measure Γ_H and compare with theory?
21. Are all production rates as expected? Will we uncover any surprising sources of $H(125)$?
22. Do loop-induced decays such as $gg, \gamma\gamma, \gamma Z$ occur at standard-model rates?
23. Can we find any sign of new strong dynamics or (partial) compositeness?
24. Can we establish the HHH trilinear self-coupling?
25. How well can we test the notion that H regulates Higgs–Goldstone scattering, i.e., tames the high-energy behavior of longitudinal WW scattering (Lee *et al.*, 1977)?
26. What is the order of the electroweak phase transition?
27. Does the electroweak vacuum seem stable, or suggest a new physics scale?

28. What conditions must we create to restore $SU(2)_L \otimes U(1)_Y$ symmetry at high energies? How will we know?

The last six entries call for sensitive studies at high energies—almost certainly higher than we have available at the $\sqrt{s} \approx 14$ TeV Large Hadron Collider.

III. MORE INSIGHTS ON THE TEV SCALE & BEYOND?

Before experiments began at the LHC, there was much informed speculation—but no guarantees—about what might be found, beyond the keys to electroweak symmetry breaking. The targets included supersymmetry and technicolor, either of which might have served as a once-and-done solution to enforcing the large hierarchy between the electroweak scale and the unification scale or Planck scale. Did these two potential solutions lead us to view the hierarchy problem and the discipline of “naturalness” too simplistically (Bardeen, 1995; Dine, 2015; Giudice, 2019; Wilson, 2005)?

Our optimism was also encouraged by the observation that a dark-matter candidate in the form of a weakly interacting massive particle would naturally reproduce (what we take to be) the observed relic density, if the WIMP mass lay in the range of a few hundred GeV. We cannot prove that an apparently stable particle produced in the collider environment has a cosmological lifetime, but if we were to produce a candidate we could explore its properties in much greater detail than we imagine doing in direct- or indirect-detection experiments. If our reading of the evidence for dark matter is correct, we will need to assemble evidence from all the experimental approaches. We will examine evidence from the state of the universe in §IX.

No direct sign of new physics beyond the standard model has come to light in laboratory experiments, but searches must continue at the LHC and beyond. The first hints may come from precision measurements—think of the (perhaps resolved) $(g - 2)_\mu$ anomaly or the fading hints of lepton nonuniversality—rather than the direct observation of new phenomena. Studies of rare processes also give us virtual access to energy scales far beyond what we can reach directly today, or perhaps ever. And there is the nagging headache that the vacuum expectation value of the Higgs field, $\langle H \rangle_0$, if taken at face value, contributes a staggeringly large energy density throughout the universe: the equivalent of one Jupiter mass inside a typical person.

These considerations invite further questions.

29. Are there new forces of a novel kind?
30. Can we find evidence of a dark matter candidate (or more than one)?

31. Why is empty space so nearly massless? What is the resolution of the vacuum energy problem?
32. Will “missing energy” events or Kaluza–Klein excitations of the graviton signal the existence of space-time dimensions beyond the familiar $3 + 1$?
33. Can we find clues to the origin of electroweak symmetry breaking? Is there a dynamical origin to the “Higgs potential?”
34. What separates the electroweak scale from higher scales?
35. Might we find indirect evidence for a new family of strongly interacting particles, such as those that are present in supersymmetric extensions of the standard model, by seeing a change in the evolution of the strong coupling “constant,” $1/\alpha_s$, at a higher-energy LHC or a “100-TeV” collider?
36. Might new phenomena appear in collider experiments at macroscopic scales (not close to a primary production vertex)?
37. How can we constrain—or provide evidence for—light dark-matter particles or other denizens of the dark in high-energy colliders or beam-dump experiments?
38. Does the gluon have heavy partners, indicating that QCD is part of a gauge structure richer than $SU(3)_c$?
39. How can we mount telling searches for magnetic monopoles (Acharya *et al.*, 2014) or sphalerons (Ellis and Sakurai, 2016; Grefsrud *et al.*, 2024) or black holes or other exotics?

IV. FLAVOR I: THE PROBLEM OF IDENTITY

For the issue of electroweak symmetry breaking, the central questions were clearly articulated for many years and we identified the 1-TeV scale as the promised land for finding answers. In contrast, we do not have a clear view of how to approach the diverse character of the constituents of matter—the quarks and leptons. To be sure, we have challenged the Cabibbo–Kobayashi–Maskawa (quark-mixing matrix) paradigm and found it an extraordinarily reliable framework in the hadron sector. Neutrino oscillations, discussed in the following Section V, give us a second take on the flavor problem. Much is to be gained if we can make sense of all the flavor issues—including quark mixing and neutrino mixing—together.

It is striking that, of all the parameters of the standard model (there are no fewer than twenty-six, as listed in Table 1), at least twenty pertain to flavor, and we have no idea what determines them, nor at what energy scale

Table 1. Parameters of the Standard Model

3	Coupling parameters, α_s , α_{em} , $\sin^2 \theta_W$
2	Parameters of the Higgs potential
1	Vacuum phase (QCD)
6	Quark masses
3	Quark mixing angles
1	\mathcal{CP} -violating quark phase
3	Charged-lepton masses
3	Neutrino masses
3	Leptonic mixing angles
1	Leptonic \mathcal{CP} -violating phase (+ Majorana phases?)
26 ⁺	Arbitrary parameters

they are set¹¹. In contrast, we can see how the low-energy values of the coupling parameters α_s , α_{em} , $\sin^2 \theta_W$ might be set by evolution from a unified theory at a high scale. If we succeed in establishing that the Higgs mechanism, as embodied in the electroweak theory, explains *how* the masses and mixing angles arise, we still will not know *why* they have the values we observe. We do not know, for example, what makes an electron an electron and a top quark a top quark. That is *physics beyond the standard model*, even in the case of the electron mass!

Flavor physics is rich in unknowns:

40. Have we found the “periodic table” of elementary particles? Is the cartoon in Figure 1 complete¹²?
41. Can we find evidence of right-handed charged-current interactions? Is Nature built on a fundamentally asymmetrical plan, or are the right-handed weak interactions simply too feeble for us to have observed until now, reflecting an underlying symmetry hidden by spontaneous symmetry breaking?
42. What is the relationship of left-handed and right-handed fermions?
43. Are there additional electroweak gauge bosons, beyond W^\pm and Z ?
44. Is charged-current universality exact? What about charged-lepton flavor universality?
45. Where are flavor-changing neutral currents? In the standard model, these are absent at tree level

and highly suppressed by the Glashow–Iliopoulos–Maiani mechanism. They arise generically in proposals for physics beyond the standard model, and need to be controlled. And yet we have made no sightings¹³! Why not?

46. Can we find evidence for charged-lepton flavor violation?
47. How well can we test the standard-model correlation among the branching fractions $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ and $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)$, and the quark-mixing matrix parameter γ ?
48. What do quark–lepton generations mean? Is there a family symmetry?
49. Why are there three families of quarks and leptons?
50. Are there new species of quarks and leptons, perhaps bearing exotic electric or color charges?
51. Is there any link to a dark sector?
52. What will resolve the discrepant values of $|V_{ub}|$ and $|V_{cb}|$ measured in inclusive and exclusive decays?
53. Is the 3×3 (Cabibbo–Kobayashi–Maskawa) quark-mixing matrix unitary?
54. Will flavor observables allow us to establish and diagnose a break in the standard model?
55. How would a high-luminosity e^+e^- collider running at the Z^0 pole enhance the study of heavy flavors?
56. Do flavor parameters *mean* anything at all? If flavor parameters have meaning (beyond engineering information), what is the meta-question¹⁴?

As the most massive constituent (by far!) the top quark is an object of special fascination. Its properties and interactions touch many topics in particle physics.

57. How much can we tighten the m_t – M_W – M_H constraints that test our understanding of electroweak quantum corrections?
58. Does top’s large $Ht\bar{t}$ (Yukawa) coupling imply a special role in electroweak symmetry breaking? How does it influence $t\bar{t}$ dynamics? Does its large mass make top an outlier or, with a Yukawa coupling close to unity, the only normal fermion?

¹¹ For the influence of standard-model parameters on everyday experience, see (Cahn, 1996).

¹² Bear in mind that when Dmitri Mendeleev constructed his table of the chemical elements, the seven noble gases that make up column 18 of the modern table were unknown.

¹³ For example, the rates observed for the rare decays $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $B_s \rightarrow \mu^+ \mu^-$ are consistent with standard-model predictions.

¹⁴ According to the string-landscape point of view, the values might not have any deep significance. See, for example, (Susskind, 2003).

59. How well can we constrain the quark-mixing matrix element V_{tb} in single-top production, or in other observables?
60. How complete is our understanding of $t\bar{t}$ production in QCD: total and differential cross sections, charge asymmetry, spin correlations, etc.? Which observables express entanglement?
61. How well can we constrain the top-quark lifetime? How free is the top quark?
62. Are there $t\bar{t}$ resonances? Might t hadronize a bit in the environment of heavy-ion collisions?
63. Can we find evidence of flavor-changing top decays $t \rightarrow (Z, \gamma)(c, u)?$

V. FLAVOR II: NEUTRINO PHYSICS

The discovery¹⁵ that neutrinos oscillate among the three known species, ν_e, ν_μ, ν_τ —made, incidentally, with neutrinos from natural sources, not accelerators—is one of the great achievements of particle physics in recent decades. Several anomalies remain to be understood, as well. Accelerator-based experiments are playing an essential role in following up the discovery, and neutrino superbeams generated by meson decay at J-PARC and Fermilab will raise proton power to a megawatt or more. The mammoth DUNE and Hyper-Kamiokande detectors as well as new short-baseline experiments are expected to begin operation over the next decade¹⁶.

A Neutrino Factory based on a muon storage ring could provide a second act for the coming generation of accelerator-based neutrino experiments. Beyond its application to oscillation experiments (Denton and Gehrlein, 2025) as an intense source with known composition, an instrument that delivered 10^{20} ν per year could be a highly valuable resource for on-campus experiments. Neutrino interactions on thin targets, polarized targets, or active targets could complement the nucleon-structure programs carried out in electron scattering at Jefferson Lab and elsewhere. (Ball *et al.*, 2000; Bogacz *et al.*, 2022; de Gouvêa and Thompson, 2025) Is such a prospect truly interesting, or merely amazing?

Among the questions we would like to answer are these:

64. In what way is neutrino mass a sign of physics beyond the standard model?
65. Do three light (left-handed) neutrinos suffice? How well can we test that the 3×3 Pontecorvo–Maki–Nakagawa–Sakata (PMNS) neutrino-mixing matrix is unitary?
66. What is the order of levels of the mass eigenstates ν_1, ν_2, ν_3 ? It is known that the ν_e -rich ν_1 is the lighter of the “solar pair,” with the more massive ν_2 . Does the ν_e -poor ν_3 lie above (“normal” mass hierarchy) or below (“inverted” hierarchy) the others?
67. What is the absolute scale of neutrino masses? What might we learn if a conflict arose between cosmological inferences and kinematic determinations from ^3H β -decay (KATRIN) or $^{163}\text{Ho} \rightarrow ^{163}\text{Dy}$ electron capture?
68. Does the see-saw hypothesis explain the smallness of neutrino masses?
69. What is the flavor composition of ν_3 ? Is it richer in ν_μ or ν_τ ¹⁷?
70. Is \mathcal{CP} symmetry violated in neutrino oscillations? To what degree?
71. Will neutrinos give us insight into the matter excess in the universe (through leptogenesis)?
72. Are neutrinos Majorana particles? While this issue is primarily addressed by searches for neutrinoless double- β decay, collider searches for same-sign lepton pairs also speak to it.
73. Are there light sterile neutrinos that lack $\text{SU}(2)_L \otimes \text{U}(1)_Y$ charges? If so, how could they arise?
74. Do neutrinos have nonstandard interactions, beyond those mediated by W^\pm and Z ? If ν_e were found to have novel interactions, how could we follow up?
75. What might we learn from neutrino observatories about astrophysical objects and processes?
76. Are all the neutrinos stable?
77. How can we detect the cosmic neutrino background? If stable, the three neutrino species and their corresponding antineutrinos should each be present in the current universe with a number density of $\approx 56 \text{ cm}^{-3}$ and a temperature of $T_\nu \approx 2 \text{ K} \approx 1.7 \times 10^{-4} \text{ eV}$.

¹⁵ For narratives of the decisive observations involving atmospheric and solar neutrinos, see (Kajita, 2016; McDonald, 2016).

¹⁶ Nonaccelerator experiments that rely on reactors (such as JUNO) or natural sources (such as the neutrino telescopes IceCube and KM3Net plus Hyper-K and DUNE as observatories) enrich the neutrino campaign.

¹⁷ Current neutrino oscillation data suggest that θ_{23} is not exactly 45 degrees, but rather lies either slightly below or slightly above this value. This ambiguity is known as the octant degeneracy.

78. Do neutrinos contribute appreciably to the dark matter component of the universe?
79. What physics opportunities are presented by TeV neutrinos from LHC interaction points or a future muon collider? How might they surpass the $e^\mp p$ studies from HERA at $\sqrt{s} \approx 320$ GeV, equivalent to 50-TeV electrons incident on stationary protons?
80. What opportunities to discover physics beyond the standard model will the next generation of long-baseline neutrino experiments open ([Abi et al., 2021](#))?

VI. DON'T FORGET THE STRONG INTERACTIONS!

Quantum Chromodynamics is the basis of hadronic physics. The fundamental fields of the theory, quarks and gluons, are manifest in proton structure, which is to say in high-resolution, hard-scattering studies, in the exploration of matter at high density, and in lattice calculations. The effective degrees of freedom of the theory show themselves as constituent quarks and Goldstone bosons and in effective field theories, isobar (resonance) models, and nuclei and nuclear structure.

We aspire to compute the properties of hadrons, explain the absence of unseen species, and predict the existence of new varieties of hadrons; explain why quarks and gluons are not observed as free particles; derive the interactions among hadrons as a collective effect of the interactions among constituents.

Collider experiments have stimulated heroic progress in perturbative methods to elaborate the consequences of quantum chromodynamics for scattering experiments. Lattice QCD has broken new ground in understanding the strong-coupling regime. It may provide insights that complement those gleaned from experiment, by giving precise form to our intuitive pictures of hadrons. Modulo the strong \mathcal{CP} problem, QCD could be structurally complete and consistent up to the Planck energy, 1.2×10^{19} GeV—but that doesn't prove it must be. We must prepare for surprises, including quark compositeness ([Question 7](#)) or new kinds of colored matter ([Question 50](#)), as well as deviations from our understanding of QCD itself.

In some contexts, it may seem that the strong interactions are chiefly of interest as backgrounds to searches for “new physics.” That view is far too narrow; among the issues we would like to resolve are these:

81. Why is isospin a good symmetry? What does it mean? Is it accidental?
82. Where is colorspin $SU(6)_{cs} \equiv SU(3)_c \otimes SU(2)_{spin}$ a useful organizing principle?

83. To what degree might we derive the parton model from first-principles quantum chromodynamics for lepton–hadron and hadron–hadron collisions? In what circumstances does factorization hold?
84. What are the limitations of the one-dimensional ∞ -momentum-frame parton model?
85. What can generalized parton distributions (GPDs) and Transverse Momentum Distributions (TMDs) teach us about the static properties and interactions of nucleons and other hadrons?
86. Will high-energy collisions reveal new phenomena within QCD? Can we use machine learning to characterize untriggered or pile-up events beyond the traditional classes of diffraction and short-range order¹⁸?
87. How will correlations among partons in a proton manifest themselves?
88. Under what circumstances is the notion of a compact diquark informative? How fruitful is the analogy between heavy–light ($Q\bar{q}$) mesons and doubly heavy (QQq) baryons?
89. What role do diquarks play in color–flavor locking, color superconductivity, etc.?
90. Might event structures distinguish spatial configurations of partons within protons, such as three separated quarks, quark–diquark, compact triquark, or flux tube? Are there any useful analogies to nucleus–nucleus collisions?
91. How are charge, flavor, etc., distributed within the proton, neutron, and pseudoscalar mesons?
92. Where does nucleon spin reside?
93. How can concepts developed for heavy-ion collisions inform our understanding of pp collisions under extreme conditions?
94. Will any surprises arise in “dead-cone” studies using boosted heavy quarks (t, b, c)?
95. How will the high density of “wee partons” that carry negligible momentum fractions affect pp collisions? How will gluon saturation manifest itself? What will be other consequences?
96. What is the importance of intrinsic heavy flavors? Might the concept extend beyond quarks?

¹⁸ Exploring the dependence on total and heavy-flavor multiplicity and comparing pp , pA , and AA collisions should be revealing. I explored some possibilities in ([Quigg, 2010](#)).

97. Can we develop a comprehensive understanding of hadron structure, including body plans beyond qqq and $q\bar{q}$?
98. How do $6q$ body plans prefigure the emergence of nuclear structure?
99. Do nuclear bound states exist in the chiral limit? What range of quark masses might lead to periodic tables resembling the one we know?
100. What lessons for hadron spectroscopy can we draw from applications of supersymmetry to nuclei?
101. Do observed patterns among $(q\bar{q})$ mesons, (qqq) baryons, tetraquarks, and pentaquarks reflect heavy-quark symmetry mass formulas such as $M(Q_i Q_j \bar{q}_k \bar{q}_\ell) - M(Q_i Q_j q_m) = M(Q_x q_k q_\ell) - M(Q_x \bar{q}_m)$?
102. What is the nature of the Pomeron? What can we learn from events with large rapidity gaps?
103. How are the confinement scale, the scale of chiral symmetry breaking, and the strong coupling parameter Λ_{QCD} related?
104. Do (nearly) pure glueball states exist?
105. What new phenomena occur in the strong interaction at high fermion density? How far can we extend the QCD phase diagram? What new insights might that bring to astrophysical phenomena such as neutron stars?
106. Can we *prove* that quantum chromodynamics confines color¹⁹? Will free quarks (or other colored objects) be observed?
107. What resolves the strong \mathcal{CP} problem?
108. How can we search comprehensively for axions and axion-like particles?

VII. UNIFIED THEORIES

The standard model based on $\text{SU}(3)_c \otimes \text{SU}(2)_L \otimes \text{U}(1)_Y$ gauge symmetry encapsulates much of what we know and describes many observations, but it leaves many things unexplained. Both the success and the incompleteness of the standard model encourage us to look beyond it to a more comprehensive understanding. One attractive way to proceed is by *enlarging the gauge group*, which we

may attempt either by accreting new symmetries or by unifying the symmetries we have already recognized.

Left-right symmetric models, based on gauge symmetries such as $\text{SU}(3)_c \otimes \text{SU}(2)_L \otimes \text{SU}(2)_R \otimes \text{U}(1)_{B-L}$, where B and L stand for Baryon and Lepton numbers, follow the first path. Such models attribute the observed parity violation in the weak interactions to spontaneous symmetry breaking—the $\text{SU}(2)_R$ (right-handed weak isospin) symmetry is broken at a higher scale than the $\text{SU}(2)_L$ —and naturally accommodate Majorana neutrinos. Left-right symmetric theories also open new possibilities, including transitions that induce $n \leftrightarrow \bar{n}$ oscillations and a mechanism for spontaneous \mathcal{CP} violation. More generally, enlarging the gauge group by accretion seeks to add a missing element or to explain additional observations.

Unified theories, on the other hand, seek to find a symmetry group $\mathcal{G} \supset \text{SU}(3)_c \otimes \text{SU}(2)_L \otimes \text{U}(1)_Y$ (usually a simple group, to maximize the predictive power) that contains the known interactions. This approach is motivated by the desire to unify quarks and leptons and to reduce the number of independent coupling constants, the better to understand the relative strengths of the strong, weak, and electromagnetic interactions at laboratory energies. Supersymmetric unified theories bring the added ambitions of incorporating gravity and joining constituents and forces.

Two very potent ideas are at play here. The first is the idea of unification itself: what Feynman calls *amalgamation*, which is the central notion of *generalization and synthesis* that scientific explanation represents. Examples from the history of physics include Maxwell’s joining of electricity and magnetism and light; the atomic hypothesis, which places thermodynamics and statistical mechanics within the realm of Newtonian mechanics; and the links among atomic structure, chemistry, and quantum mechanics. The second is the notion—further developed in §VIII—that the human scale of space and time is not privileged for understanding Nature, and may even be disadvantaged.

These considerations lead us toward a more complete electroweak unification, which is to say a simple $\mathcal{G} \supset \text{SU}(2)_L \otimes \text{U}(1)_Y$; a quark-lepton connection; a “grand” unification of the strong, weak, and electromagnetic interactions, based on a simple group $\mathcal{G} \supset \text{SU}(3)_c \otimes \text{SU}(2)_L \otimes \text{U}(1)_Y$. If we choose the task of grand unification, we must find a group that contains the known interactions and that can accommodate the known fermions—either as one generation plus replicas, or as all three generations at once. The unifying group will surely contain interactions beyond the established ones, and we should be open to the possibility that the fermion representations require the existence of particles yet undiscovered.

109. Quarks and leptons are structureless spin- $\frac{1}{2}$ particles that come in matched sets, as required by

¹⁹ A proof of confinement, in the form of a mass gap in Yang–Mills theory, is one of seven Millennium Problems set by the Clay Mathematics Institute (Jaffe and Witten, 2000).

anomaly cancellation for a renormalizable $SU(2)_L \otimes U(1)_Y$ theory. What is the relationship of quarks to leptons?

110. Is it productive to regard lepton number as the “fourth color?”
111. Why is charge quantized? [$Q_d = \frac{1}{3}Q_e$, $Q_p + Q_e = 0$, $Q_\nu - Q_e = Q_u - Q_d$, $Q_\nu + Q_e + 3Q_u + 3Q_d = 0$.]
112. What is the meaning of electroweak universality, embodied in the matching left-handed doublets of quarks and leptons?
113. Are there new gauge interactions that link quarks with leptons? If so, which quark doublet (or mixture) is matched with which lepton doublet? Are there other sources of lepton- and baryon-number violation?
114. What is the (grand) unifying symmetry?
115. What determines the low-energy gauge symmetries?
116. What are the steps to unification? One more, or multiple?
117. Can the three distinct coupling parameters of the standard model ($\alpha_s, \alpha_{em}, \sin^2 \theta_W$) or (g_s, g, g') be reduced to two or one²⁰? Is perturbation theory a reliable guide to coupling unification? Is there a unification point where all (suitably defined) couplings coincide?
118. How can we define a nonperturbative ultraviolet regulator for chiral gauge theories such as the standard model?
119. What sets the mass scale for the additional gauge bosons in a unified theory? ...for the additional Higgs bosons?
120. Is the proton unstable? If so, how does it decay?
121. Is neutron–antineutron oscillation observable?
122. Are there millicharged particles? Other signs of additional $U(1)$ gauge symmetries?
123. How can we incorporate gravity?
124. Why is gravity so weak?
125. To what distance scale (small or large) does the inverse-square law of gravitation hold?
126. What is the nature of spacetime? Is it emergent? How many dimensions?

²⁰ Here g and g' are respectively the couplings of the $SU(2)_L$ and $U(1)_Y$ interactions.

VIII. WHERE IS THE NEXT IMPORTANT SCALE?

A popular—and productive—way to introduce the grand sweep of science is to show what the world looks like when viewed at various magnifications ([Morrison et al., 1982](#)). Colleagues who spend time at CERN may be familiar with the 200 Swiss Franc note²¹. On close inspection, the security strip reveals an abstract map of the geological ages of Switzerland with a timeline²² of milestones in the evolution of the universe, from the Planck epoch, ($t_{Pl} \approx 10^{-43}$ s)²³, to the current age of the Universe, $13.8 \text{ Gyr} \approx 4.35 \times 10^{17}$ s ([Aghanim et al., 2020](#)).

The timeline’s sixty orders of magnitude do not span the full range of our observations—or our imagination. Perhaps Planck time is a lower limit; I for one find it hard to think rationally about the universe at earlier times. But at the upper end, our observations extend well beyond the current age of the universe. The measured rates²⁴ for double- β decay and double electron capture,

$$T_{1/2}({}^{136}\text{Xe}_{\beta\beta\nu\nu}) \approx 2.2 \times 10^{21} \text{ yr} \text{ (Albert et al., 2014)}$$

$$T_{1/2}({}^{124}\text{Xe}_{\text{ECEC}\nu\nu}) \approx 1.1 \times 10^{22} \text{ yr} \text{ (Aprile et al., 2022)}$$

add a dozen more orders of magnitude. Lower bounds on the electron and proton lifetimes add at least six more. We can contemplate corresponding spans in energy and distance.

The point of this discussion is not merely to be dazzled by large numbers. Within physics, the utility of multiple scales has grown in significance since the quantum-mechanical revolution of the 1920s. To understand why a rock is solid, or why a metal gleams, we must discern its structure on a scale a billion times smaller than the human scale, and we must learn the rules that prevail there²⁵.

²¹ The [CHF200 note](#), issued 22 August 2018, illustrates the theme of scientific expertise, depicting the right-hand rule and a particle collision.

²² The timeline was constructed with the advice of our colleague [Günther Dissertori](#).

²³ Max Planck defined “natural units of measurement” in terms of a few fundamental constants ([Planck, 1899](#)):

$$\begin{aligned} \text{Length: } L_{Pl} &\equiv \sqrt{\hbar G_N / c^3} \approx 1.6 \times 10^{-35} \text{ m} \\ \text{Mass: } M_{Pl} &\equiv \sqrt{\hbar c / G_N} \approx 1.2 \times 10^{19} \text{ GeV}/c^2 \\ \text{Time: } t_{Pl} &\equiv \sqrt{\hbar G_N / c^5} \approx 5.4 \times 10^{-44} \text{ s} \end{aligned}$$

Here $G_N = 6.70883(15) \times 10^{-39} \hbar c (\text{GeV}/c^2)^{-2}$ is Newton’s gravitational constant. A little perspective—the gigantic Planck mass is only about 22 micrograms in macroscopic units.

²⁴ Half-life $T_{1/2}$ is related to the mean life conventional in particle physics by $\tau = T_{1/2} / \ln 2$.

²⁵ A moment’s reflection will reveal parallels throughout science. Studies in biology, cosmology, and ecology range over distances and time spans both exponentially larger and exponentially smaller than the human scale.

Other scales may well be privileged for understanding certain globally important aspects of the universe. For example, a unification scale might be privileged for understanding how it came to be that the fine structure constant $\alpha \approx 1/137$ in the long-wavelength limit and the strong coupling constant $\alpha_s \approx 1/5$ at energies characteristic of the Υ resonances; or why fermion masses exhibit the (seemingly irrational) pattern they do. What has matured recently is our comfort at cruising between different scales of momentum or distance and our understanding—through the renormalization group and effective field theories—of how one scale relates to another.

I believe that the discovery that *the human scale is not preferred* is as important as the discoveries that the human location is not privileged (Copernicus) and that there is no preferred inertial frame (Einstein), and will prove to be as influential. I consider this insight to be The Great Lesson of Twentieth-Century Science.

In the recent past, we had the good fortune to identify the 1-TeV scale as the place to find new physics, specifically to elucidate the nature of electroweak symmetry breaking. We do not (yet!) have a similar target for the next step.

The puzzle of the next important scale is wide-open. Here are a few questions to encourage further thought:

127. At what scale are the Yukawa couplings that determine (we think!) charged-fermion masses set? What about neutrino masses?
128. Can we establish experimental evidence for a unification scale, perhaps $\sim 10^{15-16}$ GeV, at which the strong, weak and electromagnetic interactions are unified? Might there be an intermediate scale for another partial unification?
129. Will new physics appear at $1\times, 10\times, 100\times, \dots$ the electroweak scale? (I hope we don't have to wait until the Planck scale!)

IX. THE COSMIC CONNECTION

A century ago, Cecilia Payne deduced the relative abundance of the elements by studying the spectra of stellar atmospheres (Payne, 1925). By mid-century, as memorably recounted by Steven Weinberg (Weinberg, 1977), astrophysicists had established the essential features of primordial nucleosynthesis. Today, we consider the universe both as a testing ground for our understanding of the laws of Nature, and as a source of challenges to the completeness of our worldview.

In the years since the discovery of the cosmic microwave background (Dicke *et al.*, 1965; Penzias and Wilson, 1965), cosmologists have developed, revised, and refined a standard cosmological model that is impressive

in its simplicity and scope (Olive and Peacock, 2024). The young universe was very hot and dense and has cooled as it expanded to its current state. At very early times, around 10^{-35} s, cosmologists surmise that the universe experienced a period of rapid, roughly exponential, growth called the inflationary epoch.

Within the framework of General Relativity, the post-inflation expansion rate is controlled by the mass-energy content of the universe. At the current epoch, indicated by the subscript 0, the principal components are matter $\Omega_{m0} \approx 0.315$, of which ordinary baryonic matter makes up $\Omega_{b0} \approx 0.05$ and (unidentified) dark matter $\Omega_{DM0} \approx 0.265$, and a “dark energy,” $\Omega_{DE0} \approx 0.685$, that impels the observed accelerating expansion of the universe (Perlmutter *et al.*, 1999; Riess *et al.*, 1998)²⁶. These energy densities are measured with respect to the critical density for which a flat, matter-dominated, expanding universe would cease its expansion asymptotically after an infinite time, $\rho_c \equiv 3H_0^2/8\pi G_N$. Here H_0 is the Hubble expansion parameter measured in the current universe as $\approx 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$.²⁷ The two copious relics of the early universe, photons at 2.73 K and light neutrinos at 1.95 K, contribute negligibly to the current energy density.²⁸

It is convenient to define the dimensionless scale factor, $a = R/R_0$, and to express the normalized energy densities of matter, radiation, and dark/vacuum energy as functions of a . The normalized densities of matter and radiation scale as $\rho_m/\rho_c = \Omega_{m0}/a^3$, and $\rho_\gamma/\rho_c = \Omega_{\gamma0}/a^4$. Provisionally interpreting the dark energy component in terms of a cosmological constant, Λ , we have $\rho_\Lambda/\rho_c = \Omega_{m0}$, a time-independent energy density. In this picture, the universe has been successively dominated by radiation, matter, and dark energy. When radiation and matter prevail, the expansion of the universe slows; when dark energy (here represented by the cosmological constant) prevails, the expansion accelerates.

Seeking an aphorism to express how Newton's third law links gravitation and spacetime, John Wheeler wrote (Wheeler and Ford, 1998), “Spacetime tells matter how to move; matter tells spacetime how to curve.” Following Wheeler's lead, we might say that “Expansion tells the matter and energy content how to evolve, content tells the expansion how to proceed.”

After centuries of observation and study of the universe, we have come to this tantalizingly successful but incomplete standard cosmology. There is much that we do not know, including the complete thermal history (to

²⁶ For an early review of the implications of accelerating expansion, see (Frieman *et al.*, 2008).

²⁷ The Hubble parameter is defined as the logarithmic time derivative of the cosmological scale factor: $H \equiv \dot{R}/R$.

²⁸ Observations indicate that the universe is flat, i.e., without intrinsic curvature. See (Lahav and Liddle, 2024) for the current status of the cosmological parameters.

now) of the universe and the detailed composition of the universe at large. To progress, we must learn to read new strata of the cosmological fossil record, refine the precision of our observations, and develop new ways of looking at the universe. The detection of gravitational radiation enriches multimessenger astronomy and is a powerful addition to the cosmological toolkit. Some timely questions that may lead to further refinements of our cosmological narrative include:

130. To what degree does the cosmological principle—the notion that the universe is homogeneous and isotropic on the largest scales—hold?
131. How can we refine our knowledge of primordial nuclear abundances, with their implications for the constituents of the early universe?
132. How precisely does the cosmic microwave background radiation follow a blackbody distribution?
133. What accounts for the predominance of matter over antimatter in the universe?
134. Is there a single species of dark matter, or many?
135. Are there any alternatives/complements to collisionless dark matter? Does our understanding of gravitation require revision?
136. Does the dark energy density evolve with the cosmic scale factor? Is the dark energy density properly characterized by a cosmological constant Λ or by a dynamical mechanism? If a cosmological constant, what sets the scale? If the dark energy density is not constant ($\propto a^{-3(1+w)}$), what is the dark energy equation of state, w ?
137. Is there a dynamical interplay between cosmological evolution and scalar-field dynamics (perhaps including the Higgs field)?
138. Can we establish the existence of an inflationary epoch? If so, what triggered it?
139. Is the Hubble tension ($H_0^{\text{local}} - H_0^{\text{Planck}} \approx (4-6)\sigma$) real? If so, what does it teach us?
140. Can we probe dark energy in laboratory experiments?
141. How can technologies developed for accelerators advance the search for feebly interacting particles? What might be the role of quantum technologies?

X. FINAL REMARKS

The progress of accelerator science and technology has driven the development of particle physics, while

the imperatives of experimental research have stimulated advances in accelerator research. I am confident that the synergy will continue. The new machines under discussion—circular e^+e^- Higgs factory, e^+e^- linear collider, “100-TeV” hadron collider, electron–hadron collider, muon collider, etc.—have compelling scientific motivations and appear achievable: they will require significant technological progress, but they do not demand cascading miracles²⁹.

Together with the detectors that our experimental colleagues mount to exploit them, they are exemplars of the most amazing achievements of human beings—all the more admirable for being dedicated to the advancement of knowledge. We do not seek to build these machines out of mere habit, but because the scientific frontiers they will open are incredibly exciting. While we do our best to predict what new understanding the next accelerators will yield, the real thrill is that we don’t know what we will find³⁰.

I suspect that every generation has wondered whether the next machine will be the last. Even if timely innovations in the past have pushed the boundaries of what we can do, that anxiety will always be present. The size, complexity, cost, and time scale of the accelerators we would like to attempt next amplify the concern. We will not execute all of these ideas. They will compete for resources, and for our enthusiasm. But it is better to have too many appealing ideas than too few!

The long duration of projects that may not come to fruition means that the particle-physics community has a special responsibility to nurture the careers of accelerator designers and builders. That responsibility falls naturally to the great laboratories, but more university physics and engineering departments should see accelerator science as a fertile intellectual discipline, with lively connections to many other fields ([US Department of Energy, 2009](#)). Breakthroughs and refinements in accelerator technology may find their first—or most consequential—applications far from the frontiers that preoccupy particle physicists.

Now, let us look over the horizon:

142. Imagine the possibilities if wake-field acceleration or some other innovation would allow us to reach gradients of many GeV—even a TeV—per meter. How would we first apply that bit of magic, and what characteristics other than gradient would be required?

²⁹ These machines do lie near the edge of practicality in terms of performance and resources required ([Bloise et al., 2025](#); [Bloom et al., 2022](#)). It is liberating—and important—for us to look beyond projects we can credibly propose today and to dream for the far future. A good model can be found in James Bjorken’s 1982 lectures on storage rings to attain $\sqrt{s} = 1000$ TeV ([Bjorken, 1983](#))!

³⁰ As a recent short subject puts it, “Real researchers don’t know what they’re looking for.” ([Perréaud and Klapisch, 2025](#))

143. If we *could* shrink the dimensions of multi-TeV accelerators, is there any prospect for shrinking the dimensions of detectors that depend on particle interactions with matter?
144. What could we do with a low-emittance, high-intensity muon source?
145. What inventions would it take to accelerate beams of particles with picosecond lifetimes?
146. How can we imagine going far beyond today's capabilities for steering beams?
147. How could we apply high-transmissivity crystal channeling, if we could perfect it?
148. How would optimizations change if we were able to shape superconducting magnet coils out of biplanar graphene or an analogous material?

In the Prologue (§I) to this essay, I expressed the wish that the open questions I pose would stimulate each of us to think anew about how we—as individual researchers and as a worldwide community—can best advance our science. A healthy intellectual ecosystem in which researchers at all stages of their careers may thrive will be built of projects large and small, of long duration and short, addressing questions great and small. We should at all times be prepared to reexamine our priorities. I believe that this is sound strategy for individuals as well as communities.

As you make your own assessments, I encourage you to keep in mind these meta-questions: What deep questions have been with us for so long that they are less prominent in “top-ten” lists (or even top-148-and-counting lists) than they deserve to be? How are we prisoners of conventional thinking, and how can we break out? And the most important question of all: What do we know that is not true?

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