Perspectives and Questions

Meditations on the Future of Particle Physics

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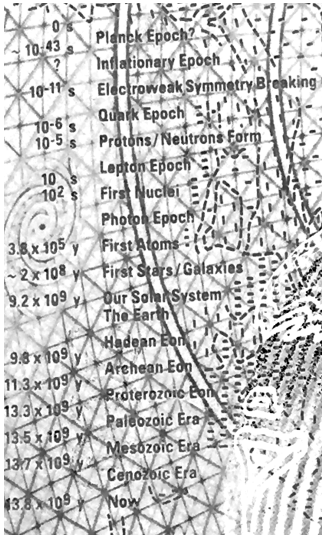
Fermilab

The Ohio State University · January 28, 2020

Supplemental reading: "Dream Machines," arXiv:1808.06036 $\rightsquigarrow$ *RAST* **10**, 3–12 (2019)

CHF200 Note (2018)

many scales



$$t_{\mathrm{Pl}} \equiv \sqrt{\hbar G / c^5}$$

Lifetimes

$^{136}\mathrm{Xe}_{\beta\beta\nu\nu}: 3.2 \times 10^{21}$ yr

$^{124}\mathrm{Xe}_{\mathrm{ECEC}\nu\nu}: 2.6 \times 10^{22}$ yr

$p: > 10^{29-33}$ yr

The importance of the electroweak (1-TeV) scale

EW theory does not predict Higgs-boson mass

Thought experiment: conditional upper bound

W^+W^-, ZZ, HH, HZ satisfy s-wave unitarity,

provided $\boxed{M_H \lesssim (8\pi\sqrt{2}/3G_F)^{1/2} \approx 1 \text{ TeV}}$

If bound is respected, perturbation theory is "everywhere" reliable

If not, weak interactions among $W^\pm, Z, H$ become strong on 1-TeV scale

New phenomena (H *or something else*) are to be found around 1 TeV

$\boxed{\Lambda_{QCD} \sim \text{scale of confinement, chiral symmetry breaking}}$

Where is the next important scale?

(Higher energies needed to measure HHH, verify that H regulates $W_L W_L$)

Planck scale $\sim 1.2 \times 10^{19}$ GeV ($3+1$-d spacetime); $\sim 1.6 \times 10^{-35}$ m

Unification scale $\sim 10^{15-16}$ GeV

1. At what scale are charged-fermion masses set (Yukawa couplings)?
2. At what scale are neutrino masses set?
3. Will new physics appear at $1\times, 10\times, 100\times, \ldots$ EW scale?
4. Might new phenomena appear at macroscopic scales?

The Great Lesson of Twentieth-Century Science

The human scale of space and time is not privileged for understanding Nature, and may even be disadvantaged.

Renormalization group · Effective field theories

Resolution and extent in time and distance

Diversity and scale diversity in experimental undertakings

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.

How to progress?

Explore the regions of the unknown,
the unanswered questions

Try to divine where the secrets are hidden

Seek out soft spots in our current understanding,
especially where the stories we tell are
unprincipled $\equiv$ not founded on sound principles

Supersymmetry: $+$ R-parity $+$ μ problem $+$ tame FCNC $+ \ldots$

Big-Bang Cosmology: $+$ inflation $+$ dark matter $+$ dark energy $+ \ldots$

Particle content, even gauge groups, of the Standard Model

Guiding Principles

Symmetry (via Noether's Theorems) & Hidden Symmetry

Poincaré Invariance

Relativistic Quantum Field Theory

Unitarity, Causality

?? Renormalizability ??

Working hypotheses:

Gauge Symmetry

Pointlike constituents

Minkowski spacetime (for most purposes)

...

Questions about fundamentals

5. Is Lorentz invariance exact?
6. Are nature's laws the same at all times and places (accessible to us)?
7. What is the domain of validity of local field theory?
8. Can causality be violated?
9. Is CPT a good symmetry?
10. Do quarks and leptons show signs of compositeness?
    Are they made of more elementary constituents?
11. Are there supplemental spacetime dimensions?
12. Are there novel sources of C, P, T, CP violation?

On-mass-shell accelerators

Large Hadron Collider Complex at CERN
Fermilab Main Injector
J-PARC Main Ring
BEPC II (IHEP-Beijing)
VEPP-2000 (BINP-Novosibirsk)
SuperKEKB/Belle II (first physics run ended July 2019)
RHIC · CEBAF · Spallation Neutron Source

Intensity improvement projects for ν physics (Fermilab, J-PARC)
[Facility for Antiproton and Ion Research (Darmstadt)]
HL-LHC, promising 3000 fb^{-1} at $\sqrt{s} \to 14$ TeV
European Spallation Source

Virtual accelerators

Japan: ILC, e^+e^- collisions initially at $\sqrt{s} = 250$ GeV

HE-LHC (energy doubler for the LEP/LHC tunnel), pp at $\sqrt{s} \approx 27$ TeV

CLIC-380, e^+e^- collisions initially up to $\sqrt{s} = 380$ GeV

LHeC, to collide a 60-GeV e beam with the LHC p beam

[Electron–Ion Collider, developed at Brookhaven and JLab]

CERN Future Circular Colliders: 100-km tunnel, ee, hh, eh studies

China: CEPC (e^+e^- Higgs factory) in large tunnel $\rightsquigarrow$ SppC

(Muon Accelerator Program & Low EMittance Muon Accelerator)

What LHC has taught us about the Higgs Boson

Evidence is developing as it would for a "standard-model" Higgs boson

Unstable neutral particle with $M_H = 125.10 \pm 0.14$ GeV

Decays to W^+W^-, ZZ implicate H as agent of EWSB

Decay to $\gamma\gamma$ as expected (loop-level) Indirect constraint on Γ_H

Dominant spin-parity $J^P = 0^+$

$Ht\bar{t}$ coupling from gg fusion, $t\bar{t}H$ production link to fermion mass origin

$\tau^+\tau^-$ and $b\bar{b}$ at expected rates

Only third-generation fermion couplings observed; $\mu^+\mu^-$ constrained

reconnaissance $\rightsquigarrow$ search-and-discovery $\rightsquigarrow$ forensic investigation

Questions about EWSB and the Higgs Sector

13. Is $H(125)$ the only member of its clan? Might there be others—charged or neutral—at higher or lower masses?
14. Does $H(125)$ fully account for electroweak symmetry breaking? Does it match standard-model branching fractions to gauge bosons? Are absolute couplings to W and Z as expected in the standard model?
15. Are all production rates as expected? Any surprise sources of $H(125)$?
16. What accounts for the immense range of fermion masses?
17. Is the Higgs field the only source of fermion masses?
    Are fermion couplings proportional to fermion masses? $\mu^+\mu^-$ soon?
    How can we detect $H \to c\bar{c}$? e^+e^-?? (basis of chemistry)
18. What role does the Higgs field play in generating neutrino masses?

More questions about EWSB and the Higgs Sector

19. Can we establish or exclude decays to new particles? Does $H(125)$ act as a portal to hidden sectors? When can we measure Γ_H?
20. Do loop-induced decays ($gg, \gamma\gamma, \gamma Z$) occur at standard-model rates?
21. What can we learn from rare decays ($J/\psi\,\gamma, \Upsilon\,\gamma, \ldots$)?
22. Does the EW vacuum seem stable, or suggest a new physics scale?
23. Can we find signs 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 WW scattering?
26. Is the electroweak phase transition first-order?

See Dawson, Englert, Plehn, arXiv:1808.01324 $\rightsquigarrow$ *Phys. Rep.*

More new physics on the TeV scale and beyond?

Before LHC, much informed speculation—but no guarantees—about what might be found, beyond keys to EWSB.

Many eyes were on supersymmetry or Technicolor to enforce

$M_W \lll$ unification scale or Planck scale.

"WIMP miracle" pointed to the TeV scale for a dark matter candidate.

Some imagined that neutrino mass might be set on the TeV scale.

No direct sign of physics beyond the standard model has come to light.

Might first hints may come from precision measurements?

Have we misconstrued naturalness and the hierarchy problem?

27. Did existence of two once-and-done candidate solutions to the hierarchy problem (SUSY and technicolor) lead us to view the discipline of naturalness too simplistically?

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The Origins of Lattice Gauge Theory

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The final blunder was a claim that scalar elementary particles were unlikely to occur in elementary particle physics at currently measurable energies unless they were associated with some kind of broken symmetry [23]. The claim was that, otherwise, their masses were likely to be far higher than could be detected. The claim was that it would be unnatural for such particles to have masses small enough to be detectable soon. But this claim makes no sense when one becomes familiar with the history of physics. There have been a number of cases where numbers arose that were unexpectedly small or large. An early example was the very large distance to the nearest star as compared to the distance to the Sun, as needed by Copernicus, because otherwise the nearest stars would have exhibited measurable parallax as the Earth moved around the Sun. Within elementary particle physics, one has unexpectedly large ratios of masses, such as the large ratio of the muon mass to the electron mass. There is also the very small value of the weak coupling constant. In the time since my paper was written, another set of unexpectedly small masses was discovered: the neutrino masses. There is also the riddle of dark energy in cosmology, with its implication of possibly an extremely small value for the cosmological constant in Einstein's theory of general relativity.

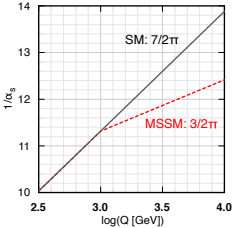
Cf. M. Dine, "Naturalness under Stress"
G. F. Giudice, "The Dawn of the Post-Naturalness Era"

Questions about new physics on the TeV scale and beyond

28. Are there new forces of a novel kind?
29. Can we find evidence of a dark matter candidate?
30. Why is empty space so nearly massless? What is the resolution to the vacuum energy problem?
31. Will "missing energy" events signal the existence of spacetime dimensions beyond the familiar $3 + 1$?
32. Can we probe dark energy in laboratory experiments?
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. Are new phenomena to be found on extended time scales?

More questions about new physics on the TeV scale and beyond

36. Might we find indirect evidence for a new family of strongly interacting particles, such as those that are present in SUSY, by seeing a change in the evolution of $1/\alpha_s(Q^2)$?



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 structure richer than $SU(3)_c$?

Flavor: the problem of identity

39. What makes an electron an electron, a top quark a top quark, . . . ?

We do not have a clear view of how to approach the diverse character of the constituents of matter

CKM paradigm: extraordinarily reliable framework in hadron sector

BUT—many parameters: no clue what determines them, nor at what energy scale they are set

Even if Higgs mechanism explains *how* masses and mixing angles arise, we do not know *why* they have the values we observe

Physics beyond the standard model!

Flavor: the problem of identity (continued)

Parameters of the Standard Model

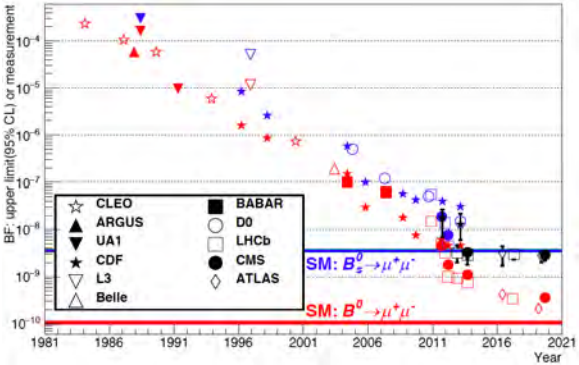
3	Coupling parameters, α_s, α_{em}, $\sin^2\theta_W$
2	Parameters of the Higgs potential
1	Vacuum phase (QCD)
6	Quark masses
3	Quark mixing angles
1	CP-violating phase
3	Charged-lepton masses
3	Neutrino masses
3	Leptonic mixing angles
1	Leptonic CP-violating phase (+ Majorana phases?)
26^+	Arbitrary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

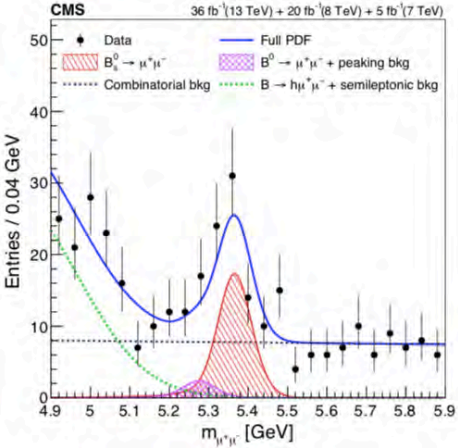
Will we see or diagnose a break in the SM?

Questions concerning the problem of identity

40. 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 hidden symmetry?
41. What is the relationship of left-handed and right-handed fermions?
42. Are there additional electroweak gauge bosons, beyond $W^{\pm}$ and Z?
43. Are there additional kinds of matter?
44. Is charged-current universality exact?
45. What about lepton-flavor universality?
46. Can we find evidence for charged-lepton flavor violation?

$B_{(s,d)} \to \ell^+\ell^-$ search and observation



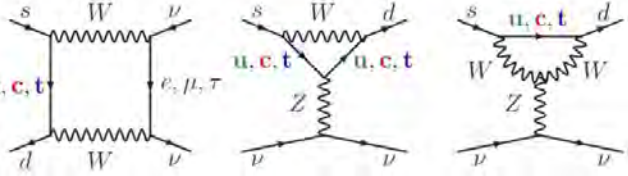


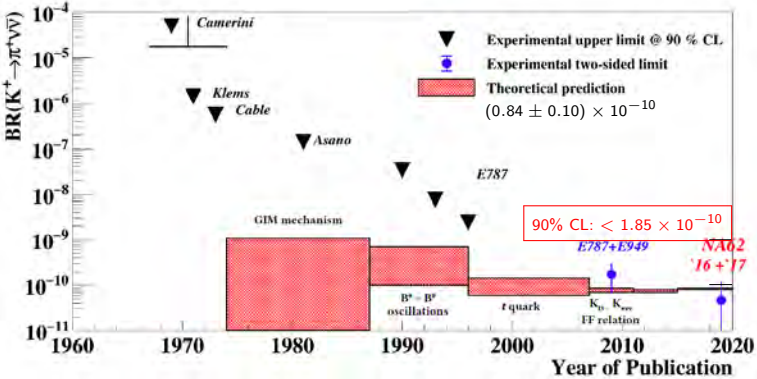
SM: $\mathcal{B}(B_s \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$
$\mathcal{B}(B_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

Recent CMS: $\mathcal{B}(B_s \to \mu^+\mu^-) = [2.9^{+0.7}_{-0.6} \pm 0.2] \times 10^{-9}$

$\tau(B_s \to \mu^+\mu^-) = 1.6^{+0.61}_{-0.44}$ ps, Coming: $B_{(d,s)} \to e^+e^-$ searches

$K^+ \to \pi^+ \nu\bar{\nu}$ search and observation



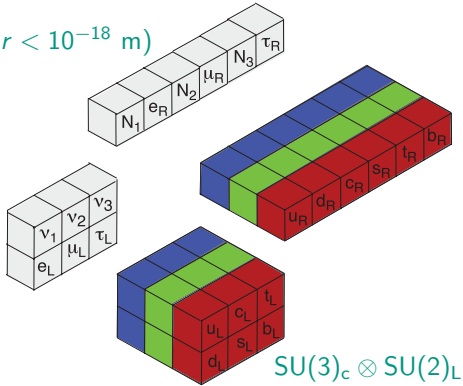


Searches for flavor-changing neutral currents

47. Where are flavor-changing neutral currents in quark transitions? In the standard model, these are absent at tree level and highly suppressed by the Glashow–Iliopouolos–Maiani mechanism. They arise generically in proposals for physics beyond the standard model, and need to be controlled. And yet we have made no sightings!
    Why not? $B_{s,d} \to \mu^+\mu^-$, $K^+ \to \pi^+\nu\bar{\nu}$, ...
48. Can we detect flavor-violating decays $H(125) \to \tau^\pm\mu^\mp$, ...?
49. How well can we test the standard-model correlation among $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$, $\mathcal{B}(B_s \to \mu^+\mu^-)$, and the quark-mixing matrix parameter γ?

Have we found the "periodic table" of elementary particles?

Pointlike spin-1/2 constituents ($r < 10^{-18}$ m)



$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \to SU(3)_c \otimes U(1)_{em}$

50. What do generations mean? Is there a family symmetry?
51. Why are there three families of quarks and leptons? (Is it so?)
52. Are there new species of quarks and leptons? exotic charges?

More questions concerning the problem of identity

53. Is there any link to a dark sector?
54. What will resolve the disparate values of $|V_{ub}|$ and $|V_{cb}|$ measured in inclusive and exclusive decays?
55. Is the 3×3 (CKM) quark-mixing matrix unitary?
56. Can we find evidence for charged-lepton flavor violation?
57. Will we establish and diagnose a break in the SM?
58. Do flavor parameters *mean* anything at all?
    Contrast the landscape perspective.
59. If flavor parameters have meaning (beyond engineering information), what is the meta-question?

The top quark touches many topics in particle physics

60. How much can we tighten the m_t-M_W-M_H constraints?
61. 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 m_t make top an outlier or the only normal fermion?
62. How well can we constrain V_{tb} in single-top production, ...?
63. How complete is our understanding of $t\bar{t}$ production in QCD: total & differential cross sections, charge asymmetry, spin correlations, etc.?
64. What can we learn from "dead-cone" studies using boosted tops?
65. How well can we constrain the top-quark lifetime? How free is t?
66. Are there $t\bar{t}$ resonances? Might t hadronize a bit in AA environment?
67. Can we find evidence of flavor-changing top decays $t \to (Z, \gamma)(c, u)$?

Neutrinos . . .

Neutrinos oscillate among the three known species, ν_e, ν_μ, ν_τ
(discovered with neutrinos from natural sources)

Accelerator-based long-baseline experiments NOνA and T2K
$\rightsquigarrow$ DUNE and Hyper-Kamiokande + new short-baseline experiments

Tritium β-decay experiment KATRIN
experiments that rely on reactors (JUNO)
or natural sources (IceCube and KM3Net)

Puzzling results: LSND–MiniBooNE, "Reactor anomaly"
$\rightsquigarrow$ MicroBooNE

Some outstanding questions about neutrino physics

68. 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 or below the other two (normal or inverted mass ordering)?
69. What is the absolute scale of neutrino masses? KATRIN vs. Cosmo?
70. What is the flavor composition of ν_3? Is it richer in ν_μ or ν_τ?
71. Is CP violated in neutrino oscillations? To what degree?
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. Do three light (left-handed) neutrinos suffice?
74. What is the nature of right-handed neutrinos?

More outstanding questions about neutrino physics

75. Are there light sterile neutrinos? If so, how could they arise?
76. Do neutrinos have nonstandard interactions, beyond those mediated by $W^{\pm}$ and Z?
77. How can we detect the cosmic neutrino background?
    Each species, now: 56 cm^{-3} $\quad T_{\nu} \approx 2\ \mathrm{K} \approx 1.7 \times 10^{-4}\ \mathrm{eV}$
78. Are all the neutrinos stable?
79. Do neutrinos contribute appreciably to the dark matter of the Universe?
80. How is neutrino mass a sign of physics beyond the standard model?
81. Will neutrinos give us insight into the matter excess in the Universe (through leptogenesis)?

Consider a neutrino factory

A Neutrino Factory based on a muon storage ring could provide a very strong second act for the coming generation of accelerator-based neutrino experiments.

Beyond its application to oscillation experiments 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. Gomez-Cadenas & Harris (2002)

Eventually: Multi-TeV muon collider in the LHC tunnel??

Don't forget the strong interactions!

Heroic progress in perturbative and lattice methods

QCD could be complete, up to M_{Planck} (modulo strong CP problem)
. . . but that doesn't prove it must be

Prepare for surprises, such as
(Breakdown of factorization)
Free quarks / unconfined color
New kinds of colored matter
Quark compositeness
Larger color symmetry containing $\text{SU}(3)_c$

Questions pertaining to QCD

82. Why is isospin a good symmetry? What does it mean?
83. Are there new phenomena within QCD? Role for machine learning?
    Multiple production beyond diffraction + short-range order?
    Long-range correlations in y (or η)? Unusual event structures?
84. How will high density of wee partons affect pp collisions?
85. How will the 1-d ∞-momentum frame parton-model break down?
86. How will correlations among partons in a proton manifest themselves?
87. Can we distinguish spatial configurations of partons within protons?
88. What is the importance of intrinsic heavy flavors?
89. Hadron body plans beyond qqq and $q\bar{q}$? $XYZ, qqqQ\bar{Q}, QQ\bar{q}\bar{q}, \ldots$
90. Can we prove that QCD confines color?
91. What resolves the strong CP problem? PQ symmetry $\rightsquigarrow$ axions?

Motivations for unified theories

Neutrality of atoms, balance of electron and proton charges

Quarks and leptons are spin-$\frac{1}{2}$ particles
that come in matched sets
as required by anomaly cancellation
for a renormalizable $\mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{U}(1)_Y$ theory

$\mathrm{SU}(3)_\mathrm{c} \otimes \mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{U}(1)_Y$ couplings tend to converge at high scales

Historical impulse for amalgamation / unification

Questions about unified theories

92. What is the relationship of quarks to leptons?
93. Should we regard lepton number as the "fourth color?"
94. Which quark doublet is matched with which lepton doublet?
95. Are there new gauge interactions that link quarks with leptons? Or other violations of lepton and baryon number?
96. What is the (grand) unifying symmetry?
97. What determines the low-energy gauge symmetries?
98. What are the steps to unification? One more, or multiple?
99. Is perturbation theory a reliable guide to coupling unification?
100. What sets the mass scale for the additional gauge bosons in a unified theory? ...for the additional Higgs bosons?

More questions about unified theories

101. Is the proton unstable? How does it decay?
102. Is neutron–antineutron oscillation observable?
103. Can we detect the magnetic monopoles of unified theories?
104. Are there millicharged particles?
     Other signs of additional U(1) gauge symmetries?
105. How can we incorporate gravity?
106. Why is gravity so weak?
107. To what scale does the inverse-square law of gravitation hold?
108. What is the nature of spacetime?
     Is it emergent?
     How many dimensions?

A word about the astro/cosmo connection

We do not know what the Universe at large is made of

We do not know the complete thermal history of the universe

e.g., $H_0^{\text{local}} - H_0^{\text{Planck}} = 6.6 \pm 1.5$ km/s/Mpc

We have not accounted for the predominance
of matter over antimatter in the observed universe

We do not know what provoked inflation (if it happened)

We do not know why the expansion of the universe is accelerating
i.e., the origin of dark energy or a cosmological constant

Imperatives: Learn to read new strata · Refine precision

Detection of gravitational radiation enriches multimessenger astronomy

Questions about the universe at large

109. To what degree does the cosmological principle hold?
110. How perfect a blackbody is the cosmic microwave background?
111. What is the "dark energy" equation of state? Dynamics or Λ?
     Dark energy evolution in time ($\propto a^{-3(1+w)}$)? If Λ, what sets scale?
112. Is there a dynamical interplay between cosmological evolution and scalar-field "relaxion" dynamics (including H)?
113. Are there any alternatives/complements to collisionless dark matter?
114. How can technologies developed for accelerators advance the search for axions? How can we observe axions, dark photons, . . . ?

G. Bertone & T. M. P. Tait, "A new era in the search for dark matter," *Nature* **562**, 51–56 (2018)

Tabletop precision experiments

Electric dipole moment d_e: CP/T violation

$|d_e| < 1.1 \times 10^{-29}\ e$ cm
ACME Collaboration, ThO

$|d_e| < 1.3 \times 10^{-28}\ e$ cm
NIST, trapped ^{180}Hf ^{19}F$^+$

(SM phases: $d_e < 10^{-38}\ e$ cm)

(How) can we observe electric dipole moments of e, μ, p?

“Tabletop” precision experiments

(Anti)proton magnetic moments: CPT test

$$\mu_{\bar{p}} = -2.792\,847\,344\,1(42)\ \mu_N$$

vs.

$$\mu_p = +2.792\,847\,344\,62(82)\ \mu_N$$

BASE Collaboration @CERN Antiproton Decelerator

Exercise 1.

How should we respond if:

(a) *The DAMA "seasonal variation" cannot be explained away?*
cf. *COSINE-100, ANAIS*

(b) *The LHC Higgs signal strength settles at* $\mu = 1.17 \pm 0.03$*?*
Or if $Ht\bar{t}$ *remains high?*

(c) *The LHCb flavor anomalies persist?*

(d) *The* $(g-2)_\mu$ *anomaly strengthens? Can we measure* $(g-2)_\tau$*?*

(e) *WIMP dark matter searches reach the* ν*-induced background?*

. . . (extra credit for questions you ask and answer)

Exercise 2.

Sketch five "small-scale" (you define) experiments with the potential to change our thinking about particle physics or related fields.

Exercise 3.

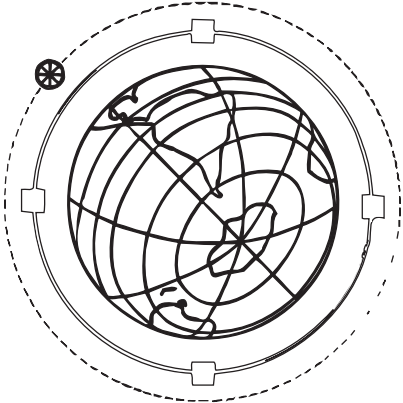
How would *you* assess the scientific potential of

(a) The High-Luminosity LHC?
(b) The High-Energy LHC?
(c) A 100-TeV pp Collider (FCC-hh)?
(d) A 250-GeV ILC?
(e) A circular Higgs factory (FCC-ee or CEPC)?
(f) A 380-GeV CLIC?
(g) A $\mu^+\mu^- \to H$ Higgs factory? *Rubbia, 1908.05664*
(h) LHeC / FCC-eh? (or an electron–ion collider?)
(i) A muon-storage-ring neutrino factory?
(j) A multi-TeV muon collider?
(k) The instrument of your dreams?

Big dreams

Fermi's dream accelerator (1954)

$E_{\text{beam}} = 5\,000$ TeV, $\$1.7 \times 10^{11}$



A THOUSAND TeV IN THE CENTER OF MASS:

INTRODUCTION TO HIGH ENERGY STORAGE RINGS[‡]

J.D. Bjorken

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I. INTRODUCTION

These lectures must begin with an apology. Normally at schools such as this, one expects the lecturer to be an acknowledged expert on the subject matter he is discussing. Here this is not the case. Design of high energy proton storage rings is not exactly my forte. Why am I doing this? There are several reasons, short of mental illness.*

1. I want to learn this subject myself and there is no better way than trying to teach it. And Ferbel didn't stop me.

2. There needs to be a broader knowledge of accelerator physics in the elementary-particle community. Experimentalists at the storage rings find themselves especially closely coupled to their machine and its operation. And theorists can find interesting and challenging questions which lie at the frontier of the very active field of nonlinear mechanics.

3. Straightforward extrapolation of existing acceleration techniques would seem to lead to very large, expensive machines. While we may envision one, perhaps two generations of future accelerators using essentially existing techniques, the question of how to go beyond that is a difficult one. There seems to be a growing feeling that it is not too soon to start to face up to the problem. A look at the alternative--as we do here--can only provide stimulation.

Questions inspired by Big Dreams

115. Suppose we could reach gradients of many GeV—even 1 TeV—per meter. How would we first apply that bit of magic, and what characteristics other than gradient would be required?
116. If we *could* shrink multi-TeV accelerators, how might we shrink detectors that depend on particle interactions with matter?
117. What could we do with a low-emittance, high-intensity muon source?
118. What inventions would it take to accelerate beams of particles with picosecond lifetimes?
119. How can we imagine going far beyond current capabilities for steering beams? How might we apply high-transmissivity crystal channeling?
120. How would optimizations change if we could shape superconducting magnet coils out of biplanar graphene or other miracle substance?

Future of the USA / CERN Relationship

A point-counterpoint in *Physics Today Online* (2012–2013)

Burton Richter, "Should the US join CERN?"

Physicists in the US risk being excluded from the world's preeminent accelerator laboratory if the US does not negotiate a new partnership agreement.

CQ, "American particle physics at CERN and at home"

The US needs a strong, well-funded domestic program in particle physics both to complement major international projects and to contribute to them.

Three final questions (for now)!

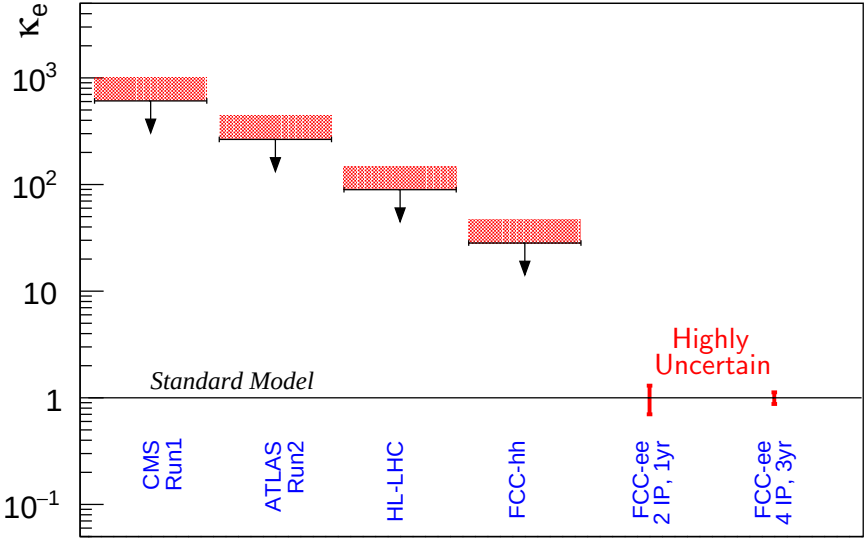
What deep questions have been with us for so long that they are less prominent in "top-ten" lists than they deserve to be?

What do we know that is not true?

How are we prisoners of conventional thinking?

How can we break out?

Constraining $H \to e^+e^-$: $\kappa_e \equiv \zeta_e/\zeta_e^{\mathrm{SM}}$



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