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# Energy Frontier

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2 [Tags, e.g. (Q#1), refer to items on the Big Question list.]

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## 1.1 Energy Frontier

4 Experiments at the “Energy Frontier” make use of high-energy accelerators to produce and study heavy  
5 elementary particles and to search for new ones. The Energy Frontier includes experiments at the Large  
6 Hadron Collider (LHC) at CERN and those at future colliding-beam accelerators proposed for lepton-lepton  
7 and proton-proton collisions.8 The first run of the LHC has closed a nearly half-century old chapter in the story of elementary particle  
9 physics. We have discovered a most unusual new particle with properties very similar to those expected of  
10 the Standard Model Higgs boson. The appearance of this particle—and further confirmation of its identity—  
11 ends one era and opens another. On one hand, the Standard Model of particle physics is complete. We know  
12 all of the particles in this model and how they interact with one another and we have at least a basic idea  
13 of their properties. On the other hand, we also know that the Standard Model is *incomplete* in important  
14 ways. It challenges us to uncover the physics behind its apparently *ad hoc* structure. We are certain that  
15 a host of observed anomalous phenomena and set of confusing conceptual questions have explanations that  
16 require new physics outside the Standard Model.17 The LHC and the CMS, ATLAS, and LHCb detectors have brought to bear impressive capabilities for  
18 exploring for the answers to these new questions. The LHC accelerator is expected to dramatically increase  
19 its ability to deliver beams in the period between now and 2030, increasing its energy by almost a factor  
20 of two and its integrated luminosity by a factor of 100. The detectors will improve their ability to collect  
21 enormous data sets and to discriminate the properties of events with increasing precision. Around the world,  
22 other new accelerators are being considered that will give us additional power in understanding the heaviest  
23 particles of the Standard Model and exploring for new ones. In this report, and in the detailed working  
24 group reports, we trace out the programs of these accelerators and present their most important goals.25 Our successful theory of weak interactions is based on the idea of an underlying symmetry that is spon-  
26 taneously broken. The symmetry of the theory of weak interactions dictates the couplings of the quarks  
27 and leptons to the  $W$  and  $Z$  bosons. Its predictions have been confirmed by high-precision experiments.  
28 However, this symmetry forbids the quarks, leptons, and vector bosons from having mass. To reconcile the  
29 symmetry of weak interactions with the reality of particle masses, one more unexpected element is required.  
30 This is a field or set of fields that couple to all types of particles and form a condensate filling the universe.  
31 The discovery of the Higgs particle establishes that this condensate exists and is the origin of particle masses.32 This is a historic achievement. It is not an end but a beginning. It highlights many questions that the  
33 Standard Model leaves unanswered. These require new, equally bold ideas. Two of these questions give  
34 particularly strong motivations for collider experiments.

35 The Standard Model does not explain the underlying structure of the Higgs field or the reason why it  
36 condenses. It does not explain the size of the condensate, which sets the mass scale of all known elementary  
37 particles. The fact that the observed Higgs particle is a scalar particle makes it very difficult to understand  
38 why this scale is smaller than other basic mass scales of nature such as the Planck scale. There are no  
39 simple models that answer this question. New fundamental structures are needed. The Higgs field must  
40 be a composite of more basic entities, or space-time itself must be extended, through supersymmetry or  
41 through extra dimensions of space. These ideas predict a rich spectrum of new elementary particles, typically  
42 including a larger set of Higgs bosons, with masses of the order of 1 TeV.

43 The Standard Model does not account for the dark matter that makes up most of the matter of the universe.  
44 The simplest and most compelling model of dark matter is that it is composed of a stable, weakly interacting,  
45 massive particle (WIMP) that was produced in the hot early universe. To obtain the observed density  
46 of dark matter, this model requires the energy scale of WIMP interactions to be roughly 1 TeV. If this  
47 model is correct, it may be possible to study dark matter under controlled laboratory conditions in collider  
48 experiments.

49 Thus: *Compelling ideas about fundamental physics predict new particles at the TeV energy scale that should*  
50 *be discoverable in experiments at the LHC and planned future accelerators. These experiments will provide*  
51 *the crucial tests of those ideas. Furthermore, if such particles are discovered, they can be studied in detail in*  
52 *collider experiments to determine their properties and to establish new fundamental laws of nature.*

53 The past successes of particle physics and its current central questions then call for a three-pronged program  
54 of research in collider experiments:

- 55 1. We must study the Higgs boson itself in as much detail as possible, searching for signs of a larger Higgs  
56 sector and the effects of new heavy particles.
- 57 2. We must search for small deviations in the standard model predictions for the couplings of the  $W$  and  
58  $Z$  bosons and the top quark, which are most affected by the physics of mass generation.
- 59 3. We must search directly for new particles with TeV masses that can address these important problems  
60 in fundamental physics.

61 The Energy Frontier study pointed to all three of these approaches as motivations for further experiments  
62 at colliders. The results of the study confirmed that the existing LHC detectors and their planned upgrades,  
63 together with proposed precision lepton collider experiments, will be nimble and sensitive enough to carry  
64 this three-fold campaign forward into the next two decades.

65 The Energy Frontier study was organized into six working groups, each associated with a physics topic. Each  
66 working group was asked to evaluate the future program for its subject both from a high-level perspective  
67 and from the viewpoint of supplying motivation for experiments at a range of proposed accelerators. In the  
68 remainder of this section, we will present the conclusions of these reports, first by physics topic, then by  
69 facility.

70 We begin with the Higgs boson. The bosonic resonance at 125 GeV was discovered at the LHC only one year  
71 ago. Its properties are now known to about the 30% level and, up to this point, its properties are consistent  
72 with those of the Higgs boson of the minimal Standard Model. The couplings of this boson roughly scale  
73 with mass. The specific form of the coupling to the  $Z$  boson indicates that the particle has spin-parity  $0^+$   
74 and that the corresponding field has a nonzero vacuum expectation value.

75 However, we cannot be complacent about the identity and role of this particle (**Q#1**). On one hand, the  
76 idea that a single scalar field is solely responsible for the generation of all particle masses is just a guess

77 and needs explicit verification. On the other hand, models with additional Higgs bosons and related new  
78 particles, and models in which the Higgs boson is composite, are hardly tested. Deviations from the minimal  
79 Higgs boson properties due to new particles with mass  $M$  are suppressed by a factor  $(m_h/M)^2$ , so to the  
80 extent that the LHC has set lower limits on the masses of new particles at many hundreds of GeV, we would  
81 not yet have expected to see the modifications to the Higgs properties caused by those particles.

82 An experimental program to probe the Higgs boson contains several elements. The first is to search for  
83 deviations from the minimal Standard Model expectation that the Higgs boson couples to each particle  
84 species according to its mass. Such deviations are expected in almost all models of new physics. However,  
85 the effects are expected to be small, at the few-percent level if induced by new particles that will not be  
86 directly detected at the LHC. There is a characteristic pattern of deviations for each new physics model.  
87 The High-Luminosity LHC is expected to measure these couplings with accuracies of several percent, varying  
88 from coupling to coupling. Lepton collider experiments have the potential to push these accuracies to the  
89 sub-percent level, which would be needed to discover predicted effects with high significance. Such a program  
90 of precision measurement of Higgs couplings requires a parallel concerted effort in precision theory. It also  
91 requires improvement of our knowledge of crucial input parameters such as  $\alpha_s$  and  $m_b$ , which can be provided  
92 by lattice gauge theory computations. Collider experiments can also probe the nonlinear Higgs field self-  
93 coupling to the 10-20% level, thereby testing the critically important question of the shape of the Higgs  
94 potential.

95 Future experiments on the Higgs particle should also improve our knowledge of its mass and quantum  
96 numbers. The spin of the observed resonance should already be clear from LHC data in this decade. A  
97 more subtle question is whether this particle contains a small admixture of a CP-odd state, signaling CP  
98 violation in the Higgs sector (Q#4) and confirmation of at least one additional Higgs-like particle. We  
99 discuss probes for this effect at various colliders.

100 Finally, it is important to search directly for additional Higgs bosons (Q#9). The LHC can probe to masses  
101 of 1 TeV with model-dependent limits. Lepton colliders can probe more model-independently to masses close  
102 to half of their collision energy.

103 The study of  $W$  and  $Z$  bosons has two aspects, first, the extension of the program of precision electroweak  
104 measurements, and, second, the search for perturbations of the three- and four-vector boson couplings.

105 The minimal Standard Model makes precise predictions for the well-studied precision observables  $M_W$  and  
106  $\sin^2 \theta_w$  (Q#8). At the moment, the observed values are within  $2 \sigma$  of the predictions; the deviations are  
107 consistent with the effects of new particles in a range of new physics models. Better precision in this program  
108 is clearly needed (Q#9). Future experiments will sharpen our knowledge of these quantities and potentially  
109 expose inconsistency with the Standard Model. The LHC, especially in its high-luminosity phase, has the  
110 potential to reduce the error on the  $W$  mass to  $\pm 5$  MeV. This requires a factor 7 decrease in the current  
111 error due to parton distribution functions and is a challenge to QCD researchers. Lepton colliders can make  
112 further improvements, to an error of  $\pm 2.5$  MeV with a dedicated measurement of the  $WW$  threshold. A  
113 linear collider with beam polarization running at the  $Z$  resonance to produce  $10^9$   $Z$  bosons (Giga- $Z$ ) is  
114 expected to reduce the error on  $\sin^2 \theta_w$  by a factor 10. Finally, a circular  $e^+e^-$  collider operating in a 100  
115 km tunnel can potentially push both errors down by another factor 4. All of these precision measurements  
116 and their interpretation push on the inflexible correlations among the Standard Model particles and their  
117 respective forces. Such precision measurements in precision electroweak observables could be discoveries  
118 should the tight constraints within the Standard Model begin to unravel.

119 The second theme of  $W$  and  $Z$  studies is the search for anomalous nonlinear couplings of the vector bosons  
120 (Q#8). Collider experiments at higher energy are sensitive to the three-gauge-boson couplings and for the  
121 first time, to non-standard four-boson interactions, indicative of new interactions in vector boson scattering.

122 Lepton collider experiments have the potential to push current uncertainties on three-boson couplings down  
123 by an order of magnitude, into the region in which new physics effects are predicted in models in which  
124 the Higgs boson is composite. Both hadron and lepton colliders can access vector boson scattering, but the  
125 total center of mass energy available in a scattering process is a crucial factor. The high-luminosity LHC is  
126 sensitive to vector boson or Higgs resonances with masses well above 1 TeV.

127 Quantum Chromodynamics (QCD) is well established as the correct theory of the strong interactions.  
128 Nevertheless, advances in QCD are needed to achieve the goals of future experiments, especially at hadron  
129 colliders. For experiments at hadron colliders, improved knowledge of the parton distribution functions is  
130 needed. This can be achieved with data expected from the LHC on the rapidity distribution of  $W$ ,  $Z$ , and  
131 top quark production. In addition, precision cross section computations, to the NNLO level, are needed for  
132 many 2- and 3-particle production processes, especially those involving the Higgs boson. This will require  
133 advances in the theoretical art of QCD computation. Finally, it is important to push the error on the value  
134 of  $\alpha_s$  below the 0.5% level. Lattice gauge theory seems to be a promising avenue for achieving this.

135 The top quark was discovered at the Fermilab Tevatron and studied there with samples of tens of thousands  
136 of  $t\bar{t}$  pairs. At the LHC, we will study top quarks in samples of billions. At future lepton colliders, we will use  
137 the electroweak couplings of top quarks as a production mode and probe these with polarization observables.  
138 Both methods will transform our knowledge of this quark, whose properties are intimately connected to the  
139 mysteries of flavor and mass generation. To this day, we are surprised at the high mass of this presumably  
140 fundamental particle and its proximity to the value of the Higgs vacuum expectation value.

141 The top quark mass is not only an important puzzle in itself but also is an important input parameter  
142 for particle physics (**Q#2**). The strongest demands on precision in the top quark mass come from the  
143 precision electroweak program, where interpretation of a 5 MeV error in  $m_W$  requires a 500 MeV error on  
144  $m_t$ . This mass must be a theoretically well-defined quantity, convertible to a short-distance parameter such  
145 as the  $\overline{MS}$  mass. There are strategies applicable at the LHC that allow the measurement of a well-defined  
146 top quark mass to this 500 MeV accuracy. At lepton colliders, measurement of the cross section at the top  
147 quark pair production threshold gives the  $\overline{MS}$  mass to 100 MeV, as required for the more accurate precision  
148 electroweak program available at these machines.

149 Top quark couplings will be studied at high accuracy both at hadron and at lepton colliders. New physics from  
150 top quark or Higgs compositeness can create few-percent corrections to the gluon, photon, and, especially,  $Z$   
151 boson couplings. These effects can be observed as corrections to the pair-production cross sections relative to  
152 the predictions of the Standard Model. The top-quark coupling capabilities of a lepton collider is especially  
153 strong, with accuracies possible at the sub-percent level (**Q#1**). The billions of top quarks produced at the  
154 high-luminosity LHC allow very deep studies of rare flavor-changing top decays, to a level that complements  
155 searches at low energy for flavor-changing quark decays (**Q#2**).

156 Models of the Higgs potential and its symmetry breaking typically require new particles that are partners,  
157 in some way, of the top quark (**Q#1**). The LHC, especially in its high-luminosity stage, will have the  
158 capability for deep searches for supersymmetric partners of the top quark, heavy vector-like top quarks that  
159 appear in models with Higgs compositeness, and heavy resonances that decay to  $t\bar{t}$ , which appear in models  
160 with new space dimensions (**Q#9**).

161 High energy colliders can search more generally for new particles with a very broad range of properties  
162 (**Q#9**). These particles are required — and required to have masses near the 1 TeV scale — in models  
163 of electroweak symmetry breaking. Other questions also call for new particles accessible to high energy  
164 colliders. A large class of models of dark matter put the dark matter particle as the lightest particle of a  
165 TeV mass spectroscopy (**Q#5**). Grand unification requires new particles near the TeV scale, including  
166 partners of known particles and perhaps also new vector bosons associated with enhanced gauge symmetry

167 (Q#8). CP violation in the Higgs boson sector is required in models that generate the matter-antimatter  
168 asymmetry at the electroweak phase transition (Q#4). More generally, new particles can bring new sources  
169 of flavor and CP violation that might be reflected in the discovery of new flavor-changing reactions at low  
170 energy (Q#2).

171 The LHC has already, in only its first run, increased the reach and power of searches for new particles  
172 over a broad scope. We expect that this power will increase dramatically in the next decade, as the LHC  
173 experiments acquire  $300 \text{ fb}^{-1}$  of data at 14 TeV. This extension probes deeply into the region expected  
174 for new particles masses in all classes of models of electroweak symmetry breaking — and so, any plan for  
175 high energy physics in the longer term must include the possibility of new particles discovery in this period  
176 and exploitation of this discovery at the facilities that will follow. The high luminosity stage of the LHC,  
177 up to  $3000 \text{ fb}^{-1}$ , will provide a further very significant extension of the search region. This extension is  
178 particularly powerful for states produced through electroweak interactions, for which a factor of 2 increase in  
179 the mass reach is available in some cases. Lepton colliders would bring new and complementary capabilities.  
180 They would carry out model-independent searches for states such as dark matter candidate particles whose  
181 signatures are especially difficult at hadron colliders, and they would uncover new decays modes and measure  
182 branching ratios and quantum numbers for any new particle within their energy range. (Q#5).

183 The physics opportunities described above are reflected as physics motivations for current and future high  
184 energy colliders. Our study considered a wide range of proposed machines. The full report from the Energy  
185 Frontier presents the cases for these machines in some detail.

186 We first point out the opportunity provided by the 14 TeV run of the LHC scheduled for the next decade.  
187 This will provide robust searches for new particles over a broad front, with great promise of the discovery of  
188 the TeV particle spectrum motivated at the beginning of this section.

189 We find the case for the high-luminosity stage of the LHC compelling. This plan to deliver  $3000 \text{ fb}^{-1}$  has  
190 been listed by the European Strategy Study as the highest priority accelerator project in Europe for the  
191 2020's. We find that it will provide a significant additional step in the search for new particles, and that  
192 it will provide other important capabilities. The most important of these is the beginning of the era of  
193 precision Higgs boson measurements, to few-percent precision. It is likely to give the first evidence of the  
194 Higgs boson self-coupling. It will provide a program of precision measurement in the Standard Model that  
195 will dramatically tighten our knowledge of the  $W$  boson and the top quark, giving sensitivity to a variety  
196 of new physics models. We have already noted that the additional luminosity will significantly enhance the  
197 capability of the LHC to search for new heavy particles.

198 We considered the scientific case for the International Linear Collider (ILC). This next-stage lepton collider  
199 has recently completed its Technical Design Report and is judged at Snowmass to be ready for construction.  
200 This facility is named as the highest priority by the Japanese high energy physics community. We find the  
201 case for this machine to be strongly motivated. It will reach sub-percent accuracy in the study of the Higgs  
202 boson, allowing discovery of percent-level effects in the Higgs couplings predicted in new physics models. It  
203 will measure the Higgs width in a model-independent way. It will give the capability to observe all possible  
204 Higgs modes, including decays to Standard Model modes not observable at the LHC, to dark matter, to  
205 other invisible and exotic states. It will extend our knowledge of the top quark and the  $W$  and  $Z$  well beyond  
206 the precision achievable at the LHC, setting up a confrontation with models that include Higgs boson and  
207 top quark composite structure.

208 Many other accelerator facilities have been proposed to the Snowmass study for construction over longer  
209 time scales. They include higher energy linear colliders, circular  $e^+e^-$  colliders, muon colliders, and photon  
210 colliders. We include a detailed discussion of the physics motivations for these facilities in our full report.  
211 There was particular interest in a proton collider of energy 100 TeV (VLHC), which would come close to

212 the capability of covering the full model space for models of “natural” electroweak symmetry breaking and  
213 WIMP dark matter. Our study developed materials and resources to begin a more complete survey of  
214 physics at such a high energy collider. This study, and a parallel development of magnet technology for  
215 higher-energy proton colliders, should be pursued over the next decade.

216 Previous surveys of the prospects for high energy accelerator experiments have spoken in terms of reducing  
217 the space of parameters—couplings, mixings, masses—as if that were the goal. Now more than ever, the  
218 momentum points not toward exclusion, but toward the discovery of new states. Many possible directions  
219 are open and must be pursued.

220 The Higgs boson discovery changes everything. It redefines the research agenda for particle physics, giving  
221 us a set of sharp questions that we cannot ignore. The study of this unusual particle to high precision,  
222 together with high precision studies of the  $W$ ,  $Z$ , and top quark and searches for new states provide us  
223 with complementary routes into the mysterious physics of symmetry breaking. The current LHC detectors  
224 and their planned upgrades are well suited to carry on this program. Future accelerators will bring new  
225 capabilities to pursue it further.

226 High energy colliders provide manifest opportunities to discover new fundamental interactions of broad  
227 consequence. We believe that the US must be a part of these programs of discovery.