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# Energy Frontier

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## 1.1 Energy Frontier

3 Experiments at the “Energy Frontier” make use of high-energy accelerators to produce and study heavy  
4 elementary particles and to search for new ones. The Energy Frontier includes experiments at the Large  
5 Hadron Collider (LHC) at CERN and those at future colliding-beam accelerators proposed for lepton-lepton  
6 and proton-proton collisions.

7 The first run of the LHC has closed a nearly half-century old chapter in the story of elementary particle  
8 physics. We have discovered a most unusual new particle with properties very similar to those expected of  
9 the Standard Model Higgs boson. The appearance of this particle—and further confirmation of its identity—  
10 ends one era and opens another. On one hand, the Standard Model of particle physics is complete. We know  
11 all of the particles in this model and how they interact with one another and we have at least a basic idea  
12 of their properties. On the other hand, we also know that the Standard Model is *incomplete* in important  
13 ways. It challenges us to uncover the physics behind its apparently *ad hoc* structure. We are certain that  
14 a host of observed anomalous phenomena and set of confusing conceptual questions have explanations that  
15 require new physics outside the Standard Model.

16 The LHC and the CMS, ATLAS, and LHCb detectors have brought to bear impressive capabilities for  
17 exploring for the answers to these new questions. The LHC accelerator is expected to dramatically increase  
18 its ability to deliver beams in the period between now and 2030, increasing its energy by almost a factor  
19 of two and its integrated luminosity by a factor of 100. The detectors will improve their ability to collect  
20 enormous data sets and to discriminate the properties of events with increasing precision. Around the world,  
21 other new accelerators are being considered that will give us additional power in understanding the heaviest  
22 particles of the Standard Model and exploring for new ones. In this report, and in the detailed working  
23 group reports, we trace out the programs of these accelerators and present their most important goals.

24 Our successful theory of weak interactions is based on the idea of an underlying symmetry that is spon-  
25 taneously broken. The symmetry of the theory of weak interactions dictates the couplings of the quarks  
26 and leptons to the  $W$  and  $Z$  bosons. Its predictions have been confirmed by high-precision experiments.  
27 However, this symmetry forbids the quarks, leptons, and vector bosons from having mass. To reconcile the  
28 symmetry of weak interactions with the reality of particle masses, one more unexpected element is required.  
29 This is a field or set of fields that couple to all types of particles and form a condensate filling the universe.  
30 The discovery of the Higgs particle establishes that this condensate exists and is the origin of particle masses.

31 This is a historic achievement. It is not an end but a beginning. It highlights many questions that the  
32 Standard Model leaves unanswered. These require new, equally bold ideas. Two of these questions give  
33 particularly strong motivations for collider experiments.

34 The Standard Model does not explain the underlying structure of the Higgs field or the reason why it  
35 condenses. It does not explain the magnitude of the condensate, which sets the mass scale of all known  
36 elementary particles. The fact that the observed Higgs particle is a scalar particle makes it very difficult to

37 understand why this scale is smaller than other basic mass scales of nature such as the Planck scale. There  
38 are no simple models that answer this question. New fundamental structures are needed. The Higgs field  
39 must be a composite of more basic entities, or space-time itself must be extended, through supersymmetry  
40 or through extra dimensions of space. These ideas predict a rich spectrum of new elementary particles,  
41 typically including a larger set of Higgs bosons, with masses at the TeV energy scale.

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

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

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

- 54 1. We must study the Higgs boson itself in as much detail as possible, searching for signs of a larger Higgs  
55 sector and the effects of new heavy particles.
- 56 2. We must search for the imprint of the Higgs boson and its possible partners on the couplings of the  $W$   
57 and  $Z$  bosons and the top quark.
- 58 3. We must search directly for new particles with TeV masses that can address important problems in  
59 fundamental physics.

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

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

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

74 However, we cannot be complacent about the identity and role of this particle. On one hand, the idea that  
75 a single scalar field is solely responsible for the generation of all particle masses is just a guess and needs  
76 explicit verification. On the other hand, models with additional Higgs bosons and related new particles, and  
77 models in which the Higgs boson is composite, are hardly tested. Deviations from the minimal Higgs boson  
78 properties due to new particles with mass  $M$  are suppressed by a factor  $(m_h/M)^2$ , so to the extent that the

79 LHC has set lower limits on the masses of new particles at many hundreds of GeV, we would not yet have  
80 expected to see the modifications to the Higgs properties caused by those particles.

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

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

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

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

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

118 The second theme of  $W$  and  $Z$  studies is the search for anomalous nonlinear couplings of the vector bosons.  
119 Collider experiments at higher energy are sensitive to the three-gauge-boson couplings and for the first time,  
120 to non-standard four-boson interactions, indicative of new interactions in vector boson scattering. Lepton  
121 collider experiments have the potential to push current uncertainties on three-boson couplings down by an  
122 order of magnitude, into the region in which new physics effects are predicted in models in which the Higgs  
123 boson is composite. Both hadron and lepton colliders can access vector boson scattering, but the total center

124 of mass energy available in a scattering process is a crucial factor. The high-luminosity LHC is sensitive to  
125 vector boson or Higgs resonances with masses well above 1 TeV.

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

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

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

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

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

160 High energy colliders can search more generally for new particles with a very broad range of properties.  
161 These particles are required — and required to have masses near the 1 TeV scale — in models of electroweak  
162 symmetry breaking. Other questions also call for new particles accessible to high energy colliders. A  
163 large class of models of dark matter put the dark matter particle as the lightest particle of a TeV mass  
164 spectroscopy. Grand unification requires new particles near the TeV scale, including partners of known  
165 particles and perhaps also new vector bosons associated with enhanced gauge symmetry. CP violation in the  
166 Higgs boson sector is required in models that generate the matter-antimatter asymmetry at the electroweak  
167 phase transition. More generally, new particles can bring new sources of flavor and CP violation that might  
168 be reflected in the discovery of new flavor-changing reactions at low energy.

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

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

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

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

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

206 Many other accelerator facilities have been proposed to the Snowmass study for construction over longer  
207 time scales. They include higher energy linear colliders, circular  $e^+e^-$  colliders, muon colliders, and photon  
208 colliders. We include a detailed discussion of the physics motivations for these facilities in our full report.  
209 There was particular interest in a proton collider of energy 100 TeV (VLHC), which would come close to  
210 the capability of covering the full model space for models of “natural” electroweak symmetry breaking and  
211 WIMP dark matter. Our study developed materials and resources to begin a more complete survey of  
212 physics at such a high energy collider. This study, and a parallel development of magnet technology for  
213 higher-energy proton colliders, should be pursued over the next decade.

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

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

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