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Energy Frontier

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

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

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

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

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

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

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

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

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

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

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

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

We begin with the Higgs boson. The bosonic resonance at 125 GeV was discovered at the LHC only one year ago. Many properties of this particle have now been measured and, up to this point, are consistent with those of the Higgs boson of the minimal Standard Model. The couplings of this boson roughly scale with mass. The specific form of the coupling to the Z boson indicates that the particle has spin-parity 0^+ and that the corresponding field has a nonzero vacuum expectation value.

However, we cannot be complacent about the identity and role of this particle. On one hand, the idea that a single scalar field is solely responsible for the generation of all particle masses is just one possibility among many and needs explicit verification. On the other hand, models with additional Higgs bosons and related new particles, and models in which the Higgs boson is composite, are hardly tested. Deviations from the minimal Higgs boson properties due to new particles with mass M are suppressed by a factor $(m_h/M)^2$, so to the extent that the LHC has set lower limits on the masses of new particles at many hundreds of GeV, we would not yet have expected to see the modifications to the Higgs properties caused by those particles.

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

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

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

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

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

The second theme of W and Z studies is the search for anomalous nonlinear couplings of the vector bosons. Collider experiments at higher energy are sensitive to the three-gauge-boson couplings and for the first time, to non-standard four-boson interactions, indicative of new interactions in vector boson scattering. Lepton collider experiments have the potential to push current uncertainties on three-boson couplings down by an order of magnitude, into the region in which new physics effects are predicted in models in which the Higgs boson is composite. Both hadron and lepton colliders can access vector boson scattering, but the total center of mass energy available in a scattering process is a crucial factor. The high-luminosity LHC is sensitive to vector boson or Higgs resonances with masses well above 1 TeV.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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