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Energy Frontier

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1.1 Introduction

The original goal of elementary particle physics was to understand the nature of the subnuclear strong, electromagnetic, and weak forces. In the late 1960's and early 1970's, specific models for these forces were proposed in the form of Yang-Mills gauge theories, giving a beautiful explanation of all three interactions from a unified point of view. Together, these theories became known as "the Standard Model." Today, we have a great deal of confidence that describing fundamental forces using the Gauge Principle is correct. Through precision experiments involving W and Z bosons carried out over the past twenty-five years, we have tested the Standard Model stringently, and the theory has passed every test. The most recent such experiments included the search for the Higgs boson, required in the Standard Model to generate quark, lepton, and vector boson masses. A year ago, the ATLAS and CMS experiments at the Large Hadron Collider discovered a candidate for this particle which, at the current level of our measurements, has all of the properties predicted in the Standard Model.

This is an historic level of success for theory and experiment: this economical model predicted the existence of fundamental fields, their dynamics, a scalar field responsible for the breaking of a gauge symmetry, and interactions among the particles with precision unmatched in the history of science. It all seems to have come true with remarkable accuracy. And yet, we find the result still unsatisfying. It is typically true in science that revolutionary changes in our understanding lead to a new set of vexing questions. The success of the Standard Model is no different. Though we have answered many questions about the structure of elementary particles, we have a new set of questions about the structure of the Standard Model itself. The discovery of the Higgs boson sharpens these issues and makes them even more mysterious.

There are many phenomena in nature that obviously lie outside of the Standard Model.

- We now know that 85% of the matter in the universe is *dark matter*—neutral, weakly interacting matter composed of one or more species not contained in the Standard Model.
- The cosmic excess of baryons over antibaryons is not explained by the Standard Model. Even though the Standard Model contains all of the necessary ingredients to generate baryon number in the early universe, including baryon number violation, CP violation, and a phase transition in cosmic history, the amount of baryon asymmetry generated is too small by ten orders of magnitude.

- The quantum numbers of the quarks and leptons under the Standard Model gauge symmetry $SU(3) \times SU(2) \times U(1)$ strongly suggests that these symmetry groups are unified into a larger *grand unification* group $SU(5)$ or $SO(10)$; however, our precision knowledge of the strengths of the gauge couplings is inconsistent with this hypothesis.
- The Standard Model cannot account for neutrino masses without the addition of some new particles.
- Further, the pattern of weak interaction mixing among neutrinos is completely different from that observed for quarks.
- The Standard Model does not include the force of gravity or the small but nonzero energy in empty space that gives rise to *dark energy*.

In addition, there is a major theoretical puzzle with the Standard Model. If the Higgs boson is an elementary scalar particle, its mass is sensitive to the masses of any heavier particle to which it couples. It appears to require a cancellation of one part in 10^{32} to explain why the Higgs boson mass is smaller than the Planck mass.

The discovery of the Higgs boson has changed our viewpoint in how we address these questions, for three reasons.

First, the Higgs boson completes the particle spectrum of the Standard Model. We have now discovered all of the Standard Model particles and have measured many of their properties. It is clear now exactly what the model does *not* explain. We have entered a new era in which the verification of the Standard Model takes second place to a search for new, unknown forces and interactions.

Second, one of the key mysteries concerns the Higgs boson itself. The Higgs boson was predicted as a direct consequence of the simplest model of the generation of mass for quarks, leptons, and gauge bosons. For a long time, many particle physicists have expressed discomfort with this model. Now the prediction has become a reality. We have to grapple with it and understand why nature chooses a particle with these properties to do its work.

Third, the Higgs boson itself gives us a new experimental approach. Within the Standard Model, all properties of the Higgs boson are precisely predicted from the value of the Higgs mass. But, as soon as we step outside the Standard Model, the properties of the Higgs boson are hardly constrained by theory. It is compelling to tug on this particle until the Standard Model breaks. We need to apply to the Higgs boson the same scrutiny that we have applied in previous decades to hadron structure, heavy quark system, the W and Z bosons, and top quark. Each study was done at the Energy Frontier machines of its day. This fruitful experimental approach has acquired a new, promising target.

For exploration of the unknown regions outside the Standard Model, we are encouraged that very powerful, experimental tools will be put into play. In the next ten years, the LHC at CERN is expected to almost double its energy and to increase the size of its total event sample from the current 20 fb^{-1} to 400 fb^{-1}. This new capability will put to the test many models that predict new physics beyond the Standard Model and address the unexplained phenomena listed earlier in this section. In the decade after that, the LHC should increase its data set by a further factor, up to 3000 fb^{-1}. Lepton colliders and higher energy hadron colliders are now receiving serious consideration for construction. The mysteries associated with the Higgs boson call for new particles and forces at the TeV energy scale or the attometer distance scale. We now have before us capabilities for a thorough exploration of this region of masses and distances. This is a compelling program; the purpose of this report is to describe it in detail.

The structure of this summary report is as follows: In Section 1.2, we present the arguments for new fundamental interactions at the TeV energy scale and the experimental program at colliders that these arguments motivate. Section 1.3 describes the organization of the Energy Frontier study. In Sections 1.4–1.9, we review in a more specific way the physics issues of collider experiments at the TeV energy scale. We consider in turn the prospects for exploration of new physics through studies of the Higgs boson, the W and Z bosons, Quantum Chromodynamics (QCD), the top quark, and searches for and study of new particles. We present the questions that need to be answered and the methodologies to attack these questions. In Sections 1.10, we present the capabilities of current and proposed colliders in relation to these physics goals. Finally, in Section 1.11, we trace out the implications of two possible scenarios for the discovery of new physics at the LHC. This gives an orthogonal way of appreciating the contributions that might be made by proposed accelerators. Section 1.12 gives our conclusions.

1.2 Importance of the TeV Scale

We have listed a number of motivations for new fundamental interactions beyond the Standard Model (SM). Where will we find them?

Explanations for baryogenesis, higher unification, and dark energy span a bewildering range of mass and distance scale. However, many of the questions we have listed in the previous section relate specifically to the energy scale of hundreds to thousands of GeV that we are exploring today at the Large Hadron Collider. We consider it imperative to understand particles and forces at this “TeV scale” thoroughly, using all of the tools at our disposal. In this section, we will discuss the importance of this regime of energies and short distances.

There is a sharp boundary at which our well-founded knowledge of the fundamental elementary particle interactions runs out. This is related to two different faces that the SM presents, which stand on very different theoretical foundations. On one side are the Yang-Mills gauge interactions, on the other side, the interactions of the Higgs field. The Yang-Mills interactions of quarks, leptons, and vector bosons are tightly determined by their quantum numbers and the strength of the coupling constants of the $SU(3) \times SU(2) \times U(1)$ vector bosons. Precision tests of the SM confirm the structure of these interactions to impressive accuracy [1]. There is little doubt that the SM is a correct representation of nature at the energies we have currently explored.

On the other hand, the interactions of the SM fermions with the Higgs field, and the dynamics of the Higgs field itself, are essentially unconstrained and conceptually even cumbersome. The SM Lagrangian is constructed by writing down the most general terms allowed by gauge symmetry and renormalizability. The resulting potential term contains much of what is perplexing about the SM:

$$V = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 + \sum_{f,f'} \left[g_{\Phi f f'} \bar{f}_L f'_R \Phi + h.c \right] . \tag{1.1}$$

Here Φ is the spin 0 doublet field and λ, $g_{\Phi f f'}$, and μ are parameters. The first two terms give the potential energy of the Φ field. When $\mu^2 < 0$, the neutral $I_3 = -1/2$ component of Φ is singled out and shifted by $\Phi^0 \to (v+h)/\sqrt{2}$, where $v = \sqrt{-\mu^2/\lambda}$ is the vacuum expectation value. At the same time, we diagonalize the matrix $g_{\Phi f f'}$. The last term in brackets then becomes

$$V(ff) = \sum_f \left[\frac{g_{Hff} v}{\sqrt{2}} \bar{f}_L f_R + \frac{g_{Hff}}{\sqrt{2}} \bar{f}_L f_R h + h.c. \right] . \tag{1.2}$$

Every term in (1.1) and (1.2) is of critical importance and each presents special challenges to interpretation and measurement. The first term in (1.2) is the new mass term for fermions, $m_f = g_{Hff} v/\sqrt{2}$. The pattern of the fermion masses is totally unconstrained and proportional to the coupling constant g_{Hff}. The Yukawa fermion-Higgs couplings (the second term of (1.2) and the angles from the diagonalization) contain the origin of mass and mixings among quarks and leptons and CP violation in the weak interactions. Many parameters in this sector are well measured, but there is no theory that explains their origin and structure.

As to the couplings of the Higgs boson itself (the first two terms of 1.1), the picture given in the Standard Model is just one choice among many possibilities. There may be additional Higgs bosons and additional particles of other types forming a larger "Higgs sector," we have almost no information about these particles except that their masses are probably larger than the mass of the known Higgs boson at 125 GeV,

1.2.1 The mystery of Higgs field symmetry breaking

The questions raised at the end of the previous section are brought to a focus by a single underlying question: In order for any SM quark, lepton, or vector boson to obtain mass, the Φ field must condense and the resultant Higgs field fills the universe. Why does this happen?

The SM itself provides no help with this question. It states only that symmetry breaking occurs if $\mu^2 < 0$, which, as a physics explanation, is completely empty. Potentials of the form of (1.1) appear in many condensed matter systems, including superconductors, magnets, and binary alloys. In those systems, it is possible to compute the parameters of the potential from the underlying details of atomic structure and explain why $\mu^2 < 0$. For the SM, if there is an underlying dynamics, its form is unknown. Attempts to compute μ^2 within the SM, even to determine its sign, give disastrous results. The answers for μ^2 depend quadratically on the values of large, unknown mass scales, with competing contributions of opposite sign.

Models are known in which μ^2 can be computed. However, they are not simple extensions of the SM. The barrier to such a model is that the quadratic dependence on unknown scale parameters at very high energy must be removed. However, this dependence is a generic property of models with fundamental scalar fields, associated with the fact that the radiative corrections to the scalar field mass are quadratically divergent. Cures for this problem require that the Higgs particle is non-generic in some important way: Either it is a composite particle or it is related by a symmetry to a fermion or a vector boson. Symmetries of these types can be included consistently only by profound extension of the structure of space-time, to supersymmetry in the fermion case or higher dimensions of space in the vector boson case.

It is remarkable that, in each of these classes of models, easily identified radiative corrections give contributions to μ^2 with a negative sign, predicting the instability of the Higgs field to condensation [2]. In all three cases, these contributions come from quantum corrections due to partners of the top quark that are predicted by the new symmetries.

The idea that the condensation of the Higgs field has a definite mechanical explanation from quantum physics thus has major implications. It requires a new set of particles at the TeV mass scale. The examples above include exotic partners of the top quark that are likely to be produced at the Large Hadron Collider. This TeV particle spectroscopy can also supply explanations for other issues that require physics beyond the SM. TeV particle spectra typically contain a massive neutral particle that can be absolutely stable and thus a candidate for the particle of dark matter [3]. New couplings among the TeV particles potentially provide new sources of CP violation, offering mechanisms for creating the matter-antimatter asymmetry of the universe. Corrections to the SM coupling constants from the new particles can correct the evolution of the SM couplings, allowing the three SM gauge interactions to unify at very short distances [4].

Most importantly, if the explanation for Higgs condensation changes our view of the SM itself — by making SM particles composite or by enlarging the structure of space-time — these changes must be taken into account in any explanation of phenomena that occur at still smaller distances scales, including the generation of neutrino masses, generation of flavor mixing among quarks and leptons, and the unification of the particle physics interactions with gravity.

In short: mechanisms that shed light on the physics behind the otherwise mysterious potential in Eq. 1.1 are needed to directly address the major experimental anomalies of Section 1.1!

1.2.2 Naturalness

So the major question is: Are there any arguments that suggest to us how high in energy must we probe to discover the particles that address the questions of physics beyond the SM? There is no crisp answer. We do have a hint from the principle of "naturalness."

Naturalness is the statement that new particles that generate the μ^2 term in the Higgs potential (1.1) must have masses at the scale of μ^2 itself,

$$\mu^2 \sim (100 \text{ GeV})^2 \ . \tag{1.3}$$

Taken most naively, naturalness implies that new particles associated with the Higgs potential should have been found in the 1990's at the experiments at LEP and the Tevatron. Today, the LHC experiments have carried out much deeper searches for these particles. How much further must we go?

One approach to naturalness looks more critically at the radiative corrections to the μ^2 parameter in the SM. The first-order corrections due to the top quark, the W and Z bosons, and the Higgs boson itself are

$$\delta\mu^2 = -\frac{3g_{Htt}^2}{8\pi^2}\Lambda^2 + \frac{3\alpha_w(3+\tan^2\theta_w)}{4\pi}\Lambda^2 + \frac{\lambda}{8\pi^2}\Lambda^2 \ , \tag{1.4}$$

where g_{Htt} is the same Yukawa coupling as in (1.2), α_w and λ are the couplings of these particles, and θ_w is the weak mixing angle. All three terms are divergent, proportional to Λ^2, where Λ is a mass scale at which the SM is replaced by a more complete underlying theory. Contributions from new particles add to (or subtract from) this expression. To give a well-defined result for μ^2, they must cancel the dependence on Λ. If we allow the new contributions to cancel the SM ones over many decimal places, Λ can be arbitrarily high. However, this might be considered "unnatural." If we assume that at most one significant figure is cancelled, we obtain interesting limits on top, W, and Higgs partners at roughly 2 TeV.

Another approach looks into the computation of μ^2 in specific models [5]. In most supersymmetry (SUSY) models, the parameter called μ_{SUSY} — the Higgsino mass term — contributes to the Higgs parameter μ^2 at the tree level. Forbidding cancellations beyond one significant figure gives for the SUSY parameter $\mu_{SUSY} < 200$ GeV. This is a strong upper bound on the mass of the supersymmetric partner of the Higgs boson, a particle that will be difficult to discover at the LHC. The supersymmetric partners of the top quark and the gluino contribute to the Higgs potential in one-loop and two-loop order, respectively. The corresponding naturalness bounds for one-significant-figure cancellations are

$$m(\widetilde{t}) < 1 \text{ TeV} \ , \qquad m(\widetilde{g}) < 2 \text{ TeV} \ . \tag{1.5}$$

In models in which the Higgs boson is a composite Nambu-Goldstone boson, the formula for the radiative correction to μ from a new fermionic partner T of the top quark has the form

$$\delta\mu^2 = C\frac{3\lambda_t^2}{8\pi^2}m(T)^2 \ , \tag{1.6}$$

where C is a model-dependent constant of order 1. This gives a bound for one-significant-figure cancellation

$$m(T) < 2 \text{ TeV} . \tag{1.7}$$

In all cases, we might have stronger cancellations in the expressions for μ^2. Perhaps these cancellations might eventually find some physics explanation. However, each factor of 10 in mass above the bounds quoted requires cancellations of another *two* significant figures. Even such an imprecise criterion as naturalness probably limits top quark partners to lie below about 10 TeV.

However unsatisfactory these naturalness estimates might be, our interest in these estimates remains very strong. Higgs condensation is the mechanism that generates the whole spectrum of masses of the SM quarks, leptons, and vector bosons. Can it be just an accident? If not, there *must* be a spectrum of new particles at the TeV scale. Even if we cannot predict the value of this scale incisively, the importance of mass scale is clear. We must find these new states.

1.2.3 The mystery of dark matter

Independently of the naturalness argument, there is another, independent argument for new particles at the TeV mass scale. The Standard Model does not account for the dark matter which makes up 85% of the total matter content of the universe. Among the many explanations for dark matter, there is one class that is particularly compelling. This is the model of dark matter as composed of a neutral, weakly interacting, massive particle (WIMP) that was produced in the hot conditions of the early universe. The WIMP model of dark matter is discussed in full detail in the Cosmic Frontier report [6]. What is interesting here is one implication of the model: In order to obtain the observed density of dark matter, the energy scale of the interactions of dark matter must be close to 1 TeV. The TeV mass scale arises as a combination of astrophysical parameters with no obvious relation to the Higgs potential. Is this a coincidence, or a suggestion that models for the Higgs potential also solve the dark matter problem?

Theoretical models with WIMPs typically contain many particles with TeV scale masses. These particles share a common quantum number. They decay to the lightest particle carrying this quantum number, which is then stable for the lifetime of the universe. Whether or not this new spectrum of particles is connected to the Higgs problem, it is important to search for the production of those particles at colliders.

1.2.4 Summary

The ideas reviewed in this section predict a spectrum of new particles at the TeV mass scale. Those particles 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.

A research program in pursuit of new particles with TeV masses consists of three threads:

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.

To the extent that the naturalness or dark matter arguments above are a guide, all three approaches will be accessible at high-energy collider experiments in the near future. In the next section, we will describe the tools that we have available for that search.

1.3 Organization of the Energy Frontier study

In this section, we briefly describe how the Energy Frontier study was organized, in terms of topical working groups and the landscape of proposed accelerators.

1.3.1 Working groups for the study of the Energy Frontier

We divided the study of the TeV energy scale thematically, in terms of probes of this scale using different particles and interactions. The results summarized here constitute the efforts of hundreds of physicists who worked through the winter and spring of 2013 within six working groups. The leaders of these groups are co-authors of this report. The working groups were;

1. The Higgs Boson
2. Electroweak Interactions
3. Quantum Chromodynamics and the Strong Force
4. Understanding the Top Quark
5. The Path Beyond the Standard Model - New Particles, Forces, and Dimensions
6. Flavor Mixing and CP Violation at High Energy

Highlights of each group's work are presented in this order in the following six sections. For each group, the summary of results is followed by their "Message," a quick summary of their conclusions. We follow with the scientific cases to be made for each possible accelerator organized around each physics group's conclusions for that facility.

1.3.2 Accelerators for the Study of the Energy Frontier

In our discussion, specific estimates of the capabilities of the methods that we discussed will be made in the context of proposed accelerator programs discussed at Snowmass. We provide here a brief orientation to these programs. Energies refer to the center of mass energy of colliding beam experiments. For details on the design and current status of these proposals, see the Capabilities Frontier working group report [7].

The baseline for our study is Large Hadron Collider (LHC), the *pp* collider now operating at CERN. The most recent LHC schedule calls for 75-100 fb^{-1} to be collected in a run starting in 2015 with, essentially, the current detectors. Following Long Shutdown 2 in approximately 2019, the Phase 1 detector upgrades will be installed and running will resume at a projected instantaneous luminosity of $2 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. This stage would produce another 300 fb^{-1} of data. Then, in approximately 2023 the luminosity is expected to increase to $5 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. In the Snowmass study, we compared the current results from the LHC, at 7-8 TeV with an integrated luminosity of 20 fb^{-1}, to future data samples at 14 TeV with 300 fb^{-1} and with 3000 fb^{-1}. We refer to the latter program as the high-luminosity LHC or HL-LHC. The projected evolution of the LHC program is described in [8].

Our study considered higher energy *pp* colliders, with energy 33 TeV and 100 TeV. Unless it is indicated otherwise, the event sample assumed is 3000 fb^{-1}. A high-energy upgrade of the LHC at 33 TeV (HE-LHC) is discussed in [9]. Colliders of 100 TeV energy are described in [10, 11]. In the following we will refer to such a collider generically as VLHC.

Our study considered e^+e^- linear colliders, both the International Linear Collider (ILC), covering the energy range 90 GeV–1000 GeV and the Compact Linear Collider (CLIC), covering the energy range 350 GeV–3000 GeV. The ILC is described in [12] and in its technical design report [13]. The TDR/CDR luminosity samples are 1000 fb^{-1} at 1 TeV and scaling linearly with energy. Luminosity upgrades of the baseline ILC using strategies outlined in the TDR, to 2500 fb^{-1} at 1 TeV and similar enhancements at other energies, with long running periods, are described in [14]. CLIC is described in [15] and in its Conceptual Design Report [16].

Our study considered $\mu^+\mu^-$ colliders operating over a range from 125 GeV to 3000 GeV. The luminosity samples assumed were similar to those for linear e^+e^- colliders. The technology of the muon collider is described in [17, 18].

Our study considered a circular e^+e^- collider in a large (80-100 km) tunnel. Accelerator parameters for such a machine are described in [19] in the context of one such proposal, TLEP, for a large tunnel near CERN. In principle, accelerator techniques invented for super-B-factors can produce very high luminosities, in excess of $10^{36}/\mathrm{cm}^2\mathrm{sec}$ at 90 GeV and $10^{35}/\mathrm{cm}^2\mathrm{sec}$ at 250 GeV, summed over 4 detectors. However, there is as yet no complete accelerator design. The luminosities are lower, and/or the power consumption rises dramatically, at 350 GeV and above. In the following, we will refer to such a collider as TLEP (wherever it might be built). We will assume the above luminosities and operation with four detectors.

Two more types of accelerators received more limited attention from our study. Linear e^+e^- colliders can be converted to photon-photon colliders, with roughly 80% of the energy and similar luminosity, by backscattering laser light from the electron beams. Proposals for photon-photon colliders are described in [20, 21]. Colliding the LHC beam with an e^- or e^+ beam from a linear accelerator offers the opportunity of high energy *ep* collisions. This has been studied for a facility at CERN called LHeC, described in [22].

1.4 The Higgs Boson

We begin with the study of the Higgs boson itself. In this section, we will refer to the new boson with mass 125 GeV as “the Higgs boson,” while recognizing that its properties could well be very different from the simplest expectations.

We have already emphasized that the study of the Higgs boson gives a completely new avenue along which to probe the physics of the TeV scale. The picture of the Higgs boson given by the SM is precise. All properties of the Higgs boson can be computed now that the mass of the Higgs boson is known. And yet, this precise theory has no conceptual foundation. Current experiments exclude deviations from the SM at the 100% level, but surprises at the 30%, 10%, or 3% level are all possible in different highly plausible models. The nature of the Higgs boson is a central part of the mystery of TeV physics. New physics responsible for Higgs condensation must couple to the Higgs boson and affect its properties at some level.

Full details of the future program on the Higgs boson, and more precise statements of the uncertainty estimates given below, can be found in the Higgs Boson working group report [23].

1.4.1 Higgs boson couplings

The most direct question to ask about the new boson is that of whether it is in fact the sole source of mass for all quarks, leptons, and gauge bosons. For this to be true, the couplings of the Higgs boson to the various species of SM particles must follow a definite pattern. The couplings of the particle to fermions and vector bosons must be, from Eq. 1.2,

$$g_{Hf\bar{f},SM} = \frac{1}{\sqrt{2}}\frac{m_f}{v} \ , \qquad g_{HVV,SM} = \frac{1}{2}\frac{m_V^2}{v^2} \ , \tag{1.8}$$

where v is the value of the SM Higgs condensate, equal to 246 GeV. (More properly, this is the leading-order prediction for a coupling defined to all orders with all three particles on shell.) These couplings have a simple pattern that should be tested for as many SM species as possible. In the following discussion, we define the scale factors

$$\kappa_A = g_{HA\bar{A}}/(SM) \ , \tag{1.9}$$

where (SM) denotes the SM prediction.

The Higgs boson also couples to pairs of vector bosons gg, $\gamma\gamma$, and γZ through loop diagrams. In the SM, these couplings are dominated by contributions from W boson and top quark loops. In more general theories, these couplings can also receive contributions from radiative corrections with new particles in loops. We will denote ratios of the on-shell couplings to the SM predictions by κ_g, κ_γ, $\kappa_{\gamma Z}$.

Corrections to the predictions (1.8) can appear at many levels. If there are multiple Higgs fields that mix into the observed boson, the κ_A will contain cosines of the mixing angles. These can be as large as the data permit. Radiative corrections to due to loop effects of new particles are expected to be below the 10% level.

Corrections to the Higgs couplings are also affected by the Decoupling Theorem [24]: If all new particles have masses greater than M, we can integrate out these particles. The result is the SM, in which the properties of the Higgs boson are predicted precisely in terms of its mass. The corrections to the SM values are generated, in this way of constructing the formalism, by effective higher-dimension operators added to the SM. These corrections will then be at most of the order of m_h^2/M^2. The Decoupling Theorem implies an apparently paradoxical but nevertheless important conclusion: In a model in which the Higgs sector is very complex but all new particles in it are heavier than 500 GeV, corrections to the Higgs boson properties are at most at the 5-10% level. We are likely to be in this situation, in which the picture of the Higgs boson may be very different from that in the SM but, since the other particles in the sector are heavy, it is difficult to conclude this except by precision measurement.

Typical sizes of Higgs boson coupling modifications are shown in Table 1-1. More details of these estimates are given in [23].

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

Table 1-1. *Generic size of Higgs coupling modifications from the Standard Model values when all new particles are $M \sim 1$ TeV and mixing angles satisfy precision electroweak fits.*

Tests of the values of the Higgs couplings relative to the SM must take account of the theoretical uncertainty in the comparison to the SM predictions. A potentially observable quantity is the partial decay width $\Gamma(h \to A\bar{A})$, related to κ_A by

$$\kappa_A^2 = \Gamma(h \to A\bar{A})/(SM) \; . \tag{1.10}$$

Currently, some of these quantities have large uncertainty in their evaluation in the SM. The uncertainty in the partial width $\Gamma(h \to b\bar{b})$, which accounts for more than half of the SM Higgs total width, is quoted as 6% [25]. A concerted program is required to bring the uncertainties in the SM predictions below 1%. This requires complete evaluation of the 2-loop electroweak corrections to the partial widths. It also requires improvement of the uncertainty in the crucial input parameters α_s, m_b, and m_c. Lattice gauge theory promises to reduce the errors on all three quantities to the required levels [26]. Further methods for improvement in our knowledge of α_s are discussed in Section 1.6.

There are only a few cases in which the partial widths $\Gamma(h \to A\bar{A})$ can be measured directly. More often, the Higgs decay partial widths are measured from the rates of reactions that involve the Higgs boson in an intermediate state. An example is the rate of $\gamma\gamma$ production through gg fusion at the LHC. The rate of this process is proportional to

$$\sigma(gg \to h) \cdot BR(h \to \gamma\gamma) \sim \frac{\Gamma(h \to gg)\Gamma(h \to \gamma\gamma)}{\Gamma_T(h)} \; , \tag{1.11}$$

where $\Gamma_T(h)$ is the total Higgs boson width. In terms of the κ_A quantities, the measured rates are proportional to

$$\sigma(A\bar{A} \to h)BR(h \to B\bar{B})/(SM) = \frac{\kappa_A^2 \kappa_B^2}{\sum_C \kappa_C^2 BR_{SM}(h \to C\bar{C})} \; . \tag{1.12}$$

The SM prediction for the total width of the Higgs boson is 4 MeV, a value too small to be measured directly except at a muon collider where the Higgs boson can be produced as a resonance. At all other cases of hadron and lepton colliders, the total width must be determined by a fit to the collection of measured rates. Such fits entail some model-dependence to control the size of modes of Higgs decay that are not directly observed.

The report [23] compares the capabilities of the LHC and a variety of lepton colliders to extract the values of the Higgs boson couplings. At the LHC, the total number of Higgs bosons produced is very high, over 170 million per experiment for integrated luminosity of 3000 fb^{-1}. However, Higgs boson production at the LHC is accompanied by very high backgrounds. The extraction of couplings from cross sections is complicated by significant QCD uncertainties in the calculation of cross sections, currently about 12% for gluon fusion and 3% for vector boson fusion.

At electron colliders, the Higgs boson is produced in the relatively background-free interactions $\ell^+\ell^- \to Zh$ and $\ell^+\ell^- \to \nu\bar{\nu}h$ (vector boson fusion). The measurements of rates are dominated by statistical errors, but

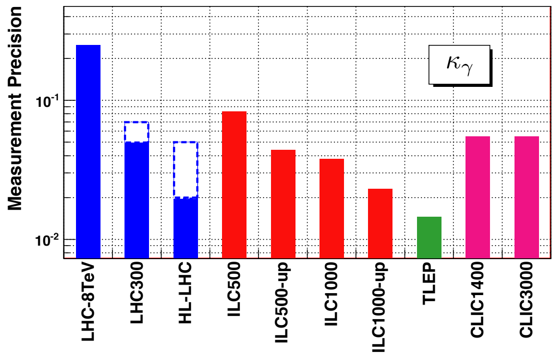

Figure 1-1. *Measurement precision on κ_γ at different facilities.*

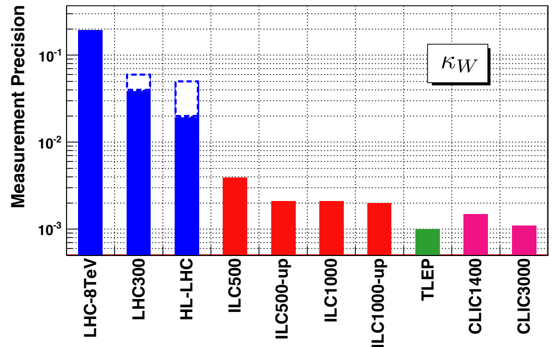

Figure 1-2. *Measurement precision on κ_W at different facilities.*

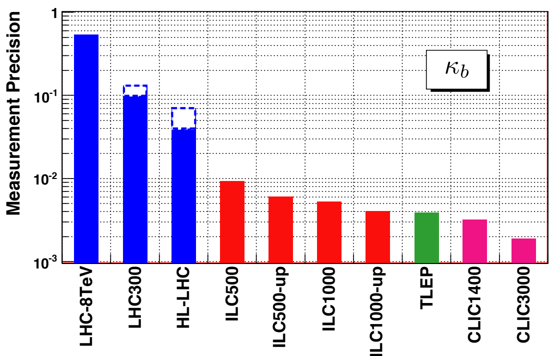

Figure 1-3. *Measurement precision on κ_b at different facilities.*

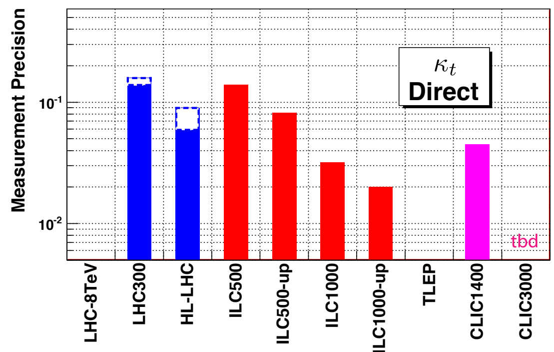

Figure 1-4. *Measurement precision on κ_t at different facilities.*

the statistics are limited. The Zh reaction offers tagged Higgs bosons, giving the possibility of observing decay modes not accessible at the LHC (such as decay to $c\bar{c}$), and invisible and exotic modes of Higgs decay. The total cross section for the two e^+e^- reactions are directly proportional to $\Gamma(h \to ZZ^*)$ and $\Gamma(h \to WW^*)$, respectively, without dependence on the $\Gamma_T(h)$. This allows lepton collider measurements to determine $\Gamma_T(h)$ and all individual partial decay widths by fitting of Higgs rates without any model assumptions.

Figures 1-1 through 1-4 show the comparison for a variety of accelerator programs of the projected uncertainty of measurement of the Higgs couplings. The first three figures show the uncertainties in the couplings to $\gamma\gamma$, WW, and $b\bar{b}$ from a 6-parameter fit appropriate to the analysis of LHC results, described in [23]. Although the model-independent results from lepton colliders do not require such a fit, the same fit is used for those cases to facilitate comparisons to the hadron colliders. The fourth figure shows the projected error on the Higgs coupling to $t\bar{t}$ from experiments directly sensitive to this quantity. The facilities considered are the LHC at its current stage, after 300 fb^{-1}, and after 3000 fb^{-1}, the ILC up to 500 GeV and up to 1000 GeV, the TLEP circular e^+e^- collider and the CLIC linear collider operating at 1400 and 3000 GeV. For LHC, the upper and lower estimates reflect a pessimistic scenario, in which systematic errors not evaluated from data do not improve, and an optimistic scenario in which theory errors are halved and all experimental systematic errors decrease as the square root of the integrated luminosity, For the ILC stages, the first error bar corresponds to the baseline event samples considered in the ILC TDR, while the second includes, more optimistically, a set of luminosity upgrades described in the TDR. Full details, and tables of the numerical results of the fits, can be found in [23]. The figures show, first, that the LHC, especially in its high luminosity phase, will measure Higgs couplings with impressively high precision. However, the discovery of perturbations of the Higgs boson couplings at the level shown in Table 1-1, at 3–5σ significance, will require both the much lower level of systematic errors available at a lepton collider and very large event samples to reduce the statistical errors.

1.4.2 Higgs boson self-coupling

A particularly important coupling of the Higgs boson is the Higgs self-coupling, λ in (1.1), which determines the shape of the Higgs potential. In the SM, after Higgs condensation, there is a triple Higgs boson coupling proportional to $\sqrt{\lambda}$, given alternatively by

$$\lambda_{hhh} = \frac{3m_h^2}{v^2} \ . \tag{1.13}$$

This coupling can be extracted from the rate for double Higgs production, for example $pp \to hh + X$ or $e^+e^- \to \nu\bar{\nu}hh$.

Theoretical models with extended Higgs sectors or Higgs compositeness can predict deviations of the triple Higgs coupling of 20% relative to the SM expectation. These are larger effects that those expected in the Higgs couplings to fermions and vector bosons, but the measurement is also much more difficult. The cross sections at lepton colliders is at the fb level. At the LHC, the cross sections are larger, but the use of rare decay modes, including $h \to \gamma\gamma$, is considered to reduce background. Studies using only a few decay modes indicate a precision of 50% in the Higgs self-coupling measurement per detector; combining the results of the detectors, first evidence of the Higgs self-coupling would be likely from the HL-LHC program. The projected uncertainties on the Higgs self-coupling are 13% in a long-term program at the ILC at 1 TeV or 10% for CLIC at 3 TeV. The double Higgs production cross section increases rapidly with energy. Measurements at a 100 TeV pp collider are estimated to reach an uncertainty of 8%.

1.4.3 Higgs boson spin and CP

A crucial test of the identification of the 125 GeV resonance with the Higgs boson is the measurement of its spin and parity. This issue is almost settled with the current data from the LHC. The fact that the resonance decays to $\gamma\gamma$ implies that it has integer spin and cannot have spin 1. The distribution of the four leptons in $h \to ZZ^*$ decays already strongly favors the 0^+ over the 0^- spin-parity hypothesis and excludes the simplest forms of spin 2 coupling [27, 28]. This issue should be decided with the next LHC data set.

However, there is a more subtle issue associate with the Higgs boson CP. If there are multiple Higgs bosons and CP violation in the Higgs sector, the Higgs boson at 125 GeV can contain an admixture of CP scalar states. CP violation in the Higgs sector has major implications. Most importantly, it can provide the new source of CP violation outside the SM that allows the matter-antimatter asymmetry of the universe to be generated at the electroweak phase transition.

CP violation in the Higgs sector can be reflected both in production and decay of the Higgs boson. The most accurate tests are available in the study of the 4-lepton final state in $h \to ZZ^*$. The scalar Higgs couplings to massive vector bosons appear at tree level, while pseudoscalar couplings are expected to appear only in loop corrections. CP-violating terms in this vertex are therefore masked by the large CP-conserving tree level amplitude. However, measurements in vector boson fusion and in associated production are potentially accurate enough to overcome the loop suppression. Lepton colliders can search for CP violation in the decay $h \to \tau^+\tau^-$ and in the production process $\ell^+\ell^- \to t\bar{t}h$. The first process can reach 1% precision in the measurement of a cross-section fraction corresponding to the CP-odd decay amplitude.

Photon-photon colliders, which produce the Higgs boson as a resonance, can use initial-state polarization to search for CP-violating terms in the Higgs boson coupling to $\gamma\gamma$, which has no tree-level contributions. Similarly, a muon collider can probe for CP-violating contributions to the Higgs boson coupling to $\mu^+\mu^-$ if the accelerator provides transverse beam polarization.

1.4.4 Higgs boson mass and width

The Higgs boson mass is currently known from the LHC experiments to better than 600 MeV. This accuracy is already sufficient for the uncertainty in the Higgs mass not to be significant in precision electroweak tests. The most important influence of a highly accurate Higgs mass within the SM comes in the evaluation of the predictions for the Higgs couplings to WW and ZZ, for which one boson must be off the mass shell. A 100 MeV error in the Higgs mass corresponds to a 0.5% uncertainty in κ_W. We expect that the error in the Higgs mass can be decreased to 100 MeV and to 50 MeV, respectively, for the LHC programs with 300 fb^{-1} and 3000 fb^{-1} by using the $\gamma\gamma$, ZZ^*, and $\mu^+\mu^-$ modes in which the Higgs boson can be fully reconstructed. A lepton collider studying the Higgs boson in the Zh production mode would push this uncertainty down further, to about 35 MeV for linear colliders and 7 MeV for a very high luminosity program at a circular collider.

Predictions of the Higgs mass in models of new physics might provide further motivation for measuring the Higgs mass accurately. An example of such a model is the Minimal Supersymmetric Standard Model (MSSM). To evaluate the prediction to an accuracy of 100 MeV, however, the masses of the top squarks must be known, and the top quark mass must be known to 100 MeV.

We have noted already that lepton colliders offer the possibility of a model-independent determination of the Higgs boson total width. Because the couplings of the Higgs boson to ZZ and WW appear both in the expressions for measurable total cross sections and branching ratios, these couplings can be eliminated to evaluate the total width through the relations

$$\Gamma_T(h) \sim \sigma(\ell^+\ell^- \to Zh)/BR(h \to ZZ^*) \sim \sigma(\ell^+\ell^- \to \nu\bar{\nu}h, h \to b\bar{b})/BR(h \to WW^*)BR(h \to b\bar{b}) \quad (1.14)$$

This gives the Higgs boson width to 3% for a long-term program at the ILC and to 0.6% for a high luminosity program at a circular collider with multiple detectors. These uncertainties are reflected in the coupling uncertainties quoted in Section 1.4.1.

A muon collider would have the capability of observing the Higgs boson as a narrow resonance. For the projected beam energy resolution of 4×10^{-5}, the mass of the Higgs boson would be measured to 0.06 MeV and the width would be measured directly in the s-channel to a precision of 4% [18]

1.4.5 Searches for additional Higgs bosons

There are strong motivations for expecting the existence of additional Higgs particles. These motivations begin with the overall mysteries of the physics of Higgs condensation and the question of whether the Higgs boson is the only particle of the SM whose quantum numbers do not come in multiples. Beyond this, virtually

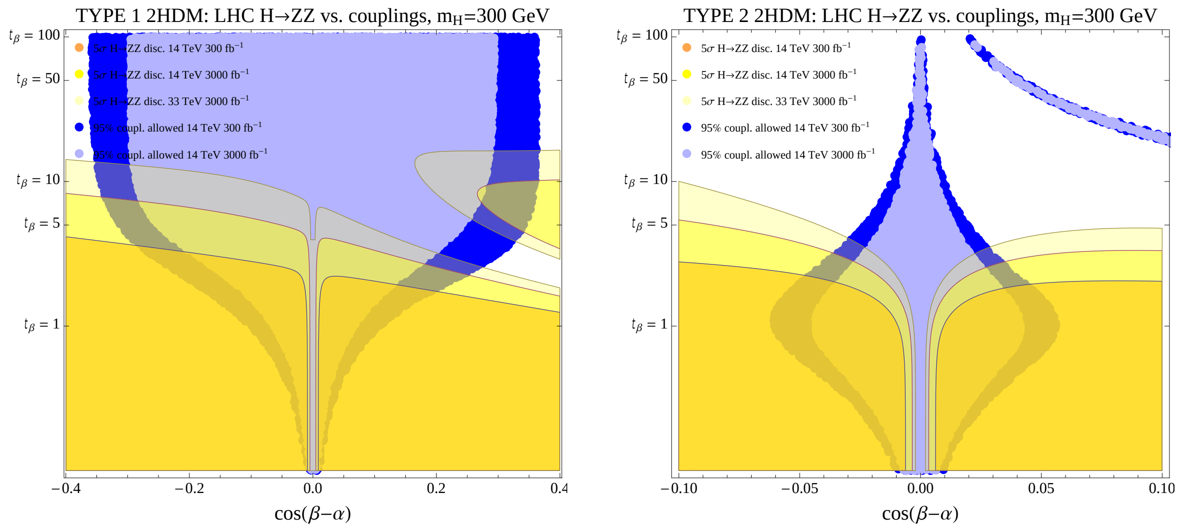

Figure 1-5. *5σ discovery reach for a 300 GeV H decaying via $H \to ZZ \to 4\ell$, for the Type I and Type II two-Higgs-doublet models, shown in the left and right panels, respectively. The yellow regions show the 5 σ reach in direct searches at the LHC. The successive larger regions correspond to the LHC at 300 fb^{-1} and 3000 fb^{-1} and a 33 TeV pp collider with 3000 fb^{-1}. The blue regions show the regions allowed at 95% CL by precision Higgs coupling measurements; the darker and lighter regions correspond to the LHC with 300 fb^{-1} and 3000 fb^{-1} [29].*

all models of new physics to explain the Higgs potential contain additional Higgs doublet fields. These fields are required in supersymmetric models in order for Higgs fields give mass to both the up-type and the down-type quarks. In models with new space dimensions, additional Higgs fields arise as the Kaluza-Klein excitations of the fundamental Higgs doublet. Each additional Higgs doublet gives rise to four new particles, CP-even and CP-odd neutral scalars H and A, and a charged pair $H^{\pm}$.

Often, extended Higgs bosons have enhanced couplings to heavy flavors, either to b and τ or to t depending on whether the extended Higgs parameter $\tan\beta$ is greater than or less than 1. This emphasizes searches based involve $b\bar{b}$ annihilation to Higgs resonances.

Currently, the LHC experiments based on heavy flavor signatures exclude additional Higgs bosons for masses as high as 1 TeV in restricted ranges of $\tan\beta$. The region of large $\tan\beta$ is surveyed by reactions such as $b\bar{b} \to H, A \to \tau^+\tau^-$, while the region of low $\tan\beta$ is surveyed by reactions such as $gg \to H, A \to t\bar{t}$, $gg \to A \to Zh$. A gap remains for intermediate values, roughly $2 < \tan\beta < 20$, which is closed only for extended Higgs boson masses up to 200 GeV. Future runs of the LHC, up to 3000 fb^{-1}, are expected to close this window up to about 500 GeV.

Additional Higgs particles typically have smaller couplings to WW and ZZ than the lightest Higgs boson. This coupling is proportional to the combination of mixing angles $\cos(\beta - \alpha)$, which is also constrained by measurement of the vector boson couplings to the known Higgs boson. The complementarity of these search strategies is illustrated with a search for additional Higgs bosons in a model with two Higgs doublets [29, 30, 31]. Fig. 1-5 shows the discovery reach for a 300 GeV Higgs boson H decaying via $H \to ZZ \to 4\ell$ compared with allowed region from Higgs coupling measurements at various experimental facilities. The reach for a pseudoscalar A decaying via $A \to Zh \to \ell\ell b\bar{b}, \ell\ell\tau\tau$ is comparable [31]. The important parameters for this search are the Higgs mixing angle α and the ratio of the Higgs vacuum expectation values $\tan\beta$, and which Higgs bosons couple to which quarks and leptons (type I or II). The line $\cos(\beta - \alpha) = 0$ is the limit where the additional Higgs particles decouple from gauge bosons and the couplings of the 125 GeV Higgs boson are Standard Model-like. Even for Type II models (which include supersymmetry), where the Higgs coupling measurements are already very constraining, the direct Higgs search probes significant additional parameter space. There is roughly a factor of 2 increase in the reach for large $\tan\beta$ in each step in going from LHC14 to HL-LHC to a 33 TeV collider with 3000 fb^{-1}.

Lepton collider experiments can search for extended Higgs boson states through the reaction $\ell^+\ell^- \to HA$ up to the kinematic limit, independently of the value of $\tan\beta$. The cross section depends only on the electroweak quantum numbers of the extended Higgs particles. This covers the parameter space up to 500 GeV for ILC and up to 1500 GeV for CLIC running at 3 TeV. Photon and muon colliders have the opportunity to discover additional Higgs bosons as resonances up to the full center of mass energy of the machine.

1.4.6 The Message

The conclusions of the Higgs Boson working group can be summarized as follows:

1. Direct measurement of the Higgs boson is the key to understanding electroweak symmetry breaking. The fact that the Higgs boson appears as a light, apparently fundamental, scalar particle needs explanation. A research program focused on the Higgs couplings to fermions and vector bosons and achieving a precision of a few percent or less is required to address these questions.
2. Full exploitation of the LHC is the path to few percent precision in the Higgs coupling and to a 50 MeV precision in the determination of the Higgs mass.
3. Full exploitation of a precision electron collider is the path to a model-independent measurement of the Higgs boson width and a sub-percent measurement of the Higgs couplings. Such precision is necessary to probe for new physics beyond the reach of LHC direct searches.

Experiments on Higgs bosons give information on the Particle Physics Questions # 1, 2, 4, 5, 8, 9, 10 listed in the Snowmass Summary [32].

1.5 Electroweak Interactions

The precision electroweak experiments of the 1990's established the $SU(2) \times U(1)$ theory of electroweak interactions at the sub-percent level of accuracy. But, they did more. All particle species with couplings to the electroweak interactions eventually influence the properties of the weak interaction bosons W and Z. Very precise measurements of the properties of these boson then have the potential to reveal new, undiscovered particles. The experiments of the 1990's indicated the presence of a heavy top quark and a light Higgs boson and estimated the masses at which these particles were eventually discovered. They disfavored a fourth generation of quarks and leptons, now excluded by direct search at the LHC.

Increased precision in the properties of the weak interaction bosons could well turn up the first evidence of the TeV spectrum of particles discussed in Section 1.2.1. There are still tensions evident in the data which have been intriguing for years; for example, the current value of M_W from many experiments persists at

1–2 σ higher than the SM expectation. Experiments over the next decade will explore whether these could become significant deviations requiring radiative corrections due to new particles.

In a description of possible new interactions in terms of effective operators, the electroweak precision observables probe only the first few terms. Experiments at higher energy probe additional operators by observing and constraining the nonlinear interactions of the W and Z bosons. These operators can receive corrections from loop diagrams involving new TeV mass particles but, more strikingly, they can receive leading-order corrections if there is new strong dynamics or resonances in the Higgs sector.

We will review these topics in this section. Full details of the program, and more precise statements of the projected uncertainties described below, can be found in the Electroweak Interactions working group report [33].

1.5.1 Precision observables M_W and $\sin^2\theta_w$

The current uncertainty in the W boson mass is 15 MeV, corresponding to an relative precision of 2×10^{-4}. It is remarkable that the most accurate determinations of M_W come from the hadron collider experiments CDF and DØ.

Precision measurement of M_W at hadron colliders is very challenging, but certain features of W boson production make it feasible to reach high accuracies. The directly measured transverse mass distribution is very sensitive to M_W, having a relatively sharp endpoint at the W boson mass. Likewise the p_T distributions of the leptons are also sensitive to the boson mass with different, but manageable systematic uncertainties. Enormous statistics will be available with very small contamination by background. The dominant errors come from the small corrections to these properties. Currently, the largest source of systematic error is the dependence of the acceptance on the rapidity of the produced W boson, requiring a correction that depends on quark and antiquark parton distribution functions (PDFs). Experimental uncertainties are at the same level as those due to PDFs and are expected to continue to decrease accordingly.

We see good prospects for improving this measurement at the LHC. The statistical component of the error will be negligible already with the current LHC data set. The error from PDFs doubles in going from the Tevatron to the LHC because proton-proton collisions give no valence antiquarks. However, we anticipate that this error will be decreased using new data on the vector boson rapidity and charge asymmetries. The issue of PDF improvement is discussed further in Section 1.6.2. The huge statistical precision will allow for control of calorimetric and tracking systematic uncertainties. In Table 1-2 we see that the PDF error in M_W can be brought down to ± 5 MeV with 300 fb^{-1} and to ± 3 MeV with 3000 fb^{-1}, leading to a final uncertainty in M_W of ± 5 MeV. In each stage, the experimental systematics are expected to keep pace. In order to reach this important level of precision, the PDF uncertainties must be pushed to a factor of 7 better precision that currently available.

Lepton colliders offer an opportunity to push the uncertainty in M_W down even further. The W mass was measured at LEP to ± 36 MeV from the kinematics of W^+W^- production. The uncertainty was dominated by statistical errors, with a substantial additional contribution from the modeling of hadronization. Both sources will benefit from the data set on W^+W^-, about 1000 times larger, that will be available at next-generation e^+e^- colliders such as ILC and TLEP. We estimate an error below ± 4 MeV from this method, and a similar error from independent measurements on single W boson production.

The ultimate W mass measurement would come from a dedicated energy scan of the W^+W^- threshold at 160 GeV. Such a measurement could reach ± 2.5 MeV with the statistics available from the ILC and ±

ΔM_W [MeV]	LHC		
$\sqrt{s}$ [TeV]	8	14	14
$\mathcal{L}[\,\text{fb}^{-1}]$	20	300	3000
PDF	10	5	3
QED rad.	4	3	2
$p_T(W)$ model	2	1	1
other systematics	10	5	3
W statistics	1	0.2	0
Total	15	8	5

Table 1-2. *Current and target uncertainties in the measurement of M_W at the LHC.*

1 MeV with the statistics available from TLEP. At this level, systematic errors become dominant. The program also requires a detailed precision theory of the W^+W^- threshold, using methods now applied to the $t\bar{t}$ threshold.

The measurement of the value of $\sin^2\theta_w$ associated with quark and lepton couplings to the Z boson resonance offers an orthogonal probe of the electroweak interactions. The current accuracy in $\sin^2\theta_w$ is at the 16×10^{-5} level of precision and is dominated by measurements from LEP and SLC. This level might be reached but, we expect, will not be surpassed at the LHC. Again, uncertainties in PDFs give the limiting systematic error. Measurements from the polarization-dependence of the Z cross section and from the b quark forward-backward asymmetry are discrepant by about 3σ, indicating an experimental question that should be resolved.

Future lepton colliders give an opportunity to improve the value of $\sin^2\theta_w$. The ILC program includes a few months of running at the Z resonance to produce a data set of 10^9 Z's, improving the statistics from LEP by a factor of 100 with highly polarized beams. The ILC detectors should also dramatically improve the capability for heavy flavor tagging. This "Giga-Z" program should improve the uncertainty in $\sin^2\theta_w$ by a factor 10. The program also would give new measurements of other Z pole observables sensitive to new TeV mass particles, most importantly, the fraction R_b of Z decays to $b\bar{b}$.

TLEP envisions a multi-year program at higher luminosity to collect 10^{12} events on the Z resonance. This potentially pushes the precision of electroweak measurements by another order of magnitude, though systematic contributions to the errors must still be understood. Among other factors, the Z mass must be measured more accurately than the current 2.5 MeV. This is possible at TLEP if transverse polarization can be achieved in single beam operation. The direct measurement of $\sin^2\theta_w$ optimally requires longitudinal polarization in colliding beam mode; the feasibility of this at TLEP needs to be understood.

Loop effects from TeV mass particles can produce effects at the 10^{-4} level in both M_W and $\sin^2\theta_w$, so the improved capabilities for precision electroweak measurements may point to new particle discovery or confirmation. Quantitative estimates for a number of models are given in [33].

1.5.2 Interactions of W and Z bosons

The interactions of W and Z bosons are studied at higher energies, through the measurement of vector boson pair production and multi-vector boson production. This study has already begun at LEP and the

Tevatron, where parameters of the 3-gauge boson interactions were bounded within a few percent of their SM values.

Vector boson interactions are described in a unified way through the formalism of effective Lagrangians. One begins from the SM Lagrangian, in which the Yang-Mills vertices for γ, W, and Z appear as terms of dimension 4. One then adds higher dimension operators invariant under the $SU(2) \times U(1)$ gauge symmetry. A typical term involving an operator of dimension 6 is

$$\delta\mathcal{L} = \frac{c_W}{\Lambda^2}(D_\mu\Phi)^\dagger W_{\mu\nu}(D_\nu\Phi) \ , \tag{1.15}$$

where Φ is the Higgs doublet field and $W_{\mu\nu}$ is the W boson field strength. This operators contributes to the 3- and 4-vector boson vertices. Additional operators of dimension 8 can modify the 4-vector interactions independently of the 3-vector interactions. A typical term is

$$\delta\mathcal{L} = \frac{f_{T,0}}{\Lambda^4}\mathrm{tr}(W_{\mu\nu})^2\mathrm{tr}(W_{\lambda\sigma})^2 \ . \tag{1.16}$$

In a weak-coupling theory such as the SM, the coefficients c_i and f_j are induced by loop diagrams and should be highly suppressed, by powers of $\alpha_w/4\pi \sim 10^{-3}$. However, in theories with strong interactions in the Higgs sector, the c_i and f_j coefficients could be of order 1, with the Λ parameters then interpreted as the masses of Higgs sector resonances. For example, the operator (1.16) would be induced by a scalar resonance in the Higgs sector.

The current bounds on triple gauge boson couplings imply that the Λ parameters associated with dimension 6 operators are higher than about 600 GeV. High statistics measurements of the triple gauge bosons by observation of W^+W^- and ZZ production in e^+e^- reactions at 500 GeV are expected to be sensitive to deviations from the SM that are 10 times smaller, pushing the sensitivity to Λ almost to 2 TeV.

It is difficult for hadron colliders to have similar sensitivity to triple gauge couplings. One source of this difficulty is that the LHC experiments study diboson reactions at higher energies, where additional terms from higher dimension operators are important and so the extraction of the coefficients of dimension 6 operators is model-dependent. But there is a compensatory advantage. Working at higher energy, the LHC will study W and Z bosons at energies where Higgs sector strong interactions can dramatically alter the amplitudes for vector boson scattering.

Some quantitative examples are presented in [33]. In examples studied there, the sensitivity to the coefficients f/Λ^4 of dimension 8 operators implies that, assuming $f = 1$, the LHC at 300 fb^{-1} would achieve exclusion of a Λ value greater than 1.5 TeV. The HL-LHC, with 3000 fb^{-1}, would roughly triple the significance of the effect, allowing 5 sigma discovery at 1.5 TeV or exclusion up to 1.8 TeV. If the origin of this new physics lies in strongly-coupled dynamics, the HL-LHC provides discovery-level sensitivity to virtual effects of new resonances with masses ($4\pi\Lambda$) up to 19 TeV. If interpreted as sensitivity to f, the HL-LHC is more sensitive by a factor of 2-3 compared to the LHC at 300 fb^{-1}.

Increasing the energy allowed for the diboson system dramatically increases the physics reach. For discovery of anomalous couplings, a 33 TeV pp collider would reach Λ values above 1.8 TeV, while a VLHC at 100 TeV would reach above 4.6 TeV. These values extend well into the region in which new Higgs sector dynamics would be expected in models of this type.

1.5.3 The Message

The conclusions of the Electroweak Interactions working group can be summarized as follows:

1. Precision measurements of the W and Z bosons has the potential to probe indirectly for new particles with TeV masses. This precision program is within the capabilities of LHC, linear e^+e^- colliders, and TLEP.

2. Measurement of vector boson interactions will probe for new dynamics in the Higgs sector. In such theories, we expect correlated signals in triple and quartic gauge couplings. The LHC and linear colliders will have sensitivity into the mass region above 1 TeV.

Experiments on electroweak interactions give information on the Particle Physics Questions # 1, 4, 8, 9 listed in the Snowmass Summary [32].

1.6 Quantum Chromodynamics and the Strong Interaction

Every probe of particle physics at high energies eventually requires detailed knowledge of the strong interactions. Even in pure electroweak processes, the strong interactions affect the values of α and α_w through coupling constant renormalization. In the next decade, when most of our new knowledge about particle physics will come from hadron collider experiments, our understanding of the strong interactions will affect every aspect of the data, through the structure of the proton, through radiative corrections to initial- and final-state quarks and gluons and their transition to hadrons, and through the detailed physics that produces multi-jet events.

The strong interactions are known to be described by the Yang-Mills theory Quantum Chromodynamics (QCD). This is a theory that is weakly coupled at short distances and strongly coupled at large distances. Our understanding of QCD is imperfect. We have limited tools for the strongly coupled regime, and precision calculation in the weakly coupled regime is technically complex. Nevertheless, our knowledge of QCD has taken enormous strides since the previous Snowmass workshop a decade ago. In this section, we review the currents state of our tools for QCD and indicate the opportunities for further progress. More details on all of the topics discussed here can be found in the working group report [34].

In our discussion of precision quantum field theory calculation, we will describe one-loop radiative corrections as next-to-leading order (NLO), and higher corrections as NNLO, *etc.*

1.6.1 α_s

The strength of the QCD coupling is determined by the value of the coupling constant α_s, usually expressed as its $\overline{MS}$ value at the Z mass. The current Particle Date Group [35] value of this quantity has 0.6% uncertainty. We have pointed out in Section 1.4.1 that this is a limiting systematic error in the evaluation of the SM prediction for Higgs boson couplings.

There are three strategies to improve the estimate. The extraction of α_s from the Z boson width or the ratio of hadronic to leptonic Z decays is theoretically unambiguous but is limited by statistics. Currently, this extraction has a 4% uncertainty and does not improve the world average. The Giga-Z program at the ILC discussed in the previous section should improve this uncertainty to 0.4%. The very high luminosity Z program envisioned for TLEP could decrease this uncertainty further to 0.1%. We judge that higher-statistics measurements of e^+e^- event shapes are not competitive with these improvements.

Proposed improvements of PDFs from LHeC will lead to an improved value of α_s from the measurement of PDF evolution. The expected statistical error would be $\pm 0.2\%$ from LHeC alone and $\pm 0.1\%$ from the combination of LHeC and HERA. The theoretical systematic error for this method is not as well understood, but we estimate this at $\pm 0.5\%$ once one further order in QCD perturbation theory (N^3LO) is calculated.

The most accurate current values of α_s come from lattice gauge theory. Higher statistics lattice estimates and calculation of additional terms in lattice perturbation theory should decrease the current uncertainties over the next decade to 0.3%. These improvements will come together with improvements in the values of the quark masses, as discussed in 1.4.1.

1.6.2 Parton distribution functions

Our knowledge of the initial state in hadron-hadron collisions is encoded in the representation of the proton structure given by the parton distribution functions (PDFs). The provision of PDF distributions with uncertainties is an innovation of the past decade [36]. The uncertainties quoted have been continually improved through the addition of new data sets, especially from the Tevatron and HERA experiments.

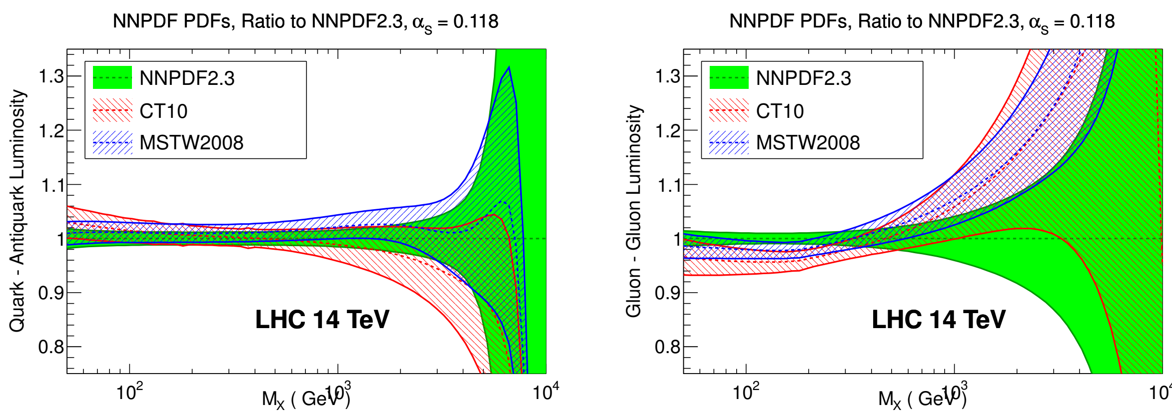

Figure 1-6. *Comparison of the partonic luminosities at the 14 TeV LHC, as a function of the parton center of mass energy, from the CT10, MSTW, and NNPDF2.3 NNLO PDF sets: Left: $q\bar{q}$ luminosity; Right: gg luminosity, from [34]*

Still, there are gaps in our knowledge, especially in the components relevant to the study of physics beyond the SM. The leading PDF distributions disagree in their estimates of the gluon-gluon luminosity function at the mass of the Higgs boson; this accounts for an 8% systematic uncertainty in the extraction of the cross section for Higgs production. The step from the Tevatron to the LHC puts added weight on the antiquark distributions in the proton. And, all parton luminosities are poorly constrained by data for parton-parton invariant masses greater than about 500 GeV. This is clearly shown in Fig. 1-6.

We expect that these difficulties can be addressed using future data from the LHC. PDFs at the few-percent level of accuracy require theoretical calculations at the NNLO level. These are already available for the Drell-Yan process [37]. The NNLO computation of the total cross section for top quark pair production has recently been completed [38] and is now being extended to the rapidity distribution. NNLO calculations for 2-jet production are in progress. Over the next few years, these calculations will be used in conjunction with a very high-statistics data set on jet, top quark, and lepton pair production from the LHC. The LHCb experiment has an important role to play in the measurement of rapidity distributions at $y > 2.5$ [39].

Further improvements in PDFs can result from the program of the LHeC. The data expected will reduce the error in the gluon luminosity to a few percent at the Higgs boson mass and to 5-10% in the multi-TeV region.

1.6.3 Electroweak corrections to hadron collider processes

The quest for few-percent accuracy in predictions for hadron colliders brings new elements into play. In particular, it requires that QED and electroweak corrections be included in all predictions for LHC.

Three elements are needed here. Electroweak corrections at NLO order are generally comparable to NNLO QCD corrections, so both types of corrections should be included, together with $\mathcal{O}(\alpha_w \alpha_s)$ terms if possible. Electromagnetic corrections to hadronic reactions cannot be consistently included without a set of PDFs derived from formulae that include NLO QED corrections. This requires a nontrivial modification of PDF fitting programs in order to introduce a photon PDF for the proton. Photon-induced reactions can contribute to LHC processes at the few-percent level, increasing to the 10% level at higher pp energies.

Finally, at energies of a TeV and above, electroweak Sudakov effects, negative corrections to two-particle production proportional to $\alpha_w \log^2 s/M_W^2$, can become important. These are 10% corrections for Drell-Yan processes producing 3 TeV dilepton systems. At higher energy pp colliders, these double logarithmic corrections must be resummed systematically.

1.6.4 High-precision calculation

In the past decade, a revolution in calculational technique has made it possible to derive formulae at NLO for the QCD cross sections for complex multiparton processes such as $pp \to W + 4$ jets and $pp \to t\bar{t} + 2$ jets. This has reduced the size of the theoretical errors in these cross sections from order 1 to 10-20%. Methods are now being developed to evaluate general 2-parton processes and even some 3-parton production processes to NNLO, to reduce these theoretical errors to the few-percent level.

We have already made reference to NNLO calculations of $t\bar{t}$ and 2-jet production. A very important target here is the cross section for Higgs boson production in association with one or more jets. Many Higgs measurements at the LHC include jet vetoes to control background from $t\bar{t}$ production and other sources, so explicit accounting for emitted jets is necessary. These cross sections often require terms to NNLO for stable summation of the perturbation series.

Beyond the fixed-order perturbation theory, many other aspects of higher-order computation remain to be understood. NNLO computations often display large logarithms, which should be systematically resummed. The merging of Monte Carlo programs with NLO QCD calculations is incompletely understood, and new difficulties arise at NNLO. We are optimistic that Higgs boson production and other QCD processes can be computed to few-percent accuracy, but many challenges remain.

1.6.5 The Message

The conclusions of the QCD working group can be summarized as follows:

1. Improvements in PDF uncertainties are required. There are strategies at LHC for these improvements. QED and electroweak corrections must be included in PDFs and in perturbative calculations.
2. An uncertainty is α_s of order 0.1% may be achievable through improvements in lattice gauge theory and precision experiments.
3. Advances in all collider experiments, especially on the Higgs boson, require continued advances in perturbative QCD.

Experiments on QCD give information on the Particle Physics Questions # 1, 2, 8, 9 listed in the Snowmass Summary [32].

1.7 Fully Understanding the Top Quark

The top quark is the heaviest quark and, indeed, the heaviest elementary particle known today. Its large mass give it the strongest coupling to the Higgs boson and to other possible particles of the Higgs sector. The mass of the top quark seems to be anomalously large—though it is sometime argued that it is the masses of all other quarks and leptons that are anomalously small. For all of these reasons, the top quark merits thorough experimental investigation.

The Tevatron experiments that discovered the top quark produced, in all, about $100,000$ of these particles. The LHC experiments have already produced 10 million and aim for many billions of top quarks by the end of the HL-LHC. Future lepton colliders will bring new precision tools to the study of the top quark. In this section, we will discuss what can be learned from these observations. More details on all of these topics can be found in the working group report [40].

1.7.1 Top quark mass

Like α_s discussed in the previous section, the top quark mass is a crucial input parameter for many SM predictions. It is already the most accurately known quark mass; a 2 GeV uncertainty on this quantity corresponds to a measurement with 1% precision. An accurate top quark mass is needed for precision electroweak fits, with an error of 600 MeV on the top quark mass yielding, for example, an error of 5 MeV in M_W. The top quark mass is also an important input to the question of ultimate vacuum stability in the SM [41]. Figure 1-7 shows the suspiciously marginal position of the measured Higgs boson mass and that of the top quark. Clearly more precision on the latter would help to elucidate whether this is another hint of strange behavior in the Higgs sector.

The top quark mass is most precisely defined as an $\overline{MS}$ quantity, evaluated most conveniently at the $\overline{MS}$ top quark mass value itself. However, experimental determinations of the top quark mass are typically done by kinematic fitting to templates, with poorly controlled errors from Monte Carlo modeling and hadronization. Thus, the precision determination of the top quark mass contains a double challenge, first, to give a definition of the top quark mass that can be cleanly related to the $\overline{MS}$ mass, and then to measure that quantity accurately.

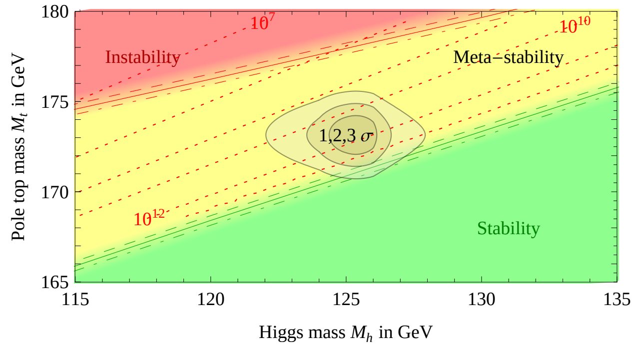

Figure 1-7. *Regions of metastability and instability of the Higgs potential in the SM, as the top quark and Higgs boson masses are varied, from [41].*

One solution to this challenge at the LHC is an idea from CMS[42] to measure the top quark mass from the endpoint of the distribution of the mass $m(b\ell)$ in top quark pair production, where ℓ is an isolated lepton and b is a b-tagged jet defined by anti-k_T or a similar prescription. The distribution of $m(b\ell)$ can be computed in QCD perturbation theory in terms of the perturbative pole mass, which can be related to the $\overline{MS}$ mass with an error of the order of 200 MeV. The results are largely insensitive to new physics contributions to top quark production. The endpoint feature in the distribution is sharp and strongly dependent on m_t. We expect that this method can reach a total uncertainty of 500 MeV with the statistics of the HL-LHC. Other methods for measuring the top quark mass at the LHC are discussed in [40].

At lepton colliders, the cross section for $t\bar{t}$ production near the threshold has a distinctive rise sensitive to the position of the lowest (unstable) $t\bar{t}$ bound state. Extensive theoretical work has evaluated this cross section to NNLO, with resummation of all large logarithms. The threshold position can be measured to 35 MeV at the ILC and somewhat better at TLEP and muon colliders. The conversion to the $\overline{MS}$ mass gives a total uncertainty of about 100 MeV. This very accurate value of m_t is well matched to the precision electroweak programs at lepton colliders described in Section 1.5.

1.7.2 Strong and electroweak couplings

The production and dynamics of top quark pairs at colliders offers many opportunities to test the strong and electroweak couplings of these particles. At hadron colliders, the dominant pair production mechanism is through QCD. The current agreement between the predicted and measured values verifies that the absolute strength of the QCD coupling to the top quark is equal to the value of α_s measured elsewhere to about 3% accuracy.

Changes in the form of the top quark coupling to gluons might be induced by new resonances associated with top quark compositeness. Possible magnetic or electric dipole couplings can be probed from the kinematics of top final states to better than 1% at the LHC with 300 fb^{-1}. Though it is difficult to measure the absolute size of the top quark width at a hadron collider, the W helicity fractions in top quark decay are sensitive to modifications of the top quark coupling to W, with similar sensitivity. The cross section for single top production provides a measure of the CKM matrix element V_{tb} which should reach an accuracy of 2.5% at 300 fb^{-1}. Couplings of the top quark to the photon and Z are constrained by measurements of radiation from a $t\bar{t}$ state. The HL-LHC is expected to reach sensitivities of a few percent for the photon couplings and 15-20% for the Z couplings.

At lepton colliders, $t\bar{t}$ pairs are produced through virtual photons and Zs, with large interference effects that depend on the beam polarization. The ILC and CLIC, which can take advantage of large beam polarization, expect to reach sensitivities below the 1% level for both photon and Z couplings. Randall-Sundrum models and other models with top quark and Higgs compositeness predict shifts of the Z couplings to $t\bar{t}$ at the few percent level; these effects could potentially be discovered in the linear collider programs.

1.7.3 Rare decays

The large samples of top quarks available at the LHC allow deep searches for flavor-changing top quark decays. Neutral current decays of the top quark such as $t \to \gamma c$ or $t \to gc$ are utterly negligible in the SM, with predict branching ratios smaller than 10^{-12}. These decays can appear with branching ratios as large as 10^{-4} in models with an extended Higgs sector or R-parity violating supersymmetric couplings that bring in two structures of flavor mixing. Searches for these decays at the HL-LHC can reach branching ratio limits below 10^{-5}.

Lepton colliders can also access these flavor changing couplings in single top production, for example, through $\gamma^*, Z^* \to t\bar{c}, t\bar{u}$. Searches for these processes can reach sensitivities close to 10^{-4} even in experiments at 250 GeV, below the $t\bar{t}$ threshold, and below 10^{-5} in the full ILC program at 500 GeV.

More details on the specific estimates for each possible neutral current coupling can be found in [40].

1.7.4 Searches for new particles related to the top quark

The motivation that we have given for new particles at the TeV scale in Section 1.2.2 directly implies the presence of exotic partners of the top quark. Examples of these particles are scalar top quarks in models of SUSY and Kaluza Klein excitations of top quarks in models with extra space dimensions. Searches for these particles have been a very high priority in the LHC program and will continue to be pursued intensively as more data accumulates.

Searches are designed individually for each type of exotic particle. The most powerful searches make use of the fact that top quarks resulting from the decay of the particle have different polarizations that those typically produced in SM pair-production. This is reflected in the kinematic distributions of the $t\bar{t}$ final states. For particles with masses of 1 TeV and above, the preferred method for identification of final-state top quarks is as single jets with high jet mass and a 3-jet substructure [43]. This “boosted top” identification is quite insensitive to the pileup associated with high luminosity.

Top squarks in SUSY might be tied to the general mass scale of supersymmetric particles, but the naturalness arguments we have given in Section 1.2.2 indicate that they might be the lightest colored supersymmetric partners. The LHC experiments have searched extensively for direct pair-production of top squarks that decay to the lightest supersymmetric particle $\widetilde{\chi}^0$ through $\widetilde{t} \to t\widetilde{\chi}^0$ and $\widetilde{t} \to b\widetilde{\chi}^+$. Current searches exclude a top squark up to about 650 GeV in the limit of light electroweak superpartners. The sensitivity should advance to about 1.0 TeV at 14 TeV and 300 fb^{-1}, and to 1.2 TeV with 3000 fb^{-1}.

In models with extra space dimensions and models with composite Higgs bosons and top quarks, the expected partners of the top quark are fermions with vectorlike couplings. The searches for these particles are similar to those for fourth-generation quarks, but they involve more complex decay patterns, with $T \to Wb$, $T \to tZ$ and $T \to th$. Searches for these particles that are comprehensive with respect to the decay mode currently exclude vectorlike top partners up to masses of about 800 GeV. The 14 TeV stages of the LHC will be able to discover these particles at masses of sensitivity to 1.2 TeV for 300 fb^{-1} and to 1.45 TeV for 3000 fb^{-1}.

Models with composite Higgs bosons and top quarks also typically include resonances in the multi-TeV mass region that decay preferentially to $t\bar{t}$. Randall-Sundrum models, for example, predict a resonance at a mass of a few TeV decaying with high top quark polarization to $t_R\bar{t}_L$. The boosted top identification described above was developed for the problem of discovering such states and is indeed expected to be very effective. Applying the same methods to larger data sets, we expect a sensitivity to such resonances up to 4.5 TeV for the 14 TeV LHC with 300 fb^{-1} and up to 6.5 TeV with 3000 fb^{-1}.

Additional examples of new particle searches involving top quarks are described in [40].

1.7.5 The Message

The conclusions of the Top Quark working group can be summarized as follows:

1. The top quark is intimately tied to the problems of electroweak symmetry breaking and flavor.
2. Precise and theoretically well-understood measurements of top quark masses are possible both at LHC and at e^+e^- colliders, in each case, matching the needs of the precision electroweak program.
3. New top couplings and new particles decaying to top play a key role in models of electroweak symmetry breaking. LHC will search for the new particles directly. Linear collider experiments will be sensitive to predicted deviations from the SM in the top quark couplings.

Experiments on the top quark give information on the Particle Physics Questions # 1, 2, 4, 8, 9 listed in the Snowmass Summary [32].

1.8 The Path Beyond the Standard Model - New Particles, Forces, and Dimensions

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Models of new physics associated with the TeV mass scale contain a wide variety of new particles. These include the particles of an extended Higgs sector discussed in Section 1.4.5 and partners of the top quark discussed in Section 1.7.4. More generally, many of the schemes discussed in Section 1.2.2 for explaining Higgs condensation are based on far-reaching principles that require a spectroscopy of new particles containing heavy partners for all SM particles. This includes additional strongly interacting particles, particles with only electroweak interactions, and new vector bosons. Some of these particles may have lifetimes long enough that their decays are not prompt in a collider experiment. One or more of these particles could be the constituents of the cosmic dark matter.

New particles could also introduce new flavor-changing interactions. Observation of such interactions of new particles can complement searches for flavor and CP violation in rare processes. This subject will be discussed in Section 1.9.

The LHC experiments have been able to search for new particles very robustly over a broad range of properties. In this section, we will discuss how higher energies and luminoisities at hadron colliders and new capabilities of lepton colliders will extend these searches.

Models of Higgs condensation and other TeV-scale phenomena based on different underlying principles make qualitatively different predictions for the quantum numbers and mass relations of the new particle spectrum. Thus, the first discovery of a new particle beyond the Standard Model will define a direction for an extensive research program, one that will be carried out over decades with multiple, complementary, experiments. In this section, we will emphasize the comparative reach of proposed collider programs to make this first discovery. Examples of the consequences of such a discovery will be given in Section 1.11. We will have room to discuss only a limited number of examples. The full range of searches for new particles accessible to TeV energy experiments is described in the New Particles and Forces working group report [44].

The dependence or search reach on luminosity deserves comment. Away from kinematic limits for a given collider energy, parton-parton luminosity functions scale such that increasing the parton-parton center of mass energy by a factor 2 decreases the luminosity by a factor 10. This rule, which implies that a factor of 10 in luminosity increases search reach by a factor of 2 in mass, must break down at masses near the kinematic limit. At the 14 TeV LHC, the reach increase falls off from the canonical factor of 2 for pair-produced particles with masses well above 1 TeV.

1.8.1 New Vector Bosons

We begin by discussing particles that show up in collider experiments as distinct resonances. An example is a color-singlet vector boson associated with an extension of the Yang-Mills symmetry group beyond that of the SM. Such bosons are required in many contexts, including models with left-right symmetric weak interactions at high energy, models of the Higgsino mass in SUSY, and models with extra dimensions. Models of Higgs composite structure often require breaking of a larger gauge group to the SM symmetry group.

Searches for these bosons are conducted at hadron colliders by looking for narrow dilepton resonances. A typical benchmark is sensitivity to the "sequential SM" Z', a boson with the couplings of the Z but with a higher mass. Current results from the LHC require the mass of such a particle to be above 2.5 TeV. With 14 TeV, it will be possible to discover such a resonance at 4.5 TeV, for 300 fb^{-1}, and at 7 TeV, for 3000 fb^{-1}. The value of the production cross section and the leptonic forward-backward asymmetry (with respect to the direction of production) give information on the couplings of the Z'. At higher pp energies, the discovery reach increases to 12 TeV for 33 TeV and 30 TeV for the 100 TeV VLHC.

Lepton colliders are sensitive to new vector bosons that interfere with the s-channel virtual photon and Z in two-fermion production $\ell^+\ell^- \to f\bar{f}$. The reach for discovery of a sequential Z' at the ILC at 500 GeV is also about 7 TeV and scales proportional to the center of mass energy for higher energy colliders. Measurements of the Z' signal with two possible beam polarizations and with individual lepton and quark final states gives a large amount of information toward the identification of the quantum numbers of the boson.

1.8.2 Supersymmetry

Searches for supersymmetry (SUSY) encompass a wide range of strategies aimed at different particles of the SUSY spectrum.

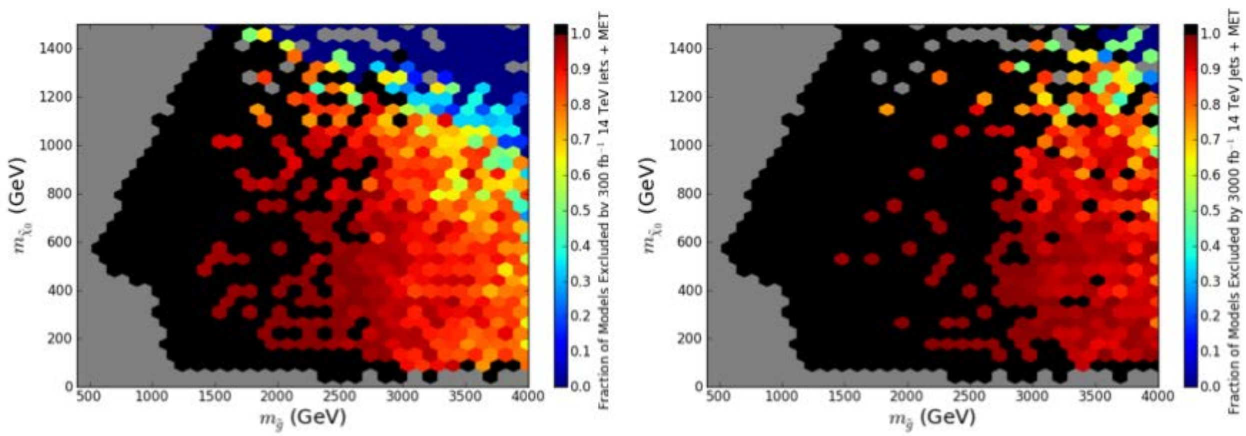

Figure 1-8. *Projections for coverage of the pMSSM 19-parameter model space in searches at the LHC at 300 fb^{-1} (left) and 3000 fb^{-1} (right), shown in the plane of gluino mass versus lightest particle mass. Black is complete exclusion; green is exclusion of 50% of the pMSSM model points. From [48].*

The most generic searches assume that supersymmetric partners of the SM particle carry a conserved quantum number, called R-parity. If the lightest supersymmetric particle is neutral, it will typically be weakly interacting and will not be observed in a collider detector. Events are then characterized as containing several hadronic jets, associated with decay to the lightest particle plus missing transverse momentum. The results of these analyses are parametrized by limits on the gluino mass and on a squark mass, assumed common to all squark flavors. Current LHC results exclude such events up to gluino masses of 1.0 TeV and, independently, squark masses of 1.3 TeV. For the future stages of the LHC, we expect to be able to discover such events up to gluino masses of 1.9 TeV and squark masses of 2.3 TeV with 300 fb^{-1}, and to 2.3 TeV and 2.7 TeV with 3000 fb^{-1}. This reflects more than a factor 2 in increased search power at the 300 fb^{-1} stage, and another 20% with the additional factor 10 in luminosity. The gluino discovery reach increases to 4.8 TeV for a 33 TeV pp collider and to 10.2 TeV for the VLHC.

It is possible that the first signal of SUSY would not be given by the generic search just described, but would require a more specialized analysis. Special search techniques are needed in models in which mass gaps in the SUSY spectrum are relatively small ("compressed spectrum"), so that hard jets are not emitted in particle decays, and models in which only the partners of top quarks, or perhaps, only color-singlet supersymmetric particles are produced at accessible energies. Such models can be highly motivated. A compressed spectrum is needed in many models of supersymmetric dark matter particles to allow "coannihilation" to produce the correct dark matter density [45]. They are also needed in models in which only the specific particles restricted by the naturalness bounds in Section 1.2.2 lie below 2 TeV. In such models, the first signal of SUSY would come from direct top squark pair production or gluino pair production with decay to heavy flavor. Reach estimates for top squark pair production were given above in Section 1.7.4.

Models in which SUSY discovery is more difficult at the 8 TeV LHC thus benefit more from the increase in luminosity to the HL-LHC. Models for which the first signal of SUSY would be the partners of W and Z bosons can be searched for at the 14 TeV LHC, with discovery expected up to masses of about 500 GeV. The factor of 10 luminosity increase to HL-LHC increases the reach by a factor of 2 in the analyses [46, 47], consistent with the argument given above.

Another way to look at this issue is shown in Fig. 1-8. The figures shows a survey of a large number of SUSY models [48] plotted in the plane of gluino mass versus lightest superparticle mass. The color-coding gives the fraction of models excluded by LHC searches, at 300 fb^{-1} on the left, and at 3000 fb^{-1} on the right.

The general shift of the boundary by about 30% is accompanied by a removal of exceptions to the right of this boundary.

One more exception should be noted. The supersymmetric partners of the Higgsino automatically have small mass splitting of a few GeV. The direct pair-production of these particles through electroweak interactions is essentially invisible at the LHC, except through searches for initial-state radiation plus invisible particles, described in Section 1.8.4. In a scenario in which these are the lightest supersymmetric particles, the ability of lepton colliders to be sensitive to very small energy depositions in decay would be crucial to observe and study these particles. Studies of Higgsino pair production at the ILC as described in [49].

1.8.3 Long-lived particles

The searches we have described so far assume that all new particles decay promptly. However, there are many models that give exceptions to this. ATLAS and CMS have carried out dedicated searches for tracks associated with long-lived massive particles and for particles decaying in the detector, perhaps out of time with the bunch crossings. Current limits are stronger than those in searches for promptly decaying particles. For example, ATLAS places limits of 310 GeV on a tau slepton, 600 GeV on a top squark, and 985 GeV on a gluino. Should such long-lived particles exist, the LHC detectors trap a sample of them for detailed studies of their decay modes and lifetimes.

1.8.4 Dark matter

The signature of jets plus missing transverse momentum discussed above for SUSY applies to a broader class of theories. In Section 1.2.3, we introduced WIMP dark matter as a general motivation for new particles with TeV scale masses. Any model with a new TeV spectroscopy characterized by a new quantum number can give rise to a dark matter candidate particle. The requirements are that the lightest new particle is neutral and that the quantum number is conserved sufficiently that this particle is stable over the age of the universe. Heavier states carrying QCD color will decay to this lightest particle, producing events with jets and missing transverse momentum. If the partners of quarks are fermionic rather than bosonic, the production cross section will be higher. The generic SUSY search described above can then be interpreted as a robust search for models predicting a TeV spectroscopy and dark matter.

It is possible that the heavier states of the TeV spectrum are out of reach kinematically. Then the discovery of dark matter would require the observation of direct pair-production of the essentially invisible dark matter particles. This can be done using the fact that the production of particles in a hard scattering process sometimes also produces gluons or photons radiated from the initial-state particles. If the particles mediating the pair-production reaction are heavy enough, this initial-state radiation can be at higher momentum than, and, thus, distinguishable from, the ordinary particle production in typical collisions.

Reach estimates for the discovery of dark matter pair-production have been studied systematically in [50], using an effective operator formalism to describe the coupling of dark matter to SM particles. This formalism also allows cross sections measured at colliders to be related to rates for direct and indirect detection of dark matter. The paper [50] also included limits on an explicit model with a lighter Z' mediator. Some results of the effective field theory analysis, comparing limits on the dark matter-nucleon cross section from LHC and higher energy pp colliders to limits from direct detection, are shown in Fig. 1-9. It is noteworthy that

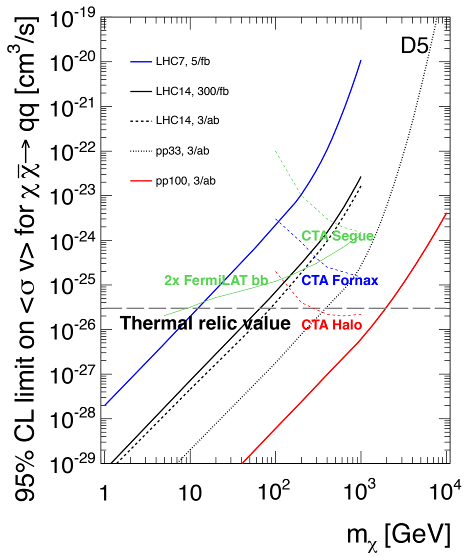

Figure 1-9. *Comparison of 95% confidence limits on the WIMP pair annihilation cross section in models of dark matter, analyzed in an effective operator formalism, for current and proposed facilities. The collider limits are constraints on the operator coefficient from searches for missing energy events; The limits from gamma ray telescopes are constraints from searches for dark matter annihilation in galaxies of the local group. From [50].*

the VLHC can place limits on the dark matter particle mass above 1 TeV, close to the unitarity limit for thermal production of such a particle in the early universe.

1.8.5 The Message

The conclusions of the New Particles and Forces working group can be summarized as follows:

1. TeV mass particles are needed in essentially all models of new physics. The search for them is imperative.
2. LHC and future colliders will give us impressive capabilities for this study. Future programs target new physics at the all-important TeV scale, as can be seen in Fig. 1-10.
3. The search for TeV mass particles is integrally connected to searches for dark matter.

Experiments on new particles and forces give information on the Particle Physics Questions # 1, 2, 3, 4, 5, 8, 9 listed in the Snowmass Summary [32].

1.9 Flavor Mixing and CP Violation at High Energy

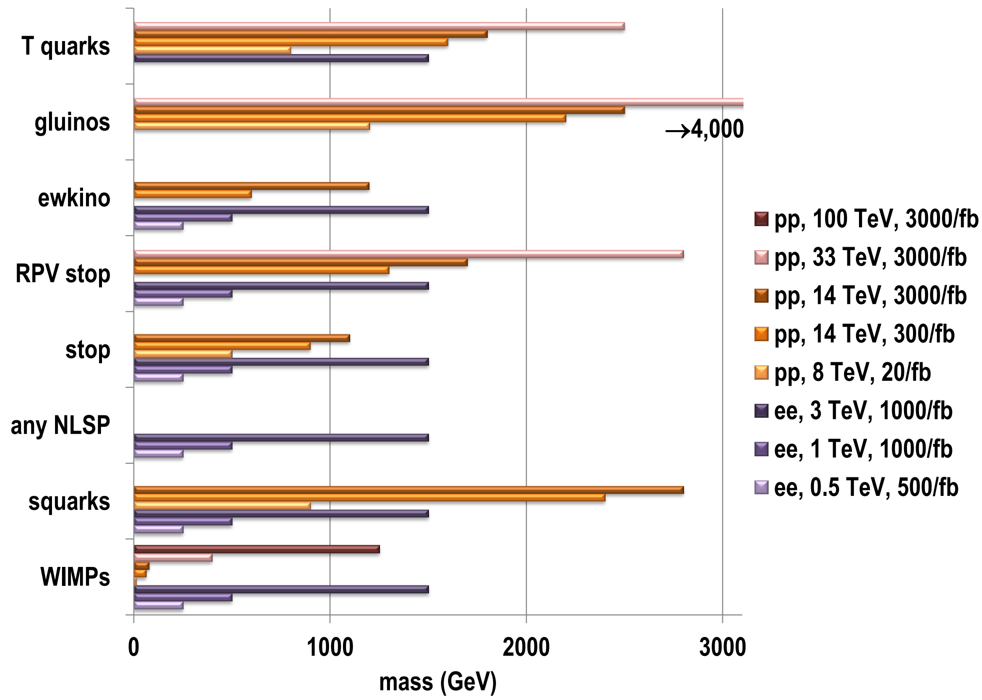

Figure 1-10. *Examples of 95% confidence upper limits for new particle searches at proposed pp and e^+e^- colliders.*

The explanation of Higgs condensation may or may not give insight into the theory of flavor. It is a mystery why quarks and leptons have a hierarchical mass spectrum, why the weak interactions are not diagonal in flavor and violate CP. In the SM, these features are parametrized by the fermion-Higgs Yukawa couplings. The idea that flavors are distinguished only through terms of the structure of the Yukawa couplings is called "Minimal Flavor Violation."

Models of new physics at the TeV scale introduce a large number of new couplings. These in principle can be proportional to flavor-violating couplings with completely new structures. Such structures are not needed to build a model of Higgs condensation. In fact, many specific models—most notably, SUSY with gauge-mediated breaking [57]—are flavor-blind. It is possible also that some principle, analogous to the GIM mechanism [58], requires that new flavor couplings are related to the Yukawa couplings. In these cases, there are no new flavor-changing effects beyond the SM arising from the TeV scale.

However, it is also possible that flavor couplings among new particles have a different pattern. Such couplings can generate rare flavor-changing weak decays. They can also affect the phenomenology of the new particles themselves, requiring new strategies for searches. In this section, we discuss examples of models of this type. There are many possibilities, only a few of which can be discussed here. A more complete catalog is given in the working group report [51].

1.9.1 SUSY with Flavor-Dependent Soft Masses

In Section 1.8, we discussed reach estimates for models of TeV spectroscopy that were either blind to flavor or singled out only the third generation. More general forms of the new particle spectrum are allowed. The most important difficulties with flavor observables come when squarks with the same gauge quantum numbers, *e.g.*, the partners of d_R and s_R, have different masses. But there is little difficulty in giving the partners of d_R and d_L smaller masses than those of the other squarks. This weakens the experimental limits on the lightest squark mass. In fact, it is possible, with other mechanisms to suppress flavor effects of new physics, to allow only the partner of c_R to be light. This has been explored in detail for SUSY models [52, 53]. The current limit on the charm squark in such models is about 300 GeV.

1.9.2 R-parity Violating SUSY

It is possible that the R-parity conservation law that should keep the lightest SUSY partner stable is violated by new interactions. These interactions necessarily have a complex structure in flavor. One possible form of the R-parity violating interaction is

$$\lambda^1_{ijk} U_i D_j D_k \ , \tag{1.17}$$

where U_i, D_i are the right-handed quarks or their squark partners and $i = 1, 2, 3$ is the generation number. This violates baryon number, allowing a squark to decay to two antiquarks. The interaction must be antisymmetric in color, and this requires it also to be antisymmetric in the flavors of the two down-type quarks. Other possible R-parity violating interactions have the forms

$$\lambda^2_{ijk} L_i L_j \bar{E}_k \ , \quad \lambda^3_{ia} L_i H_a \tag{1.18}$$

where L_i, $\bar{E}_i$ are left-handed leptons or antileptons or their slepton partners and H_a is a Higgs or Higgsino field. These interactions violate lepton number. The coefficients of these operators are usually taken to be small to avoid unwanted flavor-changing rare decays. In particular, either the operator (1.17) or the lepton number violating operators must be highly suppressed to avoid rapid proton decay.

In R-parity violating models with the operator (1.17) only, SUSY decay chains typically end with the lightest SUSY particle decaying to jets. These jets must have a nontrivial flavor structure, possibly with a b jet always included.

R-parity violation with the Higgs operator in (1.18) can produce neutrino masses through the "Type III seesaw": A neutrino converts to a Higgsino, which then converts back to an antineutrino, possibly of a different flavor. The difference between the quark and lepton flavor mixing patterns is explained by the statement that the mass matrices come from unrelated operators. In such models, the branching ratios of the Higgsino are related to the neutrino mixing angles, and this relation can be confirmed by direct measurement [54]. In more general seesaw models of neutrino mass, it is possible that the seesaw scale could be the TeV scale, setting up other relations between TeV mass neutral leptons and the neutrino mixing matrix [55].

1.9.3 Models with Electroweak Baryogenesis

To explain the asymmetry between the numbers of baryons and antibaryons in the universe, a new source of CP violation is needed beyond that of the CKM phase. One natural place to look for this is in an extended Higgs sector. A second requirement is that the electroweak phase transition be first-order. Then the transition takes place through the growth of bubbles, with top quarks scattering from the bubbles because they are massless outside and massive inside. A CP phase in the Higgs sector makes this scattering asymmetric between matter and antimatter. Both criteria can be satisfied in models with multiple Higgs fields [56]. Measurements of the Higgs self-coupling and of CP violation in Higgs decays, described in Sections 1.4.2 and 1.4.3 above, test models of this type.

1.9.4 The Message

The conclusions of the Flavor and CP working group can be summarized as follows:

1. TeV mass particles may or may not introduce couplings with new types of flavor violation. These possible new couplings affect the search methods for new particles, in many cases, requiring new strategies.
2. The search for new particles is integrally connected to searches for rare flavor changing decays.

Experiments on flavor associated with new particles give information on the Particle Physics Questions # 1, 2, 3, 4, 5, 8, 9 listed in the Snowmass Summary [32].

1.10 Scientific Cases for Future Colliders

In the previous sections, we presented the physics opportunities for the next steps in the Energy Frontier in terms of individual particles and research areas under study. It is also interesting to assemble these topics in terms of the experimental program that each accelerator in the list given in Section 1.3.2 will provide. Integrating over the topics in this way, we see that many of these proposed accelerators have very substantial physics programs that will explore the TeV energy scale across a broad range of measurements.

In this section, we present the cases for the various accelerators as if each accelerator stood on its own, with no further physics discoveries between now and the time that it begins operation. However, one should always keep in mind the possibility of discoveries would open up the study of physics beyond the SM. We have argued already that the likelihood of the discovery of new particle is very high even for the coming runs of the LHC at 14 TeV up to 300 fb^{-1}. Such a discovery would need to be followed up by further exploration that would benefit from accelerators with complementary capabilities or higher energy. This might, in the end, be the most important benefit of building the accelerators that come later in the timeline below. We will expand on this idea in Section 1.11.

1.10.1 LHC in This Decade: 300 fb^{-1}

First of all, we emphasize the many opportunities that will be provided by the coming run of the LHC at 14 TeV. Operation of the LHC at 14 TeV up through the 300 fb^{-1} with the Phase 1 upgrades offers a tremendous increase in the power of new particle searches, close to a factor 2 in mass in most channels. Many of these searches, for example, the search for the gluino almost to 2 TeV and the search for vectorlike top partners above 1 TeV, access ranges of the masses that are strongly motivated in models of Higgs condensation.

This impressive capability is only one aspect of a broad program that will be carried out at the LHC over the next ten years. Its features include:

1. Clarification of Higgs boson couplings, mass, spin, CP to the 10% level.
2. First direct measurement of top-Higgs boson couplings
3. Precision W boson mass measurement below 10 MeV.
4. First measurements of VV scattering.
5. Theoretically and experimentally precise top quark mass to 600 MeV.
6. Measurement of top quark couplings to gluons, Z and W bosons, and photons with a precision potentially sensitive to new physics—a factor 2–5 better than today.
7. Search for top squarks and top partners and $t\bar{t}$ resonances predicted in models of composite top, Higgs.
8. New generation of PDFs with improved gluon and antiquark distributions.
9. Precision study of electroweak cross sections in pp collisions, including a new photon PDF.
10. Extension by a factor 2 in the sensitivity to new particles: SUSY, Z, top partners—key ingredients for models of the Higgs potential—and the widest range of possible TeV-mass particles.
11. Deep ISR-based searches for dark matter particles.

1.10.2 High-Luminosity LHC: 3 ab^{-1}

The second high luminosity running of the LHC is referred to as the "Phase 2" upgrade period with instantaneous luminosities of 5×10^{34} cm^{-2}s^{-1}. This running with 3,000 fb^{-1} of accumulated data truly inaugurates the high-precision electroweak era at LHC with few percent precision for most Higgs boson couplings as well as the 5 MeV threshold in M_W mass determination.

1. The precision era in Higgs boson couplings begins, with sensitivities to 2-10%, and 1% for the ratio of $\gamma\gamma$ and ZZ couplings.
2. Measurement of rare Higgs boson decays, $\mu^+\mu^-$ and $Z\gamma$, with 100 M Higgs bosons.
3. First evidence of the Higgs boson self-coupling.
4. Powerful searches for extended Higgs bosons.
5. Precision W mass to $\pm$ 5 MeV.
6. Precise measurements of VV scattering with access to Higgs sector resonances.
7. Precision top mass to $\pm$ 500 MeV.
8. Deep study of rare, flavor-changing, top couplings with 10G tops.
9. Search for top squarks and partners in models of composite top quarks and Higgs bosons in the expected range of masses.
10. Further improvement of q, g, and γ PDFs to higher x and Q^2.

11. A 20-40% increase in mass reach for generic new particle searches which can be as much as a 1 TeV step in mass reach.

12. Extension by a factor of 2 in the mass reach for particles produced by the electroweak interactions.

13. Any discovery at LHC — or in dark matter or flavor searches — can be followed up.

1.10.3 ILC, up to 500 GeV

The ILC would run at 250 GeV, 350 GeV, and 500 GeV, in a program that could begin as early as the second half of the next decade. It would study the properties of the Higgs boson, the top quark, and possibly also newly discovered particles, in very fine detail.

1. Tagged Higgs boson study in $e^+e^- \to Zh$: model-independent Higgs boson width and branching ratio measurements, direct study of all Higgs decay modes, including invisible and exotic decays.

2. Model-independent Higgs boson couplings with percent-level precision necessary to probe for new physics beyond the reach of LHC direct searches.

3. Higgs boson CP studies in fermionic channels (e.g., $\tau^+\tau^-$).

4. Giga-Z program for EW precision, W boson mass to 4 MeV and beyond.

5. Improvement of triple vector boson couplings by a factor 10, to a precision below expectations for models with Higgs sector resonances.

6. Theoretically and experimentally precise top quark mass to $\pm$100 MeV.

7. Sub-% measurement of top couplings to γ and Z, with precision well below expectations in models of composite top quarks and Higgs bosons.

8. Search for rare top couplings in $e^+e^- \to t\bar{c}, t\bar{u}$.

9. Improvement of α_s from the Giga-Z program.

10. Unambiguous search capability for new particles in LHC blind spots – Higgsino, stealth stop, compressed spectra, WIMP dark matter.

1.10.4 ILC at 1 TeV

In the farther future, the extension of ILC to 1 TeV will access additional Higgs boson reactions for precision study and, possibly, also reach new particle thresholds.

1. Precision measurement of the Higgs boson coupling to top, to 2%.

2. Measurement of the Higgs boson self-coupling, to 13%.

3. Discovery of any extended Higgs boson states coupling to the Z, up to 500 GeV.

4. Improvement in precision of triple gauge boson couplings by a factor 4 over 500 GeV results.

5. Model-independent search for new particles with coupling to γ or Z to 500 GeV

6. Search for Z using $e^+e^- \to f\bar{f}$ to masses of about 5 TeV, a reach comparable to LHC for similar models. Multiple observables for diagnostics of the Z couplings.
7. Any discovery of new particles dictates a lepton collider program: search for electroweak partners, 1% precision mass measurement, the complete decay profile, model-independent measurement of cross sections, branching ratios and couplings with polarization observables, search for flavor and CP-violating interactions

1.10.5 CLIC: 350 GeV, 1 TeV, 3 TeV

Extremely high energies in e^+e^- collisions will likely require technologies beyond that envisioned for the ILC. CLIC is proposed as an e^+e^- collider capable of multi-TeV energies. It would probe Higgs boson self-couplings and exotic scattering of both standard model particles and any new particles found or hinted at in earlier machines.

1. Precision measurement of the Higgs boson coupling to top, to 2%.
2. Measurement of the Higgs boson self-coupling to 10%.
3. Discovery of any extended Higgs boson states coupling to the Z, up to 1500 GeV.
4. Improvement in precision of triple gauge boson couplings by a factor 4 over 500 GeV results.
5. Precise measurement of VV scattering, sensitive to Higgs boson sector resonances.
6. Model-independent search for new particles with coupling to gamma or Z to 1500 GeV: the expected range of masses for electroweakinos and WIMPs.
7. Search for Z using $e^+e^- \to f\bar{f}$ accessing masses above 10 TeV.
8. Any discovery of new particles dictates a lepton collider program, with the elements listed for the 1 TeV ILC.

1.10.6 Muon Collider: 125 GeV, 350 GeV, 1.5 TeV, 3 TeV

A muon collider holds promise as a technique for reaching very high energies in lepton-lepton collisions and for s-channel production of the Higgs boson and possible additional Higgs states. Studies of the muon collider are not yet mature, particularly in designing a detector that can overcome the background from decays of the muons circulating in the ring. However, promising first results on physics analysis including machine backgrounds were reported at Snowmass.

1. Similar capabilities to e^+e^- colliders described above.
2. Ability to produce the Higgs boson, and possible heavy Higgs bosons, as s-channel resonances. This allows a sub-MeV Higgs boson mass measurement and a direct Higgs boson width measurement.

1.10.7 Photon Collider

Another technique for producing Higgs bosons in the s-channel is to convert an electron collider to a photon collider by backscattering laser light from the electron beams. This allows resonance studies at 80% of the electron center-of-mass energy.

1. Production of Higgs or extended Higgs bosons as s-channel resonances, offering percent-level accuracy in $\gamma\gamma$ coupling.
2. Ability to study CP mixture and violation in the Higgs sector using polarized photon beams.

1.10.8 TLEP, Circular e^+e^-

An e^+e^- collider in a very large tunnel offers the possibility of very large integrated luminosity samples at 250 GeV and below and reasonable integrated luminosity at 350 GeV, especially if multiple detectors can be used simultaneously.

1. Possibility of up to 10 times higher luminosity than linear e^+e^- colliders at 250 GeV. Higgs boson couplings measurements might still be statistics-limited at this level.
2. Precision electroweak programs that could improve on ILC by a factor 4 in $\sin^2\theta_w$, a factor 4 in M_W, and a factor 10 in M_Z.
3. Theoretically and experimentally precise top quark mass to ±100 MeV.
4. Search for rare top couplings in $e^+e^- \to t\bar{c}, t\bar{u}$.
5. Possible improvement in α_s by a factor 5 over Giga-Z, to 0.1% precision.

1.10.9 VHLC, at 100 TeV

One of the ideas at Snowmass that gained momentum through the week was renewed interest in a Very Large Hadron Collider (VLHC). Our study recommends reinvigorating R&D toward realization of a VLHC.

1. High rates for double Higgs boson production; measurement of Higgs boson self coupling to 8%.
2. Sensitivity to new Higgs bosons and states associated with extended Higgs sectors at 1 TeV.
3. Dramatically improved sensitivity to vector boson scattering and multiple vector boson production.
4. Increased search reach for new particles associated with naturalness—including SUSY particles, top partners, and resonances—by almost an order of magnitude in mass over LHC. This corresponds to two orders of magnitude in fine-tuning.
5. Sensitivity to WIMP dark matter up to TeV masses, possibly covering the full natural mass range.
6. Any discovery at LHC — or in dark matter or flavor searches — can be followed up by more detailed measurements at VLHC, in addition to searches for related higher-mass particles. Both luminosity and energy are relevant.

1.11 Discovery stories

Another way to integrate over the physics topics presented in Sections 1.4–1.9 is to consider the consequences of a discovery of new physics at the LHC later in this decade. We have emphasized, first, that the presence of new particles at the TeV scale is necessary to build a physics explanation of electroweak symmetry breaking, and, second, that the coming run of the LHC, up to 300 fb^{-1}, will improve the depth of searches for new particles by more than a factor of 2. The conclusion from these statements is that the discovery of new physics at the LHC is likely. This means that we should have a plan for following up this discovery and exploring its implications. This program of course depends on the nature of the particle discovered, so a full analysis would be presented as a large number of case studies. We give two examples here for illustration. Further examples of these "discovery stories" are presented in the working group reports.

1.11.1 Well-Tempered SUSY

The New Particles and Forces working group [44] considered in some detail the consequences of a particular SUSY model that could be discovered at the LHC with 300 fb^{-1}. This particular model had a gluino at 1.9 TeV, squarks ranging in mass from 1.3 TeV to 2.6 TeV, and bino and Higgsino states near 200 GeV. The bino and Higgsino were assumed to mix so that the lightest supersymmetric particle (LSP) would be a dark matter particle with the correct thermally generated cosmic density. This dark matter scenario is called the "well-tempered neutralino" [59].

The LHC at 300 fb^{-1} would observe a robust jets plus missing transverse momentum signal. The signal would be dominated by the decay of the lighter squarks to a quark jet plus the unobserved LSP. The mass difference could be measured from kinematic distributions. Assuming that the LSP was light, this would also give an estimate of the squark mass. With the measured cross section, this would favor SUSY over models with fermionic partners.

The HL-LHC would produce some of the heavier squarks and the gluino. Detailed kinematic measurements would identify at least one more mass scale in the spectrum and give further evidence for the SUSY hypothesis. The direct production of electroweak states would not be observed at the LHC, because these states have a compressed spectrum.

A lepton collider with center of mass energy of 500 GeV would be able to pair-produce the Higgsinos and observe their decays to the LSP. Measurement of the polarized cross sections would give information about the quantum numbers of the electroweak states. It would also give an indirect determination of the mass of the electron-type slepton (750 GeV in this model) to 10 GeV. Using this information, it would be possible to evaluate the LSP annihilation cross section and show that it was consistent with that required for a dark matter particle.

Experiments at higher-energy colliders would be needed to discover the heaviest sleptons (at 3.3 TeV) and squarks (at 2.6 TeV). Eventually, the complete SUSY spectrum would be determined, and the data on the mass spectrum could be used to deduce the pattern of SUSY breaking.

1.11.2 $t\bar{t}$ Resonance

An alternative scenario might be based on a Randall-Sundrum model with top and Higgs compositeness. The first evidence of this model would be the discovery of a resonance in pp collisions that decayed to $t\bar{t}$. Such a resonance at 3 TeV would be discovered at the LHC with 300 fb^{-1}. Study of kinematic distributions of the $t\bar{t}$ final state would reveal that the top quarks were highly polarized, a prediction of this model.

The HL-LHC would discover an electroweak singlet top quark partner, and, possibly also, a doublet of quarks with vectorlike coupling to the electroweak interactions. It is possible that very accurate studies of the $t\bar{t}$ spectrum would also reveal the presence of a color-singlet resonance, somewhat below 3 TeV. Its higher-statistics study of the TeV resonance might reveal at decay to $t\bar{c}$ with branching ratio 10^{-3}.

A lepton collider at 500 GeV would observe a significant 3% enhancement of the right-handed top quark coupling to the Z boson. The pattern of Higgs boson couplings would be shifted by the influence of the new top quark partners, with a substantial increase in the $t\bar{t}$ coupling, a 4% decrease in the $b\bar{b}$ coupling, and a 2% increase in the $\gamma\gamma$ coupling. The last of these effects would be observed by combining the high statistics measurement of $BR(\gamma\gamma)/BR(ZZ^*)$ from the HL-LHC with the precise measurement of the Higgs coupling to Z at a lepton collider.

These measurements would give a tantalizing first glimpse of the structure of the underlying composite Higgs model. Experiments at higher energy colliders capable of producing resonances up to 20 TeV in mass would be needed to explore the full structure of the spectrum of states.

1.12 Conclusions

In this report, we have described the future program of research at high-energy colliders and summarized the efforts of six Snowmass 2013 Energy Frontier working groups. The detailed conclusions that we have reviewed come back repeated to a set of four points that deserve special emphasis.

1. The search for new particles with masses of order 1 TeV is a central issue in particle physics. The mysteries associated with the Higgs field and dark matter give compelling arguments for a new particle spectroscopy at the TeV mass scale. Such particles must exist to provide a physics explanation for the Higgs condensation and symmetry breaking. We need to know their nature, and their implications for the laws of physics at very short distances. We have given many examples in which these particles address other major questions of particle physics, including the questions of flavor, dark matter, and the unification of forces.

2. The central capability of high-energy collider experiments is to produce massive elementary particles directly. In Energy Frontier experiments, we observe the W and Z bosons, the top quark, and the Higgs boson as real particles whose production and decay we can study in detail. The same will be true for any new particles that we can create. This is a unique, direct, and powerful method to learn about the laws of physics.

3. There are three essential aspects in the exploration of the physics of the TeV mass scale.

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.

4. This program can be realized at accelerators now envisioned to operate in the coming years.

1. We have emphasized the great opportunity that is being provided by the coming operation of the LHC at 14 TeV. The next stage of the LHC will double the range of searches for new particles and give similar leaps in capability for other probes of TeV physics.
2. We have projected quantitatively what will be achieved in running the LHC at high luminosity, to ultimately acquire 3000 fb^{-1} of data per experiment. For some physics topics, the gain is incremental, but for others, in particular, the precision study of Higgs couplings and the search for new particles with only electroweak interactions, we move to a qualitatively new level. Looked at in total, this is a compelling physics program.
3. We have listed many essential contributions to the exploration of the TeV scale that can be provided by lepton colliders. These include precision studies of the Higgs boson, the W and Z bosons, and the top quark, capable in all cases of discovering percent-level corrections predicted as the effects of TeV particles. The construction and operation of the ILC in Japan will realize these goals.
4. We have emphasized that the quest to understand the TeV scale will not be finished with the results of accelerators of the next generation. It is likely that the discovery of new particles at the next stage of collider physics will open a definite path for exploration to still higher energies. Our study called attention, in particular, to the capabilities of a VLHC for further exploration of the TeV mass scale. The journey to still higher energies begins with renewed effort to bring advanced accelerator technologies to reality.

We emphasized in our introduction that the discovery of the Higgs boson changes everything. This discovery points to potentially profound modifications of the laws of physics at energies relatively close to those we now access at accelerators. The quest for new phenomena and the insights they will provide has just begun.

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