Chapter 2

Physics Goals of the Next Linear Collider

2.1 Introduction

During the past several decades, significant advances have been made in elementary particle physics. We now have a renormalizable quantum field theory of strong and electroweak interactions, based on the principle of local $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge invariance. That theory properly describes the interactions of all known particles, incorporating the proven symmetries and successes of quantum electrodynamics, the quark model, and low energy V–A theory. It correctly predicted weak neutral currents, the now observed gluons and weak gauge bosons, and the special properties of the heavy fermions τ, b, and t. Since it is a renormalizable theory, its predictions can be tested at the quantum loop level by high precision experiments. It has already confronted a wealth of data at the level of 1% or better without any significant evidence of inconsistency. Because of those impressive successes, the $SU(3)_c \times SU(2)_L \times U(1)_Y$ theory has been given the title "The Standard Model", a designation which establishes it as the paradigm against which future experimental findings and new theoretical ideas must be compared.

The Standard Model cannot be the final theory of Nature, but it does represent the completion of a major stage toward the uncovering of that theory. To make further progress, we must examine both the strengths and failings of this model and direct experimental effort toward the weakest points in its structure.

The Standard Model is based on the interactions of fermions and vector gauge bosons. The fermions are grouped into three generations of leptons and quarks which span an enormous mass range. Their newest member, the top quark, is exceptionally heavy. Why is the top so massive, or why are the other fermions so light? This question highlights the broader problem of why Nature chose to repeat the fermion generations three times and endow quarks and leptons with their observed pattern of masses and mixing. It is likely that future intense scrutiny of the top quark's properties will provide new insights regarding this important problem.

The vector bosons of the Standard Model are grouped into eight massless gluons of $SU(3)_c$ which mediate the strong interactions, plus the $W^{\pm}$, Z, and γ which are responsible for electroweak interactions. The $\mathrm{SU}(3)_c$ gauge theory, called quantum chromodynamics (QCD), taken on its own, is an ideal theory. It has no arbitrary or free parameters but can, in principle, explain all hadronic dynamics including confinement, asymptotic freedom, proton structure, and baryon and meson spectroscopy. Confirming those properties and uncovering additional more subtle features of QCD remains an important experimental and theoretical challenge.

In contrast with QCD, the electroweak sector has many arbitrary parameters. Most stem from the Higgs mechanism which is used to break the $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ symmetry and endow particles with mass. In the simplest realization of this symmetry breaking, one introduces a scalar doublet ϕ, the Higgs field, which obtains a vacuum expectation value v. This assumption introduces into the theory an electroweak mass scale $v \simeq 250$ GeV. The masses of the W and Z bosons and the various quarks and leptons are proportional to v. Their disparity reflects extreme differences in their couplings to the scalar field ϕ. It is true that this simple model with one Higgs field can parametrize all electroweak masses, quark mixing, and even CP violation. But it does not provide insight into any of these phenomena, or even into the basic fact that the electroweak gauge symmetry is spontaneously broken. The many unanswered questions associated with the Higgs field, or whatever more complicated structure leads to the breaking of the electroweak symmetry, call for experiments which thoroughly explore this sector.

An important testable prediction of the simple Higgs model is the existence of a neutral spin-0 remnant particle H, called the Higgs scalar. Its mass depends on the self-coupling λ of the Higgs field through the relation

$$m_H = \sqrt{2\lambda} v \ , \tag{2.1}$$

but it is unspecified as long as λ is unknown. There is an experimental lower bound on m_H of 65 GeV from direct searches at LEP. That search reach is expected to be extended up to about 90 GeV at LEP II. There is also an approximate upper bound on the Higgs mass $m_H \lesssim 800$ GeV from theoretical bounds on λ. For example, perturbative partial wave unitarity in high energy scattering of longitudinal W bosons, $W_L W_L \to W_L W_L$ requires $|\lambda| \lesssim 8\pi/5$. This gives a large window in which to search. However, there is a much stronger upper bound which comes from the stronger assumption that the Higgs boson is a fundamental particle with no nonperturbative interactions up to the grand unification scale. This requires $m_H \lesssim 200$ GeV; we will refer to a Higgs boson satisfying this hypothesis as a 'light Higgs'.

Even more daunting than the problem of finding the Higgs boson H in the context of the simple Higgs theory is the prospect that this theory is inadequate to correctly describe the weak interaction scale. This simplest theory has theoretical problems of self-consistency, particularly when it is extrapolated to a unified theory at high energies. Also, the fact that its pattern of couplings must be input without any explanation is a sign that this theory is only a parametrization of electroweak symmetry breaking rather than being a fundamental explanation of this phenomenon. This state of affairs has led to many speculations on the true symmetry breaking mechanism and, from there, to interesting new physics possibilities beyond the Standard Model with observable manifestations at high energy.

In order to build a theory in which electroweak symmetry is naturally broken by the expectation value of a fundamental Higgs field, it is necessary to incorporate supersymmetry (SUSY) at the weak interaction scale. That elegant boson-fermion symmetry allows a simple connection to gauge or string theory unification and provides a logic for the symmetry-breaking form of the Higgs potential. Achieving these goals, however, requires introducing novel partners for all Standard Model particles. It also requires at least two Higgs doublets and thus predicts five remnant scalars, h, H, A, $H^{\pm}$. The h should have a mass below about 150 GeV and should be most similar to the Standard Model Higgs boson. Finding that particle and determining its properties may be our first window to supersymmetry. If supersymmetry does indeed appear below 1 TeV, there will be a wealth of supersymmetry partner spectroscopy waiting to be explored. Currently, supersymmetry has no direct experimental support. However, there are two very suggestive pieces of evidence that are in favor of this theory. The first is the values of the $SU(3) \times SU(2) \times U(1)$ coupling constants. These coupling constants are in just the relation predicted by a supersymmetric grand unified theory. The second is the tendency of the precision electroweak data to favor a light Higgs boson, which is an indication that the mechanism of electroweak symmetry breaking involves weakly-coupled fields.

Alternatively, one might imagine that there is no fundamental Higgs field, and that the electroweak symmetry is broken dynamically by fermion-antifermion condensation due to new strong forces at high energy. Scenarios ranging from $t\bar{t}$ condensation to complex extended technicolor models have been proposed. Their basic premise is very appealing, but no compelling model exists. Nevertheless, the generic idea of new underlying strong dynamics gives rise to testable consequences for anomalous top and gauge boson couplings and high energy scattering behavior.

This issue of whether the mechanism of electroweak symmetry breaking is weak-coupling or strong-coupling is the most important question in elementary particle physics today. The NLC should resolve it definitively. For the case in which this physics is weak-coupling, the NLC should have a rich experimental program involving the detailed study of Higgs bosons and supersymmetric particles. The precise spectrum and branching ratio determinations for these particles should give information which, like the values of the strong and electroweak coupling constants, can be extrapolated to the unification scale. This scenario offers the tantalizing possibility that experimental data collected at the NLC would be directly relevant to supergravity and superstring theories at very high energy. On the other hand, if the mechanism of electroweak symmetry breaking is strong-coupling, this could imply a new spectroscopy at the TeV energy scale which the NLC might access directly.

In addition to these two options which relate directly to the physics of electroweak symmetry breaking, there are many other possibilities for new physics at the TeV energy scale.

These include larger gauge groups with additional W' and Z' gauge bosons, heavy new fermions, and additional scalars. Many of these possibilities are realized in specific models of electroweak symmetry breaking, so a broad-based search for new phenomena is an essential part of the experimental program devoted to this question. The most direct way to uncover such new particles and their associated phenomena is to search at very high energies above particle production threshold. Important indirect evidence can also be inferred from precision studies of Standard Model parameters such as m_W, $\sin^2\theta_W$, and the couplings of heavy quarks and W bosons to the γ and Z^0.

For the exploration of all of these possibilities, which defines the next step in experimental high-energy physics, the Next Linear Collider (NLC) will play an essential role. We envisage this machine as an e^+e^- collider which operates initially at a center of mass energy of about 500 GeV and can be upgraded to 1.5 TeV, providing a luminosity corresponding to 10^4 events per year for a process with the point cross section for QED pair production. This machine will employ polarized electrons and offers the possibility of e^-e^-, $e\gamma$, and $\gamma\gamma$ collider options. With such a facility, it is possible to carry out crucial and unique experiments across the whole range of possibilities we have just described for the physics of the weak interaction scale. In this report, we will summarize the capabilities of the NLC to explore the physics of the weak interaction scale across this broad front. A design for the NLC is presented in an accompanying report [1].

In Section 2 of this chapter, we will summarize the basic conclusions of this report relevant to the physics studies, including the basic accelerator parameters of energy and luminosity. We will also describe the basic assumptions on detector performance that we will use to describe the physics capabilities of this machine. In Sections 11 and 12, after our discussion of the physics opportunities that the NLC will provide, we will give a more detailed description of a detector design and the constraints on the detector which come both from the physics goals and from the accelerator.

One of the first physics goals of the NLC will be the detailed study of the top quark at its threshold and just above. We will explain in Section 3 the special features of the $t\bar{t}$ threshold region which make it a unique laboratory for the precision measurement of the top mass and width, the QCD coupling of the top quark, and the possible couplings to the Higgs boson and other new particles. We will also describe how the NLC will make precision measurements of the couplings of top to electroweak gauge bosons, couplings which might contain signals of new strong interactions which connect top to the sector responsible for electroweak symmetry breaking.

Whether the electroweak gauge symmetry is broken by fundamental Higgs bosons or by new high-energy strong interactions, the NLC will bring important contributions to the experimental study of this sector. First of all, though the LHC and other facilities have the capability to find a light Higgs boson in many decay channels, the NLC is the only planned facility at which the existence of a light Higgs boson can be ruled out in a model-independent way. If the light Higgs boson is indeed present, we will show in Section 4 that the NLC will be able not only to discover this particle but also to characterize many of its interactions.

We will show that the NLC has a unique capability to determine the couplings of the Higgs boson to Z and W, to heavy quarks and leptons, and to photons. These measurements dovetail nicely with the expected measurement of the Higgs production cross section from gluon fusion at the LHC to give the complete phenomenological profile of this particle.

If the presence of a relatively light fundamental Higgs particle is accompanied by the appearance of supersymmetry at the TeV scale, the NLC can perform crucial experiments to characterize the new supersymmetric particles. We will show in Section 5 that the NLC can detect the supersymmetric partners of W and Z over essentially the complete range of parameters expected in the model. But, even more importantly, the NLC can measure the masses and mixing angles of these particles and, in so doing, determine the most important underlying parameters of supersymmetry. This determination of parameters will be essential not only for the exploration of the physics of fermion partners at e^+e^- colliders, but also for the extraction of detailed information about the underlying theory from the complementary signatures of supersymmetry seen at hadron colliders.

If electroweak gauge symmetry is broken by new forces at high energy, one can look for the signs of these forces in the couplings of W bosons to the γ and Z and in the study of WW scattering. We will show in Section 6 that the NLC is an ideal machine for the study of the gauge couplings of the W, capable of achieving parts per mil precision on the W form factors. We will show in Section 7 that the NLC at the high end of its energy range can achieve constraints on WW scattering comparable to those of the LHC, in an environment with a number of qualitative advantages. We will also show that the NLC also offers new windows into WW interactions through the precision study of $e^+e^- \to W^+W^-$ and through high-energy $t\bar{t}$ production.

Finally, these capabilities of the NLC to explore specific models of electroweak symmetry breaking are balanced by the ability of this facility to perform broad searches for novel fermions, scalars, and gauge bosons. We will describe the abilities of the NLC to search for exotic particles in e^+e^- annihilation in Section 8. In Section 9, we will show how this broad capability is extended further by the availability of e^-e^-, $e\gamma$, and $\gamma\gamma$ collisions. In Section 10, we will show that the NLC will also contribute to the future program in the study of the strong interactions, in particular, through the precision measurement of α_s.

Section 13 will present our conclusions. We will review the unique capabilities of the NLC and contrast its prospects with those of the next generation of hadron colliders.