New Physics at the TeV Scale and Beyond [RO]New Physics at the TeV Scale and Beyond

Introduction

The impressive amount of data collected in the past several decades in particle physics experiments is well accommodated by the Standard Model. This model provides an accurate description of Nature up to energies of order 100 GeV. Nonetheless, the Standard Model is an incomplete theory, since many key elements are left unexplained: (i) the origin of electroweak symmetry breaking, (ii) the generation and stabilization of the hierarchy, *i.e.*, the large disparity between the electroweak and the Planck scale, (iii) the connection of elementary particle forces with gravity, and (iv) the generation of fermion masses and mixings. These deficiencies imply that there is physics beyond the Standard Model and point toward the principal goal of particle physics during the next decade: the elucidation of the electroweak symmetry breaking mechanism and the new physics that must necessarily accompany it. Electroweak symmetry is broken at the TeV scale. In the absence of highly unnatural fine-tuning of the parameters in the underlying theory, the energy scales of the associated new phenomena should also lie in the TeV range or below.

Numerous theories have been proposed to address these outstanding issues and embed the Standard Model in a larger framework. In this chapter, we demonstrate the ability of a linear collider operating at 500 GeV and above to make fundamental progress in the illumination of new phenomena over the broadest possible range. The essential role played by e^+e^- machines in this endeavor has a strong history. First, e^+e^- colliders are discovery machines and are complementary to hadron colliders operating at similar energy regions. The discoveries of the gluon, charm, and tau sustain this assertion. Here, we show that 500-1000 GeV is a discovery energy region and that experiments there add to the search capability of the LHC in many scenarios. Second, e^+e^- collisions offer excellent tools for the intensive study of new phenomena, to precisely determine the properties of new particles and interactions, and to unravel the underlying theory. This claim is chronicled by the successful program at the Z pole carried out at LEP and the SLC. The diagnostic tests of new physics scenarios provided by a 500–1000 GeV linear collider are detailed in this chapter. For the new physics discovered at the LHC or at the LC, the linear collider will provide further information on what it is and how it relates to higher energy scales.

Chapter 9 of this book gives a survey of the various possible mechanisms for electroweak symmetry breaking that motivate the search for new physics beyond the Standard Model at energies below 1 TeV. Among these models, supersymmetry has been the most intensively studied in the past few years. We have devoted Chapter 4 of this document to a discussion of how supersymmetry can be studied at a linear collider. But supersymmetry is only one of many proposals that have been made for the nature of the new physics that will appear at the TeV scale. In this chapter, we will discuss how several other classes of models can be tested at the linear collider. We will also discuss the general experimental probes of new physics that the linear collider makes available.

The first few sections of this chapter present the tools that linear collider experiments bring to models in which electroweak symmetry breaking is the result of new strong interactions at the TeV energy scale. We begin this study in Section 2 with a discussion of precision measurements of the W and Z boson couplings. New physics at the TeV scale typically modifies the couplings of the weak gauge bosons, generating, in particular, anomalous contributions to the triple gauge couplings (TGCs). These effects appear both in models with strong interactions in the Higgs sector, where they are essentially nonperturbative, and in models with new particles, including supersymmetry, where they arise as perturbative loop corrections. We document the special power of the linear collider to observe these effects.

In Section 3, we discuss the role of linear collider experiments in studying models in which electroweak symmetry breaking arises from new strong interactions. These include both models with no Higgs boson and models in which the Higgs boson is a composite of more fundamental fermions. The general methods from Section 2 play an important role in this study, but there are also new features specific to each class of model.

In Section 4, we discuss the related notion that quarks and leptons are composite states built of more fundamental constituents. The best tests for composite structure of quarks and leptons involve the sort of precision measurements that are a special strength of the linear collider.

In Section 5, we discuss the ability of linear collider experiments to discover new gauge bosons. New Z and W bosons arise in many extensions of the Standard Model. They may result, for example, from extended gauge groups of grand unification or from new interactions associated with a strongly coupled

Higgs sector. The linear collider offers many different experimental probes for these particles, involving their couplings to all Standard Model species that are pair-produced in annihilation. This experimental program neatly complements the capability of the LHC to discover new gauge bosons as resonances in dilepton production. We describe how the LHC and linear collider results can be put together to obtain a complete phenomenological profile of a Z'. Grand unified models that lead to Z' bosons often also lead to exotic fermions, so we also discuss the experiments that probe for these particles at a linear collider.

It is possible that the new physics at the TeV scale includes the appearance of new dimensions of space. In fact, models with extra spatial dimensions have recently been introduced to address the outstanding problems of the Standard Model, including the origin of electroweak symmetry breaking. In Section 6, we review these models and explain how they can be tested at a linear collider.

Further new and distinctive ideas about physics beyond the Standard Model are likely to appear in the future. We attempt to explore this unchartered territory in Section 7 by discussing collider tests of some unconventional possibilities arising from string theory. More generally, our limited imagination cannot span the whole range of alternatives for new physics allowed by the current data. We must prepare to discover the unexpected!

Finally, we devote Section 8 to a discussion of the determination of the origin of new physics effects. Many investigations of new phenomena at colliders focus only on defining the search reach. But once a discovery is made, the next step is to elucidate the characteristics of the new phenomena. At the linear collider, general methods such as the precision study of W pair production and fermion-antifermion production can give signals in many different scenarios for new physics. However, the specific signals expected in each class of models are characteristic and can be used to distinguish the possibilities. We give an example of this and review the tools that the linear collider provides to distinguish between possible new physics sources.

We shall see in this chapter that the reach of the linear collider to discover new physics and the ability of the linear collider to perform detailed diagnostic tests combine to provide a facility with very strong capabilities to study the unknown new phenomena that we will meet at the next step in energy.

Gauge boson self-couplings

The measurement of gauge boson self-couplings at a linear collider can provide insight into new physics processes in the presence or absence of new particle production. In the absence of particle resonances, and in particular in the absence of a Higgs boson resonance, the measurement of gauge boson self-couplings will provide a window to the new physics responsible for electroweak symmetry breaking. If there are many new particles being produced—if, for example, supersymmetric particles abound—then the measurement of gauge boson self-couplings will prove valuable since the gauge boson self-couplings will reflect the properties of the new particles through radiative corrections.

Triple gauge boson coupling overview

Gauge boson self-couplings include the triple gauge couplings (TGCs) and quartic gauge couplings (QGCs) of the photon, W and Z. Of special importance at a linear collider are the $WW\gamma$ and WWZ TGCs since a large sample of fully reconstructed events will be available to measure these couplings.

The effective Lagrangian for the general V vertex ($V = \gamma, Z$) contains 7 complex TGCs, denoted by g_1^V, κ_V, λ_V, g_4^V, g_5^V, $\tilde{\kappa}_V$, and $\tilde{\lambda}_V$ Hpzh:1987. The magnetic dipole and electric quadrupole moments of the W are linear combinations of κ_γ and λ_γ while the magnetic quadrupole and electric dipole moments are linear combinations of $\tilde{\kappa}_\gamma$ and $\tilde{\lambda}_\gamma$. The TGCs g_1^V, κ_V, and λ_V are C- and P-conserving, g_5^V is C- and P-violating but conserves CP, and g_4^V, $\tilde{\kappa}_V$, and $\tilde{\lambda}_V$ are CP-violating. In the SM at tree-level all the TGCs are zero except g_1^V=κ_V=1.

If there is no Higgs boson resonance below about 800 GeV, the interactions of the W and Z gauge bosons become strong above 1 TeV in the WW, WZ or ZZ center-of-mass system. In analogy with $\pi\pi$ scattering below the ρ resonance, the interactions of the W and Z bosons below the strong symmetry breaking resonances can be described by an effective chiral Lagrangian Bagger:1993. These interactions induce anomalous TGC's at tree-level: eqnarray $\kappa_\gamma = 1 + e^2 32\pi^2 s_w^2 \left(L_{9L} + L_{9R}\right)$

Standard Model radiative corrections Ahn:1988fx cause shifts in the TGCs of $\mathcal{O}(10^{-4} - 10^{-3})$ for CP-conserving couplings and of $\mathcal{O}(10^{-10} - 10^{-8})$ for CP-violating TGC's. Radiative corrections in the MSSM can cause shifts of $\mathcal{O}(10^{-4} - 10^{-2})$ in both the CP-conserving Arhrib:1996dm and CP-violating TGC's Kitahara:1998bt.

Triple gauge boson measurements

The methods used at LEP2 to measure TGCs provide a useful guide to the measurement of TGCs at a linear collider. When measuring TGCs the kinematics of an event can be conveniently expressed in terms of the center-of-mass energy following initial-state radiation (ISR), the masses of the W^+ and W^-, and five angles: the angle between the W^- and initial e^- in the W^+W^- rest frame, the polar and azimuthal angles of the fermion in the rest frame of its parent W^-, and the polar and azimuthal angles of the anti-fermion in the rest frame of its parent W^+.

In practice not all of these variables can be reconstructed unambiguously. For example, in events with hadronic decays it is often difficult to measure the flavor of the quark jet, and so there is usually a two-fold ambiguity for quark jet directions. Also, it can be difficult to measure ISR and consequently the measured center-of-mass energy is often just the nominal $\sqrt{s}$. Monte Carlo simulation is used to account for detector resolution, quark hadronization, initial- and final-state radiation, and other effects.

The TGC measurement error at a linear collider can be estimated to a good approximation by considering and channels only, and by ignoring all detector and radiation effects except for the requirement that the fiducial volume be restricted to $|\cos\theta_W| < 0.9$. Such an approach correctly predicts the TGC sensitivity of LEP2 experiments and of detailed linear collider simulations Burgard:1999. This rule-of-thumb approximation works because LEP2 experiments and detailed linear collider simulations also use the , and channels, and the increased sensitivity from these extra channels makes up for the lost sensitivity due to detector resolution, initial- and final-state radiation, and systematic errors.

table[ht!] center tabular—l—cc—cc— 4c—error $\times 10^{-4}$

Table tab:cp-conserving contains the estimates of the TGC precision that can be obtained at $\sqrt{s} = 500$ and 1000 GeV for the CP-conserving couplings g_1^V, κ_V, and λ_V. These estimates are derived from one-parameter fits in which all other TGC parameters are kept fixed at their tree-level SM values. Table tab:cp-violating contains the corresponding estimates for the C- and P-violating couplings $\tilde{\kappa}_V$, $\tilde{\lambda}_V$, g_4^V, and g_5^V. An alternative method of measuring the $WW\gamma$ couplings is provided by the channel $e^+e^- \to \nu\bar{\nu}\gamma$ k1.

The difference in TGC precision between the LHC and a linear collider depends on the TGC, but typically the TGC precision at the linear collider will be substantially better, even at $\sqrt{s} = 500$ GeV. Figure fig:gauge$_lc_lhcshowsthemeasurementprecisionexpectedfortheLHC\ atlas:1999andforlinearcollidersofthreedifferentenergiesforfourdifferentTGCs.$

If the goal of a TGC measurement program is to search for the first sign of deviation from the SM, one-parameter fits in which all other TGCs are kept fixed at their tree-level SM values are certainly appropriate. But what if the goal is to survey a large number TGCs, all of which seem to deviate from their SM value? Is a 28-parameter fit required? The answer is probably no, as illustrated in Fig. fig:tgc$_pair_corr$.

Figure fig:tgc$_pair_corrshowsthehistogramofthecorrelationcoefficientsforall171pairsofTGCswhen19differentTGCsaremeasuredatLEP2usingone-parameterfits.TheentriesinFig.\ fig:tgc_pair_corrwithlargepositivecorrelationsarepairsofTGCsthatarerelatedtoeachotherbytheinterchangeof\gamma$ and Z. The correlation between the two TGCs of each pair can be removed using the dependence on electron beam polarization. The entries in Fig. fig:tgc$_pair_corrwithlargenegativecorrelationsareTGCpairsofthetypeRe(\tilde{\kappa}_\gamma)/Re(\tilde{\lambda}_\gamma)$, $Re(\tilde{\kappa}_Z)/Re(\tilde{\lambda}_Z)$, *etc.* Half of the TGC pairs with large negative correlations will become uncorrelated once polarized electron beams are used, leaving only a small number of TGC pairs with large negative or positive correlation coefficients.

10pt$fig:gauge_lc_lhcExpectedmeasurementerrorfortherealpartoffourdifferentTGCs.Thenumbersbelowthe$ file="LC/relative/gauge_lc_lhc.eps",height=1... figure[htp] $energyofthelinearcolliderinGeV.TheluminosityoftheLHCisassumedtobe300\ fb^{-1}$, while the luminosities of the linear colliders are assumed to be 500, 1000, and 1000 fb^{-1} for $\sqrt{s}$=500, 1000, and 1500 GeV respectively.