Why We Need Both the LHC and an $e^+e^-$ Linear Collider *

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1 Introduction

The next high energy collider will be the Large Hadron Collider (LHC), to be completed in 2007. The LHC, combined with RUNII at the Fermilab Tevatron, will greatly expand our knowledge of physics at the TeV scale. In this note, we examine some of the physics questions likely to be left unanswered by the LHC and discuss the role of a high energy $e^+e^-$ linear collider (LC) in providing answers. We consider the connection between the understanding to be found at the LHC and an LC, using Higgs physics, low energy supersymmetric models, and the top quark sector as examples.

One of the central questions of particle physics is the origin of mass. In the Standard Model, both fermion and gauge boson masses are generated through interactions with a single scalar particle, the Higgs boson, $h$. The Higgs boson will certainly be discovered, if it exists, at Fermilab or the LHC. However, discovery is not enough. Both the LHC and a high energy $e^+e^-$ linear collider will be needed in order to completely elucidate the properties of a Higgs boson and to verify its role in the origin of mass.

The Standard Model with a single Higgs boson is unsatisfactory, however, in several respects, among them the lack of unification of the gauge coupling constants at high energy and the emergence of quadratic divergences in the Higgs boson mass renormalization at 1-loop. Both of these problems are solved by the introduction of supersymmetry at the TeV scale. The minimal supersymmetric model has a large number of new particles, many of which can be discovered at the LHC. Determining that these particles correspond to an underlying supersymmetric model, however, requires input from both the LHC and a linear collider. Furthermore, the scalar partners of leptons will be extremely challenging to observe at the LHC.

Finally, we consider the role of the top quark. Precision measurements of the $\tilde{t}h$ Yukawa coupling, $g_{tth}$, and of the top quark mass, $M_t$, can help to restrict models with new physics in the top quark sector. The top quark mass is a fundamental parameter for precision electroweak measurements and is vital for determining the consistency of the Standard Model. We summarize the expected precisions for $g_{tth}$ and $M_t$ at the LHC and an LC.

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The theme is clear: the physics requires a high energy $e^+e^-$ collider in addition to the LHC in order to complete our understanding of the TeV energy scale.

## 2 Higgs Physics

The Higgs mechanism implies the existence of a scalar particle, the Higgs boson, $h$. The mass of the Higgs boson is a free parameter in the theory, but the couplings to fermions and gauge bosons, along with the Higgs self-couplings, are fixed, allowing for definitive experimental searches. The current direct search limit from LEP is $M_h > 114 \text{ GeV}$, while precision measurements suggest $M_h < 193 \text{ GeV}$. A Higgs boson in this mass region can, with sufficient luminosity, be discovered at the Fermilab Tevatron, while the LHC will find a Higgs boson of any mass below 1 TeV. In order to verify that this particle is the source of mass, we must do more than simply observe it. We must:

- Measure the Higgs couplings to fermions and gauge bosons. In the Standard Model, the couplings to fermions, $g_{ffh}$, and to gauge bosons, $g_{WWh}$, are proportional to mass:

  $$g_{ffh} = \frac{m_f}{v}$$

  $$g_{WWh} = g M_W.$$  

- Measure the Higgs self-couplings. The Higgs self-couplings are proportional to the Higgs mass and arise from the potential:

  $$V = \frac{M^2}{2} h^2 + \frac{M^2}{2v} h^3 + \frac{M^2}{8v^2} h^4.$$  

- Verify the Higgs spin- parity assignments, $J^{PC} = 0^{++}$.

The LHC can measure combinations of Higgs coupling constants arising in the products of production cross sections multiplied by Higgs branching ratios, $\sigma \cdot BR$, as shown in Fig. 1. The experimental accuracy depends sensitively on the Higgs boson mass. For $M_h > 200 \text{ GeV}$, only the $h \rightarrow WW$ and $h \rightarrow ZZ$ channels are observable. For a Higgs boson below the ZZ threshold, more decay modes are accessible. The measured values of $\sigma \cdot BR$ depend on parton distribution functions and various combinations of Higgs couplings to fermions and gauge bosons. By combining the different channels, ratios of Higgs boson partial decay widths can be extracted and many of the uncertainties cancel. The accuracy is typically 10-20% and only a subset of the Higgs couplings can be obtained in this manner.

A linear collider benefits from a well determined initial state with fixed quantum numbers and energy. The linear collider will measure $e^+e^- \rightarrow Zh$
Why We Need Both the LHC and an $e^+e^-$ Linear Collider

Fig. 1. Relative error on $\sigma \cdot BR$ at the LHC with $\mathcal{L} = 200$ fb$^{-1}$. The $t\bar{t}h, h \rightarrow WW$ and $Wh, h \rightarrow b\bar{b}$ curves assume $\mathcal{L} = 300$ fb$^{-1}$.[5].

Fig. 2. Higgs branching ratios from $e^+e^- \rightarrow Zh$ at $\sqrt{s} = 350$ GeV with $\mathcal{L} = 500$ fb$^{-1}$. The bands represent theory uncertainty.[6].
with a large rate ($\sim 40,000$ $h$’s per year). If the Higgs boson is kinematically accessible, an LC can observe the Higgs boson independent from the Higgs decay pattern using missing mass techniques. The Higgs branching ratios can then be measured in all channels with a typical precision of $2 - 10\%$ as shown in Fig. 2[6,7]. The data points in Fig. 2 correspond to an integrated luminosity of $L = 500$ $fb^{-1}$ at a center of mass energy, $\sqrt{s} = 350$ $GeV$. The bands correspond to the theory error, of which the largest component comes from uncertainties on the $b$ quark mass. The cross section for $e^+e^- \rightarrow Zh$ decreases by roughly a factor of two as the center of mass energy is increased from $\sqrt{s} = 350$ $GeV$ to $\sqrt{s} = 500$ $GeV$ and so the more precise measurements of Higgs branching ratios are obtained at the lower energy.

A precise measurement of the mass of the Higgs boson is interesting primarily for comparison with the value extracted indirectly from electroweak observables. At the LHC, the Higgs mass is extracted from reconstruction of the decay products in the channel, $h \rightarrow \gamma\gamma$. For $M_h < 150$ $GeV$ and an integrated luminosity of $L = 300$ $fb^{-1}$, a precision of $\delta M_h \sim 100$ $MeV$ can be obtained. A more precise value can be obtained at the linear collider where a precision of $\delta M_h \sim 50$ $MeV$ can be found for $M_h = 120$ $GeV$ at $\sqrt{s} = 350$ $GeV$ and $L = 500$ $fb^{-1}$[8].

The Higgs mechanism requires that the Higgs boson be a spin 0 particle with positive charge and parity. The threshold dependence of the $e^+e^- \rightarrow Zh$ cross section depends sensitively on the spin of the Higgs boson and can be measured with a modest amount of integrated luminosity. The data points shown in Fig. 3 correspond to $20$ $fb^{-1}$ per point and clearly distinguish between spin 0,1, and 2 assignments for the Higgs boson. The angular dependence of the $Z$ decay products in $e^+e^- \rightarrow Zh$ are also sensitive to the Higgs CP assignments.[10]

### 3 Supersymmetry (SUSY)

If low mass scale ($< 1$ $TeV$) supersymmetry exists, some indications will be seen in the first $10$ $fb^{-1}$ of data at the LHC through a large excess in the missing $E_T$ plus jets signal. The task of the LHC and LC will then be to untangle the supersymmetric spectroscopy and to verify that the new particles are indeed the result of an underlying supersymmetric theory.

#### 3.1 SUSY Higgs Sector

The Higgs sector of a supersymmetric model is very predictive, with an upper limit on the neutral Higgs boson mass of around $130$ $GeV$ and all masses and couplings predicted at tree level in terms of two parameters. These parameters are usually taken to be $M_A$, the mass of the pseudoscalar Higgs boson, and $\tan \beta$, the ratio of neutral Higgs boson vacuum expectation values. In order to claim discovery of a supersymmetric Higgs sector, it will be necessary
Why We Need Both the LHC and an $e^+e^-$ Linear Collider

Fig. 3. Dependence of the $e^+e^- \to Zh$ cross section on the spin of the Higgs boson. The error bars correspond to $20 \text{ fb}^{-1}$/point.

to observe at least two of the five Higgs bosons of a SUSY theory with the predicted properties. The LHC can discover the lightest neutral Higgs boson in all regions of parameter space in the minimal supersymmetric model, but for a significant portion of the parameter space it cannot observe the other Higgs bosons. This is the decoupling regime, shown as the white region in Fig. 4, where the lightest Higgs boson has Standard Model couplings and the other Higgs particles are heavy.

The ability of an LC to make precision measurements of the Higgs couplings will be critical in probing the decoupling region of a supersymmetric model. Deviations in Higgs boson branching ratios from their SM values can provide information on the heavy Higgs bosons of a SUSY model, even when these particles are kinematically inaccessible. With $\mathcal{L} = 1000 \text{ fb}^{-1}$, an LC will be sensitive to the pseudoscalar Higgs mass up to approximately 600 GeV.

3.2 SUSY Partners

Strongly interacting SUSY particles will be observed with large rates at the LHC. The classic signal, jets with missing $E_T$, will arise predominantly from squark and gluino production. The squarks and gluinos then decay to ordinary quarks and gluons, along with the lightest SUSY particle (LSP). The region of SUSY parameter space accessible at the 5σ significance level at the LHC is shown in Fig. 5. After a year of running at the design luminosity, SUSY mass scales in the 1–2 TeV region can be observed.

It will be difficult to untangle the details of the SUSY signals, however, since the signatures depend sensitively on the details of the specific supersymmetric model. The challenge is then to make precision measurements of masses and couplings. By measuring cascade decays of SUSY particles, some
Fig. 4. Supersymmetric Higgs parameter space accessible at the LHC with $\mathcal{L} = 300 \text{ fb}^{-1}$. In the white region, only a single Higgs boson can be observed, with couplings close to those of the SM.\[11\]

mass differences can be measured at the LHC, with the precision being limited by the unknown mass of the lightest SUSY particle (LSP)\[14\].

The linear collider can make precise measurements of particle masses by scanning threshold cross sections. If the particles are within the kinematic reach of the linear collider, they will be pair produced and the masses measured unambiguously\[15\]. In order to verify that the new particles observed correspond to a supersymmetric model, the full spectrum of superpartners must be observed. For example, both the $\tilde{\ell}_L$ and the $\tilde{\ell}_R$ scalar partners of the electron must be seen. The polarization capabilities of a linear collider are critical for this measurement.

4 The Top Quark

The origin of the fermion mass spectrum in the Standard Model is not well understood. A precise measurement of the top quark mass is of interest for understanding the source of fermion masses. Since the coupling of the Higgs boson to a $t\bar{t}$ pair is proportional to $M_t$, a deviation of the top quark Yukawa coupling, $g_{tth}$, from its Standard Model value would be a signal for new physics.

The top quark Yukawa coupling can be measured through $t\bar{t}h$ production, which has a small rate, but a spectacular signature. At the LHC, the signal and background for $t\bar{t}h$ production have the same shape and there is
Why We Need Both the LHC and an $e^+e^-$ Linear Collider

$$\int L \ dt = 1, 10, 100, 300 \text{ fb}^{-1}$$

$$A_0 = 0, \tan \beta = 35, m > 0$$

$E_T(300 \text{ fb}^{-1})$ miss

$E_T(100 \text{ fb}^{-1})$ miss

$E_T(10 \text{ fb}^{-1})$ miss

$E_T(1 \text{ fb}^{-1})$ miss

$g(1000) \sim q(1500) \sim g(1500) \sim g(2000) \sim q(2500) \sim g(2500) \sim q(3000) \sim g(3000)$

$W_h^2 = 0.4$

$W_h^2 = 1$

$W_h^2 = 0.15$

$h(110)$

$h(123)$

$1400$

$1200$

$1000$

$800$

$600$

$400$

$200$

$5000$

0

$1000$ $1500$ $2000$

$m_0$ (GeV)

$m_{1/2}$ (GeV)

EX

TH

CMS

one year @10^{34}

one year @10^{33}

one month @10^{33}

one week @10^{33}

Fermilab reach: < 500 GeV

cosmologically plausible region

Fig. 5. $5\sigma$ discovery reach for supersymmetric particles with the CMS detector at the LHC[13].

Fig. 6. The threshold cross section for $e^+e^- \rightarrow t\bar{t}$ as a function of the center of mass energy in GeV at LO (dashed-dotted), NLO(dashed), and NNLO(solid), for three values of the arbitrary renormalization scale[17].

a $15 - 20\%$ scale uncertainty from the arbitrary renormalization scale. With an integrated luminosity of $\mathcal{L} = 300 \text{ fb}^{-1}$, the LHC can obtain an accuracy of [12].

$$\frac{\delta g_{th}}{g_{th}} \sim 16\%, \quad \text{LHC.}$$

(4)
The signature for $t\bar{t}h$ production is cleaner at an $e^+e^-$ linear collider, but the rate is limited by phase space and requires $\sqrt{s} \sim 700 - 800$ GeV in order to be observable. With a large integrated luminosity of $\mathcal{L} = 1000 \, fb^{-1}$, a linear collider at $\sqrt{s} = 800$ GeV can obtain

$$\frac{\delta g_{tth}}{g_{tth}} \sim 6.5\%, \quad \text{LC.} \hspace{1cm} (5)$$

At $\sqrt{s} = 500$ GeV, the accuracy is significantly less.

At the LHC with $\mathcal{L} = 50 \, fb^{-1}$, the top quark mass can be measured by reconstruction of the decay products with a precision

$$\delta M_t \sim 1 - 2 \, GeV, \quad \text{LHC.} \hspace{1cm} (6)$$

A linear collider can measure the top quark mass quite precisely with a threshold energy scan with a relatively small amount of luminosity, $\mathcal{L} = 40 \, fb^{-1}$,

$$\delta M_t \sim 200 \, MeV, \quad \text{LC.} \hspace{1cm} (7)$$

The dependence of the $e^+e^- \rightarrow t\bar{t}$ threshold cross section is shown in Fig. 6. The cross section has been calculated to NNLO and with the proper definition of the top quark mass the perturbation theory is well defined. The QCD effects are well understood and the scale uncertainty is roughly 20%\(^{[17]}\).

The precise value of the top quark mass is of importance for the extraction of the Higgs boson mass from precision electroweak measurements\(^{[18]}\). Combined with a precise measurement of $M_W$, a value for the Higgs mass can be extracted indirectly. Consistency of the SM requires that this prediction agree with the direct measurement of $M_h$. Assuming $M_h = 115$ GeV and a measurement of $\delta M_W = 15$ MeV, the LHC indirect measurement of the Higgs boson mass will have an error, $\delta M_h \sim 100 \, MeV$. Similarly, assuming $\delta M_W = 10 \, MeV$, the linear collider will indirectly measure the Higgs mass with an accuracy of $\delta M_h \sim 50 \, MeV$.

The precision measurement of the top quark is particularly interesting in the case of a supersymmetric model. Fig. 7 demonstrates the allowed parameter space from measurements of $M_W$ and $M_t$ at the LHC and shows the improvement at a LC running at high luminosity at the $Z$ pole (giga-Z). In this case, the precision measurements will clearly discriminate between the SM and the MSSM\(^{[19]}\).

5 Conclusion

The physics program of a high energy $e^+e^-$ linear collider, in conjunction with that of the LHC, can vastly expand our understanding of the TeV scale. Preliminary studies of possible run plans at a linear collider\(^{[15]}\) indicate that with 1000 $fb^{-1}$, most of the physics goals described in this note should be obtainable.
Why We Need Both the LHC and an $\epem$ Linear Collider

Fig. 7. Indirect measurement of $M_h$ in the SM and in the minimal supersymmetric model [10].

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