Physics at e^+e^- Linear Colliders

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Abstract. I discuss the motivation and physics potential of an electron-positron linear collider with a center-of-mass energy at the 1 TeV scale, in light of what we may expect to learn with the LHC. The comparison is illustrated with examples drawn from Higgs physics, top quark physics, and the search for large extra spacetime dimensions.

INTRODUCTION

The past decade of precision electroweak experiments has seen outstanding confirmation of the Standard Model at the per mille level. But the successes of the Standard Model have drawn increased attention to its deficiencies, notably its unsatisfactory treatment of the mechanism behind electroweak symmetry breaking. This phenomenon occurs roughly at the 1 TeV scale, which the LHC will access directly. The merits of any additional machine must therefore be evaluated within the context of the LHC program. A TeV-scale e^+e^- linear collider (LC) is a leading candidate for such a facility. Such a machine offers control over the beam energy and polarization, and a clean environment that enables precision event reconstruction. In this paper I illustrate aspects of the LC physics program with examples drawn from Higgs physics, top quark physics, and the study of large extra spacetime dimensions. More comprehensive reviews of physics at e^+e^- linear colliders are given in Refs. [1], [2], and [3].

MACHINE AND DETECTOR OVERVIEW

Well-developed LC designs have been put forward by the SLAC-KEK joint effort (the NLC/JLC designs) [4] and by DESY (the TESLA design) [5]. The two machines differ technologically but achieve similar ends. The NLC uses warm rf cavities operating in the X-band (11.4 GHz). The baseline design assumes initial operation at $\sqrt{s} = 500$ GeV at a luminosity of 5×10^{33} cm^{-2}s^{-1}, with an e^- beam polarization of 80-90%. The linac is designed to allow adiabatic energy upgrades to $\sqrt{s} = 1$ TeV through the addition of klystrons. The size of the beam-delivery and final focus systems would allow eventual operation at 1.5 TeV. The TESLA design uses superconducting rf operating at 1.3 GHz, and reaches a center of mass energy of 800-1000 GeV. Initial operation would be in the 200-500 GeV range, with an e^- polarization of 80% as well as a positron beam polarization of 60%, which would introduce new measureables into physics processes. This design permits operation at very high luminosity, up to 5×10^{34} cm^{-2}s^{-1}. The two designs have rather different beam characteristics and time structures. A brief comparison of the TESLA and NLC parameters is shown in Table 1; a more complete list can be found in Ref. [6].

Designing a detector for a linear collider is widely regarded, at least by those who work at hadron colliders, as an easy problem. Certainly the LC does not share the LHC's formidable challenges of high event rates and radiation exposures. The challenges for a linear collider detector stem from the desire to fully exploit the clean machine environment by building a detector of the highest possible precision. Current designs are evolutionary extensions of the LEP and SLD detectors and feature CCD pixel vertex detectors, silicon or TPC outer trackers, and a fine-grained EM calorimeter located inside the magnet coil. Several designs incorporate the hadronic calorimeter inside the coil as well. In contrast to the LHC where triggering is a major challenge, at a linear collider the full detector can be read out between bunch trains and triggers formed in software.

TABLE 1. Summary of JLC/NLC and TESLA accelerator parameters. Luminosities include the pinch enhancement.

Design	$\sqrt{s}$ (GeV)	Lum. ($\times 10^{33}$)	bunches/ pulse	bunch sep. (ns)	$\delta E/E$ (%)	σ_x/σ_y at IP (nm)
JLC/NLC 500	500	6.5	95	2.8	3.7	330/4.9
JLC/NLC 1000	1000	12.9	95	2.8	10.3	234/3.9
JLC/NLC 1500(B)	1478	12.4	95	2.8	14.1	200/3.7
TESLA	500	30	2820	337	2.8	553/5
TESLA	800	50	4500	189	4.7	391/2
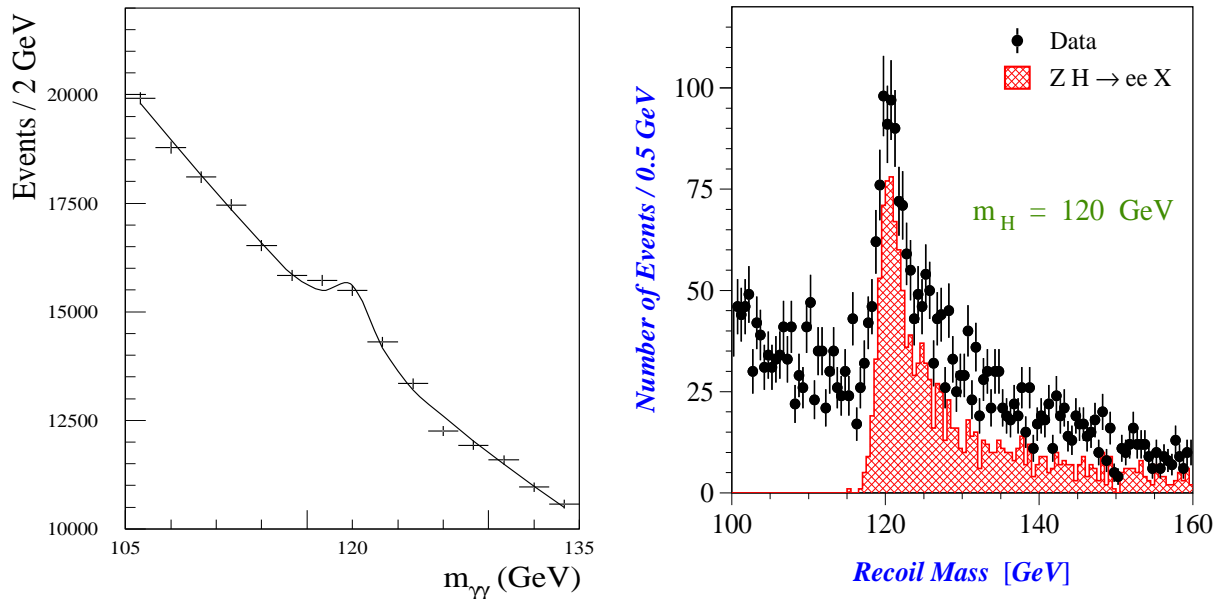
FIGURE 1. 120 GeV Higgs comparison. Left: $H \to \gamma\gamma$ signal in 100 fb^{-1} at the LHC [10]. Right: $ZH \to \ell^+\ell^- X$ signal at the LC for 500 fb^{-1} at $\sqrt{s} = 350$ GeV [11].

LIGHT HIGGS PHYSICS

Current electroweak data point to the existence of a light Higgs between roughly 100 and 200 GeV, with the lower end of this range being favored by the fits [7]. If so, the Higgs may be discovered in the near future at LEP [8] or the Tevatron [9], but if not there then certainly at the LHC. A Higgs in this mass range can be convincingly observed at the LHC through such channels as $H \to \gamma\gamma$, $H \to ZZ^{(*)}$ or $WW^{(*)}$, and production of $t\bar{t}H$ followed by $H \to \gamma\gamma$ or $b\bar{b}$ [10]. Yet the LHC cannot see, or can see only with great difficulty, many important Higgs decays, such as $H \to c\bar{c}$ and $H \to \tau^+\tau^-$, that are critical to determining if this object is indeed *the* Higgs, the relic of electroweak symmetry breaking that couples to fermions in proportion to their masses.

At the LC, a light Higgs can be cleanly observed in recoil off the Z [11,12]. The cross section for this process peaks in the 250-400 GeV range, making light Higgs physics an attractive target for the initial phase of the LC physics program. Since the signature of this process is a monoenergetic Z boson, these events can be reconstructed with high efficiency independent of the Higgs decay mode. This gives a clean inclusive sample in which to study Higgs decays, measure m_H to 100-200 MeV (similar to the LHC), and obtain an extremely precise measurement of the H-Z Yukawa coupling [12]. A sample recoil mass plot is shown in Figure 1, in comparison to the dominant $H \to \gamma\gamma$ discovery signal for the same-mass Higgs at the LHC.

To exploit this inclusive sample fully, however, it is necessary to have a vertex detector capable of cleanly separating bottom, charm, and light quark jets. This ability is provided at the LC by a CCD pixel vertex detector, which can be located as close as 1 cm from the beam. Such a device is far too slow and rad-soft to be practical at a hadron collider, but the more forgiving environment of the LC allows one to exploit its superior spatial resolution for excellent flavor separation. The payoff of this capability is demonstrated in a recent study by Battaglia [13], summarized in Figure 2. With 500 fb^{-1} at $\sqrt{s} = 350$ GeV, the branching ratios $H \to b\bar{b}, c\bar{c}, \tau^+\tau^-, gg$, and WW* can be measured with an

accuracy of 2-5%. Interestingly, the $H \to \gamma\gamma$ mode, which is the prime discovery channel for a ~ 120 GeV Higgs at the LHC, is undetectable in this production mode at the LC due to its very small ($\sim 10^{-3}$) branching fraction. (The inverse process $\gamma\gamma \to H$ can be observed if the LC is operated as a $\gamma\gamma$ collider, using backscattered Compton photons from the primary e^+e^- beams.)
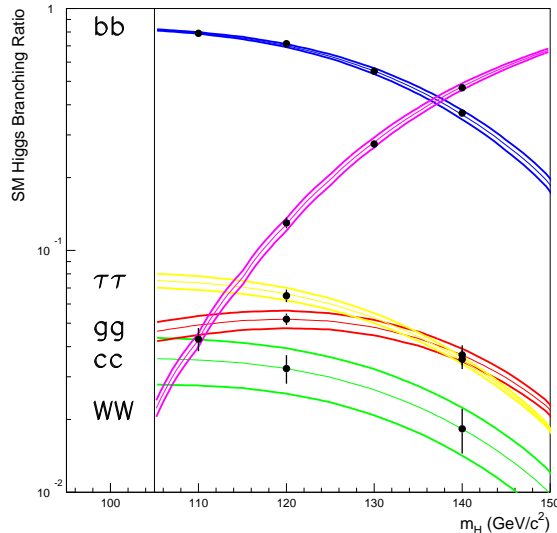
FIGURE 2. Predicted SM Higgs branching ratios, together with the measured values obtainable with 500 fb^{-1} at $\sqrt{s} = 350$ GeV, from the study in Ref. [13].

This ensemble of branching ratio measurements can be used to distinguish a SM Higgs from the lightest Higgs (h^0) of the MSSM. Typically the branching ratios of the h^0 are equal to those of the SM Higgs, times a function of $\tan\beta$ and M_{A^0}, where the A^0 is the heavy, CP-odd Higgs of the MSSM. A likelihood fit can therefore be used to determine whether the collection of observed BR's is more consistent with the SM or with the MSSM. Separation of the SM from the MSSM Higgs can be determined at the 90% confidence level with the above measurements for M_{A^0} up to 730 GeV, with the dominant uncertainty coming from knowledge of the b and c quark masses [13]. If SUSY exists at this scale, it will most likely have been discovered at the LHC, but measurements such as this will constitute a vital precision test that can only be performed at the LC, as a muon collider, too, has difficulties with high-precision charm ID.

TOP QUARK PHYSICS

The top quark's privileged status as the most massive known matter particle, and the only fermion with a mass at the "natural" electroweak scale, make it a prime target for all future colliders. The LC aims to carry out a complete program of top quark physics, including measurements of top's mass, width, form factors, and, perhaps most interestingly, its Yukawa coupling to the Higgs. Furthermore, the process $e^+e^- \to t\bar{t}\nu\bar{\nu}$, accessible at a 1.5 TeV LC, can be a sensitive probe of electroweak symmetry-breaking by new strong interactions [14].

The mass of the top quark, m_t, is a precision electroweak parameter that affects relationships among other electroweak observables such as M_W, M_Z, $\sin^2\theta_W$, and m_H. Future measurements at the Tevatron and the LHC are likely to give a 2-3 GeV precision on m_t, dominated by systematics. At the LC, the top quark's mass can be determined to about 100-200 MeV, and the width to about 7%, in a relatively low-luminosity (10-50 fb^{-1}) threshold scan [15]. But what would we gain from such a high precision measurement? Table 2 shows the fractional precision on m_H that would follow from various uncertainties on M_W and m_t [3]. A 200 MeV uncertainty on m_t, together with a 15 MeV uncertainty on M_W (which may be achievable from a high-luminosity return to the W pair threshold with the LC) yields a 17% uncertainty on m_H. For comparison, an uncertainty of about 50% is expected from measurements at LEP II and the Tevatron. The Higgs is likely to have been discovered by the time the LC makes this measurement, in which case it will serve as a key consistency test—much like the comparison of the directly measured m_t to the value inferred from electroweak data does today.

Experiment	$\delta M_W, \delta m_t$	$\delta m_H/m_H$
LEP II + Tevatron	30 MeV, 4 GeV	57%
LEP II + LHC	15 MeV, 2 GeV	26%
LC	15 MeV, 200 MeV	17%

Of still greater interest, however, is a direct measurement of the top-Higgs Yukawa coupling, $\lambda_{t\bar{t}H}$. Such a measurement, like those of the Higgs branching ratios discussed above, is needed to establish the "Higgsness" of the Higgs, and may also probe the special nature of the top quark. At the LHC, the ratio $\lambda_{t\bar{t}H}/\lambda_{WH}$ can be measured to an accuracy of 25% for $80 < m_H < 120$ GeV [10]. For a light Higgs, $\lambda_{t\bar{t}H}$ can be measured at the LC in $t\bar{t}H$ production. For Higgs masses around 120 GeV, the cross section for this process peaks at about 2.6 fb for $\sqrt{s} = 700$-800 GeV and then falls off slowly. This is some three orders of magnitude smaller than the dominant $t\bar{t}$, WW, and $t\bar{t}Z$ backgrounds. But the spectacular nature of these events ($qqqqbbbb$ if both tops decay hadronically, or $qqbbbb + \ell^{\pm} + \not{E}$ if both tops decay semi-leptonically), and their many kinematic constraints, provide enough handles that backgrounds can be acceptably reduced through direct mass reconstruction [16] or a neural net [17]. In the latter study, the authors assume 1000 fb^{-1} (about 3 years of running at $\mathcal{L} = 10^{34}$) at $\sqrt{s} = 800$ GeV, and obtain a 5.5% uncertainty on $\lambda_{t\bar{t}H}$. Outstanding flavor-ID is again a prerequisite for this measurement. The possibility of measuring $\lambda_{t\bar{t}H}$ with such high precision is a strong argument in favor of the highest possible luminosities.

LARGE EXTRA DIMENSIONS

The recent proposal [18,19] to resolve the hierarchy problem through a theory of low-scale quantum gravity with large extra spacetime dimensions has generated great interest because of its testable consequences at colliders [20–22]. In these models, Standard Model fields are confined to the 4-dimensional boundary of a "bulk" with n compact extra dimensions of characteristic size R. Gravitons propagate in the bulk, where they couple with a strength of order the electroweak strength (hence the elimination of the hierarchy). The apparent weakness of gravity in our 4-dimensional world arises from the geometrical suppression of the gravitational flux lines by a factor proportional to the volume of the compact extra dimensions:

$$M_{\rm Pl}^2 = V_n M_s^{n+2},$$

where $M_{\rm Pl} = 10^{19}$ GeV is the Planck scale, $V_n \sim R^n$ is the volume of the compact extra dimensions, and M_s is the fundamental Planck scale in the bulk. If we require $M_s = \mathcal{O}(\text{few TeV})$ to eliminate the hierarchy, we can obtain the characteristic size R of the extra dimensions for various values of n. Values of R as large as a fraction of a millimeter are permitted by current limits from Cavendish-type experiments [23].

For phenomenological purposes, we are most concerned with the effective Lagrangian that describes the interactions between gravitons and SM fields in our 4-dimensional world [21]. Gravitons then appear as a Kaluza-Klein tower, or series, of closely-spaced massive spin-2 states that can be emitted or exchanged along with SM gauge bosons. Each such state has a very weak coupling to matter, of order $1/M_{\rm Pl}$, but because of the large number of these states their cumulative effect is comparable to that of Standard Model processes at energies near M_s.

One way to search for the effect of these large extra dimensions at the LC is through the effect of graviton exchange on fermion pair production [22]. This process is extremely well-understood theoretically and is a sensitive probe of many types of new physics, including Z''s, compositeness, and technicolor. Graviton exchange turns out to leave the total cross section and integrated left-right asymmetry unchanged, but modifies the angular distributions in a way that depends on a single parameter, λ/M_s^4. Here λ is a dimensionless parameter of order one (but of either sign) that depends on model-dependent physics above M_s. A fit to the angular distribution of $e^+e^- \to \ell^+\ell^-, b\bar{b}$, and $c\bar{c}$ gives the exclusion reach shown in Figure 3(a). A 1 TeV LC with 200 fb^{-1} can exclude M_s up to 6.6 TeV, similar to the 6.0 TeV achievable with the LHC in 100 fb^{-1} using e^+e^- and $\mu^+\mu^-$ final states only. However, the LHC may have difficulty distinguishing a graviton signal from some other new physics process, such as a Z'. At the LC, the polarized beams and the ability to observe $b\bar{b}$ and $c\bar{c}$ final states allow a clear separation between spin-1 and spin-2 exchange for M_s up to about $5\sqrt{s}$, as shown in Figure 3(b).
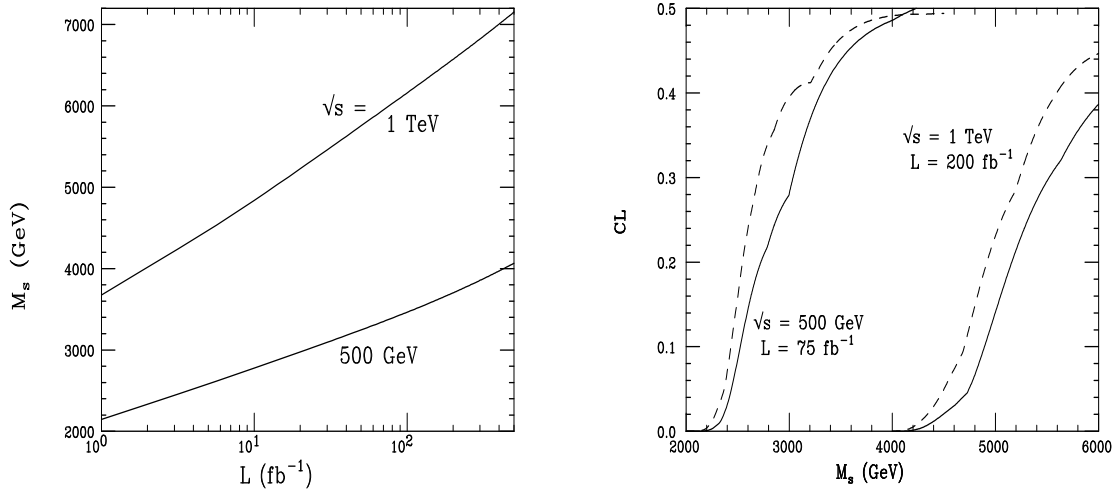
FIGURE 3. Sensitivity of the LC to low-scale quantum gravity, from Ref. [22]. Left: 95% confidence level exclusion reach as a function of integrated luminosity for $\sqrt{s} = 500$ GeV and 1 TeV. Right:Confidence level of fitting low-scale quantum gravity "data" with a given M_s to the hypothesis of spin-1 exchange, demonstrating the ability of the LC to distinguish spin-2 from spin-1 exchange for M_s up to about $5\sqrt{s}$. The dashed (solid) curves correspond to $\lambda = +1(-1)$.

CONCLUSIONS

TeV-scale e^+e^- linear colliders offer complementary access to the physics of electroweak symmetry breaking that will be explored initially by the LHC. Assuming that both the NLC and TESLA designs prove technologically (and financially) feasible, the choice of which one to build may depend on the relative importance of high luminosity for the highest precision measurements at lower energies (TESLA), versus upgradability to 1-1.5 TeV for exploratory physics and possible fuller elucidation of the SUSY spectrum. More advanced accelerator designs, such as the two-beam CLIC [24] design, may open the path to even higher energies in coming decades, ensuring a vibrant future for e^+e^- physics in the post-LHC era.

ACKNOWLEDGEMENTS

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