The Next e^+e^- Linear Collider

Arthur K. A. Maciel

Physics Department, Northern Illinois University, DeKalb, IL 60115 USA

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Following the recent realization by the worldwide high energy physics community for the need of a next generation e^+e^- collisions machine, we review the main reasons for such a proposal, and the current status of that endeavor. General aspects of the physics program, the collider itself, and its detectors are covered.

1 Introduction

The field of High Energy Physics (HEP) has experienced several leaps in the understanding of the subatomic world during the past three to four decades. In the late 1960's deep inelastic (e^-N collision) experiments revealed the existence of nucleon substructure, and the 1970's solidified the new (and current) concept of elementarity, with quarks and leptons organized in three generations. The existence of some entries was first speculated, then observed in the ensuing decades. Flavordynamics, neutral currents and the electroweak (EW) unification as a gauge theory were juxtaposed with the quantum chromodynamics of the strong interactions, to yield this spectacularly successful model of the fundamental interactions known as the Standard Model (SM). Since the pivotal observation of the EW gauge bosons (by the UA1 and UA2 collaborations at CERN) in 1983, the experimental activity in the HEP frontier may be broadly summarized as a persistent and ever more accurate confirmation of the predictions of the SM, eventually achieving part-per-mil precision in some key measurements such as parity violating asymmetries performed at the e^+e^- colliders at CERN and SLAC. A particularly noteworthy event was the discovery of the top quark (by the CDF and DØ collaborations at Fermilab) in 1995, thus completing the cadre of expected matter particles (fermions) in the SM. Equally rewarding has been the ever increasing cross fertilization among the fields of HEP and Cosmology, whose rapport has evolved in the past few decades from intimate to *symbiotic*, with the emergence of one fundamental field of research often called *astroparticle* physics.

Despite the recent progress, there is however compelling evidence that the SM model cannot be the ultimate theory of the fundamental interactions. Among its foremost problems is the fact that the (mass giving) non-gauge sector of the fundamental interactions is incomplete and unexplained. A postulated scalar *Higgs* boson has not yet been observed, nor is its mass predicted by the theory. Equally disturbing is the mere concept of a fundamental scalar boson in the SM framework, since its mass will undergo quantum corrections that are quadratically divergent, and will require cancellation mechanisms that are hard to justify (the "hierarchy problem").

HEP now faces a new set of fundamental questions, led by the need to understand the origin of electroweak symmetry breaking (EWSB) with its associated mechanism that endows masses to the elementary particles. A creative stream of tentative answers has been steadily flowing, and a distinct trait that seems common to all proposals is that some kind of new physics phenomenology must exist at an energy scale that does not exceed one (or a few) TeV. This new physics is of course expected to hold the SM as some form of low energy limit, but beyond that it should also address EWSB and the origin of mass, explain flavor and flavor generations, hopefully bring added hints (or fully explain) grand unification, and perhaps reveal the unseen elements of the universe (*e.g. dark matter*). Candidate theories may be broadly classified as weakly coupled (*e.g. Supersymmetry*), strongly coupled (*e.g. Technicolor*), as well as various models with additional space dimensions, some dedicated to accomodating fundamental gravity.

It is extraordinary that the answers to most of the current fundamental questions in HEP seem to live in the few TeV range, and that we are about to experimentally reach this energy scale. The main motivation behind this article is a discussion of how best to prepare for this new era of HEP challenges. We review the proposal that a new e^+e^- Linear Collider [1], with the characteristics and parameters to be discussed below, is a key element in the set of tools that need to be in place for this new chapter in HEP exploration.

2 Hadron and Lepton Colliders

The question we are trying to answer is; what is the best set of tools for efficiently mapping out the new physics expected at the TeV scale? The Large Hadron Collider (LHC) — a 14 TeV C.M. proton-proton collider — is under construction at CERN and on schedule to start operations in 2007[2]. One unmistakable lesson that we have learned from recent past experience is that of the *complementarity* between hadron and lepton colliding machines. A pattern has emerged that most discoveries were made at hadron machines, followed by precision studies at lepton machines, and a clear example is again the observation of the EW gauge bosons in the $Sp\bar{p}S$ at CERN, followed by the detailed studies of their properties in e^+e^- colliders at CERN (LEP) and SLAC (SLC).

TABLE I. LHC production rates at $\mathcal{L} = 10^{33} cm^{-2} s^{-1}$ for a few benchmark processes. Note that 1 *Snowmass* year $\sim$ 10^7 secs (physics running).

process	evts/yr.	total collected at other machines by 2007
$W \rightarrow e\,\nu$	10^8	10^7(Tevatron) , 10^4(LEP)
$Z \rightarrow e\,e$	10^7	10^5(Tevatron) , 10^7(LEP)
$\bar{t}t$	10^7	10^4(Tevatron)
$\bar{b}b$	10^{12}	10^9(Belle/BaBar)
$H(m_H = 130\,GeV)$	10^5	(?)
$\tilde{g}\tilde{g}(m = 1\,TeV)$	10^4	(?)

Hadron colliders reach the highest accessible beam energies and therefore can be thought of as the natural pushers of the energy frontier, the powerful probes that first access a new energy range, the *discovery machines*. This is the role expected of the LHC[3] whose dynamic reach is such that it should discover or exclude any form of an EWSB Higgs-like sector, and should reveal or exclude Supersymmetry (*SUSY*) in most of its parameter space. To exemplify that reach, we list in table 2 the production rates of the LHC in its “low” luminosity regime for a few benchmark processes. Note for instance the top quark pair production at a rate of one per second.

Parton-parton collisions in hadron machines imply a wide band of C.M. energies and a wide range of physics processes and final states. Some of the drawbacks are (i) very large backgrounds due to the strong interactions, and (ii) largely unknown initial state quantum numbers and C.M. energy and momentum. In sharp contrast, e^+e^- collisions have well defined initial “parton” four- momenta and quantum numbers ($J^P = 1^-$). They naturally bypass the uncertainties introduced by parton density functions (PDF’s) in hadron colliders, and avoid difficulties associated with the perturbative breakdown of the strong interactions under certain conditions. Another consequence of structureless particles in the initial collision is a precise access to the missing energy due to unobserved final state particles. This is a major asset of e^+e^- colliders, where the systematic causes of beam energy smearing (initial state radiation and beamstrahlung) are measurable and well understood.

Lepton colliders (and the case here is made for e^+e^- collisions) are therefore the natural *precision machines*, with a much simpler collision environment than that of hadron machines. Most processes in e^+e^- collisions have simple two-body kinematics, and their cross sections are largely comparable. Exotic processes share a large fraction of the total e^+e^- annihilation cross section, and final states of interest are relatively free of backgrounds. If cross sections are shared democratically among final states, they are however comparably much smaller than those of hadron colliders, and luminosity becomes a vital commodity. For a simple comparison, the top quark pair production rate in e^+e^- collisions at 500 GeV C.M. and $\mathcal{L} = 10^{34} cm^{-2} s^{-1}$ is about one per minute.

3 The Next Lepton Collider

As a complement to the LHC, the international HEP community is considering the construction of a new e^+e^- collider[4, 5, 6]. Given the fact that electron beam energy loss in a circular accelerating ring scales as the 4th power of the beam energy, the proposed collider energies, well above the Z boson mass, necessarily imply a *linear* collider. In fact, LEP represents the practical engineering limit for circular ring e^+e^- collisions. The proposed setup for this next e^+e^- machine consists of two identical linear accelerators shooting head-on against one another, with a total site length of about 30km[7, 8, 9].

A worldwide proposal for a next e^+e^- linear collider has been gathering momentum since the mid-90’s, and is now being carried out under the leadership of three main organizing bodies located in Europe[10], Japan[11] and the USA[12]. Given the common interests of these organizations, and the practical certainty that only one collider will eventually exist, an international linear collider steering committee (ILCSR) has been convened by the ICFA (the International Committee for Future Accelerators) with the charge of facilitating the convergence of all three projects into one optimized e^+e^- collider for the worldwide HEP community.

Very broadly, the proposed ILCSR convergence plan can be divided in three stages. (1) In the next few months the three interested regions (Europe, Japan and the USA) must come up with a technical proposal for their preferred choice of machine technology and parameters. (2) At the November 2003 meeting in Paris, the ILCSR shall appoint an international technical panel that must extract from the existing proposals a machine design that embodies the best of all proposed technologies and parameters. The timeline for this is the end of 2004. (3) The project then becomes one for the whole planet, an international collaboration sometimes referred to as the global linear collider (GLC).

Among the existing projects the current degree of convergence is remarkable, and some vital aspects of the proposals are already common ground: the next e^+e^- linear collider should (i) start operations at 500 GeV C.M., with energy extendable to about 1.2 TeV (ii) have enough flexibility to run at different C.M. energies, including the Z-pole, and perform precision C.M. energy scans for production threshold studies (iii) supply beams for two interaction halls (iv) start operations at an instantaneous luminosity around $\mathcal{L} = 2 \times 10^{34} cm^{-2} s^{-1}$, with an initial collection capacity of 200 fb^{-1}/yr of data. Note that while the energy upgrade with respect to the SLC (the existing linear collider) is of a factor of 10, the upgrade in luminosity covers four orders of magnitude! A technical review committee convened by the ICFA has recently completed a thorough review[13] of the status of the existing LC studies, and has concluded that the necessary technology already exists to support the construction of an e^+e^- linear collider with the desired parameters of energy, luminosity etc.

The two main accelerator technology options are; (i) superconducting (Nb) RF cavities favoring beam stability, and

(ii) room temperature (Cu) cavities favoring beam energy upgradability. The former tolerates longer bunch intervals and higher beam spot sizes, while the latter necessitates shorter bunch intervals and beams that are twice as narrow. Proposed beam spots are ∼5 to 10 nm, about the size of a virus! Bunch spacing in the european superconducting (TESLA[8]) proposal is 5 Hz while that of the warm counterparts in the USA (NLC[7]) and Japan (JLC[9]) is about 120 Hz.

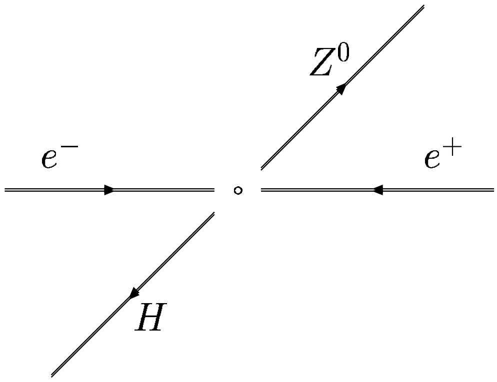
4 The Case for an e^+e^- Collider

The linear collider (LC) is expected to provide critical precision measurements to complement LHC findings, such as quantum number assignments and theory model discrimination. Given the observation of a scalar boson, the LC is a powerful tool in determining whether it is a Higgs or something else, with direct tests of whether it generates masses for (i) the gauge bosons, (ii) fermions, and (iii) itself. In the absence of a Higgs boson, it is also a precision tool in the scanning of resonances or other strong interaction effects in longitudinal WW scattering, as is expected in non-Higgs (or composite Higgs) EWSB models. In the case of observation of some new physics by the LHC, it is easy to come up with scenarios in which the LC could be extremely useful in determining whether it is a *SUSY* manifestation, under which specific model, and proceeding towards investigations of a *SUSY* breaking mechanism [14].

Beyond LHC complementarity, the LC has a rich program of its own, spanning QCD details such as fragmentation, precision flavor physics such as single top production and top polarization, and continued precision EW physics. A detailed review of the LC physics capabilities can be found in [14]. Here we highlight one particular and critical measurement that is unavailable to a hadron collider. Given a Higgs boson, the LC will have direct access to the full ZZH coupling (as well as the Higgs mass), independently of the Higgs decay modes, even if some modes exist that are invisible (such as $H \to \tilde{\chi}_1^0\tilde{\chi}_1^0$). Fig. 1 shows the resulting Higgs signal, after a simulation of the $e^+e^- \to ZH$ process, detected as the missing mass that recoils against the (mono-energetic) Z [15]. This measurement directly extracts the full g_{ZZH} coupling constant, responsible for *both* the $e^+e^- \to ZH$ cross section and for endowing the Z with its mass. One could therefore determine whether this coupling is responsible for the full Z mass, or possibly the existence of more Higgses otherwise. Given the high rates for associated ZH production, enough data for such a measurement could be collected in less than six months.

5 Collision Modes

One important property of e^+e^- machines is that beams can be polarized. Electron beam polarizations of about 80% have already been achieved at SLAC, and the polarization of positron beams, while not yet efficiently achieved, is under intensive study. A high degree of beam polarization (nominally 80% (e^-) and 60%(e^+)) is a key item in the LC project, and is instrumental in the separation of overlapping signals, in the selective suppression of backgrounds, in the measurement of parity violating couplings and many other applications. As an example, consider W-pair production ($e^+e^- \to W^+W^-$). This is the largest single process contribution to the e^+e^- annihilation cross section, and a potentially significant background in many studies. Because of maximal parity violation in the W couplings (left currents only), this cross section is extremely sensitive to beam polarization, as demonstrated in Fig. 2. The fact that the total rate for this process can be reduced by about a factor of 30 simply with R-polarization of the electron beam, makes beam polarization an ideal *dial* for reducing (or determining) background levels. Besides, $\sigma(e^+e^- \to W^+W^-)$ is very sensitive to the SM relations between $WW\gamma$ and WWZ couplings, making comparative measurements with different beam polarizations a powerful test-bench for trilinear gauge coupling anomalies. Other examples of uses for beam polarization will be given.



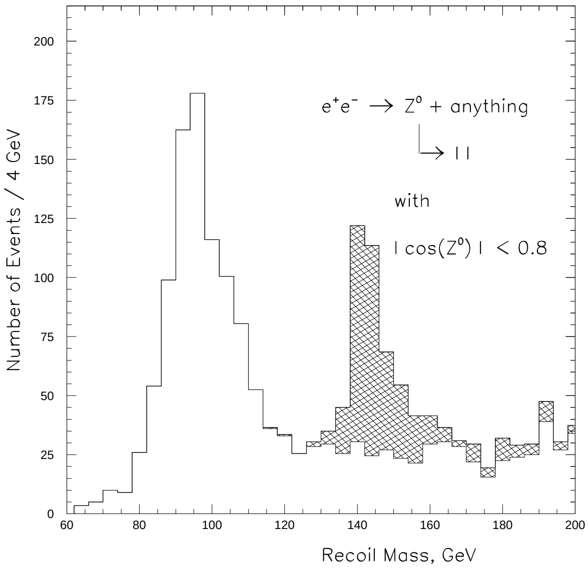


Figure 1. Dilepton(Z) recoil mass in the simulation of $e^+e^- \to ZH$ ($Z \to \ell^+\ell^-$ and H →anything) for a Higgs mass of 140 GeV. The C.M. energy is 360 GeV, and the integrated luminosity is 50 fb^{-1} [15].

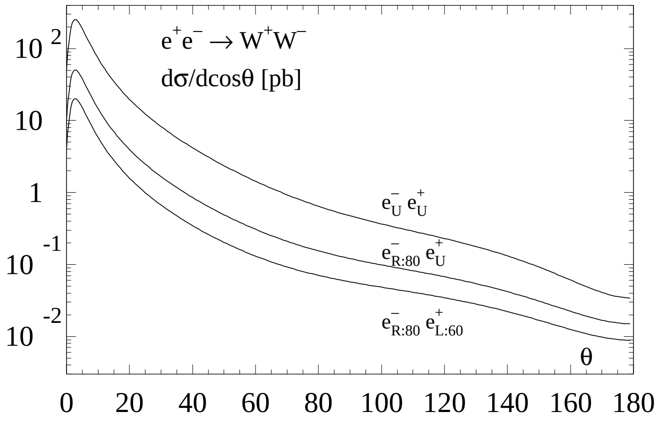


Figure 2. The effect of beam polarization on $\sigma(e^+e^- \to W^+W^-)$. U denotes unpolarized beam, then adding 80% e^-(Right) and 60% e^+(Left). θ is the scattering angle.

Another important aspect of e^+e^- colliders is that nearly monochromatic γ beams can be achieved by shinning a high intensity laser beam against the primary e^- beam. Compton backscattering of the laser light will provide the secondary γ beam. Electron polarization to a high degree (and opposite to the laser beam helicity) is a necessity here, in order to reduce e^+e^- conversions near the collision point and thus enhance monochromaticity in the resulting γ beam. This is a technologically simple (and relatively inexpensive) extension to the collider hardware, and therefore an efficient method of achieving $e^-\gamma$ and $\gamma\gamma$ (besides e^+e^- and e^-e^-) collision modes.

There are many physics applications for the e^-e^- mode, despite the drawbacks (with respect to e^+e^-) of increased C.M. energy smearing due to initial state radiation (ISR) and beamstrahlung. One specific measurement of interest is that of s-electron ($\tilde{e}$) production in a *SUSY* scenario [16]. The t-channel exchange of a neutralino ($\tilde{\chi}^0_1$) between the two initial electrons is the best reaction for high precision measurements of $\tilde{e}$ (L& R)masses and need very little integrated luminosity since lepton number conservation acts as a natural $\tilde{e}$ selection mechanism.

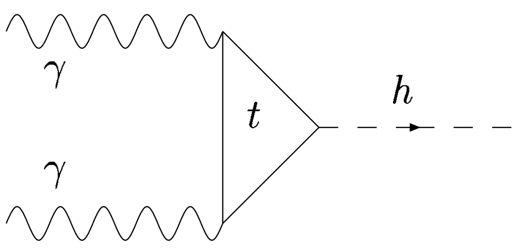


Figure 3. Leading SM Higgs production mechanism in the $\gamma\gamma$ collision mode.

The $\gamma\gamma$ collision mode is above all an extremely clean Higgs factory, with very low backgrounds and ideal for collecting rare Higgs decays (*e.g.* for low mass couplings). The main production mechanism in the SM (Fig. 3) is through the top Yukawa coupling. This entails a high sensitivity to other massive particle states (such as s-top) that may interfere with the top loop. The determination of the $H \to \gamma\gamma$ partial width needs a lot less integrated luminosity if performed in the $\gamma\gamma$ collision mode. The same luminosity that achieves a $\delta\Gamma/\Gamma \sim 20\%$ in the e^+e^- mode, delivers an uncertainty $\delta\Gamma/\Gamma \sim 1\%$ in the $\gamma\gamma$ mode. The possibility of linearly polarized γ beams gives access to an interesting CP test. The asymmetry

$$\mathcal{A} = \frac{\sigma(\gamma_L\gamma_L) - \sigma(\gamma_R\gamma_R)}{\sigma(\gamma_L\gamma_L) + \sigma(\gamma_R\gamma_R)} \qquad (1)$$

will vanish for either a pure scalar or pure pseudo-scalar Higgs. The observation of a non-zero $\mathcal{A}$ will necessarily mean that the Higgs is a mixture of CP eigenstates (a CP violation quite similar to that in the $\overline{K}K$ system).

6 A Program for Higgs Studies

The main production diagrams for SM Higgs bosons in e^+e^- annihilations are shown in Fig. 4, and their respective cross sections for various values of the Higgs mass at two C.M. energies are in Fig. 5. For an example of event rates, suppose E_{cm}=500GeV, M_h=120GeV and $100 fb^{-1}$ of integrated luminosity (∼1 yr); this yields ∼6000 higgstrahlung (ZH) and 8000 WW fusion events. To illustrate the difference between gauge couplings and Yukawa couplings, we note that the largest of the latter (top-Higgs) is such that $\sigma(e^+e^- \to \bar{t}tH)$ barely makes it into the lower left corner of Fig. 5 for E_{cm} = 1 TeV.

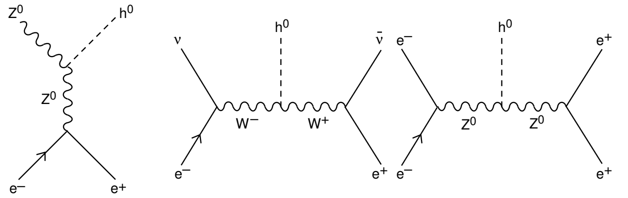


Figure 4. Leading SM Higgs production mechanism in the e^+e^- collision mode.

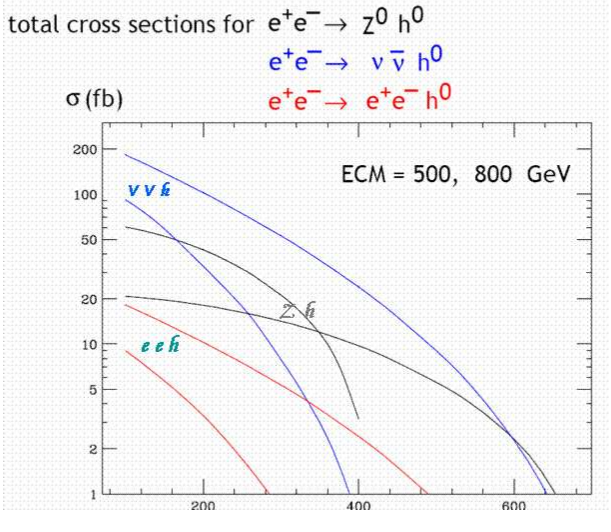


Figure 5. SM Higgs production as a fn. of its mass(GeV)

The initial Higgs program of course will consist of spectroscopy and quantum number determinations, followed by $\Gamma_{\rm tot}$ and individual coupling tests to determine its mass-giving nature. The LC expects to measure couplings and $\Gamma_{\rm tot}$ to better than 5%. A second neutral Higgs-like particle with $J^{PC} = 0^{-+}$ would be a strong pointer to *SUSY*. Another curiosity would be the access to the charm quark mass via the Higgs-charm coupling measurement, therefore bypassing the difficulties associated with charm bound states.

The determination of the Higgs spin and parity quantum numbers through ZH associated production is *e.g.* described in [17, 14]. This is a rather accurate measurement, unique to lepton colliders, where the angular distributions of the produced Z and H, and those of their decay products, are used in conjunction with a scanning of the cross section behavior near the production threshold to unambiguously determine J^P(Higgs). But we choose to highlight here a more difficult and elaborate measurement, one that is likely to be possible only at the next e^+e^- collider; that of the light Higgs self-coupling[18].

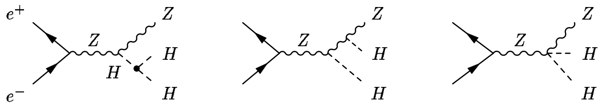


Figure 6. Double “Higgs-strahlung” diagrams in $e^+e^- \to ZHH$

Direct and independent measurements of the Higgs mass ($M_h^2 = 4\lambda v^2$) and of the Higgs self-coupling ($g_{hhh} = 6\lambda v/\sqrt{2}$) provide two-way access to the Higgs potential constant λ (as in $[V = \lambda(\Phi^2 - v^2/2)^2]$) and therefore represents a powerful constraint on the SM validity, or a pointer to new physics. The Higgs self-coupling can be extracted from double “Higgs-strahlung” events ($e^+e^- \to ZHH$), with contributing diagrams shown in Fig. 6. Considering a light Higgs (*e.g.* below the WW threshold), their most favored decays are to $\bar{b}b$ pairs. This makes $H^2Z \to (\bar{b}b)^2(\ell^+\ell^-)$ the easiest final state signature, but it has a branching ratio of only 8%. Given the smallness ($\sigma(e^+e^- \to H^2Z) \approx 0.2fb$) of the signal cross section, a wider access to more final states (as well as integrated luminosity) becomes a vital asset. It is found[18] that the inclusion of generic two-jet Z decays is a necessity in this measurement. The analysis now deals with a difficult six-jet final state ($H^2Z \to (\bar{b}b)^2(\bar{q}q)$), but benefits from an added branching fraction of 60%.

Main backgrounds to the six-jet ZHH final states are due to triple boson production($\sigma(e^+e^- \to WWZ) \approx 28fb$ and $\sigma(e^+e^- \to ZZZ) \approx 1.5fb$) and must be rejected through reconstructed di-jet masses. This puts an extremely high strain on precision calorimetry, and is commonly cited as one of the performance benchmarks for the proposals of calorimeters for the next e^+e^- linear collider. We will return to this point when we consider detectors. The use of beam polarization to detect gauge boson contamination levels plays a vital role here. Detailed simulation studies[18] indicate that a measurement of λ to an accuracy of $\Delta\lambda/\lambda \approx 20-30\%$ can be achieved after the collection of $1000fb^{-1}$ of data.

7 A Program for Supersymmetry

Perhaps second to the observation and understanding of the Higgs sector comes the need to explain the origin of its existence (*i.e.* EWSB). It is well known that the SM Higgs boson is unstable (the hierarchy problem) to quantum corrections in its mass which diverge quadratically. *SUSY* tames these corrections into only logarithmic divergences, a huge solution to a huge problem. At the same time, *SUSY* provides a (radiative) mechanism for EWSB — the Higgs field naturally condenses into vacuum if the top quark is massive (it needs $150 < m_{top} < 200\ GeV$) just as observed. Being a weakly coupled theory, *SUSY* remains compatible with all precision EW measurement results (the MSSM value for $\sin^2\theta_w$ matches experimental observation to better than 2 ppm) and with a light Higgs boson. *SUSY* predicts the correct unification relation among the SM-like gauge coupling constants $g_3\ g_2\ g_1$, and holds the neutralino($\tilde{\chi}_1^0$) as a natural candidate for cosmological *dark matter*. While all this represents a remarkable achievement, it comes at the expense of introducing a parameter space that is so vast as to house various forms of sub-models and scenarios. Nevertheless, among all proposals for (beyond SM) TeV scale theories, we believe that *SUSY* is (arguably) the one most strongly motivated.

It is of course expected that, if *SUSY* exists, the LHC should find it relatively soon [3]. Given that, some of the main goals for a *SUSY* program at the linear collider would be; (i) to determine the underlying *SUSY* model (a severe reduction of parameter space) through a survey of masses, couplings, quantum numbers and other parameters. (ii) to understand the spontaneous *SUSY* breaking mechanism and deduce its scale. (iii) to dedicate special focus to *dark matter* candidates. If the neutralino, then use beam polarization to resolve its higgsino/wino/bino contents. (iv) mixing angles and heavy sleptons versus $\tan\beta$, flavor physics (generation patterns), search for FCNC, CP phases etc.

The simplest (yet very informative) *SUSY* process at the linear collider is that of s-muon pair production ($e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-$) with a single leading diagram as shown in Fig. 7. Typically the s-muon will decay ($\tilde{\mu} \to \mu + \tilde{\chi}_1^0$) into a muon and a neutralino which escapes undetected. The final state consists of a $\mu^+\mu^-$ pair plus missing energy ($\not{E}$). This large $\not{E}$ component leaves only W-pair production as a background candidate, which can be understood, measured and removed by means of different beam polarizations. The scalar muon decays isotropically and the boost in the lab frame gives the final muon a flat energy distribution with endpoints $E_\pm$ as shown in Fig. 7, and algebraically given by

$$E_\pm = \frac{\sqrt{s}}{4}(1\pm\beta)(1-\frac{m^2_{\tilde{N}^0}}{m^2_{\tilde{\mu}}})\ ;\ \beta = (1-\frac{4m^2_{\tilde{\mu}}}{s})^{1/2} \quad (2)$$

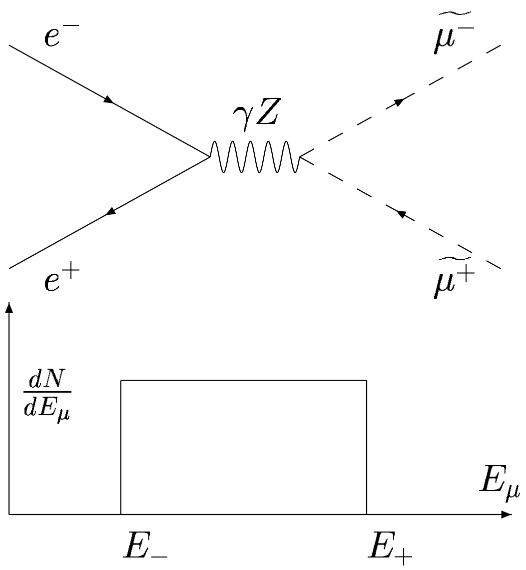


Figure 7. e^+e^- annihilation into a s-muon pair.

The $\tilde{\mu}$ and $\tilde{\chi}_1^0$ masses can be accurately extracted [19] from the observed muon spectrum endpoints ($E_\pm$). This procedure is simpler for the lighter $\tilde{\mu}_R$ pair production, and slightly more involved for the heavier $\tilde{\mu}_L$ variety (see ref.[19]). Further *SUSY* checks can be performed over the same events. The e^+e^- annihilation cross section to a massive scalar pair takes the form

$$\frac{d\sigma}{d(\cos\theta)} \sim \frac{\alpha^2}{s}\,\beta^3\,\sin^2\theta\,|f_p|^2 \qquad (3)$$

where β^3 is the expected p-wave threshold behavior, $\sin^2\theta$ is the p-wave angular distribution for the decay products and f_p holds the γZ interference effects due to initial state polarization.

Improvements on s-particle masses may be achieved through production cross section scans near threshold (constrains β), and the shape of the onset, as well as the angular distribution of the final muons, can be used to confirm $\tilde{\mu}$ quantum numbers. Furthermore, given that
– the γ couples to $Q = I^3 + Y$ with strength e
– the Z couples to $(I^3 - s_w^2 Q)$ with strength $e/(s_w c_w)$
the factor $|f_p|^2$ in equation 3 will vary according to initial and final state helicities as indicated (relative normalization) in the following table [20];

$\lvert f_p\rvert^2$	$\tilde{\mu}_L^+\tilde{\mu}_L^-$ $(I^3 = 1/2\;Y = 1/2)$	$\tilde{\mu}_R^+\tilde{\mu}_R^-$ $(I^3 = 0\;Y = 1)$
$e_L^- e_R^+ \rightarrow$	1.0	0.21
$e_R^- e_L^+ \rightarrow$	0.21	0.85

With different options of beam polarization one may (yet again use s-muon pair production to) check whether *SUSY* is preserving the SM gauge relations as it should.

Instead of pursuing with further *SUSY* analysis examples (for reviews see [4, 5, 14]) we conclude this section with some comments on the complementarity between *SUSY* measurements in the LHC and the LC [21].

LHC reactions are QCD dominated, and typical *SUSY* events will have lengthy decay cascades of squarks (Fig. 8) or gluinos. Under such crowded environment the problem becomes the discrimination of many different decay channels that originate from many possible parent states, and *SUSY* becomes an important background to *SUSY*, thus enhancing the model dependence of event interpretations. A further difficulty is the LSP ($\tilde{\chi}_1^0$) at the end of every decay chain. A hadron collider has no access to the 4-vector "missing energy", and therefore no direct access to mass reconstruction, but only to mass relations. One of the main analysis tools for the extraction of mass relations is the identification of kinematic end-points for combinations of visible particles that belong to a same decay chain. For example, in the neutralino decay (see Fig. 8) $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^+\ell^- \rightarrow \tilde{\chi}_1^0\ell^+\ell^-$, the $\ell^+\ell^-$ mass distribution has an end-point with a sharp edge at $M_{\ell\ell} = \sqrt{\frac{(M^2_{\tilde{\chi}_2^0} - M^2_{\tilde{\ell}})(M^2_{\tilde{\ell}} - M^2_{\tilde{\chi}_2^0})}{M^2_{\tilde{\ell}}}}$ as is shown in Fig. 9.

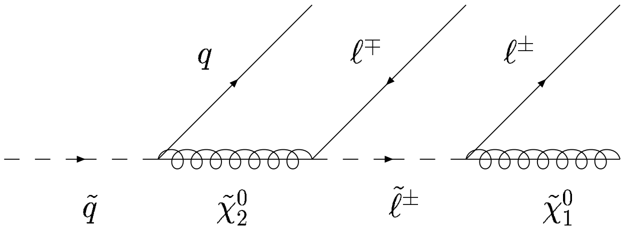


Figure 8. Example decay chain of a s-quark.

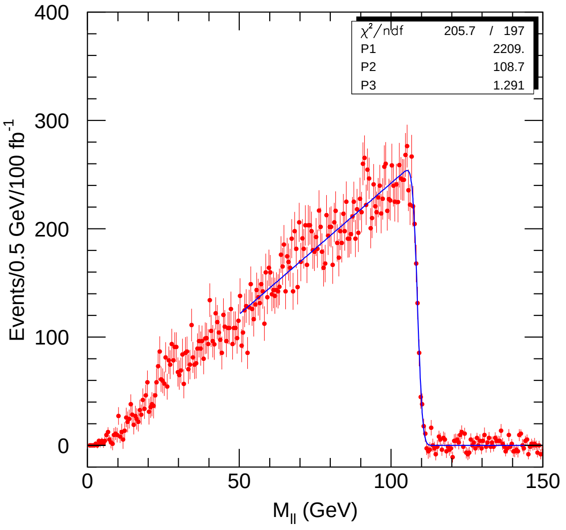


Figure 9. Dilepton kinematic edge in $\tilde{\chi}_2^0$ decay (Atlas TDR).

Such end-point analyses introduce strong s-particle mass inter-dependences and correlations. *SUSY* studies at the LHC[3] often have the LSP ($\tilde{\chi}_1^0$) mass as the largest source of systematic errors. These, in some cases, *may go down by one order of magnitude* if the LC-measured $\tilde{\chi}_1^0$ mass is used as input![22] Reciprocally, various LC studies in *SUSY* will need the LHC discoveries and initial mass windows as input.

The strength of the LC *SUSY* program is that the events are simple and allow for no or minimal model dependence. Special features are the direct access to non-colored states, generally believed to be lighter than color, (pair production of neutralinos, charginos or sleptons) and access to mixing angles through beam polarization.

8 Detector Challenges

The main motivation behind the linear collider project is the potential for high precision measurements, and this requires unprecedented performance standards from its detectors. The typical cross section "democracy" among the various processes of interest in the e^+e^- annihilation environment, associated with the high luminosities that are being planned, imply that we may expect abundant statistics even for new or exotic physics. Detection systematics must necessarily match the statistical accuracy. One important item in detector development that does not represent a challenge to the LC is that of radiation hardness. Technology has already been developed that survives the many times hotter LHC environment.

Among some of the physics oriented performance goals for LC detectors are; (i) momentum resolution capable of reconstructing the recoiling dilepton (Z) mass in Higgs-strahlung events (see Fig. 1) with resolution better than beam energy spread (this due mostly to initial state radiation and beamstrahlung) (ii) two-jet mass resolution capable of clearly separating the $\bar{q}q$ decays of the W and Z bosons (the benchmark for calorimetry) (iii) hermeticity and coverage to very forward angles to precisely determine the missing momentum (iv) exceptional flavor tagging ability (with displaced vertices) to separate b, c and light quark jets (*e.g.* in the discrimination of Higgs couplings). Also desirable is the control over jet profiles for quark and gluon jet discrimination and enhanced τ identification.

A current and interesting debate concerning the tracking detectors is largely centered around two different technologies that may surround the inner high-resolution Silicon based vertex detectors. While large volume gas-filled tracking detectors are being proposed by the European [23] and Japanese [24] developers, the USA counterpart [25] suggests a smaller Silicon based tracking chamber. The ultimate goal of course is maximal resolution with minimal material density (to minimize multiple scattering). The gas detectors (such as time proportional chambers) naturally have lower densities, but the Silicon chamber studies are reaching comparable material density due to an absolute minimum of supporting structures (carbon fibers), with the added bonus of a significant cost reduction in the smaller calorimeters that will surround a more compact tracking volume.

While the steady stream of detector capability improvements is truly remarkable (see [26] and recent workshops reachable from LC web pages [10, 11, 12]), we do think that the giant step in detection techniques is occurring in calorimetry, where a rather new concept is being developed and tested, that of the *imaging calorimeter*, to be used in conjunction with the technique of *particle flow* reconstruction. We explain both next.

Consider 500 GeV C.M. collisions of type $e^+e^- \rightarrow$ hadrons. Table II shows the expected breakdown in percentual energy of the various final state components. Charged particles and photons carry about 90% of the detectable energy, the rest being due to neutral hadrons. The goal of the particle flow reconstruction method is to (i) use the hadronic calorimeter (HC) only for the neutral hadron component of the final state (ii) use the eletromagnetic calorimeter (EC) only for photons (iii) charged hadron and lepton momenta are to be extracted from the tracker with much better resolution than that available through calorimetry. Here the calorimeters act solely as particle identification devices. For this reason, the ability to image the various track paths and interactions through the calorimeter becomes more important than collective jet energy resolution. Charged tracks in the tracking chamber are used as seeds for calorimeter particle flow reconstruction. Electrons will be identified by their track matching EC showers, and charged hadrons by their matched HC showers. All showers associated with charged tracks are removed from calorimetry, the remainder being photons (EC) and neutral hadrons (HC). To minimize scattering material between the tracking chamber and the calorimeters and also to make use of the magnetic bending of charged tracks in the calorimeters, these are now placed inside the magnetic coil. This is a significant change from previous standards, and also a cost reduction in the (very expensive) calorimeters due to their consequent reduction in size.

TABLE II. Breakdown of final state component energies in $e^+e^- \rightarrow \bar{q}q$ events at 500GeV CM.

source	% of E_{tot}	detector
charged ptcles	60	Tracker
photons	20	EM Cal
neutral hadrons	10	Had Cal
neutrinos	10	Lost

The goal of imaging calorimetry places enormous constraints and challenges in calorimeter building and usage. The imaging ability requires a much finer segmentation than that of present calorimeters. As an example we compare the calorimeter in the DØ experiment (Tevatron) with 5×10^4 readout channels, to the expected $\sim 5 \times 10^7$ channels in the LC calorimeters. Problems associated with the routing of millions of detection signals are agravated by their being inside a magnetic field of 4-5 Tesla. Such conditions have led hadron calorimeter proponents to consider digital signal extraction from each small detection cell (*e.g.* two-bits, for below/above a set threshold). This reduction in information content may be the only way to render signal extraction and treatment manageable.

While particle flow calorimetry in the EC seems a solid bet [27], it is not yet clear that it can be achieved in the HC. Intense research and development efforts are under way in various institutions [28]. The leading EC designs consist of some 20 radiation lengths of ∼5mm thick tungsten plates as radiators, interspersed by collector layers of 5×5mm Silicon pixels. This is now the single most expensive sub-detector in the LC system. Various different options of HC technology are still under consideration. An informative study of calorimetry for the LC is that of reference [29], where the discrimination of W and Z di-jet masses mentioned above in connection with six-jet events and the Higgs self-coupling (see Figs. 6 and 10) is addressed in detail. This is a calorimetry performance target that is vital for the success of the LC program.

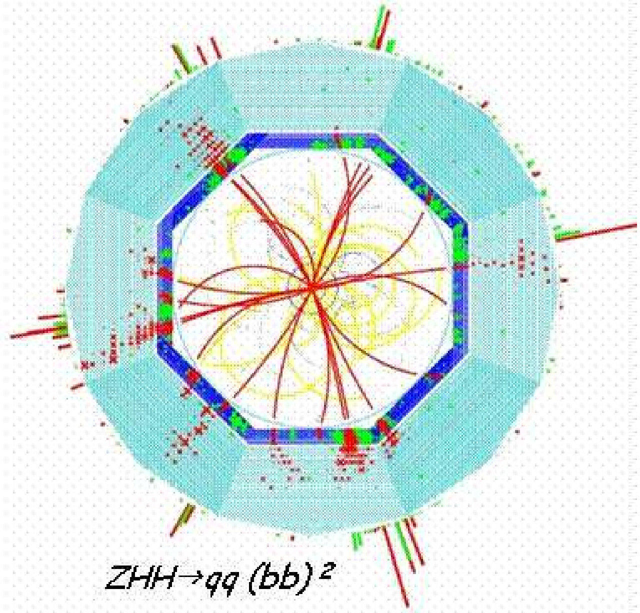


Figure 10. A six-jet event in the TESLA detector. Calorimeter thicknesses are about 20cm (EC) and 1 meter (HC).

9 Comments and Conclusion

While this brief review does not cover important phenomenology such as that associated with EWSB through new strong forces, or additional gauge bosons from extended gauge groups, we would like to add a comment on the somewhat intriguing idea that extra space dimensions may play a role in the TeV scale physics. A particular class of models [30] holds that our observable 4-dimensional world is a membrane in a space of more dimensions. The consequent dilution of gravity in this multi-dimensional world allows for fundamental quantum gravity to become a strong interaction well below the Planck scale, possibly even at the few TeV scale. If this is the case, effects of gravitational radiation become relevant for experiments at the LHC and the LC. Current searches for Graviton interference (virtual G-exchange effects), or direct (on shell) Graviton radiation at LEP and the Tevatron [31, 32] do place lower limits on the gravity scale at about 1 TeV. When repeated at the next generation of colliders (the LHC and the LC), these limits can be pushed further into the 10 GeV region. If the hypothesis of extra dimensions is true, the evidence will most likely come from collider experiments. Here again the LHC⊕LC complementarity may play a vital role, with brute force (higher C.M. energy) monojet searches at the LHC leading to a detailed access to the missing energy sources at the LC.

In conclusion, the present lore of HEP contains significant experimental evidence and enticing theoretical reasoning that important new physics exists at the TeV scale, and we are about to reach it. First, the LHC (circa 2008) is expected to reveal this new physics and indicate the critical items for detailed exploration. A few years later the next e^+e^- linear collider may join in the exploration program. Initially, a sub-TeV LC is planned for precision Higgs boson physics and EWSB scenario discrimination. Subsequent upgrades to higher energy may prove essential to understand in detail the nature of the new physics. The needed technology for the e^+e^- collider now exists — and beam polarization is a necessary ingredient in its program — but the project is very ambitious and alas, very costly (an estimated US$6B total). Such enterprise can only go ahead under truly global consensus and worldwide collaboration, and will probably represent another major advance in the sociology and inner organization of HEP. While we can only guess what new physics will show up, it is our belief that a sound program for this new age of exploration is taking shape. Indeed, these are extraordinary times in HEP...

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