Experimental Approaches at Linear Colliders

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1. Introduction

Precision measurements have played a vital role in our understanding of elementary particle physics. Experiments performed using e^+e^- collisions have contributed an essential part. Recently, the precision measurements at LEP and SLC have probed the standard model at the quantum level and severely constrained the mass of the Higgs boson [1]. Coupled with the limits on the Higgs mass from direct searches [2], this enables the mass to be constrained to be in the range 115–205 GeV. Developments in accelerator R&D have matured to the point where one could contemplate construction of a linear collider with initial energy in the 500 GeV range and a credible upgrade path to $\sim$ 1 TeV. Now is therefore the correct time to critically evaluate the case for such a facility.

The Working Group E3, *Experimental Approaches at Linear Colliders*, was encouraged to make this evaluation. The group was charged with examining critically the physics case for a Linear Collider (LC) of energy of order 1 TeV as well as the cases for higher energy machines, assessing the performance requirements and exploring the viability of several special options. In addition it was asked to identify the critical areas where R&D is required (the complete text of the charge can be found in the Appendix). In order to address this, the group was organized into subgroups, each of which was given a specific task. Three main groups were assigned to the TeV-class Machines, Multi-TeV Machines and Detector Issues. The central activity of our working group was the exploration of TeV class machines, since they are being considered as the next major initiative in high energy physics. We have considered the physics potential of these machines, the special options that could be added to the collider after its initial running, and addressed a number of important questions. Several physics scenarios were suggested in order to benchmark the physics reach of the linear collider and persons were appointed to maintain contacts with the relevant activities in the various Physics Working Groups. Special options considered were precision electroweak studies that could be done by running the collider at and near the Z pole (so called Giga Z running); collisions involving $\gamma\gamma$, e^+e^-, or $e\gamma$ interactions; and positron beam polarization. The following questions were posed in order to focus the discussions: (1) In view of the fact that the luminosity is a function of energy, what are the trade-offs involved in selecting the energy. (2) What is the argument for proceeding with the construction of a Linear collider as soon as possible rather than waiting for data from LHC? (3) In the context of a definite physics scenario, what is a realistic run plan (i.e., how much luminosity at each energy)? (4) What should be the initial energy of a linear collider and to what energy should that machine extended?

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While the reports from these various activities should be consulted for details [3, 4, 5, 6, 7, 8], the group summary will cover the most important activities and conclusions of the group. While we have tried to reflect the consensus of the working group, the conclusions expressed in this report are the responsibility of the authors.

Exploiting the full potential of a Linear Collider requires a powerful detector. The conceptual detector designs that have emerged from the TESLA [9],NLC [10] and JLC [11] are aggressive evolutions from the LEP and SLC detectors. These designs are driven by the requirements of precision measurements of the properties of a Higgs boson, reconstruction of final states involving W and Z bosons, and the precise mass measurement of new particles. These issues occupied many of the groups discussions [3] with a view to identifying the critical areas where R&D is needed.

As many important issues such as the experimental environment and the performance trade-offs involve machine physics, there were several joint sessions with the M3 group. In particular, we wanted to obtain a clear understanding of the accelerator R&D issues that need to be resolved before the proposed machine could be constructed.

This report covers the activities of the group on TeV-class machines in some detail and provides the overall group summary by drawing on the work of the other subgroups. Section II is devoted to the energy frontier and the expected physics thresholds based on our current knowledge of the Standard Model (SM). Section III covers the important detector issues and the special options listed above. Section IV is devoted to issues associated with the run scenarios and Section V with the more esoteric physics possibilities. Section VI is devoted to the ultimate energy of the machine and the possibilities for achieving it. Finally, Section VII has our conclusions.

2. New Physics Thresholds at the LC

Historically, elementary particle physics has gained important new insights into the fundamentals of the structure of nature at high energies by precisely measuring the interactions between known particles and by discovering new particles. As has been documented in many published reviews, and as will be further illustrated in these proceedings, a linear collider is an exceptional machine to make precision measurements provided it has sufficient energy so that new thresholds can be reached.

Foremost, there are good indications that a light Higgs boson can be studied at such a collider. There is compelling evidence that the Higgs boson will be accessible to a machine with energy in the 500 GeV range. Firstly, precision electroweak measurements such as the Z-pole measurements at LEP and SLC of total Z-width, forward-backward asymmetry, left-right asymmetry, etc. have put serious constraints on any theoretical description of electroweak symmetry breaking (EWSB). Many proposed models of new physics are excluded because they have not passed the test of making correct predictions for these observables. Other models have been given more credibility by being compatible with the precise data. The W boson mass measurements at LEP [12], CDF[13] and D0 [14] and the top quark mass measurement at CDF [15] and D0 [16] are also important additions to the constraints on theories.

The standard model with a single Higgs boson works very well as a description of the data, provided the Higgs boson mass is below about 200 GeV (see Figure 1). Since Higgs bosons can be produced in association with the Z-boson at e^+e^- colliders, the predicted mass is well within the kinematically accessibile range of a 500 GeV linear collider. Precise studies of this new threshold (Higgs boson) associated with EWSB will be available at a linear collider.

Models can be constructed that include additional states and are capable of conspiring with a heavy Higgs boson to mimic the effects of a light Higgs boson in the precision electroweak data. An exhaustive review was carried out [17], and it is expected that most such models require exotic states (scalar pseudo-Nambu-Goldstone bosons, Z', etc.) which are detectable at a 500 GeV linear collider. In some cases, there would be no directly observable state at this energy. However, more precise measurements of the W mass and implementation of the GigaZ option would see deviations from the standard model, and would be able to yield information about the nature of the new physics. In all cases, the linear collider adds crucial information to previous data and to the data that the LHC will obtain.

The unification of the three gauge couplings works to impressive precision in supersymmetric theories, giving strong support for perturbative grand unified theories incorporating supersymmetry. In these theories, an upper bound on the lightest Higgs mass can be obtained [18], of

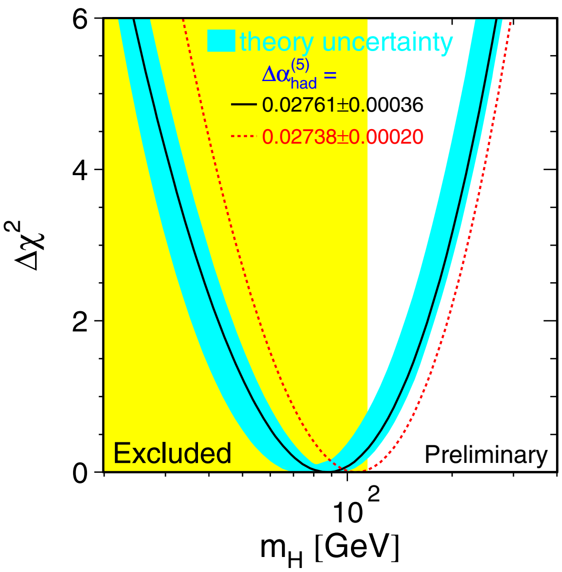


Figure 1: The χ^2 of the fit to the electro-weak observables measured at LEP, SLC and Tevatron as a function of the Higgs boson mass. The preferred value is $M_H = 88^{+53}_{-35}$ GeV and the one-sided 95% C.L. upper limit is 196 GeV (from [1])

205 GeV [19]. This bound is almost the same as the 95% upper limit from precision electroweak data, which of course is derived independently.

The standard model must be embedded into a more fundamental theory valid at higher energies if an explanation of its many parameters is to be obtained. In such models. the W mass is very sensitive to new high scales, and therefore it is expected that the dynamics associated with electroweak symmetry breaking be not too far above 1 TeV. Otherwise, large numbers anchored to a large high-scale must conspire to cancel out and give a small number of order $\sim m_W$. Differences arise due to uncertainty in what physics is to be associated with this new more fundamental scale Λ and can affect the precise value. It could be the scale below which the Higgs boson is a composite particle, and above which no fundamental scalars exist. Or it could be the new scale where superpartners exist, completing the states needed for a supersymmetric description of nature that protects scalars from receiving dangerous quadratic divergences.

The supersymmetric interpretation is the simplest perturbative explanation for low-scale electroweak symmetry breaking, and its minimal model predicts that the lightest Higgs boson must be below about 130 GeV, independent of the precision electroweak data or the gauge coupling unification argument given above. Furthermore, since supersymmetry is a highly predictive and highly developed theory, many studies have been made to quantify the naturalness requirements that the weak scale places on the superpartner masses. Upper limits disagree in their precise values, but the general consensus is that some superpartners should be accessible at a 500 GeV linear collider (see Chapter 4, Sec. 2 of Linear Collider Resource Book [10]).

One new threshold is known to be accessible a linear collider. The top quark mass is 35 times larger than any other known quark, and about 100 times larger than any known lepton. It is the only fermion that has an $\mathcal{O}(1)$ Yukawa coupling to the standard model Higgs boson. Its strong Yukawa coupling makes it unique among fermions. Studying all observables associated with this quark may yield critical insights into a more fundamental theory of its mass generation, and electroweak symmetry breaking in general.

Finally, we remark that there is the logical possibility that no Higgs boson exists, fundamental or composite, and that strong dynamics sets in at the TeV scale. It is not clear how the precision electroweak data would be satisfied in such a theory, but it would probably need to involve other light states [17] (see above). In the unlikely event that such light states are not present, a linear collider still has capabilities in detecting subtle behavior in longitudinal vector-boson scattering, e.g. $e^+e^- \to \nu\bar{\nu}W^+W^-$ and W pair production from $e^+e^- \to W^+W^-$ Signal significance at a 500 GeV collider could be comparable to that of the LHC (see sect. 3.1 of the Linear Collider Resource Book [10]).

3. LC Experimental Issues and Special Options

The linear collider must be able to provide critical data which will enable the answers to today's major questions on the mechanisms responsible for the breaking of some of the symmetries in nature, on the origin of mass and on the nature of the new physics to be obtained. This will require flexibility of operation, high luminosity and a carefully designed interface with the experimental apparatus. A significant flexibility will be necessary for adapting the modes of operation to the nature of the new physics signals to be investigated. This implies the ability to vary the center-of-mass energy over a wide range, to perform closely spaced energy scans of resonances and to collide different kinds of beams in different polarization states. High luminosity will allow the accuracy achievable in determining the properties of the phenomena under study to be at the level required to identify their nature and to complement the LHC measurements. Finally the interface between the accelerator and the detector requires special care for achieving the needed accuracy in the reconstruction of the events, despite the backgrounds originating in the delivery and interaction of the intense beams and also the final focus stabilization system.

3.1. Machine Constraints and Performance

A linear collider operating at energies around 500 GeV has the sensitivity to study the new phenomena as discussed in the previous section. This center-of-mass energy is reachable by accelerator technologies that are ready for large scale implementation. Therefore 500 GeV can be assumed as the primary initial energy of a TeV-class LC. At this energy the LC will be sensitive to most of the Higgs boson properties and should be able to detect and untangle signals of new physics, either directly or indirectly.

While the precise center-of-mass energy requirement of further stages of LC operation will be refined by the details of the phenomenology as it will emerge from the TEVATRON and LHC data, indications already exist. At present, the highest energy known to correspond to the excitation of a particle threshold to be studied at the LC is the $t\bar{t}$ threshold around 350 GeV. This motivates the $\sqrt{s}$ = 350 GeV energy for a phase of the LC operation. The scan of the top production threshold requires about 100 fb^{-1} of integrated luminosity to achieve an statistical accuracy on the top quark mass of $\simeq$ 50 MeV [20], comparable to the systematic uncertainty of $\simeq$ 50 MeV [21] from theoretical sources. In the context of the SM, where the Higgs boson is expected to be light, as indicated by the electro-weak data and of Supersymmetry a similar energy also corresponds to the peak of the associated H^0Z^0 production rate. However, a detailed study of the Higgs boson requires more luminosity. Figure 2 shows the integrated luminosity needed to produce 10^5 Higgs bosons through either of the Higgs–strahlung or WW fusion processes. Such a sample guarantees a statistical accuracy of the order of few % in the determination of the principal Higgs couplings to force and matter particles. Therefore a luminosity of at least to 10^{34}cm^{-2}s^{-1} needs to be achieved in this phase.

Apart from the exploration of the top threshold and of possible other thresholds that may appear up to 500 GeV, energy and integrated luminosity can be traded to obtain a given sample of signal events. At energies up to about 3 TeV the s-channel is the dominant process for production of pairs of fermions and gauge bosons. Since the corresponding cross-sections decrease as $1/s$, operating at higher energies requires even larger luminosities. This is, for example the case for the important H^0Z^0 associate production process, as highlighted in Figure 1 which shows the luminosity required to produce a constant sample of H^0 bosons increases for energies above about 300 GeV. Eventually the WW fusion process becomes dominant around 0.8–1.0 TeV.

3.2. Physics Constraints and Detector Concept

The defining features of e^+e^- collisions, i.e. the known energy, $\sqrt{s}$, the known identity of the initial state partons, and the opportunity to control the helicities of the initial state partons, apply

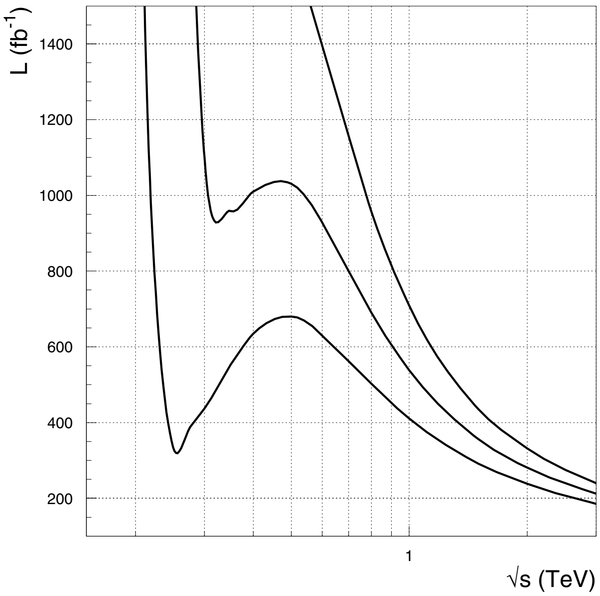


Figure 2: The scaling of the integrated luminosity, necessary to produce 10^5 Higgs bosons in e^+e^- collisions, with the center-of-mass energy $\sqrt{s}$ for three values of the Higgs mass: 120 GeV, 180 GeV and 240 GeV.

to .5–1 TeV collisions essentially as they did at LEP and SLC energies.

To be sure, high energy collisions at a linear collider involve extremely intense beam–beam interactions, which produce beamstrahlung and secondary beamstrahlung–electron/positron interactions at levels far exceeding those at lower energies. This radiative process, like the initial state radiation inevitable in e^+e^- interactions, causes a radiative tail in the collision energy. But, since the effects are rather comparable to those occurring naturally, 67% of the collisions are still within 1% of the nominal EM energy, and 90% are within 5%. For all intents and purposes, the center of mass energy is still well-defined at a TeV-class LC

The physics production cross-sections are electroweak at the LC, so the raw event rate and the resultant radiation field are low, and there is probably no need for a trigger. The beamstrahlung involving the interaction of an electron with the opposing electron bunch causes copious production of e^+e^- pairs, but present detector designs, which incorporate multi-Tesla solenoidal magnetic fields, capture the pairs close to the beam line, and divert them away from the Interaction Point (see Figure 3). This strategy is so successful that the first vertex layer can be placed within nearly a centimeter of the beamline. The LC environment is benign compared to that of hadron colliders. Detector designs can be optimized for physics performance, not radiation hardness or high-rate capability. A broad range of detector technologies can be considered.

Reaching the full potential of a TeV class linear collider will require new detector technologies to be developed and existing technologies to be refined. The designs are driven by the requirements of precision Higgs physics, precise measurements of the masses of supersymmetric particles, and the clean identification of W, Z, Higgs, and top by reconstructing multi-jet final states.

1. Vertex Detection at the LC

The Vertex Detector (VXD) will provide fermion flavor tagging, which is needed to understand electroweak symmetry breaking and the mechanism of mass generation. Precision measurements of the Higgs boson couplings to different fermion species are essential to test that the Higgs mechanism is indeed responsible for the generation of mass. Accurate determinations of the decay rates to $b\bar{b}$, $c\bar{c}$, $\tau^+\tau^-$, and gluon pairs will determine whether the Higgs coupling is indeed proportional to mass. Determining these branching fractions with high precision may also distinguish

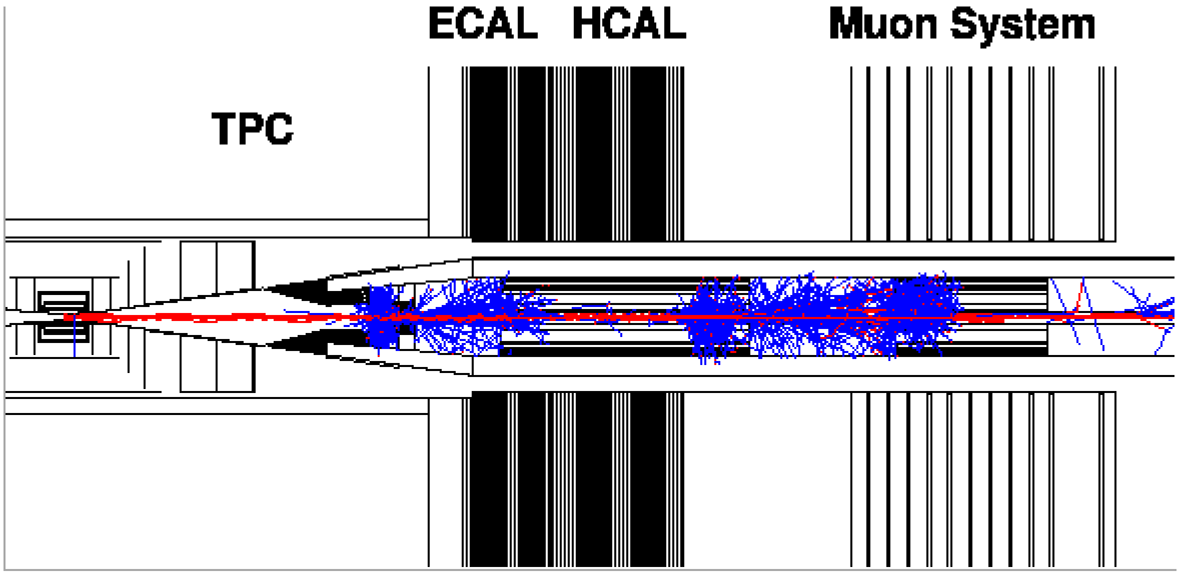


Figure 3: The LC interaction region with the e^+e^- pair background confined by the solenoidal magnetic field and shielded by a system of forward masks.

Standard Model behavior from that expected in its extensions, such as supersymmetry. Since the rates for the Higgs decay modes into lighter fermions or into gluon pairs are expected to be only about 10% or less of that for the dominant $H^0 \to b\bar{b}$ process, the extraction and measurement of these signals requires a strong suppression of the $b\bar{b}$ contribution while maintaining good efficiency (see Figure 5). Distinguishing charm and light flavors from bottom by identifying the decay vertex and determining its multiplicity and reconstructed mass [22], puts a premium on improvements to impact parameter resolution, especially for low momentum tracks.

In order to fulfill these challenging requirements, the LC VXD aims to improve the current state of the art several fold to achieve impact parameter resolution of 3–5 μm for high momentum tracks, and to reduce the multiple scattering contribution to the momentum resolution to $\sim$5 μm/p (GeV/c). Two environmental constraints are significant [23]. The accelerator-induced background at the radius of the innermost sensitive layer causes a hit density of the order of 0.2–1.0 hits mm^{-2}, larger than those expected at the LHC. This, and the track density in highly collimated jets, require detectors with small pixel cells and relatively fast read-out or time stamping capabilities. The flux of neutrons incident on the innermost layers of the vertex detector is of the order of 10^9cm^{-2}year^{-1}, which is large enough to be of concern for CCD sensors.

Several VXD designs have been proposed, relying on different sensor technologies (see Figure 4). All these designs rely on pixel devices, and all try to minimize the detector thickness to improve the impact parameter resolution for low momentum tracks. A substantial R&D effort is underway already for CCD detectors [24, 25], aiming at radiation hardening [26] and boosting readout speeds by developing new architectures. Other pixel detector technologies are also being evaluated, including monolithic CMOS detectors [27, 28], in which readout electronics is incorporated directly on high purity silicon; and bump-bonded pixel sensors [29].

2. Central and Forward Tracking

Higgs physics, and the study of supersymmetric particles, both demand extremely high momentum resolution. In Higgstrahlung ($e^+e^- \to H^0Z^0$), the model-independent identification of the Higgs boson depends on the accuracy with which the recoil mass to the Z^0 can be reconstructed from the dilepton decay $Z \to \ell^+\ell^-$ (see Figure 5). Th accuracy in the recoil mass is fundamentally limited by beamstrahlung and beam energy spread, which broadens the spike in the center of mass energy to the 0.2% level. To saturate that limit, the momentum resolution for charged particles should be pushed towards $\delta p/p^2 \simeq 10^{-5}$GeV^{-1}, an order of magnitude beyond what has been achieved at LEP. Such momentum resolution would also sharpen the distinctive box spectra

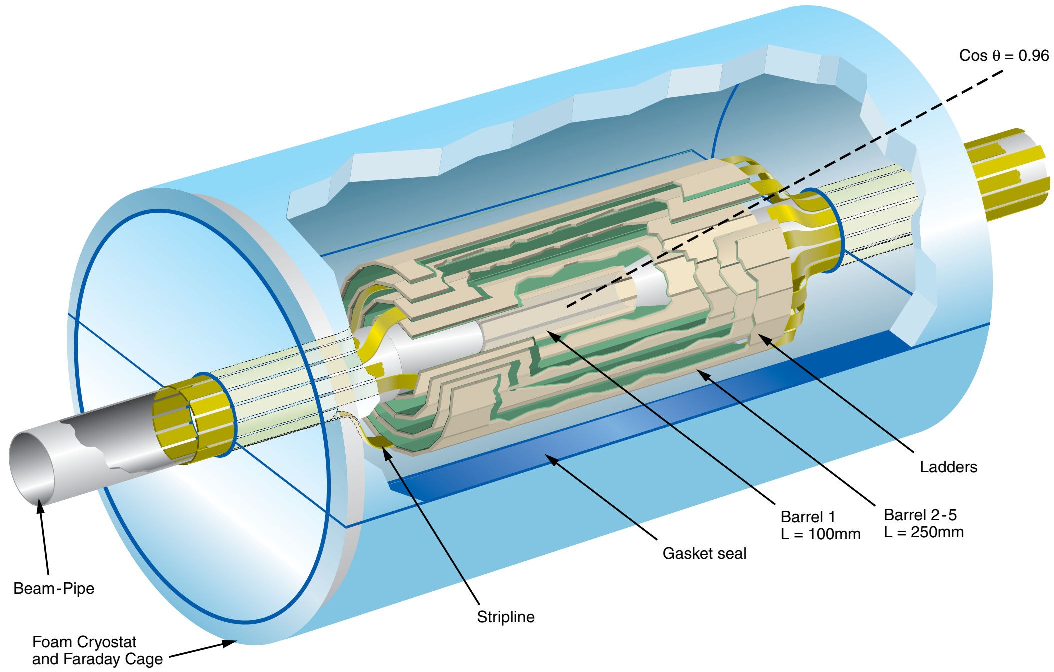


Figure 4: Isometric view of the Vertex Detector surrounding the interaction region. The concentric layers of high resolution Si pixel detectors ensure the discrimination of charged particles produced in the decay of short-lived heavy hadrons from those originating at the point of beam interaction (from [9]).

expected from two body SUSY decays, thus improving the accuracy on the mass measurement of supersymmetric particle partners (see Figure 6).

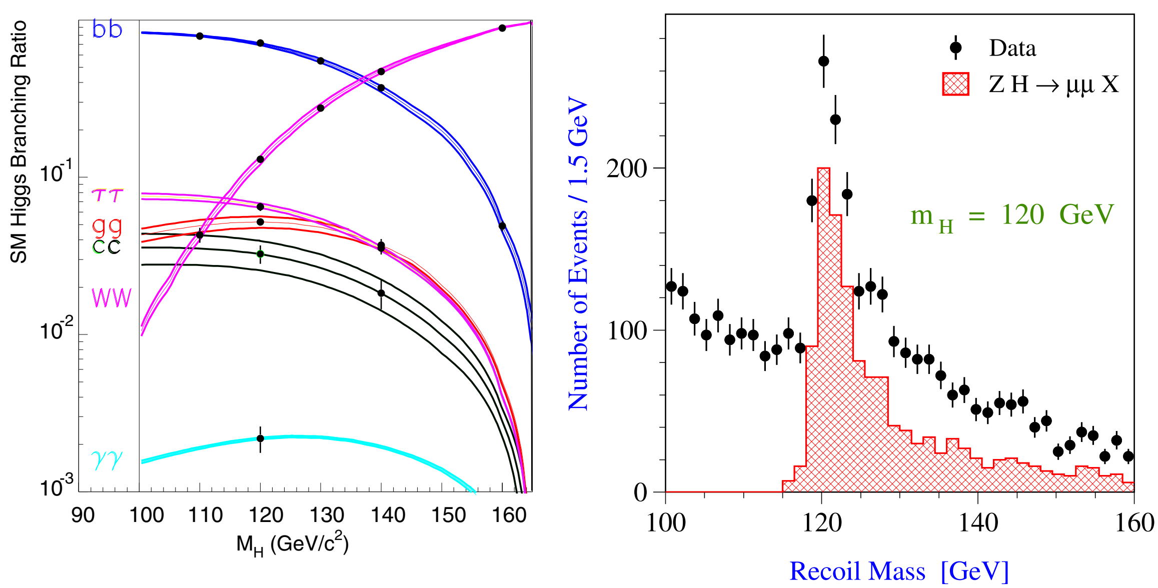


Figure 5: Left: Higgs decay branching fractions predicted in SM as a function of the Higgs boson mass. The lines represent the expected range due to uncertainties in the input parameters and the points with error bars represent the estimated statistical accuracies obtainable at a LC with 500 fb^{-1} (from [30]). Right: reconstructed recoil mass spectrum showing the mass peak due to a 120 GeV Higgs boson produced in the $e^+e^- \rightarrow ZH$ process (from [9]).

Additional requirements on the tracking include pattern recognition capability in the presence of backgrounds, adequate track separation resolution to resolve all the tracks in the dense core of a high energy jet and full solid angle coverage. Several technologies for central tracking are presently being considered to meet these challenging requirements. The study in [11] has concentrated on a traditional drift chamber design. Issues such as electrostatic stability, gravitational sag, and cell design have already been addressed with detector R&D. Pattern recognition capability in the presence of backgrounds must still be evaluated. [9] has advanced the idea of a large volume Time Projection Chamber (TPC), extending radially between about 30 and 170 cm, with about 120 radial measurements. The high granularity of the sensitive cells in the gas volume provides excellent pattern recognition capabilities, even in presence of backgrounds. Present designs of trackers incorporating a TPC offer good momentum resolution, $\delta p/p^2 = 5 \times 10^{-5}$ GeV^{-1}, if critical systematics and calibration issues can be adequately addressed [31]. The inherent dE/dx information available in a TPC also gives some particle ID capability. R&D is underway on new ways to detect the drifted electrons [32], including GEM [33] or Micromega [34] detectors replacing the traditional MWPCs; on optimal gas mixtures [35]; on integrated readout electronics; and on thinning the TPC endplate [36]. A different approach, advocated in [10] is to rely on a multi-layered silicon tracker, based on either silicon microstrip or silicon drift sensors. Such a device has excellent momentum resolution ($\delta p/p^2 = 2 \times 10^{-5}$ GeV^{-1}), but reduced stand-alone pattern recognition capability. The robustness and the efficiency of the combined vertex detector + silicon tracker pattern recognition against the expected backgrounds and efficient enough in reconstructing K_s^0 and Λ^0 have yet to be demonstrated. R&D is proceeding on several items: long and short shaping time options for the silicon detectors; the effect of high magnetic fields on the detectors; and power cycling to match the very low LC duty cycle and detector alignment.

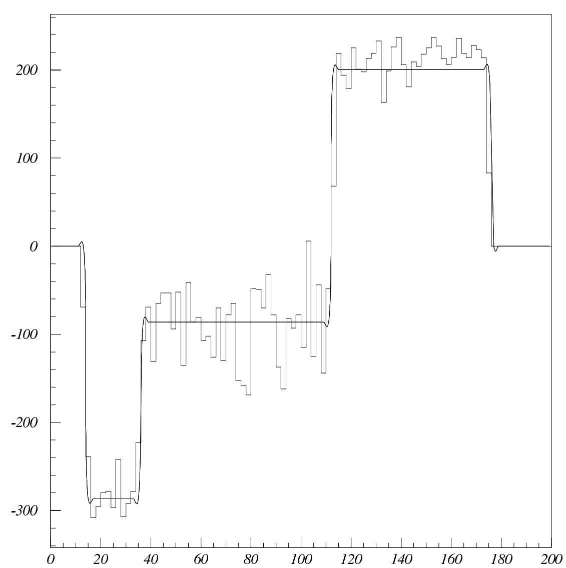


Figure 6: Example of determinations of masses of sleptons from the measured momentum distribution of muons detected in events produced with different beam polarization states (from [37]).

Many tracking issues remain, some of which are under active investigation. The track-pair resolution achieved for each technology is being tested in energetic and highly collimated jets. The usefulness of recording timing information, in order to associate tracks with a particular bunch crossing is being investigated. The importance of thinning TPC endcaps, and designs for doing so, are under study, as are designs for chambers which would reside behind the endcap to boost resolution for forward going tracks. A high precision tracking layer located between the vertex detector and the central tracker (an "intermediate tracker") has been proposed to boost momentum resolution. It needs further study. Forward tracking systems, which must have excellent resolution in collinearity angle for the measurement of the differential luminosity spectrum, need further development.

The goal of the calorimetry is to unambiguously identify W, Z, Higgs bosons, and top quarks on the basis of the invariant mass of multi-jet combinations (see Figure 7). To do so will require significant advances in jet energy resolution and calorimetric pattern recognition. Several ideas are being explored for improving jet energy resolution [38, 39]. The most topical, and promising, is that of energy-flow calorimetry, in which one measures the electromagnetic showers in such fine-grained 3-D cells, that the energy deposits arising from charged tracks penetrating the calorimeter are separable from the electromagnetic energy clusters (see Figure 8). If this is done, the charged energy can be measured with high precision in the central tracker, the electromagnetic energy with moderate precision in the electro-magnetic calorimeter (ECAL), and the remaining neutral hadronic energy in the hadronic calorimeter (HCAL). The resolution on the sum improves significantly in this approach. In the ideal case, where there is no confusion in assigning the energy to charged and neutral components, the jet energy resolution is $18\%/\sqrt{E}$, in contrast with that expected with a calorimeter-only resolution of $64\%/\sqrt{E}$, even if the calorimeter is fully compensating. Studies indicate that improvements in the HCAL resolution are very important to improve the overall jet energy resolution. The concept of a "digital calorimeter," in which the fine-grained cells of the hadronic calorimeter simply record if they have been hit, has been proposed [9, 38] and looks promising.

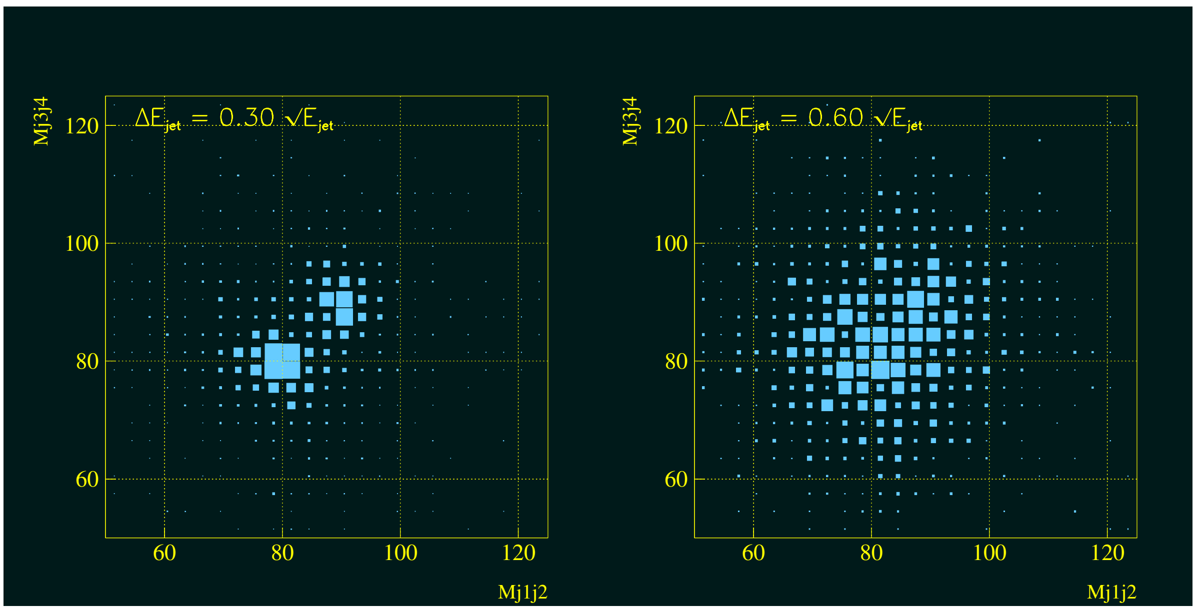


Figure 7: An exemplification of the impact of jet energy resolution on the separation of WW from ZZ hadronic decays: the masses of each di-jet pairs are shown for $60\%/\sqrt{E}$ (right) and $30\%/\sqrt{E}$ (left) (from [38]).

The study of energy flow calorimetry is dependent on full and accurate simulations of shower development, and well-developed pattern recognition and clustering software. These are still in their infancy, leaving much to be done toward understanding what realistic performance gains might be and how best to optimize the detector. Although results are still preliminary and no full agreement between different algorithms has been reached, a jet resolution of $26\%/\sqrt{E}$ appears achievable with $30\%/\sqrt{E}$ resolution in the HCAL and $15\%/\sqrt{E}$ resolution in the ECAL. Such a resolution is adequate for distinguishing W from Z bosons or Z from low mass H bosons, which is not possible with jet energy resolutions in today's calorimeters. Ongoing R&D looks into optimizing the longitudinal segmentation vs cost and studying the effect of the dead channel fraction on the ultimate performance and cost of the device.

Energy-flow calorimetry depends on isolating charged and neutral particles, which is best done in a dense detector medium where shower spread is minimized. Silicon/tungsten is favored, but its high cost demands understanding tradeoffs in pixel size, longitudinal segmentation, and detector quality [38, 40]. It will be necessary to develop distributed electronics that can be integrated

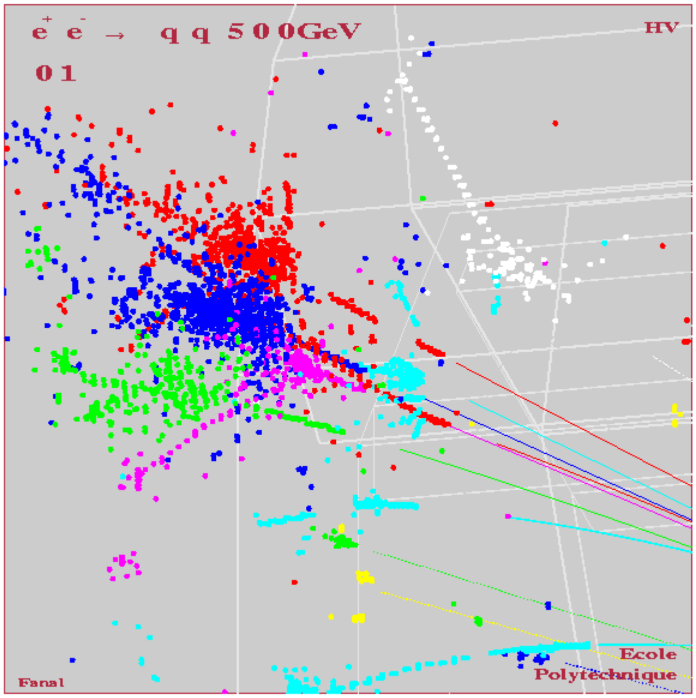


Figure 8: The response of a tungsten digital hadronic calorimeter to Particles from an hadronic jet (from [38]).

with the silicon detectors, and to solve the mechanical problems associated with constructing such a detector. More traditional calorimeters are also being considered for use at the LC such as 5×5 cm^2 scintillator tiles interspersed with Fe, readout via wavelength shifting fibers by Avalanche photodiode pixel arrays. A prototype calorimeter is under construction. Other studies [11, 41] have focused on a nearly compensating lead/scintillator design for the ECAL, which is segmented longitudinally into three parts. The device has already been beam-tested.

4. Other Systems

The LC detector will certainly require muon identification. Preliminary designs for the muon system have emerged, but work is needed to select an optimal detector technology. The LC physics may, particularly for GigaZ studies, benefit from dedicated particle identification. For example, in B mixing or asymmetry measurements at the Z, identified kaons can be used to tag the flavor of the parent B hadron. The overall value of particle ID in the high energy LC environment is still uncertain, but needs further investigation [42].

A linear collider detector also comprises subsystems uncommon to present e^+e^- storage rings detectors, some of which will need significant R&D. Extreme forward calorimetry, designed to veto the two-photon backgrounds to selectron searches, must isolate high energy electrons from large, but more diffuse electromagnetic backgrounds. A pair monitor will provide the instantaneous luminosity if it can separate signal from background close to the beam line. The beam energy will likely be determined by use of a dedicated spectrometer; getting the desired level of precision will require R&D [43]. Beam polarization must be monitored, presumably by Compton backscattering polarized laser light.

3.3. LC Special Options

The capability of the LC to interact elementary particles with well defined energy and quantum numbers is further enhanced by the availability of polarised beams [44]. Colliding electrons in a given polarisation state allows tests of the helicity structure of the reactions originated by the particle collision. While the SM processes are mostly initiated by electrons polarised in the same directions, such as $e_L^+ e_R^+$, new physics, as SUSY, may be manifested in the interactions of $e_L^+ e_L^+$ and $e_R^+ e_R^+$. This allows to efficiently separate these physics processes from those due to standard interactions. The use of beam polarisation carries three major benefits: i) enhance the production rate of signal processes, ii) improve the signal-to background ratio by reducing the rate of SM backgrounds, iii) provide an analysers of the quantum numbers of the particles produced (see Figure 9). In order to fully exploit these benefits, it is important to ensure the implications of the LC operation with polarised beams. The feasibility of operating a linear collider with a large degree of polarisation of the electron beam has been demonstrated at the SLC, where $\mathcal{P}_{e^-}$=0.76% has been routinely achieved. Measurement of the polarisation within 0.5% has also been demonstrated. While this is presently considered as a possible upgrade at a later phase of LC operation, there is now ongoing R&D addressing the issues related to obtaining polarised positron beams of sufficient intensity. For the LC the simultaneous polarisation of the electrons and positrons has important benefits. This enhances the analysing power since the effective polarisation $\mathcal{P}_{\rm eff} = \mathcal{P}_{e^-} - \mathcal{P}_{e^+}/(1 - \mathcal{P}_{e^-}\mathcal{P}_{e^+})$ exceeds the degree of polarisation achievable for each single beam (see Figure 9). Further the exact degree of the beam polarisation during the interactions can be extracted directly from the data recorded. This will largely reduce the systematic uncertainties, otherwise expected to dominate the overall achievable measurement accuracy. But a second aspect has to be taken into account which concerns the impact of operating with polarised beams on the achieveable luminosity. The anticipated decrease in luminosity has to be factored in when accounting for the enhancement of signal cross sections and highlights the main benefit of positron polarisation from its use as analyser.

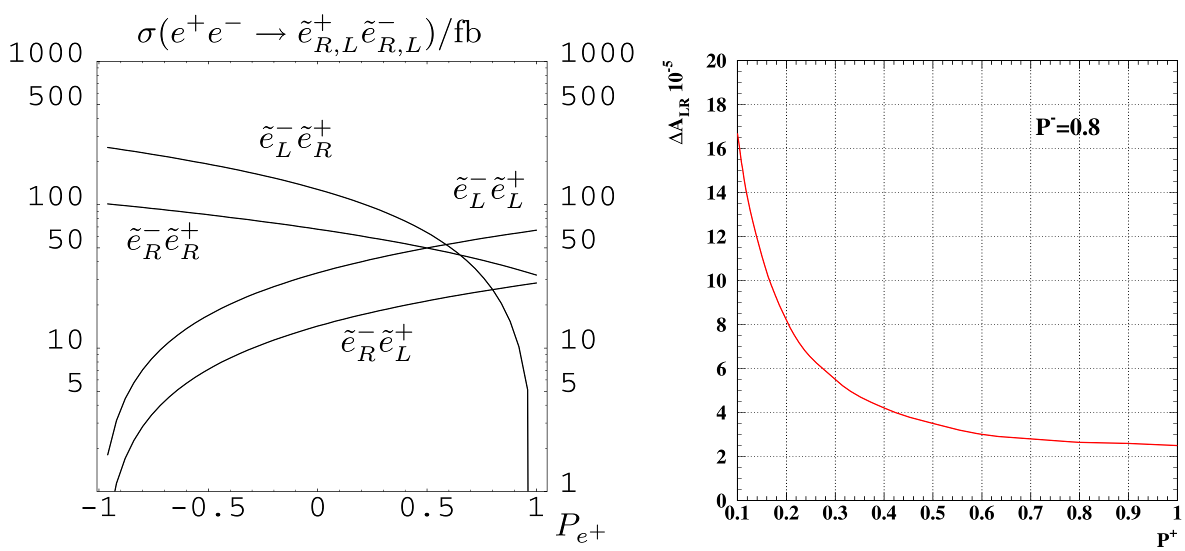


Figure 9: Two examples of the advantages of e^- and e^+ polarisation in studying new physics and performing precision tests of the SM. Left: cross section for the production of the supersymmetric electron partners as a function of the positron beam polarisation $\mathcal{P}_{e^+}$ (from [44]). Right: statistical uncertainties for left-right asymmetry A_{LR} in the $e^+e^- \to Z^0 \to \ell^+\ell^-$ reaction, measured operating the LC at the Z^0 pole energy, as a function of the positron beam polarisation (from [7].

The operation of the LC as a $\gamma\gamma$ collider may significantly extend its physics reach [8]. The principle of colliding photon beams, generated by scattering intense laser beams on the electron bunches, was proposed since long. Recently the technical implications and the engineering solutions for a realistic design of the $\gamma\gamma$ interaction region and the intense laser system have been investigated in great details. This has provided a proof of principles for this option. The point of strength of the photon collider largely rely on its ability to concentrate the full collision energy in the creation of a single spin-0 Higgs boson. On the contrary in e^+e^- collisions these bosons are pair produced, either with a Z^0 or with another Higgs particle. By gaining access to the effective $H\gamma\gamma$ coupling, that involves loop of virtual particles, much can be learned on new particles even if their masses happen to be too large to be directly produced. The single Higgs production also ensures that the sensitivity to the heaviest of these particles can be pushed to higher masses compared to e^+e^- collisions.

For some specialised physics cases there are advantages in operating the LC colliding electrons on electrons, for shorter periods. A good example is offered by the superior capability of a e^-e^- collider in determining the $\tilde{e}_R$ mass due to the significantly sharper onset of the $\tilde{e}_R\tilde{e}_R$ threshold as discussed below.

4. Running Scenarios at the LC

The control of the beam energy at a linear collider will allow complicated new physics to be disentangled and precisely measured, one threshold at a time, if necessary. But skeptics have argued that this approach is so luminosity-hungry that it is not practicable—there simply is not enough time or luminosity to study each threshold this way if, for example, low energy Supersymmetry is realized in nature. We sought a resolution to this issue at Snowmass 2001 by posing a test case: can a realistic machine, in a finite amount of time, do justice to a physics-rich scenario? The paper describing this interesting exercise, and its answer in the affirmative, is included in the proceedings [4], and is summarized here.

4.1. Definition of the Scenario and Assumptions on Machine Performance

The new physics we imagined was a scenario rich with low mass supersymmetric particles and was one of the benchmarks defined for Snowmass studies. The physics is defined by the following minimal Sugra parameters [45]: $m_0 = 100$ GeV, $m_{1/2} = 250$ GeV, $\tan\beta = 10$, $A_0 = 0$, and μ positive. The resulting particle spectrum, and the principal decay modes of the particles, are given in Figure 10. The sleptons and sneutrinos are all kinematically accessible at 500 GeV in this scenario; the lighter chargino and the two lightest neutralinos can be pair produced at 500 GeV, while the heavier chargino and the two heaviest neutralinos can be made in association with the lighter states. The remaining particles in this scenario, with the exception of the light h^0 at 113 GeV, are inaccessible at LC-500: the lighter squarks and gluinos have masses between 500 and 600 GeV and the stop states have masses of 393 and 572 GeV. The remaining Higgs states are all near 380 GeV.

Machine performance was assumed to range from a few percent of design luminosity in the first year of LC operations up to the design value by year five, allowing integration of 1000 fb^{-1} over a seven year period. This integrated luminosity would obtain if all the running were at 500 GeV, where the luminosity is highest. For running at lower energies, the luminosity is scaled back in proportion to the energy, so the actual net integrated luminosity is lower than 1000 fb^{-1} reflecting some lower energy running. It was assumed that electron beam polarization, of magnitude 80%, was available, but that positron polarization was not. It was also assumed that e^-e^- collisions could be arranged, albeit with luminosity reduced to 20% of that possible for e^+e^-. Operation with $\gamma\gamma$ collisions may also prove desirable, but it has not been considered here, as it would possibly be a later option.

The physics model defines the cross-sections for the pair and/or associated production of all sparticle states, which of course depend on the polarization of the incident electron beam. Cross-sections range from of order 10 fb for associated chargino and neutralino production and muon and tau sneutrino pair production, to roughly 50 fb for smuon and stau pair production, to greater than 100 fb for the lightest chargino and selecton pairs. Physics goals for the program included the full elucidation of the above sparticle spectrum, detailed studies of the Higgs, and a thorough study of the top quark threshold region.

4.2. Run Strategy

Running at or near the highest energy was allotted about half the total integrated luminosity. This ensured production of all the kinematically allowed states. The common experimental signature for production of these SUSY states is lepton pairs plus missing energy. Sparticle masses can be deduced by measuring the endpoints of the lepton energy distributions. In the case where a single sparticle is pair produced and decays via a two body process into a second sparticle and a lepton, a simple box energy spectrum emerges with unambiguous endpoints which are related to

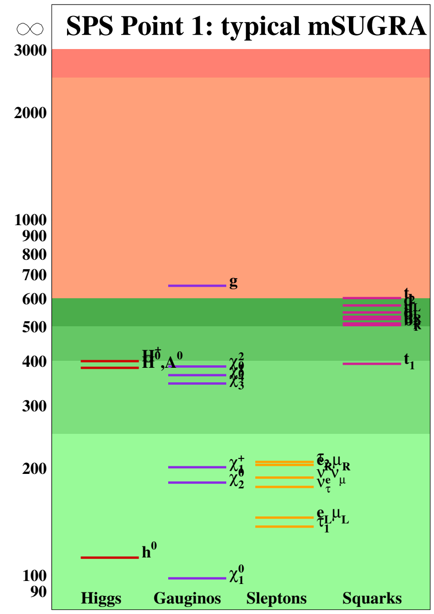


Figure 10: The particle spectrum of the mSUGRA scenario considered for the definition of the run strategy.

the masses of the parent and daughter sparticles. The energy distributions are more complicated when several sparticles contribute to the same observable final state, leading to superpositions of such spectra. Papers cited in the Snowmass study have shown how these cases can be disentangled, and have provided the estimates of the precision with which sparticle masses can be obtained. With appropriate scaling of the statistics, these results lead to estimates of how accurately end-point masses can be measured with the given luminosity assumptions. Given this coarse determination of the masses of many sparticle states, one knows how to choose the machine energy for threshold scans of selected states, which can yield more accurate mass determinations. A simple, non-optimized scan strategy was employed; the luminosity is divided among 10 mini-runs which are distributed over energy in even steps. The scans yield some information on sparticle widths, in addition to precise information on the masses.

Electron polarization is used to good advantage in the measurement process. Using equal amounts of L and R running at the higher energy points helps distinguish L and R sparticles, even though they may decay to the same final states. For the threshold scans, the cross-sections for production of particular states can be enhanced by correct choice of the electron polarization, so many scans use exclusively L or R electrons, but not both. Since the cross-section for $\tilde{e_R}\tilde{e_R}$ near threshold rises as β in e^-e^- interactions (versus β^3 in e^+e^-), it is advantageous to use e^-e^- collisions for the precision determination of the $\tilde{e_R}$ mass. The resulting run plan is shown in Table I. Roughly one half of the running is at the nominal maximum energy of the machine, and a little is even above the nominal maximum (which is possible by trading luminosity for additional energy). The rest is distributed among threshold scans, with extra running time going to low cross section processes. A good deal of running is near the Higgs–strahlung threshold, so precision studies of the Higgs boson properties are possible.

4.3. Results

Table II shows the accuracies of the mass determinations for both endpoint and threshold measurements. Most slepton, sneutrino, chargino, and light neutralino masses are determined

Table I Run allocations for the SPS1 Minimal Sugra parameters.

Beams	Energy	Pol.	$\int \mathcal{L}dt$	$[\int \mathcal{L}dt]_{\text{equiv}}$	Comments
e^+e^-	500	L/R	335	335	Sit at top energy for sparticle end point measurements
e^+e^-	270	L/R	100	185	Scan $\tilde{\chi}_1^0\ \tilde{\chi}_2^0$ threshold (R pol.) Scan $\tilde{\tau}_1\ \tilde{\tau}_1$ threshold (L pol.)
e^+e^-	285	R	50	85	Scan $\tilde{\mu}_R^+\ \tilde{\mu}_R^-$ threshold
e^+e^-	350	L/R	40	60	Scan $t\bar{t}$ threshold Scan $\tilde{e}_R\ \tilde{e}_L$ threshold (L & R pol.) Scan $\tilde{\chi}_1^+\ \tilde{\chi}_1^-$ threshold (L pol.)
e^+e^-	410	L/R	100	120	Scan $\tilde{\tau}_2\ \tilde{\tau}_2$ threshold
e^+e^-	580	L/R	90	120	Sit above $\tilde{\chi}_1^\pm\ \tilde{\chi}_2^\mp$ threshold for $\tilde{\chi}_2^\pm$ end point mass
e^-e^-	285	RR	10	95	Scan with e^-e^- collisions for $\tilde{e}_R$ mass

with a fractional accuracy of a few parts per mil or better. Only the staus and tau sneutrino are measured at the per cent level or worse (excepting χ_4^0, which is observed but not well-measured). These are impressive precisions, which would add significantly to what will have been learned at the LHC. When these results are taken in conjunction with existing information from the LHC, it may well be possible to distinguish the broad class of SUSY model responsible for the observed spectral pattern. In the context of the particular Sugra model, it will be possible to determine the fundamental model parameters to high precision.

Table II Mass precision estimates in GeV for benchmark point SPS1 for end point (EP), threshold scan (TH) and combined measurements, and the combined estimates for the RR1 point.

	SPS1			RR1
particle	δM_{EP}	δM_{TH}	δM_{SPS1}	δM_{RR1}
$\tilde{e}_R$	0.19	0.02	0.02	0.02
$\tilde{e}_L$	0.27	0.30	0.20	0.20
$\tilde{\mu}_R$	0.08	0.13	0.07	0.13
$\tilde{\mu}_L$	0.70	0.76	0.51	0.30
$\tilde{\tau}_1$	$\sim 1-2$	0.64	0.64	0.85
$\tilde{\tau}_2$	–	0.86	0.86	1.34
$\tilde{\nu}_e$	0.23	–	0.23	0.4
$\tilde{\nu}_\mu$	7.0	–	7.0	0.5
$\tilde{\nu}_\tau$	–	–	–	10.0
$\tilde{\chi}_1^0$	0.07	–	0.07	0.07
$\tilde{\chi}_2^0$	$\sim 1-2$	0.12	0.12	0.30
$\tilde{\chi}_3^0$	8.5	–	8.5	0.30
$\tilde{\chi}_4^0$	–	–	–	observed
$\tilde{\chi}_1^\pm$	0.19	0.18	0.13	0.09
$\tilde{\chi}_2^\pm$	4.1	–	4.1	0.25

The run scenario includes a lot of running above the Z^0h^0 threshold, so many Higgs parameters will be determined with high precision. Many fundamental couplings will be measured to the level of 1 or 2% for g_{ZZh}, g_{WWh}, g_{bbh}, and $g_{\tau\tau h}$. The g_{cch} coupling will be measured to 4% and the coupling to top will be measured to about 30% from the top threshold running. The Higgs mass is measured to 0.03%; and its width is indirectly determined to 7%. The run plan devotes time to top threshold running. This will fix the top mass to 150 GeV and the width to 5%.

The run time plan developed at Snowmass provides a proof that a 1000 fb^{-1} data set, gathered over a period of about seven years, is adequate for a full range of high precision measurements of sparticle masses, Higgs properties, and top properties in a physics-rich scenario. A second mSugra point, considered in the TESLA TDR (point RR1) and now excluded by the LEP-2 data, was also studied, to get some feel for the sensitivity of the conclusions to the particulars of the initial assumptions. The same conclusions hold.

5. LC and Alternative Physics Scenarios

Recently a whole new class of models has been considered. These models go under the general banner "large extra dimensions" or "brane world." The basic idea is that there are more than three spatial dimensions, and that the geometry and size of the extra dimensions can help us explain the huge differences in scales between, for example, the Planck scale and the weak scale, and between the weak scale and the mass scale associated with neutrinos. So far, complete models that explain the size and stability of the extra dimension(s) are not available. However, investigations into these theoretical structures are relatively new and complete models may emerge given time. It is already possible to identify generic signals that are expected to be present in these models Many contributed articles to these proceedings, and the chapters of the Linear Collider Resource Book [10] and the Tesla TDR [9], contain a great deal of information about the phenomenology of extra dimensions. In the following we briefly list some broad categories of these theories and describe how a linear collider could constrain them.

New gravity dimensions: One of the most exciting recent ideas to address the question of why $M_P/m_W \gg 1$ was introduced by Arkani-Hamed, Dimopoulos and Dvali [46]. They explain that if there are n extra dimensions in a volume $V_n = (2\pi R)^n$ then the fundamental scale of gravity M_D could be of order the weak scale provided the radius of the extra dimensions satisfies the relation $M_P^2 = M_D^{2+n} R^n$. The radius of compactification can be as large as ~ 1 mm for $n = 2$ extra dimensions.

There are collider consequences in such a model, the most important of which involve gravitons, which are more strongly coupled at higher energy than in ordinary gravity because $M_D \simeq M_W$. A classic signature is $e^+e^- \to G^{(n)}\gamma$. The $G^{(n)}$ represent the Kaluza-Klein excitations of the graviton kinematically accessible in the collision and exit the detector without interacting. The result is a final state of photon and missing energy. Similar signatures arise from quarks annihilating into gravitons plus jet at the LHC.

The production cross-section depends strongly on the center of mass energy, and scales with energy as a power of the number of extra dimensions, $\sigma \sim s^{n/2}/M_D^{2+n}$. Therefore it is possible to vary the center of mass energies and fit for the number of extra dimensions by seeing the energy scaling behavior of the cross-section. This is demonstrated nicely in Figure 11.

In this class of models the gauge fields of the standard model cannot propagate in the extra dimensions. If the size of the extra dimension is TeV^{-1}, then gauge fields may propagate in the extra dimensions [47]. This possibility uses the compacification scale to to set a scale for electroweak symmetry breaking (or supersymmetry breaking, etc.). For example, consider all gauge fields living in $4 + 1$ spatial dimensions, where the fifth dimension is compactified in a volume characterized by a radius R. The gauge fields will then all have Kaluza-Klein excitations at integer multiples of $1/R$. These KK states have couplings determined by their zero-mode counterparts and are therefore predicted.

The search for KK excitations of gauge bosons is similar to the searches for Z'/W' bosons in theories with extra gauge symmetries. The strategies of those searches can be directly applied to KK searches. While it may not be possible to produce the states directly, there presence will cause distortions in, for example, $e^+e^- \to \mu^+\mu^-$ and a reach well beyond the center of mass energy can be obtained. For example, at a 500 GeV linear collider with $100\,\text{fb}^{-1}$ integrated luminosity, KK states cause clear deviations from the SM predictions of $e^+e^- \to f\bar{f}$ if the KK masses are below 10 TeV.

Another class of models invokes *Warped gravity dimensions*. Here it has been shown that the weak scale may arise as a byproduct of a warped-geometry extra-dimensional space [48]. This possibility and many variants of it have phenomenological predictions, the most spectacular of which is the observation of TeV-scale KK excitations of the graviton (or other states), whose masses are spaced in a pattern characteristic of this class of models. One of the earliest signs of warped extra dimensions would be the discovery of the radion—a modulus associated with the stability of the extra dimensions. Models of brane separation stabilization imply that the radion is expected to be the lightest state directly related to the extra dimension. Recent papers have emphasized how similar the radion is to Higgs in collider searchers, but the branching fractions follow a decidedly different pattern [49]. Careful studies of the production cross-sections and

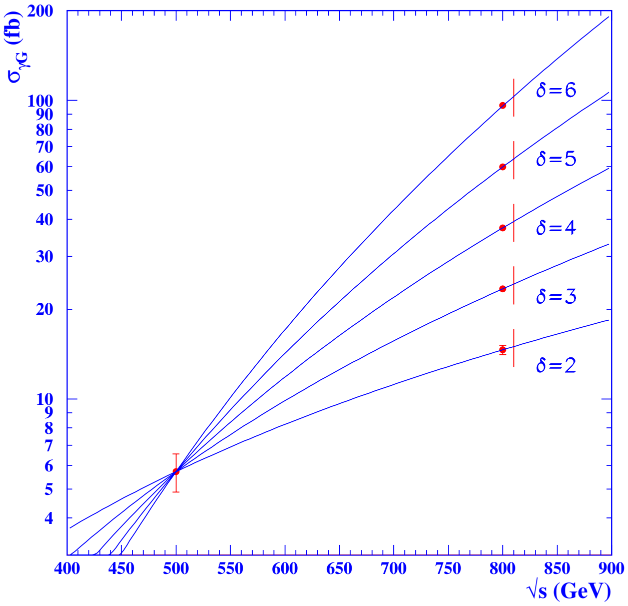


Figure 11: Determination of the number of extra dimensions from anomalies in the single photon cross section measured at $\sqrt{s}$=500 GeV and 800 GeV. Points with error bars indicate the expected measurement performed on 500 fb^{-1} of data with polarized electron and positron beams. The curves show the expected dependence of the cross section on the collision energy for different number of extra dimensions (from [9]).

branching fractions of the radion and Higgs boson may even provide information about gravity-induced mixing between the radion and Higgs boson.

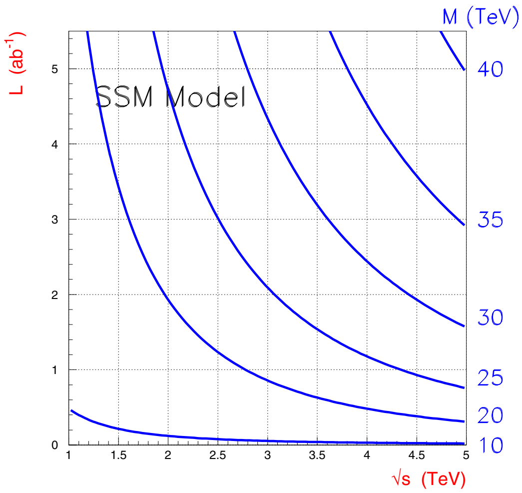
Multi-TeV e^+e^- collisions are expected to break new ground and extend the search for new physics well beyond the LHC reach [5]. In particular precision measurements will allow to probe scales of new physics in the range of several hundred TeV.

Several possible scenarios of new physics in the TeV region are being considered. The upper end of the SUSY sparticle mass spectrum is likely to extend up to, or beyond, 1 TeV, requiring multi-TeV e^+e^- collisions to produce those particles and measure their properties with high precision. Beyond 1 TeV, the phenomenology implied by alternative physics scenarios, such as new gauge bosons, Kaluza-Klein excitations, a new strong sector, etc., leads in many cases to the production of new resonances in the multi-TeV range. The total production cross section as a function of center of mass energy could therefore show a spectacular new structure. For a collider with large enough energy, e.g., the production and decay of KK excitations of the graviton can give direct access to the graviton self couplings [51]. If the center-of-mass energy is even larger than the fundamental scale of gravity, which may happen in scenarios with extra dimensions, e^+e^- collisions may even result in the abundant production of black holes [52, 53], which would subsequently evaporate in a large number of partons (see Figure 12), and re-shape our view of the evolution of elementary processes at high energies.

6. LC Extendibility, Upgradeability and multi-TeV Option

While the physics program of a linear collider providing collisions at energies in the range 0.3 TeV $< \sqrt{s} <$ 0.5 TeV appears rich and compelling, its extension to higher energies must already be considered [6]. The physics case for this extension, cannot be fully detailed from our present understanding and it will most likely be specified one the signals and measurements obtained from the data from the LHC and also from the LC operation at 0.5 TeV and lower.

However, our present favored picture of the new physics possibilities and even the alternative physics scenarios discussed in the previous section, all will eventually require study with e^+e^-



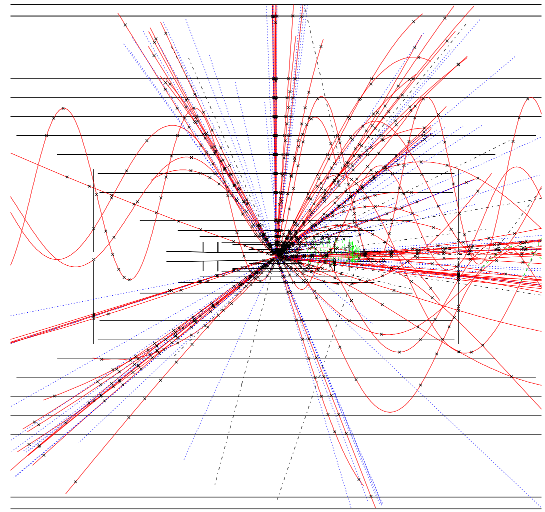


Figure 12: Examples of multi-TeV physics. Left: the sensitivity to an additional Z' gauge boson through measurements of electro-weak observables as a function the integrated luminosity and center-of-mass energy (from [50]). Right: an event of production and evaporation of a black-hole in 5 TeV e^+e^- collisions (from [5]).

collisions at energy beyond 0.5 TeV. The investigation of the coupling of the Higgs with the heaviest known elementary particle can only be performed at energies of 0.8 TeV-1.0 TeV where the radiation of a Higgs boson off a top quarks measures the top Yukawa coupling g_{Htt}. If SUSY exists, the spectrum of supersymmetric partners may already be studied, in part, at lower energies but it will most likely require energies in excess of 0.5 TeV to make these studies exhaustive. The approach to 1 TeV also promises to open an additional window on new physics. If the breaking of the electro-weak symmetry is not due to the Higgs mechanism, then the $e^+e^- \to W^+W^-\nu\bar{\nu}$ and $Z^0Z^0\nu\bar{\nu}$ processes will reveal a new dynamics of gauge boson interactions [54]. Even if the Higgs boson measurements has validated the Higgs mechanism, the study of triple gauge boson couplings via pair production at energies beyond 0.5 TeV will be needed to look for the effect of new interactions [9, 55].

The extension of the LC energy can be achieved by three different strategies (see Figure 13). The first is to increase the energy at the expense of the luminosity, where the limit is set by the available power. The second is to increase the accelerating gradient and/or adiabatically extend the active linac by adding extra accelerating structure. This scheme was successfully adopted at LEP in raising the collision energy by more than a factor of two. Here the limit is set by the site length, the achieved gradient and the RF power. Beyond these limits, a further energy upgrade could be achieved by replacing the full active part of the linac.

In the case of an X-band LC, the first scenario is expected to provide e^+e^- collisions at $\sqrt{s} = 0.60$ TeV with about 15% of the nominal luminosity at 0.5 TeV. The TESLA superconducting technology can achieve collisions at $\sqrt{s} = 0.65$ (0.75) TeV with about 55 (10)% of the nominal luminosity at 0.5 TeV. This may be of interest for the first exploration of this higher energy region or for clarifying the nature of possible new signals which have emerged at the lower energies. However in order to fully profit from the higher energy, the luminosity also needs to be increased, to compensate for the fall of s-channel cross sections. This is addressed in the different designs, that foresee a possible second stage upgrade. The NLC project aims at achieving 1 TeV with luminosity of 3.4×10^{34}cm^{-2}s^{-1}, by doubling the number of components and, possibly, increasing the gradient. The TESLA TDR proposes an upgrade, based on operating the linac with a gradient of 35 MeV/m, instead of 23.4 MeV/m. This would enable collisions at $\sqrt{s} = 0.8$ TeV with a luminosity of 5.8×10^{34} cm^{-2}s^{-1}. Both these upgrade paths require accelerating gradients higher than presently demonstrated and significant R&D is presently being pursued. However, the first indications are quite encouraging.

Beyond these energies, the extensions of the SC and X-band technology are more speculative. In order to attain collisions at energies in excess of 1 TeV, with high luminosity, significantly higher gradients are necessary so that the total linac length and the needed power are within acceptable limits. Also, the number of active elements in the linac must be kept lowe enough to ensure reliable operations. The two-beam acceleration scheme, developed at CERN in the framework of the CLIC study in collaboration with other laboratories in Europe and in the US, aims at a collider capable of providing collisions at $\sqrt{s}$ = 1 TeV - 5 TeV with a luminosity of 1×10^{35} cm^{-2}s^{-1} at 3 TeV [56]. To demonstrate the feasibility of the CLIC scheme and the achievability of the design gradient of 150 MeV/m, an intensive program of tests is under way. Whether a multi-TeV LC is best realized as a standalone facility or as the second stage of an existing TeV-class collider must be considered before committing to a particular site and a layout. In fact, in the latter case the possibility to install the two linacs at a finite crossing angle, which is necessary to avoid parasitic collisions upstream of the interaction region, and the site requirements in terms of ground stability and coherence, which is needed to preserve luminosity from the collision of sub-nanometer size beams, both need to be taken into account.

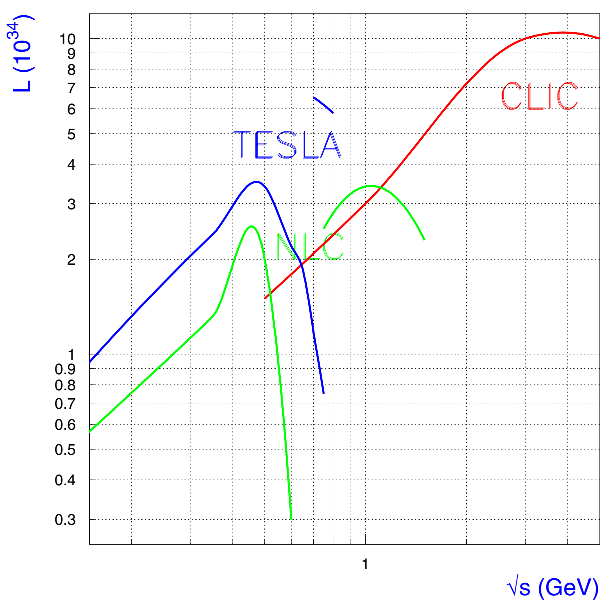


Figure 13: Estimated luminosity as a function of the $\sqrt{s}$ energy for different LC projects. The two sets of curves for NLC and TESLA refer to the baseline projects where the luminosity is traded for the beam energy, keeping the beam power constant, and to a possible linac upgrade.

Beyond about 1 TeV the fusion processes start becoming the dominant modes of fermion and boson pair production. From 1 TeV to 3 TeV, the production of $WW\nu\nu$, $ZZ\nu\nu$ and $t\bar{t}\nu\nu$ starts exceeding that from the s-channel WW, ZZ and ZZ processes. Since these cross sections increase as $\log(s/M^2)$, the luminosity can be traded with energy in this regime. In some searches, the option of colliding photons at a Compton collider extends the reach in mass. An interesting example is offered by heavy Higgs bosons, that are pair produced in e^+e^- collisions only up to $M_H \simeq 0.5 \times \sqrt{s}$ and may be observed in $\gamma\gamma$ collisions up to $M_H \simeq 0.8 \times \sqrt{s_{ee}}$.

At multi-TeV energies, the phenomenology implied by alternative physics scenarios, such as the existence of extra dimensions, may yield spectacular signatures. Large resonances corresponding to the KK excitations of gauge bosons or new gauge bosons may design a different landscape for the evolution of the cross sections of two fermion processes. At the same time it is important to ensure a good sensitivity to the scaling of electro-weak observables at these high energy. Measurements of two fermion cross sections and asymmetries with good statistical accuracy may represent a unique window on new phenomena at mass scales of the order of tens or hundreds of TeV [50]. As the typical sensitivity to these new physics scales with energy and integrated luminosity as $(s \times \mathcal{L})^{1/4}$, trade-offs between these two fundamental parameters can be defined (see Figure 12).

7. Conclusions

The constraints from precision tests of the standard model provide convincing evidence that the Higgs boson of the standard model should be light [1]. These tests can be reinterpreted in the context of extensions to the standard model and imply [17] that the physics responsible for electroweak symmetry breaking, or a manifestation of new physics, will be accessible to a linear collider with center of mass energy of 500 GeV. The LHC will investigate this energy regime before a linear collider could begin operation. While the LHC will enable many measurements of the properties of a Higgs boson, data from a linear collider will be needed to measure the properties in detail and complete the study; in particular some decay modes are expected to be inaccessible at LHC. The need to measure the Higgs properties with high precision at a linear collider demand a detector that is capable of fully exploiting the physics. This demands, in particular, a vertex system capable of discriminating jets with charm and bottom quarks, excellent track momentum resolution and good jet energy determination.

The standard model is known to be incomplete. Many extensions have been proposed. In the case of supersymmetry, a linear collider is capable of precision measurements of the masses and other properties of the supersymmetric particles that are kinematically accessible. Detailed measurements of standard model processes such as $e^+e^- \to WW$ can be used to constrain new physics models. Such measurements can be used, in conjunction with those made at the LHC, to give a more complete understanding of the underlying physics. A linear collider of high luminosity also offers the opportunity to extend the current precision tests of the standard model by obtaining a sample of 10^9 Z bosons.

An enormous amount of accelerator R&D has been undertaken over the last decade (for more informations see [57]). It is clear that this work is sufficiently mature that the construction of a collider of energy 500 GeV could be undertaken. R&D should be pursued to guarantee high gradient operation in the accelerating structures, so that an eventual upgrade to higher energies is possible. Electron polarization is a vital component in the initial operation of a linear collider. R&D should be pursued with a view to providing psoitron polarization. While such polarization need not be part of the initial configuration, it is highly desirable for a complete exploitation of the physics, if supersymmetric particles are found or if the collider is used to obtain a large sample of Z bosons. The ability to extend the initial energy to of order 1 TeV should be an essential part of the facility.

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8. Appendix – Charge to E3 group

- The eeLC group should coordinate with the physics groups to help compile and critically examine the case for an initial phase of the ee collider at a cm energy of up to about 500 GeV, depending on the results from prior experiments at the Tevatron and LHC. For some representative physics scenarios, what is a reasonable goal for integrated luminosity at various cm energies, beam polarizations and beam particles? is there a compelling initial physics program at a luminosity of a few $\times 10^{33}\text{cm}^{-2}\text{s}-1$? Are there particular advantages or challenges to experimentation raised by the different running conditions in the TESLA and NLC/JLC designs?

- The eeLC group should review the case for and feasibility of special options for LC operations:

  - Catalog the physics needs that may require positron polarization, gamma gamma collisions or e-e- collisions. Compare the capabilities of an electron-positron collider and a gamma-gamma collider for making detailed measurements of the properties of Higgs bosons, and for discovering Higgs bosons. What are the R&D issues remaining for each option? What are the requirements on the initial design to allow any of these to be added after the initial phase?

– Examine the case for high-luminosity operation at the Z pole. What are the benefits and drawbacks from the design of a special beam delivery system for low energy collisions? Should there be a special detector devoted to operating below 500 GeV?

– What special requirements are imposed if a free electron laser program is added to the high energy physics facility? What should the HEP community do to facilitate the potential for a FEL program?

· Evaluate the scientific case for an initial-phase "Higgs factory" at an energy of about 300 GeV.

· What new physics landmarks come into view as the energy of a linear collider is raised to 1 TeV; to 1.5 TeV; to 2 TeV; to 5 TeV? What luminosity and other performance characteristics would be required to maximize the scientific output?

· Are there particular issues that detector R&D must address to guarantee the productivity of a linear collider?

· What are the beam physics limits and accelerator limits imposed on LC performance, and what are the primary outstanding R&D issues that are critical to study in the next several years?

· The eeLC group should assume that a technical review panel will likely be established within the next year to evaluate the superconducting L-band and warm rf X- or C-band accelerator proposals. That review, conducted under the auspices of some worldwide body, would examine the performance parameters of the machines, the technical risks, needed R&D, comparative costs and upgradability. Without undertaking the work that such a panel would do, the eeLC group should work to sharpen the questions that this review panel should examine, and consider the way in which the panel should operate.

· What are the paths for upgrade of an initial LC, both in energy and in luminosity? What extensions in energy using the original TESLA or X-band LC designs are feasible? What R&D issues should be given priority? What is the possibility of upgrading either TESLA or X-band LC using two-beam drive power sources? What are the critical R&D issues? What constraints on the initial phase would ultimate conversion to two-beam drive impose?

· How can full international collaboration on a LC project be realized? Is it feasible to assign full responsibility for design, construction, commissioning, test and operation of major subsystems to different portions of the world community while maintaining effective overall project management?

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