

**The Linear Collider Physics Case: International Response to the
Technology Independent Questions Posed by the International
Technology Recommendation Panel**

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The International Technology Recommendation Panel distributed a list of questions to each major laboratory. Question 30, part b and d, were technology independent and related to the physics goals of the Linear Collider. An international panel, with representation from Asia, Europe, and the Americas, was formed by the World Wide Study during LCWS04 to formulate a response. This is given below and constitutes the response of the world-wide Linear Collider community.

30b) How do you make the case for determining the final energy choice for the LC prior to the LHC results? What if LHC results indicate that a higher energy than design is required?

The physics case for the 200 – 500 GeV Linear Collider, upgradable to energies around 1 TeV, rests on arguments that are independent of the findings at the LHC. (We note that this design and upgrade energy are common to both the warm and superconducting technologies.) There are many reports that document this physics case. We cannot repeat all of these documented arguments, so will only recall the essential points here. The question of whether the top end energy should be 800 or 1000 GeV will be commented on at the

end of this response.

1) Electroweak Symmetry Breaking: The LC will decipher the mechanism responsible for electroweak symmetry breaking, regardless of whatever it may be. If the Standard Model is a good low energy effective theory, the current precision electroweak data indicate that the Higgs boson is lighter than about 250 GeV. In addition, supersymmetric extensions to the SM also predict that a light Higgs boson exists. If the Higgs is similar in nature to that predicted by the Standard Model, it will be discovered at the LHC and a LC will be essential in order to study its properties in detail in a model independent way. The precision measurements of the Higgs couplings available at the LC will distinguish the Standard Model Higgs from those which can arise in many other scenarios. In particular, the 500 GeV LC can precisely measure the elementary couplings of the Higgs boson to quarks, leptons, and gauge bosons, and the spin and CP properties of the Higgs boson may be determined via a threshold scan. These measurements are essential for an experimental verification of the scalar dynamics underlying the electroweak symmetry breaking.

Some scenarios predict that a light Higgs may decay in such a way that it escapes detection at the LHC. By utilizing the recoil mass technique in the reaction $e^+e^- \rightarrow Z+\text{Higgs}$ will allow for a Higgs discovery at the LC in a model independent fashion.

If the Higgs boson is heavier than indicated by the precision electroweak data, its properties can be accurately determined at a 1 TeV LC. Furthermore, consistency with the precision electroweak data implies that other new particles whose masses lie below 1 TeV must also be present. As discussed below, the LC then plays a crucial role in identifying the nature of this new physics.

A last possibility is that a light Higgs boson is not realized in nature. In this case, WW scattering violates unitarity at around a TeV unless there is new physics. If the associated new states would be out of direct reach, precision measurements would enable the LC to observe the effects of these states through their virtual contributions to existing processes. This has been studied in great detail for many scenarios, such as strong electroweak symmetry breaking. In particular, the complete threshold region of the new strong interaction can be explored at a LC with energies around 1 TeV.

2) The Hierarchy Problem: A shortcoming of the Standard Model is its instability against the huge hierarchy of the vastly different scales relevant in fundamental physics. The Higgs and gauge boson masses are unstable to quantum fluctuations and would naturally rise to the Planck scale without the onset of new physics around a TeV. It is essential that this hypothesis be tested as precisely as possible. The leading candidates for resolution of this hierarchy problem are:

(i) Weak-scale Supersymmetry. The lightest superpartners are expected to be within reach of a 500 – 1000 GeV LC. A LC with its capabilities of polarized beams and threshold scans will precisely determine the properties of this spectrum. Only the combined information of the LHC and LC measurements can decipher the supersymmetry breaking mechanism and provide clues about the physics at the grand unified scale.

(ii) Extra Spatial Dimensions. In this case, a 1 TeV LC can observe both the direct production and virtual effects of Kaluza-Klein excitations of the graviton and Standard Model particles. The LC with its superb energy resolution does a particularly good job observing the narrow resonances characteristic of some models. Including virtual effects, the discovery reach of a 1 TeV LC for these excitations is 6 – 20 TeV and will cover the natural region of parameter space that is relevant for resolution of the hierarchy problem.

(iii) Little Higgs Models. These models predict a strongly interacting sector and predict the existence of new scalars, gauge bosons, and fermions at energies of order 10 TeV. The sensitivity to physics that lies beyond the direct energy reach of the LC can provide important clues to the high energy behavior. In particular for this case, the LC can determine the couplings of these new particles to the Higgs sector and verify the specific structures of such models.

In any scenario addressing the hierarchy, precision measurements of Standard Model processes at the LC with polarized beams are sensitive to virtual effects at high energy scales and will be crucial to determine the nature of the new physics.

3) Dark Matter: One of the simplest explanations for cosmic dark matter, the invisible matter that constitutes 80% of the mass of large clusters of galaxies, is that it is composed of a new stable particle with weak interaction cross sections. Astrophysical observations are consistent with the mass for such a particle being of the order of 100 GeV and it would thus be copiously produced at the LC. In this case the LC would be ideally suited for establishing the quantum numbers of dark matter candidates; this is discussed more in the answer to 30d.

4) Precision measurements of the Standard Model: A 500 GeV LC will make important precision measurements within the Standard Model. (i) The mass of the top quark can be measured to an accuracy better than 100 MeV and the top quark couplings to the photon and the Z can be determined at the percent level. The uncertainty on the top quark mass is a limiting factor in the global fit to the electroweak data set. A measurement with 100 MeV precision, together with the improved measurement of the W mass at the LHC (or with even better accuracy by running the LC at the W pair threshold),

thus allows for much better exploitation of the LHC results and a precise consistency check of the Standard Model with unique sensitivity to new physics beyond 1 TeV. (ii) The LC can measure the $WW\gamma$ and WWZ couplings to parts in 10^4 . The radiative corrections to these couplings within the Standard Model are at the level of 10^{-3} . The LC thus has the sensitivity to probe new physics contributions at a high level of precision. In particular, these are key experiments that are sensitive to new strong interactions in the Higgs sector. (iii) The LC can determine α_s to better than 1%, and a precise evolution of α_s is an important ingredient for models of grand unification. (iv) The option exists to run the LC at the Z -boson pole, and at the W -boson pair production threshold. The high luminosity of the LC will allow for 10^9 Z -bosons to be produced. This Giga- Z option will allow for the measurement of the effective weak mixing angle at the 10^{-5} level (an order of magnitude improvement), of the W boson mass to 6 – 7 MeV, and of α_s to 0.4%. Together with the 100 MeV top mass determination, this will be an unprecedented precision test of the Standard Model, which would be all the more important in the unlikely event that the LHC discovers nothing.

The arguments stated above demonstrate the need for a 500 – 1000 GeV LC, regardless of LHC results. If the LHC experiments only discover a particle sector at mass scales beyond 1 TeV, it will be important to establish the effects on Standard Model processes via precision measurements, and to search for lower mass states which might have couplings or backgrounds which would prevent their observation by LHC experiments. In many cases, the sensitivity to new physics via virtual effects at the LC exceeds that of direct searches at the LHC. Precision EW measurements by a LC are important for distinguishing among multiple interpretations of new physics which may be observed by the LHC.

It is difficult to make a strong case for whether the top energy of the LC should be 800 GeV or 1 TeV. Certainly, the higher energy provides a somewhat higher window to new physics and gives larger production rates for some Standard Model processes, such as those relevant for the Higgs self-coupling determination. However, there is an energy-luminosity tradeoff which also must be considered for the different processes.

The combined knowledge gained from both the LHC and LC programs will be necessary to make qualified decisions about post LHC/LC facilities. In particular, the experience of operating of a 0.5 – 1.0 TeV LC will be crucial to outline the design of a multi-TeV machine.

30d) Considering the LC will start much later than LHC (although it can have a concurrent operation period), what physics capability

does LC have which LHC does not share? Can this be realized at 500 GeV or does it require much higher energy?

The LHC and the LC have complementary and synergetic physics capabilities. This synergy can be best explored if both machines run concurrently. However, the LC has unique physics capabilities that are crucial to our understanding of nature and will be needed regardless of the LHC findings and the LC startup time. The LHC strength lies in its mass reach, while the LC is a precision machine with:

- better knowledge of the initial state,
- well defined energy and ability to perform energy scans,
- much lower backgrounds than LHC and therefore the ability to detect signals which have low cross sections (e.g. sleptons) or prohibitive backgrounds at LHC (e.g., Higgs bosons decaying hadronically into light quarks),
- better measurement of angular distributions and therefore particle helicities,
- polarized beams which allow measurement of quantum numbers, and the reduction of major backgrounds (e.g., WW).

The LC is uniquely capable of measuring the quantum numbers of new particles. In this way, the LC can determine the nature and underlying origin of new phenomena discovered at the LHC and also provides a unique discovery window on its own. The search reach for new physics via virtual effects at the LC exceeds that of the LHC in many scenarios. The LC is both sensitive to new physics that LHC cannot observe (or cannot observe well), and can aid LHC in distinguishing multiple interpretations of TeV-scale phenomena. These capabilities have been detailed in the answer to question 30b. To further illustrate this point, we expand on several of the items presented in the answer to 30b.

(1) Electroweak Symmetry Breaking: The LC will precisely measure, at the percent level, the properties of the Higgs boson in a model independent way and thus experimentally verify the scalar dynamics responsible for electroweak symmetry breaking; this is not possible at the LHC for a light Higgs boson. For example, for a 120 GeV Higgs boson, the $b\bar{b}$ (tau, charm, gluon) branching fraction can be determined at the level of 1% (5%, 10%, 10%) at a 500 GeV machine. At a 1 TeV LC, the top-quark Yukawa coupling and Higgs self-coupling can be measured with an accuracy better than 10%.

For strong electroweak symmetry breaking, detailed measurements of cross sections and angular distributions at a LC will be essential for identifying the new states and disentangling the underlying physics. The 500 GeV LC can establish the existence of a new state with a significance better than 5 sigma for values of the model parameters in accordance with current constraints; the significance increases by more than a factor of two at a 1 TeV machine. In addition, the LC can separate the different isospin production channels, such as those responsible for the reactions $WW \rightarrow WW$ and $ZZ \rightarrow WW$, which is not accessible at the LHC.

(2) Hierarchy Problem: The prospects that the color neutral part of the supersymmetric spectrum (sleptons, charginos, neutralinos) is accessible at 500 – 1000 GeV are very good. The LC can make precise (100 MeV or better) mass measurements, as well as coupling, spin, and mixing parameter determinations of the supersymmetric partners. In particular, the accurate mass determination of the lightest supersymmetric particle will sharpen all the mass determinations and understanding of superpartner decay chains at the LHC. These measurements can uniquely confirm the symmetries predicted by supersymmetry. A general exploration of the SUSY breaking mechanism and extrapolation to the GUT scale is only possible by combining the data from the LC and LHC (see LHC/LC report).

In the case of extra spatial dimensions, the polarized beams and accurate measurement of angular distributions at a LC allow for the simultaneous determination of the size, geometry, and number of the additional dimensions in a model independent fashion. This is achievable at a 500 GeV (1 TeV) LC for the direct production of gravitons in models with extra dimensions for a fundamental scale of 3 – 5 (6 – 10) TeV. In addition, the LC capability for the identification of spin-2 exchange in all scenarios can demonstrate the connection to gravity.

In any scenario addressing the hierarchy, precision measurements of Standard Model processes at the LC with polarized beams are sensitive to virtual effects at energy scales significantly beyond 1 TeV and will be crucial to determine the nature of the new physics. Important information will come from a 500 GeV LC; running at higher energies will, of course, improve the precision and sensitivity to new physics. For example, limits obtained from difermion production on compositeness and extra gauge bosons scale with the center-of-mass energy; spin-2 exchange scales somewhat less with energy.

(3) Dark Matter: Good candidates for the dark matter are neutralinos from supersymmetry and Kaluza-Klein excitations of the photon from extra dimension theories. A 500 – 1000 GeV machine is expected to cover the cosmologically favored parameter region within supersymmetry. This affords an

intriguing opportunity to compare particle accelerator measurements to those from astrophysics experiments. In fact, the LC is unique in its capability to provide a measurement of the supersymmetric dark matter relic density to a precision of 3% which matches the level expected from future astrophysical observations of 2% (such as PLANCK). In addition, the LC is necessary to identify the superpartners which can complicate the SUSY dark matter scheme. For instance, if the LSP has a slightly heavier partner with the same quantum numbers and a larger annihilation cross section, the effective LSP annihilation is significantly altered. Simply knowing the LSP mass and self annihilation cross section is not enough to place this as the dark matter as precise measurements of the full spectrum are needed. If the dark matter consists of KK excitations, the LC with its superb energy resolution will be essential in identifying the narrow states, and their spin can be determined from angular distributions.

4) Precision measurements: this has been described in the answer to 30b, but indeed this is also very important for this question. The LC capability for precision measurements of Standard Model processes provides a unique window on new physics. The 500 GeV LC has a sensitivity to many processes of new physics with a mass reach well beyond that of the LHC in many cases.

In conclusion, the clean experimental environment of the LC and the unique ability to select helicity channels and measure quantum numbers open new avenues to discover, identify, and reveal the underlying structure of new physics. As for the energy question, we have shown that the baseline LC operating at 200–500 GeV (or as low as 90 GeV as an option) is an essential tool for understanding the physics of the TeV scale, independent of LHC. Upgrading to 1 TeV opens new potentials for discovery.

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