Experimental Program Issues

Chapter 10 Scenarios for Linear Collider Running

In the literature on physics studies at e^+e^- linear colliders, one typically finds each process analyzed in isolation with a specific choice of energy and polarization. This naturally raises the question of how the full program for the linear collider fits together and whether all of the important physics topics can actually be scheduled and investigated. In this chapter, we will examine this issue. We will suggest some simple run plans that accomplish the most important goals of the linear collider program under different physics scenarios.

Under almost any scenario, one would wish to run the linear collider at two or more different energies during the course of its program. Operation of the collider at energies lower than 500 GeV typically yields lower luminosity, scaling roughly as $E_{\rm CM}$. In this chapter, we will craft scenarios using the following guidelines: We assume that the collider has a single interaction region that can run at any energy from m_Z to 500 GeV, with instantaneous luminosity strictly proportional to the CM energy. We plan for a campaign equivalent to 1000 fb^{-1} at 500 GeV, corresponding to 3–5 years at design luminosity. We then ask how the collider running should be allotted among the various possible conditions. These assumptions are rather simplistic, but they frame a problem whose solution is instructive. In Chapter 11, we describe in a more careful way how a collider with two interaction regions, sharing luminosity, would be configured for a flexible program covering a large dynamic range in CM energy.

1 Preliminaries

In designing a plan for linear collider running, we should consider the alternative strategies for energy and for polarization. In this paragraph, we consider these two topics in turn.

There are three different ways to choose the energy of an e^+e^- collider:

- *Sit:* Choose an energy that is optimal for a particular interesting process, and accumulate integrated luminosity at that point.
- *Scan:* Step through a threshold for pair-production of some particle, taking enough data to define the threshold behavior.
- *Span:* Go to the highest available energy, and take a large sample of data there.

In the application of e^+e^- colliders to the J/ψ and Υ systems, and to the Z^0, the e^+e^- annihilation cross section contained narrow structures that put great importance on the exact choice of the beam energy. For most of the important processes considered for study at the next-generation linear collider, the choice of energy should be less of an issue, since the Higgs boson, the top quark, supersymmetric particles, *etc.*, will be studied mainly in continuum production of a pair of particles. These processes have cross sections that peak within 50–100 GeV of the threshold and then fall as $E_{\rm CM}^{-2}$. This dependence is somewhat compensated by the higher collider luminosity at higher energy. Since the signatures of different particles seen in e^+e^- annihilation are distinctive, many different reactions can be studied at a single energy.

As an example, consider the measurement of Higgs boson branching ratios. For this study, the Higgs boson is produced in the reaction $e^+e^- \to Z^0h^0$. For a Higgs boson of mass 120 GeV, the peak of the cross section is at 250 GeV. However, taking into account the increase of luminosity with energy, the penalty in the total number of Higgs bosons in working at 500 GeV instead of at the peak of the cross section is only a factor of 2. At higher energy, more reactions become accessible, and more effort must be made to isolate the Higgs sample. On the other hand, the Higgs production process has a distinctive signature, the monoenergetic Z^0. As the energy increases, the kinematics become more distinctive as the Higgs and the Z^0 are boosted into opposite hemispheres. We conclude that LC experimenters will continue to accumulate statistics for the Higgs branching ratio study as they move to higher energies. Thus, though concentration on this process would favor a sit at an energy below 300 GeV, one could well adopt a span strategy if other physics required it. This example illustrates that it is important, in future studies of linear collider measurements, to evaluate explicitly how the quality of the measurement depends on CM energy.

Only a few reactions among those anticipated for the LC require a detailed scan of some energy region. These include the measurement of the top quark mass by a threshold scan, the precision measurement of supersymmetric particle masses (to the parts per mil rather than the percent level), and, in the precision electroweak program of Chapter 8, the measurement of the W mass to 6 MeV. The top quark mass measurement actually becomes limited by theory errors after about 10 fb^{-1} of data, though a longer run would be justified to obtain a precision measurement of the top quark width and the decay form factors. Other threshold scans require similarly small increments of luminosity, except for the cases of sleptons, where the threshold turns on very slowly, as β^3, and the W, where extreme precision is required.

As for the choice of beam polarization in LC running, it is important to understand how polarization will be implemented. The choice of a polarized or unpolarized electron source is not a limiting factor for the electron currents in the machine. So there is no penalty in choosing a polarization that is as large as possible—80%, with current technology. Polarized electrons are created by shining circularly polarized light on an appropriate cathode. In the SLD polarization program at the Z^0, the polarized light was created by passing a linearly polarized laser beam through a Pockels cell, a device that is effectively a quarter-wave plate whose sign is determined by an applied voltage. The signal applied to the cell changed sign randomly at the 120 Hz repetition rate of the machine. This random sign was supplied to the experimenters and used to determine the initial-state polarization in detected events. We anticipate that the beam polarization will be created in a similar way at the LC. Thus, there will be no 'unpolarized' running. The normal running condition will be a half-and-half mixture of left- and right-handed electron polarization, switching randomly at the repetition rate for bunch trains. In this arrangement, it is straightforward to measure polarization-averaged cross sections. The rapid switching allows polarization asymmetries to be measured with many systematic errors cancelling.

For certain processes, it is advantageous to take the bulk of the data in a single state of beam polarization. For example, the supersymmetric partners of the right-handed sleptons are most easily studied with a right-hand polarized electron beam, while WW pair production and fusion processes such as $W^+W^- \to t\bar{t}$ receive most or all of their cross section from the left-handed electron beam. In contrast, $e^+e^- \to Z^0h^0$ has only a weak polarization dependence. It is possible that our knowledge of physics at the time of the LC running will single out one such process as being of great importance and call for a run with an unequal (90%/10%) distribution of beam polarizations. As in the case of the energy choice, this is a shallow optimum, winning back, in the best case, less than a factor of 2 in luminosity.

2 Illustrative scenarios

With these considerations in mind, we now propose some sample run plans appropriate to different physics scenerios. For each plan, we quote the luminosity sample to be obtained at each energy and, in parentheses, the corresponding sample scaled to 500 GeV. These latter values are constrained to add up to 1000 fb^{-1}.

In most cases, the luminosity assigned below to 500 GeV would be accumulated at the highest machine energy if higher energies were available. Many physics issues, including the measurement of the Higgs coupling to $t\bar{t}$ and the Higgs self-coupling in addition to studies of new heavy particles, benefit greatly from CM energies above 500 GeV. The integrated luminosities given are totals, which might be accumulated in any order. In the scenarios presented here, we omit, for simplicity, the possibility of positron polarization and $\gamma\gamma$ or e^-e^- running. These options are discussed in the later chapters of this section. In considering any of these options, it is important to keep in mind that these options entail trade-offs against e^+e^- integrated luminosity.

2.1 A Higgs boson, but no other new physics, is seen at the LHC

In this case, we would want to apply a substantial amount of luminosity to a precision study of the branching ratios of the known Higgs boson. It will also be important to search for Higgs bosons not seen at the LHC, to search for new particles with electroweak couplings that might have been missed at the LHC, and to measure the W and top gauge couplings to look for the virtual influence of new particles. Thus:

- 300 GeV: 250 fb^{-1} (420 fb^{-1}) sit
- 350 GeV: 100 fb^{-1} (140 fb^{-1}) top threshold scan
- 500 GeV: 440 fb^{-1} (440 fb^{-1}) span

This run plan gives a data sample for the Higgs boson branching ratio measurement equivalent to 600 fb^{-1} at 350 GeV.

2.2 No Higgs boson or other new particles are seen at the LHC

In this case, we would want to apply the largest amount of luminosity to the highest available energy. The issues for this study would be the search for additional Higgs bosons not seen at the LHC and the search for new particles. The measurement of the W and top gauge couplings would be of essential importance. Because the absence of a light Higgs conflicts with the precision electroweak fits within the SM, it will also be crucial in this case to include running at the Z^0 and the WW threshold.

- 90 GeV: 50 fb^{-1} (280 fb^{-1}) sit
- 160 GeV: 70 fb^{-1} (220 fb^{-1}) W threshold scan
- 350 GeV: 50 fb^{-1} (70 fb^{-1}) top threshold scan
- 500 GeV: 430 fb^{-1} (430 fb^{-1}) span

2.3 Light Higgs and superpartners are seen at the LHC

In this case, it is necessary to compromise between the optimal energies to study each of the new states, the optimal energy for the Higgs study—since a light Higgs must also appear in supersymmetric models—and searches for new superparticles, such as the extended Higgs particles and the heavier charginos and neutralinos, that could have been missed at the LHC. The program will begin with extended running at 500 GeV, and perhaps also at a lower energy, to determine the superpartner masses to percent-level accuracy. This could be followed by detailed threshold scans.

Martyn and Blair [1] have studied a particular scenario in which the lightest neutralino has a mass of 70 GeV, the lighter charginos and sleptons lie at about 130 GeV, and the heavier charginos and neutralinos are at about 350 GeV. Converting their suggested program to our rules, we have for this case:

- 320 GeV: 160 fb^{-1} (250 fb^{-1}) sit
- 500 GeV: 245 fb^{-1} (245 fb^{-1}) span
- 255 GeV: 20 fb^{-1} (40 fb^{-1}) chargino threshold scan
- 265 GeV: 100 fb^{-1} (190 fb^{-1}) slepton ($\ell_R^-\ell_R^+$) threshold scan
- 310 GeV: 20 fb^{-1} (30 fb^{-1}) slepton ($\ell_L^-\ell_R^+$) threshold scan
- 350 GeV: 20 fb^{-1} (30 fb^{-1}) top threshold scan
- 450 GeV: 100 fb^{-1} (110 fb^{-1}) neutralino ($\chi_2^0\chi_3^0$) threshold scan
- 470 GeV: 100 fb^{-1} (105 fb^{-1}) chargino ($\chi_1^-\chi_2^+$) threshold scan

The threshold scans would be done with the dominant beam polarization chosen, respectively, right, left, equal, left, left. The threshold with β^1 cross sections are given small amounts of running time; thresholds with β^3 cross sections or cross sections that are intrinsically small are given 100 fb^{-1}. The running time at the top threshold is more than sufficient to push the determination of m_t to the systematics limit. While running at each threshold, pair production of all lighter species can also be studied. In particular, the total statistics for the Higgs branching ratio measurement is equivalent to about 700 fb^{-1} at 350 GeV.

References

[1] H. Martyn and G. A. Blair, in *Physics and Experiments at Future Linear e^+e^- Colliders* (LCWS99), E. Fernandez and A. Pacheco, eds. (Univ. Auton. de Barcelona, Bellaterra, 2000), hep-ph/9910416.