A future linear collider will complement the programme of the Large Hadron Collider, especially for precision physics. The RADCOR community has an important part to play in refining the predictions for rates and processes in Electroweak, Higgs, SUSY, top and QCD physics, for $e^+e^-$, $e^-e^-$, $\gamma\gamma$ and $\gamma e$ collisions.

1 Introduction

Linear colliders in the range from 300 GeV to some TeV will tackle many more topics in precision physics than can be dealt with in this short talk. They will also set out to discover new effects and new particles. Studies of the whole physics programme are under way in Europe\cite{1}, in Asia\cite{2} and America\cite{3}, with Worldwide co-ordination\cite{4}. The participants will get together to present results at the Linear Collider Workshop (LCWS) at Sitges, just down the road from here, next April. Those who want to know more should come back to Barcelona then. But enough is already known about the goals of such machines from previous studies\cite{5,6,7,8} to motivate a highlighted shopping list of topics where input from the RADCOR community will be particularly important. Some of them are picked out in the text of this review with the shopping-list symbol $\{SL\}$. A lot of phenomenological Ph.D. projects will need to be completed before we are ready to exploit the full physics potential of a linear collider.

There are likely to be two stages of machine-building over two decades; perhaps following one-another in the same tunnel, or perhaps on different continents. The first will cover the range from 300 GeV, near the top threshold, to about 1 TeV. Such a machine might also be able to revisit the $Z^0$ region and the $W^+W^-$ threshold with high luminosity and polarised beams, if the physics interest is strong enough to justify the extra engineering required. The luminosity will be in the range from $5 \cdot 10^{33}$ to $5 \cdot 10^{34}$, giving useful event samples for a year of running between $50 fb^{-1}$ to $500 fb^{-1}$ in a given small energy range. Figure 1 shows cross sections for some of the interesting channels.
Note that many of them are comparable with the $e^+e^- \rightarrow \mu^+\mu^-$ rate; “a few units of R” as we say, where R is the ratio of the cross-section for a given process to the QED dimuon cross section. The option of running with $e^-e^-$ as well as $e^+e^-$ will be relatively easy to provide. There are also possibilities for special Compton-backscattered photon beams at up to 80% of full beam energy and almost the full luminosity, giving a much better source of $e\gamma$ and $\gamma\gamma$ events than ever before. These will require the solution of some tricky, but probably not insuperable, technical problems. The RADCOR community should be involved in making the physics case to justify these developments [S L].

The second-stage machine, in the energy-range from 1.5 to 4 TeV, will be particularly important if it turns out that there is no narrow Higgs boson below 600 GeV, and/or if new physics (such as SUSY) is discovered at the LHC or at the first-stage collider, with a predicted spectrum of particles which are too massive to be seen by those machines. The luminosity scaling law $L \propto s$ will compensate the fall in cross-sections with rising energy, so long as the ever-smaller beamspots can be kept in collision. On the time scale for building the second-stage linear collider it is possible that a muon collider could be a feasible and cost effective alternative [13, 14, 15].

There are four active design programmes for a linear collider, based on four major laboratories. SLAC and KEK are collaborating on an X-band normally conducting machine [16, 17]. A serious technical proposal for this may be submitted within three years. DESY (and collaborators) have the rival superconducting TESLA design [10] which has recently been upgraded to predict a luminosity approaching $5 \times 10^{34}$ at 500 GeV C. of M. They also plan an early technical proposal. KEK also has a normally conducting C-band design under study. And at CERN successful first steps have been made to prove the feasibility of a two-beam accelerator called CLIC [18] which looks like the best prospect for the second-stage linear collider.

2 The Detectors

The demands of physics at the first-stage machine will be a little more stringent than at LEP2, but nowhere near as difficult as at the LHC. Some of the most interesting channels (e.g. $t\bar{t} \rightarrow W^+bW^−\bar{b}$) will have six jets instead of two or four, and better resolution of energy flow in the calorimeters will be needed to separate them. The beam pipe can have a much smaller radius than at LEP, 1 or 2 cm compared with 10 cm, which will allow much better resolution of beauty decays. If the radius is brought down to 1 cm then the efficiency for identifying charm will be greatly enhanced at the cost of a longer and more
Figure 1: Cross sections for some interesting channels.
expensive final-focus insertion in the linac. Phenomenologists must be involved in developing the case for this \([S_L]\).

After all the R&D on radiation-hard, fast, high density detector technology for the Large Hadron Collider there are many new techniques available for the Linear Collider detector. A number of contrasting strategies are being investigated. One radical approach, discussed in the Snowmass study in 1996 \([1]\), is to build a compact silicon tracker in a 4 tesla solenoid field and start the electromagnetic calorimetry within a meter from the intersection point. European \([2]\) and Japanese \([3]\) studies have gone for much larger tracking volumes with gaseous detectors (TPC or Jet Chamber). There is a debate at the moment on the need for special cerenkov or transition-radiation devices for particle identification. The developing consensus is to omit them. The choice between the different detector options will be made by looking at their performance on a set of “reference reactions” which will include both the most important channels and those which put the heaviest demands on detector performance. The RADCOR community is already involved, helping choose the channels and writing Monte Carlo generators; but experimenters are never satisfied with the available generators so much more work will be needed \([4]\).

Because of the electromagnetic background at a future linear collider the parts of the detector close to the forward beam directions will be much less effective than at LEP. This will make the detector less hermetic than the best LEP detectors and will undermine some new particle searches. The reasons are inescapable. The only way of achieving high luminosity with beams making a single pass is to pinch them down to a few nm in the vertical direction, but this gives rise to new electromagnetic effects including beamstrahlung, beam disruption and copious pair production by the high energy leptons of one beam interacting with the electromagnetic field of the whole opposing bunch. The disrupted beams can be accommodated by careful beamline design, but the soft pairs come out at angles of tens of degrees and contain a total of many TeV of energy per beam crossing. The electrons and positrons are trapped by the solenoid field and go in the forward direction. When they collide with small-angle forward detectors or with the final-focus quadrupole magnets they produce large numbers of backscattered soft gamma rays and x-rays. To stop this background from swamping the main tracking detectors all detector designs incorporate a thick conical tungsten mask which cuts off the region within approximately 100 mr from the beam direction and which projects some 10s of cm from the intersection point, see Figure \([5]\). Outside the mask detectors should operate in a relatively quiet environment. Inside the mask any detectors will need to be radiation-hard, and will have to identify wanted signals on top of the wash of soft electromagnetic background energy.
Some of us are looking at ways of incorporating a minimal quantity of sampling material in the mask itself so that the solid angle which it covers is not totally dead.

![Figure 2: Schematic layout of the inner region of a linear collider detector.](image)

### 3 Top Quark Physics

The scan across the threshold for $t\bar{t}$ production is one of the first jobs to be done, and one requiring the highest precision. The first goal is to measure the mass of the top quark. It may also be possible to deduce something indirectly about the width. The experimental systematic error could be as low as $\pm 120$ MeV\(^{-1}\) with a ten-point scan of 50\(fb^{-1}\) integrated luminosity; if the effect of beamstrahlung upon the luminosity spectrum can be adequately monitored, see section 4 below [SL]. The short lifetime of the top quark acts as a cutoff which permits a perturbative QCD calculation of the excitation curve. But recent work has shown that the NLO and NNLO corrections move the position of the step on the curve sideways by about 1 GeV and change the predicted height of the step in cross section by tens of percent. The eventual precision on the top mass is now a problem for the theorists, so this item is firmly on the shopping list [SL].

The other great goal in $t\bar{t}$ studies is to measure the Yukawa coupling $\lambda$ of the higgs boson to the top current. In the early 1990s, before the top quark mass was known, we wondered if it might be possible to measure $\lambda$ from the height of the step in the threshold excitation curve; for a very heavy top quark the higgs loop would become significant compared with the leading order
But now we know the top mass is too light for any such effect to be detected (and, for the moment, we cannot calculate the QCD contribution to sufficient precision).

But the Yukawa coupling should be measurable by more direct methods, especially if the high luminosity promised by TESLA can be delivered. If the higgs mass is more than twice the top mass then we search for \( h \to t \bar{t} \), Figure 3a. Old studies by Fujii \cite{23} (with \( m_h = 300 \) GeV and \( m_t = 130 \) GeV!) suggested that a clear signal would be seen with \( 60 fb^{-1} \) at \( \sqrt{s} = 600 \) GeV. These need updating \([SL]\) to take account of the known top mass and the possibility of higher luminosity. If the higgs mass is less than the top mass there will be a significant rate for the radiation of higgs bosons from an outgoing top quarks in \( t \bar{t} \) production, see Figure 3b. Juste’s old study \cite{24} predicted a signal of 48 such events, after cuts, with background of 29 events, in \( 50 fb^{-1} \) with \( \sqrt{s} = 750 \) GeV. At that level he suggested that a significant measurement of \( \lambda \) would be “barely possible”. But with 10 times the luminosity the situation would be very different. And a new calculation \cite{25} of corrections to Figure 3b shows a significant enhancement to the rate for lower values of \( \sqrt{s} \approx 500 \) GeV; another process already on the shopping list \([SL]\).

4 Monitoring the Luminosity Spectrum

Measuring luminosity at a Future Linear Collider will be a much more difficult task than at LEP or SLC, but precision physics at the \( t \bar{t} \) threshold, or at any SUSY particle thresholds, will depend on it. If the mass of the top quark is to be measured to \( \pm 175 \) MeV (say) then the resolution on the collision energy has to be better than \( 1/1000 \). The big problem is beamstrahlung, the loss of energy by electrons in one beam from the intense electromagnetic field of the opposite bunch. This causes a variable amount of radiative energy loss before the main collision takes place. There can also be a significant spread of energy in the linac beams, much more than in a circular collider, though this can be reduced in most linac designs – sometimes at the expense of reduced luminosity. For any period of running we will need to determine the luminosity spectrum of the collisions, not just the integrated luminosity. And no experimenter is going to trust a luminosity estimate which is based solely on beam diagnostics; the luminosity spectrum must come from interaction data. Nothing else can reflect all of the fluctuations which might take place in the detailed dynamics of beam-beam collision as well as the bunch to bunch variations of linac behaviour.

The job can not be done by counting small angle (\( 30^\circ < \theta < 120^\circ \)) Bhabha scattering events, as we do at LEP or SLC. The only way of knowing the energy of such events would be by direct calorimetric measurement of the electrons.
Figure 3: Ways of measuring the Higgs boson Yukawa coupling for a) heavy Higgs, b) light Higgs.

- inside the mask. But even the best electromagnetic calorimetry could do little better than 1%, which is not good enough, and even that will be hard to achieve with the severe background and shower-containment problems in the mask region.

Table 1 shows some of the possible processes which might be used for luminosity monitoring. The ideal process would have a rate which is much higher than any of the interesting physics processes - "many units of R" - and the final state tracks should be sufficiently well measured in the main part of the detector so that the event energy can be obtained to better than 1/1000 by fitting the angles. Nothing fully satisfies these criteria. Radiative return to the \( Z^0 \) (\( e^+e^- \rightarrow Z^0\gamma \)) is one of the interesting channels because the final state gamma ray will usually be unseen and can be constrained to lie within some tens of milliradians from the beam direction. The angles of the \( Z^0 \) decay products then give a good measure of the energy. But only 7% of the 30 units of R will have \( Z^0 \rightarrow e^+e^- \) or \( \rightarrow \mu^+\mu^- \) which can be well measured. It will be much harder to get accurate directions for the jets from the hadronic \( Z^0 \) decays, especially since they will be strongly boosted towards the endcap.
regions where detectors will be less uniform and some jet energy will be lost into
the masks. Nevertheless, this will be an important channel, especially because
the mass of the $Z^0$ is so well measured, giving an absolute energy scale quite
independently from measurements on the beams. Good calculations of the
radiative corrections to $Z^0 (e^+ e^- \rightarrow Z^0 \gamma)$ must be on the shopping list [SL].

My recommended best solution to the problem is to use large-angle Bhabha
scattering events, with electrons going into the endcap regions of the detector.
The rates are large because the t-channel exchange still dominates, and there
are only two clean lepton tracks to measure, with well determined angles in a
properly designed detector. There is, of course, no way of fitting these events
to get individual event energies $\sqrt{s}$ from angles alone. But we can measure
a different quantity for each event, the acollinearity angle between the two
electrons, $\theta_A$, see Figure 4. The luminosity spectrum can be unfolded from the
distribution of $\theta_A$. This was first demonstrated analytically in 1992 [26] and has
since been checked numerically [27], though a full Monte Carlo simulation has
not yet been done.

If the spread of the beam energies at collision were simply Gaussian then
it is easy to show that

$$\sigma_{\sqrt{s}} = \sigma_{\Delta p} = (\sigma_{\theta_A} p_b) / \sin \theta,$$

where, for a small momentum mismatch $\Delta p$ between the two interacting parti-
cles, $\Delta p = p^+ - p^-$, $\sqrt{s} = p^+ + p^-$, $p^+ \approx p^- \approx p_b$ and $\thetaited
150 < \theta < 500 \text{mr}$ is likely to be the most useful, see Table 1.

The actual distribution of beamstrahlung losses is very nongaussian, and it
combines with the inescapable initial state radiation (ISR) losses for individual

Table 1: Approximate rates for possible luminosity and measurement processes

| Process | Rate | Comment |
|---------|------|---------|
| Bhabha 180–300 mr | 223R | Endcap. Best statistics, adequate precision |
| Bhabha 300–800 mr | 104R | Intermediate |
| Bhabha 800–2341 mr | 8R | Barrel. Lower statistics, good precision |
| $\mu^+\mu^-$ | R | Low statistics, good precision |
| $Z^0\gamma$ | 30R | Reasonable statistics. Should study further |
| $W^+W^-$ | 12R | Reasonable statistics. Poor precision |
| Two real $\gamma$ | 2R | Low statistics, reasonable precision |
| $t - \bar{t}$ | $\sim R$ | Signal |
events to give spectra for the colliding electrons which have a strong peak at close to the nominal beam energy and a long tail due to radiation. From the signed acollinearity distribution we can separately extract the shape of both the $e^+$ and $e^-$ momentum distributions at collision and hence calculate the distribution of $\sqrt{s}$. It is important to reconstruct correctly the spike of events with very small radiation losses because these give the sharpness to the threshold step in the excitation curve from which the mass can be measured. So we must resolve the acollinearity to better than 1/1000; not an impossible job for a good tracking detector, so long as the endcap regions are designed with it in mind. In the 1992 study\cite{26} we found that approximately 20% of events were in the spike with $\theta_A < 1$ mr for the best linac designs, after beamstrahlung, ISR and linac beamspread had been considered.

Cross sections for Bhabha scattering at more than 150 mr have never been calculated as precisely as those at small angles, where they are needed for LEP luminosity measurements and where systematic errors are now dropping below 1 per mille. If the high-luminosity TESLA gets built then we will have physics samples of 500 $fb^{-1}$ with $10^6$ events in some channels, so it is time to put this region of Bhabha scattering onto the shopping list for precision calculations. The cross sections will be needed to normalise high statistics channels $[S_L]$, and good acollinearity distributions from initial state radiation will be required for the luminosity spectrum measurement $[S_L]$.

5 Light Higgs

This summer’s fits\cite{28} to electroweak data tell us that if the Higgs boson has properties close to the standard model it should either be seen at LEP ($m_h < 105$ GeV) or early in the LHC programme. But discovering it will just
be the beginning of Higgs physics. It will then be necessary to establish what kind of Higgs boson we have seen; standard model, minimal supersymmetric extension, next to minimal extension, etc. etc. The linear collider will be where these questions are answered. Measuring the Yukawa coupling to top quarks, Section 3 above, is one of the tests, but the most important goal is to determine the total width of the Higgs and its partial widths for different quark, gluon and boson flavours. A worthwhile step towards this will be the measurement of the total rate for $e^+e^- \rightarrow Z^0h$, where the $Z^0$ decays to $e^+e^-$ or $\mu^+\mu^-$ and the missing mass of the recoiling Higgs boson is measured without relying on any of the Higgs decay products. The resolution required on the two outgoing lepton tracks in this process dictates the precision needed in the tracking detectors at the Future Linear Collider. Within this Higgs sample it is then necessary to identify particular sets of final states. With $50 fb^{-1}$ at $\sqrt{s} = 350$ GeV and $m_h = 140$ GeV the 1996 ECFA/DESY study showed that in its standard detector the product $\sigma_{Zh} \cdot BR(h \rightarrow b\bar{b})$ could be measured to 6.2% but $\sigma_{Zh} \cdot BR(h \rightarrow c\bar{c} + gg)$ would have an estimated error of 47%, clearly not good enough. The extra statistics at the high luminosity version of TESLA would be very important for this measurement. The Snowmass detector, with its smaller beampipe radius and good microvertex system, aims to separate the $c\bar{c}$ from the $gg$ events. All of these processes must be on the phenomenologists’ shopping lists for more refined calculations [SL].

6 The Compton Collider

To measure the absolute width of the Higgs boson may require the Compton Collider mode of the linac. From Higgs decays at the LHC or at the Linear Collider we should be able to measure the branching ratio to $\gamma\gamma$. Then with a known real two-photon flux we can measure the partial width $\Gamma^{h\gamma\gamma}$ for $m_h < 350$ GeV. This quantity is also of great interest in its own right because it gets finite and comparable loop contributions, see Figure 5, from every heavy charged particle which couples to the Higgs boson, with no upper mass limit. It is very important to check all of the calculations of these cross sections and branching ratios [SL]. If the Linear Collider is built after a light Higgs has already been discovered there may be an overwhelming case to install a second interaction region with a backscattered laser photon facility from the start.

If the $\gamma\gamma$ luminosity can be made comparable with the $e^+e^-$ luminosity of the linac then the production rate of $W^+W^-$ will actually be higher in the $\gamma\gamma$ mode, and a complementary set of processes can be studied. Even if the luminosity is substantially lower than for $e^+e^-$, scattering electrons from real photons in the $e\gamma$ mode will give by far the best way of measuring the structure
of the photon. But already at LEP we are limited in the precision of our analysis by inadequacies in the available Monte Carlo models that have to be used in unfolding the structure functions. More work is needed from the phenomenologists, especially on the right way to treat the $c\bar{c}$ threshold.

7 SUSY

There is an infinite set of shopping lists in SUSY because there are so many possible combinations of – as yet unconstrained – parameters, but the circumstantial evidence for the existence of Supersymmetry continues to grow. If SUSY has been discovered at the LHC before the Linear Collider is built there will still be the question “which SUSY model is this?”. The LHC may already have seen some coloured SUSY particles, and part of the Higgs sector, but the Linear Collider would be needed to find the charginos and sleptons. And the well defined kinematics of $e^+e^-$ collisions will allow threshold scans, or precise mass determinations from the spectra of recoil particles. The 1996 ECFA/DESY Study found, for instance, that in 50 fb$^{-1}$ at $\sqrt{s} = 500$ GeV the mass of a 170 GeV $\tilde{\chi}^+$ could be measured to $\pm 100$ MeV, see Figure 6. We are promised polarised electrons and perhaps polarised positrons at the same time. How can these be used to probe the subtleties of the theory?

At recent workshop meetings the consequences of the alternative gauge-mediated SUSY-breaking scheme have been discussed, including the possibility that long-lived sparticles will decay some tens of centimetres into the detectors. To make good measurements on events like this would require the capacity to point-back gamma rays from the calorimeter with very good angular precision. Should we be trying to do this in the first stage of Linear Collider operation?
Figure 6: Upper part: Threshold behavior of the cross section for $e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$ including initial-state radiation and beamstrahlung. Lower part: Simulation of the energy spectrum in the decay $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 + jj$ based on the input values $m_{\tilde{\chi}_1^+} = 168.2$ GeV and $m_{\tilde{\chi}_1^0} = 88.1$ GeV at $\sqrt{s} = 500$ GeV; Ref. 10.
8 QCD

A sample of $500 fb^{-1}$ at $\sqrt{s} = 500$ GeV, for a high luminosity collider, will have $10R \approx 4 pb$ of $q\bar{q}$, giving 2 million events with two and more final state jets, comparable to the samples studied at LEP on the $Z^0$ peak where the errors on $\alpha_s$ were systematics limited. With such statistics it would be possible to make a significant step in charting the running of $\alpha_s$ up to a much higher scale. Phenomenology must follow [SL]. There might also be an opportunity to use the radiative return sample $e^+e^- \rightarrow Z^0\gamma$ with $Z^0 \rightarrow q\bar{q} \rightarrow$jets to repeat measurements on the $Z^0$ in the same detector, cancelling out some of the systematics involved in a comparison with LEP data. But these $Z^0$s would be highly boosted into the endcap regions of the detector. If the physics case for such measurements is strong enough there are two alternative strategies for producing an unboosted $Z^0$ sample in the same detector; either the machine can be adapted for running at the $Z^0$ energy, or it might be run with asymmetric energies to give a sample of radiative-return events with reduced forward boost. Again, better models [SL] of the radiative return will be needed.

9 Electroweak Physics

Study of the $W^+W^-$ final state is a growth industry at LEP2. There will be even more sensitivity to anomalous couplings at the linear collider: the increased energy will change the balance between the three tree level graphs, giving better intrinsic sensitivity; the greater luminosity (especially at TESLA) will more than compensate for the falling cross section; and it should be possible to polarise both beams to alter the balance of the graphs in a controlled way [SL]. Also, at $\sqrt{s} = 500$ GeV, the single $W$ rate grows to the same size as $W^+W^-$, giving a new handle on the couplings. Figure 7 shows cross sections for processes which can be studied in the $e\gamma$ and $\gamma\gamma$ modes of the machine, some of which are sensitive to different electroweak couplings [SL]. Some of these cross sections grow with $\sqrt{s}$ so they will be even more important at 1 TeV.

10 Conclusions

1. A linear collider, especially with high luminosity, will do much new precision physics which will be complementary to the LHC.

2. Many of the processes involved need better calculations than are at present available, and better Monte Carlo generators.
3. Theoretical input is needed soon for decisions which have to be taken about:

- Precision of detectors,
- Need for polarised $e^-$ and $e^+$,
- Importance of the $e^-e^-$, $\gamma e$ and $\gamma\gamma$ options,
- Need to measure $h \rightarrow c\bar{c}$, requiring small beampipe, low background etc.
- How to measure $\Gamma_{\text{total}}^{\text{higgs}}$.

4. Phenomenologists are encouraged to join their local linear collider workshops (see webpages 1, 2, 3, 4).

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