

## LINEAR COLLIDER PHYSICS\*

David J. Miller

*Physics and Astronomy, University College London,  
Gower St., London WC1E 6BT, UK. [dave.miller@cern.ch](mailto:dave.miller@cern.ch)*

### Abstract

Studies of the physics potential of the Future Linear Collider are establishing a broad programme which will start in the region of 350 to 500 GeV C. of M. energy. The main goal is to understand why the standard model works; by studying the properties of the Higgs sector, if it is within reach, and by exploring the complex world of Supersymmetry, if it is real. If the Higgs boson is not found soon, then the Linear Collider can test the standard model with high precision measurements, both at energies approaching 1 TeV and with high statistics at the  $Z^0$ .

---

\* Invited talk at Les Rencontres de Physique de la Valle d'Aoste, La Thuile, Italy; February 27-March 4, 2000

## 1 Where are we?

If there is a decision in 2003 to go ahead with a Linear Collider programme the machine and detectors could be ready for operation in 2010. By then the LHC at CERN will have overcome any teething troubles and be well into its mainstream programme. In particular, it may have found at least one Higgs boson, if the Higgs mass lies in the range below 250 GeV which is favoured by current fits to the standard model <sup>1)</sup>, or if Higgs bosons are generated by SUSY theories which are perturbative up to a high scale <sup>2)</sup>. There may still be discovery opportunities for the Linear Collider, but its main role will be to make clean precision measurements, whether or not new physics has already been found. These will either identify just what it is that has been found and see how it explains electroweak symmetry breaking, or they will further constrain the standard model in order to anticipate how the symmetry will be broken.

Studies of physics for the future linear collider are now focussing on the case to be made for funding. This case will be presented in Europe in Spring 2001 and at about the same time in the USA. Japan has plans on a similar timescale. By 1 March 2001 DESY will produce a Technical Design Report (TDR) for the TESLA machine, including an X-ray free-electron-laser facility for biomedical and condensed matter studies. European physicists are collaborating in the 2nd ECFA/DESY Study <sup>3)</sup> which will provide the sections of the TDR on the physics programme, the detector and the machine-detector interface. Unlike earlier studies, this TDR will contain a full costing of all parts of the programme. The ECFA/DESY Study has held a series of workshops in Orsay, Lund, Frascati, Oxford and Obernai (France), continuing in Padova in May 2000 and DESY in September 2000. There will be a TESLA “launch conference” in Autumn 2001 when the TDR is ready. In parallel with the ECFA/DESY study there are North American workshops <sup>4)</sup>, the next at LBL in March 2000 <sup>5)</sup>, ACFA workshops in Asia <sup>6)</sup> and a worldwide series where the three regions exchange ideas. The next worldwide Linear Collider Workshop (LCWS) will be at Fermilab in October 2000. (Previous LCWS were at Saariselka, Finland <sup>7)</sup>; Waikoloa, Hawaii <sup>8)</sup>; Morioka-Appi, Japan <sup>9)</sup>; Sitges, Spain <sup>10)</sup>)

There is no space here for a description of the possible detector to do this physics. The ECFA/DESY study has based most of its simulations on the detector design outlined in the 1997 Conceptual Design Report <sup>11)</sup>, though the version now being used includes developments in vertexing - which will improve the identification of charm, a higher magnetic field - which will improve the resolution on missing masses (see section 3.1 below), and more finely segmented calorimetry -

expressly driven by the need to make the best possible measurements of hadron jets in multi jet final states.

## 2 Requirements on the Accelerator

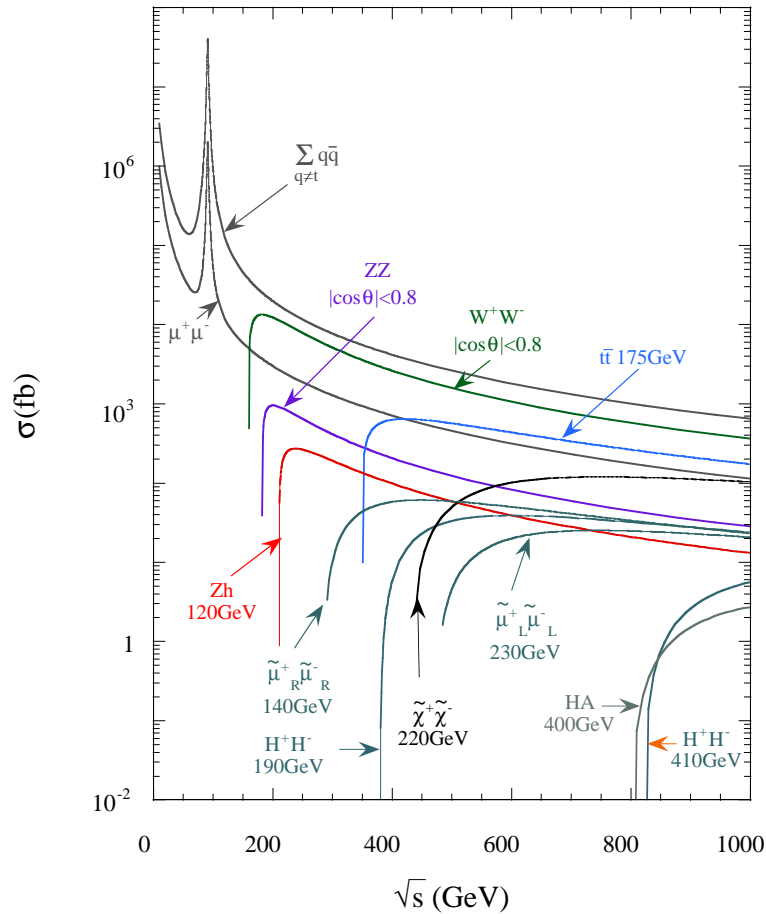


Figure 1: *Cross sections for real and possible processes at a linear collider.*

The main factor which has delayed Linear Collider development has been the imperative need to achieve very high luminosities, much higher than LEP which delivers  $250 pb^{-1}/\text{year}$  at best. LEP felt like a high luminosity machine when it was sitting on  $30 \text{ nb}$  total cross section at the  $Z^0$  resonance peak, but even with improved luminosity at LEP2 we can still only produce handfuls of  $Z^0$ -pair events. Figure 1 shows how the cross sections for some interesting processes should vary with beam energy. The standard reference process is  $e^+e^- \rightarrow \mu^+\mu^-$ , “1 unit of R”, whose cross section falls like  $1/s$ , as do  $t\bar{t}$  or light Higgs boson production in the

higgstrahlung channel  $e^+e^- \rightarrow Z^0H$ . Some other channels, with dominant t-channel exchanges, rise more slowly from their thresholds - for example single W production  $e^+e^- \rightarrow e^\pm\nu W^\mp$ ,  $e^+e^- \rightarrow \nu\bar{\nu}H$  or  $e^+e^- \rightarrow \nu\bar{\nu}W^+W^-$  or some of the SUSY processes in Figure 1.

Table 1 shows the numbers of events to be expected in some interesting channels on the assumption that  $500fb^{-1}$  can be collected at  $500GeV$ , or  $1000fb^{-1}$  at  $1TeV$ . The relativistic shrinkage of emittance in the machine will actually help to increase the luminosity at higher energies, so long as the beam alignment can be kept under control. With event numbers like these definitive studies can be made of, for instance, the branching ratios of a light Higgs boson - see below.

To get  $500fb^{-1}$  in a  $10^7$ sec machine-year will require a luminosity of  $5.10^{34}cm^{-2}sec^{-1}$ . We believe this to be possible, both because of what has been learned from running the Stanford Linear Collider, and because of the advances beyond that made by the competing linear collider development teams - including the Russians until they were forced by financial circumstances to drop out. The single most important advance over SLC will be a reduction in vertical spot size from a few microns to a few tens of nanometres. A big part of the technology needed for this was proven by the world wide collaboration that worked with the Final Focus Test Beam at SLC. Another big part of it has to come from high brightness electron guns and from damping rings to reduce the beam emittance. The most advanced damping ring test is under way at KEK in Japan.

The largest part of the cost will be for the accelerating structure of the linac itself. Here the competition is primarily between the normally-conducting X-band structure being developed by SLAC <sup>12)</sup> and KEK <sup>13)</sup> and the superconducting TESLA concept from DESY and collaborators <sup>11)</sup>. Each has strengths and weaknesses. After the costed Technical Designs appear it will be important to make a choice between them which is driven by the quality of the physics, not the nationality of the supporting laboratories. Both designs will initially be optimised for  $\sqrt{s} = 500GeV$ . TESLA at the moment appears to offer better luminosity for a given power consumption. Its larger aperture and more widely spaced bunches

$500fb^{-1}$ @ $\sqrt{s} = 500GeV$		$1000fb^{-1}$ @ $\sqrt{s} = 1000GeV$	
30,000	$ZH_{120}$	3,000	$\nu\bar{\nu}H_{500}$
50,000	$\nu\bar{\nu}H_{120}$	2,000	$WW\nu\bar{\nu}$ , No Higgs
$3.5 \times 10^6$	$WW$ or $e\nu W$	6,000	$WWZ$ , No Higgs

Table 1: Numbers of events in some possible channels.

may make it easier to overcome alignment and vibration problems. Once a tunnel is built the ultimate energy of the machine will be limited by the peak accelerating gradient. The very best performance so far from TESLA-type cavities suggests that their present design, which is already capable of delivering the accelerating gradient needed for  $\sqrt{s} = 500\text{GeV}$  in the planned tunnel, might be developed to give maximum energy of a little over 800 GeV in the same tunnel. The proponents of the X-band design hope that with more and better klystrons they may eventually be able to raise the energy to 1 TeV. The longer term future, however, may rest with a change of technology to the CLIC concept developed at CERN<sup>14)</sup>. This might eventually achieve six or seven times the 23.5 MV/m which is the design gradient of TESLA for 500 GeV.

The possibility to polarise of the electrons to about 80% is another legacy from SLC, and the TESLA designers are hopeful that their positron production scheme will give 60% polarisation, though R&D is needed to prove this.

Although the principal programme of the future collider will be with  $e^+e^-$  collisions at high energies from the top threshold at 350 GeV upwards, there are other important options being studied. A Novosibirsk group<sup>15)</sup> suggested the Compton Collider, in which one or both beams from an  $e^-e^-$  linear collider are intercepted with laser light a few millimetres before the interaction point. With the right choice of laser energy, laser polarisation and beam polarisation the resulting  $\gamma\gamma$  collisions can have more than 1/10 of the luminosity of the collider in its  $e^+e^-$  mode, with a peak at close to 80% of the full energy. In the  $e^-\gamma$  mode the peak in the photon energy spectrum contrasts extremely favourably with the soft bremsstrahlung of virtual photons used in  $e\gamma$  scattering until now. There is R&D to be done before the Compton Collider can be considered a proven option, but there are no known showstoppers<sup>16)</sup>.

No R&D is needed to prove the possibility of  $e^-e^-$  collisions, just a polarised electron gun at the nominally positron-end of the linac. The other options which have been discussed in both Japanese and European studies are to modify the linac for high luminosity running at the  $Z^0$  peak and/or at the WW threshold.

### 3 Physics

The main question to be tackled is “why does the standard model work?” How the linear collider starts to answer that will depend upon the second question, “what will the LHC have discovered?” The ECFA/DESY Linear Collider workshop at Obernai<sup>17)</sup> involved some of the leaders of the LHC physics studies in detailed

debate on the relative strengths of the two colliders in tackling different analyses. The conclusion was that there are a clear roles for both LHC and the Linear Collider. LHC may be first to find a Higgs boson (if we do not see it at LEP this year - and if it is indeed there to be seen), but the linear collider is where its properties will be pinned down and the kind of Higgs boson established.

### 3.1 Properties of a light Higgs boson

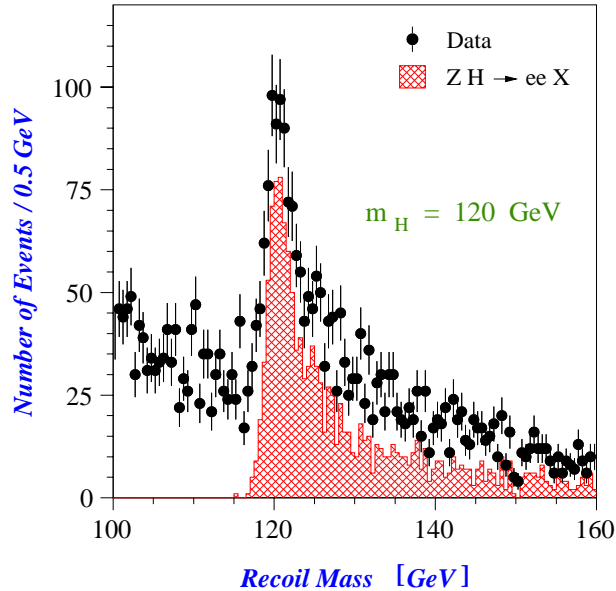


Figure 2: *Missing mass versus  $Z^0 \rightarrow e^+e^-$ .*

Figure 2 shows the key to precision measurement of Higgs boson properties at the Linear Collider. In the higgsstrahlung channel  $e^+e^- \rightarrow Z^0H$ , the  $Z^0$  decays to  $e^+e^-$  and  $\mu^+\mu^-$  can be well measured and constrained to the  $Z^0$  mass. The missing mass peak in the recoiling system then contains all of the decays of the Higgs boson, visible or invisible. For the standard model Higgs there should be no invisible channels, and with a good microvertex detector it will be possible to “mine” into the peak in Figure 2 for its branching ratios. And, of course, for the clearer channels such as  $H \rightarrow b\bar{b}$ , recoils against the much more copious hadronic  $Z^0$  decays can also be used, not just the leptonic events shown in Figure 2 which are used in the search for exotic or invisible Higgs decays. See Figure 3 for the kind of precision which may be achieved in different channels with an integrated luminosity of  $500pb^{-1}$  at  $\sqrt{s} = 500GeV$ . Note the large error bars on the “cc” measurement. The best possible vertex detector will be needed to resolve the charm-pair sample from the much more copious beauty-pairs. There are two promising strategies for

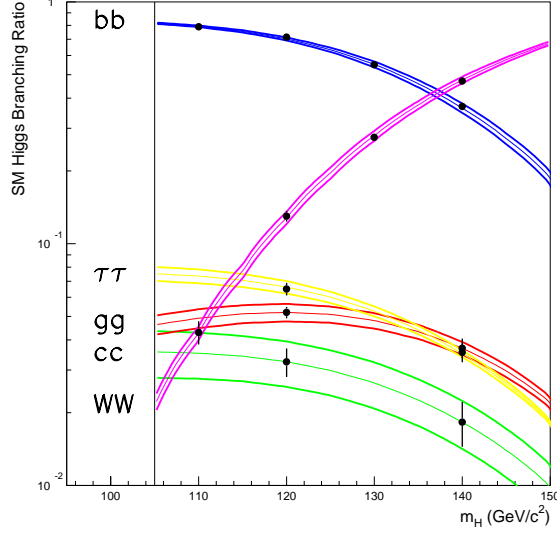


Figure 3: *Branching ratios for the standard model Higgs boson to the channels listed on the left ( $b\bar{b}$  pairs,  $\tau^+\tau^-$ , gluon pairs,  $c\bar{c}$  and  $W^+W^-$ ). The error bars and bands represent estimates of the expected errors with  $500\text{pb}^{-1}$  of integrated luminosity at  $\sqrt{s} = 500\text{GeV}$ .*

measuring the total width of the Higgs boson. If its mass is more than  $115\text{GeV}$ , which it must be if LEP2 has not seen it, then the total width can be found from the ratio

$$\Gamma_{total}^H = \frac{\Gamma_{W^*W^*}^H B(H \rightarrow b\bar{b})}{B(H \rightarrow WW^*)B(H \rightarrow b\bar{b})}. \quad (1)$$

Where the branching ratios on the bottom line can be measured in the higgsstrahlung final states, and the product on the top line is deduced from the rate of the  $W^*W^*$  fusion process  $e^+e^- \rightarrow \nu\bar{\nu}H$  with  $H \rightarrow b\bar{b}$ .

If the Higgs mass is less than  $140\text{ GeV}$  there is an alternative possibility:

$$\Gamma_{total}^H = \frac{\Gamma_{\gamma\gamma}^H B(H \rightarrow b\bar{b})}{B(H \rightarrow \gamma\gamma)B(H \rightarrow b\bar{b})}. \quad (2)$$

Again, the branching ratios on the bottom line may be measured from higgsstrahlung final states (though  $B(H \rightarrow \gamma\gamma)$  needs at least  $1000\text{pb}^{-1}$  integrated luminosity. The top line would have to be measured in the Compton Collider mode. Perhaps the strongest part of the case for the Compton Collider will come after a light Higgs boson has been discovered, because  $\Gamma_{\gamma\gamma}^H$  receives contributions from any loops of new charged particles which couple perturbatively to the Higgs - so the

Compton Collider could look ahead to higher masses than the Linear Collider would see directly. The branching ratio to gluons is also sensitive to loops which couple to colour, though the gluon pair final state is likely to be hard to separate from  $c\bar{c}$ .

Measurement of the branching ratios shown in Figure 3 gives direct tests of the Yukawa couplings of the Higgs boson to different fermion flavours, which could discriminate between SUSY models. But the strongest of the Yukawa couplings of a light Higgs boson is to the top quark, and that cannot be measured in Higgs decays. The Barcelona group<sup>18)</sup> has studied what can be done to measure the  $ttH$  coupling by looking at the bremsstrahlung of Higgs bosons in top-quark pair production,  $e^+e^- \rightarrow t\bar{t}H$ , which has a cross section of  $2.5fb$  for 800 GeV collisions. In  $1000fb^{-1}$  of running they show that a signal can be found with expected statistical errors of less than 10 %, but the backgrounds to be overcome are huge, especially from top-pair production with gluon radiation in the final state. Their verdict is that this coupling will only be measurable when the background calculations are all thoroughly understood, modelled and checked. This is one of the studies which demands the best possible separation and measurement of hadronic jets.

### 3.2 SUSY

Another possible answer to “why does the standard model work?” could be that supersymmetry exists at an accessible scale. If it does then there could be many signatures of it within the range of the Linear Collider - as well as the possibility of measuring non-SM coupling strengths for the light Higgs boson, as is likely to be required if SUSY remains perturbative up to a high scale. The slepton sector will be hard to see at the LHC, but any slepton states below the pair production threshold will be directly accessible in  $e^+e^-$ . Feasibility studies show that the masses of such states will be measurable to  $\pm 500GeV$ , using final state kinematics. Threshold scans could give even better precision. Chargino and neutralino pair production will also be much easier to measure at the Linear Collider. The heavier Higgs bosons could be pair produced;  $e^+e^- \rightarrow hA$ ,  $e^+e^- \rightarrow H^+H^-$ . Polarisation will be very important for their analysis. The Compton Collider would be able to prove that the A is CP odd.

### 3.3 WW Physics

If no light higgs boson is found at LHC or Linear Collider, and no SUSY, then the reason for the standard model to work has to be some other source of Electroweak Symmetry Breaking which must show up at some stage in the behaviour of the WW



system. The triple gauge boson couplings are already being investigated at LEP, but the Linear Collider will measure them with much better precision. Figure 4 shows that, for instance, the anomalous coupling  $\Delta\kappa_\gamma$  can be determined to  $\sim 4 \times 10^{-4}$  at a high luminosity 500 GeV linear Collider, compared with  $\sim 6 \cdot 10^{-2}$  at LEP or  $\sim 2 \cdot 10^{-2}$  at LHC. Again, polarised beams will give extra sensitivity. To exploit the Linear Collider measurements it will be necessary to make substantial improvements to the precision of calculations of the electroweak matrix elements, including higher order loops which have been neglected so far. To get such calculations going in the ECFA/DESY Study we have just instituted a dedicated theorists' working group called the "Loopverein" (19).

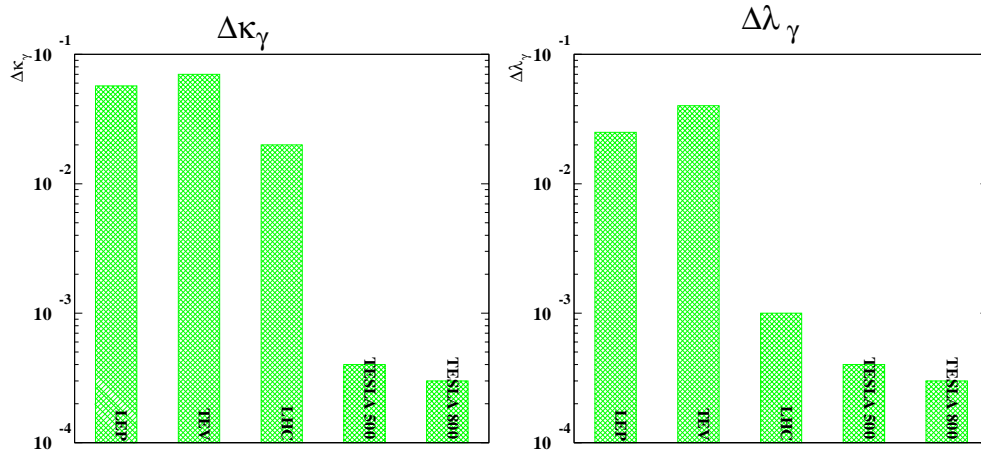


Figure 4: *Estimated precision on anomalous triple gauge couplings at different colliders.*

An important search channel for strong electroweak symmetry breaking will be direct vector-vector scattering, especially  $W^+W^-$ . The LHC will certainly be able to look for this, but may be forced to use only those events with a leptonic W decay. At 800 GeV the Linear Collider would have about 2000  $e^+e^- \rightarrow W^+W^-$  in  $1000 \text{ fb}^{-1}$ , all of which could be reconstructed if the detector has the good jet separation and energy flow resolution which is planned in the detector design from the ECFA/DESY Study.

### 3.4 Other ways of pressing the Standard Model

A classic task for the Linear Collider is to scan in small energy steps across the threshold for top quark pair production. The rapid decay of the top quark prevents the formation of narrow "toponium" resonances, but it also damps higher order corrections to the shape of the threshold excitation. Extensive simulations in Eu-

rope, the USA and Japan have shown that the top quark mass can be determined from the scan to a precision of about  $\pm 120 MeV$ . To do this it will be necessary to limit the energy spread in the colliding beams to less than about 2 parts in  $10^3$ . The spectrum is also spread out by beamstrahlung - the radiation of energy from electrons before collision due to scattering off the coherent electromagnetic field of the opposing bunch - but with current designs for the Collider there is always a significant spike of events in which the beamstrahlung loss is small. These effects combine to give a luminosity spectrum which can be well monitored by using the acollinearity of Bhabha scattered electrons <sup>20)</sup> in the endcap region of the detector ( $\sim 100$  to  $\sim 300mr$  from the beam direction).

With high luminosity and polarised beams it is also worth considering returning to the LEP/SLC energy region, running at the  $Z^0$  peak to make precise measurements of  $\sin^2\theta_W$  (to  $\pm 0.00002$ ). The  $W^+W^-$  threshold will also be worth revisiting, to reduce the error on the W mass to  $\pm 6 MeV$ . This will require special by-pass facilities in the LINACs to maintain high luminosity; it is inefficient to run the beams through all of the accelerating the cavities at much less than their maximum gradient. TESLA should be able to produce  $10^9 Z^0$ s per year with a by-pass. Combining these precise electroweak measurements with the precise measurement of the top mass will enable even tighter constraints to be placed on the parameters of the theory - probing beyond the first Higgs boson, if one has been found, or tying down the possibilities for a Higgsless theory.

There are also worthwhile jobs to be done in testing QCD. High statistics at 500 GeV will allow another point to be measured in the running of  $\alpha_s$ , using event shapes and jet multiplicity ratios, with comparable errors to the LEP1 measurements <sup>21)</sup>, and with a significantly increased lever-arm compared with LEP2. The Compton Collider in its  $e^-\gamma$  mode will be ideally suited to making measurements of the photon structure function  $F_2^\gamma(x, Q^2)$  at the highest possible  $Q^2$ . We are fighting hard to reach  $Q^2 \simeq 1000 GeV^2$  at LEP2, with poor reconstruction of the Bjorken variable  $x = Q^2/(Q^2 + W^2)$  because the target photon is drawn from a continuous bremsstrahlung spectrum and the mass  $W$  of the  $\gamma\gamma$  system can only be measured from the final state hadrons. At the Compton Collider with a nearly monochromatic photon beam  $x$  will be much better determined and there will be good statistics for  $Q^2$  up to  $\sim 10,000 GeV^2$ . This will allow a completely independent measurement of the strong coupling to be made from the evolution of the contribution due to the direct photon-quark interaction.

## 4 Conclusions

The designs for the Linear Collider machines are looking increasingly solid and believable. The choice between the options is about 2 years away. The physics programme of a linear collider will be an essential complement to that of the LHC, whether or not a light Higgs boson is discovered. The detectors will have to be better than those at LEP but they will be recognisably related to them and there are no very daunting performance goals to be achieved. More effort is needed to do feasibility studies of physics processes and to study the detector and the machine-detector interface. Come to your local linear collider workshops <sup>3, 4, 6</sup>).

## 5 Acknowledgements

I must thank all of the participants in the 2nd ECFA/DESY Study on Physics and Detectors for a Linear  $e^+e^-$  Collider <sup>3)</sup> who have done most of the work reported in this talk. In particular, Marco Battaglia and Ties Behnke have supplied figures.

## References

1. See summary of present fits etc. from the LEP Electroweak Working group at <http://lepewwg.web.cern.ch/LEPEWWG/>
2. J. R. Espinosa, J. F. Gunion; Phys.Rev.Lett. 82 (1999) 1084-1087
3. Second ECFA/DESY Study on Physics and Detectors for a Linear  $E^+e^-$  Collider, see <http://www.desy.de/conferences/ecfa-desy-lc98.html>
4. See webpage <http://lcwws.physics.yale.edu/lc/america.html>
5. See webpages <http://www-physics.lbl.gov/div-office/Berkeley2000.html>
6. See webpages <http://acfahep.kek.jp/>
7. Proceedings of the Workshop on Physics and Detectors for a Linear Collider, Saariselkä, Finland, September 1991, eds R.Orava, P.Eerola, M.Nordberg; World Scientific, Singapore (1992)
8. Proceedings of the Workshop on Physics and Detectors for a Linear Collider, Waikoloa, Hawaii, April 1993, eds F.A.Harris, S.L.Olsen, S.Pakvasa; World Scientific, Singapore (1993)

9. Proceedings of the Workshop on Physics and Detectors for a Linear Collider, Morioka-Appi, Japan, September 1995, eds Y.Fujii, T.Matsui, S.Iwata; World Scientific, Singapore (1996)
10. Proceedings of the Workshop on Physics and Detectors for a Linear Collider, Sitges, Spain, 29 April - 5 May 1999, ed E.Fernandez; to be published by U. of Barcelona. See webpages <http://physics.web.cern.ch/Physics/LCWS99/>
11. Conceptual design of a 500 GeV  $e^+e^-$  Linear Collider with integrated X-ray laser facility, 2 volumes, editors R.Brinkmann, G.Materlik, J.Rossbach, A.Wagner; DESY 1997-048 (or ECFA 1997-182)
12. See webpages <http://www-project.slac.stanford.edu/lc/nlc.html>
13. See webpages <http://www-jlc.kek.jp/>
14. See webpages  
<http://cern.web.cern.ch/CERN/Divisions/PS/CLIC/Welcome.html>
15. I. Ginzburg, G. Kotkin, V. Serbo, V. Telnov, *Pizma ZhETF* 34 (1981) 514; *JETP Lett.* 34 (1982) 491; *Nucl. Instr. Meth.* 205 (1983) 47
16. Proceedings of the workshop on  $\gamma\gamma$  colliders. Berkeley, Cal., 1994, ed. A.Sessler; *Nucl. instr. Meth.* A355 (1995) 1-194.
17. ECFA/DESY workshop at Obernai, France. See webpages  
<http://ireswww.in2p3.fr/ires/ecfadesy/index.html>
18. G.Merino "Direct Measurement of the top Yukawa coupling in  $e^+e^- \rightarrow t\bar{t}H$ " to be published in proceedings of LCWS Sitges <sup>10</sup>). Slides available as <http://wwwpc.ifaes.es/lcws99/G.Merino.pdf>
19. See webpages  
<http://www.ifh.de/theory/TLV/TheLoopVerein.html>
20. M.Frary and D.J.Miller; "Monitoring the Luminosity Spectrum"; DESY 92-123A 379-391
21. G.Abbiendi *et al*; the OPAL collaboration, CERN-EP/99-175, submitted to Eur. Phys. J. C