1 Introduction

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A future e^+e^- linear collider (LC) operating at a centre-of-mass energy in the range 500 GeV-1 TeV is a high priority for the future of High Energy Physics. It was strongly supported by the recent HEPAP review panel in the US [1]. A future linear collider would play a strong rôle in complementing the physics program of the LHC. Research and development work towards a linear collider has been proceeding for the past decade at DESY, KEK and SLAC. Although the exact specification of a future linear collider has yet to be decided the feasibility of such a project is demonstrated in the TESLA Technical Design Report (TDR) [2], published in the past year.

This proposal concerns an R&D project, CALICE, aimed at providing the most effective calorimetry for an experiment at the LC. Specifically, the solution proposed for the electromagnetic calorimeter is a Silicon-Tungsten sandwich calorimeter with high spatial segmentation.

In this document we first outline the physics case for the LC, and the requirements this imposes on the calorimeter performance. We then introduce the CALICE R&D project and explain its objectives before describing in detail the proposed UK contribution.

2 Physics at a Linear Collider

The physics case for a future linear collider has been established at a series of workshops under the aegis of ECFA and DESY, and is stated in the TESLA TDR [2]. The main goals of the physics programme are summarised below:

Higgs Physics If the Higgs boson exists, it is probable that it will have been discovered at the LHC or Tevatron before the start of the LC. Once discovered, the emphasis will be on establishing its nature. Precise measurements will be essential to establish whether the particle has the properties expected in the SM, or whether it corresponds to one of the Higgs bosons of a supersymmetric theory. However, the measurement of the properties of the Higgs boson at the hadron colliders will be relatively crude compared to what can be achieved at the LC. The measurements which the LC can perform include:

- Measurements of the Higgs boson mass and width with respective precisions of 0.1% or better and $\mathcal{O}(5\%)$.
- Precise measurements of its couplings to fermion pairs, to massive gauge bosons and to photons.
- Determination of the spin and parity of the Higgs boson.
- The Higgs boson self-coupling and hence the Higgs potential can be probed using the ZHH final state ($\rightarrow 6j$ or $\rightarrow 4j\ell^+\ell^-$).
- The Higgs-top Yukawa coupling can be measured in the final state $t\bar{t}H$.
- Supersymmetric Higgs bosons may be studied in final states like $H^+H^- \rightarrow t\bar{b}b\bar{t}$ and $h^0A^0 \rightarrow 4b$.

On the basis of these measurements it will be possible to establish the nature of the Higgs boson.

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Supersymmetry Supersymmetry (SUSY) is widely believed to be the most likely theory for physics beyond the Standard Model. However, if correct, the theory will need to be constrained by experiment since there a large number of parameters and several possible scenarios for SUSY breaking. If SUSY particles exist in the sub-TeV energy range, they are likely to be discovered at the LHC where squarks and gluinos would be copiously produced. In this case, it is important to determine the properties of the SUSY particles in order to constrain the many parameters of the supersymmetric theory. The LC would fulfil a powerful complementary rôle to the LHC here, especially in determining the properties of sleptons, gauginos and the $\tilde{\mathrm{t}}$-squark. In addition to determination of the mixing parameters in the gaugino sector, precise measurements can be made of sparticle masses, widths, and branching ratios. The wealth of precise measurements possible at the LC will provide a powerful probe of the underlying structure of the SUSY theory.

Strong Electroweak Symmetry Breaking If the Higgs boson is not discovered at the LHC or Tevatron, the LC should see evidence of other new physics. In the absence of the Higgs boson the cross-section for the process of longitudinal W-boson scattering, $\mathrm{W_L^+W_L^-} \rightarrow \mathrm{W_L^+W_L^-}$, would grow, violating quantum mechanical unitarity. To avoid unitarity violation it is required that the interactions between the vector-bosons becomes strong at energies of order 1 TeV. This would be manifested in anomalous triple or quartic gauge boson couplings. Observation of $\mathrm{W^+W^-}$ and $\mathrm{Z^0Z^0}$ scattering processes will be possible using the final states $\nu\overline{\nu}\mathrm{W^+W^-}$ and $\nu\overline{\nu}\mathrm{Z^0Z^0}$. Anomalous gauge boson couplings can be studied using similar techniques to those used at LEP, such as the reconstruction of angular distributions and correlations.

Top-quark Physics An $\mathrm{e^+e^-}$ LC provides a clean environment in which to study the properties of top quark. In particular, the mass of the top quark is a key input in fits to high precision electroweak data. At the LC the top quark mass can be determined with a precision of ~ 200 MeV compared to $\sim 1-2$ GeV at LHC. In addition to the top quark mass, precise measurements of many of its other properties may be made at the LC.

3 Calorimetry at a Linear Collider

Most of the physics processes mentioned above are characterised by multi-jet final states sometimes accompanied by charged leptons and/or missing transverse energy associated with neutrinos or the lightest supersymmetric particles. The reconstruction of the invariant mass of two or more jets will provide a powerful tool identifying the physical process and in rejecting background. In addition, decays commonly involve a cascade through several massive states, which can be elucidated by mass reconstruction. To give just three examples: *a)* the separation of the rare but important $\mathrm{Z^0H^0H^0} \rightarrow 6j$ final state from background will rely on identifying pairs of jets with the invariant masses of the $\mathrm{Z^0}$ and Higgs; *b)* the identification and separation of the $\nu\overline{\nu}\mathrm{W^+W^-}$ and $\nu\overline{\nu}\mathrm{Z^0Z^0}$ final states will rely almost entirely on di-jet mass reconstruction; *c)* the measurement of the $\tilde{\chi}_1^{\pm}$ mass and the $\tilde{\chi}_1^{\pm} - \tilde{\chi}_1^0$ mass difference in the process $\mathrm{e^+e^-} \rightarrow \tilde{\chi}_1^-\tilde{\chi}_1^+ \rightarrow \ell^{\pm}\nu\mathrm{q}\overline{\mathrm{q}}'\tilde{\chi}_1^0$ may be achieved by measurement of the di-jet mass and energy distributions.

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3.1 Lessons from LEP

Since the reconstruction of the invariant mass of two or more jets will play a major rôle in the analyses of numerous processes at the LC, a good measurement of the jet energies is of great importance. At LEP is was found that the jet energy resolution was not limited by the intrinsic momentum/energy resolution of the tracking chambers/calorimeters. Rather the resolution is limited by the ability to separate and correctly associate tracks and energy deposits in electromagnetic and hadronic calorimeters.

3.1.1 Energy Flow and Jet Energy Resolution

Measurements of jet fragmentation at LEP have given us a good understanding of the particle composition of jets (*e.g.* [4, 5]). On average, after the decay of short-lived particles such as Λ^0 and K^0_S, roughly 62% of the energy of jets is carried by charged particles (mainly hadrons), around 27% by photons, about 10% by long-lived neutral hadrons (n/K^0_L), and around 1.5% by neutrinos. Charged particles are most accurately measured in the tracking detectors, photons in the electromagnetic calorimeter (ECAL), and n/K^0_L by the hadron calorimeter (HCAL). To measure the energy of the jet, information from all three detector elements has to be combined taking into account correlated energy deposits; for example a charged hadron will typically deposit energy in both calorimeters, while a neutral hadron may often start showering in the electromagnetic calorimeter. The most successful algorithms for jet reconstruction at LEP have used an *energy flow* method, in which geometrical associations between tracks and energy clusters in the calorimeter and between clusters in the electromagnetic and hadronic calorimeters are used to minimize double counting of energy. So, for example, the energy deposited in the calorimeters by a charged particle is not double counted along with the energy determined from the tracking chambers.

The ALEPH experiment at LEP obtains a jet energy resolution[1] $\Delta E/E = 60\%(1+|\cos\theta|)/\sqrt{E}$ using such a method [6]. For comparison OPAL achieves $\Delta E/E \sim 80\%/\sqrt{E}$. Despite the OPAL lead-glass calorimeter having a better energy resolution than ALEPH's, the ALEPH calorimeter has significantly better spatial resolution, permitting better matching and separation of the various energy deposits within a jet.

3.1.2 The Rôle of Kinematic Fitting at the Linear Collider

It is worth noting that at LEP precise measurements of the W boson mass have been performed by direct reconstruction of the invariant mass of the W boson decay products. The LEP experiments did not provide particularly accurate measurements jet energies. However, this limitation was overcome using kinematic fitting. By imposing the constraints of energy and momentum conservation, the jet energies could be determined, largely from angular information, much more accurately than by direct measurement[3].

Although kinematic fitting will undoubtedly play a significant rôle at the LC, its applicability will be more limited. As already mentioned, many of the interesting final states have missing energy. In final states with more than one unmeasured particle, there are insufficient constraints to perform a kinematic fit. Furthermore, the energy lost to initial state radiation (ISR), which is only ~ 3 GeV at LEP in W^+W^- events, becomes ~ 25 GeV at 500 GeV and ~ 50 GeV at 800 GeV. Thus at LEP the average ISR energy is much smaller than the jet energy resolution,

[1] In this and similar expressions for resolutions throughout this document, the energy E is assumed to be measured in GeV.

whereas at the LC it would be much greater. In addition, the beams at the LC will lose similar amounts of energy through beamstrahlung (radiation in the electromagnetic field of the other beam). Therefore, a significant proportion of events at the LC will not be susceptible to kinematic fitting. Consequently, good jet energy resolution becomes of paramount importance at the LC. Since jet energy resolution is mainly determined by the ability to resolve separate energy deposits in the different detector components, the calorimeters a the LC must have excellent transverse spatial resolution.

3.2 Calorimetry at the Linear Collider

The principal requirements for the electromagnetic calorimeter in a LC experiment may be summarised as follows:

- Good energy resolution for photons and electrons; needed for example for e/π separation and for the identification of H$\rightarrow \gamma\gamma$ events.
- Excellent transverse spatial resolution, in order to separate particles in jets and make energy flow measurements.
- Good longitudinal segmentation as an aid to e/π separation.
- The ability to identify non-pointing photons; for example in the gauge mediated SUSY breaking scenario where a long-lived neutralino may decay to a photon and a stable gravitino: $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{\mathrm{G}}$.
- Excellent hermeticity.
- Good time resolution, to avoid pile-up.
- Compact, so that the calorimetry can be placed inside the magnet coil without prodigious cost.

The preferred solution adopted for the TESLA TDR envisages a silicon-tungsten electromagnetic calorimeter (ECAL), followed by a hadron calorimeter (HCAL). Specialised calorimetry in the forward region would complete the angular coverage. Tungsten is an attractive choice for the showering medium in the ECAL, having a very low radiation length of 3.5 mm and a small Molière radius of 9 mm. The small Molière radius allows nearby showers to be resolved. By using silicon as the detecting medium, the gaps between tungsten layers can be kept thin, so that the whole ECAL of 24 radiation lengths thickness can be fitted into a thickness of about 20 cm. The granularity of the silicon readout, *i.e.* the size of the silicon pads is determined by the Molière radius, which defines the transverse size of electromagnetic showers. If the pad size is significantly greater than the Molière radius the shower can only be localised to within the area of one pad and the spatial resolution is degraded. Consequently a pad size of $\sim$1 cm^2 is envisaged. The present design has 40 longitudinal samples. The HCAL would consist of stainless steel plates, instrumented either with scintillator tiles, or with wire chambers or resistive plate chambers with digital readout.

3.2.1 Energy Resolution

The performance of such a calorimeter has been extensively studied using Monte Carlo simulations as part of the TESLA TDR. The energy resolution of the proposed ECAL for photons has been found to be approximately given by $\Delta E/E = 1\% + 10.3\%/\sqrt{E}$ [7], leading for example to a mass resolution in $H^0 \to \gamma\gamma$ of 2.1 GeV (for $M_H = 120$ GeV). The angular resolution for photons was found to be $\Delta\theta = (8 + 68/\sqrt{E})$ mrad, corresponding to a resolution on the impact parameter at the collision point of ~ 4 cm for a 20 GeV photon [7]. Electron-pion separation, based on shower shape and matching the ECAL energy with the track momentum in the central tracker, has been estimated to yield a probability for misidentifying a pion as an electron of around 10^{-4} [7].

The case for the Si-W ECAL rests largely on its energy flow performance, which in turn leads to good jet energy reconstruction and good di-jet mass resolution. An elementary kinematic calculation shows that a jet energy resolution $\Delta E = \alpha\sqrt{E}$ leads to a di-jet mass resolution of roughly $\Delta M/M = \alpha/\sqrt{E_{jj}}$ where E_{jj} is the energy of the di-jet system. A reasonable goal is to match ΔM for the W or Z bosons to their natural widths, *i.e.* ~ 2 GeV. Since E_{jj} ~250 GeV at the LC, this suggests that one should aim for $\alpha \sim 0.3$, *i.e.* more than a factor two better than that achieved by the LEP detectors. For the proposed LC detector, using an energy flow algorithm[7], an energy resolution of $\Delta E/E \sim 33\%/\sqrt{E}$ has been achieved, with scope for improvement in the algorithm, already meeting the above requirements. As an example, Figure 1 shows the reconstructed Z^0 mass distribution (from $e^+e^- \to q\overline{q}$ at $E_{cm} = M_Z$) determined by applying the energy flow algorithm to the jets. A mass resolution of ~ 3 GeV is achieved.

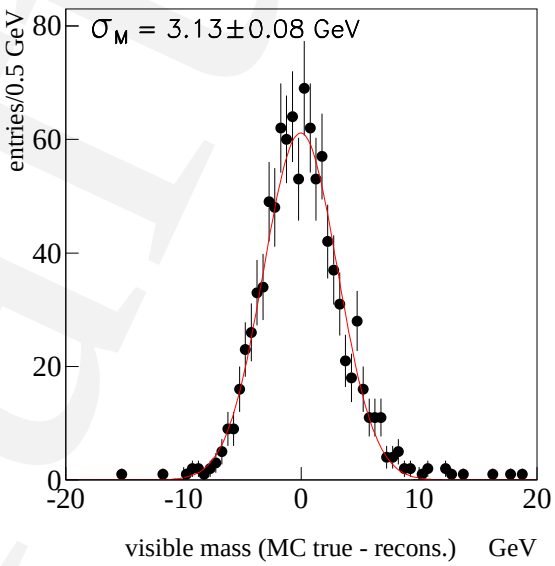

Figure 1: *Mass resolution for hadronic Z^0 decays at rest.*

3.2.2 Physics Simulation

The impact of the quality of the electromagnetic and hadronic calorimeters on the physics results at the LC has been studied as part of TESLA TDR. Two examples are given here. The

process $e^+e^- \to Z^0H^0H^0$ probes the Higgs boson self-couplings and is of considerable interest in the determination of the exact nature of an observed Higgs boson. However the signal, with a corresponding cross-section of ~ 0.5 fb, needs to be separated from a large background. The reconstructed invariant masses of the reconstructed di-jet pairs may be used to significantly reduce background. Having identified six jets, a useful discriminating variable is

$$D = \sqrt{(m_{12} - m_H)^2 + (m_{34} - m_H)^2 + (m_{56} - m_Z)^2}.$$

Figure 2 shows the distributions of D for signal and background for two cases: $\Delta E = 0.3\sqrt{E}$ (proposed LC) and $\Delta E = 0.6(1+|\cos\theta|)\sqrt{E}$ (LEP-like) [7]. The impact of improved jet resolution is apparent and is quantified in Figure 3, which shows the significance (signal/$\sqrt{\text{background}}$) as a function of the jet energy resolution parameter α, for an integrated luminosity of 1 ab^{-1} [2]. The increased significance of the signal above the background expectation in going from $\Delta E = 0.6\sqrt{E}$ to $\Delta E = 0.3\sqrt{E}$ is equivalent to a fourfold increase in luminosity. Given the smallness of the cross-section, a jet energy resolution of a least $\Delta E = 0.35\sqrt{E}$ is required to establish the signal for an integrated luminosity of 1 ab^{-1}.

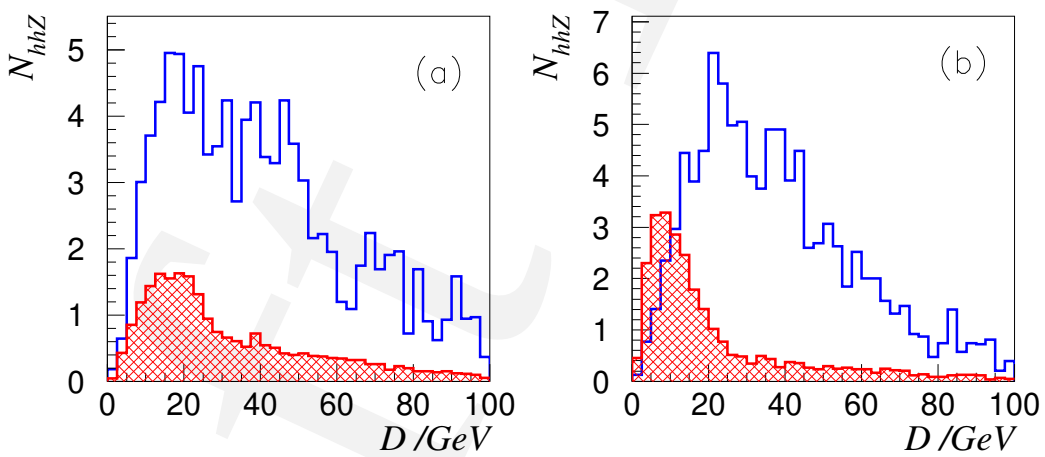

Figure 2: *Distributions of the discriminating variable D for $Z^0H^0H^0 \to 6j$ signal and background, for two values of jet energy resolution: a) $\Delta E = 0.6(1+|\cos\theta|)\sqrt{E}$ (LEP-like); b) $\Delta E = 0.3\sqrt{E}$.*

Another example of the importance of the resolution of the calorimeters at the LC is the analysis of WW scattering events which would be great interest if no elementary Higgs boson is discovered. The identification of, and separation between, the channels $\nu\overline{\nu}W^+W^-$ and $\nu\overline{\nu}Z^0Z^0$ when the bosons decay hadronically depends crucially on di-jet mass resolution. Figure 4 shows how the separation between these two channels using the two di-jet masses in the event is improved when the jet energy resolution is changed from $\Delta E = 0.6\sqrt{E}$ to $\Delta E = 0.3\sqrt{E}$ [8]. The increased separation has been estimated to be equivalent to an increase of approximately 40% in luminosity.

3.3 Summary

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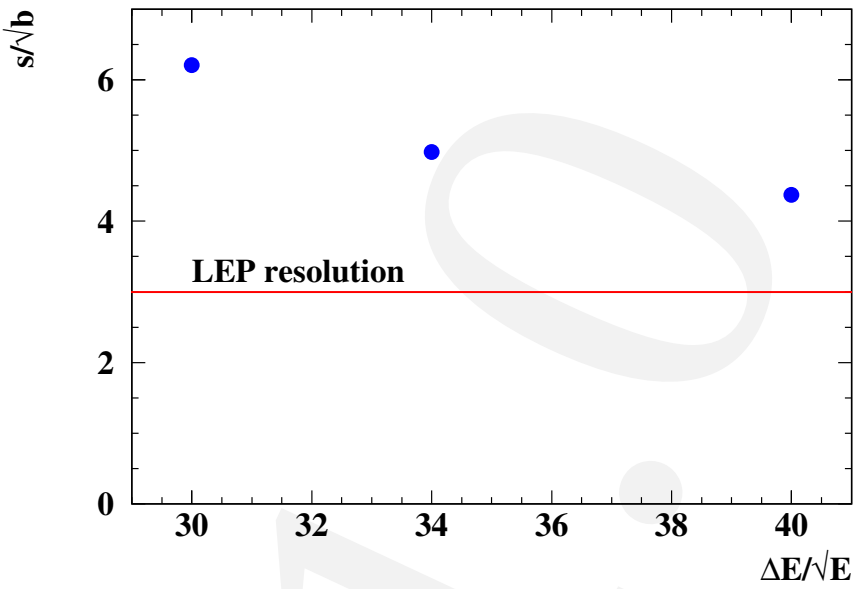

Figure 3: Signal/$\sqrt{\text{background}}$ *for the separation of* $Z^0H^0H^0 \to 6j$ *using 1* ab^{-1} *of data, as a function of the jet energy resolution parameter* α *(in %), where* $\Delta E = \alpha\sqrt{E}$*. The horizontal line indicates the LEP-like case* $\Delta E = 0.6(1 + |\cos\theta|)\sqrt{E}$*.*

An important design goal for the calorimetry at the LC is a jet energy resolution of $\Delta E \sim 0.3\sqrt{E}$. At this value the typical uncertainty on reconstructed W/Z boson masses due to jet energy uncertainty is approximately equal to Γ_W. To achieve this level of performance energy flow techniques will be vital. At LEP it was found that the performance of the energy flow algorithm depends crucially on the ability to match tracks/calorimetric clusters from the same particle and the ability to separate energy deposits from different particles. Consequently good transverse spatial resolution is of great importance. A silicon-tungsten electromagnetic calorimeter with silicon pad size of 1 cm^2 represents the most promising possibility for achieving these goals. Monte Carlo studies of the current design for the LC calorimetry yield a jet energy resolution of $\Delta E \sim 0.3\sqrt{E}$, a factor of two better than achieved at LEP. This improvement in jet energy resolution has a large impact on the physics capabilities of the LC, significantly improving the separation between signal and background in important physics channels and as a result significantly reducing the integrated luminosity (*i.e.* the running time) required to make a discovery.

References

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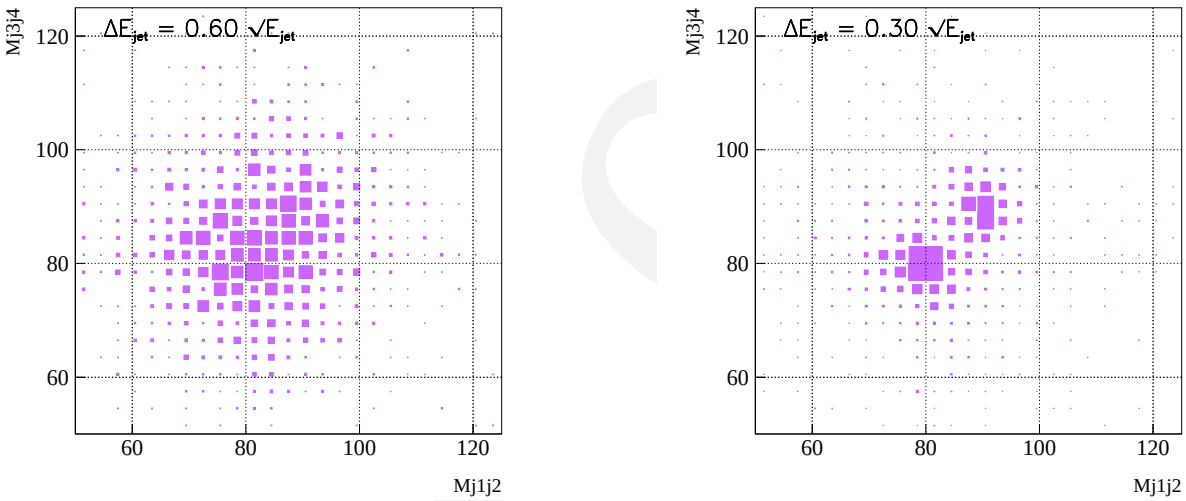

Figure 4: *Reconstructed di-jet masses for* $\nu\overline{\nu}\mathrm{W}^+\mathrm{W}^- \to 4j$ *and* $\nu\overline{\nu}\mathrm{Z}^0\mathrm{Z}^0 \to 4j$ *for two values of jet energy resolution: a)* $\Delta E = 0.6\sqrt{E}$*; b)* $\Delta E = 0.3\sqrt{E}$*.*

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