Ideas for the NLC Detector

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Representing the NLC Detector Group

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ABSTRACT

Key requirements for a detector at the future e^+e^- Linear Collider are excellent hermeticity, jet energy resolution and jet flavour identification. We describe preliminary ideas for achieving these goals, while easily tolerating the calculated backgrounds. The detector will be modest compared with those required at hadron colliders, due to the harmonious conditions for physics in the e^+e^- environment.

1. INTRODUCTION

The design of a possible NLC detector is in a relatively early stage, appropriately so, since the future Linear Collider is expected to take shape as an international project and design details will be best worked on within that organization. However, even at this early stage, it is essential to explore the extent to which the physics aims for the TeV energy scale can be realized. The requirements of machine energy, energy spread and luminosity have been discussed in many workshops. Luminosity depends on excellent mechanical stability of the final focus (FF) system. In this area, there has been remarkable recent progress [1]. A further question is whether a particular machine design that satisfies these requirements will also be sufficiently clean, in terms of backgrounds in a detector system having the capability to extract the physics from complex events.

In order to address these issues, the NLC IR group (led by T Markiewicz) has been meeting regularly for several years. The ideas for the detector design discussed in this paper have resulted from a three-sided study process in which the detector designer aims to achieve the physics aims, to satisfy the accelerator constraints, and to come up with a detector that he knows how to build with currently available components.

As the e^+e^- collision energy is increased, one feature that remains constant is the physics interest in *whole-event* analysis. The bulk of the cross-section appears as multi-jet final states, and (with an appropriate detection system) these can be used to extract a vast amount of physics. The first requirement for such a detector is the highest possible level of hermeticity in the calorimetry. Figure 1 shows the correspondence between energy flow and the underlying quark-level event in $t\bar{t}$ production, a simple process at the lower end of the energy range for the new machine. As $\sqrt{s}$ increases to 1 TeV and above, jet multiplicities will grow as high as 12 or more, and gaps in the detector coverage could lead to the loss of one or more jets, with a consequent serious deficiency in the analysis capability.

The overall NLC detector design is sketched in Fig. 2, and the (very preliminary) parameters of the main components are listed in Table 1. The degree of hermeticity is phenomenal. Even below the 100 mrad masking cone angle, background conditions are sufficiently homogeneous to permit an extension of the calorimeter that will pick up significant energy deposition within that aperture. The only real holes in the acceptance are the small entry and exit apertures of the FF quadrupoles. Despite the unprecedented degree of segmentation

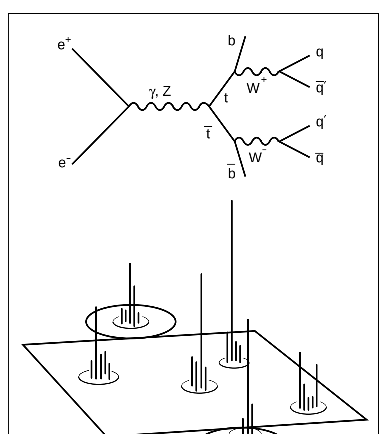

Fig. 1 (based on [2]). Close connection between Feynman diagram and energy flow (unfolded barrel and endcaps).

Table 1 Preliminary Parameters of the NLC Detector (main components)

System	Technology and Coverage	Segmentation	Performance	Background Rate/Occupancy (per bunch train)
Vertex Detector VXD	5 CCD barrels 0.12% X_0/barrel R1 = 12 mm R2 = 24 mm : R5 = 54 mm $\lvert\cos\theta\rvert \leq 0.9$ (5 hits)	20 μm^2 pixels B1: 12 Mpixels B2: 48 Mpixels : B5: 300 Mpixels Total: 660 Mpixels Active area 0.26 m^2	2-D space point resolution = 3.5 μm Imp. param. at IP $\sigma_{XY} = \sigma_{RZ} =$ $4.5 \oplus 5.5/(p\sin^{3/2}\theta)$	B1: 5/mm^2 B2: 0.5/mm^2 : B5: 0.01/mm^2 Even in B1, occupancy is <1%
Silicon Central Tracker SCT	5 microstrip barrels (2 co-ordinates each, by 2 single-sided detectors) 1.2% X_0/barrel R1 = 12 cm R2 = 17 cm : R5 = 48 cm $\lvert\cos\rvert \leq 0.97$ (3 hits)	40 cm $\times$ 50 μm strips B1: 68 k channels B2: 134 k channels : B5: 627 k channels Total: 1.69 M channels Active area 34 m^2	1-D co-ordinate resolution 10 μm $\sigma\left(1/p_T\right) =$ $1.3 \times 10^{-4} (\mathrm{GeV/c})^{-1}$ for $p_T \geq 100$ GeV/c and $\lvert\cos\rvert \leq 0.9$	Average occupancy 1.3%
Electromagnetic Calorimeter E-Cal	Silicon/Tungsten Thickness 25 X_0 $R_{\mathrm{inner}} = 50$ cm $\lvert\cos\rvert \leq 0.995 + \ldots$ (augmented by LUM)	1 cm^2 pads, 50 depth samples Total: 3 M channels	$\frac{\sigma(E)}{E} =$ $0.5\% \oplus \frac{12\%}{\sqrt{E}}$ (single particle)	1.7 hits/tower; mean deposition 1.2 MeV/tower
Solenoid	Superconducting Thickness 1.3 X_0 $R_{\mathrm{inner}} = 70$ cm $R_{\mathrm{outer}} = 90$ cm L = 2.3 m		4 Tesla	
Hadron Calorimeter H-Cal	Iron/Scintillator Thickness 6λ $R_{\mathrm{inner}} = 95$ cm	100 depth samples	$\frac{\sigma(E)}{E} =$ $2\% \oplus \frac{45\%}{\sqrt{E}}$ (single particle)	≤ 1 muon, including muon tracker
Muon Tracker/ Return Flux	Thickness 6λ			≤ 1 muon, including H-Cal

X_0 : radiation length
λ : interaction length

in the detector (discussed below), the data transmission from the front-end electronics can be handled easily by highly multiplexed fibre links, as at SLD. Taking advantage of the 8 ms interval between bunch trains for the event readout allows a fully hermetic detector with no significant dead material associated with the data transmission.

In addition to hermeticity, we require excellent jet energy resolution; this is discussed in Section 2. We also need the highest possible efficiency and purity for identification of heavy flavour jets; this is discussed in Section 3. Finally, these aims must respect the constraints of the backgrounds at a linear collider; this is discussed in Section 4.

This paper sketches our ideas for a general purpose detector, aimed at an optimal analysis of the bulk of the final states that will be encountered, both from Standard Model and novel processes. In some special cases the design optimization would be somewhat shifted; eg for $H \to \gamma\gamma$, the highest possible electromagnetic energy resolution is desirable. In future, design compromises taking account of such special cases will need to be considered.

2. JET RECONSTRUCTION

The primary purpose of jet reconstruction is to permit the most precise determination of the dijet invariant mass in decays such as $Z^0 \to q\bar{q}$, $W^\pm \to q\bar{q}'$, $H \to q\bar{q}$. In general, it is the jet energies rather than their directions which dominate the uncertainty in determining the dijet mass; the proposed strategy for jet energy measurement proceeds as follows:

1) Measure all charged particle energies using the Silicon Central Tracker (SCT), to the limit of its angular coverage.

2) Use the data from the very fine grained calorimeters (E-cal and H-cal), to reconstruct and excise the showers associated with these charged tracks (see Fig. 3).

3) Use the residual energy measured in the E-cal plus H-cal together with the total charged particle energy from the SCT, to determine the visible jet energy.

The rationale behind this approach is the superior determination of charged particle energy by the tracker as compared with the calorimeter, over essentially the complete energy range of interest. This is particularly advantageous in view of the distribution of energy between the three classes; for example for a 50 GeV quark jet, we have 62% charged particle energy, 25% electromagnetic energy and 13% hadronic energy.

The suggested detector is sketched in Fig. 4. The tracking system consists of a vertex detector followed by the SCT consisting of five 'long barrels', each having two-coordinate readout ($R\phi$ and Z). With a relaxed shaping time $(\sim 1\ \mu\mathrm{s})$, a strip readout length of 40 cm is acceptable. This results in a much lower power dissipation than in a LHC tracking detector, so that the required mechanical stability (10 μm) should be achievable with less material (support structure and cooling pipes). The parameters and high momentum performance are summarized in Table 1. Below 100 GeV/c, the performance is increasingly limited by multiple scattering, as shown in Fig. 5. The SCT design rests firmly on the extensive R&D and construction now underway for CDF, D0, ATLAS and CMS.

The electromagnetic calorimeter consists of a tungsten/silicon sandwich; details are discussed in [3]. Despite the small inner radius of 50 cm, early GEANT simulations

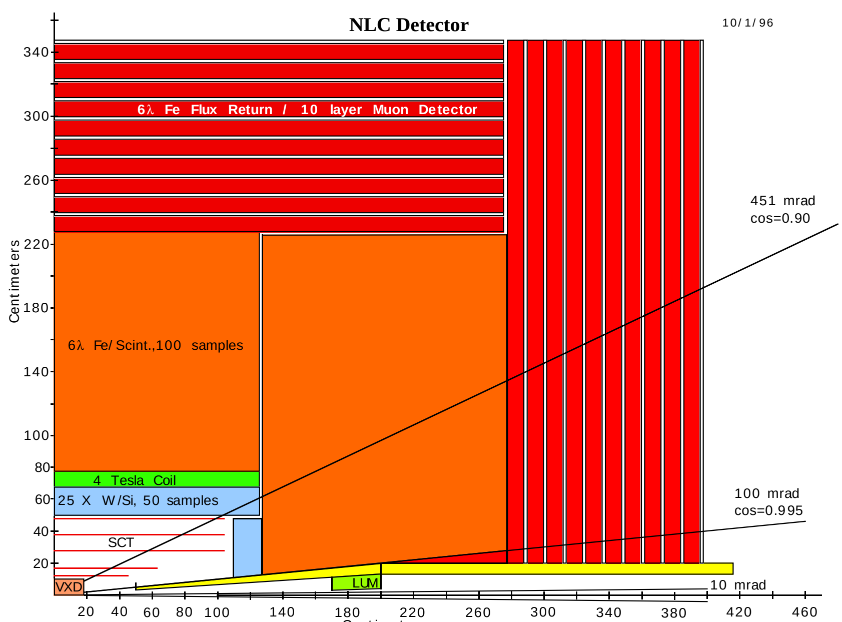

Fig. 2 Cross-section (quadrant view) of overall NLC Detector design.

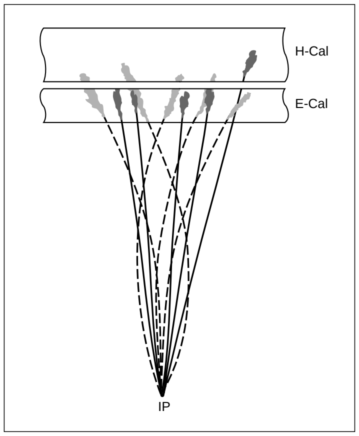

Fig. 3 Separation of charged and neutral particles in calorimeters

suggest that the separation between charged and neutral showers will probably be adequate. If not, one could scale up the radius by a factor of 1.5-2 and still have an extremely modest solenoid compared with that for CMS, which has an inner radius of 2.9 m. The estimated energy resolution plotted in Fig. 5, demonstrates the importance of using the SCT to determine the charged particle energy wherever possible, except at very high energies.

Outside the coil, the hadron calorimeter will also be highly segmented in a pad geometry. One option is an iron/scintillator sandwich with APD readout.

The overall jet energy resolution depends on a detailed simulation, including a realistic procedure for optimally disentangling the charged and neutral energy in the E-cal and (less importantly) in the H-cal. We are hoping to achieve a visible energy resolution in the region of $\sigma(E_{jet})/E_{jet} = 30\%/\sqrt{E_{jet}}$ for a jet of energy E_{jet} GeV. Comparable resolution has already been achieved using this procedure for the JLC detector, where the calorimeter segmentation is not as fine [4]. For heavy flavour jets, the

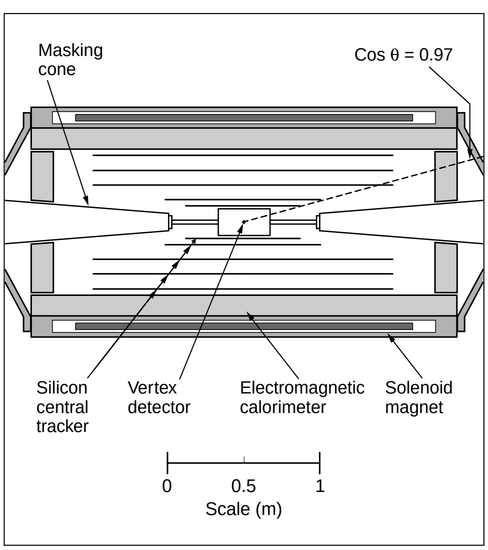

Fig. 4 Inner region of detector; VXD, SCT, E-Cal and solenoid.

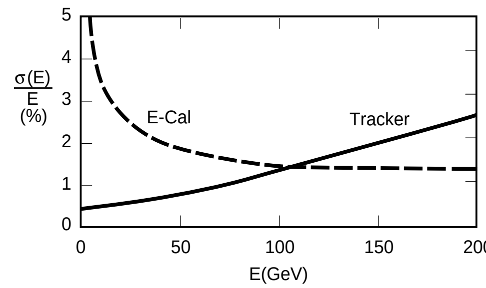

Fig. 5 Energy resolution of SCT and E-cal for single particles.

resolution may be limited by fluctuations in the missing neutrino energy. In any event, it will certainly be possible to achieve excellent separation of W and Z in dijet mass distributions, and powerful background rejection for novel particles decaying to hadronic final states.

3. JET FLAVOUR IDENTIFICATION

In order to meet the physics requirements for heavy flavour identification, we are planning on a vertex detector with unprecedented performance capability. Details of this detector (sketched in Fig. 6) are discussed in [5]. Due to the very low power dissipation (about 20 W) it is possible to thin the ladders down to the point where the excellent spatial measurement precision is matched by an appropriately small multiple scattering term. The procedure for flavour identification is helped enormously by the fact that the beam spot is small (sub-micron in cross-section) and stable in position, on a timescale of many seconds or even minutes. This means that the position of the primary vertex (PV) for any event can be determined (in the XY view) with great precision even if no stiff tracks at all emerge from the PV for that particular event, by averaging over the previous ten or more events. For each jet, a topological vertex finding procedure is followed [6], which looks for secondary and tertiary vertices (SV and TV) in the jet. Other information can then be used to establish the jet flavour (for the three categories *udsg*, *c* and *b*) with high efficiency and purity [5]. In brief, the main criteria are the invariant mass of the particles

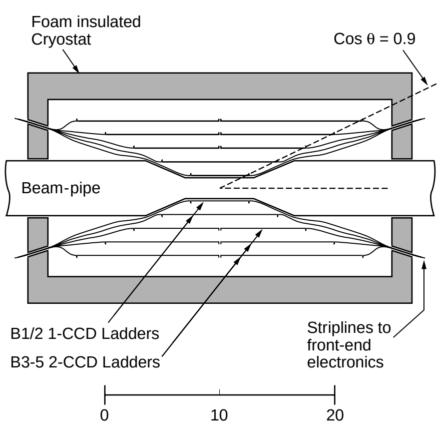

Fig. 6 5-barrel vertex detector

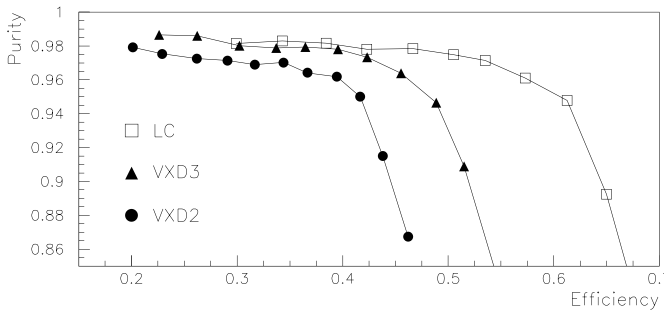

Fig. 7 Performance on *b*-jet flavour tag.

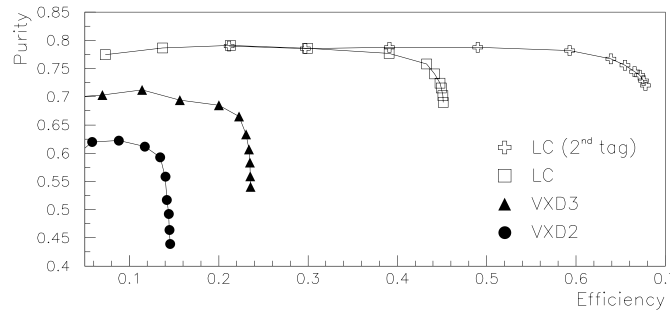

Fig. 8 Performance of *c*-jet flavour tag.

associated with the SV + TV, and a 'p_T – added mass' which makes some allowance for missing neutrals associated with the heavy flavour decays. These procedures for jet flavour ID have grown out of recent work for SLD.

As a performance indicator, we have looked at the efficiency and purity of *b* and *c* tagging in a mixture of jets from Z^0 hadronic decays at rest in the detector. The improvement in performance through two generations of SLD detectors, to that expected for the future LC detector is apparent in Figs. 7 and 8. The efficiency for *b* flavour identification shows a very useful enhancement as the detector is upgraded, particularly since one will sometimes need to demand more than one identified *b* jet, so the efficiency is raised to some power greater than 1. For the charm ID, the improvements are even more dramatic. The original SLD vertex detector VXD2 (a LEP-quality detector, as regards impact parameter precision) was very poor for charm. This situation is greatly improved by the SLD upgrade detector VXD3, and charm identification will be an extremely powerful tool at the future LC. These performance figures are summarized for a typical set of criteria in Table 2. Note that they will improve for increased jet energy, due to reduced multiple scattering. Furthermore, the cleaner topological vertexing lends itself to refinements and new ideas for flavour tagging, as discussed in [5].

4. BACKGROUNDS

The SLC/SLD combination has proved to be a marvellous instrument for understanding and learning to control the complex backgrounds at a linear collider. The resulting benefits are apparent in the extensive treatment of backgrounds in the NLC Zeroth-Order Design Report [7]. More recent work is summarized in a contribution to this Workshop [8]. Compared with the SLC experience (where backgrounds were initially serious) the NLC design looks extremely robust. Even if some details (eg, related to new features such as the multi-bunch operation) turn out other than as currently simulated, the 5 km section between the end of each linac and the detector will permit great flexibility compared to the short, densely packed, terrain-following arcs of the SLC machine. The best defence of the detectors against backgrounds is a high degree of segmentation. In SLC, the 307 Mpixel CCD vertex detector is comfortable in high background conditions. This example will be followed for *all* the detectors in the NLD design. A high degree of segmentation will be implemented for reasons of performance, and this will also provide very robust background protection. Before considering the effects of backgrounds on specific detectors systems, let us list the different sources, and mention in general terms what action is taken to protect against them.

Table 2 Typical jet flavour tag efficiencies (%)

	b-jet	*c*-jet	*uds*-jets
b-tag	60	3	~1
c-tag	18	64	~0
b or *c*	96	79	~0

1) Muons from beam tails scraped in the post-linac collimators

These collimators are very far from the detector ($1/R^2$ really helps here) and the use of magnetized iron spoilers in the tunnel is extremely effective.

2) Lost beam particles (eg due to beam-gas scattering)

These, very few in number, are effectively absorbed by shielding before the FF quads (as at SLC).

3) SR photons from final telescope

These are fully shielded by a new mask in the design.

4) SR photons from final focus doublet

These pass through the aperture of the exit quads (unlike at SLC!) and do no harm.

5) e^+e^- pairs from beam-beam interaction

This potentially huge background (10^6 to 10^7 per train) is controlled by the 4 T detector solenoid (which is essential in protecting the vertex detector) plus the conical masks.

6) Backscattered particles (from the pair electrons)

The compensating solenoid, plus low-Z liner on surfaces struck by the pair electrons, provide strong suppression.

7) 'Mini-jets' (hadrons from beamstrahlung photon interactions)

These occur at a rate of a few per bunch train, and deposit low energy clusters in the small angle calorimetry. Rejected by fast timing within the bunch train.

What are the effects of the these various backgrounds on the detector systems? The vertex detector sees mainly a small residual tail from the pair background and backscattered particles. The SCT sees photons from the backscatter region and SR-related photons (which have to convert in order to cause problems). The E-cal sees the same sources of photons, depositing small uniform energy clusters over its inner pads. Beyond the solenoid, the H-cal and Muon Tracker see ≤ 1 halo muon per train. The associated hit rates and occupancies are included in Table 1. There is clearly a huge safety margin regarding background in every element of the detector.

5. CONCLUSIONS AND FUTURE PLANS

As was explained in the Introduction, the NLC detector design is at an early stage. We have nevertheless already established a design concept that meets all the key requirements. These are: *hermeticity, jet energy resolution, jet flavour identification,* and *tolerance of background.*

In all these areas work is continuing. Improvements to the machine design, or new requirements, can change the picture. New ideas for the detector systems can similarly influence the design. However, the global situation is already relatively stable; one can with confidence foresee a phenomenally powerful tool for physics. We have profited greatly from conversations with our colleagues working on JLC and TESLA, and we eagerly look forward to working closely with them on the detailed detector design.

As well as satisfying the technical requirements, it appears at this stage that the design can be modest and inexpensive by the standards of the LHC detectors. This combination of extremely powerful physics capability with modest scale reflects the harmonious conditions for physics that will be presented to us at the future Linear Collider.

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