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PERFORMANCE GOALS AND DESIGN CONSIDERATIONS FOR A LINEAR COLLIDER CALORIMETER*

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We demonstrate that the physics potential at a future linear electron positron collider (LC) demands a detector with excellent performance, in particular with unprecedented jet energy resolution. This can be achieved within the so-called particle flow approach which puts high emphasis on the imaging capabilities of the calorimeters. We discuss some principal design considerations for the electromagnetic and hadronic calorimeters which follow from this approach, and point to the most relevant technological challenges in the LC calorimeter R&D program.

1. Introduction

In the past years, a consensus has emerged in the international particle physics community that an electron positron linear collider (LC) with an initial centre-of-mass energy of 500 GeV, upgradeable to 1 TeV, should be the next big accelerator facility, and it should have significant running concurrent with the large hadron collider LHC. The presently envisaged time line with a start of commissioning in 2015 implies that conceptual detector design choices need to be made well before the end of this decade. A vigorous R&D program has therefore been started with the goal to advance the candidate technologies and to provide an experimental basis for these choices.

2. Physics performance goals

The excellent physics potential of the linear collider [1] stems from the possibilities for discoveries as well as for precision measurements which provide sensitivity to physics far beyond its nominal energy reach. The detector has to match this precision with unprecedented resolution and minimized systematic effects. Some key measurements involve final states with heavy bosons (W, Z, H) which must be reconstructed in their hadronic decay mode in order to optimally exploit the available statistics. In general, in these multi-jet events no kinematic fits (as often applied in LEP physics) are possible.

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The most demanding detector challenge is to achieve a jet energy resolution which separates W and Z bosons by their dijet invariant mass. Fig. 1 illustrates that the precision of a LEP-like detector of σ(E)/E = 60%/√E is not sufficient, but that the LC design goal of 30%/√E is well motivated. The quoted resolution is given here with respect to the jet energy as obtained from the true particle momenta; the parton hadron transition is separately taken into account in these studies. The separation of WWνν events from the ZZνν background is crucial for the study of electroweak symmetry breaking in scenarios without elementary Higgs bosons by analyzing WW scattering: the envisaged gain in resolution is here equivalent to a luminosity increase of 40%.

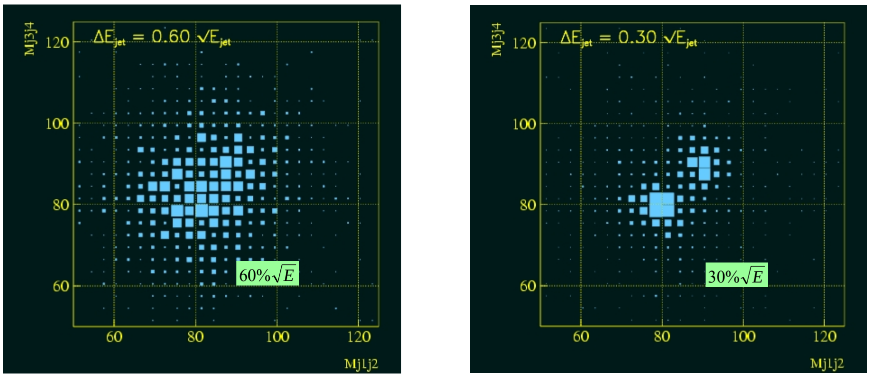

Figure 1. Reconstructed dijet masses in simulated WWνν and ZZνν events, for a detector with LEP-like energy resolution (left), and with the envisaged linear collider detector performance (right).

A similar gain has been found in a simulation study [2] of the branching ratio measurement for the process H→WW*. Together with the Higgs cross section in the WW fusion channel it provides the Higgs boson's total width which enters any absolute determination of its fundamental couplings to fermions and bosons.

A measurement of the trilinear Higgs (self) coupling via double Higgs strahlung (e^+e^-→ZHH) would constitute a corner stone in establishing the spontaneous symmetry breaking mechanism. This requires the reconstruction of an observable based on 3 dijet masses in a few tens of events after several years of running at design luminosity. With a jet energy resolution of 30%/√E a signal to background separation corresponding to 5σ could be achieved in simulations [3], but with a LEP-like detector this key measurement would be simply impossible.

Further design requirements - apart from the jet energy resolution - are directional resolution for photons (which could originate from decays of longlived neutralinos), hermeticity (crucial for the suppression of two-photon background to supersymmetric processes with missing energy), and excellent lepton identification capabilities.

Finally, time resolution may also become important, since pile-up from hadronic events created by the interaction of Beamstrahlung photons can pose a problem at a LC. Such events (with center-of-mass energy above 5 GeV) are produced at a rate of 0.1-0.4 per bunch crossing, depending on the accelerator technology and beam energy. How much of this background is overlaid to physics events depends on the capability of the detector and its electronics to assign the signals to the proper bunch crossing. Residual background and tightened cuts would then disturb the measurements. Fig 2 shows an example where the signal-over-background ratio rapidly deteriorates with the number of bunch crossings not resolved by timing. Similar effects were seen in other channels [4]. With a bunch spacing of 1.4 ns as expected at a "warm" normal conducting accelerator this would put ambitious demands on the calorimeter electronics.

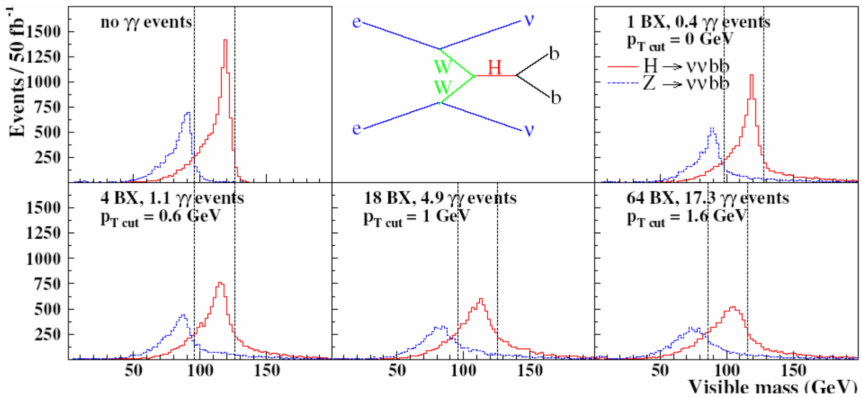

Figure 2. Visible mass of Hνν events and irreducible Zνν background events, for different amounts of overlaid hadronic background. Analysis cuts have been re-optimized for each scenario.

3. The particle flow paradigm

The final states of LC multi-jet events are complex – see Fig. 3 for an example – but the individual particles have moderate energies, with mean values of 3 – 12 GeV and typically below 100 GeV, i.e. in a range where the resolution of track detectors is superior to that of calorimeters. Moreover, about 65% of the energy is carried by charged particles, about 25% by photons, and only a small fraction by neutral hadrons. The particle flow concept optimizes the jet energy resolution by measuring each particle individually with the most suitable detector component, i.e. charged particles with the tracker, photons with the electromagnetic calorimeter (ECAL) and only the neutral hadrons with the hadronic calorimeter (HCAL). This requires that the calorimetric energy depositions of the individual particles are well separated from each other and can be uniquely assigned to them. In the ideal case where this assignment would be 100% correct, $\sigma(E)/E = 14\%/\sqrt{E}$ would be achieved. More realistic simulations take into account that some confusion between energy depositions and reconstructed particles is unavoidable but predict that $30\%/\sqrt{E}$ should be possible. The important point to note is that the additional "confusion" term actually dominates the resolution, followed by the contribution due to neutral hadrons. The particle flow paradigm therefore addresses the confusion term first and emphasizes the spatial resolution of calorimeters even more than their intrinsic energy resolution. The event in Fig. 3, after detailed detector simulation, has been reconstructed in such an approach.

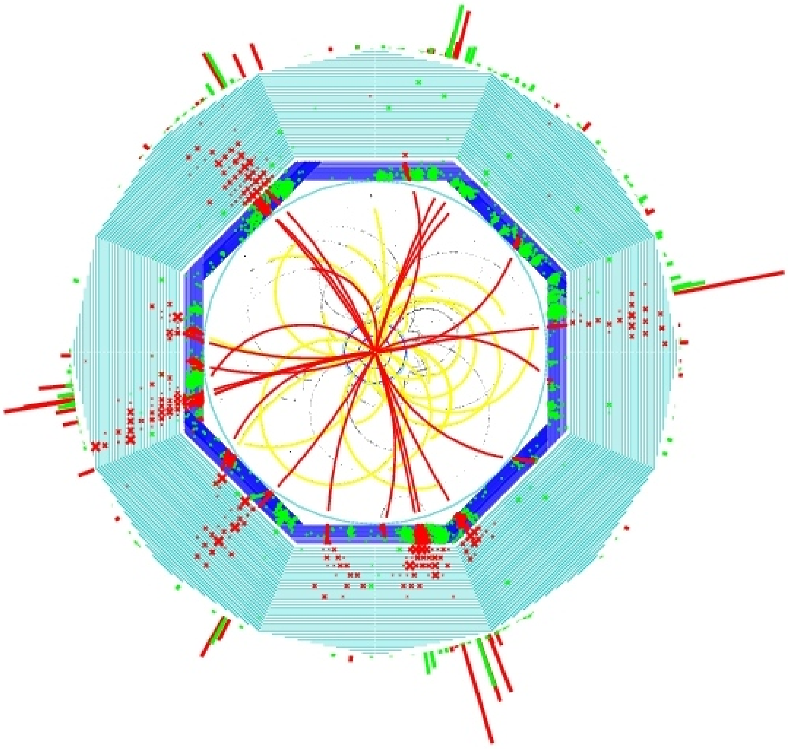

Figure 3. Simulated ZHH → 6 jets event, reconstructed following a particle flow approach. .The bars at the detector circumference represent the energy of the reconstructed particles and their direction at

the interaction point.. Charged particles (dark red) were measured using the trackers, neutral particles (light green) were measured in the calorimeter.

4. Detector design considerations

4.1. *General calorimeter concept*

A detector optimized for particle flow reconstruction should have large radius R_{calo} and length – to separate the particles from each other – and high magnetic field B, to sweep out charged tracks and measure their momenta precisely. The particles should traverse a minimum amount of material before reaching the calorimeters; these should consequently be located within the volume of a large solenoid. A small (effective) Moliere radius $r_{Moliere,\ eff}$ should minimize shower overlap, and small cell size r_{cell} should allow resolving the internal topology of showers. Altogether one may roughly express these considerations in a figure of merit scaling as $BR_{calo}^2/\sqrt{(r_{Moliere,\ eff}^2+r_{cell}^2)}$, which has to be optimized with respect to cost. The main cost-driving components are the electromagnetic calorimeter and the magnet.

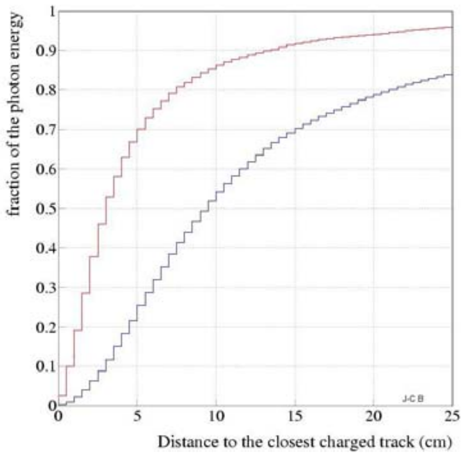

Figure 4. Fraction of photon energy carried by photons the in vicinity of charged tracks, vs. distance of closest charged track. Simulation of ZH events at 500 GeV for two different detector geometries: TESLA TDR (lower curve) and a smaller variant as proposed for Silicon based main tracking (here with B=6T and R=1.68m).From [6].

Obviously one can trade magnetic field against detector radius, but in practice this can be done only within limitations set by the mechanical stability of the coil, demanding $B^2R_{coil}<60\ T^2m$ [5]. Also, since the field does not act on neutrals, the trade-off actually seen in simulations is smaller than that expected from simply scaling the figure of merit. Figure 4 compares two detector variants

– the TESLA TDR geometry and a version with a Silicon based main tracker - with $BR^2 = 11.3$ Tm^2 and 9.7 Tm^2, respectively. The energy fraction of photons which can be expected to be difficult to resolve as they come closer to a charged track than about one Moliere radius is distinctly larger for the smaller detector. This fraction is subject to fragmentation fluctuations and can attain large values: in the larger detector, for example, 14% of WW events at $\sqrt{s} = 800$ GeV have more than 50 GeV carried by photons closer than 2.5 cm to a charged track. In the smaller option, this percentage is about twice as large [6]. The study indicates that for a small detector a compact ECAL design (small $r_{\text{Moliere, eff}}$) is even more crucial, and the reconstruction must be pushed to the extreme.

4.2. *Electromagnetic calorimeter optimization*

The requirement of a small Moliere radius leads to tungsten as the favored ECAL absorber material (r_{Moliere} = 9mm). Tungsten holds the further advantage of a small ratio of radiation length X_0 *vs.* hadronic interaction length λ, which longitudinally separates electromagnetic and hadronic energy depositions and helps resolving the internal structure of a hadronic shower. However, the imaging capabilities depend on the effective Moliere radius, which for the typically envisaged 2.5 mm thick W absorber plates tungsten increases with readout gap size G as (1+G / 2.5 mm). Realizing a 2-3 mm thin readout gap for a large area detector with 05 – 1 cm transverse pad size represents a major technological challenge. The main R&D directions favor Silicon as active material [7]. The cost of the ECAL is then mainly driven by the area of the Si sensors - about 3000 m^2 are needed – and is almost independent of the channel count. With an optimistic extrapolation of the evolution of the price for blank Si wafers over time one may hope for 2$/cm^2 at the time the ECAL needs to be built, but from the total amount it is clear that the overall geometry – radius, length and number of layers – must be very carefully optimized, taking tracking system considerations into account. As the particle flow approach emphasizes spatial over energy resolution, one may consider sacrificing sampling fraction (number of layers) for detector radius and length, as long as the pattern recognition does not suffer.

For cost reasons, and since with particle flow energy resolution is still important, scintillator-based alternatives to the Si/W concept are also being followed, some as hybrid in conjunction with interleaved silicon layers to enhance position resolution, e.g. [8]. The absorber is tungsten, too, or lead, in a compensating calorimetry approach. The sampling structure of hybrid concepts is another open issue for optimization. An overview of the R&D activities is given in [9].

4.3. *Hadron calorimeter options*

For particle flow to work, the HCAL must have imaging capabilities, too. Tungsten as absorber would be the best, but iron is generally chosen for affordability. For the readout, two basic concepts are being followed, a classical analogue one, using scintillators, but with much higher granularity than in a conventional HCAL, and the more radical so-called digital approach in which the segmentation is so fine that the energy is measured by simply counting the hits, in a gaseous or scintillator detector [10].

Simulations show that with a pad size of about 1cm the asymptotic resolution (i.e. that corresponding to counting hits in infinitesimally fine granularity) can be obtained for not too high energies, see Fig. 5. The energy resolution is expected to be better than in the analogue case at low energies, due to the suppression of Landau fluctuations of the deposited energy. (This could of course be reversed with a more elaborate use of the measured amplitude in the analogue case.) The degradation of the resolution at higher energies is due to an increasing probability of multiple hits per cell in dense showers. It can be overcome either by reducing the cell size further, or by adding minimum amplitude information in the form of thresholds. Scintillator as active medium allows to trade between granularity and dynamic range. The semi-digital approach consists of a moderate choice of granularity combined with a 2 bit readout [11].

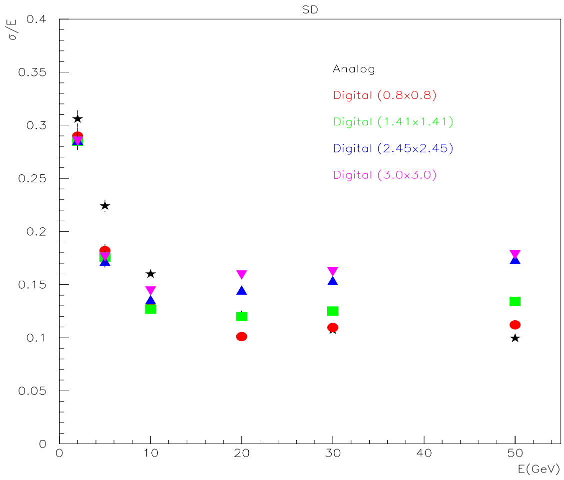

Figure 5. Simulated hadron energy resolution for a scintillator calorimeter as a function of energy for different transverse segmentations (in cm).No weighting factors have been applied in the analogue case.

The hit distribution (ignoring any amplitude information) seen in a gaseous calorimeter appears more compact than in a scintillator, due to a different response to low momentum neutrons and electrons, and thus seems to *a priori* favor gas detectors for their imaging performance. However, it could be shown that by adding amplitude or even only local hit density information, the effect can be compensated.

The candidate technologies for a gaseous digital HCAL are resistive plate chambers (RPCs) or thin chambers with gas electron multiplier (GEM) foils. Several groups have optimized RPC operation parameters and have chosen the safer avalanche mode, e.g. [12]. For both RPC and GEM options one still needs to develop large area detectors and demonstrate their long-term reliability. However, given the huge number of about 40 million channels, the biggest challenge is to develop concepts for low cost electronics; one aims at less than 1$ per channel.

For a scintillator HCAL, new possibilities are opened up by the advent of novel types of photo-detectors. The silicon photomultiplier for example [13] is a millimeter size solid state device with a gain as high as that of vacuum phototubes. It can be mounted directly on scintillator tiles, without pre-amplifier and avoiding complex fiber routing, such that high transverse and longitudinal granularities can be realized. In fact, simulation studies show that with $3x3cm^2$ tiles read out in every layer, it is possible to reconstruct the internal “tree” structure of hadron showers and to separate neighboring particles even in the case of partial overlap of the hadronic cascade (Fig. 6). The development of reconstruction algorithms for calorimetric energy deposition patterns is an important branch of this R&D effort, and the optimization of granularity and amplitude information is closely correlated with it. Since details of the geometric pattern are exploited, which in general are not resolved in conventional hadron calorimeters, it is indispensable to confront these concepts with experimental hadron test beam data to be acquired with highly granular prototypes [14], and to validate the simulation studies.

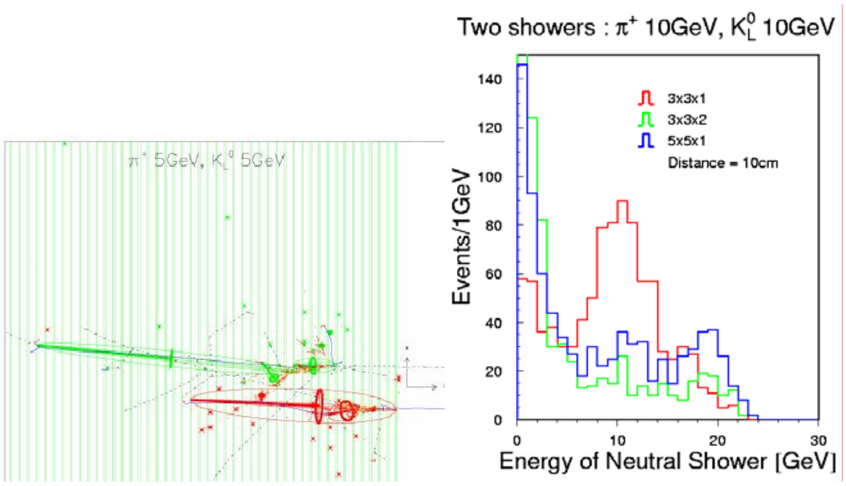

Figure 6. Reconstruction of two neighboring particles in a scintillator HCAL (left), Reconstructed energy of a simulated neutral kaon shower in the vicinity of a charged pion, for 3 different transverse granularities. The longitudinal sampling is 20 mm iron, 10 mm gap.

5. Conclusion

The linear collider physics potential represents a formidable challenge for the detector, and the calorimeter concept is the key for the overall detector architecture. This challenge is met by an internationally coordinated effort, partially organized in (proto-) collaborations like CALICE, which is joining more than 160 physicists from 28 institutes in America, Europe and Asia. This community is actively preparing prototypes for a test beam series to test, compare and further develop novel technologies and reconstruction concepts. The window of opportunity for such a program starts now, and first data will be collected in 2005.

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