Particle Flow Algorithm Calorimetry

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This paper presents the status of the development of Particle Flow Algorithm Calorimetry as a means of achieving the required precision on the measurement of jet energies for experiments at the future International Linear Collider (ILC). A brief introduction is given to the physics program for the ILC and the role of the calorimeter in particular. The physics requirements drive the need for a new approach to hadron calorimetry. The hardware prototype developments underway to support this approach are described, followed by examples of PFA development with representative results on jet energy resolution.

1. INTRODUCTION

The International Linear Collider (ILC) will study electron-positron collisions at center-of-mass energies between 500 GeV and 1 TeV. This will be a program of both discovery and precision physics measurements. It will include a detailed exploration of the electroweak sector, searching for one or more Higgs particles and the source of electroweak symmetry breaking, precision studies of the top quark, and the search for new physics, such as W', Z' bosons, leptoquarks, and extra dimensions. Much of this program requires high precision measurements of jet energies and jet-jet invariant masses, and hence creates the need for a new approach to hadronic calorimetry.

2. ILC PHYSICS AND THE GOALS FOR PFA

2.1. ILC Physics examples

Recent studies [1] have shown that processes such as:

$$e^+e^- \to Zh, WW, ZZ$$

$$e^+e^- \to Zhh$$

$$e^+e^- \to t\bar{t}h$$

(with W, Z, h producing jets)
demand efficient jet reconstruction and separation, a jet energy resolution in the region of 30%/√E, and excellent jet-jet mass resolution, to allow, for instance, the clear distinction between W and Z bosons on an event-by-event basis. In addition, jet flavor tagging is needed, as well as good forward calorimetry for SUSY selectron studies, and the ability to find and reconstruct photons from secondary vertices, arising from the decay of long-lived particles in the calorimeter. The fine-grained calorimeters described in this paper have the potential to satisfy all these requirements in an efficient manner.

Calorimetry choices and PFA's

Traditional calorimetry using optimized sampling fractions, and equalized electromagnetic and hadronic responses ("compensation"), can yield good energy resolution, but not at the level required by the ILC physics. For instance, ZEUS [2] with an Uranium/Scintillator combination achieves a single hadron energy resolution of 35%/√E ⊕ 1%, and a jet energy resolution of 50%/√E, while D0 [3] using Uranium/Liquid Argon achieves 50%/√E ⊕ 4% and 80%/√E respectively.

To achieve a better jet energy resolution for the ILC, it was realized that one could use the information on charged particle momentum from the tracking system to better determine the dominant charged particle component of most jets. Figure 1 shows the composition of jets in the process (ttbar to 6 jets) at 500GeV center-of-mass energy[4].

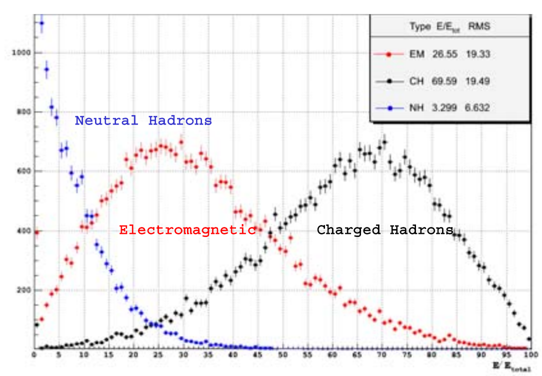

Figure 1: Jet components in e+e- to ttbar 6 jets.

Thus, charged hadrons and electrons are usually the dominant components of jets and their energies are best taken from momentum measurements in the tracking system. Photons are measured with good (~15%/√E) precision in the electromagnetic calorimeter. This leaves the residual neutral hadron energy to be measured directly in the calorimeter. It should be noted, however, that there will be classes of events having jets with lower charged hadron/electron components and a potentially much higher neutral hadron component. Such events may well show a degraded jet energy resolution, depending on the efficiency achieved by the Particle Flow Algorithm (PFA).

The implementation of a PFA with separate measurements of the energies jet components sets requirements on the design of the calorimeter system. The electromagnetic calorimeter should be fine grained, have a reasonable energy resolution, and provide good separation of charged particles and photons.

The hadron calorimeter show have good charged particle tracking capabilities, using fine granularity, and acceptable energy resolution for direct calorimeter measurement of neutral particle energies.

Finally, depending on the overall thickness of the calorimeter system, it may be necessary to install a "tail-catcher" to measure the few percent of a jet's energy that may leak through the superconducting coil (assumed to be outside the combined electromagnetic and hadronic calorimeter system).

The three main ILC detector design concepts, SiD, LDC, and GLD, feature different electromagnetic and hadronic calorimeter implementations. The calorimeter systems for LDC and GLD have a larger inner radius than those of SiD due to their location outside a large volume gaseous tracking time-projection systems. By contrast, the SiD calorimeter is located outside a compact all-silicon tracking system. The SiD electromagnetic calorimeter is also silicon-based and features very small cells – hexagons equivalent to a squared area of $(3.63\text{mm})^2$. The SiD hadronic calorimeter baseline is either a gas-based system using either Gas Electron Multiplier technology or Resistive Plate chambers, or a scintillator based system with small tiles. The LDC electromagnetic calorimeter is also silicon-based, and the hadronic calorimeter baseline uses small scintillator tiles readout using silicon-photomultipliers. The GLD calorimeters are both based on scintillator tile and strip designs. Figures 2-4 show quarter sections of these detector design concepts.

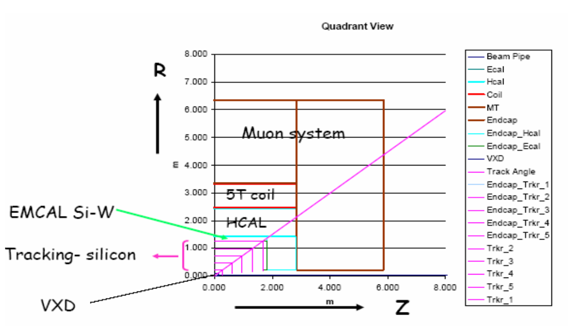

Figure 2: The SiD detector concept [5].

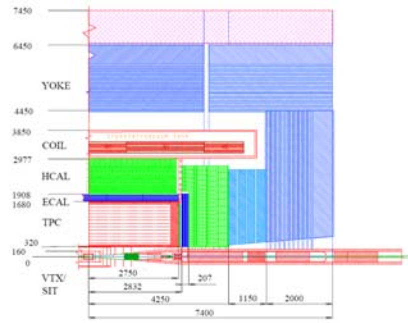

Figure 3: The LDC detector concept [6].

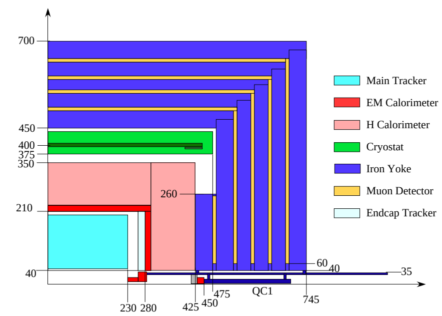

Figure 4: The GLD detector concept [7].

The PFA approach to jet energy measurement results in very integrated designs for the detectors, with each subsystem providing essential input to jet energy measurement and identification. This is illustrated by the track and energy patterns seen from a simulated interaction in Figure 5.

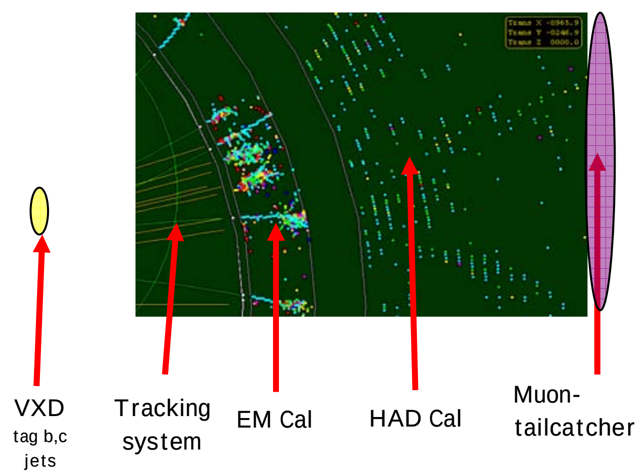

Figure 5: Integrated detector design for the SiD concept.

2.2. Calorimeter Technologies

Details of calorimeter technologies may be found elsewhere. Here we summarize and give some examples of approaches being studied to implement calorimetry that can deliver the required jet energy resolution.

Electromagnetic Calorimeter (ECal). For the electromagnetic calorimeter the physics requirements emphasize longitudinal and transverse segmentation over intrinsic energy resolution. Localization of electromagnetic showers and the separation of electron/photon showers from hadrons is achieved through the use of a dense (small radiation length) calorimeter with fine segmentation. The SiD concept is developing a Si-Tungsten calorimeter with 4mm x 4mm effective segmentation, read out via the KPix chip [8] with 1024 channels. Figure 6. shows a wafer and one cell of the KPix chip for this design. Construction and beam testing of a full-depth Si-W stack is foreseen for 2007-8.

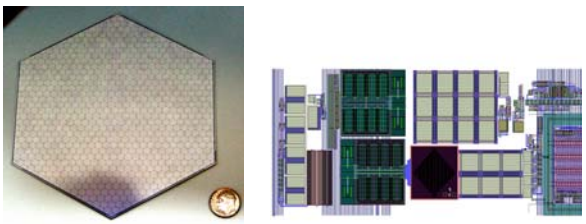

Figure 6. Silicon wafer and a cell from the KPix chip.

The CALICE collaboration is also developing a Si-W calorimeter, with detector slabs incorporated into a carbon-fiber alveola structure. A one-third depth stack has been exposed to a test beam at DESY with performance in agreement with simulations. A full-depth stack will be completed in time for beam tests at CERN in Fall 2006, to be followed by testing in combination with hadronic modules at Fermilab in 2007-9. A schematic of the CALICE module is shown in Figure 7 together with an earlier measurement of the signal-to-noise ratio for a single wafer [9].

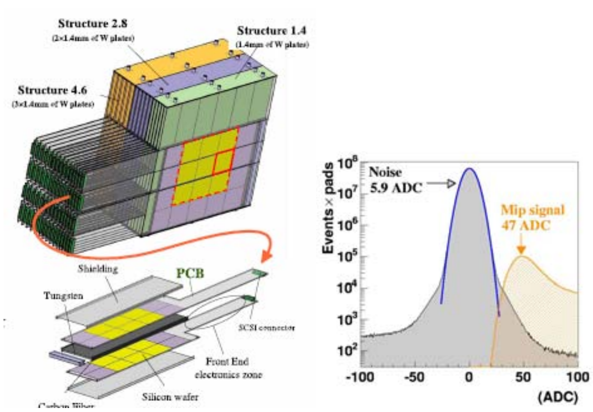

Figure 7. CALICE ECal schematic and signal-to-noise ration measurement.

The GLD concept is investigating a number of different scintillator strip and tile configurations, using wavelength-shifting fiber and multi-pixel photon counter readout. An example of one possible configuration is shown in Figure 8.

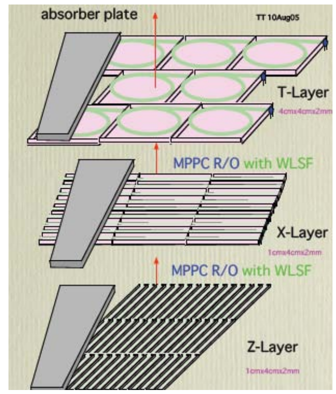

Figure 8. GLD concept option for scintillator ECal.

Hadronic Calorimeter (HCal). As for the electromagnetic calorimeter, the physics requirements for the HCal emphasize fine segmentation over intrinsic energy resolution since the goal is to track charged particles through the calorimeter and associate them with energy deposits. In addition, for the digital HCal, the segmentation should be sufficiently fine to give a linear energy vs. hits relation for the direct energy measurement of neutral clusters in the calorimeter. To ensure excellent track following a high efficiency for MIPs is required in association with a low hit multiplicity (number of individual cells above threshold per layer for the passage of a single particle). The depth of the HCal should be at least 4λ (not including approximately 1λ in the ECal.

The CALICE collaboration is constructing an analog HCal with 38 layers of 1m^2/layer with a total of 8000 small scintillator tiles read out via wavelength-shifting fibers and silicon photomultipliers (SiPMs). Figure 9 shows an assembled layer and the MIP response of a tile.

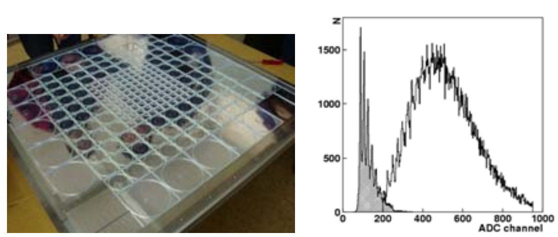

Figure 9. A layer of the CALICE analog HCal, and a tile MIP response.

The goal for this effort is to have at least a partial stack ready for the test beam at CERN in Fall 2006, followed by a move of the (completed) stack to Fermilab.

The digital hadron calorimeter effort is pursuing two technologies: Gas Electron Multipliers (GEMs) [10] and Resistive Plate Chambers (RPCs [11]). Both use 1 cm^2 anode pads as the basic granularity. The GEM-based approach uses a double-GEM structure to amplify the signals from the passage of charged particles through a 3mm ionization creation region. The two GEM foils are 1mm apart and a further 1mm region separates them from the anode collection layer. The goal is to have the readout layer, including a high density chip, occupy no more than an additional 2mm for a total active layer thickness of 7mm. Another possibility being investigated to reduce the active layer thickness involves the use of a single "thick-GEM" [12] – made from a drilled circuit board. Individual GEM chambers of 30cm x 30cm have been constructed and tested. The goal is to build full $1m^2$ layers using large GEM foils during 2007-8 and test a full $1m^3$ stack in beam at Fermilab in 2008. Figure 10 shows a schematic view of the GEM-digital HCal approach and an example of a large foil from 3M Corp.

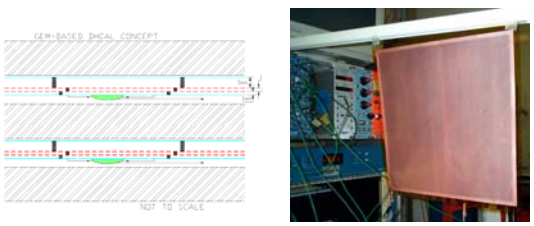

Figure 10. GEM-DHCAL concept and 30cm x 30cm foil from 3M Corp.

The RPC approach uses chambers constructed from two parallel glass plates and signals extracted via external signal pads. Many different prototype configurations have been assembled and tested. Figure 11 shows one example of an RPC chamber together with typical results on multiplicity vs. efficiency.

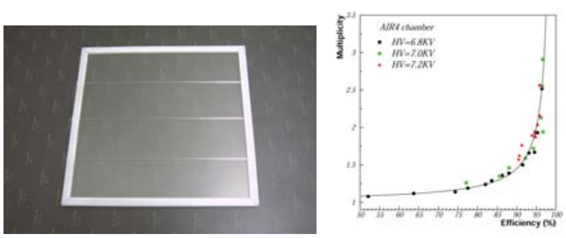

Figure 11. RPC chamber and results on Multiplicity vs. efficiency.

2.3. Using the New Calorimetry – Particle Flow Algorithms.

Assuming that the various contributions to the jet energy resolution are independent, or at least the coherence can be factored into a separate term, the in general one can write:

$$\sigma^2[E_{jet}] = \sigma^2[charged] + \sigma^2[electromagnetic] + \sigma^2[neutral-hadron] + \sigma^2["confusion"]]$$

The charged particle momentum measurement is excellent in the tracking system and makes a negligible contribution to the jet energy resolution. Photons are measured with a resolution of ~15%/√E. The neutral hadron energy is measured directly in the calorimeter and relies on the existence of a known energy vs. hits relation in the hadronic section. Finally, the confusion term represents the shortcomings of a particular PFA in assigning specific energy deposits to jets.

In addition to PFA development, there have been studies of effects of particle interactions in simulated calorimeters for various active media and absorber materials [ ]. For instance, neutron – antineutron differences appear in the hits vs. energy relation, Figure 12.

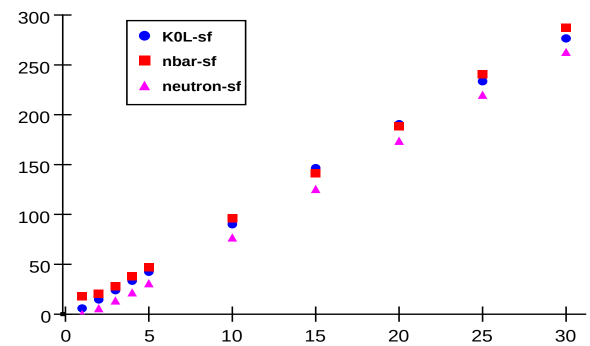

Figure 12. Mean number of hits vs. energy [13].

However, if the energy for the neutrons is scaled down by the mass of the neutron, and the energy of the antineutrons is scaled up its mass, then there is agreement, see Figure 13.

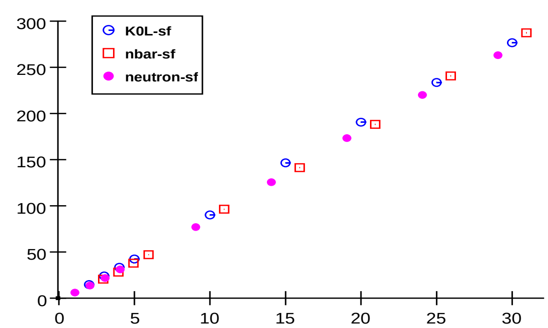

Figure 13. Mean number of hits vs. scaled energy.

PFA development is being pursued by a number of individuals/groups in parallel with several different approaches to track following and energy clustering and track association. For instance, groups at SLAC [14], Northern Illinois University [15], ANL [16], University of Iowa [17], and University of Cambridge [18] are variously developing a nearest neighbor clustering algorithm, a density-weighted cluster algorithm, a minimal spanning tree algorithm (MST), and a topological algorithm, to give a few examples of current activity. The Iowa algorithm [17] starts with finding track segments in the ECal and/or HCal, removing their hits in the calorimeters, then finding electromagnetic showers and removing their hits. Then dense clumps of hits are identified, followed by large scale hadronic shower recognition using the MST approach and examination of the internal structure of these showers linking track segments and clusters. Finally, the helix extrapolation of tracks from the tracker to the ECal is carried out to get primary showering energies and particle type identification. The result is a jet energy resolution at the Z-pole with no ‘cheating” of 49%/√E versus a perfect pattern recognition result of 21%/√E.

A SLAC/ANL algorithm [14] approaches the problem from the other direction, finding first MIP hits on extrapolated tracks and determining the first layer of interaction in the calorimeter using cell hit density. Next photons are identified using an longitudinal H-matrix working on ECal clusters. Then track-linked electromagnetic and hadronic clusters are associated and the process iterated to match the tracker momentum to energy measured in the calorimeter. This is followed by a neural net technique to find neutral clusters. Finally, a jet algorithm is applied using tracks, photons and neutral clusters as input. The results of this approach at the Z-pole are shown in Figure 14.

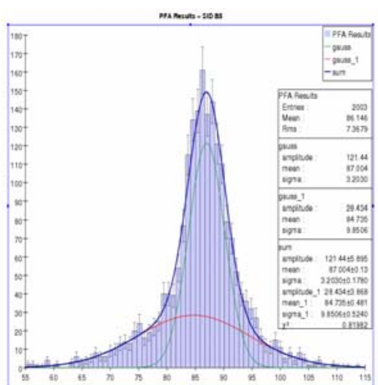

Figure 14. SLAC/ANL PFA results at Z-pole showing 34%/√E jet energy resolution for the central 59% of events.

As a final example there is the approach taken at the University of Cambridge, using a topological technique [18]. There is an initial preparatory stage establishing hit ordering and track quality. There is then an initial clustering to form protoclusters of collections of hits. This is followed by cluster association and merging with tight topological linking of clusters, looser merging of clusters, and track-driven merging. The final PFA then consists of track-cluster matching. Some examples of the topological linking are given in Figure 15.

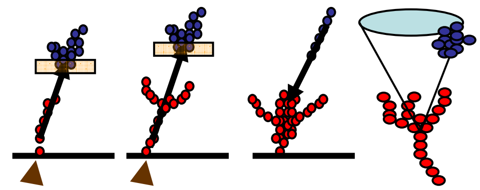

Figure 15. Examples of topological cluster linking.

Figure 16 shows the results of this algorithm for a 4 Tesla central magnetic field.

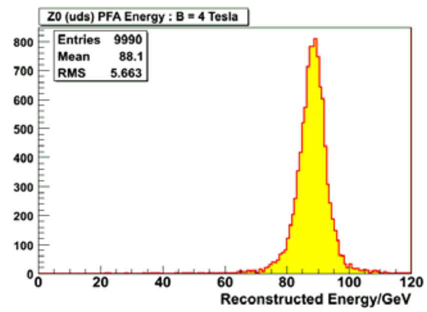

Figure 16. Topological PFA result: 35.9%/√E for the RMS of the central 90% of events.

Interestingly, this approach has also shown that there is only a weak dependence on the value of the magnetic field from 2 to 6 Tesla.

2.4. PFA Issues

While encouraging results have been obtained at the Z-pole, there is an open question as to whether a jet energy resolution of ~30%/√E can be achieved for events at higher energies with many jets. Even at the Z-pole there are still significant tails in the mass plots. These can presumably be reduced by developing better algorithms that can successfully handle the event-to-event fluctuations and minimize the mistaken energy assignments and general confusion. This must be vigorously pursued in order to avoid an effective loss of luminosity resulting from any cuts applied to the mass peaks.

There are many questions concerning our ability to obtain agreement between the GEANT4 simulations and the data to be taken using prototypes of the new calorimeter techniques at the test beams.

In order to prepare realistic ILC detector proposals, we must learn how to best use the test beam results from the $1m^3$ hadronic stacks to develop PFAs that we can rely upon to correctly characterize the performance of future detectors. This will be an interesting challenge for the next several years of ILC detector development.

Acknowledgments

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