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Comparison of Simulated Analog Versus Digital Energy Measurement in a Finely-Segmented Hadron Calorimeter

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Abstract. Precision calorimetry for jet measurements at a future e^+e^- linear collider will only be possible using so-called Energy Flow Algorithms. While there are many possible implementations of E-flow techniques, they all have in common separation of induced calorimeter showers from charged and neutral hadrons (as well as photons) within a jet. This means that both the calorimeter cell granularity transverse to the particle trajectory and the longitudinal segmentation must be optimized to minimize shower overlaps. It is probable that as the cell volume decreases, it will become increasingly harder to get an energy measurement from each cell (analog calorimetry). Using only the hit information (digital calorimetry) may be the best and most economical way to measure the neutral hadron energy contribution to jets. In this paper, comparisons of analog and digital methods of measuring the neutral hadron contribution to jets from Z boson decay are made in simulation, indicating that the digital method is somewhat better than the analog case in energy resolution.

INTRODUCTION

The primary goal of a detector at a future e^+e^- linear collider will be to make precision measurements, mainly on processes suspected of containing information about mechanisms of Electroweak Symmetry breaking. For example, it will be important to measure accurately the cross sections for the processes $e^+e^-\rightarrow\nu\nu WW$ and $e^+e^-\rightarrow\nu\nu ZZ$. Because of the missing neutrino energy, beam energy constraints can not be used in this measurement, and since these cross sections are small, it will be important to include all of the decay modes of the vector bosons – especially the dijet mode which represents ~70% of the total decay width. This means that the dijet mass must be used to identify the vector boson flavor in the interaction. Using present standard "calorimeter-only" jet measurement techniques, a dijet mass resolution of typically ~75%/√M can be obtained. This represents an uncertainty on the measured W and Z masses of ~7 GeV. Since this is a large fraction of the 9 GeV mass separation between these particles, clean event selection cuts will drastically reduce the amount of luminosity used in this measurement. However, if a dijet mass resolution of ~30%/√M is obtained, the W and Z are well-separated as shown in Figure 1, and full use of the available luminosity is possible.

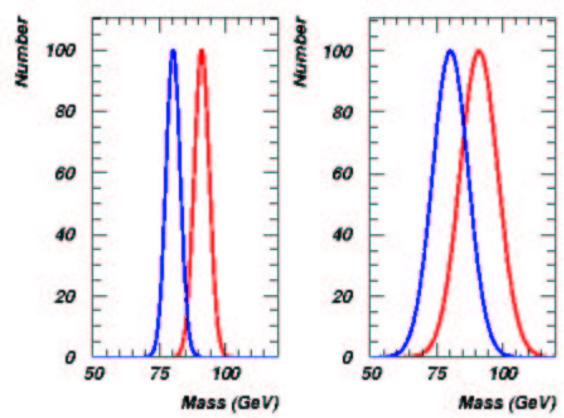

FIGURE 1. (left) W(blue) and Z(red) dijet masses with mass resolution of 30%/√M, and (right) with 75%√M.

In most jet algorithms, the trajectory of the jet (angular direction) is well-determined, so to get the required dijet mass resolution, individual jet energies must therefore be measured to ~30%/√E. On average, 62% of the jet energy in a hadronic Z decay from the process $e^+e^- \rightarrow ZZ$ at 500 GeV CM is carried by charged hadrons, mostly pions. About 25% of the energy is made up of photons, and other than some missing energy carried away by neutrinos from heavy quark fragmentation, the remaining ~13% of the jet energy is carried by neutral hadrons – K_L^0 and neutrons. The best measurement of the total jet energy should therefore consist of complete separation of the calorimeter showers from charged hadrons, photons, and neutral hadrons. The very precise measurement of the charged particle momentum afforded by the tracker in a high magnetic field would contribute a negligible amount to the total jet energy resolution. Photons are well-defined objects which are contained in the electromagnetic calorimeter (ECAL) and measured with resolutions of ~15%/√E. The dominant contribution to the energy resolution of a jet from Z decay comes from the measurement, primarily in the hadronic calorimeter (HCAL), of the neutral hadrons. This technique of jet energy measurement has come to be known as an Energy Flow Algorithm (EFA), or E-flow.

SAMPLING CALORIMETRY – DIGITAL VERSUS ANALOG

In a sampling calorimeter, incoming particles are induced to shower in dense absorber layers, with the energy loss being measured in the interspersed active media. Shower development in a calorimeter is characterized by a quantity "track length" which is the sum of all charged particle tracks produced in the shower and crossing the active media. The reason that calorimetry works is because the track length is proportional to the energy of the incident particle. For a digital sampling calorimeter, the resolution of the measurement is determined by sampling fluctuations - fluctuations in the total number of charged particle tracks. Assuming the tracks are independent, the measurement resolution is therefore Gaussian and proportional to $1/\sqrt{N}$, where N is the total number of tracks. The total energy is given by $E = \delta E \times N$, where δE is the energy lost by a MIP in one active layer.

The performance of a digital calorimeter is dependent on the incident energy and the cell size. As the incident energy increases, increasing the total number of tracks; if the cell size remains fixed, the digital measurement degrades as the density of tracks becomes >1 per cell. Therefore the cell size must be small to take advantage of the $1/\sqrt{N}$ statistics. The E-flow shower separation requirement also means that the cell size should be small, therefore digital calorimetry seems to be a good (and maybe necessary) match for E-flow type analyses.

In an analog calorimeter, where the energy is measured in each cell, in addition to sampling fluctuations, the energy measurement itself fluctuates according to a (asymmetric) Landau distribution; and also, differences in the path length of a track through the active media contribute to the measurement uncertainty. These effects increase the total energy resolution for the analog measurement compared to the digital case. If the active media is dense (solid or liquid), the resolution is dominated by sampling fluctuations, while in low density media (gas), Landau and path length fluctuations contribute a significant amount to the resolution. For more detail on the differences between analog and digital calorimetry, see [1].

EVENT SIMULATION AND DETECTOR MODEL

Interactions of the type $e^+e^- \rightarrow ZZ$ at 500 GeV CM were generated in PANDORA_PYTHIA[2] and run through the fast MC program, GISMO[3], to simulate hits in a detector. The detector model chosen was the SD detector [4] of the American linear collider study groups. Events were selected in which at least one of the Z bosons decayed hadronically with at least one jet in the barrel region of the detector. The SD calorimeter properties are displayed in Table 1.

TABLE 1. SD Detector Barrel Calorimeters.

ECAL	HCAL
127 cm inner radius 142 cm outer radius	153 cm inner radius 255 cm outer radius
30 layers	34 layers
W(0.25 cm)/Si(0.04 cm)/ (0.21 cm G10/Air)	SS(2.0 cm)/Scin(1.0 cm)
~20 X_0, 0.8 λ_I	~40 X_0, 4 λ_I
~5 mm × ~5 mm cells (projective)	~1 cm × ~1 cm cells (projective)

ENERGY MEASUREMENT OF NEUTRAL HADRONS

In both the analog and digital cases, it is assumed that the calorimeters are used in a "perfect" E-flow algorithm, i.e., perfect separation of showers from neutral hadrons, photons and charged hadrons is obtained. Since, in practice, the ECAL will be an analog device, the contribution to the neutral hadrons from the ECAL will always be assumed to be an analog energy measurement. The HCAL contribution will be added to the ECAL as either an analog or digital measurement for comparisons.

HCAL Analog Measurement

The traditional measurement of neutral hadrons is done by adding the energy of cells grouped into clusters in the calorimeter. For this comparison, K_L^0s were chosen from Z decays and a perfect clustering cell grouping was used. Only perfect clusters from K_L^0 mesons, as determined from the MC particle list, with no contribution from other particles, were used in this analysis. This corresponds to a complete and perfect separation of the K_L^0s from other particles in the jet, i.e., a perfect E-flow analysis. Figure 2 shows the analog measurement of K_L^0 mesons as a ratio of cluster energy to particle energy, including the ECAL and analog HCAL contributions.

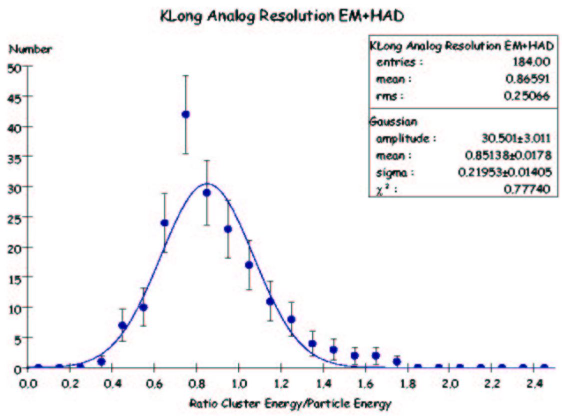

FIGURE 2. Ratio of cluster energy to K_L^0 particle energy measured in analog HCAL.

The analog resolution (σ/E) is ~26% as described by a reasonable Gaussian fit distribution.

Figure 3 shows the distribution in energy of the KL0 mesons used in the analog resolution determination. The average of this steeply-falling distribution is ~13 GeV – also the same as for neutrons.

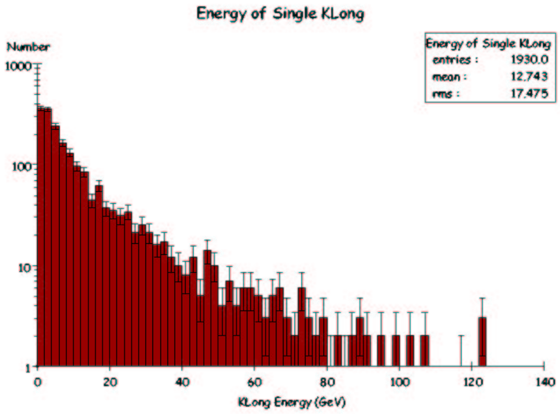

FIGURE 3. K_L^0 particle energy distribution.

HCAL Digital Measurement

The digital measurement was done by counting all of the hits contained in the perfect K_L^0 cluster in the HCAL. Again, this represents a perfect application of E-flow using a digital calorimeter. Figure 4 shows the number of calorimeter cells hit versus the part of the particle energy contained in the HCAL for neutral hadrons and also charged pions.

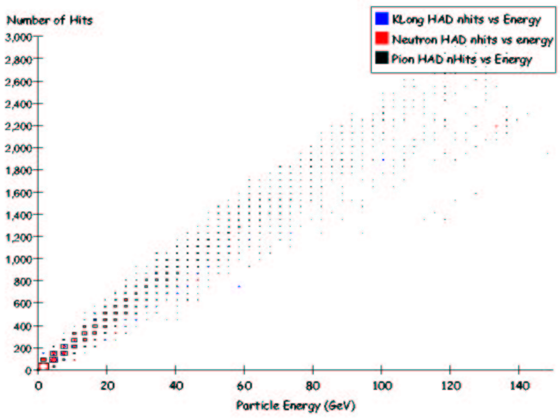

FIGURE 4. Number of cell hits versus energy for neutral hadrons and pions in the digital HCAL.

No threshold cuts were applied on the energy of individual calorimeter cells. Either muons or fully-contained hadrons can be used to determine the calibration factor, δE. The value obtained was 43

MeV/hit. Using this value and the number of hits (N) in the digital HCAL, the measured K_L^0 energy was determined by adding $\delta E \times N$ to the ECAL analog contribution. Figure 5 shows the ratio of measured K_L^0 energy to particle energy from this procedure.

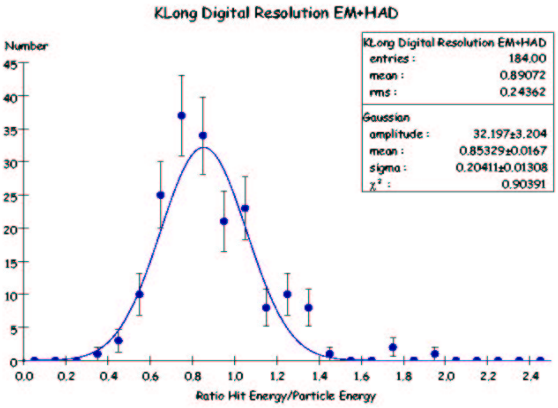

FIGURE 5. Ratio of digitally-measured K_L^0 energy to particle energy.

The digital resolution (σ/E) is ~24% from a reasonable Gaussian fit. This number is slightly better than the analog value as expected.

To enhance the analog versus digital difference, a separate selection of KL0 mesons in which the entire hadronic shower was contained in the HCAL (no ECAL contribution) was done and the resolutions were determined. Figure 6 shows the results of this analysis.

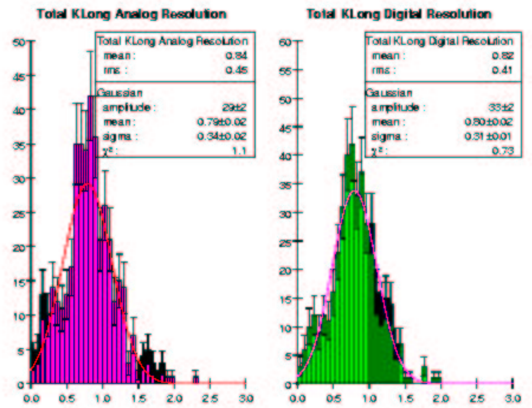

FIGURE 6. Ratio of measured K_L^0 energy to particle energy for (left) analog measurement and (right) digital measurement.

In this case, the analog resolution (σ/E) is ~45%, while the digital resolution (σ/E) is ~39%, consistent with the idea that the digital measurement resolution is based solely on sampling fluctuations, while the analog measurement contains additional contributions.

EFFECT OF VARYING THE STANDARD SD PARAMETERS

The standard SD detector HCAL was modified in two ways: 1) Tungsten (W) replaced stainless steel as the absorber material, and 2) the cell size was increased. In this way, the resolution dependence on absorber type and thickness could be tested, and the limits of digital HCAL performance could be tested as the density of hits per cell increased.

Absorber Type And Thickness Variation

The total number of HCAL layers was increased from 34 to 60 by replacing the SS with 0.7 cm of W (~2 X_0). While this increased the sampling fraction, the effect on the resolution was mostly offset by the increase in the atomic number (Z) of the material. The transverse size of the cells was kept the same at ~1 cm $\times$ ~1 cm. The energy resolution, as determined from sampling fluctuations, is proportional to a term - $\sqrt{\varepsilon t}$, where ε is the "critical energy" approximated by $\varepsilon \cong 550/Z$ (MeV), and $t = x/X_0$ is the sampling fraction. Figure 7 shows the digital resolution as measured in the SS and W HCALs.

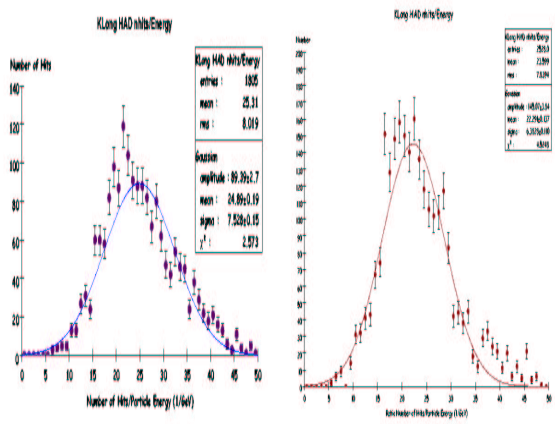

FIGURE 7. Ratio of digitally-measured K_L^0 energy to particle energy for (left) SS HCAL and (right) W HCAL.

The resolution (σ/E) is ~30% for both HCALs.

Transverse Cell Size Variation

The transverse cell size was varied from ~1 cm × ~1 cm (SD A) to ~3 cm × ~3 cm (SD B) to ~5 cm × ~5 cm (SD C) in the W HCAL. First, comparisons of analog and digital readout as described above were done for K_L^0 mesons in the ECAL and HCAL. Figure 8 shows the analog ratio of K_L^0 cluster energy to particle energy.

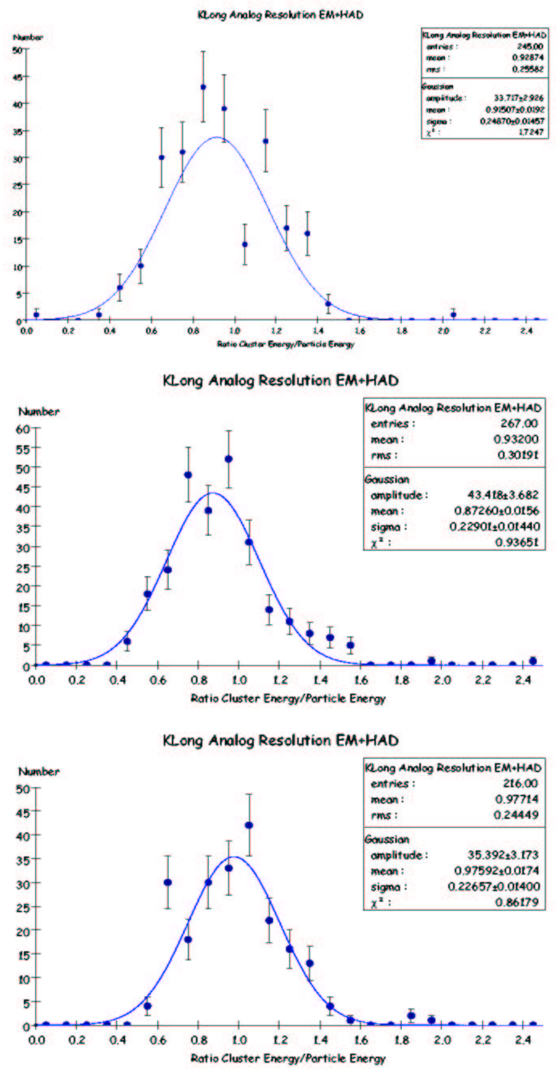

FIGURE 8. Ratio of analog K_L^0 cluster energy to particle energy for (top) SD A, (middle) SD B, and (bottom) SD C HCALs.

The energy resolutions (σ/E) are all consistent at ~ 25% as expected, since granularity should not enter into the analog measurement of perfect clusters.

Figure 9 shows the same detector configurations, but with the HCAL energy measured digitally. The energy resolutions (σ/E) hardly change from the very small cell size to the largest, averaging ~20%, even better than the previously-observed improved resolution for digitally-measured energy.

It is possible that with the K_L^0 mesons starting to shower in the ECAL, the effect of increased track density per cell in the HCAL only is too small to significantly affect this measurement. In order to better illustrate the effects of larger cell size, a comparison of the digitally-measured resolution using only the HCAL part of the KL0 shower is done.

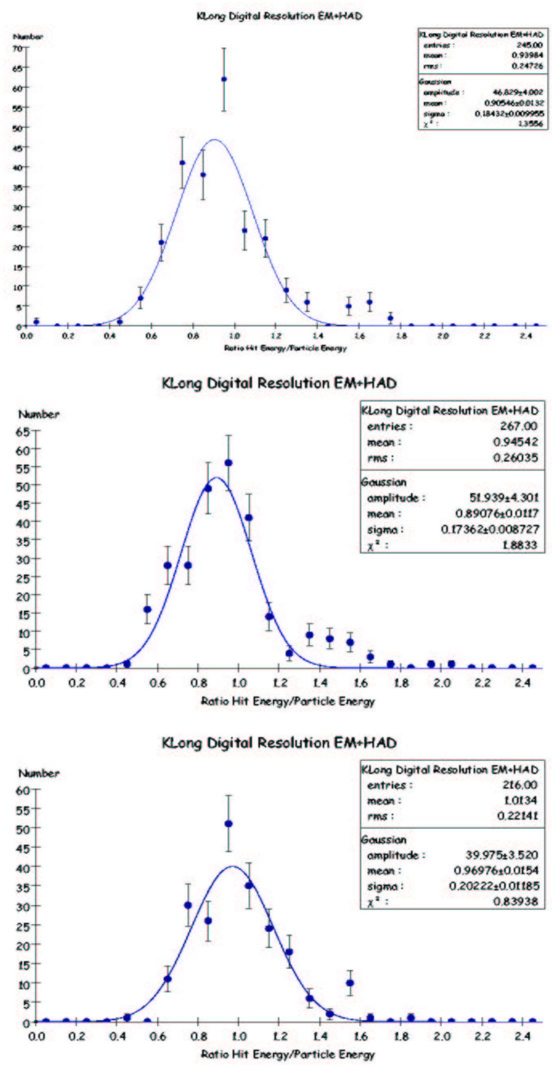

FIGURE 9. Ratio of digitally-measured K_L^0 energy to particle energy for (top) SD A, (middle) SD B, and (bottom) SD C HCALs.

Figure 10 shows the results of this analysis for the 3 SD detector configurations. Now, a progression of worsening resolutions (σ/E) is seen with a value of ~29% in SD A, ~31% in SD B, and ~34% in SD C, indicating that the reduced number of counted hits due to higher track density per cell is directly related to the precision of the measurement as expected. While this effect is not very large in the resolution, the larger cell size probably has a more serious effect on the E-flow shower separation capabilities of the HCAL, which leads to much worse jet energy resolutions if some charged hadrons need to be measured in the calorimeter instead of the tracker.

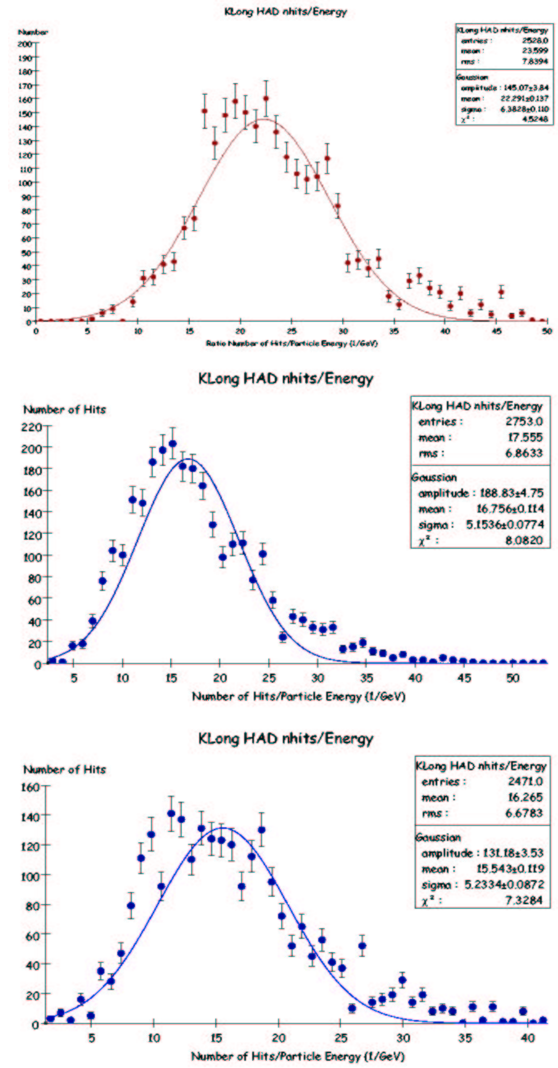

FIGURE 10. Ratio of digitally-measured K_L^0 energy to particle energy in HCAL only for (top) SD A, (middle) SD B, and (bottom) SD C HCALs.

SUMMARY

Studies of the characteristics of analog versus digital energy measurement in a finely-grained hadronic calorimeter indicate that the energy resolution from the digital measurement is better than the corresponding analog measurement. This can be understood by investigating the contributions to the resolution in each case. The digital resolution is dominated only by sampling fluctuations, but the analog measurement has significant additional contributions to the resolution from other sources, presumably Landau fluctuations and track path length differences. Results obtained by varying the absorber type and thickness and the transverse cell size support these ideas. In the E-flow approach to jet reconstruction, optimization of the HCAL implies that transverse cell sizes be very small and that there is sufficient longitudinal segmentation so that all showers can be separated. This approach seems very conducive to the use of digital calorimetry in the hadron calorimeter and future work on Energy Flow Algorithms will include optimization of a digital HCAL.

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