Particle-Flow Algorithm development efforts in America

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By combining track momentum measurement of charged particles with calorimetric measurement of neutrals, particle-flow algorithms may help us measure jet energies at the next linear collider detector with twice the precision achievable by purely calorimetric methods. We have developed algorithms to separate the energies deposited by charged and neutral particles in a jet. These algorithms are suited to both analog and digital read-out options that are being considered for the hadronic section of calorimeter. We have also studied, using GEANT4 simulation of detector models, how the performance of analog and digital measurements depend on the calorimeter sampling layers' lateral segmentation. Initial findings from PFA-based jet-reconstruction programs, one starting with cluster-finding in the calorimeter, and another that follows tracks into the calorimeter, are presented here.

1 Introduction

Excellent measurement of jets from decays of vector bosons and other heavy particles such as the top quark, the Higgs boson(s), etc. will be crucial to the success of the International Linear Collider (ILC) physics program. In particular, it will be important to be able to distinguish, in the final state of an e^+e^- interaction, the presence of a Z or a W boson by its hadronic decay into 2 jets. This requires dijet mass to be measured within ~ 3 GeV, or, in terms of jet energy resolution, $\sigma(E) \approx 0.3\sqrt{E}$ (E in GeV). Such high precision in jet energy measurement cannot be achieved by purely calorimetic methods in the absence of a kinematically overconstrained event topology. Similar precision in measurements of jet and missing momentum will be needed for discovery and characterization of several other new physics processes as well as for precision tests of the Standard Model. Such ambitious objectives place stringent demands on the performance of the calorimeters working in conjunction with the tracking system at the ILC, and require development of new algorithms and detector technology.

The most promising means to achieving such unprecedented jet energy resolutions at the ILC is through particle-flow algorithms (PFA). A PFA attempts to identify in a jet its charged, electromagnetic, and neutral hadron components, in order to use the best means to measure each. On average, neutral hadrons carry only $\sim$11% of a jet's total energy, which can only be measured with the relatively poor resolution ($\sigma(E) \approx 0.5\sqrt{E}$) of the hadronic calorimeter (HCal). The tracker is used to measure the charged particles with much better precision, and the electromagnetic calorimeter (ECal) to measure the photons with a resolution $\sigma(E) < 0.15\sqrt{E}$, which typically carry about 64% and 24%, respectively, of the jet energy.[a] A net jet energy resolution of $\sigma(E) \approx 0.3\sqrt{E}$ is thus achievable by using the HCal only to measure the neutral hadrons.

A calorimeter designed for PFAs must be finely segmented both transversely and longitudinally for 3-dimensional shower reconstruction necessary for the separation of neutral and charged clusters, and association of the latter to corresponding tracks. In other words, we need a "tracking calorimeter". The work presented here was done by people from NIU, ANL,and SLAC.

2 Cell-counting with single charged pions

For all studies, the nominal SD geometry was used for all material volumes. For most part, plastic scintillator was used for the HCal live volume, but gaseous media, such as RPC or GEM, were also modelled for some comparisons. Only the transverse segmentation of active layers in the calorimeter were varied. The "projective" geometry refers to constant $\Delta\theta \times \Delta\phi$ segmentation, with the size in centimeters representing the rough average of a side of a square cell, at about $\theta = \frac{\pi}{4}$, in the respective section (electromagnetic or hadronic). The "non-projective" geometry refers to square cells with constant linear dimensions. Within one type of geometry, the cell size and dynamic range were varied only in the HCal, leaving the electromagnetic calorimeter (ECal) untouched at 0.25 cm^2 and analog readout.

For the digital measurements, first a single threshold corresponding to 0.25 MIP was used to decide if a cell is hit when a single charged pion of a given energy and uniform distribution in θ, ϕ was shot through the calorimeter. The left pane of Fig. 1 shows the number of cells hit (in non-projective geometries) as a function of incident energy, with the cell size as a parameter. The representative square cells range from 2 cm^2 to 16 cm^2 in size. The linearity is seen to degrade with increasing energy. The larger the cells, the more rapid the degradation. The resolution of energies measured using these curves, as well as the analog measurements using constant sampling fractions for the ECal and the HCal, are shown as functions of incident energy in the right pane of Fig. 1. Figure 2 shows the ratio of resolutions of digital measurements with up to 4 thresholds to the analog measurements of energy. We see that even with nothing more than cell-counting,the digital approach gives better resolu-

[a] For single charged pions with $p < 20$ GeV, where most of the particles in ≥ 4 jets events at $\sqrt{s} = 500$ GeV are concentrated, $\frac{\sigma(p)}{p}$ from the tracker is two orders of magnitude smaller than that from the calorimeter in the nominal SD design.[1] Even at $p = 100$ GeV, a value rarely exceeded by a charged particle in a jet, the tracker is $\sim$25 times more precise.

tions for single particle energies below 15 GeV, where most of the particles in a jet will be. Of course, unlike the traditional analog approach, results from the digital approach are expected to degrade significantly as the separation between particles decrease. However, a slightly more sophisticated scheme of using local densities of hits as weights for estimating the energy goes a long way to compensate for this. It should be noted also that the simulations used here did not account for real-life effects such as non-linearities, inefficiencies, noise, and cross-talk in signal collection and digitization. We conclude that up to 12 cm^2 cells with 3 thresholds (i.e., a 2-bit readout) is an acceptable choice.

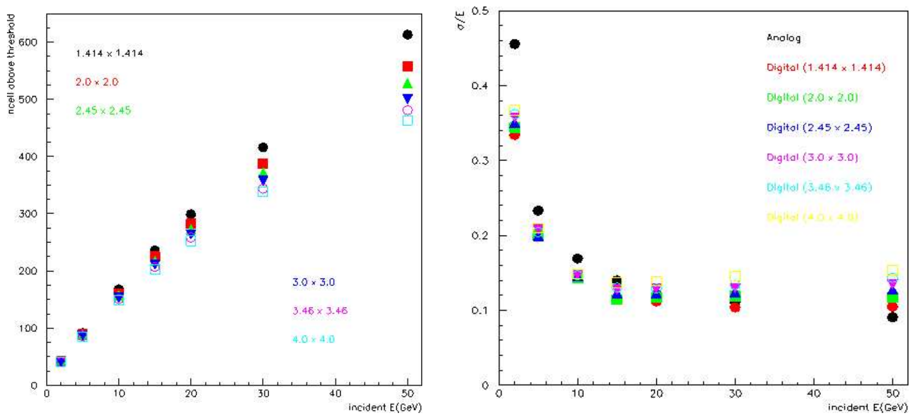

Figure 1: Left: the number of cells above a 0.25 MIP threshold as a function of the incident single π^+ energy. Shown here are square cells of areas 2 cm^2 (solid circles), 4 cm^2 (solid squares), 6 cm^2 (upward-pointing triangles), 9 cm^2 (downward-pointing triangles), 12 cm^2 (blank circles), and 16 cm^2 (blank squares). Right: fractional resolution ($\sigma(E)/E_{true}$) as a function of the incident single π^+ energy. The solid circles represent analog measurements using 9 cm^2 cells. The rest are 1-bit (i.e., a single 0.25 MIP threshold) digital measurements with the same sizes as on the left pane, with the resolution gradually worsening as the cell size increases.

3 A calorimeter-first particle-flow algorithm

This algorithm, developed by V. Zutshi of NIU, starts with density-weighted clustering in the calorimeter. The local density at the ith cell is defined as

$$d_i = k\Sigma_j R_{ij}^{-1}, \tag{1}$$

where R_{ij} is the angular distance between cells i and j, the summation is carried out over all hit cells j within some user-defined neighborhood of i, and

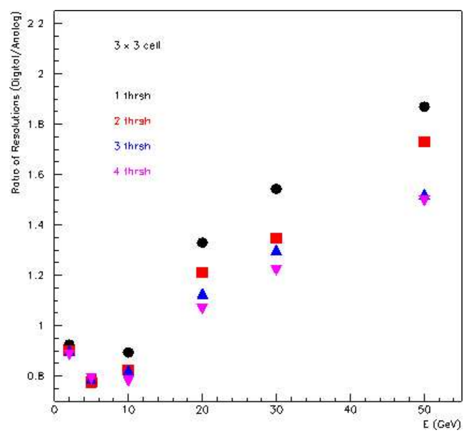

Figure 2: The digital-to-analog ratio of resolutions as a function of the incident single π^+ energy frpm 1 to 50 GeV, for 3 cm $\times$ 3 cm cells using 1 (circles), 2 (squares), 3 (upward-pointing triangles), and 4 (downward-pointing triangles) thresholds. The improvement from 3 thresholds to 4 is small.

k is a constant. The density-weighted clustering is applied in both the ECal and the HCal. The clusters are then matched to and replaced by tracks whenever possible. The clustering study is repeated with monochrmatic charged pions for 5 mm scintillators, 5 mm gas, and 1 mm gas for the active medium in the HCal. The angular width of isolated single-pion clusters show a similar trend in both energy- and density-weighted clustering. Clusters tend to be more spread out in a scintillator HCal compared to gas HCals. The resultant loss in separability can be kept in check by weighing the cells according to the local density of hits.

With density-weighted clustering applied to 1 cm^2 cells, the energy resolution for 20 GeV single charged pions in gas HCals relative to 5 mm thick scintillator HCal is 1.2 for 1 mm and 1.8 for 5 mm thick gas layers. We note, however, that the smallest scintillator cells currently under consideration are 9 cm^2 in lateral area.

The density-weighted clustering also yields excellent photon reconstruction inside jets. The reconstructed jet energy resolution using only the calorimeter and that using the above-mentioned PFA are shown in Fig. 3. The jets are those from $e^+e^- \rightarrow ZZ \rightarrow 4$ jets events at $\sqrt{s} = 500$ GeV.

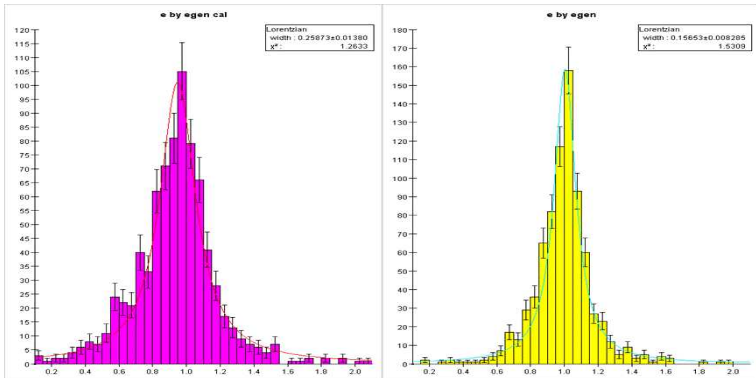

Figure 3: The measured-to-generated ratio of jet energies in $e^+e^- \to ZZ \to 4$ jets events. Left: calorimeter-only measurement using fully analog read-out. Right: PFA-based measurement using analog ECal and digital HCal read-out. The width of the Lorentzian fits are 0.259 and 0.157, respectively.

4 A track-first particle-flow algorithm

This algorithm, developed by S. Magill and S. Kuhlmann of ANL, in collaboration with N. Graf of SLAC, starts with extrapolating tracks through the calorimeter to measure the energy deposited by charged particles. The pre- and post-interaction stages are identified as MIP segments and density-weighted clusters, or "tubes" for showers, in the ECal and HCal. The iterative procedure of tube-finding attempts to afford the best E/p ratio. The average radius of these tubes are 0.1 (0.2) radian in the ECal (HCal). Either the (energy-weighted) analog or the (density-weighted) digital technique can be applied in the HCal. Next, photons are found using longitudinal and transverse profiles in a covariance matrix. Finally, the charged clusters and the photons are added to all the remaining calorimeter cells within a cone, which are attributed to neutral hadrons. The energy- and density-weighted methods are found to agree very well in shower reconstruction.

The results of this PFA for $e^+e^- \to Z \to 2$ jets events at $\sqrt{s} = 500$ GeV using both analog and digital methods in the HCal are shown in Fig. 4. They give very similar results, but either energy distribution is twice as wide as the target of 3 GeV.

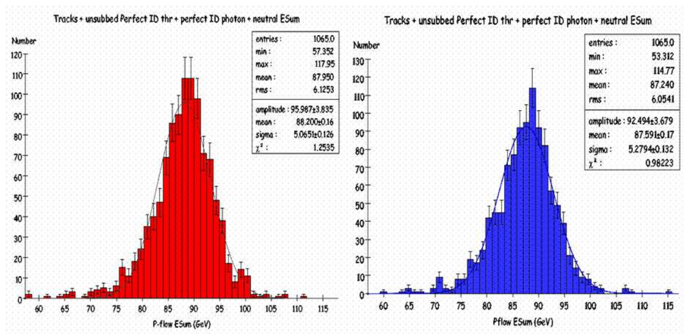

Figure 4: Dijet mass distribution of $Z \rightarrow 2$ jets events reconstructed using the track-first PFA. Left: analog HCal (energy-weighted), digital HCal (density-weighted).

5 Summary

Our studies suggest that a finely segmented digital HCal can be as good as analog, perhaps even better, especially for PFAs. We have had good success with two independent implementations of PFAs, both built from scratch. These are complete, if not optimized, and we are currently re-factoring the code for maximal unison, especially with other independent work done on extrapolation of tracks into the calorimeter taking ionization energy loss into account, and finding MIP traces in the calorimeter. Our goal is to produce a class of PFAs that are as nearly independent of specific technology and geometry choices as possible. To this end, we are trying to come up with a set of objects that will have absorbed all the detector characteristics, yet prove sufficient input for PFAs. This should greatly facilitate sharing of algorithms across regional and detector design boundaries.

6 Acknowledgement

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References

1. `http://www.slac.stanford.edu/grp/th/LCBook/detectors.pdf`, p404.