

STATUS REPORT

Project Name

Development of Particle-Flow Algorithms and Simulation Software for ILC Detector(s)

Personnel and Institution(s) requesting funding

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Project Overview

The Northern Illinois University(NIU)/Northern Illinois Center for Accelerator and Detector Development (NICADD) group is interested in calorimeter R&D for the proposed ILC [1]. We are developing, in simulation and in prototype, designs for a hadron calorimeter (HCal) optimized for jet reconstruction using particle-flow algorithms (a.k.a. “energy-flow algorithms”). Simulation/algorithm development and hardware prototyping are envisaged as the two main components of our efforts. This project addresses the first component while the second is the subject of a separate project.

An e^+e^- linear collider is a precision instrument that can elucidate Standard Model (SM) physics near the electroweak energy scale as well as discover new physics processes in that regime, should they exist. In order to fully realize the potential anticipated from a machine of this type, the detector components must be optimized, sometimes in unprecedented ways, taking full advantage of the most recent developments in technology. One such example is the hadron calorimeter which will play a key role in measuring jets from decays of heavy particles such as vector bosons, the top quark, the Higgs boson(s), etc. 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 measurement within ~ 3 GeV, or, in terms of jet energy resolution, $\sigma(E) \approx 0.3\sqrt{E}$ (E in GeV). Such precision in jet energy measurement, without a kinematically overconstrained event topology, is beyond any collider calorimeter to date. Similar precision in measurements of jet and missing momentum will be crucial for discovery and characterization of several other new physics processes as well as for precision tests of the Standard Model. Such ambitious objectives place strong demands on the performance of the calorimeters working in conjunction with the tracking system at the ILC, and requires development of new algorithms and technology.

The most promising means to achieving such unprecedented jet energy resolutions is through particle-flow algorithms (PFA). A PFA attempts to separately 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 of the HCal ($\sigma(E) \approx 0.6\sqrt{E}$). The tracker is used to measure with much better precision the charged components ($\sim 64\%$ of jet energy), and the electromagnetic calorimeter (ECal) to measure the photons with $\sigma(E) \approx 0.15\sqrt{E}$ ($\sim 24\%$ of jet energy). On average, only a small fraction of a jet's energy is carried by particles with momenta greater than 20 GeV. Momentum measurements by the tracker are at least two orders (one order) of magnitude more precise than those from the calorimeter for particles below 20 GeV (100 GeV). If all particles in a jet could be identified correctly and all the energy could be associated perfectly, then a net jet energy resolution of $\sigma(E) \approx 0.18\sqrt{E}$ would be possible. Such perfection cannot be attained in reality, but $\sigma(E) \approx 0.3\sqrt{E}$ is still deemed achievable. However, this will certainly require extensive and simultaneous optimization of detector design and tuning of algorithm parameters.

A calorimeter designed for PFAs must be finely segmented both transversely and longitudinally for 3-d shower reconstruction, separation of neutral and charged clusters, and association of the charged clusters to corresponding tracks. This requires realistic simulations of

1. parton shower evolution,
2. particle interactions in the detector volume, and
3. sensor response to energies deposited in the sensitive media.

Accurate simulation relies heavily on analysis of data from beam test of prototype modules. The detector optimization requires the simulation, visualization, and analysis packages to be highly flexible, which calls for careful design and implementation of the software itself. For the first time in the history of particle collider experiments, detector design and algorithms will evolve in a bootstrap process through iterative feedback to each other.

Very large numbers of events will have to be simulated to evaluate competing detector designs vis-a-vis ILC physics goals. Characterization of signatures arising from processes predicted by some extensions of the SM will require simultaneous coverage of broad ranges of undetermined parameters. Parametrized fast simulation programs will thus have to be developed once the algorithms have stabilized. Parametrization of PFAs will require much work, and is one of our key objectives.

Status Report

Members of NIU, ANL, SLAC, and UTA began collaborating on PFAs, simulations, and software development efforts in January, 2002. Fermilab and universities of Kansas and Iowa have since joined the effort, and links have been established with European colleagues who had been active in this area already. The results that emerged have been presented at the Calor conferences, ECFA and ACFA meetings, the American LC workshops, and at the International LC Physics and Detector Workshops.

1. Detector optimization: Toward the optimization of the HCal design, the NIU team has pioneered investigations of energy estimators based on local hit densities as alternatives to the traditional way of simply dividing the energy measured by each cell by a fixed sampling fraction to estimate its energy. The former can be used quite effectively with the so-called “digital” calorimetry, where each cell offers only a binary (1-bit) output indicating whether or not it has received at least the energy expected from a minimum ionizing particle (MIP), as foreseen for the gas-based HCal designs (RPC, GEM). But it also helps extract more precise information out of multi-bit read-out of each cell, which remains an attractive option for scintillator-based designs.

We have been studying the performance of such estimators as functions of different weighting schemes, active media, dynamic ranges of the cell energy measurement, cell size etc. Our preliminary findings suggest that with sufficiently small cells, the density-based method yields a more precise measurement of the hadron energy, i.e., fluctuations in hit (or energy) density are smaller than those in the sampled energy of a hadronic shower. Use of local hit/energy density in lieu of the deposited energy to weigh the calorimeter hits results in superior energy resolution and separation of nearby showers. Through extensive simulation and analysis, we have gained some sense of the optimal cell sizes and geometry for best charged/neutral hadron shower separation in jets within the context of some specific overall detector parameters, but we continue to work on making the simulations more realistic and improve the credibility of these results.

We will now briefly summarize our HCal optimization and algorithm development efforts. The HCal must be optimized to achieve, with due consideration of costs, benefits, and risks, the best balance between the reconstruction and energy resolution of neutral-hadron-initiated clusters in a jet, and the ability to separate them from the charged components. This is intimately related to the first step in the development of a particle-flow algorithm as described below. The elements are highly inter-related, and must be optimized simultaneously. All figures in this section were generated using GEANT4-based detector simulation programs and reconstruction algorithms developed at NIU.

HCal absorber/active media properties: The reconstruction and analysis of physics events within the Java Analysis Studio (JAS)-based software environment developed at SLAC, is flexible in the choice of absorber and active media type and thickness within the limits of the HCal volume. Our group developed a GEANT4-based detector simulation package called LCDG4 that is fully compatible with this environment, and produced many data sets spanning a range of cell sizes and event types (sin-

gle particles as well as benchmark physics processes). LCDG4 served as the official standard for all mainstream algorithm development activities in America for 2+ years until the 2005 Snowmass workshop, when it was succeeded by a more sophisticated package called SLIC.¹ Teams from NIU, ANL, SLAC, and Iowa, studied a wide variety of events simulated with LCDG4, which resulted in a set of algorithms that can be combined in a number of alternative ways in a full chain for jet reconstruction. We have been optimizing the HCal by comparing scintillator- vs. gas-based devices (e.g. RPC, GEM) as active media. Comparisons between dense materials (e.g. W) to less dense ones (e.g. Stainless Steel) as absorbers, are underway. Single-particle and jet energy resolutions will be used as performance measures. Substantial progress has been made in this direction already. The left panel of Fig. 1 shows the energy resolution as a function of single π^\pm energy, estimated using hit density weighting, for two different lateral segmentations of the scintillator option, and the proposed segmentation for a realistic RPC design. The right panel of Fig. 1 shows the density-weighted angular widths of single-hadron showers as functions of their momenta in reasonably realistic scintillator- and gas-based designs. The more realistic gas-based geometry and the scintillator design under consideration give comparable results.

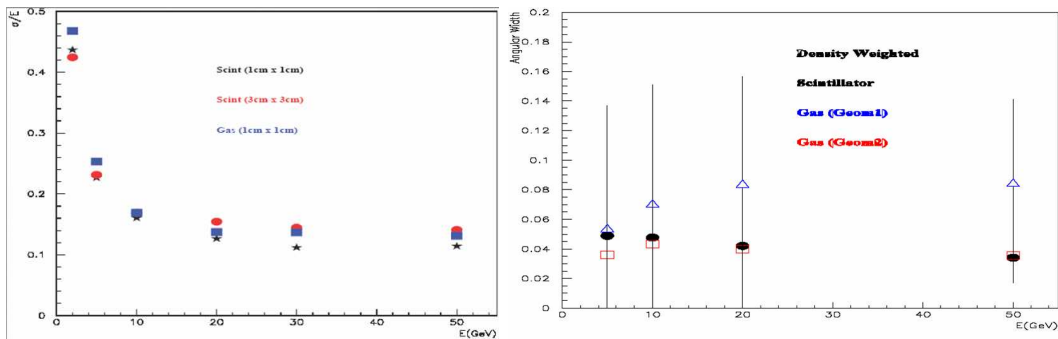


Figure 1: Comparisons of scintillator vs. gas as the HCal active medium. Left: the fractional energy resolution of single π^\pm using density-weighted clustering in scintillator and gas-based geometries. Scintillator tiles of 1 cm^2 (stars) is not a practical proposition, but it is studied to understand the dependence of energy resolution on lateral segmentation of the active layer for a given choice of technology. Even the realistic 9 cm^2 scintillator option (circles) offers a somewhat better resolution than a 1 cm^2 gas configuration (squares) under this particular weighting scheme. The two are comparable at higher energies. Right: the density-weighted angular width of single π^\pm s showers as function of their momenta, in HCals with 9 cm^2 square scintillator tiles (circles) and those with 1 cm^2 square gas-based cells (triangles for “Geom1” and squares for “Geom2”). The “Geom2” configuration is fairly close to the RPC design currently under consideration.

¹Jeremy McCormick, the primary developer of SLIC, is a former NIU graduate student who gained experience in GEANT4 while working with our group. He was on a joint NIU-SLAC appointment during the development of SLIC.

HCal transverse granularity/Longitudinal segmentation: We plan to optimize the 3-d granularity of cells for the most promising PFAs vis-a-vis the active medium technology (see the left panel of Fig. 1). The methods developed here are generalizable to different total detector concepts, namely, SiD (most compact, Si wafers for tracking and ECal), LDC (medium sized, TPC for tracking, Si wafers for ECal), and GLD (large, TPC for tracking, scintillator-based ECal). The basic performance measure here is the ability to separate showers initiated by charged and neutral hadrons - the key to any PFA. The limiting factor in the overall jet energy resolution is the confusion term arising from imperfect association due to finite granularity and misassignment. From the reconstruction algorithm's point of view, it is this term that poses the biggest challenge.

Analog vs. digital readout for the HCal: The question of optimal 3-d granularity is intimately related to that of the dynamic range of the readout, which needs to be evaluated by comparing jet energy resolutions. At the extreme, "digital" readout means a single-bit "yes/no" decision on whether or not a minimum ionizing particle (MIP) has passed through a given cell. Since such digital measurements are less susceptible to Landau and path-length fluctuations than full (12-15 bit) analog measurements, hit counting has smaller spread than energies samples in the active medium. We have shown that with small cell sizes ($< 10 \text{ cm}^2$), and for single hadrons below 20 GeV, the number of cells hit can be a more precise estimator of the particle's total energy than the sampled energy is. Since the spatial spread of a shower increases in a less-than-linear proportion to its energy, the advantage gradually disappears at higher energies. We have shown that a slightly expanded dynamic range (two bits, instead of just one) allowing multiple thresholds to classify the hit status of a cell can be effectively used account for this non-linearity.

2. Particle-flow algorithms: For the first time in calorimeter development, it is necessary to take into account the reconstruction algorithms in designing the detector(s). How good the jet energy resolution will be depends ultimately on how well the PFA is formulated and tuned. As the first step of a PFA, in 2003-2004 we implemented an algorithm that produces clusters of calorimeter cells using local densities of hits as weights. In 2005, this has been supplemented by the "directed tree" algorithm, which uses local density gradient vectors for cluster reconstruction. In both cases, the user can choose the parameters such as thresholds, neighborhood definitions etc. The clusters serve as a quasi-geometry-independent set of objects for the subsequent steps.

The directed-tree algorithm proceeds in two iterative stages. Figure 3 shows an example of the result of the first stage, which attempts to identify primary clusters in the calorimeter and secondary "satellite"s or "fragments" that have been splintered from the primaries. In the second stage, an attempt is made to correctly associate the fragments with their parent primary clusters using the angular distance (alternative association schemes are under investigation). We see in Fig. 3 that there are, as one would expect, very few fragments when the showers are well separated. An example performance of the two-stage process is shown in Fig. 4. While the parameters for the EM calorimeter

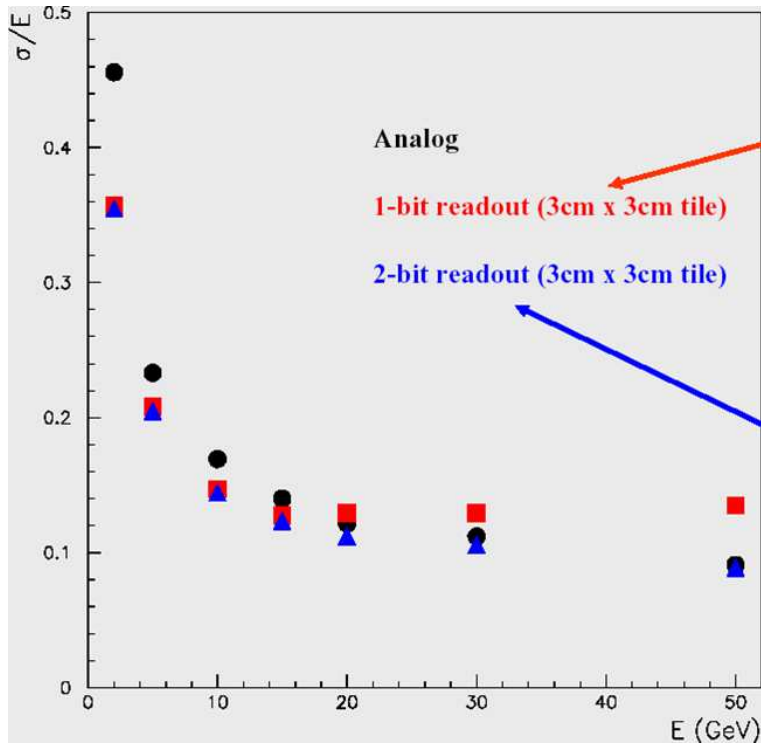


Figure 2: The fractional resolution of single π^\pm energy using full analog (circles), 1-bit digital (squares), and 2-bit digital (triangles) read-outs. We find that 3 thresholds (i.e. 2-bits) is optimal.

seem to be reasonably well-tuned, those for the hadron calorimeter need further tuning (we have just implemented the algorithm, no work has yet been done on parameter optimization.)

The second step is to extrapolate the tracks and match them to clusters whenever appropriate, so that the energies of all charged-hadron-induced clusters can be replaced with the corresponding track momenta. The third step is to identify the photons by shower-shape analysis in the ECal. The final step involves combining the track momenta with photon and neutral hadron energies to produce high-precision jet energy measurements. To facilitate portability of the algorithms across regional boundaries and detector design choices, we always try to minimize the dependence of implementations of the high-level algorithms on detector geometry details.

In addition to the clustering algorithm from NIU and alternative ones from ANL and Iowa, we already have separate preliminary codes for identification of minimum-ionizing-particle track segments (NIU, Iowa), propagating the tracks through the calorimeter taking energy loss into account (FNAL, NIU), photon reconstruction (SLAC, Kansas), and reconstruction from these of PFA jets (ANL, NIU, Iowa). We are very close to combining these pieces into fully functional and completely honest jet-finding algorithms.

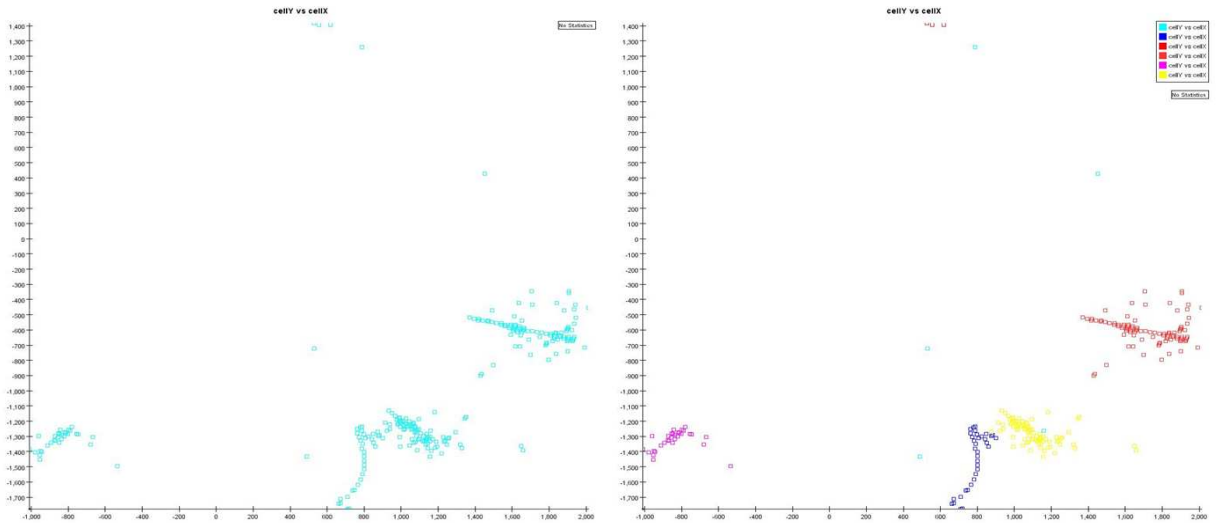


Figure 3: Cluster-finding by the “directed tree” algorithm. The left panel shows the end-view of a number of single hadrons hitting the calorimeter at the same polar but different azimuthal angles. The right panel shows how the directed-tree algorithm resolved the individual clusters.

The PFA developed at NIU, leads to full jet reconstruction by using Monte Carlo “truth” for track matching. A representative result of this is shown in Fig. 5 (this figure uses the older clustering algorithm - we are working on integrating the new algorithm into full jet reconstruction). We see that this PFA affords a 40% improvement in jet energy resolution compared to a traditional purely calorimetric measurement. For full PFA-based jet reconstruction, the current resolution on M_Z is 3.9 GeV, 30% above the target of 3 GeV. We have some ideas on how it can be improved (see plans for out-years below), although how far they will take us remains to be seen.

- 3. Detector simulation:** The NIU group has also made significant contributions to LC detector simulation software during the past 3 years. We ported and have been maintaining all of the current American software on the Linux platform. Since mid-2002, we have been processing simulation requests from several groups engaged in LC R&D, on Linux farms at NIU and Fermilab. We organized a workshop at NIU/NICADD in November, 2002, to bring the groups together, chart a plan, and set out in an organized manner. This was followed by similar workshops at SLAC in 2003, at ANL in 2004, and at U. of Colorado, Boulder, in 2006. In FY2004 we produced, with groups across the world as signatories, a preliminary “requirements document” for the simulation software suite for the ILC detector(s) [3].

We have made substantial contribution to the following simulation software projects:

Simulation of full detector concepts: We developed, in close collaboration with our colleagues at SLAC, a stand-alone GEANT4-based simulation package called LCDG4.

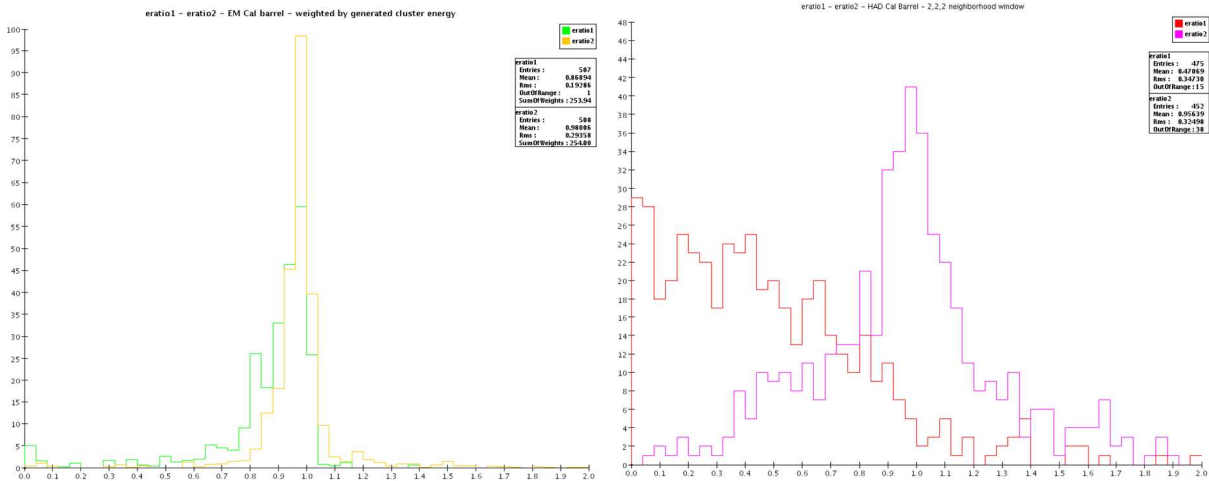


Figure 4: Left: the cluster energies reconstructed by the directed-tree algorithm normalized by their true energies in the EM calorimeter in 500 events where two charged pions of 10 GeV each hit the calorimeter face 10 cm from each other. The green (yellow) histogram shows the results after the first (second) stage. Right: the same plot for the Hadron calorimeter, with the red (magenta) histogram showing the results after the first (second) stage.

It supports run-time geometry specification, and fully complies with the model put forth by the ALCPG simulation group, and adds several useful functionalities to it[5]. It produces “raw” hit output in the globally accepted LCIO format and supports projective geometries in θ , ϕ , as well as non-projective ones with cells of constant linear dimensions. For over 2 years, LCDG4 was the official standard detector simulator for ALCPG. It has recently been succeeded by a newer, more versatile, package named “SLIC”.

Simulation of test-beam prototype modules: As members of the CALICE collaboration (Calorimeter for the LInear Collider with Electrons[2]), and in active cooperation with our European colleagues, we produced a GEANT4-based simulator for the detector prototype module that is expected to be exposed to test beams over a period of 3-4 years starting in mid-2006. This program, called “TBMokka” is built on an alternative simulation framework called “Mokka”, developed independently by our European colleagues. Our involvement in the development of TBMokka gradually came to an end when the student who was working on it moved to SLAC to subsequently become the primary developer of SLIC.

Simulation of the signal extraction process following energy deposition: In another major endeavor, we have designed and implemented the first version of a package, called “DigiSim”, to simulate the conversion of energy deposits in the active media (simulated by GEANT4) to electronic read-outs[7]. This package offers the user a simple, flexible, extensible, and standard way for parametric fast simulation of the effects of thresholds, noise, cross-talk, inefficiencies, attenuation, and timing, that are involved

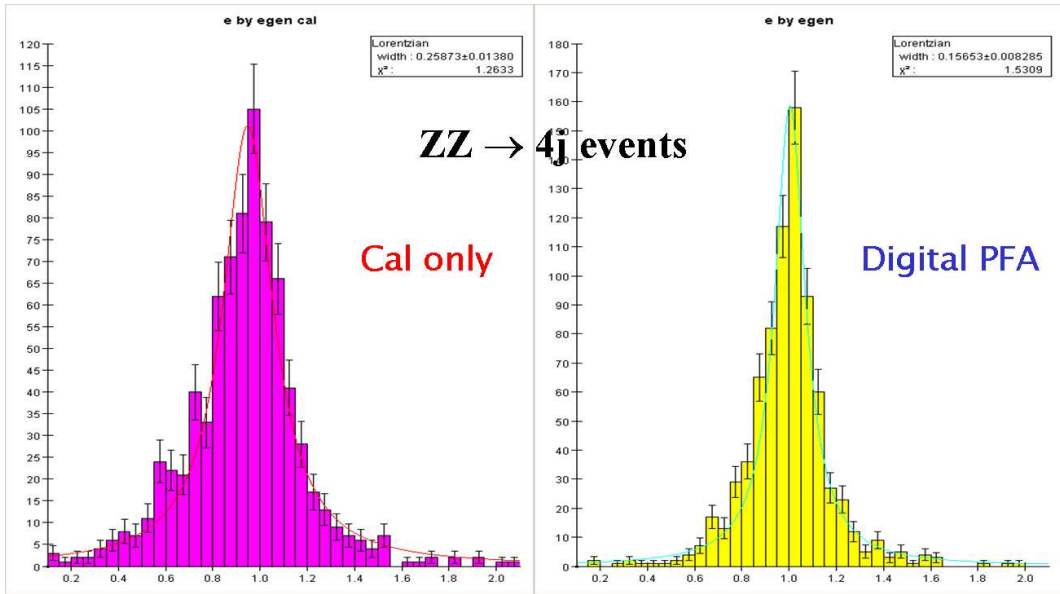


Figure 5: The estimated jet energy normalized to the true energy in $e^+e^- \rightarrow ZZ \rightarrow 4$ jets events at $\sqrt{s} = 500$ GeV events using purely calorimetric measurement (left) and the PFA developed at NIU (right). The calorimetric estimation uses traditional analog energy measurement, while the PFA uses semi-digital (2-bit) measurement in this case. The PFA can be used in analog mode as well. No kinematic fitting based on event topology is used in either measurement.

in signal collection, propagation, and conversion to persistable form (digitization). The process consists of reading the simulated energy deposits in cells, applying any user-defined transfer function, and finally writing out the digitized hits in the same “raw data” format as for real data. The transfer function can be encoded in one or more sequential “modifier”s. While most modifiers will operate on single cells, those that correlate multiple cells (e.g. cross-talk) are geometry-dependent. DigiSim reads the detector geometry and makes the neighborhood definition available to the user in a transparent way. As a result of inefficiencies, some cells that received energy deposits from a particle will not appear in the collection of digitized hits, while the opposite will happen due to cross-talk. DigiSim keeps a complete account of these mappings so as to allow the user to trace the effects of DigiSim and the performance of his/her algorithms. A supplemental ADC-to-GeV conversion step, which would correspond to applying the calibration constants in real data, is supplied as well. This allows reconstruction and analysis codes written for “ideal” simulated hits (the GEANT4 output) to be run essentially unchanged on the post-digitization hits through an interface that is inherited from the older version without DigiSim.² To estimate how the above-mentioned effects affect

²Only minor modifications are needed to account for the fact that the mapping between the two sets may not be exactly one-to-one due to the detector inefficiencies and cross-talk, as explained in the text.

a given algorithm, one would then simply compare the results obtained using a realistic set of values for the detector effects to those obtained using an “identity” modifier. The identity modifier thus allows DigiSim to be permanently integrated into the simulation chain. A simplified class diagram of DigiSim is shown in Fig. 6, while Fig. 7 shows the scheme for transforming the list of GEANT4 energy deposits to digitized “raw hits”. Although so far we have only tested DigiSim for the calorimeter, it can be used for other subdetectors just as well. Applications to central tracking and muon system are anticipated in the near future.³

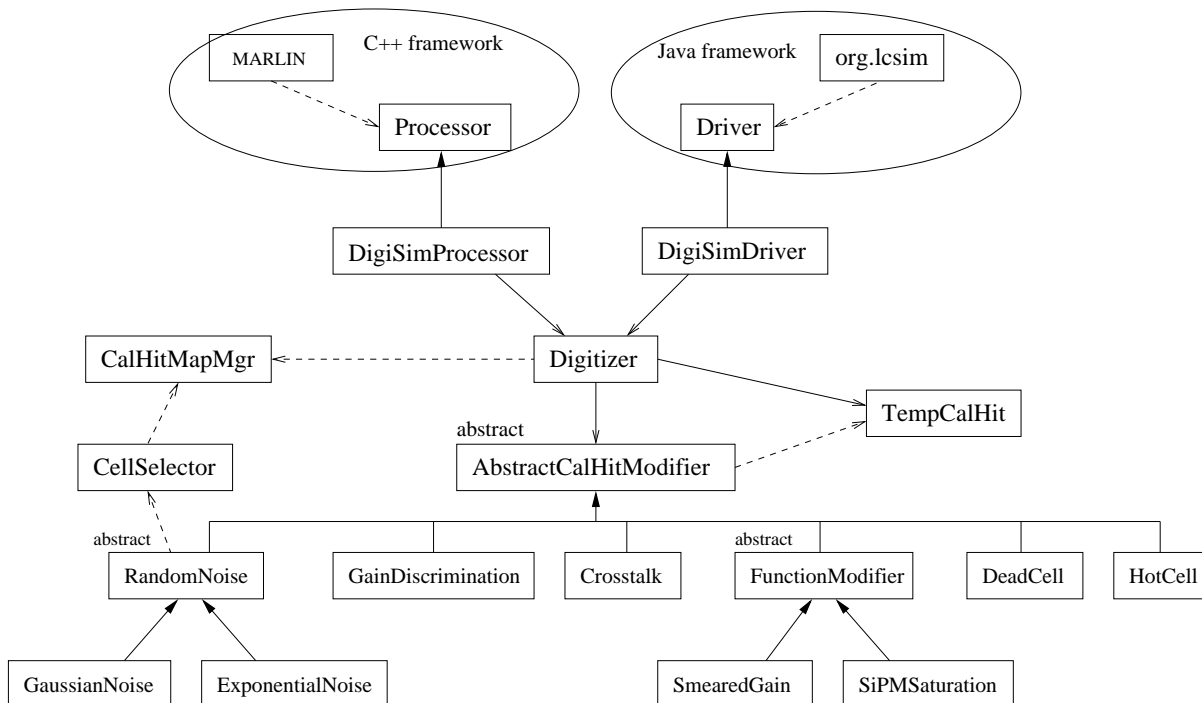


Figure 6: A simplified class diagram of DigiSim. Full arrows represent inheritance. Hollow arrows represent containment (solid) or use (dashed) relationships. New modifiers can be added easily using the existing ones as examples. Only the part dealing with calorimeter hits is shown in this example.

Here are some of the salient features of DigiSim:

- DigiSim adheres to the LCIO event data model, which is now universally accepted by the ILC detector community. As a result, it can be used on all the different detector concepts - SiD, LDC, GLD, as well as test beam prototypes - even if the GEANT4 simulation is done by different programs, as is presently the case.⁴

³We have even received an enquiry for possible use of DigiSim in a particle astrophysics experiment.

⁴The official GEANT4-based simulation programs are: SLIC for SiD, Mokka for LDC, Jupiter for GLD, and

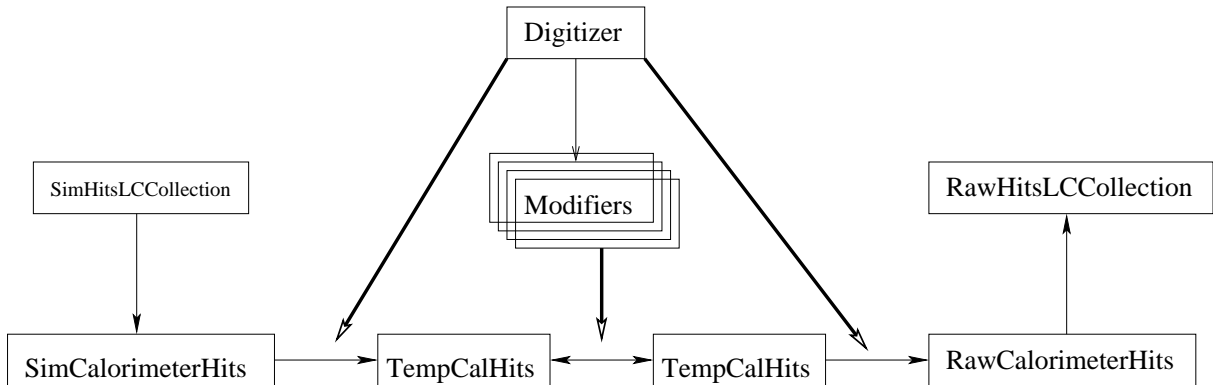


Figure 7: The DigiSim chain in (the calorimeter part of) an event loop. Similar chains can be added to other detector components as well.

- DigiSim has been implemented in both Java and C++. The Java implementation is designed for use in the `org.lcsim` environment adopted in the Americas, while the C++ implementation works within the `Marlin` framework, which is the official standard in Europe.
- DigiSim reads all its parameters from intuitive ASCII “steering” files that are read at run time. Thus, the user does not have to recompile his/her reconstruction/analysis code to change a DigiSim parameter.
- The steering files have the same format in the Java and C++ implementations - a given steering file will produce the same effect in `org.lcsim` and in `Marlin`.
- DigiSim can be used either in a stand-alone mode to produce a persistent output, or as an on-the-fly preprocessor to the reconstruction program. In stand-alone mode, it produces output in the same format as that envisaged for the real data (except, of course, the simulation output also contains the “Monte Carlo truth”, which the real data does not). Since DigiSim is fast compared to most pattern-recognition algorithms used in event reconstruction, the on-the-fly mode is suitable when one does not wish to write large intermediate output files on disk, e.g. when one is changing the DigiSim parameters from one run to another. The stand-alone mode may be the better choice when a stable set of parameters has been agreed upon for sharing between multiple users.

An example of some of the effects simulated using DigiSim is shown in Fig. 8. Distribution functions of parameters such as efficiencies, cross-talk etc. may be expressed in either continuous (analytic) or discrete (histogram) form. Since particle-flow algorithms must deal with individual showers in a jet, they are expected to be more sensitive to systematic deviations at the single hit level than traditional jet-finding algorithms, where a single post-reconstruction scaling often suffices to bring Monte Carlo in satisfactory

TBMokka for the CALICE test beam prototype.

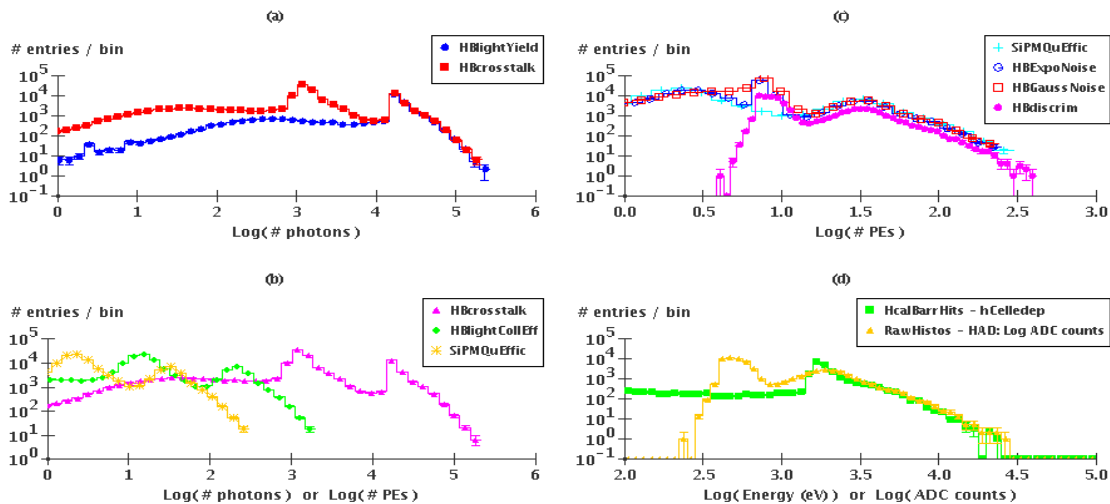


Figure 8: The effect of DigiSim on energy deposits by 10 GeV muons through a scintillator-based hadron calorimeter: (a) Scintillation light yield before (blue) and after (red) modeling of cross-talk, (b) After cross-talk simulation (magenta), effects of the geometric acceptance (green) and quantum efficiency (yellow) of the photodetector are simulated, (c) Effects of exponential (indigo) and Gaussian (red) noise and discriminator (magenta), (d) Comparison between the particle energy deposited in elements of the active medium (green) vs. “raw” hits as expected in real data (yellow). In all plots, both the abscissa and ordinate are in shown in log scale.

agreement with data. Therefore, any high claim to the performance of such an algorithm must be substantiated with a realistic accounting of the above-mentioned detector effects. Thus, DigiSim plays a vital role, and has been warmly welcomed by the user community worldwide. After a due certification process, the Java implementation has recently been released in a production version. The American ILC detector simulation group has ratified DigiSim as an integral part of its simulation chain. We hope that it will be adopted in Europe as well once some features still missing in the C++ implementation are incorporated.⁵ We expect DigiSim to be used extensively in the near future in the simulation of both the various test-beam prototypes and full-detector designs.

To summarize, we have met all of the objectives for FY2005 put forth in our original proposal, namely completion of DigiSim and a first version of a class of particle-flow algorithms that can work with both analog and digital readouts. We have also continued to process detector simulation requests from the entire ILC community. All of our code is publicly available through the official repository of the ALCPG simulation and algorithms working group. Extensive documentation is available at our web site[1]. Additional information and interactive

⁵This is not entirely trivial since there are fundamental differences in the ways detector geometries are handled by the simulation/analysis frameworks in the Americas and in Europe.

help are provided on request.

The steady progress that we have achieved so far has been made possible by funding received for this purpose during the past 4 fiscal years from DOE and NSF, in addition to generous, but less specific, funding from the Department of Education. In FY 2002 we received \$45K from the DOE under its Advanced Detector Research program. An exploratory grant of \$8.5K was awarded by the NSF in FY2003. In FY2004 and FY2005 we were awarded \$35K and \$44.5K, respectively, through LCDRD for our simulation software and algorithm development activities.

Activities outlined in this proposal are synergistic with the proposals for hardware prototyping of different technology choices. We will continue to remain in close contact with the groups involved in hardware development for the ECal and the HCal.

FY2006 Project Activities and Deliverables

Experience gained during the past year have led to recognition of new issues and some re-arrangement of priorities. In FY2006 we will integrate DigiSim into our reconstruction algorithms and study the effects of various detector imperfections on algorithm performance. Although DigiSim is ready for use, some improvements are planned in order to further enhance its flexibility, ability to keep track of history (e.g. in the stand-alone mode, to record in the output exactly what transformations have been applied), and error-reporting capabilities.

On the reconstruction algorithm development front, we will continue to improve pattern-recognition techniques, optimize the parameters of the algorithms, and compare simulations of different options for active medium technology, absorber material, and geometry (segmentation). In particular, we need to understand how the performance of an algorithm depends on the radial segmentation of the HCal vis-a-vis its thickness in terms of interaction lengths. It is extremely important to strike the right balance between the thickness and the number of layers since the geometric thickness of the calorimeter is severely constrained by considerations of the calorimeter and the magnet costs - so much so that the containment of hadronic showers is a matter of concern in the SiD design.

Also, there are several issues that need to be addressed to fully assess the limit of PFA performance:

- Much work is needed to minimize incorrect associations of “fragment” clusters: significant errors can result when a fragment originating from a neutral particle is incorrectly associated with a charged particle, or vice-versa.
- An important action item is to improve the propagation of charged particle tracks through the calorimeter using progressive fitting techniques that take into account the energy loss and possible scattering. We have started working on this with C. Milstene of Fermilab.
- The calorimeter designs currently on the table are not inherently compensating. Separate determination of response to electromagnetic and hadronic interactions in different sections of the calorimeter is high on our list of priorities. The dependence of these

responses on the polar angle needs to be studied as well. Since all cells in a given section have fixed linear, rather than angular, dimensions, the difference may be significant.

- Another important issue is the differences in energy deposition patterns between different types of neutral hadrons, e.g. n , \bar{n} , and K_L^0 . For a given kinetic energy, these particles will deposit different amounts of visible energies in the calorimeter. We need to investigate how much we may stand to gain by identifying those differences.

We expect to accumulate a substantial volume of test beam data by the end of FY2006. Careful analysis of those will be critical for tuning our simulation and reconstruction programs. A significant part of our efforts will have to be devoted to this.

Comprehensive studies of critical physics processes will have to be carried out in order to understand the impact of the calorimeter performance on the physics program of the Linear Collider. These studies will employ both the analog and digital versions of our PFAs. We plan to continue with further development of PFA-based jet-reconstruction and a partial assessment of physics reach vs calorimeter performance for the ILC.

Although we plan to start addressing most of the above issues during FY2006, considering the available resources, it is not realistic to expect to complete them all within the span of one year. We intend to report on tangible progress by the end of FY2006 and hope to come to reasonable conclusions on the key issues by the end of FY2007.

FY2007 Project Activities and Deliverables

In FY2007, we will try to complete the studies listed above. We will also complete the physics assessment with a clear statement on the desirability of a digital or analog option for the hadronic calorimeter. This will, of course, depend to a large extent on the test beam experience as well. If all goes well, we will also start the development of parameterized simulations of the particle-flow algorithms. The technology and geometry are expected to have been narrowed down by that time, thus setting the stage for such parametrized fast simulation for extensive physics studies. By the end of the third year we expect to produce, in collaboration with other groups, a fast simulation program based on PFAs. In addition, extensive benchmarking of critical physics processes, as well as evolution of pattern-recognition and reconstruction algorithms will continue.

Budget justification:

The above activities will be carried out by NICADD staff members. Specifically, one Research Scientist has been working full time on the proposed software R&D, and is expected to continue likewise through the next 2 years. We request that half of his salary be borne by the grant in question.

Communication of progress and exchange of ideas through international workshops and conferences will be crucial for our endeavor to have a global impact. Based on the FY2005 experience, we estimate five domestic and two international trips per year. A part of these travel expenses should be covered as well.

Fringe benefits to personnel at NIU’s mandated rate of 52% of salary, and indirect costs at the off-site rate of 26% (instead of the usual 45%, since the requested personnel will work in offices at Fermilab allocated specifically for ILC R& D) are included in the requested amount.

Two-year budget, in then-year K\$

Institution: Northern Illinois University

Item	FY2006	FY2007	Total
Research Scientist (0.5 FTE)	28.32	29.18	57.5
Graduate Students	0	0	0
Undergraduate Students	0	0	0
Total Salaries and Wages	28.32	29.18	57.5
Fringe Benefits	14.73	15.17	29.9
Total Salaries, Wages and Fringe Benefits	43.05	44.35	87.4
Equipment	0	0	0
Travel	10.00	10.30	20.3
Materials and Supplies	0	0	0
Other direct costs	0	0	0
Total direct costs	53.05	54.64	107.7
Indirect costs (26% of non-equipment)	13.79	14.21	28.0
Total direct and indirect costs	66.84	68.85	135.7

References

- [1] The NICADD web page, presentations, documents: <http://nicadd.niu.edu/> and <http://nicadd.niu.edu/research/lcd/>,
- [2] <http://polywww.in2p3.fr/flc/calice.html>,
- [3] The ILC detector Simulation Requirements document: <http://forum.linearcollider.org/> → “Full Simulations” → “Simulation Requirements Document”.
- [4] <http://nicadd.niu.edu/~jeremy/lcd/simreq/>,
- [5] <http://nicadd.niu.edu/lcdg4/>,
- [6] <http://nicadd.niu.edu/~jeremy/lcd/tbeam/>,
- [7] <http://nicadd.niu.edu/digisim/>,