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Linear Collider Detector Calorimetry

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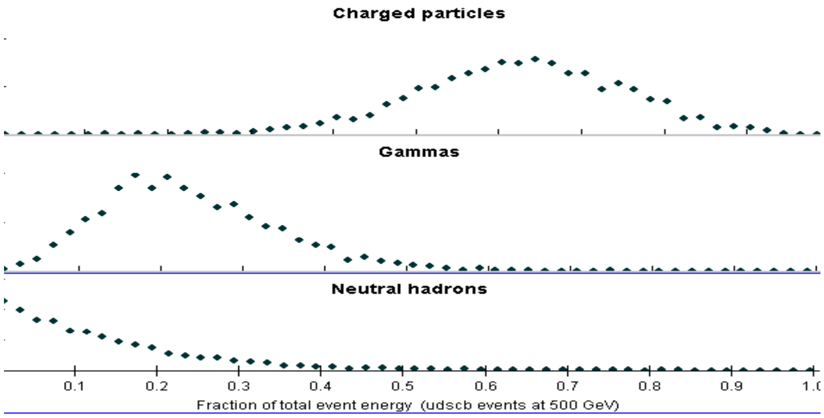
Abstract

We describe the requirements for calorimetry at a high-energy linear collider. The energy response linearity and resolution of two baseline detectors is presented and we show that these detectors can isolate individual photons.

Introduction

The next generation high-energy e+e- linear collider will take us into a new regime just recently entered at LEPII. In this regime several high mass particle states will occur which will present themselves in a detector as hadronic jets and the detectors must enable us to reconstruct these particles from the jets. Although these high mass states will have leptonic decay modes the great majority of interesting physics processes will have at least one jet. Further, it is probable that all interesting measurements at the linear collider will be statistically limited with the exception of the measurement of alpha-s, the QCD coupling constant. Thus, it will be essential to make good measurements of jet events.

Modern tracking is already up to this challenge and should easily be able to separate and accurately measure individual charged particles in jets. The challenge will be for calorimetry to do the same for the neutral particles. The following plot shows the fraction of the total energy for different categories of particles in ee -> qq (q = u, d, s, c, or b) events at 500 GeV. The plots for other processes are quite similar. On average, we see that, two-thirds of the energy in jets will appear as charged particles that will be well measured by tracking if they lie where there is tracker coverage. The plots also show that the remaining neutral particle energy is roughly equally divided between gammas and hadrons. Although not shown here, there is also a significant contribution from neutrinos in a small fraction of top quark jets. Also, the plots show that there is a wide variation from these averages with events with as much as half the energy in neutral hadrons or gammas.



The ideal detector will be able to reconstruct the high mass jet-producing particle by reconstructing each individual particle in the jet. Can calorimetry meet this challenge for the neutral particles? The situation regarding gammas and neutral hadrons, the two categories of neutrals, is somewhat different and we will discuss each case.

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Comparison of gamma and hadron showers

When photons shower in matter the photon penetrates (without interacting) to some depth determined by the radiation length of the material. It then interacts to begin a cascade of electrons and positrons that produces measurable ionization. The shower is compact in the transverse direction with the shower diameter characterized by the Moliere radius for the material. Even in a finely granulated calorimeter, all the hit cells will be topologically connected as neighbors and the overall cigar shape will be common to all photon showers.

Although very different than gammas, neutral hadrons shower in a manner identical to charged hadrons. The only difference is that charged hadrons have a minimum ionizing track through the calorimeter leading to the first interaction. The interaction length of the material characterizes the distance to the first hadronic interaction and that distance is of order ten times longer than the radiation length that characterizes the interaction distance for a photon. This means that photon showers will tend to have initiated and terminated at a shallower depth than where hadron showers begin. Thus, a standard calorimeter begins with a section optimized for photons, the EM Cal, followed by the Had Cal. Hadronic showers tend to be very diffuse, widespread and irregular in shape compared to photon showers. Often, due to the production of neutrons, different parts of a hadron shower are topologically disconnected by any ionization trail.

Putting it all together, the requirements for a calorimeter, including its acquisition system and reconstruction software, can be stated as follows. The photon showers and the neutral hadron showers must be identified and isolated and the energy they deposit must be measured as precisely as possible. As we will show below identifying and isolating photon showers appears well within reach. The main limitation for photons will be an energy resolution of about 15% for a sampling detector. We have not yet studied the problem of neutral hadronic showers but the approach and the challenges are already clear. The aim will be to extend charged tracks from the tracker into the calorimeter and follow their ionization trail to their showers and then attempt to identify the elements of the shower for each charged hadron. Once the photon showers and the charged hadron showers are identified then what remains are the neutral hadron showers. (We have neglected to discuss the occasional electron and muon here but their signatures make them easily identifiable and separable.)

However, due to the wide dispersal of hadronic showers they will tend to overlap making separation of different hadronic showers difficult. Also, the fact that neutrons create topologically disconnected shower fragments makes it difficult to identify all the showering due to charged hadrons. One possible approach is to build a very highly pixilated calorimeter with fine granularity, each pixel recording a simple “hit or not hit”. The fine granularity may allow for the development of pattern recognition algorithms that minimize the overlap and separation problems. In this scenario, referred to as “digital calorimetry”, energy resolution somewhat worse than that of sampled photon showers might be attainable. (A variation on this approach is for each cell to have a two or three bit ADC to count the number of minimum ionizing particles but Landau fluctuations will probably defeat this idea.) To fully determine whether this approach is technically feasible and economically justified is an extensive project yet to be fully studied. If it is not a viable approach much study will still be required to optimize the less ideal approach of a more traditional sampling hadronic calorimeter. Another alternative is that a new approach is proposed.

Results of studies of the L and S detector

The North American Linear Collider Detector Study Group has established two baseline detector designs for comparison. Although these are complete detectors in the sense of containing tracking, vertexing, etc we will report here only on studies of the calorimeters. The tables below describe the calorimeters.

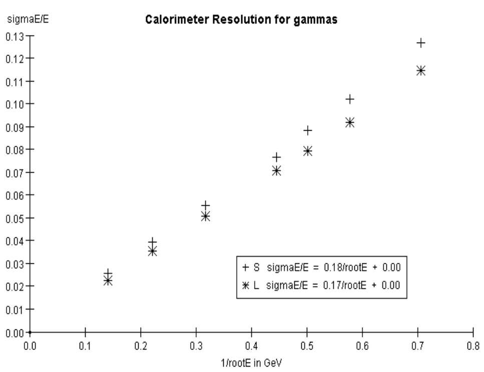
S Detector	EM	Had
Act mat/thick cm	Si/0.04	Polystyrene/1.0
Rad mat/thick cm	W /0.25	Stainless_steel/2.0
#Rad len/#Int len	~20/~0.8	~40/~4
Samp Frac/ e/h	2.19% /1.40	6.99% /1.10
Tower	Projective	Projective
#layers	30	34
#cells in θ/φ	840/1680	600/1200
Inner rad/Outer z	142/210 cm	153/312 cm
Coil location	Outside EM	Outside Had

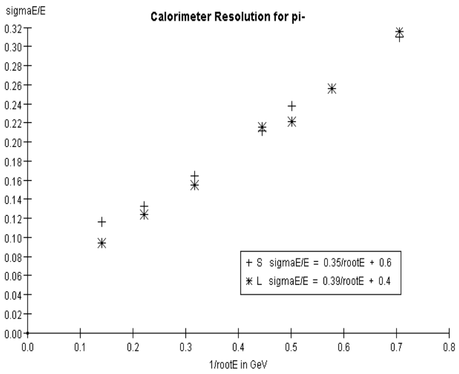
L Detector	EM	Had
Act mat/thick cm	Polystyrene/0.1	Polystyrene/0.2
Rad mat/thick cm	Pb/0.4	Pb/0.8
#Rad len/#Int len.	~30/~0.9	~200/~6
Samp Frac/ e/h	2.66% /1.11	2.66% /1.11
Tower	Projective	Projective
#layers	40	120
#cells in θ/φ	150/300	50/100
Inner rad/Outer z	196/322 cm	233/466 cm
Coil location	Outside EM	Outside Had

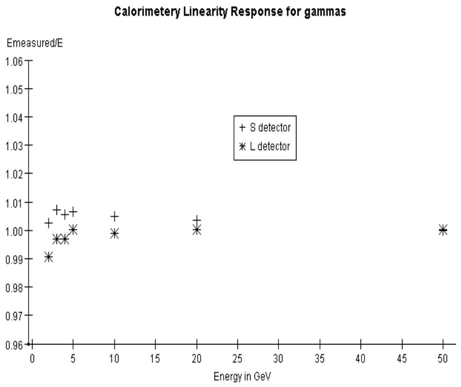
The L detector contains a large TPC in a 3 Tesla solenoidal field and the S detector contains a compact five layer Silicon Tracker with a 5 Tesla field. Both contain a 5-layer pixel vertex detector. It should be clear from the tables that all four calorimeters are sampling detectors. With a sampling detector the readout from the active material has to be scaled by a sampling fraction to get the correct energy reading. In the case of hadronic showers an additional factor often referred to as e/h describes the ratio of measured ionization energy loss between photon and hadronic showers. For the same energy input a hadronic shower deposits less ionization energy due to the energy lost in neutrons and nuclear binding energy. We have assumed that the type of each shower can be correctly identified and we have measured and applied sampling fractions and e/h factors accordingly in the studies.

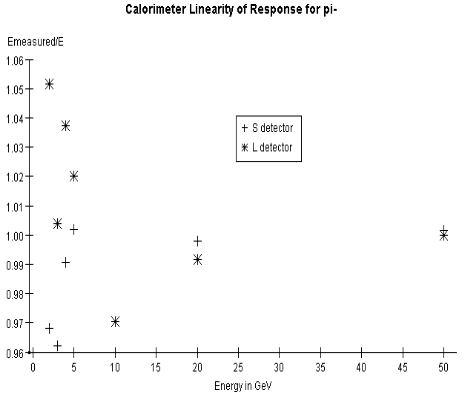
For the detector simulation we used the program GISMO. EGS is used for electromagnetic showering and Gheisha is used for hadronic showering simulation. Our initial results for the hadronic showering did not seem reasonable with energy linearity variations of 20% and resolutions of 0.5/rootE. We embarked on a detailed study to understand the hadronic showering. We believe we have discovered and corrected two errors In the GISMO/Gheisha interface and five errors in Gheisha and we believe there are still more errors in Gheisha which we are still studying. An example of a rather extreme error in Gheisha is 1 GeV antiprotons on some materials result in as much as 5GeV of ionization energy deposited. Several of the Gheisha errors involved non-conservation of energy and there was a serious error in the angular distribution of the interaction products in some interactions. We were initially skeptical of our discovery of problems in Gheisha since it has been used for many years but we are now convinced there are important problems. We have also received reports that other groups have found similar problems.

The standard resolution and linearity plots for the calorimeters are shown below. For each energy data point 5000 single particle events were simulated. The single particle in each event originated at the IP location and had its initial direction at right angle to the beam line. The azimuthal angle was chosen randomly for each particle. We see that both detectors yield similar results for both particle types.

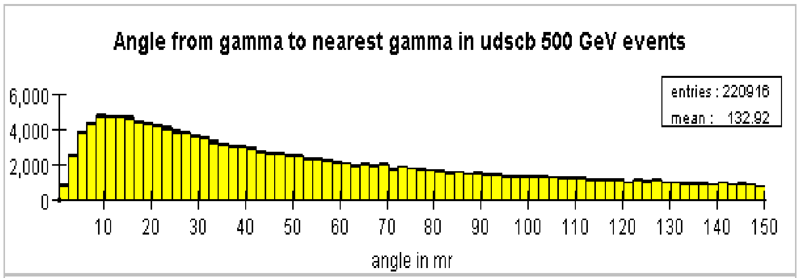


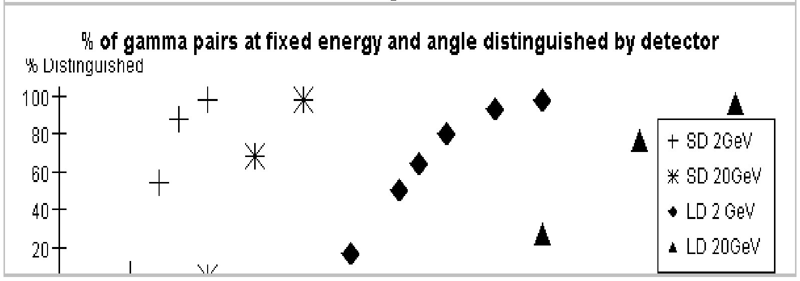






As stated above the ideal calorimeter will be able to isolate neutral particle showers. We have studied the capability of the S and L detectors to isolate photon showers. The following plots show the results.





The upper plot illustrates the environment in 500 GeV ee->qq (q=u, d, s, c or b) events with a boost less than 0.2c to eliminate forward events due to ISR down to the Z pole. For each final state photon in the event the nearest photon neighbor is found and the angular separation between the pair is determined. The plot shows the distribution of this angle for each photon in the events.

The lower plot presents the results of measurements of the S and L detector. Special event sets were prepared where each event contains a single pair of gammas with the same angular separation and both gammas have the same energy. The direction of the pair was approximately at right angle to the beam line and random in azimuth. Two energies, 2 and 20 GeV were studied and a range of angular separations was chosen. For each energy chosen and for each angular separation chosen the percentage of shower pairs in that data set that were separated by a detector was measured. The points in the plot show these percentages as a function of angular separation. (The angular separation axis scale on the upper plot should also be used with the lower plot.) The hit-clustering algorithm used simply grouped together all hits that were topological neighbors. It was found in both detectors that almost every photon deposited nearly all of its energy in a single cluster. In other words, the gamma showers did not fragment into topologically separate clusters with this simple algorithm.

The plots show trends that would be expected. Both detectors can separate 2 GeV showers better than they can separate 20 GeV showers. The S detector with its finer granularity can separate showers down to smaller angles than can the L detector. Furthermore, comparing both upper and lower plots we see that both detectors can separate a high percentage of photons in the physics signal events since the upper plot has a very long tail not shown.

We have not presented quantitative results on separation rates since further refinements in progress will certainly increase the abilities of both detectors. We will simply note a few further results we have obtained without presenting supporting plots. An electromagnetic shower, in addition to being a compact cigar shaped object, also has a decreasing energy density from its longitudinal axis out to its perimeter. By setting a minimum hit energy threshold in the clustering algorithm, thus picking up only the core of the shower, the angular separation results can be improved significantly using the simple clustering algorithm. Also, increasing the granularity of both detectors improves the separation characteristics.

Summary and conclusion

We have described the requirements for calorimetry at a high-energy linear collider. We believe the goal of the calorimeters should be able to isolate the showers of individual neutral final state particles and measure their energy with adequate accuracy to enable reconstruction of hadronic jets into their underlying high mass parent particle. We have presented studies of two detector designs with sampling EM and Hadronic calorimeters. We have shown they are capable of energy resolutions of below 0.20/rootE for the EM calorimeter and below 0.40/rootE for the Hadronic calorimeter. We have shown that identification of individual gammas is quite feasible. We have not yet studied their ability to isolate neutral hadrons but it is clear this is both very important and very challenging.

We believe there are three areas where significant effort is required to design the best possible calorimeters. First, establishing an accurate hadronic shower simulation program that has been compared with beam test results and data from existing detectors. Second, development of sophisticated software tools for such things as cluster building from hits and track-cluster association to identify charged hadronic clusters. Third, extensive optimization and cost/benefit studies of materials, designs and realistic electronic readout systems are required.

Acknowledgements

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