Particle Flow Calorimetry at ILC Experiment

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Most of the important physics processes to be studied in the International Linear Collider (ILC) experiment have multi-jets in the final states. In order to achieve best attainable jet energy resolution, a so-called Particle Flow Algorithm (PFA) will be employed, and there is a rather wide consensus that PFA derives the overall ILC detector design. Three out of four are proposing a detector which is optimized for the PFA, though the technical realization is quite different. In this paper, the PFAs currently being developed and their performances are reviewed.

1 Introduction

The International Linear Collider (ILC) is a future energy-frontier electron-positron collider currently being designed by a world-wide collaboration[2]. The physics goal of the ILC experiment ranges over a wide variety of processes in a wide energy region of center of mass energy[3, 4]. Most of the important physics processes to be studied in the ILC experiment have multi-jets in the final states, and therefore precise jet energy reconstruction plays an important role to the ILC physics. One of the performance goal required to the ILC detector is that two-jets invariant mass resolution is comparable with the natural widths of W and Z ($\sim$ 2GeV) for their separation in hadronic final states. A jet energy resolution of $\sigma_E/E = \alpha/\sqrt{E}$ leads to a two-jets mass resolution of $\sigma_M/M = \alpha/\sqrt{E_{jet}}$ where E_{jet} is the energy of the two-jets system. At the ILC, the E_{jet} is typically $\sim$ 150 GeV, suggesting the target resolution of $\sigma_E/E = 30\%/\sqrt{E(GeV)}$[2] which is a factor two better than the best jet energy resolution achieved at LEP, $\sigma_E/E = 60\%(1+|\cos\theta|)/\sqrt{E(GeV)}$[5]. Study on measurements of the Higgs mass in the four jet channel, $e^+e^- \rightarrow ZH \rightarrow q\bar{q}b\bar{b}$, shows significant benefit from such very high jet energy resolution[6]. Larger statistics than $e^+e^- \rightarrow ZH \rightarrow l^+l^-b\bar{b}$ channel can be expected for this channel as long as the Higgs mass is small enough that the branching ratio to b-quarks pairs is large enough. The study was performed by assuming a Standard Model Higgs with a mass of 120 GeV and an integrated luminosity of 500 fb^{-1}. Figure 1 shows the invariant mass of the two b-quark jets for $\sigma_E/E = 30\%/\sqrt{E(GeV)}$ (left) and $\sigma_E/E = 60\%/\sqrt{E(GeV)}$ (right). The error in the Higgs mass improves by a factor 1.2, corresponding to an equivalent 40% luminosity gain. The importance of achieving very high jet energy resolution in ILC detectors are also shown by studies on several other physics processes[2].

2 Particle Flow Algorithm

Achieving a jet energy resolution of $\sigma_E/E = 30\%/\sqrt{E(GeV)}$ is rather technical challenge for ILC detectors. Such energy resolution could be achieved by a combination of highly efficient and nearly hermetic tracking system with a very fine transverse and longitudinal segmented calorimeter. Since the momentum resolution for the charged particle measured by tracking system is much better than the energy resolution of calorimeters, the best jet

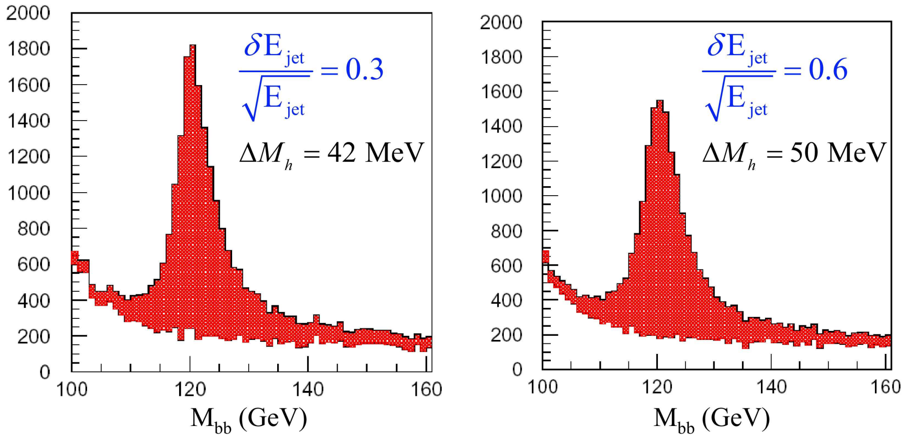


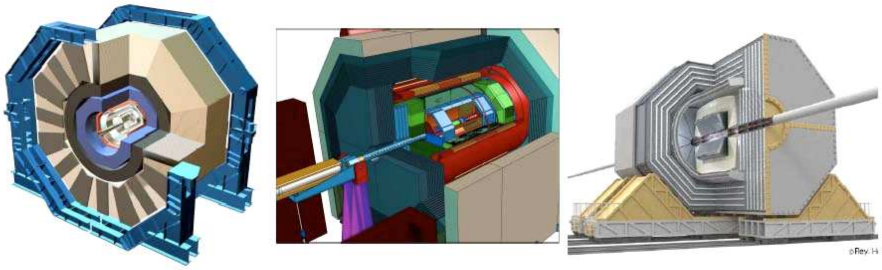
Figure 1: Higgs two-jet invariant mass for $e^+e^- \to ZH \to q\bar{q}b\bar{b}$ channel for $\sigma_E/E = 30\%/\sqrt{E(GeV)}$ (left) and $\sigma_E/E = 60\%/\sqrt{E(GeV)}$ (right). The error in the Higgs mass improves by a factor 1.2, corresponding to an equivalent 40% luminosity gain.

energy resolution is obtained by reconstructing momenta of individual particles avoiding double counting among trackers and calorimeters; charged particles, whose energy fraction in a jet is about 60%, are measured by trackers, photons, whose energy fraction is about 30%, are measured by electromagnetic calorimeter (ECAL) and neutral hadrons, which carry the rest of energy, are measured by both ECAL and hadron calorimeter (HCAL). To be more precisely, the total energy of an event E_{Total} is calculated as follows:

$$E_{Total} = P_e + P_\mu + P_{ChargedHadron} + E_\gamma + E_{NeutralHadron}, \tag{1}$$

where P_e, P_μ and $P_{ChargedHadron}$ are momentum of the electron, muon and charged hadron measured by the tracking system, respectively, and, E_γ and $E_{NeutralHadron}$ are energy of the γ and neutral hadron measured by the calorimeters. This is known as a Particle Flow Algorithm (PFA) and it is widely believed that PFA is the most promising way to achieve a jet energy resolution of $\sigma_E/E = 30\%/\sqrt{E(GeV)}$. The crucial part of the PFA is that separation of particles in the calorimeter – i.e. reducing the density of charged and neutral particles at the calorimeter surface. Figure of merit is often quoted as $\frac{BR^2}{\sqrt{\sigma^2+R_M^2}}$, where B is the magnetic field, R is the ECAL inner radius, σ is the calorimeter granularity and R_M is the effective Moliere radius. As can be seen from the figure of merit, stronger magnetic field and large ECAL radius as well as the fine segmentation of the calorimeter are preferable for transverse separation of particles at the ECAL surface.

Four detector concepts for the ILC experiment have been proposed so far in the world[7]. Figure 2 shows an illustration of the four detector concepts. Three out of four (SiD, LDC and GLD) are proposing a detector which is optimized for the PFA, though the technical realization is quite different. The SiD detector has the highest magnetic field and the smallest ECAL inner radius, the GLD detector has the weakest field and the largest radius and the LDC detector is in between other two detectors. These values are summarized in Table 1. The 4th detector differs from the other three concepts; they utilizes a novel implementation



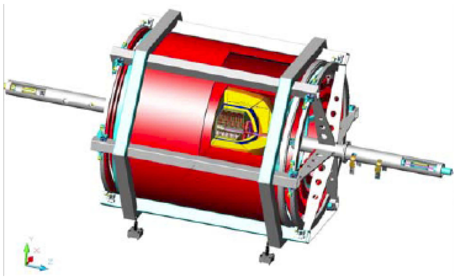


Figure 2: Illustration of the four detector concepts. SiD (top-left), LDC (top-middle) and GLD (top-right) are optimized for the PFA, though the technical realization is quite different. The 4th concept (bottom) utilizes a novel implementation of compensating calorimetry, and do not rely on the PFA.

of compensating calorimetry, and do not rely on the PFA. The magnetic field and ECAL inner radius for the 4th detector are also summarized in Table 1.

Concept	Magnetic Field Strength (Tesla)	ECAL Barrel Inner Radius (m)
SiD	5	1.3
LDC	4	1.6
GLD	3	2.1
4^{th}	3.5	1.5

Table 1: Magnetic field strength and ECAL barrel inner radius of the four detector concepts.

3 Review of Current PFA

Each detector concept has their own full detector simulator based on Geant4[8] and reconstruction package[9]. Figure 3[10] shows $e^+e^- \to t\bar{t}$ event at center of mass energy 500 GeV generated by Geant4-based full simulator for the SiD detector, named SLIC. Dense jets are clearly seen in the event display, and main issues of PFA is to separate energy deposit in such high density environment. Several PFAs have been intensively developed in the framework of these software tools. While the algorithms are distinct, there are a number of features which are common. Basic features and current performance of the PFAs are shown in the following. Notice that study by the cheated/perfect PFA which use simulation information to connect a charged track and calorimeter signals is also on-going[11]. They are useful to understand factors which affect the jet energy resolution.

Figure 4 shows a structure of one of the PFA developed for SiD detector[12]. In the SiD-PFA, first of all, a clustering algorithm and track finding algorithm are applied to the

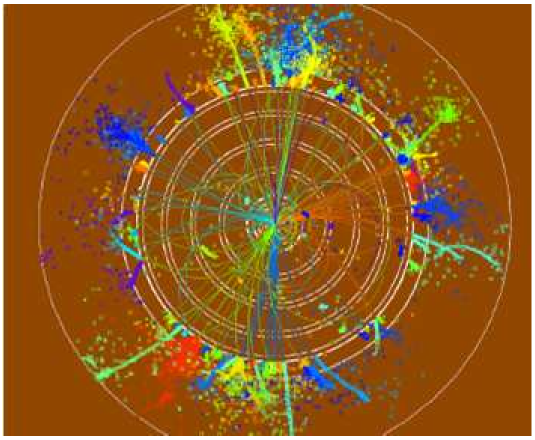


Figure 3: An event display of $e^+e- \rightarrow t\bar{t}$ event at center of mass energy 500 GeV generated by Geant4-based full simulator for the SiD detector, named SLIC. Main issues of PFA is to resolve such dense jets.

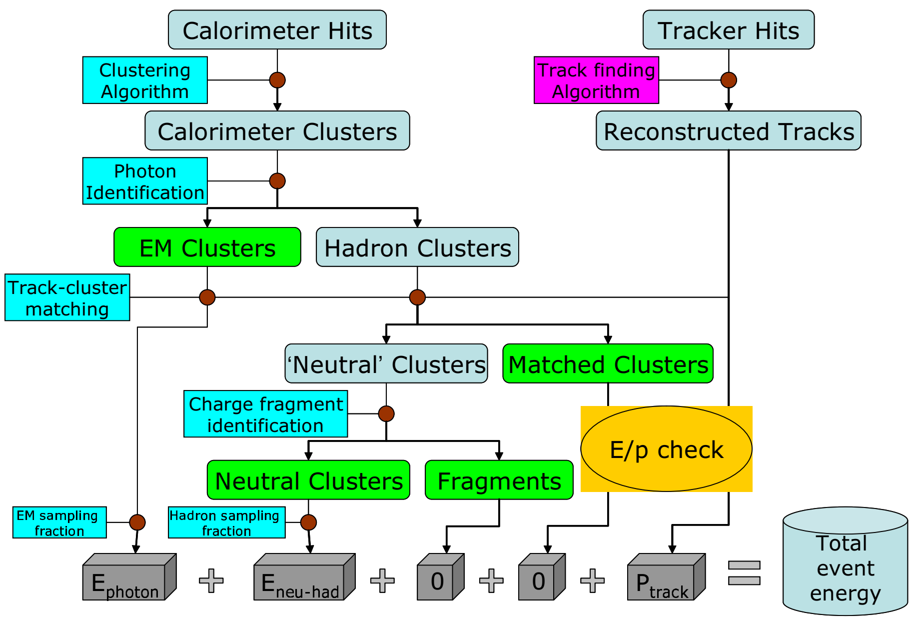


Figure 4: Flow of PFA for SiD detector. It consists of several methods: clustering algorithm, photon identification method, track-cluster matching method and fragment identification method. The total event energy is calculated by summing up E_{photon}, $E_{NeutralHadron}$ and P_{track} as it has already shown by eqn.(1). See text for more detail.

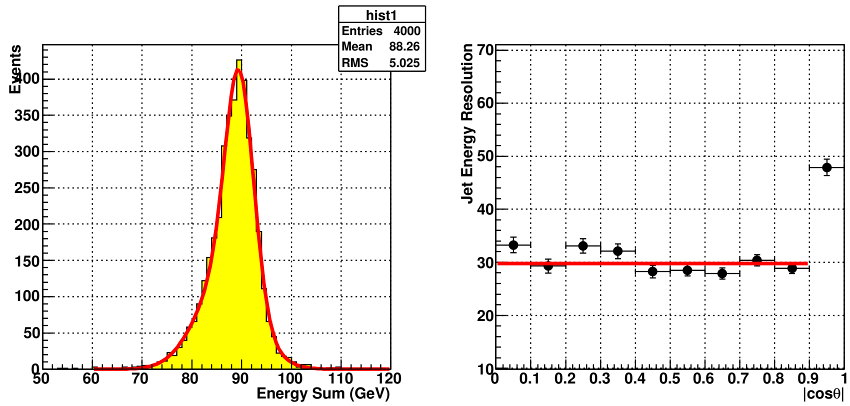


Figure 5: (left) The total reconstructed energy of $e^+e^- \to q\bar{q}$ events at center of mass energy of 91.18 GeV when the GLD-PFA is applied. (right) The jet energy resolution, defined as the α in $\sigma_E/E = \alpha/\sqrt{E}$, as a function of the initial quark direction.

calorimeter hits and tracker hits, respectively. In the next, the calorimeter clusters previously formed are classified according to the cluster type; EM clusters or Hadron clusters. Then, matching between the calorimeter clusters and the reconstructed tracks is examined (Track-Cluster matching). If there is no matched track for an EM cluster, they are considered to be a photon cluster, and the calorimeter energy is used in calculating the total event energy. The Track-Cluster matching is also performed to the Hadron clusters. If there is no matched track for a Hadron cluster, they are temporarily considered to be a neutral hadron cluster. Those clusters are further bifurcated, and classified to the neutral hadron clusters or fragments. The calorimeter energy is used for the neutral hadron clusters, while the energy of fragments are thrown away because they are considered to be the charged hadrons fragments. For the matched clusters among the hadron clusters, the charged track momentum is used instead of the calorimeter energy. Finally, the total event energy is calculated by summing up these quantities as it has already shown by eqn.(1).

The structure of the GLD-PFA is basically very similar to the SiD-PFA. It also consists of several methods: clustering algorithm, photon identification method, track-cluster matching method and fragmentation identification method. Figure 5 shows the current performance of the GLD-PFA. In this study, $e^+e^- \to q\bar{q}$ events at center of mass energy of 91.18 GeV (Z-pole) were generated by Jupiter, Geant4-based full simulator for the GLD detector. Only u, d, s quarks were generated by Pythia[13] without initial state radiation. Left figure shows the total reconstructed energy when the GLD-PFA is applied and right figure shows the jet energy resolution, defined as the α in $\sigma_E/E = \alpha/\sqrt{E}$, as a function of the initial quark direction. Each bin in the right figure was evaluated by the RMS90 method, which is the rms in the smallest range of reconstructed energy which contains 90% of the events. The ILC goal of $30\%\sqrt{E}$ has been achieved for the barrel region ($|\cos\theta| < 0.9$) of the Z-pole events ($E_{jet} \sim 45$ GeV) as shown in the right figure of Figure 5, but PFA becomes more challenging when considering higher energy jets. Figure 6 shows the event displays for 45 GeV jet (left) and 250 GeV jet (right). As clearly seen in the Figure 6, the opening angles between particles decreases due to the large Lorenz Boost for high energy jets, hence the

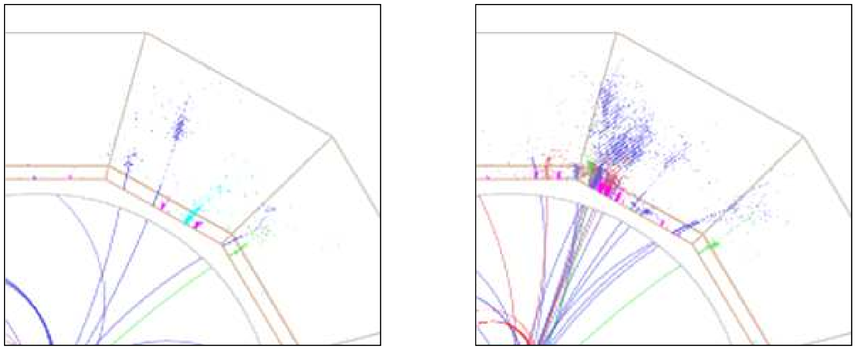


Figure 6: Event displays for 45 GeV jet (left) and 250 GeV jet (right). For high energy jets, the opening angles between particles decreases due to the large Lorenz Boost, hence the particle separation in PFA is more difficult.

particle separation in PFA is more difficult. In fact, the resolution with the current algorithm of the GLD-PFA degrades at higher energy, $\sim 45\%\sqrt{E}$ for $E_{jet} \sim 100$ GeV.

The PandoraPFA[14] has a special algorithm to take care of the high energy jets in addition to the basic methods as explained in the above. If track momentum and cluster energy are inconsistent, they perform reclustering; the clustering parameter is changed until the cluster splits and get sensible track-cluster match. Figure 7 shows the jet energy resolution, defined as the α in $\sigma_E/E = \alpha/\sqrt{E}$, as a function of the initial quark direction for different center of mass energies when the PandoraPFA is applied to $e^+e^- \to q\bar{q}$ event generated by Mokka, Geant4-based full simulator for the LDC detector. The jet energy resolutions in barrel region ($|\cos\theta| < 0.7$) are summarized in Table 2 and the ILC goal of $30\%\sqrt{E}$ has been achieved for even high energy jet ($E_{jet} \sim 100$ GeV). There are known flaws in the algorithm and the performance will become even better for more than 100 GeV jet.

E_{jet} (GeV)	α in $\sigma_E/E = \alpha/\sqrt{E}$ $\lvert\cos\theta\rvert < 0.7$
45	0.295
100	0.305
180	0.418
250	0.534

Table 2: The jet energy resolution in barrel region ($\cos\theta < 0.7$) for different four center of mass energies when the PandoraPFA is applied to $e^+e^- \to q\bar{q}$ event.

4 Detector Optimization Study

As shown in the previos section, the PandoraPFA performance is good enough to start the detector optimization and physics study using full detector simulator. A number of detector optimization studies have already been started by using the PandoraPFA[15]. Figure 8 shows jet energy resolution as a function of TPC radius with different magnetic field for 100 GeV jet. As can be seen from Figure 8, the jet energy resolution improves with increasing radius and increasing magnetic field as expected. Also, another studies shows higher granularity gives better jet energy resolution as expected.

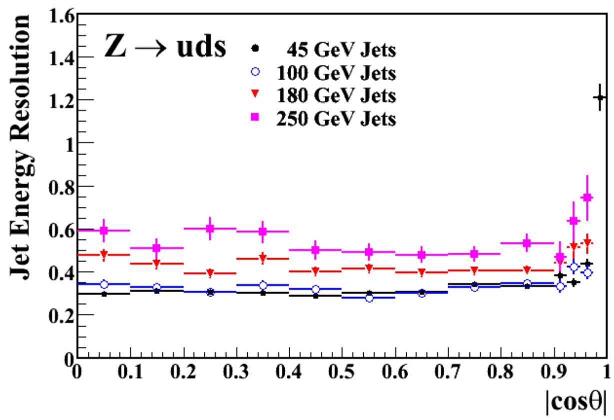


Figure 7: The jet energy resolution, defined as the α in $\sigma_E/E = \alpha/\sqrt{E}$, as a function of the initial quark direction for different center of mass energies when the PandoraPFA is applied to $e^+e^- \to q\bar{q}$ event.

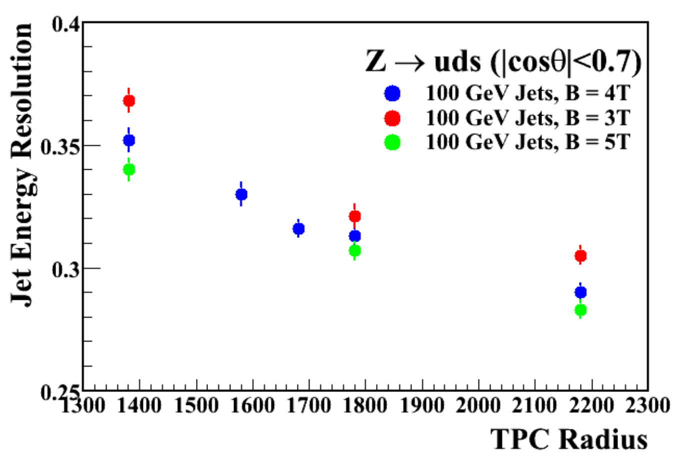


Figure 8: The jet energy resolution as a function of TPC radius with different magnetic field for 100 GeV jet. This result is obtained by using the PandoraPFA. The jet energy resolution improves with increasing radius and increasing magnetic field as expected.

5 Conclusion

Most of the interesting physics processes at the ILC experiment have multi-jets in the final state, and precise jet energy reconstruction, say $\sigma_E/E = 30\%/\sqrt{E(GeV)}$, is therefore the key to the ILC physics. Achieving such a high jet energy resolution is very challenging, and there is a rather wide consensus that PFA is the most promising way to realize it. As shown in this paper, it has already confirmed that we can certainly achieve such resolution by using the PFA for the jet energy of less than 100 GeV. Current PFA performance is good enough to start the detector optimization and physics study using full detector simulator.

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