Implementation of Particle Flow Algorithm and Muon Identification

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We present the implementation of the Particle Flow Algorithm and the result of the muon identification developed at the University of Iowa. We use Monte Carlo samples generated for the benchmark LOI process with the Silicon Detector design at the International Linear Collider. With the muon identification, an improved jet energy resolution, good muon efficiency and purity are achieved.

1 Introduction

The majority of the interesting physics processes at the International Linear Collider (ILC) involve multi-jet final states originating from hadronic decays of heavy gauge bosons. To fulfill its physics goals, the reconstructed di-jet mass resolutions for $W$ and $Z$ decays should be comparable to their widths. This di-jet mass resolution, in turn, requires di-jet energy resolution to be as good as $3\%$\(^a\). In order to achieve this goal, the Particle Flow Algorithm (PFA) approach has been adopted by the Silicon Detector (SiD) and the International Large Detector (ILD): two leading detector concepts at the ILC.

The goal of a Particle Flow Algorithm is to reconstruct events at the level of individual particles, identifying charged and neutral particles separately in the calorimeters with minimal confusion. The energy of the shower from each charged particle is replaced by the momentum of its track measured in the tracking system which has orders of magnitude better precision than the calorimeters while the energy of photons and neutral hadrons are obtained from the calorimeters. Without any confusion between charged and neutral showers in the calorimeters, a theoretical jet energy resolution of approx. $\sigma_E/E = 20%/\sqrt{E(\text{GeV})}$ can be reached. In reality, however, it is not feasible to disentangle all charged showers from close-by neutral showers \(^b\). The shower leakage also has been shown as the another main source of deterioration of resolution \(^c\). Due to confusion and leakage, the theoretical limit can not be reached. Muon identification can reduce the confusion as presented in this paper.

We present here the current status of the PFA based on the SiD concept developed by the University of Iowa group in collaboration with SLAC National accelerator Center (SLAC) and others.

2 Particle Flow Algorithm at University of Iowa

For the PFA performance, we use Monte Carlo (MC) samples of $e^+e^- \rightarrow Z(\nu\bar{\nu})Z(q\bar{q})$, where $q = u, d, s$ at 500 GeV and $e^+e^- \rightarrow q\bar{q}$ samples at 100, 200, 360 and 500 GeV with 10000 events each generated with GEANT4 simulation of SiD. LCIO serves as persistent data format.

Initially the PFA at the University of Iowa was developed with a ‘cheat’ tracking. Now we use the tracking package \(^d\) for the PFA while the cheat tracks can still be used for

\(^a\Delta M/M = \Delta E/E\) within the approximation $M = \sqrt{2E_1E_2(1 - \cos \theta)}$

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development. Initial track and cluster association in PFA identifies photons, electrons and muons. Electromagnetic (EM) showers are firstly reconstructed by looking at the shape and location of the cluster. Clusters in the EM showers which are unassociated with tracks are reconstructed as photons. Clusters identified as the EM showers whose position coincides with a charged track and whose energy matches the track’s momentum are identified as electrons. A muon is reconstructed by matching the extrapolated track in the calorimeters, consistent with energy deposited by a minimum ionizing particle (mip), with the muon direction obtained from hits in the muon detector. The details are discussed in Section 3. These reconstructed tracks and clusters do not participate in the later clustering for charged hadron showers.

Initial clustering is done for each sub-detector using hits in the calorimeters and the muon endcap system. Better jet energy resolution is obtained when the muon endcap is used as a tail catcher. The barrel section is not currently used as a tail catcher because of the meter-thick solenoid between the hadronic calorimeter and the muon system: this makes matching incoming tracks to hadronic showers correctly much more difficult.

Tracks found in the tracking system are extrapolated as helices to the inner surface of the EM calorimeters. Every track is supposed to have a seed where the seed is defined as the ‘earliest’ cluster in the calorimeters directly connected to the extrapolated track. When the track has too low momentum to reach EM calorimeters, there is no seed found. In this case, the track in the tracking system is used without clustering in the calorimeters. When the seed of the track is not found due to early decay in the tracking system even though the track reaches EM calorimeters, the track is not used to avoid the double counting the energy assuming it deposited its energy somewhere in the calorimeters. If two tracks are overlapping, it is possible to have the same seed or connected via the showers. In this case, the two or more tracks are grouped together to compare the energy deposited in the calorimeters with the momenta of these tracks.

The next important step of PFA is the assignment of the calorimeter hits correctly to the charged hadrons. This also means the efficient discrimination of showers produced by nearby charged and neutral hadrons. We use a scoring system to add clusters to the shower. A score is defined by the shower-related geometric quantities in the range from 0 to 1. We assign the score to the link between two clusters based on how close two clusters are. Having assigned a score to the link, we build a charged hadron shower starting from seed of the track. The charged hadron clusters are found and assigned to the shower of the track by searching the highest score link until the energy of clusters found are equal to the momentum of track within a given uncertainty. We iterate this process by loosening the selection criteria for clusters.

Even though electromagnetic showers are well-contained, consisting of a dense, almost needle-like longitudinal core, it has a halo of nearby hits and back-scattering hits for low energy showers. Hadronic showers have clear internal structure and often produce secondary neutral particles which deposit energy far from the main cluster. We take into account these back-scattering and secondary neutral particles by assigning the clusters in a conical order to the tracks whose energy in the calorimeters do not match the momentum of track measured by the tracking system. The neutral hadron showers are from the remaining clusters not assigned to any track.

The last step of PFA is to reconstruct the four-momentum of all visible particles in an event. The four-momentum of charged particles are measured in the tracking system while the energy of photons and neutral hadrons are obtained from the calorimeters assuming that
the charged and neutral hadron are pion and kaon, respectively. All reconstructed particles are filled into a reconstructed particle collection assigned to the event.

3 Muon Identification

Muon identification performance has been measured with the benchmark LOI samples like $e^+e^- \rightarrow t\bar{t}$, $e^+e^- \rightarrow ZH$, $e^+e^- \rightarrow \tau\bar{\tau}$ and Standard Model (SM) background events [5]. These have plenty of muons and are used for physics benchmark analyses.

Muon identification procedure is done at the first stage in PFA. When clustering for charged hadron showers, this muon identification can reduce the confusion with charged hadrons by subtracting muon tracks and clusters at the beginning. The minimum momentum to reach endcap and barrel muon detector is 2 GeV and 5 GeV, respectively. The muon identification study in this paper has been performed with tracks higher than 5 GeV, to reach either muon detector. Below 5 GeV, muons are badly reconstructed so the efficiency and purity are poor.

The muon identification algorithm starts with identifying the standalone muon mip in the muon detector. The standalone muon mip is defined as the group of isolated hits in the muon detector close to projective line from the interaction point. The requirement of at least 5 isolated hits is optimized for high purity. Since SiD has a longitudinal segmentation of 20 cm thick iron return yokes which is longer than transverse granularity of 3 cm [6], it is conceivable that the direction of mip in the muon detector can be obtained by using the first and second hit of standalone muon mip in the muon detector assuming that there is no magnetic effect outside the calorimeters so track’s trajectory is close to a straight line. Track in the tracking system is extrapolated through the end of hadronic calorimeters using a helical trajectory used in simulation studies. The tangent direction of the extrapolated track at the last layer in hadronic calorimeters is compared with the direction of mip in the muon detector. Then, the best matched track is selected as the muon track.

Figure 1 shows the muon efficiency and purity with different samples. Efficiency is

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defined as the ratio of the number of the good reconstructed muons to the number of real muon tracks using MC truth information. Purity is defined as the ratio of the number of the good reconstructed muons to the number of reconstructed muons. The average muon efficiency above 5 GeV is obtained as 96% for \( t\bar{t} \), 97% for \( ZH \), 100% for \( \tau\bar{\tau} \) and 99% for SM background sample, while the average muon purity above 5 GeV is also obtained as 92% for \( t\bar{t} \), 93% for \( ZH \), 98% for \( \tau\bar{\tau} \) and 95% for SM background sample.

Purity worsens with decreasing track momentum. The stray magnetic field outside the calorimeters has an effect on the lower momentum tracks even though it is not taken into consideration, leading to inferior matching. An additional source of misidentification as muons is from weak decays of charged pion and kaons in the final state. Even though these are not true prompt muons, for the purpose of calorimeter pattern-recognition we exclude these tracks with its associated clusters from hadron shower clustering as the mip-like behavior leave no showering in the calorimeters and muon systems.

### 4 Result

| Sample                  | Barrel (0 < cosθ < 0.8) | Endcap (0.8 < cosθ < 0.95) |
|-------------------------|-------------------------|-----------------------------|
| \( e^+e^- \rightarrow q\bar{q}, \sqrt{s} = 100 \text{ GeV} \) | 3.7 % 3.6 % | 3.8 % 3.6 % |
| \( e^+e^- \rightarrow q\bar{q}, \sqrt{s} = 200 \text{ GeV} \) | 3.0 % 2.9 % | 3.2 % 3.1 % |
| \( e^+e^- \rightarrow q\bar{q}, \sqrt{s} = 360 \text{ GeV} \) | 2.7 % 2.6 % | 2.7 % 2.6 % |
| \( e^+e^- \rightarrow q\bar{q}, \sqrt{s} = 500 \text{ GeV} \) | 3.5 % 3.4 % | 3.3 % 3.2 % |
| \( e^+e^- \rightarrow Z(\nu\bar{\nu})Z(q\bar{q}) \) | 4.7 % 4.7 % | 3.9 % 3.8 % |

Table 1: Energy resolution for di-jet samples of \( \sqrt{s} = 100, 200, 360 \) and 500 GeV and mass resolution for \( e^+e^- \rightarrow Z(\nu\bar{\nu})Z(q\bar{q}) \) sample, where \( q = u,d,s \) at \( \sqrt{s} = 500 \text{ GeV} \) in barrel and endcap region before and after muon identification. Both jets should be in the required angular region. cosθ is defined as |\( \frac{p_z}{\sqrt{s}} \)|.

Table 1 shows the PFA performance is slightly better after muon identification. In this table, the performance of the reconstruction is measured by the root-mean-square of the smallest range of reconstructed energies containing 90% of the events (rms90). This shows that muon identification improves the jet energy resolution overall energy range in the reasonably good muon reconstruction efficiency and purity for above 5 GeV. In the future, the optimization of each parameter in the algorithm is necessary to improve the resolution.

### References

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