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Particle Flow Algorithm and calorimeter design
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Abstract. The boson tagging at ILC, based on di-jets masses reconstruction, has lead to consider the reconstruction of multijet events as a major goal for the detector on this machine. One technique to optimise the multijet reconstruction is called Particle Flow Algorithm (PFA) and consists in software compensation and individual particle reconstruction. The main direction of the R&D studying calorimetry optimised for PFA, is concentrating on fine granularity calorimeters with a high degree of longitudinal segmentation. These studies include comparison of simulation models with data to measure their degree of agreement, the technical issues of building a detector optimised for PFA calorimetry, and development of algorithms for software compensation and particle flow reconstruction. Several technologies for electromagnetic and hadronic calorimeters are pursued with prototypes in test beam and new generation prototypes , very close to ILC like detector are under development with a very high degree of integration.

1. Introduction
The boson tagging is essential to fulfil the physics program at the International Linear Collider, which is mainly related to W, Z and Higgs boson production studies. The majority of these boson decays to quark-antiquark, leading to dijet decays of the boson. The optimisation of the dijet mass resolution will improve the tagging of the different bosons. A technique called PFA for Particle Flow Algorithm has been proposed [1] to optimise the dijet mass resolution. The detector could therefore be optimised to achieve the best possible performances in the PFA, that is to reconstruct individually each particle of the final state. It is possible to classify the particles in a jet in 3 “species”: The charged tracks, the photons and the neutral hadrons (neutrons, neutral kaons). The short lived neutral hadrons (K°short and Λ are reconstructed in the tracker device and are no longer considered as neutral hadrons). The charged tracks are reconstructed from the tracker device, the photon are reconstructed in the electromagnetic calorimeter (ECAL) and the neutral hadrons in the ECAL and hadronic calorimeter (HCAL). This is supposing that it is possible to disentangle for each particle the deposited energy in the calorimeter. This is the goal of the calorimeter design to optimise the PFA performances. In this case, the energy resolution can be written like σ^2 jet = σ^2ch. + $\sigma^2\gamma$ + $\sigma^2 h^0$. With a typical charged track resolution on momentum ($\Delta p/p$ ~ few 10^{-4}), an ECAL energy resolution ($\Delta E/E \sim 12\%$) and a typical energy resolution in HCAL of $\Delta E/E \sim 45\%$, the jet energy resolution could be as good as $\sigma_{jet}=0.14\sqrt{E_{jet}}$, which is by far much better than what was obtained up to now with calorimetric approach

2. Starting from Physics

An important part of the physics programme at ILC is based on multi boson final state. It is summarised in the following table 1.

Table 1. main physics processes to be studied at ILC

Bosons only	Fermions-bosons
ZH	e+e-H, e+e-Z
WW	νν H, νν Z
ZZ	tt H , νν HH
ZHH	e ν W
ZWW	ννWW, ννZZ

The Z and W bosons decay predominantly to quarks pair, with a ratio of branching fraction BR(Boson →q qbar)/BR(Boson →Leptons) of 7 for the Z boson, 2.1 for the W boson and about 5.7 for a standard model Higgs with a mass of 120 GeV/c^2. The situation of the Higgs could be more complicated if the Higgs is non-standard. Therefore the multijets final state could be used to tag the boson using their reconstructed masses. It is possible only because of the signal to background ratio (i.e. the background of qqbar production for multijets final state) at the cross section level which is favourable (less few order of magnitude). It is illustrated in figure 1

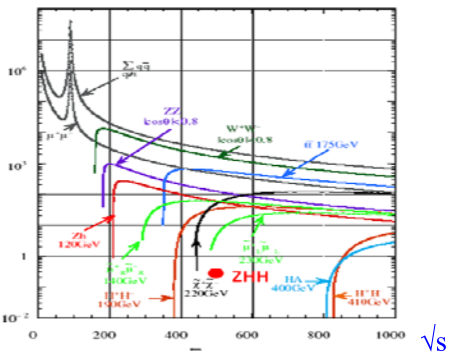

Figure 1. Some interesting cross section in e+e- interaction from Z peak to 1 TeV

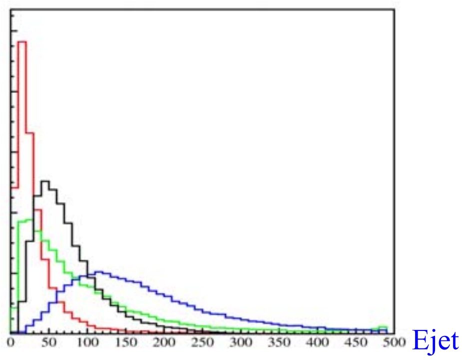

Figure 2. Jets energy distribution for ννH (2jets) in red, ttbar (green) and WW (blue) at 1 TeV and ZH(with 120GeV mass) at 500 GeV

The energy distribution of these jets shows a peak at low energy, with most of the distributions below 250 to 300 GeV. Figure 2 shows some examples of these distributions.

3. The jet energy resolution for the ILC physics programme

The energy resolution on the jets can be written as follows: $\Delta E = a \sqrt{E} + b\,E + c$, where E is the jet energy. Studies have been performed [2] showing that a=0.3 and b=0 fit the requirement for the physics programme at ILC. It is illustrated on figure 3, with the ZZ/WW separation based on the two dijet masses. The two peaks at different masses (W,Z) is clearly seen for a=0.3 while it is largely diluted for a=0.6. Similar studies have been done for Higgs mass measurement, for Higgs couplings, but also for SUSY, for Higgs CP violation decays, analysed with tau decays, etc...

4. Particle Flow Algorithm

One way to obtain the value of a=0.3 and b=0., could be to use the method called Particle Flow Algorithm (PFA), which consists in reconstructing each particle individually [1,3]. This method has been partially already used at LEP, for example by ALEPH. The idea is to reconstruct the charged tracks in the tracker device, then to use the ECAL for the photon(s) and the ECAL and HCAL for the other neutral particle(s) (K°,neutron). An important point to note is the difference with the energy flow method, where balance of energy is made between momentum measurement given by the tracker device and the energy deposited in the calorimeter.

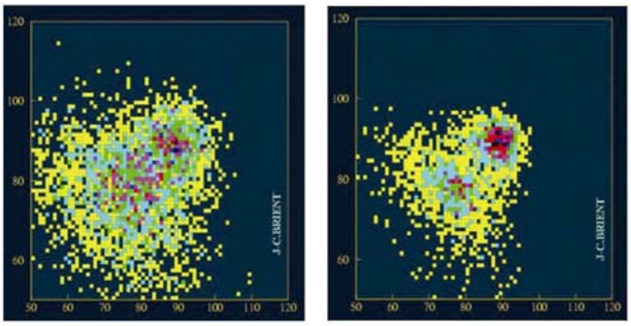

Figure 3. WW and ZZ separation in the 4jets events, with the two dijets masses.
Right for a=0.6 and left for a=0.3 (a is defined in the text)

For PFA, the tagging of particle is given by topological separation between showers from charged tracks and from neutral particles. Such an approach can be compared to the calorimetric approach for what concerns the resolution. It is summarised in the table 2.

Table 2. a,b, and c for a jet energy resolution given by $\Delta E = a \sqrt{E} + b E + c$

Detectors	**a**	**b**	**c** (GeV/c²)
ALEPH *(real data)*	0.6	0.	0.6
ATLAS central region	0.6	0.03	0.
H1 (*real data)*	0.5	0.05	0.
Goal for ILC detector	0.3	0.	0.5

The topological reconstruction leads to a kind of recommendation's list for the detector and more precisely for the calorimeter.

A good lateral granularity gives a better separation. It is mandatory to have a good longitudinal segmentation, in order to avoid showers mixing (helping for good pattern recognition of the showers). The calorimeter has to be at a large distance from the interaction point giving a better opening of the jets, making easier to separate the showers. A large magnetic field will also help because of_the bending of the charged particles. Eventually, in order to have a good efficiency to reconstruct all the low energy particles, the coil has to be put outside the calorimeter, avoiding having too large matter in front of the calorimeter. From the recommendation list, we can extract some logical consequences for a calorimeter dedicated to PFA performances:

- A calorimeter with a very large number of channels ("high number of pixels for the shower picture), leading to a unprecedented level of integration
- A very compact calorimeter , which reduces the radius of the coil

- Prototype in test beam to debug such a device (essential for such brand new view of this type of device)

Among the consequences, we can list (non-exhaustive): the VFE electronics has to be embedded in the detector, leading to the problem of power dissipation, the local zero suppress has to be done locally, a very strict care of the common mode has to be performed in order to maintain a very good signal over noise ratio at the mip level, etc... and eventually , the active device must be very stable in time but also in temperature, etc...

5. The expected performances with PFA

A large amount of work has been devoted to develop a good PFA reconstruction program in the last 2 years. Interesting results based on full GEANT4 simulation and full reconstruction has been obtained. The simulated detectors were similar, with gas tracker device but with different types of calorimeters. However, both reconstruction programs are based on PFA approach. Figure 4 shows the jet energy resolution curve as a function of the jet energy, for calorimetric approach from ATLAS and H1, and ALEPH for PFA. Moreover, on the figure, there are results from M.Thomson [4] for silicon diode ECAL and results from A.Miyamoto et al [5] for scintillator ECAL and HCAL. The results shows a value of the parameter a better than 0.3 and b very small as long as the jet energy is in the good region for the ILC physics program (below 250-300 GeV).

The calorimetric approach is less interesting even with a good stochastic term because of the constant term which is inherent to this approach and due to dead zone, inter-calibration, non-linearity, electronics response, etc... The constant term per pixel could be relatively large in PFA approach without playing a role because of the large number of pixels per GeV and per particle. A simulation with 5% constant term per pixel has been shown to be reduced to negligible effect in PFA approach.

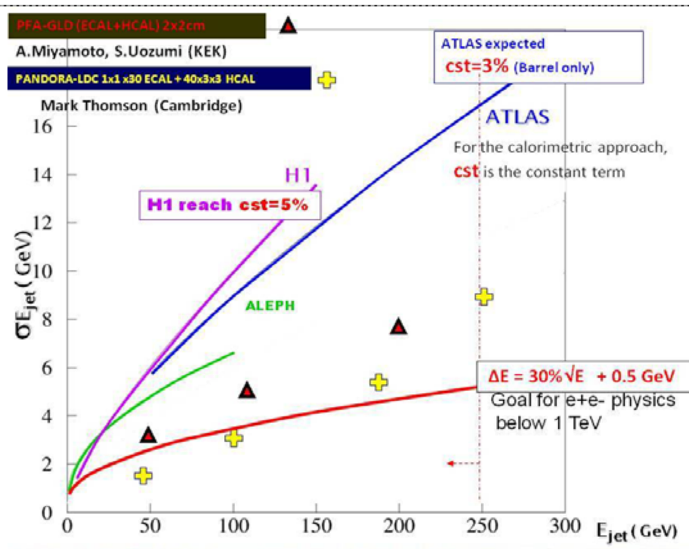

Figure 4. Jet energy resolution for calorimetric approach (H1, ATLAS) and for ALEPH (partial PFA) and for fully simulated GEANT4 events, reconstructed by two different PFA programs

5.1. Questioning the expected performances

The quality of the description of the hadronic shower in GEANT4 is relatively poor, especially when speaking about width and depth at such a level of precision (cm size). A first attempt has been made to change the physics list in order to observe the impact on the expected performances. The results of the

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study are shown in Table 3. Between these 2 models, the hadronic shower width differs by about 20%, therefore, as a first conclusion; it can be said that the jet energy resolution based on PFA depends only marginally on the hadronic shower model.

The second possible problem could be the real condition for a detector with a very large number of readout channels. The noise, the dead zone of the geometry, the intercalibration, etc.. which could cause large degradation in the performances could be tested in real condition during the test beam period

Table 3. Variable a as function of energy and hadronic shower model used in the detector simulation. (studied by M.Thomson [4])

Hadronic physics list in GEANT4	Jet energy (GeV)	Value of a
QGSP_BERT	45	0.226
LHEP	45	0.232
QGSP_BERT	100	0.293
LHEP	100	0.302

6. The CALICE collaboration
A large collaboration, called CALICE for **CA**lorimeter for **LI**near **C**ollider **E**xperiment [6], is working on such device since 2002. The collaboration is made of about 280 physicists/engineers from 45 institutes and 12 countries. Electromagnetic calorimeters (ECAL) as well as hadronic calorimeters (HCAL) are studied in the collaboration. Three different types of ECAL are proposed to reach the goal. Two are more or less classical, first a silicon diode–tungsten sampling calorimeter, then a scintillator strip-tungsten sampling calorimeter but read by MPPC, the new photo counter in fashion. The third one is based on MAPS, (CMOS Active Pixel Sensors) with digital readout of pixel with size of 50x50 μm^2. The last one is still at the level of first demonstration of feasibility, while the two “classical” are already prototyped with test beam for 2 years at CERN and now at Fermilab. On the side of hadronic calorimeter (HCAL), the classical solution is proposed as a sampling device made of stainless steel and very small scintillator tiles (3x3 cm^2) read by silicon photomultiplier. In addition, a brand new type of calorimeter is proposed with gas devices (RPC, GEM or Micromegas) with pad size of about 1x1cm^2 and read only on 1 to 3 bits (DHCAL). In this last case, the hadronic energy would be given by the shower development (size, depth, area and volume) and believing GEANT4, with an energy resolution better than the one with tile and analogue readout. This last point has clearly to be demonstrated and the concept has to be validated

7. Prototypes in test beam
Test beam has been performed in 2006 at DESY with electrons from 1 to 6 GeV and at CERN H6b with electrons, pions and protons, with energy from 8 GeV to 120 GeV. The figure 5 hereafter shows the ECAL prototype silicon-tungsten in front of a prototype of 1m3 of AHCAL (tile-iron) behind and finally a tail catcher (TCMT), made of strip of scintillator , used to monitor the longitudinal leakage of high energy shower. The level of complexity of assembling and running is illustrated by figure 6, which shows the PCB and the readout cables for the ECAL prototype with its 9720 channels in an active volume of 18x18x18 cm^3. The test beam has allowed checking the level of noise, the stability of the response, the readout and DAQ system capability and more generally the quality of the detector during the test beam period.

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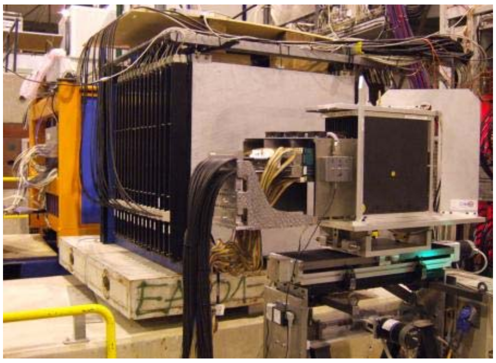

Figure 5. Test beam area at CERN H6b, with the prototypes of ECAL, of Tile HCAL and the one of TCMT behind.

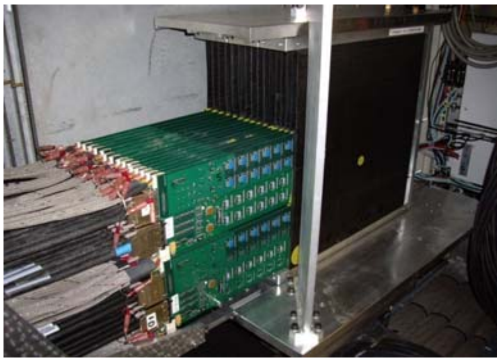

Figure 6. The silicon tungsten ECAL prototype. The number of readout lines and cables can be noted.

8. Test beam for PFA

In addition to the standard goal for test beam, we want to use the test beam data to study the issue of the hadronic shower. Among the related question, we can list:

- The separability of the clustering on the hadronic shower of the PFA by superposing real interaction taken in our prototypes.
- The test of the hadronic shower model in the GEANT4 simulation (depending of particle type and energy)
- The energy resolution of each device AFTER clustering, which the relevant parameter for PFA approach

The test at low energy in progress at Fermilab is an important part of this programme. It is illustrated by figures 7 and 8, showing the on-line event display of typical events of this test beam data.

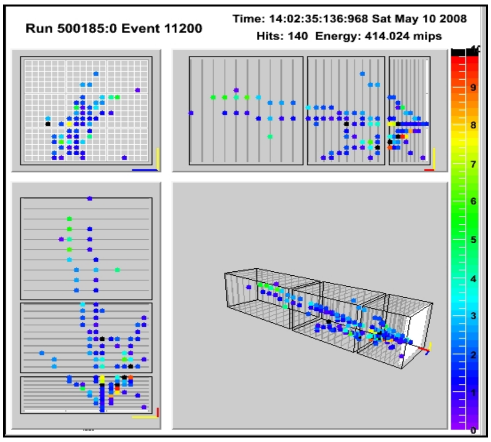

Figure 7. 8 GeV pion interacting in ECAL at the MTBF-FNAL test beam spring 2008

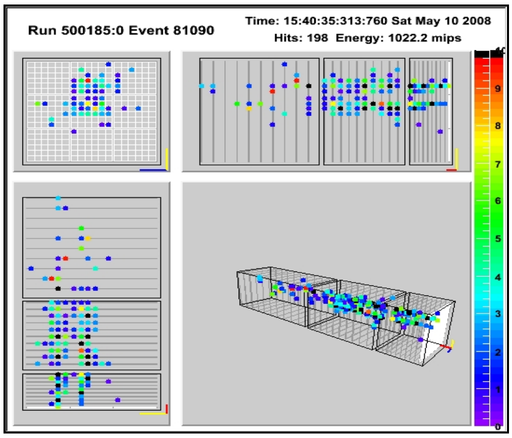

Figure 8. Simultaneous arrival at the FNAL test beam. Visual inspection confirms easy separation between the 2 showers

The data taken from 2006 to 2007 at DESY and CERN shows at least a satisfactory global behaviour of the detector. Important points were discovered during this test beam, such as the capacitive coupling between floating guarding and external pixels in the silicon wafers for the ECAL or the need for very precise monitoring of the data condition for the use of silicon photomultiplier. The analyses are in good progress and preliminary results will be shown at this workshop.

9. Conclusion

To optimise the use of the luminosity for an ILC machine, the decays of the bosons to jets have to be used for physics analysis. It is possible, because the signal to background ratio of the cross section e^+e^- to multijets final state is favourable, that is below few order of magnitude before selection. A new technique, called the Particle Flow Method, has been introduced to optimise the jets reconstruction in the jet energy region below 300 GeV. Results of full GEANT4 simulation and reconstruction with this technique have shown performances such as the ones needed for the ILC programme up to a centre of mass energy of 1 TeV. These results are based on simulation of ultragranular calorimeters, which give the best performances for PFA.

The CALICE collaboration designs prototypes of such ultragranular device, gaining expertise in this brand new domain for calorimeter, where the key word is reconstruction and not the energy resolution of single particle. Test beam data has been taken with the first generation prototype, at DESY and CERN. New test beam period, devoted to very low energy hadron, is in progress at Fermilab. Several tens of millions of interactions of electrons, positrons, and different types of hadrons with the first generation prototype have been registered and analyses are in good progress, with preliminary results shown at this workshop and papers to come.

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