Energy flow or Particle flow - The technique of ”energy flow” for pedestrians

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Energy flow or Particle flow
The technique of “energy flow” for pedestrians.

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In the prospect of elucidating the physics accessible to an electron-positron linear collider in the range 0.09 to 1. TeV it is of prime importance to be very efficient and not miss any signal. This leads to the question of collecting every interesting event and extracting as much information as possible from every collected event. To achieve that, and considering that most of the physics of interest implies bosons like W, Z or possibly Higgses, the identification of these bosons when they decay into hadron jets is essential. This is the motivation for developing a method which best reconstructs the direction, energy and mass of these di-jets. We believe to have such a method with the so-called “energy flow” or “particle flow” approaches.

1 Introduction

The aim of this paper is to present the arguments and basic facts about a method called “energy flow” or “particle flow” which could provide an adequate reconstruction of the bosons involved in the reactions we wish to study at the linear collider. This has already been discussed in different places [1].

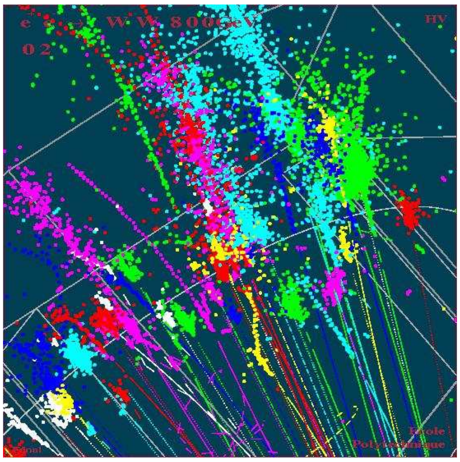


Figure 1: Flowers of energy. Pedestrians wandering around flows of energy flowers

In view of the physics interest, and of the cost, of the collider we have to be able to collect “all” the physics accessible in the energy and luminosity domain we will explore. We can wonder if such a noble goal can be reached by inventing a smart and inexpensive way or if we will have to make it the painful way, by reconstructing at best every single piece of every event. This second approach, limited by the detector performance, is what we mean by ”energy flow” or ”particle flow” approach even though these appellations do not sound really adequate to describe the process in that they evoke more a global approach than an analytical one.

The physics we are likely to have to tackle is a cocktail of final states like $t\bar{t}$ decaying in $bWbW$, or $t\bar{t}H$, ZH, ZHH, $\nu\bar{\nu}WW$ and many others, stop pairs, ... Most often we want just to identify, see and measure Z, W or H bosons as ”standard particles” while they decay in leptons, including neutrinos, and jets in detectors like the one shown in figure 2 where the different compo-

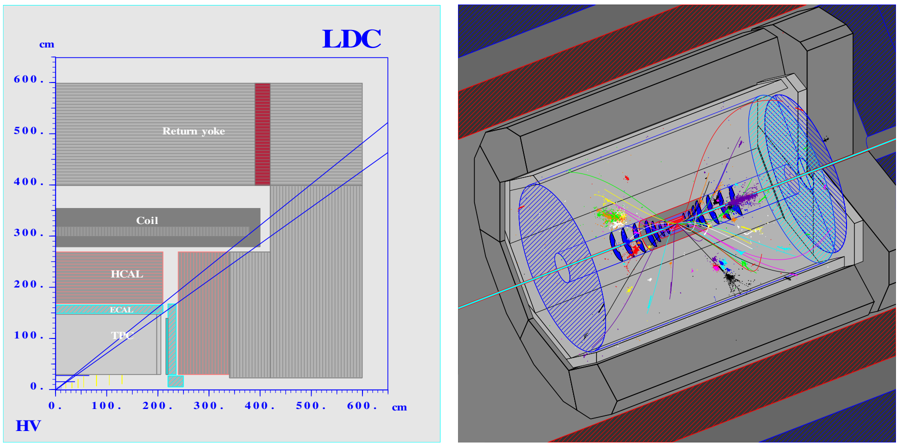


Figure 2: View of a typical detector, on the left a sketch of the detector structure, on the right a perspective view.

nents can be seen, vertex detector around the interaction point, intermediate tracker, time projection chamber, forward tracker, electromagnetic calorimeter, hadronic one, coil and return yoke instrumented as a muon detector.

To understand better the problem it can be useful to have a quick look at different types of events in the detector sketched above. Some events look extremely clear and simple, some look very busy. Can they really be analysed globally or rather don’t we have to disentangle every component? The first

ZH events are very simple, but for the fact that the tau decays may have to be analysed to extract the polarisations and their correlation, see figure 3.

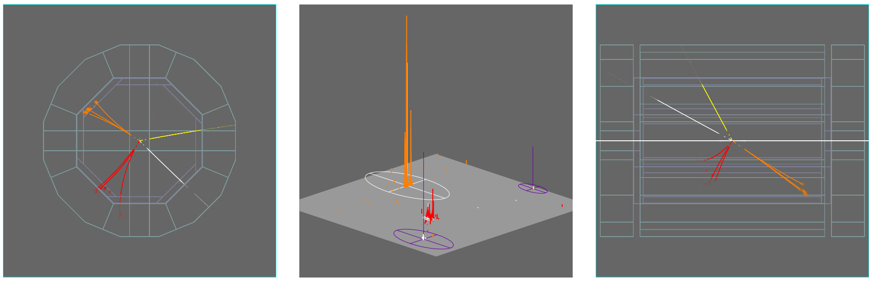


Figure 3: Views of a $e^+e^- \to ZH$ event with $Z \to \mu\mu$ and $H \to \tau\tau$. On the left view along the beam, in the middle $\theta - \phi$ view, on the right view in a plane containing the beam.

The figure 4 exhibits even more scarcity.

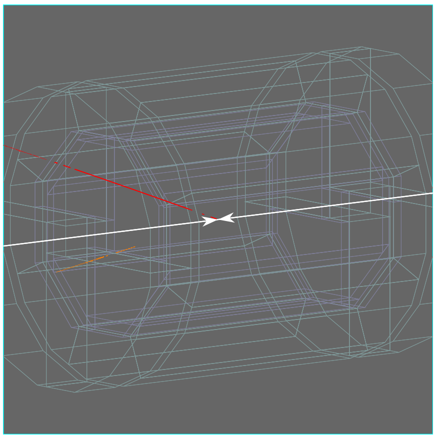


Figure 4: Perspective of a $\nu\bar{\nu}ZZ$ event where one Z goes to neutrinos and the other to a muon pair.

But most often hadronic jets with rather low energy tracks populate the detector, as shown on figure 5. This figure illustrates the effect of the high magnetic field. On one side it provides a good momentum measurement and disperses the track impacts in the calorimeter, on the other side it makes the low energy tracks curl around to end up in the end caps. This is even clearer in the figure 6 a which shows a $t\bar{t}$ event.

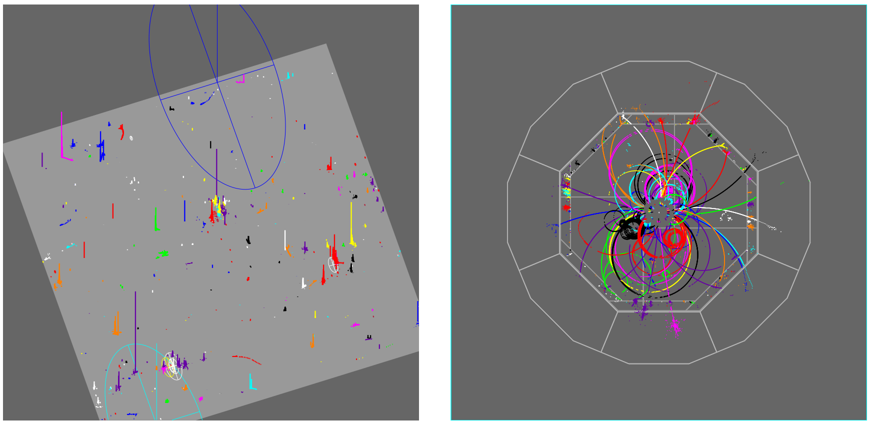


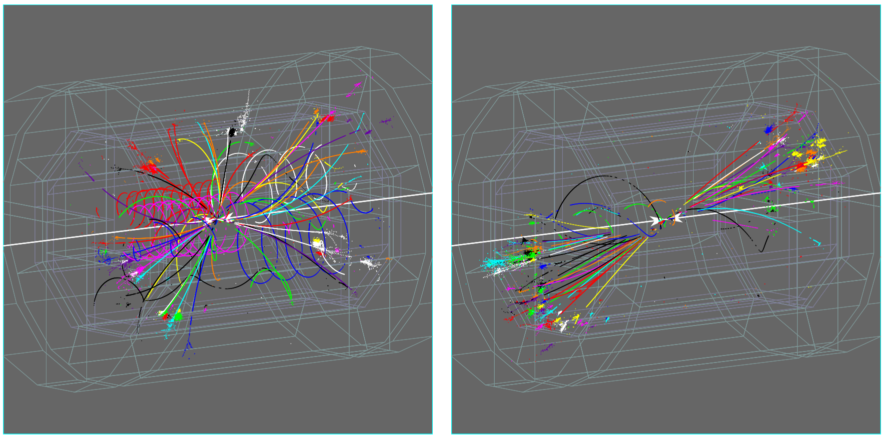
Figure 5: $e\nu ZW$ event with hadronic Z decays. The particles are swept around by the magnetic field. On the left a θ/ϕ view shows the power of the high calorimeter granularity. The ellipses show the impacts of the e and ν with a size proportionnal to the energy

A strong magnetic field is needed to confine the machine background in the beam pipe and seems an excellent tool to have less confusion in jets. Nevertheless some reactions of interest like the production of W pairs have a tendency to populate the end caps as can be seen in the figure 6 b. and, if the field provides an opening in BR^2 in the barrel, the opening at low angle varies only with the distance of the calorimeter to the interaction point. In one word, a high field does not really compensate for a small radius or a small length.

In conclusion we have a large variety of events presenting isolated charged leptons which have to be measured very accurately and jets or rather dijets where the separation in jets is of no interest, the only relevant parameters being the mass and momentum of the dijet.

2 The Energy Flow

Coming now to the theme of this talk, we will first analyse the object of the study, list the requirements we have to fulfill, review the basics of the method, develop two examples of the old approaches, and then explain what is the current approach.



(a) $t\bar{t}$ event (b) WW at 800 GeV

Figure 6: Perspectives of events showing the large track multiplicity. The WW event populates the detector end caps.

2.1 The subject of the study

We should first review the properties of the particles we are dealing with.
- neutrinos, there is not much to be done with them except to know than one is there, signed by a charged lepton near by, and may be estimate their momentum as missing,
- electrons, their momentum and energy are measured respectively by the tracker and the calorimetry, but both measurements are hampered by the occurence of Bremsstrahlung and δ rays. they are identified by the calorimetry above about 1 GeV of P_t, and by dE/dx below, but this may have to be done in a dense environment; we have also to know where they come from, in particular if they are not a photon conversion?
- muons, the only information on their momentum comes from the tracker with the magnetic field, they are identified possibly in a dense environment by the calorimetry and above 6 GeV by the muon detector. They usualy sign a weak decay involving a neutrino.
- charged hadrons, they are measured in the tracker and, unfortunately, by the calorimeter, they are identified as "no lepton" and it is essential to know where they are coming from, primary interaction, short decays, V^0's,
- neutral hadrons, they are seen only in the calorimeter and their measurement is the grail of the method.

With a very strong dependence on the type of reaction the fraction of energy taken by the different types of particle is about 60 % for the charged tracks, 12 % for the neutral hadrons, and 28 % for the photons. The energy spectra are shown on figure 7, most is of rather low energy. We can note that the photon energy is typically half that of the two other components.

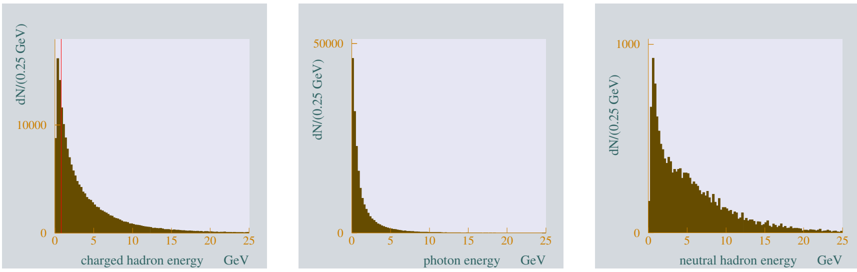


Figure 7: Typical distributions of energy for particles produced at the ILC. On the left spectrum of the charged particle energy, in the middle energy of the photons and on the right energy of the neutral hadrons.

2.2 Requirements

We can start by recognising that its curvature in a magnetic field is the only way to measure the energy of a muon. This measurement makes use of B, the track length L and the sagitta precision δs. For a given precision A on $\delta p_t/p_t$ we play on δs, B and L through $\delta s = 410^{-5}ABL^2$, where B is in Tesla and the lengths in metres. A high B is necessary to keep the background away from the vertex detector but it is not an alternative to L, a lot of physics being at low angle where we can count only on natural opening and distance to separate the particles. On the other side a high B on rather low energy particles in jets, smears the jet impact on the calorimeter and distorts completely a purely calorimetric approach from the point of view of measuring mass and angle.

In summary we need to get the charged particles from the tracker. A specific point is the measurement of the possibly "invisible" Higgs. The production of a ZH final state where the Z goes to muons offers the possibility to measure the Higgs mass as a mass recoiling to the muon system identifying by its mass to be a Z, whatever its decay. Such a measurement is shown on figure 8. This sets a very stringent constraint on the tracker resolution to be better than 10^{-4}.

The photons, except those converted, are measured in the first part of the calorimeter, we call for that reason abusively electromagnetic calorimeter.

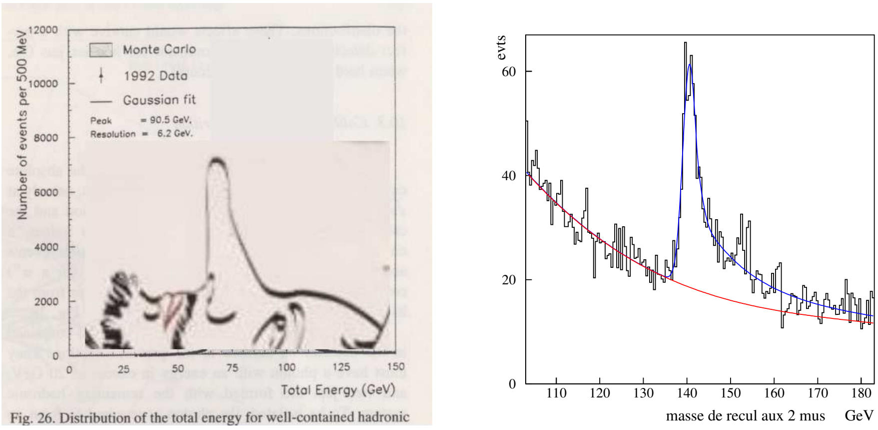


Figure 8: Study for the mass recoiling to a muon pair. On the left we can observe how, after a 90 degrees rotation, the nose of Cyrano de Bergerac is similar to a Higgs mass distribution.

But they interfere there also with the charged hadrons, already taken into account through the tracker and with the neutral hadrons. An estimation of this interference is presented on figure 9.

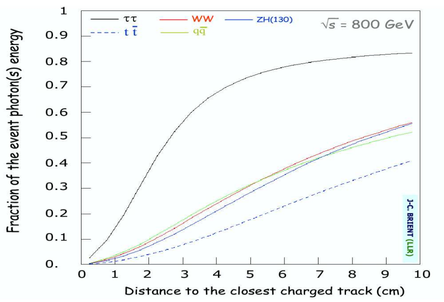


Figure 9: Distance of photons to the closest charged track at the entrance of the calorimeter.

The calorimeter design has to optimise the distinction between photon and hadrons through field and distance as already explained but also on the photon and hadron apparent shower size and on the interaction to radiation length ratio. For the neutral hadrons we can emphasize the shower size but also the ramified structure of hadronic showers when developed in an adequate medium.

2.3 Reminder on the analytical energy flow basics

What are the old ideas on how to handle the problem of the neutral hadrons? The isolated particles are not much of a problem as long as the intrinsic resolution of the detector is adequate (see above the discussion on muons). A special mention has to be made on taus which, most of the time, appear as a narrow jet. For the jets, or more accurately in our case the boson di-jets, we have to know their energy but also their nature, their mass. We have to resolve the jets in their particle content to make sure that their energy and mass are properly estimated in particular to separate W and Z, as illustrated in figure 10.

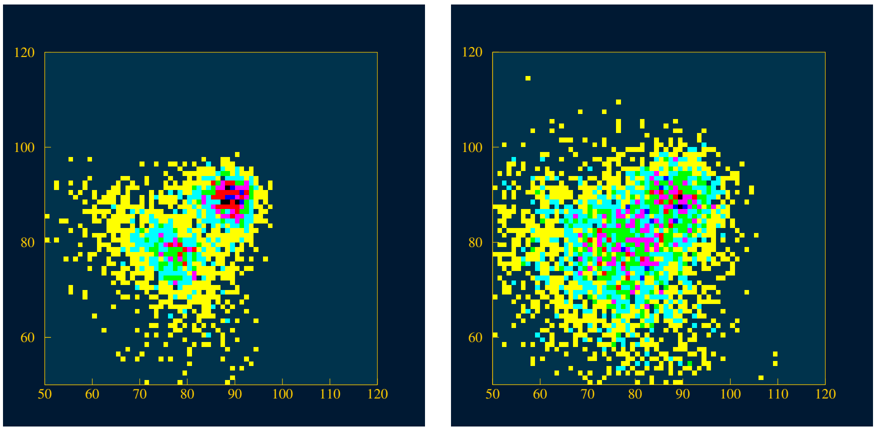


Figure 10: Study for the W_L scattering. Pairs of W's and Z's have been generated with different jet resolutions. The resolution is parametrised as $\Delta E = \alpha/\sqrt{E}$, on the left $\alpha = 0.3$, on the right $\alpha = 0.6$.

To reach an adequate resolution the hermeticity of the detector has to be ensured, with enough interaction lengths not to let the neutral hadrons escape. The separation between hadronic showers has to be good enough to avoid inefficiency to neutral hadrons or double counting for the charged ones.

The basic question is then to know how to handle hadronic calorimeters.

One could dream of using only a well compensated calorimeter segmented according to the hadronic shower size or even the jet size. This could offer an adequate measurement of the energy, except for muons, but not of the mass of the bosons. The alternative is to develop a detector such that you identify and measure separately every particle produced. This is an asymptotic solution, can you get close enough to the perfection that it is useful? This is the analytical energy flow approach used already at LEP and in particular in ALEPH. In fact, you can find under the same designation of energy flow, techniques which do not attempt to reconstruct fully jets but do some adequate weighting in the calorimeters to optimise the energy resolution, this will be discussed later.

2.4 A historical example of energy flow method: ALEPH

The technique is described in the "Performances of the ALEPH detector at LEP" paper [2]. To understand the value and the weaknesses of the method we can first have a look at the detector it was designed for, see figure 11: Around

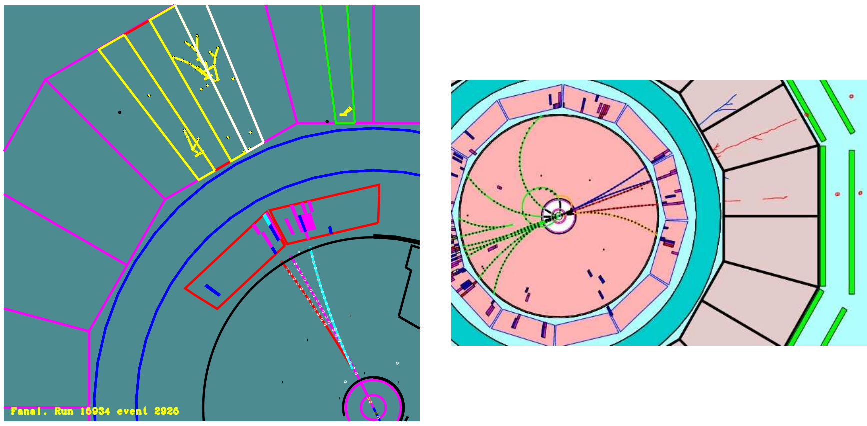


Figure 11: An example of calorimeter misconnexion: ALEPH. On the left a $\tau \rightarrow \nu K_l^0 K_s^0 \pi$, on the right a $B \rightarrow \psi' \phi$.

a big tracker, a Time Projection Chamber(TPC), you find an electromagnetic calorimeter (ECAL) made of three layers of 3x3 cm cells, followed by the 1.5 T coil in front of a hadronic calorimeter (HCAL) read analogically in towers equivalent to a 4x4 group of ECAL towers and digitally (yes or no) in tubes providing the shower pattern.

The method, as used in ALEPH, is based on a topological separation of the showers. They are linked, when relevant, to charged tracks, or identified as photons, then the non identified calorimetric objects are taken as neutral hadrons, on top of which neutral hadronic energy appears by subtracting from

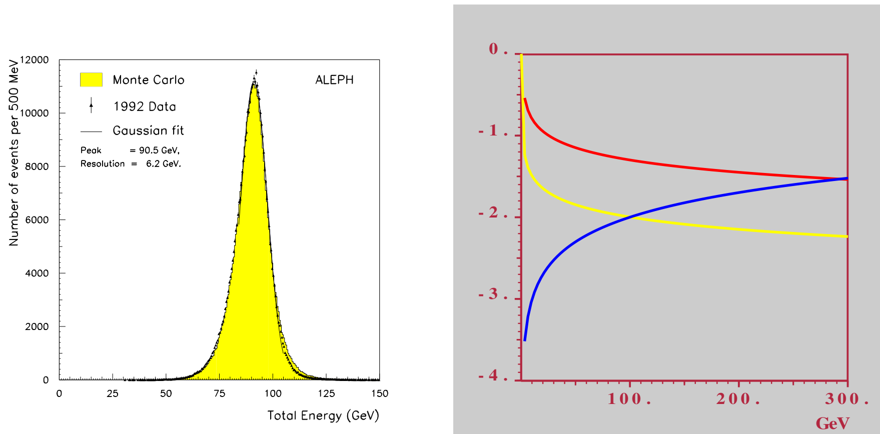


Figure 12: On the left the jet resolution as achieved in ALEPH with an energy flow algorithm, on the right the components of the resolution for a particle flow at ILC shown in a logarithmic scale.

the global calorimetric energy the energy of these identified objects after proper weighting.

The procedure can be summarised in the following steps:
Step 1 - Cleaning
Step 2 - Build calorimeter objects from connected tracks and calorimeter clusters
For each such object:
Step 2 - The charged tracks with their origin, interaction point or secondary vertex, provide the charged energy.
Step 3 - For identified electrons remove the calorimetric energy up to the momentum + 3 σ.
Step 4 - For identified muons remove the calorimetric energy up to a defined value.
Step 5 - γ 's and π^0's identified provide the neutral electromagnetic energy.
Step 6 - Then the neutral hadronic energy is the difference between the weighted calorimetric energy and the track energy augmented by its error.

This last operation bears the weakness of the method: The neutral hadronic error contains the fluctuations from the charged showers energy measurement. It was forced on us by the presence of a coil equivalent to one interaction length in the middle of the calorimeter and by a still inadequate read out granularity.

As a result a purely calorimetric energy resolution of $1.2/\sqrt{E}$, without any trick to improve it, goes down to $0.6/\sqrt{E}$, when a perfect separation of the components would provide $0.3/\sqrt{E}$, with an angular jet resolution of 18 to 19 mrad, half of it coming from low energy tracks and γ's, the other half from detector imperfections.

2.5 An example of optimisation of the resolution: H1

The problem of hadronic calorimetry is known to be related to the different response of the calorimeter to the hadronic component and to the electromagnetic one, i.e. π^0. There are two solutions: one is to adjust the hardware response to be equal for both components, the other to identify them and weight them adequately. This last solution is being used in the H1 experiment at DESY with a liquid argon calorimeter. That is also the solution we recommend. These methods to optimise the hadronic resolution are often referred to as "energy flow" techniques and indeed the ideas behind are similar.

The H1 method is described in a paper [3]. The energy collected in every cell of the calorimeter is corrected by a weighting factor which is dependent on the energy density in the cell, ratio of the cell energy to its volume, and on the total energy of the cell cluster. The first dependence distinguishes between dense electromagnetic deposits and mip type hadronic deposits. The second accounts for the dependence of the electromagnetic fluctuations amount with the total energy. As a result of these corrections , the energy distributions present less tails, a more Gaussian shape and a resolution better by about 15%.

An approach by neural net on LC simulation shows an improvement in hadronic resolution by 30%. All this demonstrates that we have to have the capability to distinguish electromagnetic and hadronic components, and that this may rely on energy density measurement if the cell size is adequate. We should also remember that it is possible to tune the relative response to electromagnetic and hadronic components by playing with the radiator interaction to radiation length ratio, (10 for Fe, 30 for W), and with the nature of the detecting medium.

2.6 The energy flow scheme

On the figure 12 the distributions of the different contributions in the energy flow expected at ILC are shown: in blue the tracker with a $\delta p/p^2 = 10^{-4}$ with p in GeV, in yellow the electromagnetic calorimeter contribution with $\delta E/E = 0.1/\sqrt{E}$ and in red the hadron calorimeter with $\delta E/E = 0.5/\sqrt{E}$, where E is also in GeV. As can be seen, in the domain of interest the tracker is always better. Only at very high energies does the electromagnetic calorimeter compete for electrons.

Would the detector be ideal for separating the different particles, we would measure :
- the charged tracks with the tracker,
- the photons with the electromagnetic calorimeter,
- and only the neutral hadrons by both calorimeters together.

Then, for a real detector, the challenges are
1) to effectively separate the particles, and not create fakes,
2) to optimise the resolutions and particularly that of the hadronic calorimeter.
3) to identify properly the vertices each track is coming from.

Once the vertices, decays, found, we can write in the ideal case the 4-momentum of a set of particles as the sum of their momenta:
$P = \Sigma[P_{charged} + P_{\gamma} + P_{neutral}]$ and $\sigma^2 = \sigma^2_{charged} + \sigma^2_{\gamma} + \sigma^2_{neutral}$.
With the values quoted above $\Delta E/E = 0.18/\sqrt{E}$. The photon resolution plays little role and the effort has to be on the hadronic resolution: going to 0.3 instead of 0.5 would achieve 0.12 on the jet resolution!

But for a real detector two effects play an important role: threshold and confusion.

There exists an effective threshold on :
- charged particles due to the high magnetic field needed for background, precision and separation,
- photons due to cell threshold and physical background,

And a probability of confusion due to:
- efficiency of track reconstruction,
- probability to generate fakes, in particular in case of a low redundancy,
- vertex misidentification,
- wrong associations between tracks and calorimeter cells.

The main enemy is confusion, far more than resolution and the design of the detector has to address this point first.

2.7 The calorimeter recipe

We then get a general recipe for a calorimeter:
- set it as far as you can afford,
- have an electromagnetic part with a large ratio λ_I/X_0 of the interaction length to the radiation length to separate photons from hadrons, very dense or very small X_0 to optimise the separation between photons by making the showers narrow, very granular because this is the true key to separation. Concerning this last point we should remember that the typical limit of separation

between a hadron and a photon is about 2 times the cell size and that the shower core is much narrower than a Moliere radius. We should then aim at a cell size much smaller than the Moliere radius.
- have a hadronic part very close to the electromagnetic one, dense and very granular not only to separate showers but also to distinguish the two components of the showers.

We can then sketch a possible algorithm for such a flow analysis, it goes by descending order of clarity: find tracks with their vertices, V^0 's and converted γ's, identify electrons, find the photons from the electromagnetic calorimeter knowing the charged tracks, identify muons, find the showers associated to charged hadrons, find neutral hadrons, by topology with energy balance only used as a check, then build masses, energies, momenta for any set.

And with a good particle flow, not only you manage the jets, but you can also manage the taus.

2.8 The tau challenge

Taus are one of the few polarimeters we have at hand and their decay identification is essential for measuring their polarisation, which in turn brings information about subjects as interesting as the violation of CP in the Higgs sector. The figure 13 shows a decay $\tau \to \nu\rho$ and gives an idea of the difficulty to disentangle the photons from the charged pion and the sort of help we can expect from a very good granularity both lateral and longitudinal. On a more

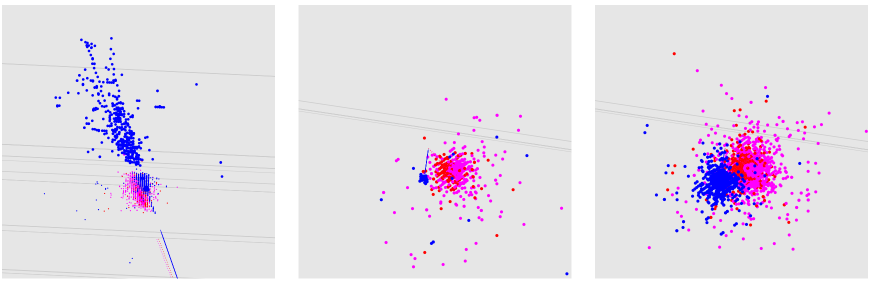
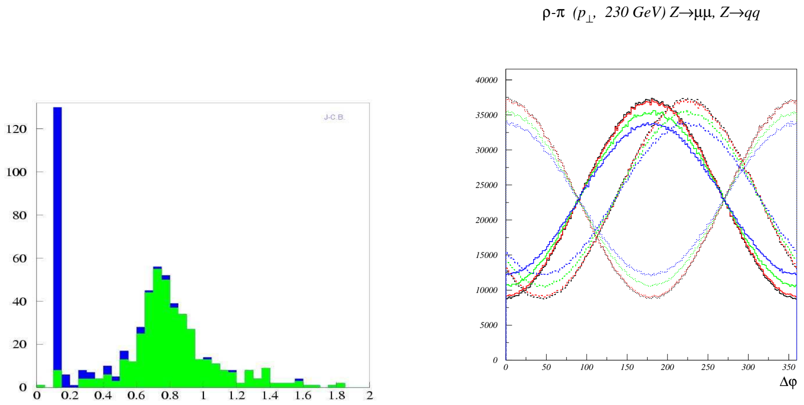


Figure 13: $\tau \to \nu\rho$ decay. On the left a transverse view, in the middle the firts 4 radiation lengths seen along the track, On the right the complete development of the showers.

quantitative basis, the figure 14 a shows how well this granularity helps separating decays into ρ from decays into π even at these high energies. Using simply the reconstructed jet mass as a separator, 82 % of the decays into pion are below 0.2 GeV with a 2% ρ contamination when between that value and

2 GeV we get 90 % of the ρ 's with a contamination of 17 % [4]. Note that, to measure polarisation or polarisation correlations (here transverse spin correlations) an excellent separation between π and ρ is essential. The figure 14 b illustrates the effect of such a separation in the analysis of the CP state of a Higgs decaying into two taus [5]. The reaction is $e^+e^- \to ZH$ with $Z \to \mu\mu$



(a) Apparent mass of the tau

(b) Measurement of the CP violation in the Higgs sector. The black curve corresponds to the theoretical distribution, the red one is obtained by adding the beamstrahlung effect, the green one corresponds to the Z into muons and the blue into quarks.

Figure 14: Using the taus and their polarisation.

or $Z \to q\bar{q}$ and $H \to \tau\tau$. The $\Delta\phi$ angle is defined as the angle between the planes containing the τ direction and the tau polarisation analyser for each τ in the Higgs rest frame. The frame is reconstructed from the Z energy and direction and the polarimeter from the tau decay reconstruction (in the case of a pion it is just its momentum). The three sets of curves correspond to a CP+, a CP- and a mixed state.

3 Conclusion

An efficient detector for the International Linear Collider is highly granular has a smart software to separate topologically, by shape and energy the different particle contributions, it optimises the hadronic resolution. Clearly it is also capable of excellent lepton identification and then provides the measurement of a Flow of particles.

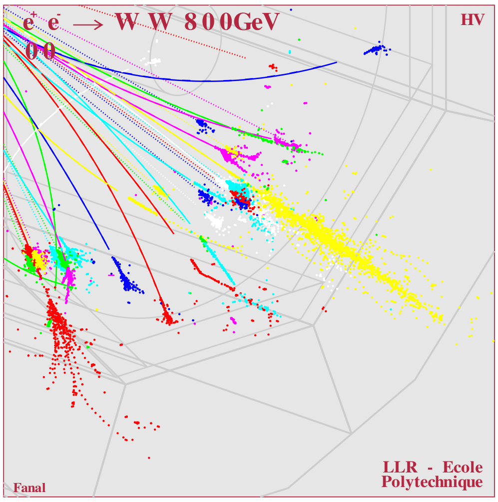


Figure 15: Particle showers as exhibited in a high granularity calorimeter for a 400 GeV W hadronic decay.

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