Summary of the calorimeter session

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Abstract.
At the future linear collider, most of the interesting physics processes have many jets in the final state. For this reason, the design of the calorimeter has to be evaluated through the jets reconstruction (Eflow). In the calorimeter session, about half of the talks were related to Eflow, the second half concerning the hardware side of the studies. All groups agreed on the importance of quantifying the proposed detector through a reconstruction program of the multi-jet events. A first attempt to reconstruct with fully simulated events using the ECFA proposed detector, reached a jet energy resolution of $\Delta \mathrm{E_{JET}} \sim 40\% \sqrt{\mathrm{E_{JET}}}$ which seemed mandatory for the very rich physics program on the Linear Collider. It corresponds to a significant improvement when compared to LEP/SLD experiments. To reach this kind of value both ECFA and LCD(US) groups followed the road of sampling calorimeter, with a large number of segmentations and a small pad size. It is not the case of JLC-group which took the road of hardware compensated calorimeter.

The hardware studies of the calorimeters have made a lot of progress in the realistic direction. A lot of R&D are foreseen, on the technical side as well as on industrialisation, cost ... On the side of hardware compensation, the JLC group, built a prototype and put it on test beam. First results were given and the goal of $e/\pi=1$ seems at hand.

INTRODUCTION

The multi-jets final states are of first importance for the physics program at the future linear collider, as we can see on the W/Z separation, the resolution on the di-b-jet mass for the Higgs, the jet multiplicity and total event mass for the top,etc... [1]. While single lepton/hadron or more generally single isolated particle was considered as the good test sample for a calorimeter up to now, it is clear now that the test has to be done with jets, that is to say through an energy flow (Eflow) reconstruction program. While first presentation about Eflow was presented in Sitges [2], the new trend we can observe now, is the general agreement on the role and importance of the Eflow to test the calorimeter. In order to give an idea, it is of importance to see the energy distribution of the charged tracks, photon and neutral hadron inside a jet. The example of $e^+e^- \rightarrow ZH \rightarrow b\bar{b}q\bar{q}$ process at $\sqrt{s} = 350$ GeV is used, and the distributions are shown in figure 1. The mean number of eflow objects are 30 photons, 31 charged hadrons and 3 neutral hadrons.
It could be noted that 22% of the photon energy in the event comes from photon with energy below 2. GeV. In this energy range, the mean photon multiplicity is 23, with a mean energy of 650 MeV. In other words, we are facing a large number of small energy photons instead of low multiplicity of high energy particle(s).

Two types of Eflow have been studied up to now for the physics at NLC. First the typical method used at LEP/LSD, wich can be called "analytic eflow", corresponding to the ultimate compensation. It consists in separatly reconstructing charged tracks, photon(s) and neutral hadrons. It was studied by the European group and the LCD group. The second road follows the method used on hadronic machine, this is the hardware compensation. It is studied by the JLC group.

These two different approaches lead to different designs of the calorimeter. First, the EFCA group as well as the LCD(US) group optimise the Eflow object reconstruction instead of the single particle energy/angular resolution.

The JLC group, which takes the option of hardware compensation has begun to work on the eflow, trying to quantify their jet energy/angular resolution and the di-jet mass resolution.

Depening on the approaches, ECFA and LDC(US) groups go in the direction of a design with a small pad size and a large number of segmentation, which optimise the reconstruction, while the JLC group has developped a program of work leading to a physics prototype with lead-tile device, working on the ratio tile/lead to reach the perfect compensation at hardware level for single particle.

THE SESSION

The following list shows the talks of the session.

1. Pascal Gay *(LPC-Clermont)*
Energy flow with high granularity calorimeters
2. Raymond Frey *(Univ. Oregon)*
Study of energy flow in jet reconstruction
3. Yoshiaki Fujii *(KEK)*
Jet reconstruction studies
4. Vasiliy Morgunov *(DESY)*
HCAL reconstruction
5. Gary Bower *(SLAC)*
Calorimetry and jet reconstruction
6. Norman Graf *(SLAC)*
Clustering algorithm studies
7. Henri Videau *(LPNHE-Ecole Polytechnique)*
The W-Si electromagnetic calorimeter
8. Volker Korbel *(DESY)*
Tile hadronic calorimeter
9. Paolo Checchia *(INFN-Padova)*
The ECAL Shashlik design
10. Toru Takeshita *(Univ. Shinshu)*
Tile/Fiber hadron calorimeter performance
11. Kiyotomo Kawagoe *(Univ. Kobe)*
Performance of preshower/showermax detectors

THE ENERGY FLOW

In the Technical Design Report studies in the ECFA group, there are two options for the ECAL as well as for the HCAL. For the ECAL, the baseline is an ambitious tungsten-silicon sampling calorimeter(W-Si) while the backup solution is a shashlik calorimeter(SHL). For the HCAL, the baseline is a classical tile-stainless steel (THC) while a second solution is a calorimeter with a digital read-out only (DIG), made for example of a sampling calorimeter with RPC's-stainless steel, a sort of device with a large number of muon chambers. The first talks on the energy flow (P.Gay) presented a review of the analytic eflow in the framework of ECFA group with the option W-SI and DIG.

The analytic eflow.
Since the expected tracker precision is very good, the charged track en-

ergy/direction are taken from the trackers and therefore the work consists in reconstructing the genuine Eflow object(s) (photon(s), neutral hadron(s)) and to separate them from the debris of the charged hadron(s) interaction in the calorimeters. This key point is called the *Track Cluster Association*(TCA), and the main contribution to the energy/direction jet resolution comes from imperfect TCA.

Therefore the relevant parameters to quantify the quality of a detector and TCA are the following:

• the efficiency to reconstruct an eflow object(photon,neutral hadron) as a function of its energy and the distance to the closest charged track

• the rate of fake objects coming from the charged hadron interaction in the detector

For a rate of fake photons comparable to the one observed in the ALEPH detector, he showed the large improvement in the efficiency to reconstruct a small energy photon as close as 1 cm from a charged hadron. The gain on Eflow was quantified using the resolution on the visible mass as given by ALEPH [3] and by the first try of fully reconstructed events. A gain of the order of 2. is observed as shown in figure 2. The Eflow algorithm used for this result is based on a classical clustering approach, while a more complex approach, is based on statistical method and on a pattern recognition of the eflow object in the calorimeter. It is illustrated by figure 3, which shows that a small energy photon can be resonctructed and correctly separeted from the debris of the interaction of a charged hadron located at 1cm from the photon. This method shows that the path for better eflow performance is open.

Using a different detector, W-Si and THC, V. Morgunov shows nice picture of reconstructed events and a clear program of work based on classical algorithm. First, it is needed to understand the behavior of single particles in the calorimeters, then to establish a strategy for the reconstruction, based on the first step. Large parts of the program are ready, and some parts remain to be done. No number was given yet, but to illustrate the W-Si capability, he shows the reconstructed lifetime when a K_s decays into 2 π^0, which is an impressive result.

On the LCD(US) side, R.Frey shows the preliminary results of the test he performed on the options small and large [4] of the proposed LCD detector.

The first check confirms the better resolution obtained with the analytic Eflow when compared to the Eflow based only on calorimetry. Then, using a fast simulation for the deposited energy, a Track Cluster Association (TCA) was developped to test different configurations of the detector, namely the option small(S) and large(L) of the LCD-group. Using $e^+e^- \rightarrow ZZ \rightarrow$ jets, a better separation and reconstruction was observed for the L option. This point is clearly related to the level arm given by the distance between the vertex and the entry point of the ECAL.

In order to keep flexibility to test different configurations, N. Graf proposed to have a generic clustering algorithm, which could work independently of the design. It is based on multidimensional fit of gausssian and exponential distribution. The work is in progress and it is hoped to have results very soon. It is illustrated by figure 4 which shows the results of the fit in a noisy environment.

Now the question to be raised is how to quantify the effectivness of the Eflow for a given set of physics processes? This point has been studied by G.Bower. He proposed a set of multi-jets final state, namely $e^+e^- \rightarrow q\bar{q}, ZZ, W^+W^-, ZH$ and $t\bar{t}$

After determining the discriminant variables, like the jets multiplicity, hemisphere mass, particle rapidity, ... the set of variables is used to feed a Neural Net, with which the separation table can be made. For each set of detector/reconstruction, such a table can be produced, as it is shown in table 1. This is one way to quantify the different detector option, which could be interesting. I think however that taking a specific physics case, like Higgs mass, Higgs width, top mass,etc ... is probably easier to interpret.

Y. Fujii presented a report on the eflow studies made with the JLC-detector. A first test was to change the magnetic field from 2 to 3 Tesla. The calorimeter proposed by the JLC-group is a projective structure made with a tile-lead sampling calorimeter, for the ECAL as well as for the HCAL. It gives the following result on single particle:

$\Delta E/E = 15\%/\sqrt{E} \oplus 1\%$ for electron/photon
$\Delta E/E = 40\%/\sqrt{E} \oplus 2\%$ for hadron

The goal of the study was to test the response to single particle, then to use a “Fake” jet made of one electron, one charged pion, and one photon. all three particles have the same direction and the same energy (19 GeV), but the electron and charged pion have opposite charges. This idea is to have 2 fake-jets like that per event, with a mass of the order of the W mass. It was hoped to test the Quick-simulation analysis which predicted a resolution of 3.0 GeV on the W mass, for standard W hadronic decays and 0.9 GeV for fake-W decaying into 2 fake-jets.

TABLE 1. Efficiencies optimised for the separation of all channels. First at the generator level and then for the fast simulation and detector L2 of the LDC(US) group. Talks of G.Bower

Level	Generator	Sim(L2)
$q\bar{q}$	91	76
W^+W^-	90	66
ZZ	97	53
ZH	96	74
$t\bar{t}$	100	86

The clustering was made using Jade jet algorithm in the ECAL and a sort of unconnected "island" clustering for the HCAL. These two clusterings give good result on the Quick-simulation. The study is now performed on full simulation.

Due to the tile size, the photon is usually in the same cluster than the charged tracks. In this condition, the TCA is based on the energy balance between the cluster energy and the charged track momentum as measured by the tracker. Using only the calorimeter informations gives a mass resolution of 2.4 GeV on the two fake-jets mass. However, when using the TCA, the resolution degrades to 4.4 GeV. Clearly, the preliminary result is not going in the right direction and further checks and tests have to be performed before any conclusion. It must be noted that Quick-simulation gives result far too good, which is not surprising when thinking about fluctuations on the hadronic shower which are not simulated.

My conclusion is that the fast simulation has to be made not at the level of energy deposition, but after the reconstruction on fully simulated events, by a modelisation of the TCA response, as proposed by the ECFA calorimeter group.

THE CALORIMETER DESIGN

The detector design has been studied on the basis of the choice for the jet energy flow. Starting from analysis or technological point of view, changes also the design.

Starting from the analysis point of view, H.Videau presented the status/prospect of the W-Si ECAL. The choice as well as the design are optimized for the reconstruction (Eflow). If the principle of silicon-tungsten calorimeter is well known (i.e. at LEP for luminometer), the way it is proposed for the ECAL is relatively new. The design is optimised for the analytic Eflow, leading to the following requirements:

• No large crack

For that the geometry is realized by an octant barrel, with the front-end electronics behind the ECAL, in the space between ECAL and HCAL. Similar design is also obtained in the end-cap Figure 5 shows the barrel response with a Z decays in 2 jets, and the end-cap design.

• The best possible separation between shower

The Moliere radius is the right order of magnitude for the pad size, and in order to perform a good pattern recognition of the showers in a jet, a large number of segmentation The choice of tungsten, leading to an average medium with 1cm of Moliere radius and a small radiation length is obvious. Because of the strong magnetic field and to optimize the compactness, it is impossible to use chambers like in ALEPH or DELPHI. To optimise the pattern recognition, the detector must have a good signal/noise ratio at the m.i.p. level. For all these reasons, the choice of silicon PIN diode seems natural.

The design proposed is 1cm pad size with 40 layers in depth and ALL PADS read at each bunch crossing. The zero suppression is made at the front-end level, by an energy cut. The large dynamics, about 15 bits, can be covered by 2 gains of 10 bits each. This also could help to have a noise at the level of 1/10 of a m.i.p. needed by the large number of channels, about 30 millions.

About the expected performance of the W-Si ECAL, it can be noted for single electron/photon , an energy resolution of $\Delta E/E \sim 0.12/\sqrt{E}$, a position resolution of $(1./\sqrt{E}+0.4)$mm, an angular resolution of $60/\sqrt{E}$ mrad and for isolated charged particles an excellent separation $e/\mu/\pi$, i.e efficiency to tag an electron of 99.8% for a hadron contamination $\sim 10^{-3}$. The performance within jet or for the jet itself was described previously. It must be noted that the energy resolution given by GEANT4, is confirmed when using EGS4 [5].

R&D on the silicon diode, front-end electronics, etc.. are foreseen in the next years. The design remains to be optimised, in particular the number of layers, which is the key parameter for what concerns the cost of such a device, estimated today at about 130 Meuros. A factor of 2 reduction seems therefore a desirable goal.

All the other talks on the calorimeter design, used the starting point of the technology. This is the case of V.Korbel, who described then the tile hadronic calorimeter which is one of the option which complements that W-Si ECAL in the ECFA group. It is a "classical" tile calorimeter, with 0.5 cm scintillator followed by 2 cm of stainless steel. The tile size is 5×5cm^2 at the HCAL entrance and 20×20cm^2 at the exit. The geometry has been adapted to the octant geometry of the ECAL. This device corresponds to 4.7(10) interaction lengths in the barrel(end-cap), for a total of 7.3 10^5 tiles and about 200K channels. There are 9 read-out layers in depth. The signal/noise for m.i.p. particle, which could be difficult, is under study, as well as the questions of the WLS fibers, the photodetectors, the preamplifiers and the number of fast ADC's. The study on the expected resolution and neutral hadron reconstruction is also in progress. A prototype is foreseen in order to validate the solutions about all the questions listed above.

For the ECAL back-up solution in the ECFA-group, namely a shashlik type calorimeter, the collaboration CALEIDO reports the test beam data for a second design of the detector, using two scintillators with different time responses. It allows to have two read-out segmentations in depth. The results of the test beam data show that requirements on single particle response have been fullfilled. It remains to quantify the loss on the jet energy resolution when using only two segmentations in depth, in order to compare with more expensive calorimeter, such as the W-Si ECAL.

As previously mentioned, the JLC group has oriented his work in the direction of the hardware compensation. First of all, the ratio e/π has to be close to 1 for a large energy range. It was studied with a prototype put in test beam. The results, reported by T.Takeshita, showed a ratio $e/\pi \sim 1$, for 9.1mm lead and 2mm scintillator, all along the wide energy range coming from 1 to 150 GeV. For the same energy range, the energy resolution for pions has been measured to be $\Delta E/E = 46.6\%/\sqrt{E} \oplus 0.9\%$ A first step has been done in the direction of the analytic Eflow, by the introduction of two devices, a pre-shower and a shower-maximum detector. These two devices are inserted in their tile ECAL in order to improve the γ/π separation and the position measurement. K. Kawagoe reported the results obtained on the test beam data. A reasonable position measurement was observed, and also a reasonable electron identification. For an electron tagging efficiency of 95% a misidentification of about 10^{-3} was observed on the hadron. However, it was tested with high energy beam, 50 to 100 GeV, and clearly a test at low momentum would help to quantify the gain for particles in jets.

THE CONCLUSION

Even if a lot of work remains to do, the picture is beginning to be clearer. The capability with multi-jets final state is the key point for the calorimeter design. A jet resolution of $\Delta E \sim 30\%/\mathrm{sqrt}E \oplus c$, with a small c value, is probably mandatory for the very large physics potential of the future linear collider.

The LCD(US) and ECFA group are going in the direction of small pad size and large number of segmentations. The pad size and the number of longitudinal segmentations and its impact for the jet(s), will be the subject of the future studies for this two groups.

Whether or not the hardware compensation, as studied by the JLC group, would be able to reach this value will give an important information for the final design of the calorimeter.

Finally, the jet energy/direction resolution as a function of the cost of the calorimeter, translated to its impact on physics, will definitly fix our view of the calorimeter for the future linear collider.

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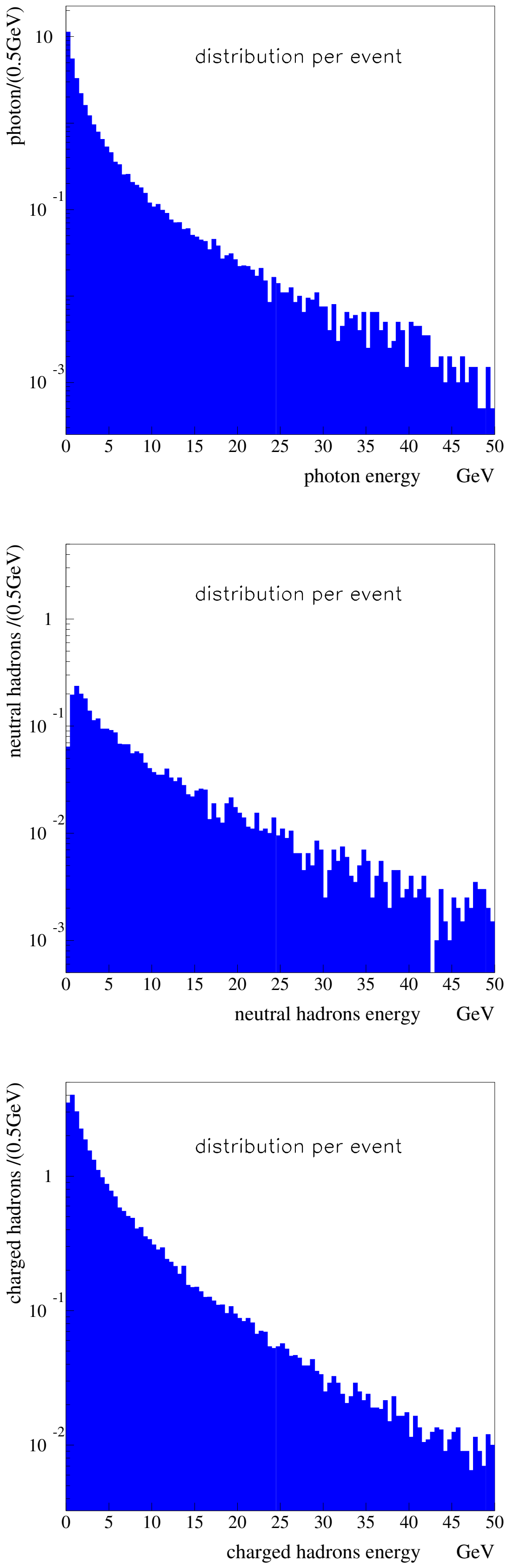

FIGURE 1. The energy distribution of the 3 types of eflow object for $e^+e^- \rightarrow ZH \rightarrow b\bar{b}q\bar{q}$ process at $\sqrt{s} = 350$ GeV

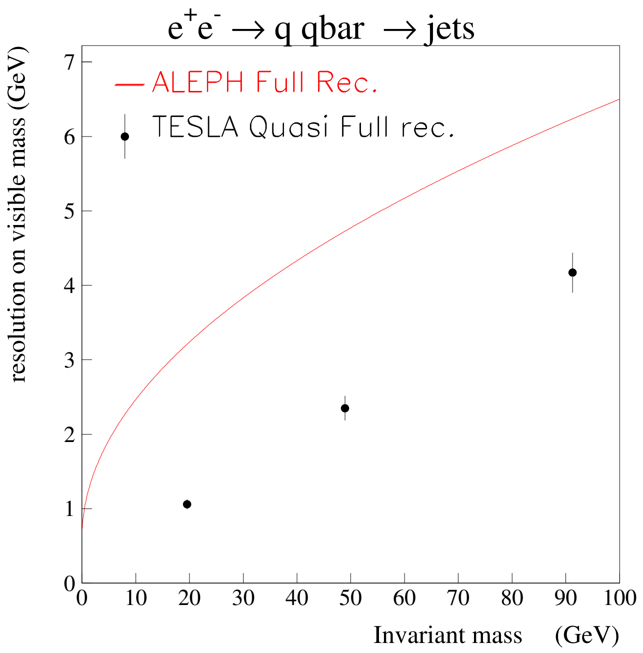

FIGURE 2. The visible mass resolution with ALEPH detector for energy perpendicular to the beam (line) and for the simulated reconstruction of W-Si and DIG calorimeter (see text.) (black dots)

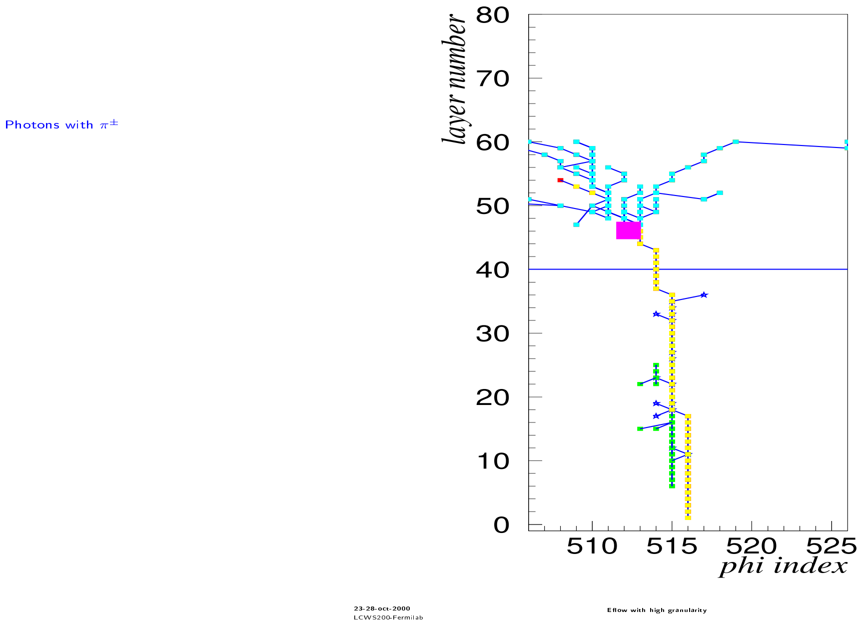

FIGURE 3. Example of pattern recognition for a photon at 1cm from a charged hadron, in the W-Si and DIG calorimeter(see text).

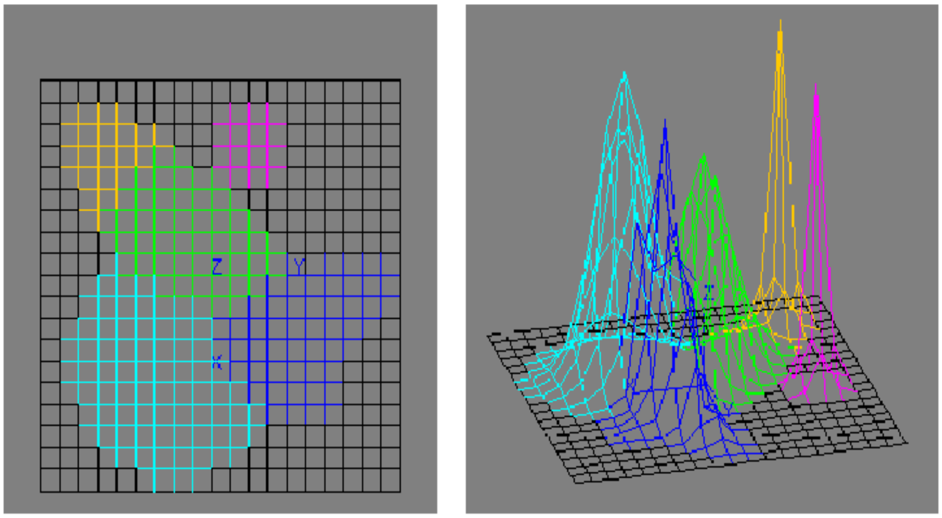

FIGURE 4. Results of the fit performed for the clustering in a multidimensional device.

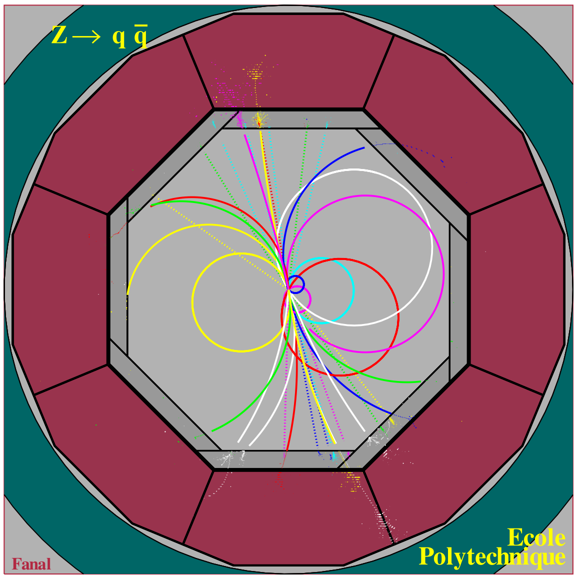

FIGURE 5. Z decays in jets simulated in the barrel of the W-Si ECAL and DIG HCAL - ECFA-group.