Particle Flow Calorimetry

Shower topologies and high-level reconstruction algorithms

Goals

The purpose of this exercise is to become familiar with topological properties, the characteristics of energy depositions and event-to-event fluctuations of electromagnetic and hadronic showers, using test beam data collected with a similar prototype as the one used in the hardware part of the calorimeter exercise.
In the second part high-level particle flow algorithms are applied to simulated di-jet events, with the goal to understand the interplay of topological reconstruction and energy resolution.

Common for the whole analysis: Access to the NAF (National Analysis Facility):
Type in terminal: ***naf*** (creates ssh connection), then ***school*** (directs to project path)

Part A: Shower topologies in a highly granular calorimeter

This part uses an interactive event display program to view showers collected In the CALICE SiPM-on-Tile (AHCAL) prototype in test beams at the CERN SPS, and simple statistical analysis tools.

Common for all tasks in this part:

- Directory with data: *EDIT2020/Data/PartA/*
- Directory with analysis tools: *EDIT2020/Analysis/PartA/*

Instructions for using the event display

- Go to folder *EDIT2020/Analysis/PartA/EventDisplay/*
- Command to start the display: *./start.sh [particle] [energy]*
    - ➡ Example: *./start.sh pion 10* or *./start.sh electron 50*
- Viewing operations
    - Rotations, zooms, transparency, background colour
    - Manual: https://github.com/iLCSoft/CED/blob/master/doc/manual.pdf (On desktop, check section 3, 6 and 7.)
- Additional information
    - Shower start (blue layer)
    - Colour coding: Green hits - low energy, red hits - high energy
    - **Longitudinal energy profile** as an **additional window**
    - Shower maximum, energies etc. as terminal print out
- Next event: Press "Enter" in the terminal. You can not go back to previous event. If you want to do so, restart the event display
- Quit event display: "CRTL"+"C" in terminal and close "CED" window manually

A1: Electromagnetic showers

Data: Electron events, beam energies 10 and 50 GeV

Task: Open a new terminal, connect to the NAF and navigate to:

EDIT2020/Analysis/PartA/EventDisplay/

Initialise the needed software by executing:

source init_software.sh

Start the event display as explained above. Two windows will open, one with the actual event display, one with the longitudinal energy profile of the event. Scan 20 events at each energy and observe how characteristic quantities change from event to event and how they vary with energy:

- Topology: Shower starting point, layer with maximum energy
- Energy deposition: Energy in first layer, energy in maximal layer, energy sum

Make yourself familiar with the typical properties of these showers.

Note 1: If you have found dedicated graphic settings in the event display ("CED" window) you can save those in the tab: Graphics -> Save settings.

Note 2: If you want to restart the event display or check another energy please make sure to properly close the previous instance by closing the "CED" window manually and executing "CRTL" + "C" in the terminal to avoid multiple instances.

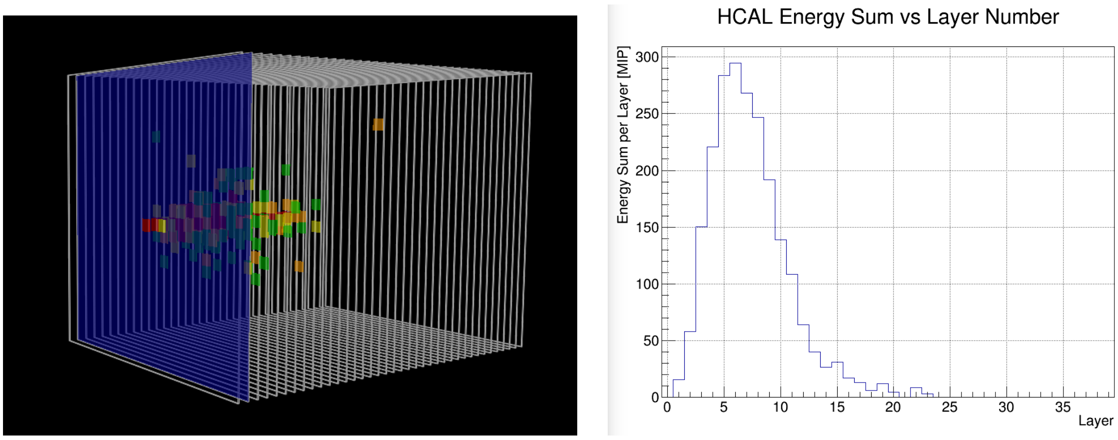


Figure 1: Electron shower 10 GeV, reconstructed first interaction layer, shower profile

Detailed analysis: Study distributions of the introduced quantities for a larger sample. To do so, change to the directory:

EDIT2020/Analysis/PartA/LargeSampleStudy/scripts

and execute the corresponding python script by

python [analysis_script].py

A ROOT file will be created in

EDIT2020/Analysis/PartA/LargeSampleStudy/output

Navigate to this folder and open the ROOT file by doing

rootbrowse [rootfile].root

Compare the extracted quantities for the different energies and summarise your observations. How is the energy sum and the shower energy profile changing? How much energy is deposited in the first and last layer of the calorimeter? In which layer is the electron shower starting typically?

Note 3: If you want to compare the same quantities for different energies or particles in the same ROOT window: In the output folder only execute:

rootbrowse

This opens all existing ROOT files in the current folder. Select the first quantity plot by clicking on it, then enter "same" in the upper left box ("Draw options:“) and click on the second quantity plot you want to compare.
By right-clicking on one of the histograms lines you are able to change its colour.

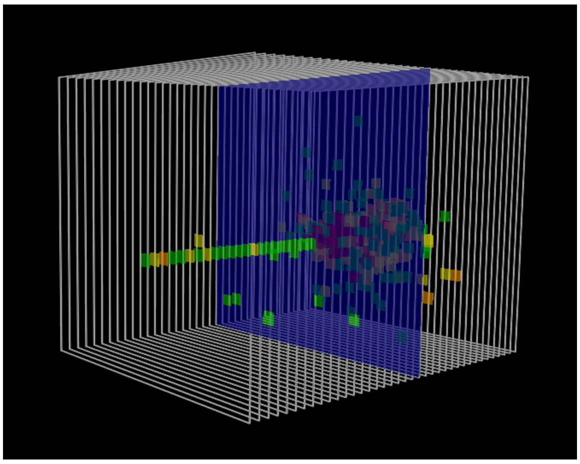
A2: Electromagnetic and hadronic showers

Data: Electron and pion events, beam energies 10 GeV

Task: Open the event display, scan ~20 pion events and study quantities as in A1.

Detailed analysis: Large sample analysis for pion events as in A1.

Compare the quantities for the pion events to the previously studied electron events and note your observations. Try to be quantitative. In which layer do the hadrons shower typically? Can you explain the first peak and the larger width of the second peak compared to electrons in the energy sum? How does the shower energy profile compare to the one for electrons?



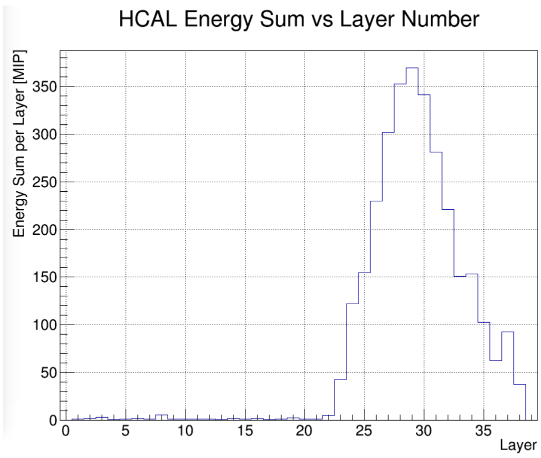


Figure 2: Pion shower 10 GeV, reconstructed first interaction layer, shower profile

A3: A closer look to hadron showers: Measure the interaction length

Data: Pion events, beam energies 20, 50 and 80 GeV

Task: Open the event display, scan ~10 hadron events at each energy and study quantities as in A1. What can you observe for higher energies?

Interaction length analysis: The number of primary, non showered hadrons is defined as:

$$N(z) = N_0 exp(-z/\lambda)$$

With N0 the initial amount of incident hadrons, z the calorimeter depth and λ the interaction length of the calorimeter.
Determine the hadronic interaction length from the distribution of the shower start layer position in z for the three different energies.
For this task navigate to the folder:

EDIT2020/Analysis/PartA/InteractionLength/scripts

and execute the corresponding python script with

python [analysis_script].py

The script performs the following exponential fit to the shower start layer position distribution:

$$f(z) = exp(Slope \cdot z + Constant)$$

It produces a ROOT file with the fit results in:

EDIT2020/Analysis/PartA/InteractionLength/output

Go to this folder, open the ROOT file as in exercise A and calculate λ from the fit parameter "Slope". Test the energy dependence of λ for the three different energies.

Compare the extracted values with an estimate based on material properties (assume steel and plastic only) of the 38 layer calorimeter prototype. Find material constants at http://pdg.lbl.gov/2010/AtomicNuclearProperties/ and use the prepared table to do the calculation.

Part B: Particle Flow Reconstruction

This part focuses on high-level particle flow reconstruction.
First, a simple single and two particle event reconstruction is studied for a standalone tracker-hadronic calorimeter scenario with CALICE SiPM-on-Tile (AHCAL) prototype data. After getting used to the fundamental concepts of particle flow reconstruction and the internal Pandora Particle Flow event display, we move on to more complicated di-jet scenarios in the ILD simulation of a full e+e- collider detector.

Common for all tasks in this part:

- Directory with data: *EDIT2020/Data/PartB/*
- Directory with analysis tools: *EDIT2020/Analysis/PartB/*
- For using analysis scripts, working with ROOT etc. see Part A

Instructions for using the Pandora Particle Flow internal event display

- Go to folder *EDIT2020/Analysis/PartB/EventDisplayHCAL/* or */EventDisplayILD/*
- Command to start the display: *./start.sh [#scenario] [#reconstruction_step]*
    - ➡ Example: *./start.sh 1 1*
- Available reconstruction steps:
  1 - Raw calorimeter hits, 2 - Initial clustering, 3 - Final clustering
  4 - Particle flow objects (PFOs) with associated tracks
- Viewing operations
    - Rotations, zooms, colour coding (PDG code: Check appendix)
    - Particle flow objects, clusters and hits selectable in left window
- Additional information (left window)
    - Reconstructed particle flow objects with tracks and clusters
    - Reconstructed energy of objects, particle type
    - Confusion matrix as summary print out for each event for ILD scenario
- Next event: Press "Enter" in the terminal. You can go back to previous events by selecting the dedicated event in the left window.
- Quit event display: "CRTL"+"C" in terminal

B1: Single particle reconstruction

Data: **Scenario #1**, pion events, beam energy 10 GeV, central detector position

Task: Open a new terminal, connect to the NAF and navigate to the folder:

EDIT2020/Analysis/PartB/EventDisplayHCAL

Start the event display as explained above and scan ~10-20 events for this simple scenario at the four different reconstruction steps. Make yourself familiar with the interactive event display, the color coding and the final PFO output (step 4).
How much energy of the 10 GeV pion is assigned to the primary (most energetic) PFO and the corresponding cluster hits? How is the reconstruction performing for pion events, which have a shower start in the last few layers or not at all (Event 1 and 14)?

Analysis:

Remark: For the "**Analysis**" exercises in part B please open a new terminal, connect to the naf, navigate to the project folder and initialise the needed software in

EDIT2020/Analysis/PartB/RecoComparison

once with:

source init_software.sh

Continue to work in this terminal for the Analysis part and not use it for the event displays. The software packages behind the event display and the init_software.sh are mutually exclusive and need to be run in separate terminals.

Compare PFO reconstructed energy with calorimeter energy for a larger sample. For this task navigate to:

EDIT2020/Analysis/PartB/RecoComparison/scripts

and execute the corresponding python script:

python scenario1.py

A ROOT file is created in:

EDIT2020/Analysis/PartB/RecoComparison/output

Additionally, the script prints out the events which have a large discrepancy between PFO and calorimeter energy. Go to this folder, open the ROOT file as in part A and investigate the difference in PFO energy sum and calorimeter energy sum. Can you explain the three different reconstruction cases in the correlation plot (check draw option "colz")? Why does the primary pion in most cases has an energy so close to the actual 10 GeV? Re-check the first four of the problematic events in the event display. What went wrong?

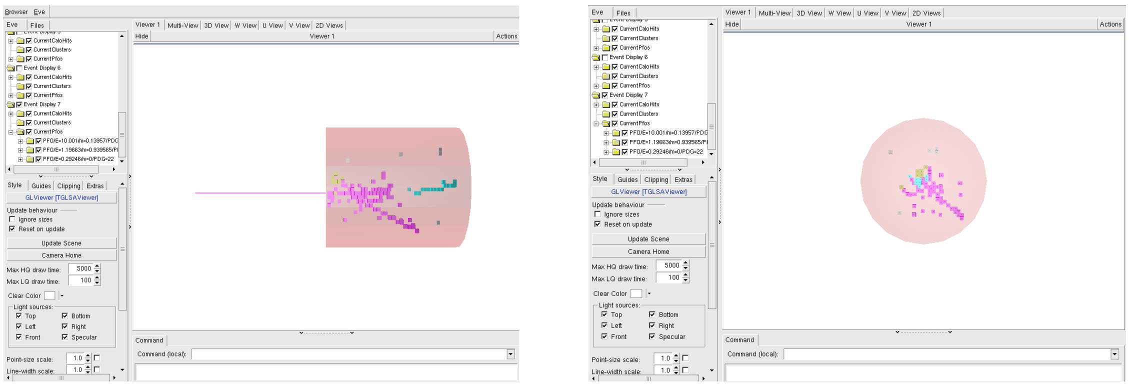


Figure 3: Pandora event display of single pion shower 10 GeV, AHCAL + track standalone scenario

B2: Two particle reconstruction

Data: Neutral kaon (K0L) events 10 GeV, overlaid with pions 10/30 GeV events at two different positions:

Scenario #2: K0L 10 GeV at Y = -180 mm, overlaid with pions 10 GeV at Y = 0 mm
Scenario #3: K0L 10 GeV at Y = -180 mm, overlaid with pions 30 GeV at Y = 0 mm
Scenario #4: K0L 10 GeV at Y = -180 mm, overlaid with pions 10 GeV at Y = 180 mm
Scenario #5: K0L 10 GeV at Y = -180 mm, overlaid with pions 30 GeV at Y = 180 mm

Note 4: The center of the layers is Y = 0

Task: Open the event display and scan ~10 event displays for each of the four scenarios as in B1 (only with final reconstruction step 4). How well can the two particles be separated? Which energies are assigned to the individual PFOs and how much energy do the corresponding clusters have? How does this change with the energy of the charged pion and its distance to the neutral cluster?

Analysis: Analyse a larger sample for the different scenarios and compare PFO energy and pure calorimeter information as in B1. For this use the corresponding python scripts in:

EDIT2020/Analysis/PartB/RecoComparison/scripts

with:

python scenario[#].py

Check the output ROOT files in the folder:

EDIT2020/Analysis/PartB/RecoComparison/output

and investigate the plotted quantities. Which reconstruction cases can you see this time in the correlation plot and how do they change with the energy and the distance of the charged pion to the neutral cluster? Re-check the first three problematic events for each scenario.

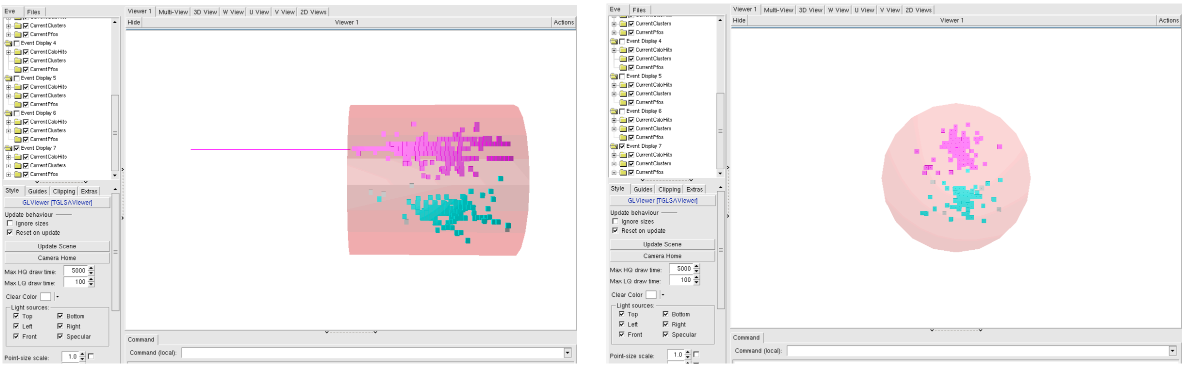


Figure 4: Pandora event display of overlaid K0L 10 GeV and pion 30 GeV showers, AHCAL + track standalone scenario

B3: ILD di-jet reconstruction

Data: ILD simulation, e+e- -> di-jet events

Scenario #6: 91 GeV
Scenario #7: 350 GeV
Scenario #8: 500 GeV

Task: Navigate to the folder:

EDIT2020/Analysis/PartB/EventDisplayILD

Open the event display and follow the four different reconstruction steps as in B1 for one of the energies for a few events in this more complex scenario.
Scan ~5 events for each energy after the final reconstruction (reconstruction step 4). Which particles are reconstructed and what is their energy?

Study the total reconstructed energy and the confusion matrix in the terminal and decide for a few events qualitatively how well the reconstruction has been performed.

Note 5: The DumpPfosMonitoringAlgorithm shows the following output as a terminal print out:

1. Total reconstructed PFO energy in GeV
2. A list of all reconstructed PFOs featuring particle type (first charged, then neural particles), reconstructed energy associated with a track, track momentum, cluster energy.
3. The confusion matrix (first absolute in GeV, second relative to total energy in %) showing which fraction of the real particles energy (simulated true information) got reconstructed as track, gamma, and hadrons.
4. A small matrix showing the unconfused part of the reconstructed energy (photons and neutral hadrons energy, using calorimeter info only) and the potentially confused part of the reconstructed energy (charged particles with associated track with assigned track energy).

Analysis: For each energy study a larger sample and compare the PFO reconstructed energy with the pure calorimeter information as in B1. For this, use the corresponding python scripts in:

EDIT2020/Analysis/PartB/RecoComparison/scripts

with:

python scenario[#].py

Carefully re-check a few problematic events with a large discrepancy between the two quantities with the event display. What might have gone wrong?

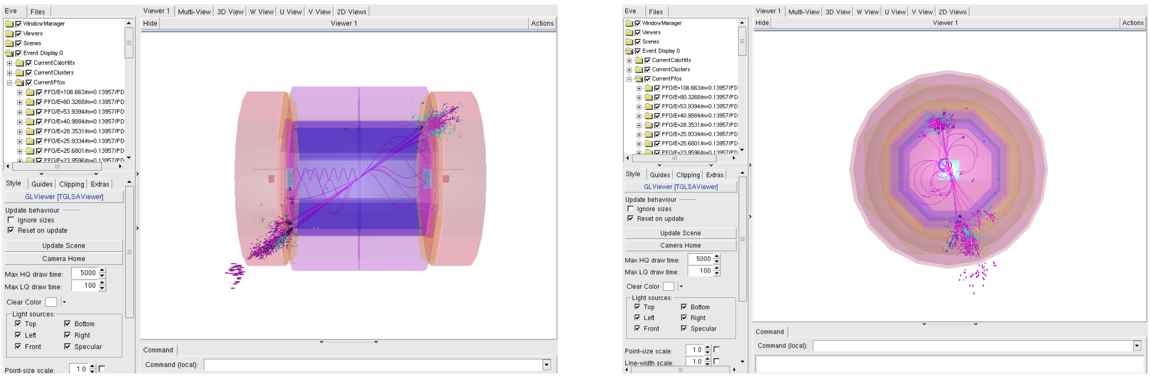


Figure 5: Pandora event display of 500 GeV di-jet event, full ILD simulation

Appendix 1: Interaction Length Calculation

Material	Thickness per layer [cm]	λ [cm] from PDG
Steel Absorber Plate (Assume Fe only)	1.72	
Cassette Steel Plate (Assume Fe only)	2 x 0.05	
Plastic Scintillator Tile (Assume 92% C, 8% H)	0.3	
Air	0.26	neglected
Others	0.24	neglected
One layer		

Appendix 2: PDG Particle Code and Color Table

particle	PDG particle code	Color
γ	22	dark yellow
e^-	11	light blue
e^+	-11	light red
μ^-	13	blue
μ^+	-13	red
τ^-	15	dark blue
τ^+	-15	dark red
ν_e	12	dark blue
$\bar{\nu_e}$	-12	dark red
ν_τ	16	dark blue
$\bar{\nu_\tau}$	-16	dark red
ν_μ	14	dark blue
$\bar{\nu_\mu}$	-14	dark red
π^+	211	magenta
π^-	-211	violet
π^0	111	light green
Λ	3122	dark green
$\bar{\Lambda}$	-3122	dark green
K^+	321	dark green
K^-	-321	dark green
K_s	310	light green
K_L	130	green
σ^-	3112	green
σ^+	3222	green
proton	2212	orange
neutron	2112	cyan

Table A.1: *PDG particle's code and color.*