APRIL : a particle flow algorithm for future e^+e^- colliders

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Plan

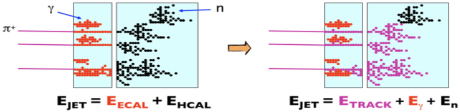
1. Introduction : Particle flow algorithms and the SDHCAL
2. The APRIL particle flow algorithm
3. Timing : APRIL 4D
4. Summary

Contents

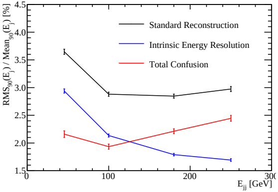
Particle flow calorimetry

Particle Flow Algorithm (PFA)

- PFA is the approach chosen for future colliders
- Use optimal sub-detector for jet energy estimation :
  tracker ($\sim 60\%$), ECAL ($\sim 30\%$), HCAL ($\sim 10\%$).
- Separate energy depositions from close-by particles : high granularity is key point



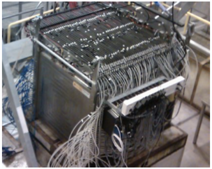
Extensive studies have been done with ILD detector option 1 (AHCAL, ILD baseline) and PandoraPFA algorithm.
At higher jet energy ($E \gtrsim 100$ GeV), dominant contribution to resolution is confusion.
See Steven Green, Cambridge University Thesis 2017

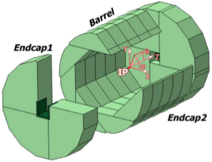


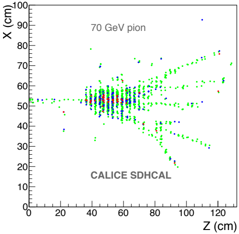
Semi-Digital HCAL

SDHCAL energy reconstruction

$$E_{reco} = \alpha_1 N_1 + \alpha_2 N_2 + \alpha_3 N_3$$







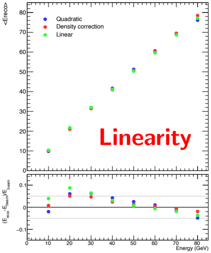
Options for E_{reco}

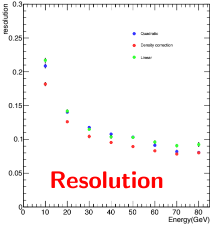
Thresholds(pC): 0.11, 5, 15

Quadratic $\alpha_i = a_i N_{hit}^2 + b_i N_{hit} + c_i$ (TB default)

Linear α_i constant (Pandora default).

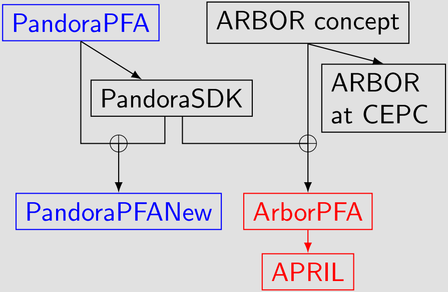
Density α_i = above × f(N neighbour hits)





PFA history

ILD PFA reconstruction



PFA strategy

Both PandoraPFA and ArborPFA, construct many small clusters then merge them.

- APRIL $\simeq$ ARBOR concept + PandoraSDK algorithms

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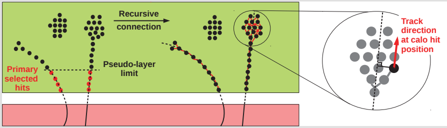
The APRIL algorithm

APRIL : Algorithm for Particle Reconstruction at ILC from Lyon.

The clustering strategy

- start from tracks (track driven clustering) extrapolate tracks in calorimeters → cluster hits close to the tracks.



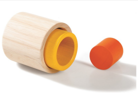
- Perform Arbor Clustering with all hits.
- → Clusters containing track cluster define charged clusters.
- Arbor parameters set to avoid making big clusters.
- → Some hits remain unclustered.
- Nearby hits merging : remaining unclustered hits are clustered with mlpack DBSCAN (efficient Nearest Neighbour clustering)
- If $E_{track} > E_{cluster}$, merge nearby cluster.

APRIL clustering

Graph theory : a shower is an oriented tree.

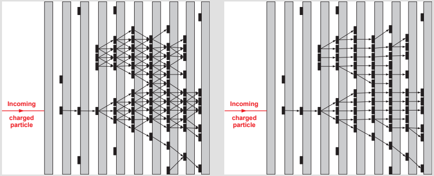
Orientation

- Rearrange hits in virtual nested cylinders (= pseudo layers)
- Count them from the inside.
- Forward direction = increase pseudo layer number.



Arbor

1. Connect all neighbouring hits (use mlpack NeighborSearch).
2. Clean connectors = keep max one backward connection per hit.



- ⇒ APRIL usable as long as you have the positions of the hits

Results

- Event samples: $e^+e^- \to q\bar{q}$, where $q = u, d, s$ ($|\cos\theta_q| < 0.7$)
- With ILD option 2 large (SDHCAL, SiW ECAL), PandoraSDK, ILCSoft
- Jet energy resolution, JER $= \frac{\mathrm{RMS}_{90}(\mathrm{E}_j)}{\mathrm{Mean}_{90}(\mathrm{E}_j)} = \sqrt{2} \cdot \frac{\mathrm{RMS}_{90}(\mathrm{E}_{jj})}{\mathrm{mean}_{90}(\mathrm{E}_{jj})}$
- JER at 91 GeV: APRIL: 4.74%; Pandora: 4.46%

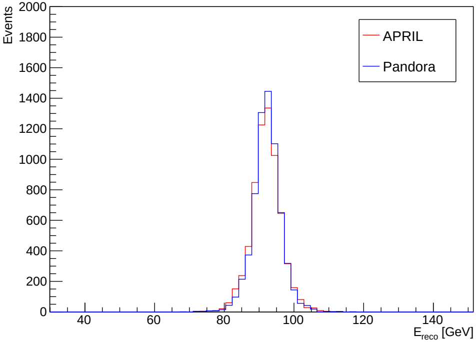
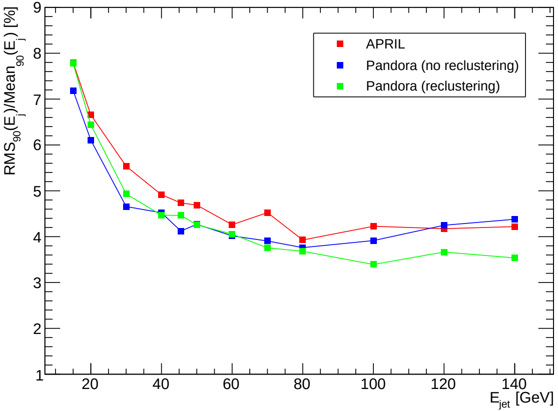


Figure: The energy of reconstructed PFO at $E_{\mathrm{CM}} = 91$ GeV

Results (continued)

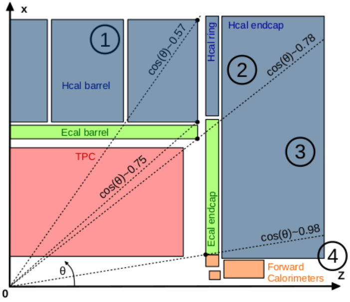
- Really recent work still in progress, cross-check needed
- PFO total energy + MC Neutrinos energy

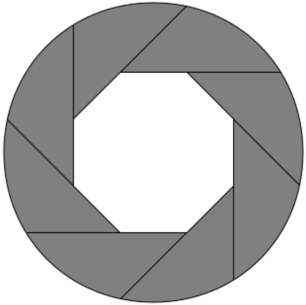


- PandoraPFA with reclustering better at higher jet energies
- APRIL has no reclustering → working on cluster splitting procedure (AMSTER)

SDHCAL corrections and calibration

- Recent work on ILD Option 2 (SDHCAL and Videau Geometry) to improve performances
- SDHCAL needed theta and phi angle correction $\rightarrow E_{\text{rec}}$ too low
- Working on a new quadratic reconstruction calibration
- Created an official SDHCALContent repository for all SDHCAL related plugins ▸ Git repo
- Separating detector (SDHCAL, ILD option 2) from PFA (APRIL).





SDHCAL corrections and calibration

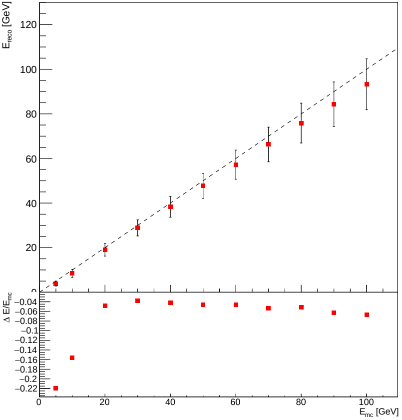


Figure: E_{rec} before corrections with classical linear reconstruction

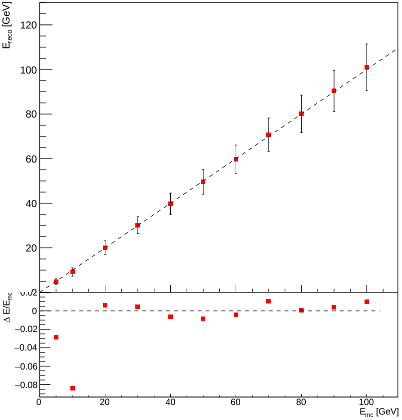
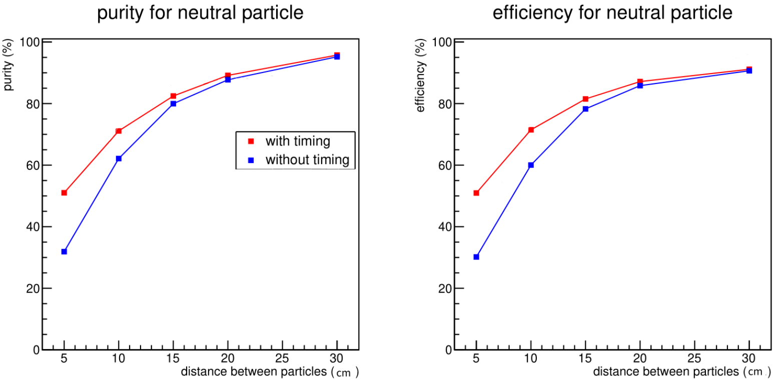


Figure: E_{rec} after corrections with new quadratic reconstruction calibration

Contents

PFA with timing

- SDHCAL should allow timing segmentation < 100 ps thanks to MRPC
- Possibility to follow the particles in "real time"
- Previous studies : timing improves separation
- **Goal** : Add timing to APRIL



Different applications

- Delete non-causal connectors between hits ($\beta > 1$)
- Late neutrons tagging to treat them separately
- Identify the seeds of the showers and count them
- Pseudo layers ordered in timing and not in space
- Each of the above can be added with a PandoraSDK algorithm

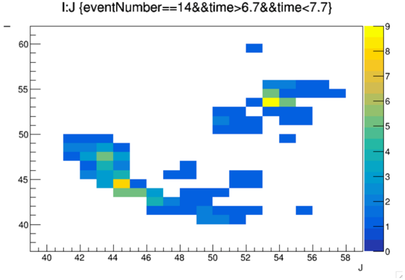


Figure: 1 ns resolution

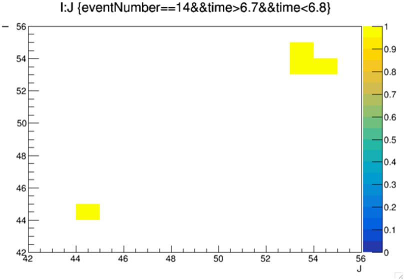


Figure: 100 ps resolution

Contents

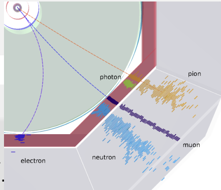
Summary

- A particle flow algorithm implementing the ARBOR approach has been developed in the PandoraSDK framework.
- Competing with PandoraPFA at low and intermediate jet energies in SDHCAL.
- New quadratic reconstruction calibration and corrections for SDHCAL give good results
- Next steps
  - Fully include timing in APRIL
  - Implement split cluster procedure (AMSTER)

Thank you for your attention !

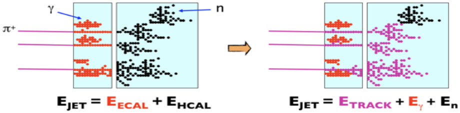
Backup

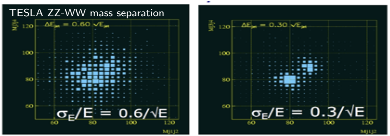
Particle flow calorimetry



Particle Flow Algorithm (PFA)

- ILC/CEPC physics program requires W/Z$\rightarrow q\bar{q}$ mass separation.
- $\Rightarrow$ jets resolution $[50, 500]$ GeV better than $\sim 3-4$ % $\sim 30\%/\sqrt{E}$.
- Use optimal sub-detector for jet energy estimation : tracker ($\sim 60\%$), ECAL ($\sim 30\%$), HCAL ($\sim 10\%$).
- Separate energy depositions from close-by particles : high granularity is key point





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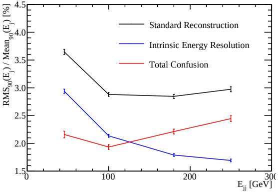


Charged cluster merging

Arbor like merging

- Connect charged cluster with all neighbour neutral clusters.
- Select neutral to charged backward connection with parameter order $\kappa = \theta^{p_\theta} \times d^{p_d}$
- Merge only if χ increase, staying below a maximum.
  - $\chi = (E_c - p_t)/\sigma_{E_c}$
  - σ_{E_c}
    - HCAL: $0.55/\sqrt{E_c}$ for hadrons.
    - ECAL: $0.15/\sqrt{E_c}$
- Cluster merging is still under optimisation.

Cluster geometry

- Cluster properties used to compute θ and d.
- For hit k, $e_k = \alpha_{threshold}$.
- The center of gravity of a cluster (COG)

$$\boldsymbol{o} = \frac{1}{\sum_k e_k} \sum_k e_k \boldsymbol{r}_k$$

- The cluster axis is computed from the eigen vector of inertial tensor (Principal Component Analysis)

$$I_{ij} = \sum_k e_k (\boldsymbol{r}_k^2 \delta_{ij} - \boldsymbol{r}_k^{(i)} \boldsymbol{r}_k^{(j)})$$

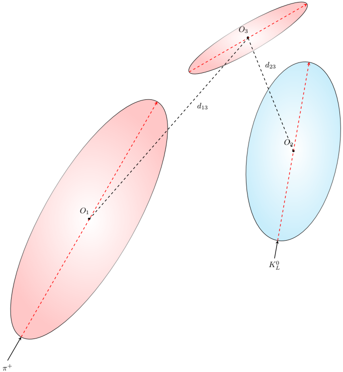
Merging clusters distances

For 2 big clusters

- d Distance of closest approach between the 2 axes.
- θ Angle between the 2 axes.

For a small cluster

- d Distance between the 2 COG.
- θ Angle between the 2 COG directions (from origin).



PFO creation

- Remaining neutral clusters to track association: add neutral cluster to existing or create new charged clusters, use position, direction and energy matching.
- PID
  - γ, $\pi^{\pm}$, neutral hadron; More particle categories (such as muon, electron) is to be considered.
  - Shower profile, energy deposition and track information are used.

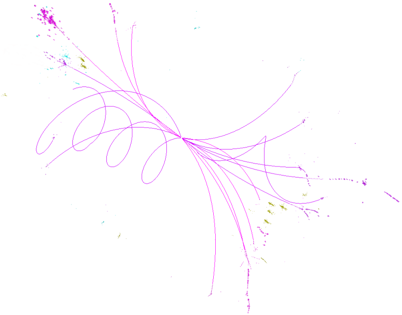


Figure: The reconstructed PFOs in an event of $E_{\mathrm{CM}} = 91.2$ GeV.

Simple "reclustering" approach

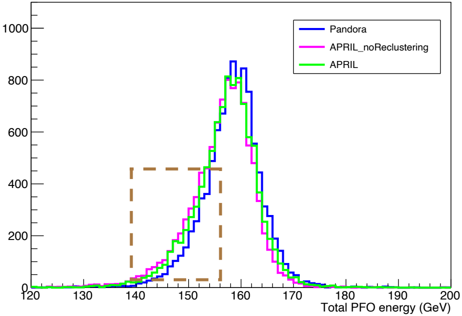


Figure: 160 GeV

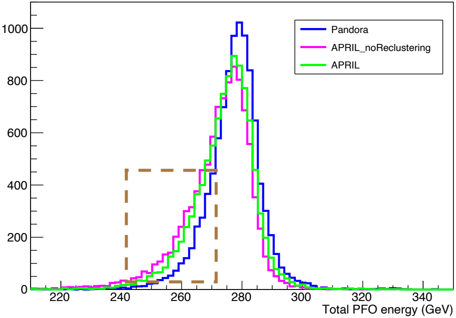


Figure: 280 GeV

- If $E_c > p_t$, remove hits from cluster until $E_c \simeq p_t$ and make a neutral hadron cluster with the removed hits.

Angle corrections

- **Goal** : implement angle corrections
- Purely geometric corrections
  - $N_{\text{hit}}^{\text{new}} = N_{\text{hit}} \times$ Effect
  - Effect $\frac{1}{\cos\theta}$ for endcap
  - Effect $\frac{1}{\sin\theta}$ for barrel
  - Effect $\frac{1}{\cos\varphi}$ for barrel only
  - Videau geometry taken in consideration
- Created SDHCALContent for all SDHCAL related plugins ▸ Git repo
- Separating detector (SDHCAL, ILD option 2) from PFA (APRIL).