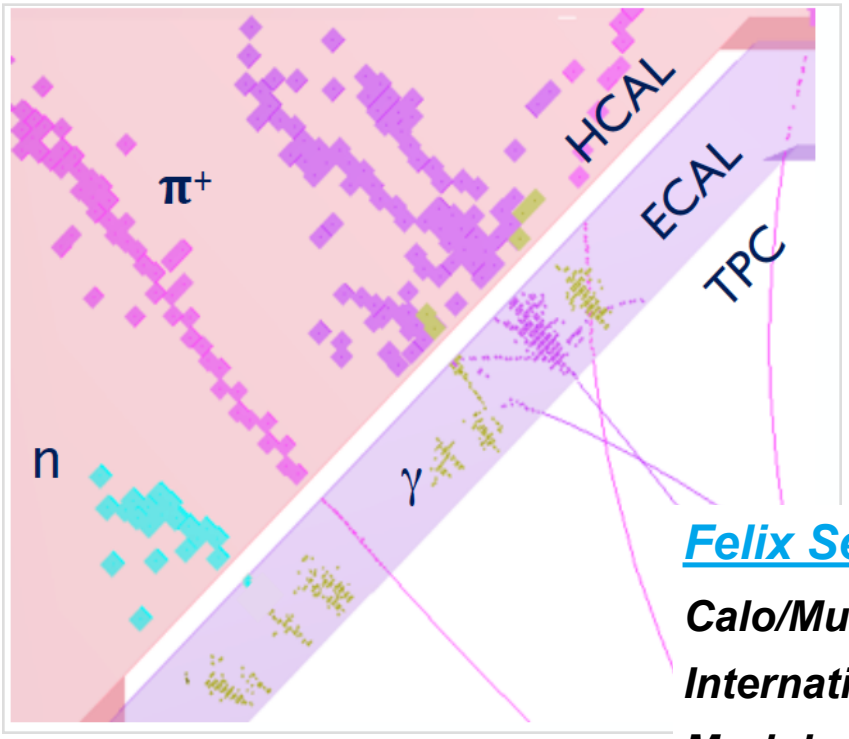
Software compensation in Particle Flow reconstruction



Felix Sefkow, Huong Lan Tran

Calo/Muon session - 07/12/2016

International Workshop on Future Linear Collider

Morioka, Japan, December 2016

HELMHOLTZ ASSOCIATION

CALICE

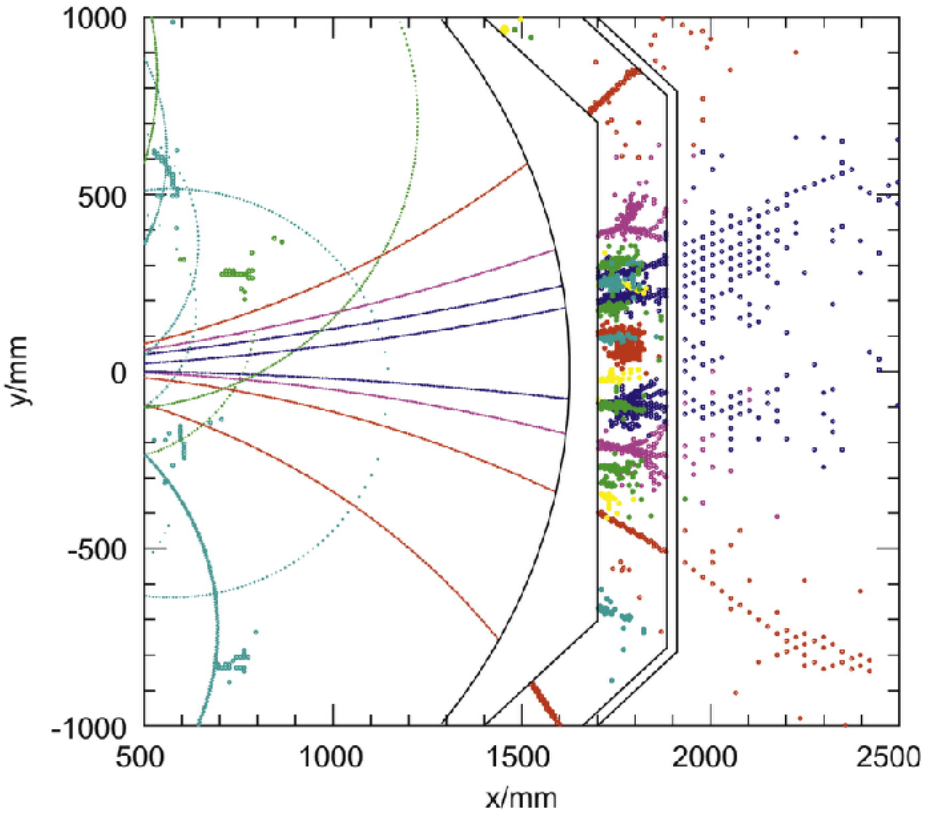
DESY

Outlines

- Particle flow reconstruction & Software compensation (SC)
- Software compensation technique
- Implementation of SC into Particle flow reconstruction
- Application of SC for ILD detector performance study
  - AHCAL transverse granularity optimisation

Particle Flow reconstruction & Software compensation

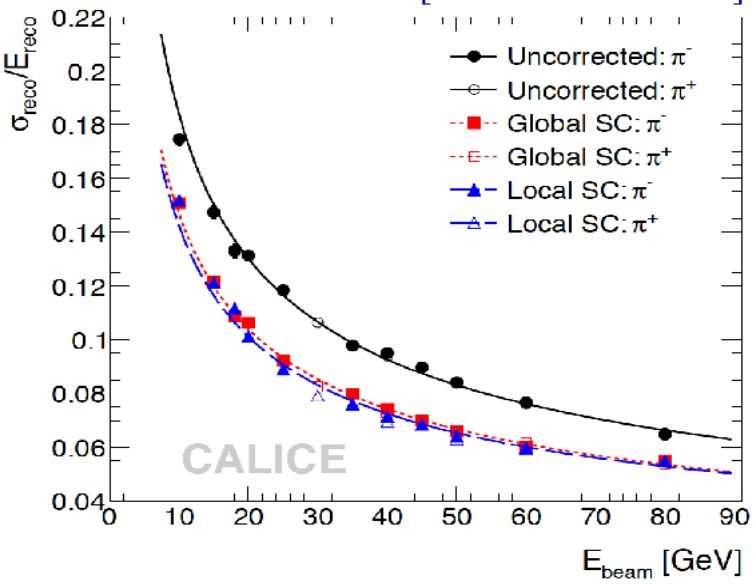
- Particle Flow reconstruction: trace individual particles
  - Need **precise measurement of particle's energy** with calorimeters
- ILD calorimeters are non-compensating: degrade energy resolution
  - Compensation with electromagnetic response truncation (cell energy truncation)
- But ILD calorimeters are highly granular:
  - Allow assessment at sub-shower level for electromagnetic and hadronic **sub-shower distinction** for software compensation



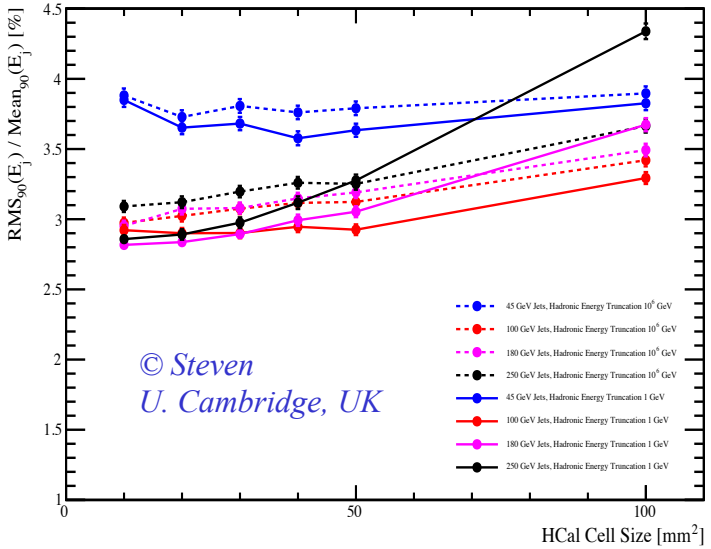
Particle Flow reconstruction & Software compensation

- Software compensation has been employed before
- **For test beam data from CALICE-AHCAL physics prototype:**
  - Improvement of hadronic energy resolution by 20% for single hadrons from 10 to 80 GeV

[arXiv: 1207.4210v2]



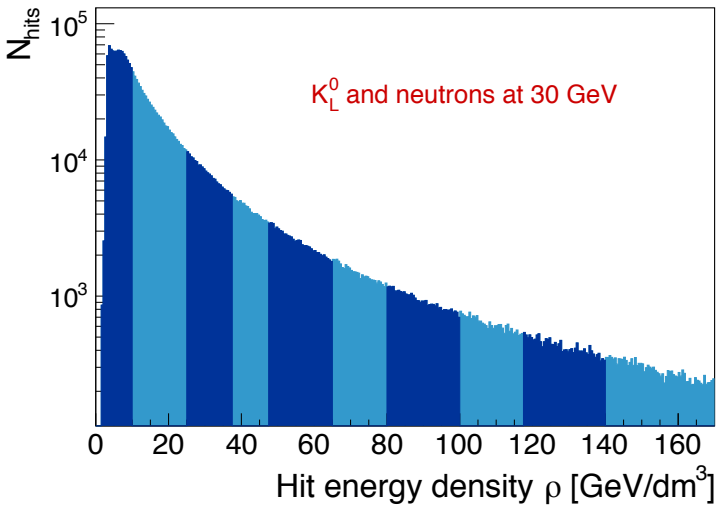
- **For JER study with PandoraPFA:** apply *HCAL cell energy truncation* to mimic SC in LoI study (solid lines)
  - HCAL cell energy truncation degrades resolution at high energy for higher cell size but improve energy resolution at smaller cell sizes → stronger dependence on cell size compared to recent results without HCAL cell energy truncation (dashed lines)

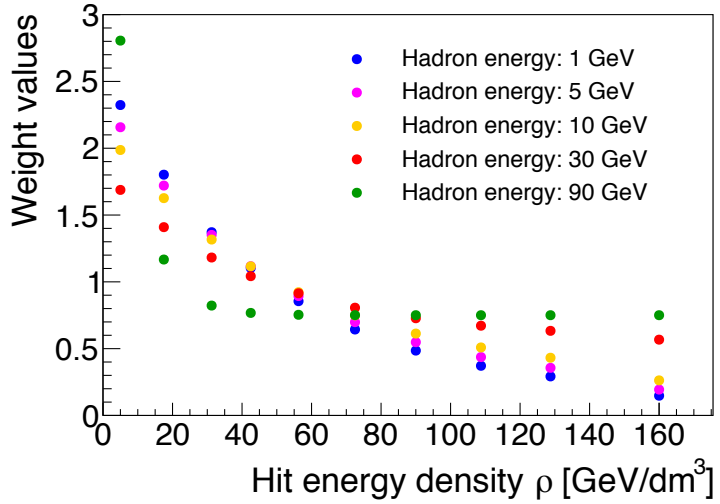


➢ Software compensation can do better and must be applied properly in Particle Flow reconstruction

Software compensation technique

- **Software compensation** technique by CALICE: weighting hit energy according to its energy density





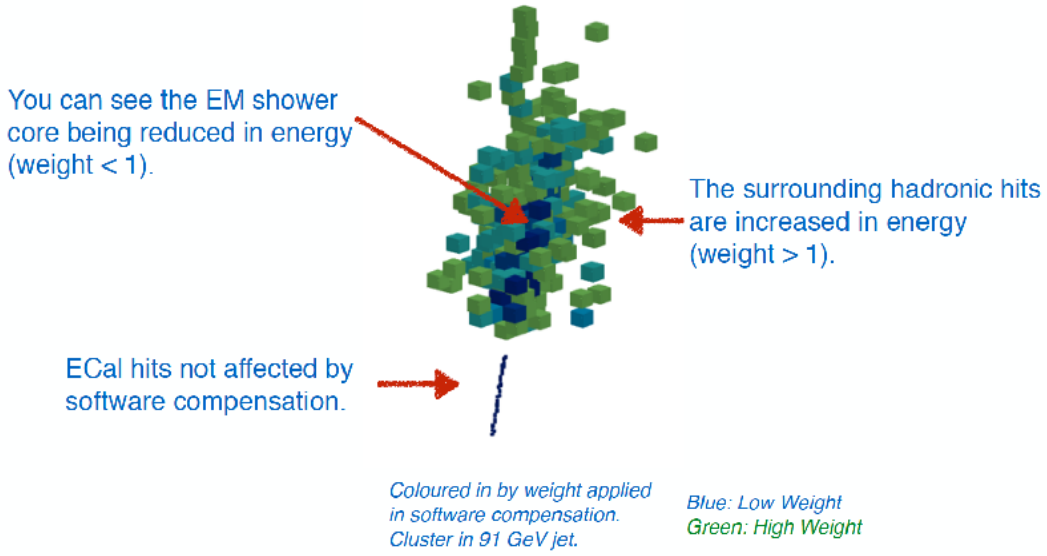
$$\omega(\rho) = p_1.exp(p_2.\rho) + p_3$$

$$E_{SC} = \sum_{hits} E_{ECAL} + \sum_{bin}(E_{HCAL}^{bin} \times \omega_{bin}(\rho))$$

$$with \;\; E_{HCAL}^{bin} = \sum_{hits \in bin} E_{hit}$$

weights depend on total particle energy
- use unweighted shower energy

Example on software compensation's operation



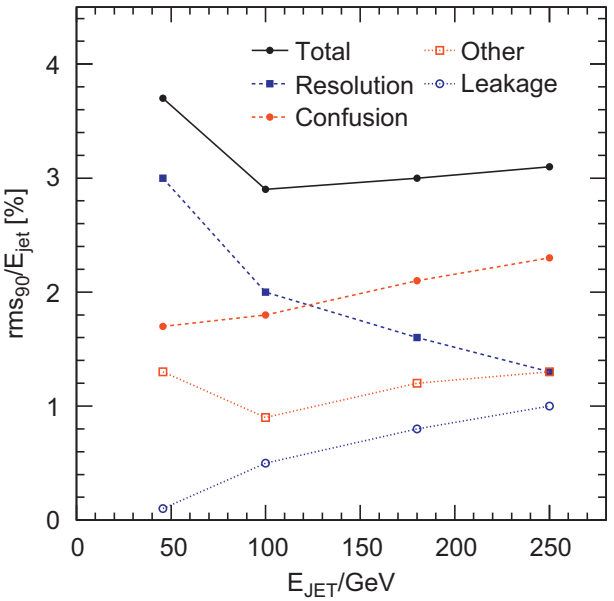
Particle flow performance

Separating the energy depositions of individual particles requires high granularity

Calorimeter energy resolution is still important

dominates for jets up to 100 GeV

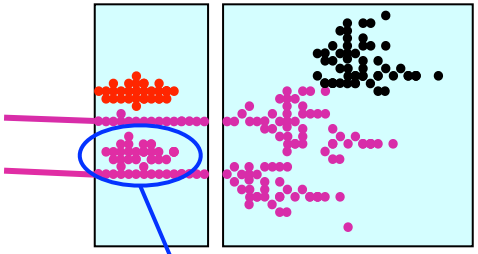
contributes to resolving confusion



Pattern recognition
based on topology and energy

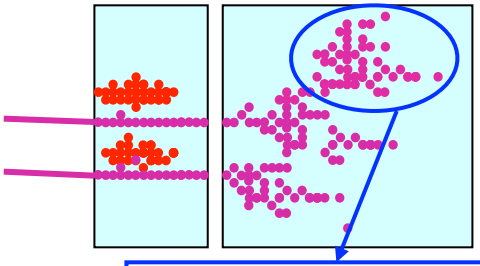
Types of confusion:

i) Photons



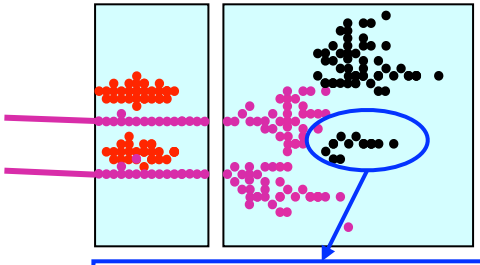
Failure to resolve photon

ii) Neutral Hadrons



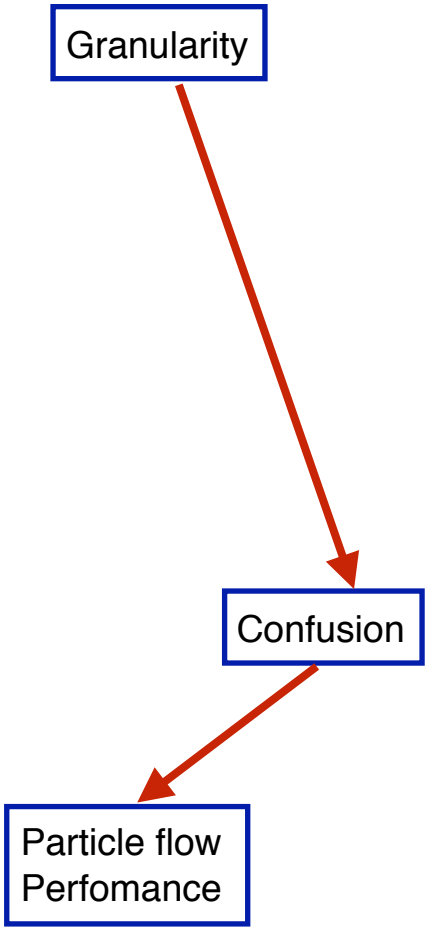
Failure to resolve neutral hadron

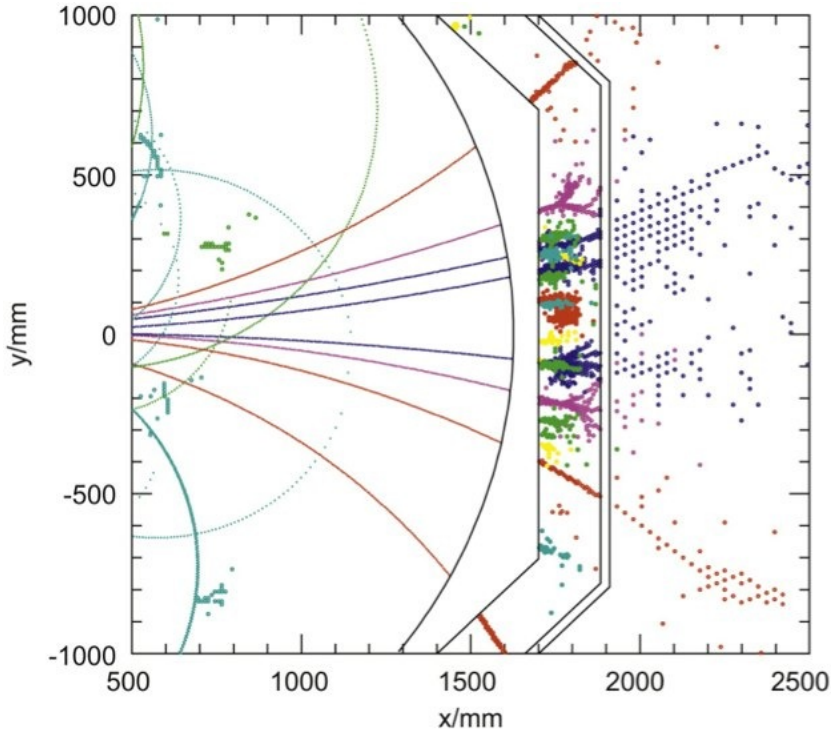
iii) Fragments



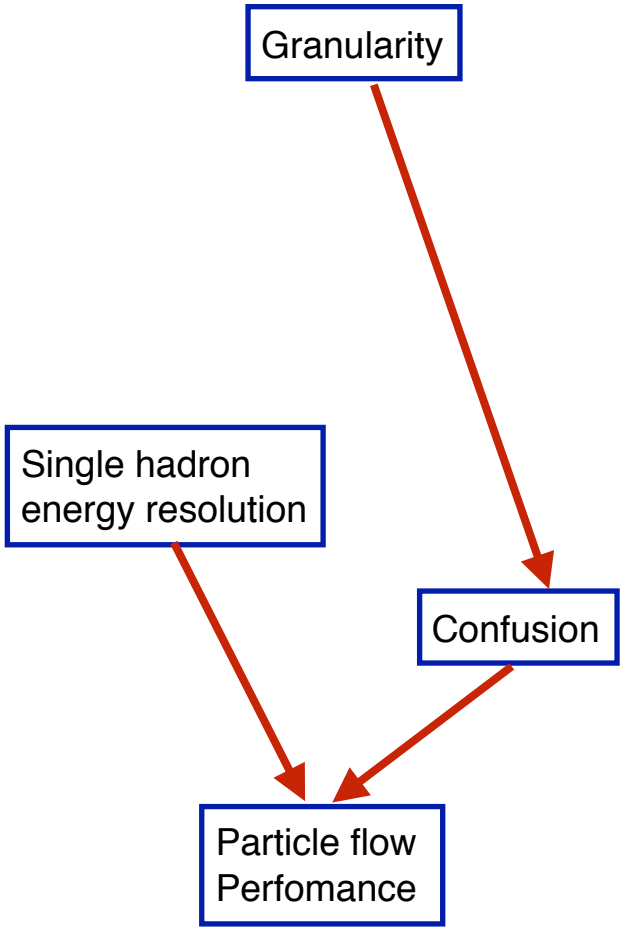
Reconstruct fragment as separate neutral hadron

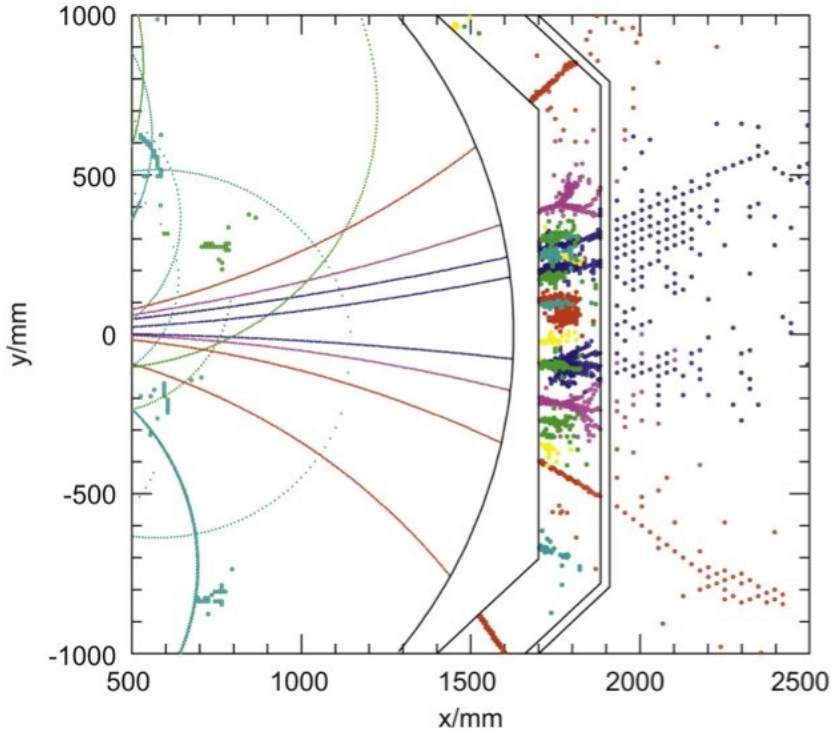
Particle flow and granularity



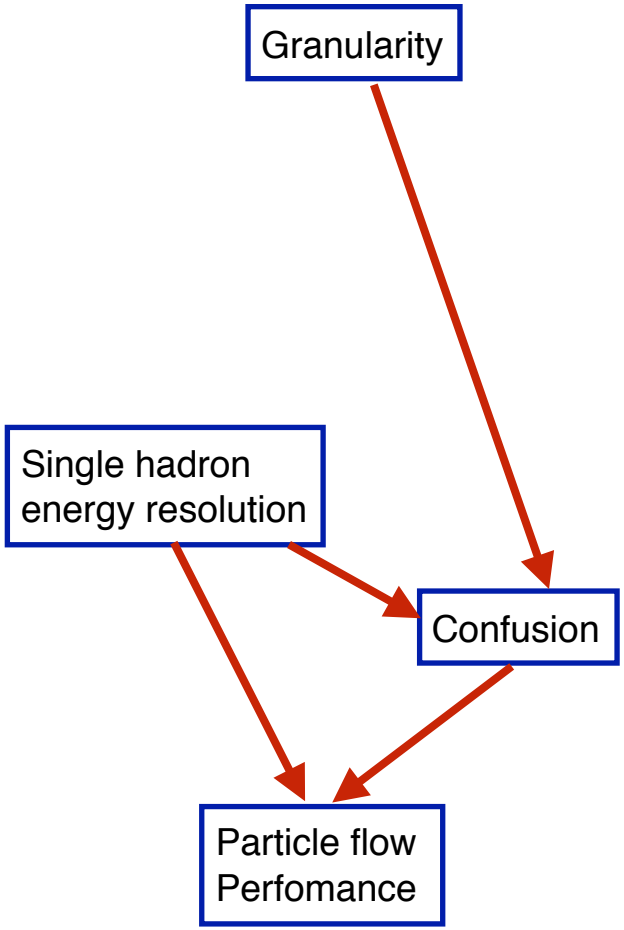


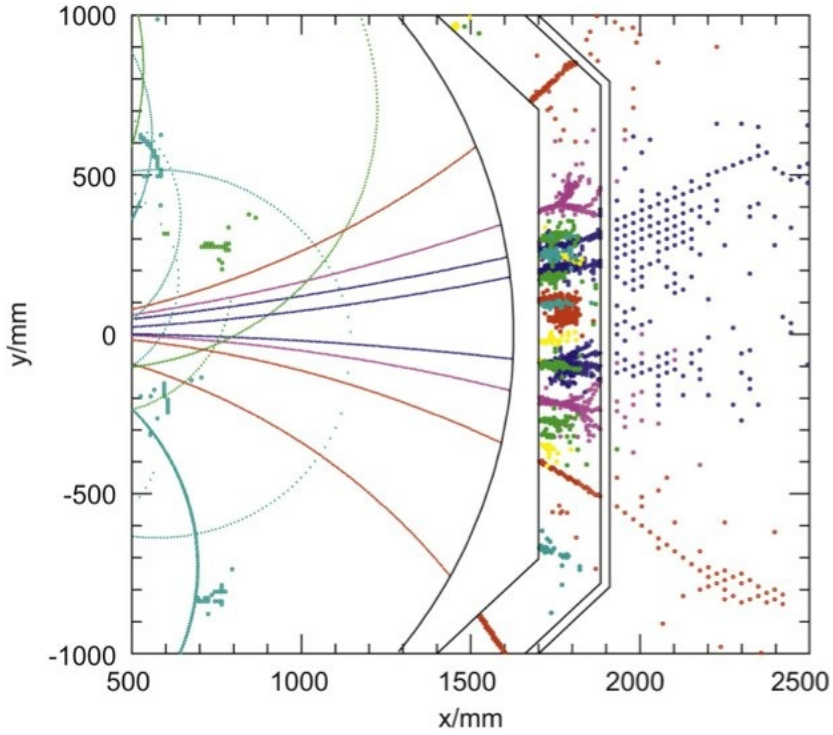
Particle flow and granularity



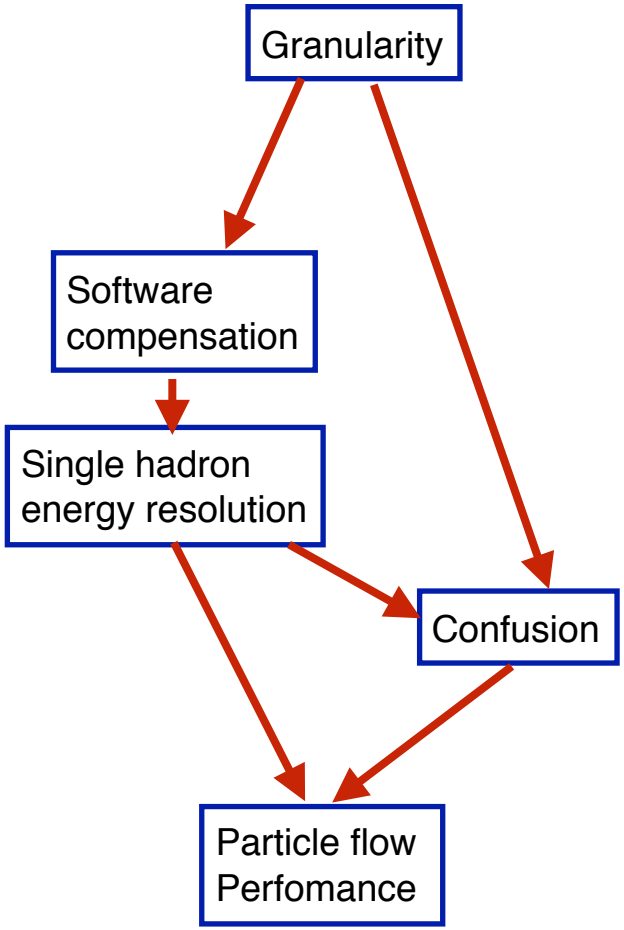


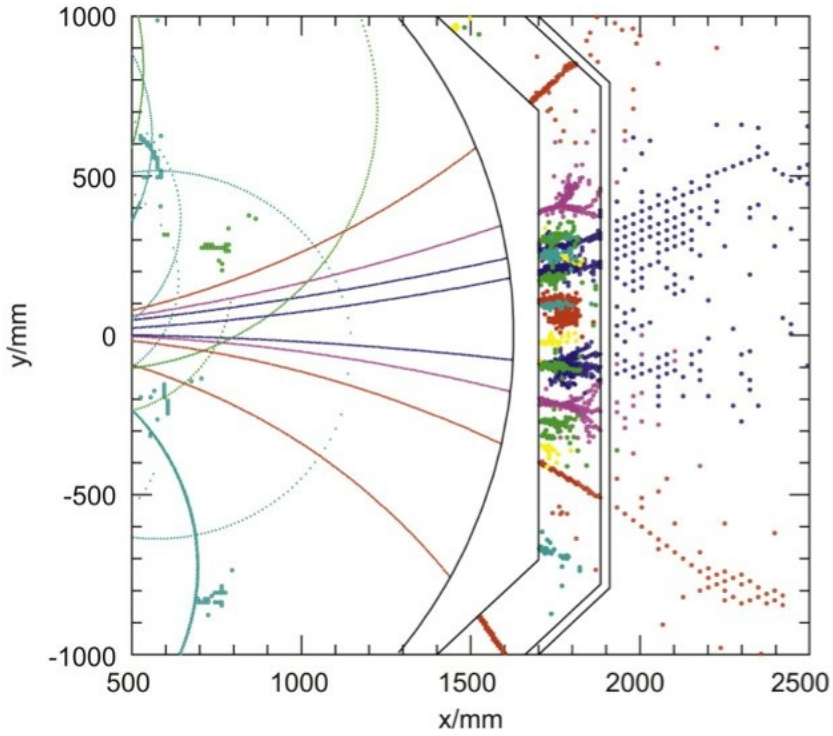
Particle flow and granularity



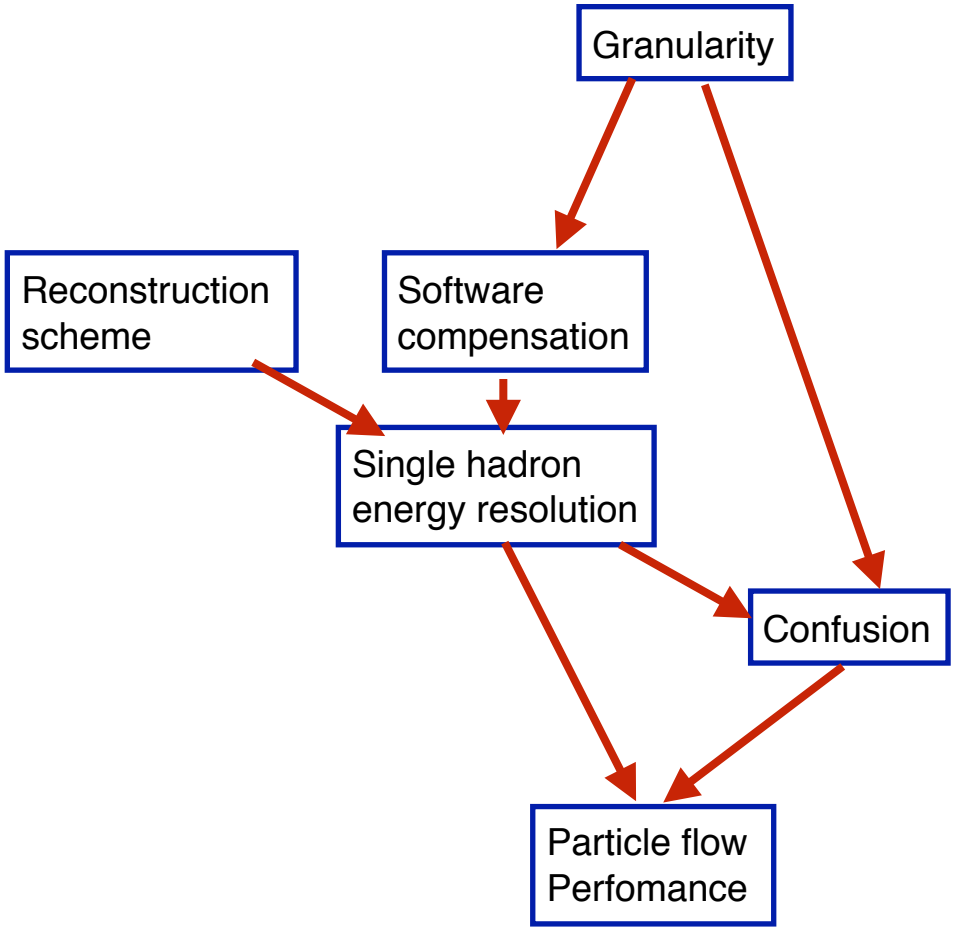


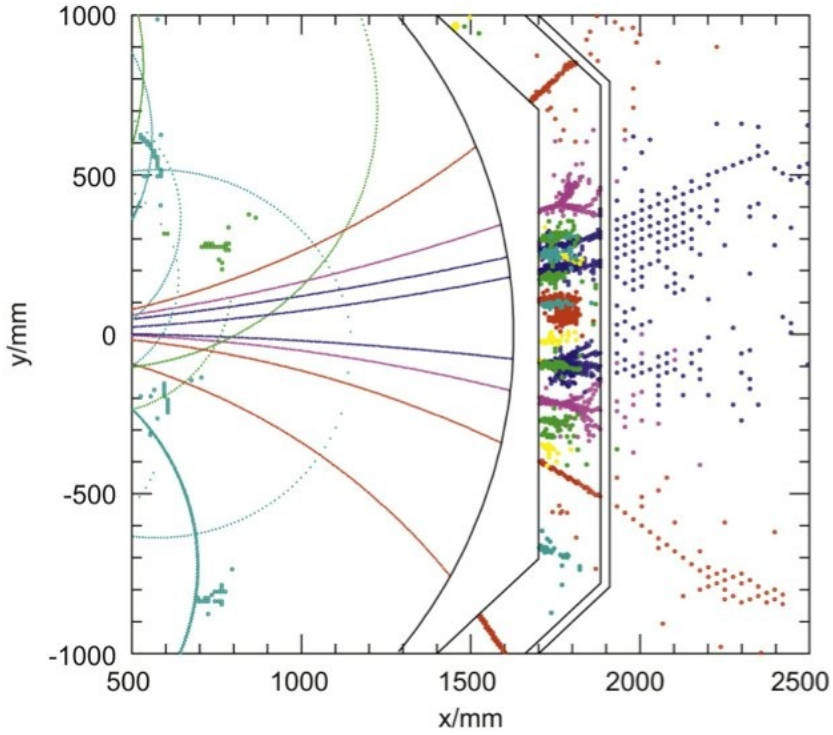
Particle flow and granularity



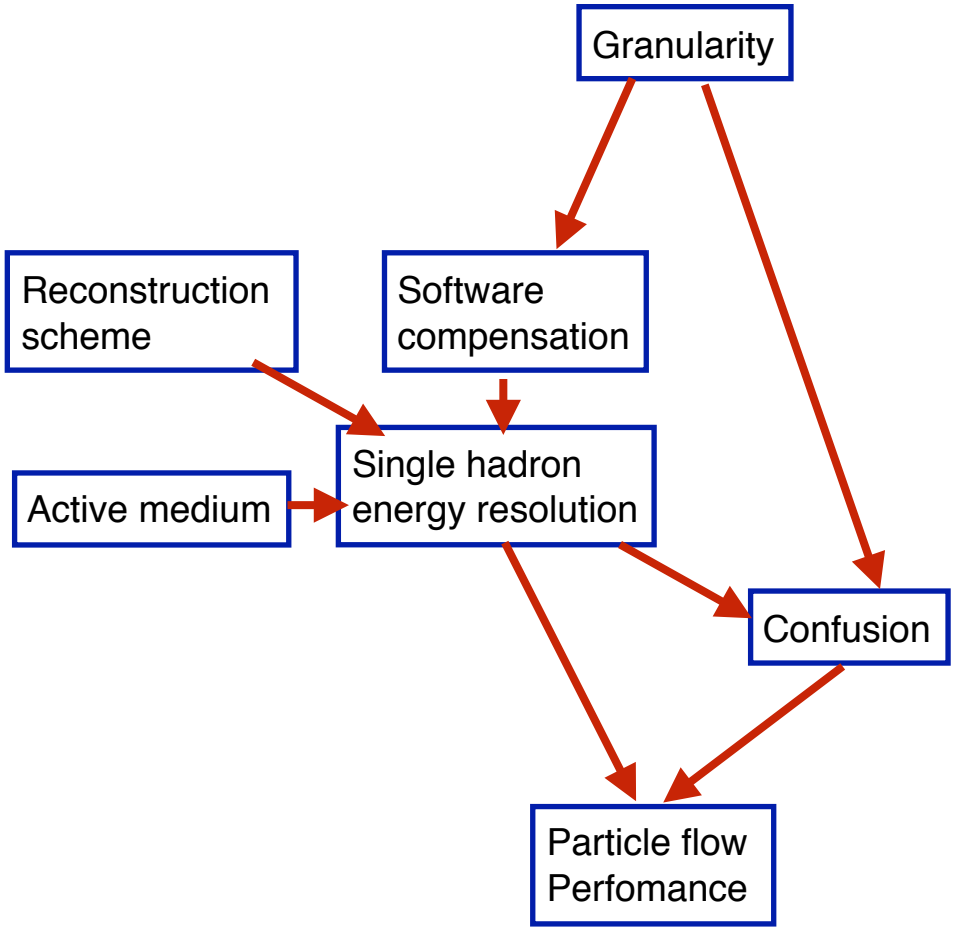


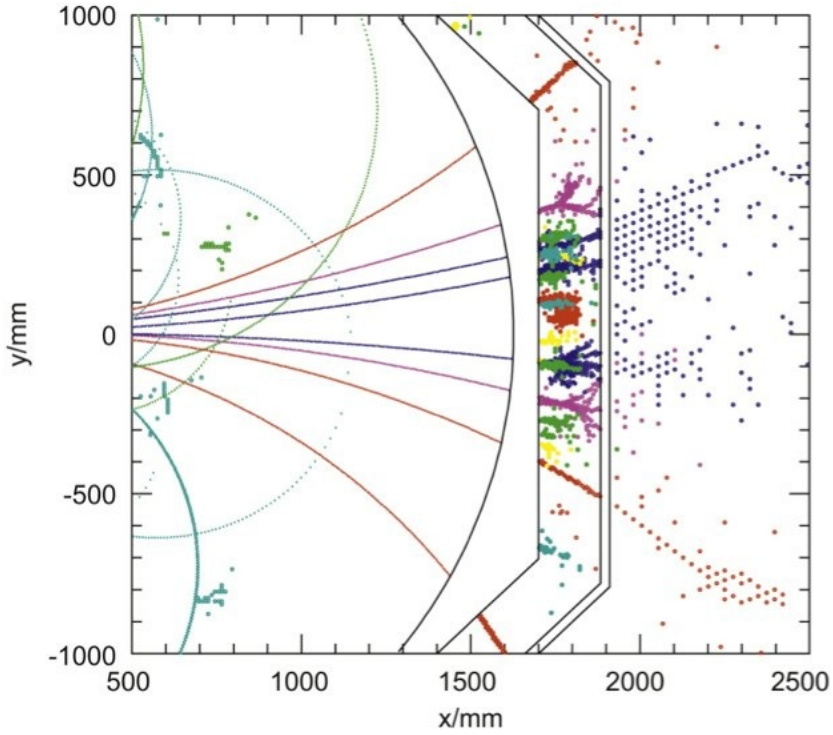
Particle flow and granularity



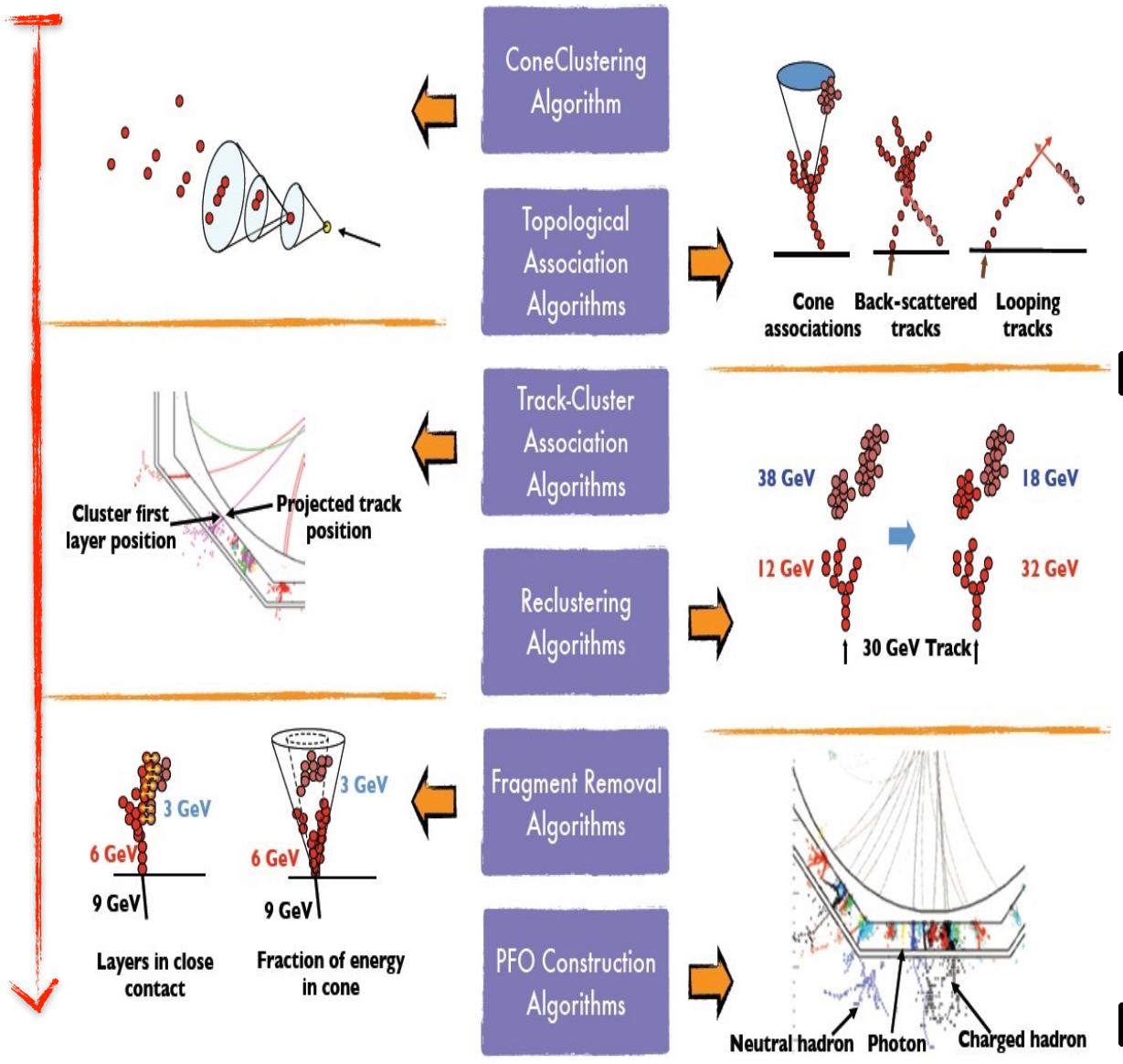


Particle flow and granularity





Software compensation application



First set of clusters obtained

- Clusters without track: neutral particles, fragment, …
- Clusters with associated track: cluster-track energy comparison. **Crucial** as it decides how good the energy reconstruction will be

➪ Software compensation for all clusters

OR

Software compensation for neutral hadrons

Software version and configuration

- **Detector model**: ILD_o1_v06
- **Reconstruction software**: ilcsoft_v01-17-07 combined with PandoraPFA version v02-09-00:
  - PandoraSDK v02-03-01
  - LCContent v02-04-00 including software compensation in LCPlugins and hits information registration for software compensation weight training in LCUtility
  - PandoraMonitoring v02-03-00

- **Digitiser**: ILDCaloDigi with realistic options for ECAL and HCAL
- **Calibration constants** optimised using PandoraAnalysis toolkit
- **Timing cut**: 100 *ns*

Final software compensation implementation

- **Setting in Pandora:** SC enabled **by default** in PandoraSettingsDefault.xml
  - Software compensation weights for standard ILD detector are used by default
  - All variables are steerable

```
<!-- PLUGIN SETTINGS -->
<HadronicEnergyCorrectionPlugins>SoftwareCompensation</HadronicEnergyCorrectionPlugins>
<EmShowerPlugin>LCEmShowerId</EmShowerPlugin>
<PhotonPlugin>LCPhotonId</PhotonPlugin>
<ElectronPlugin>LCElectronId</ElectronPlugin>
<MuonPlugin>LCMuonId</MuonPlugin>
```

- Paper written on this: in finalising state
  - Soon to be on review

Software compensation in Particle Flow reconstruction

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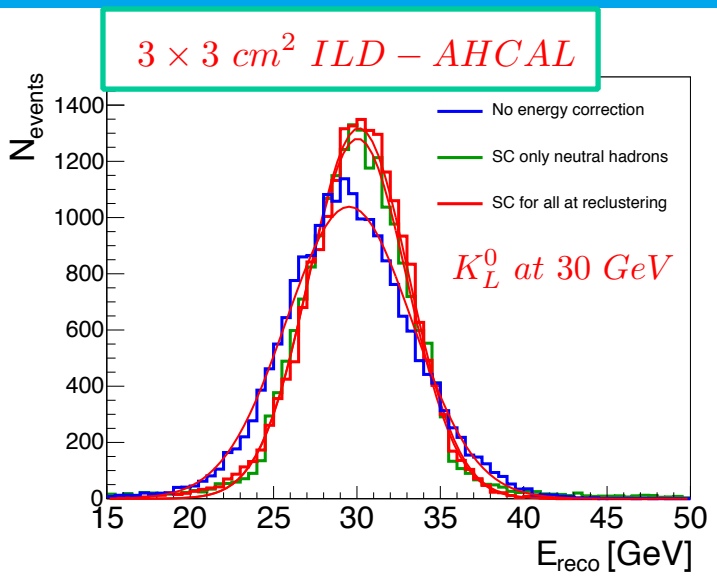
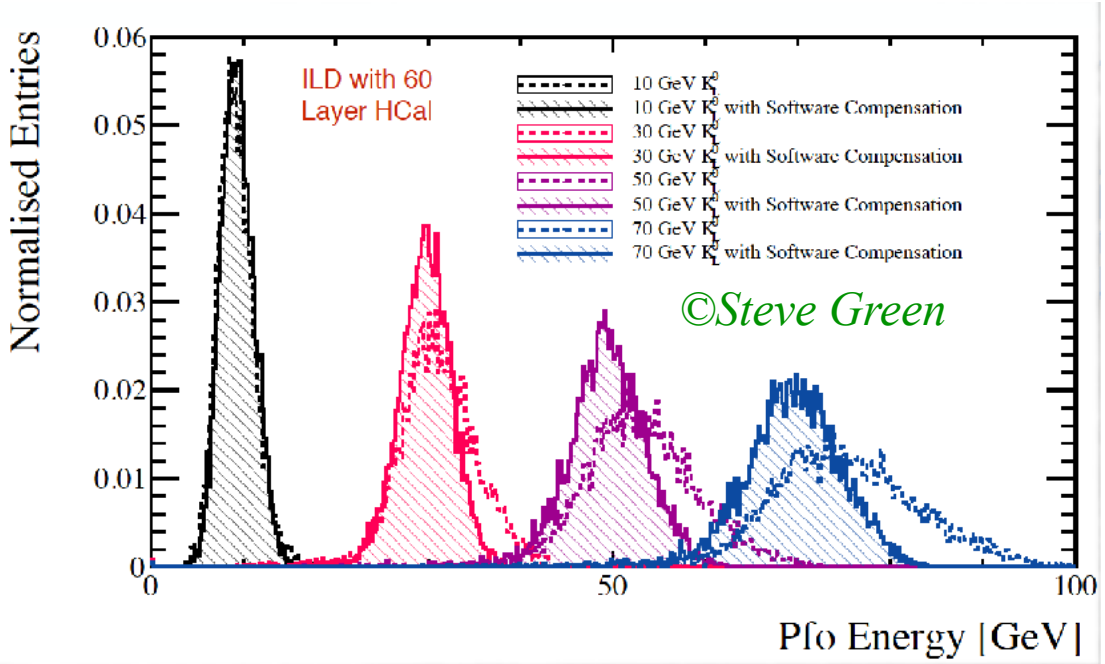
Abstract

The Particle Flow approach to calorimetry requires highly granular calorimeters and sophisticated software in order to reconstruct and identify individual particles in complex event topologies. The high calorimeter granularity can be further utilised in the so-called *software compensation technique*, in which it provides a discrimination of the

Energy resolution with software compensation

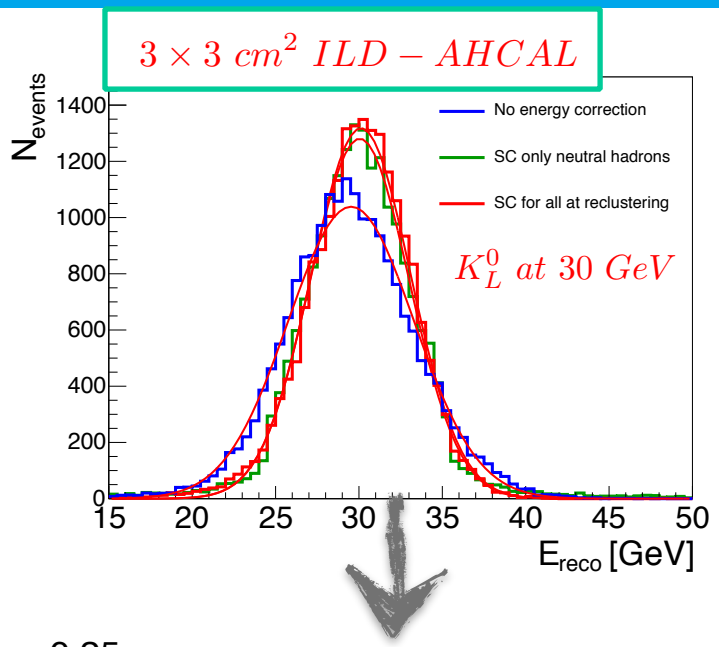


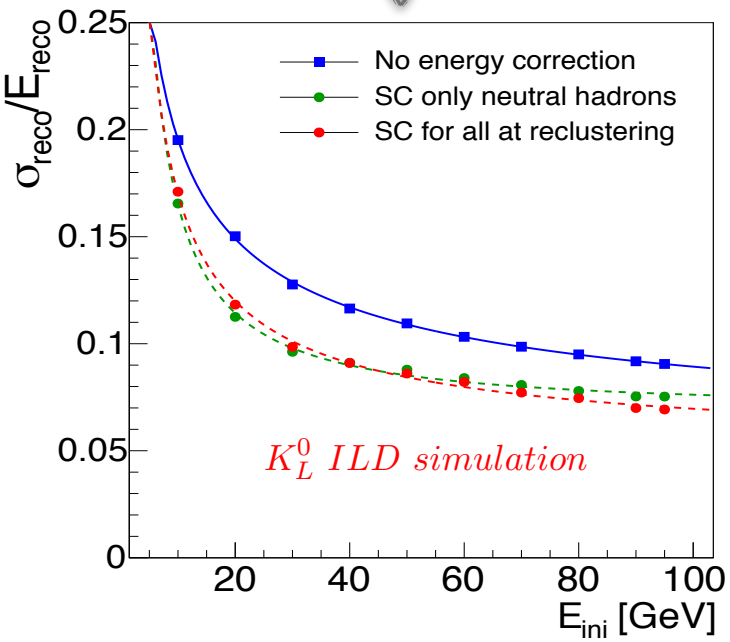
- Software compensation benefits in two-fold way:
  - Improve energy reconstruction of neutral objects
  - Improve cluster energy estimator for better track-cluster association ➢ confusion mitigation



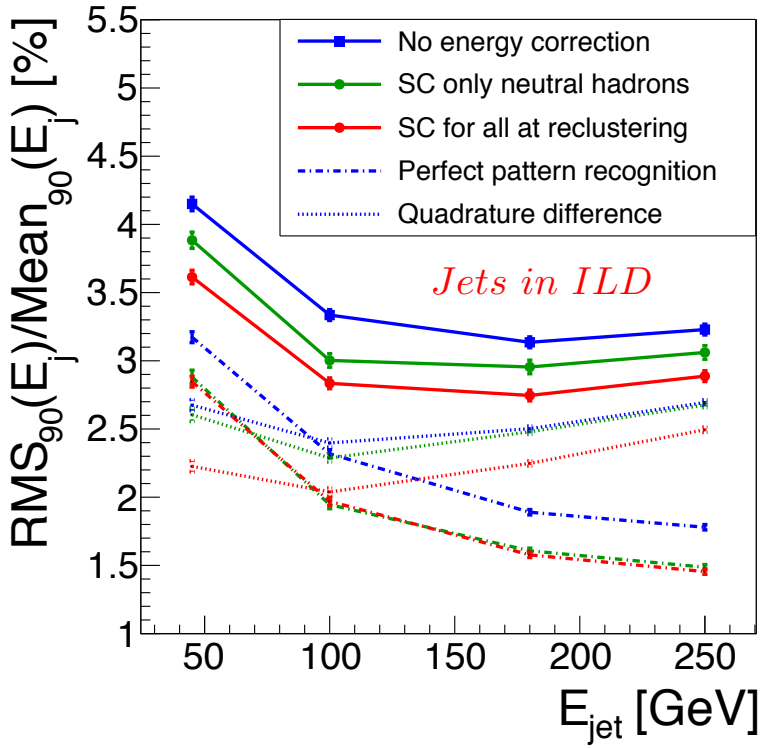
Study with 60 layer HCAL and higher jet energies (CLIC studies)

Energy resolution with software compensation



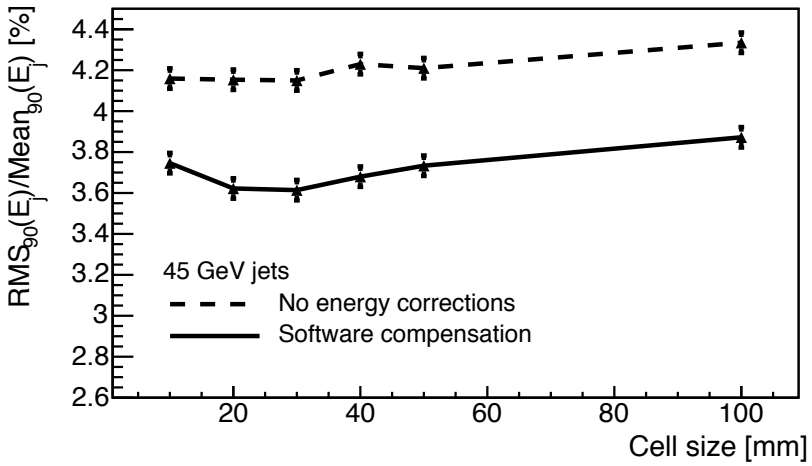


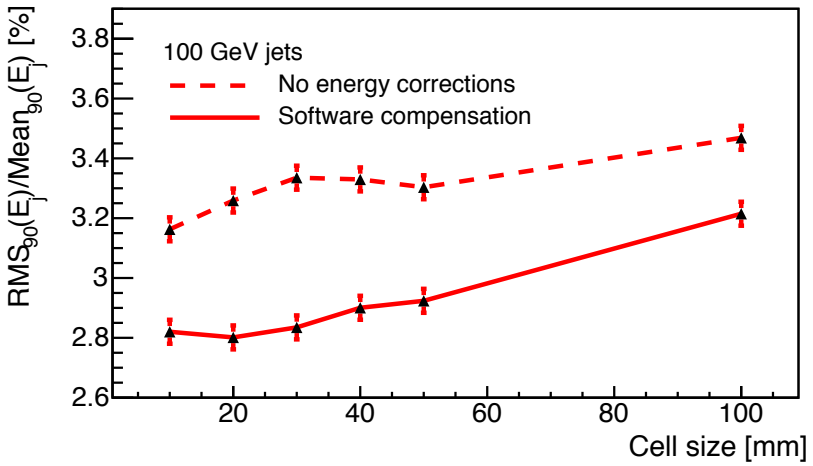
- Software compensation benefits in two-fold way:
  - Improve energy reconstruction of neutral objects
  - Improve cluster energy estimator for better track-cluster association ➢ confusion mitigation
- Significant improvement at both single particle and jet level
- Software compensation applied at re-clustering stage more beneficial for jet energy resolution

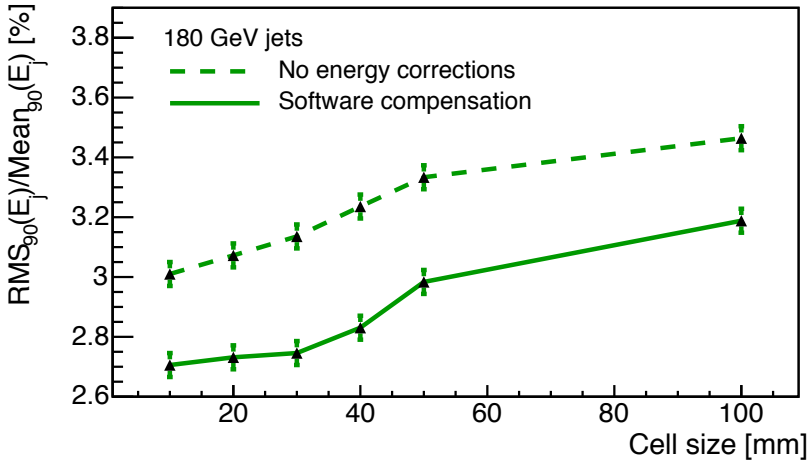


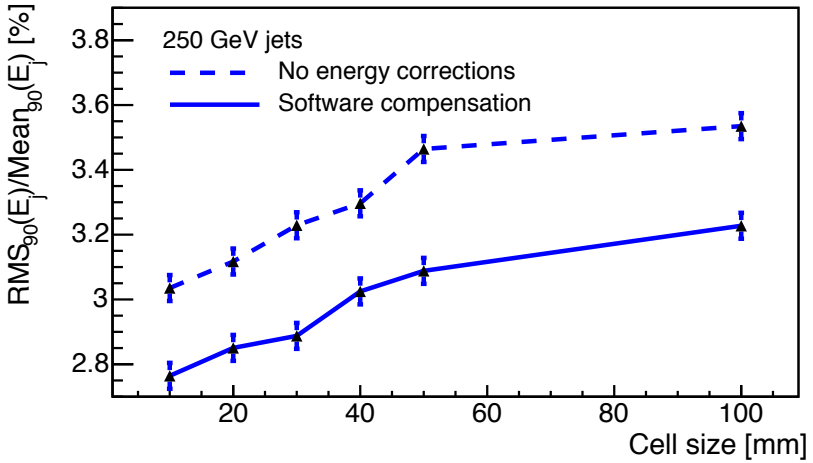
JER vs cell size

- Effectiveness of software compensation depends on granularity
  - Software compensation included in cell size optimisation
  - Weights optimised for each cell size



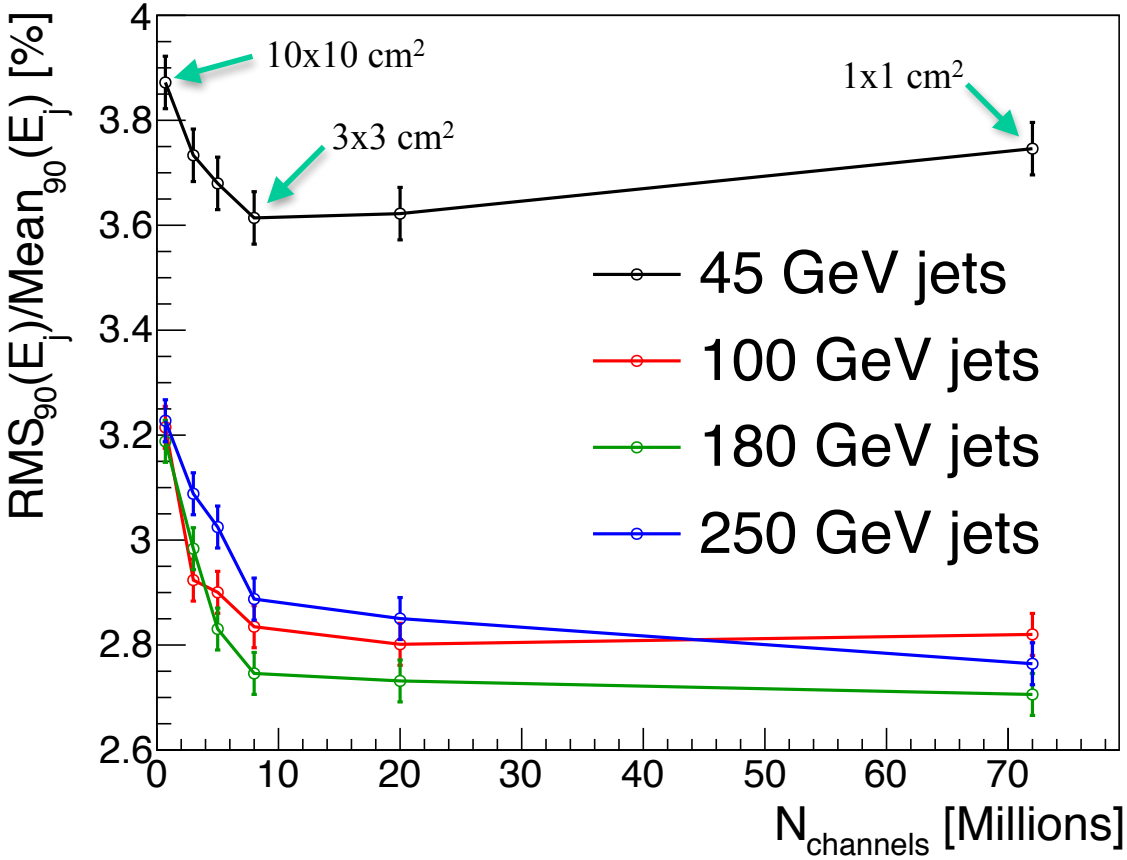






JER vs number of cells

- Jet energy resolution plotted as a function of number of HCAL cells
  - Towards cost optimisation
  - 3 x 3 cm^2 cell size is still a very reasonable choice

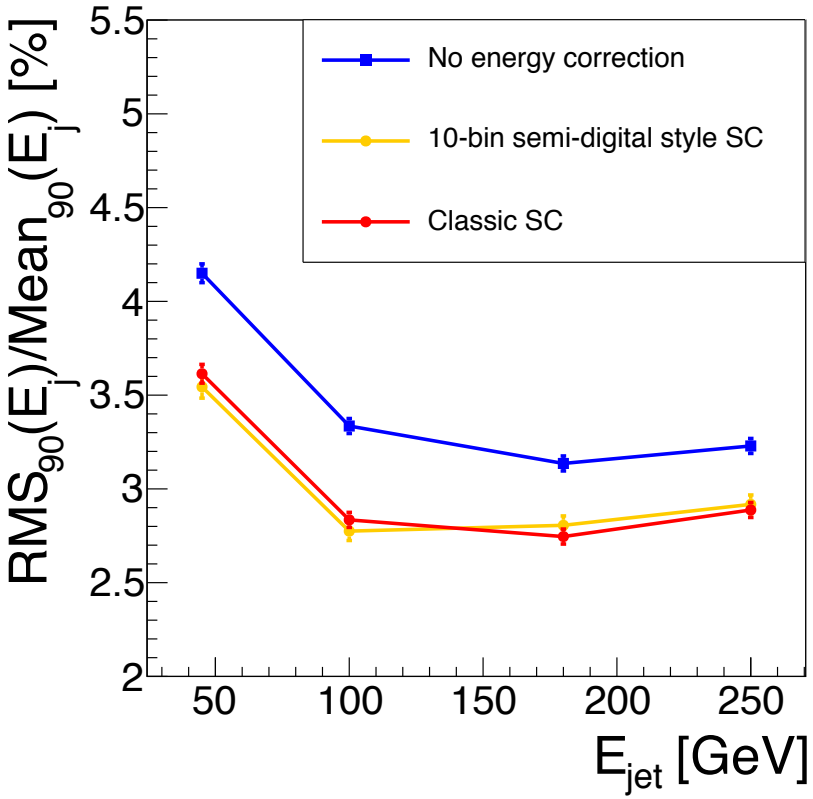


Software compensation and semi-digital reconstruction

- Semi-digital reconstruction is particularly successful at low energies
  - Counting hits at 3 thresholds N_1, N_2, N_3
  - Suppress Landau fluctuations
- Reconstructed energy: $E_{SD} = \sum_{bins} \alpha_i . N_i$ $\alpha=\alpha(N_{tot})$

or

$$E_{SD} = \sum_{hits} \alpha_i . \frac{E_j}{E_j} = \sum_{hits} \omega_j . E_j \text{ with } \omega_j = \frac{\alpha_i}{E_j}$$

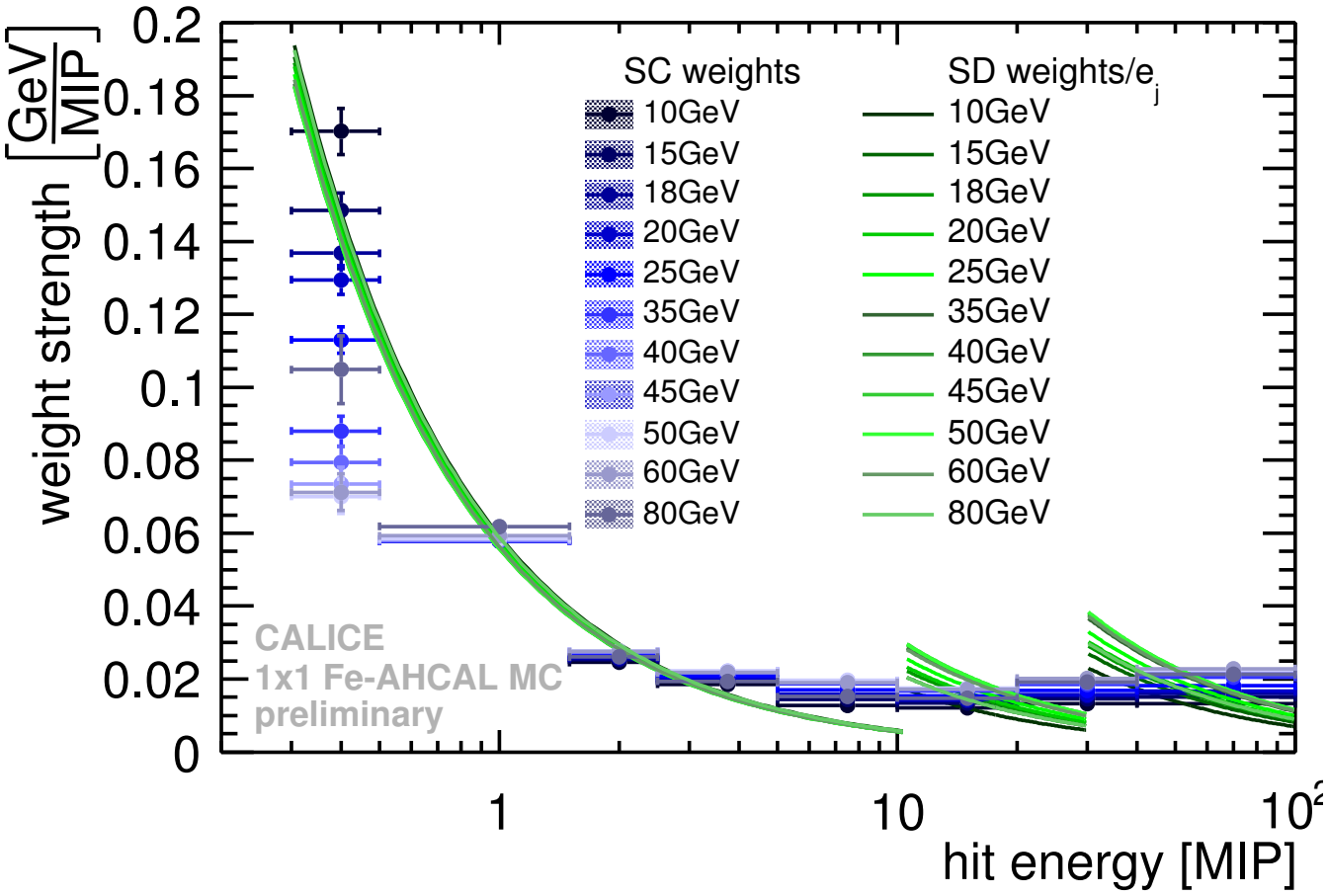


- Can apply software compensation using the **same formalism**

$$E_{SC} = \sum_{hits} E_{ECAL} + \sum_{bin} (\alpha + \beta E_{sum} + \gamma E_{sum}^2) \times E_{HCAL}^{bin}$$

- Gives results consistent with classic software compensation
  - Number of bin and binning definition steerable
- Allows for semi-digital reconstruction in the same framework for direct comparison by introducing $1/E_j$ factor (counting hits) - not shown here, 3x3cm^2 case

Analogue and semi-digital weights



Summary

- Jet energy resolution with software compensation in Pandora:
  - Significant gain in performance over a wide jet energy range,
    best performance achieved for ILD detector
  - Inclusion of SC does not significantly alter view on transverse granularity optimisation

- Software compensation code and utilities in latest version of PandoraPFA
- Includes semi-digital reconstruction scheme

- Installed in new ILCsoft v01-17-10
  - Being used as standard cluster energy correction, shows improvement everywhere
    (even with DD4hep, without re-optimisation of SC weight yet)

- Study summarised in a paper, soon to be on review

Back-up slides

Software Compensation in AHCAL optimisation

- ***Idea:*** Applying different weights for hits of different energy densities
- ***Weight*** defined as:

$$\omega(\rho) = p_1.exp(p_2.\rho) + p_3$$

where ρ is hit energy density, p_1, p_2, p_3 are *beam energy dependent parameters*

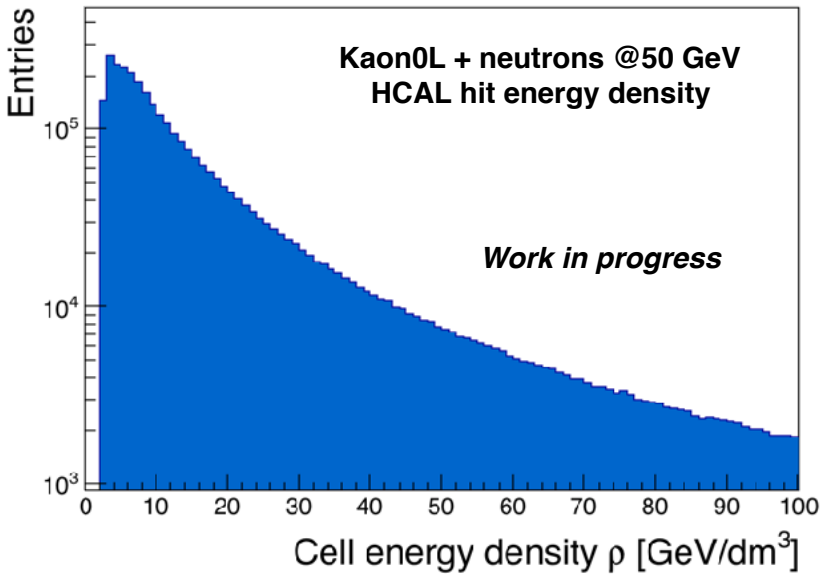
- Energy of cluster then computed in software compensation method as:

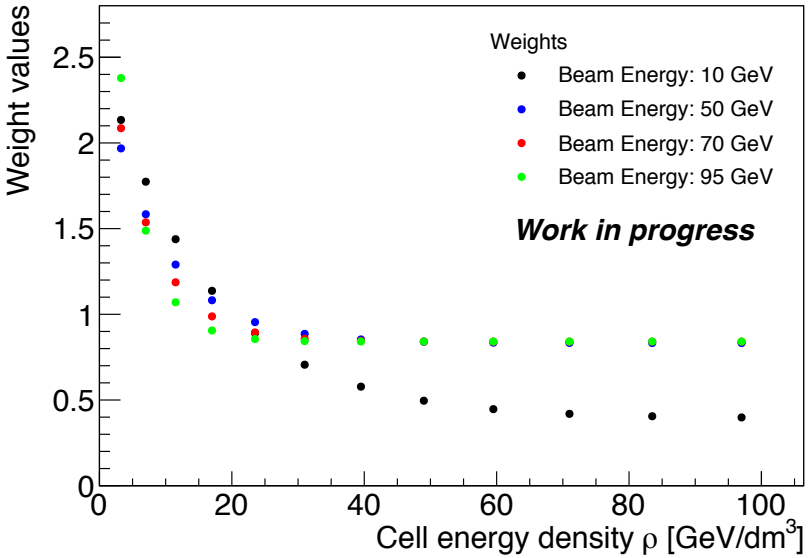
$$E_{SC} = \sum_{hits} E_{ECAL} + \sum_{hits} (E_{HCAL}.\omega(\rho))$$

- Weights determined through minimising a χ^2function:

$$\chi^2 = \sum_{events} (E_{SC} - E_{beam})^2$$

Hit Energy Density and Weights





Weight determination:

- Through χ^2 minimisation
- For each beam energy weights are defined with three parameters p_1, p_2, p_3

$$\omega(\rho) = p_1.exp(p_2.\rho) + p_3$$

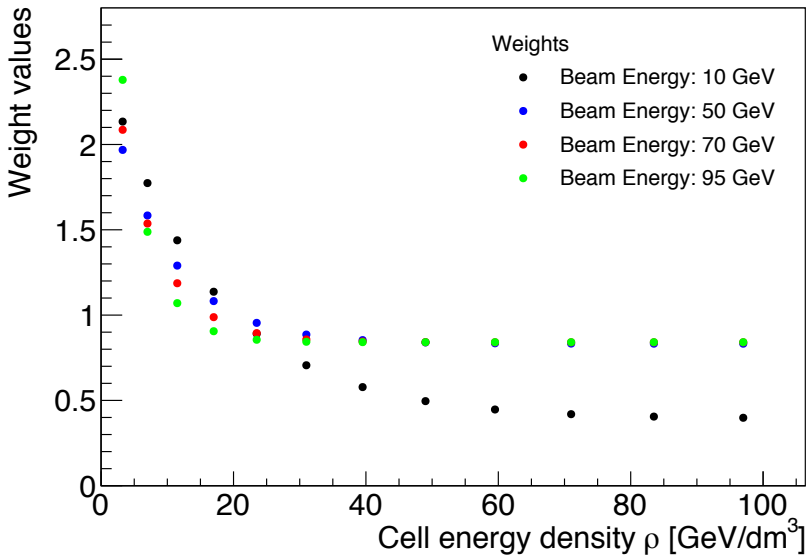
where p_1, p_2, p_3 are energy dependent parameter (defined directly in χ^2)

$$p_1 = p_{10} + p_{11} \times E_{ini} + p_{12} \times E_{ini}^2$$

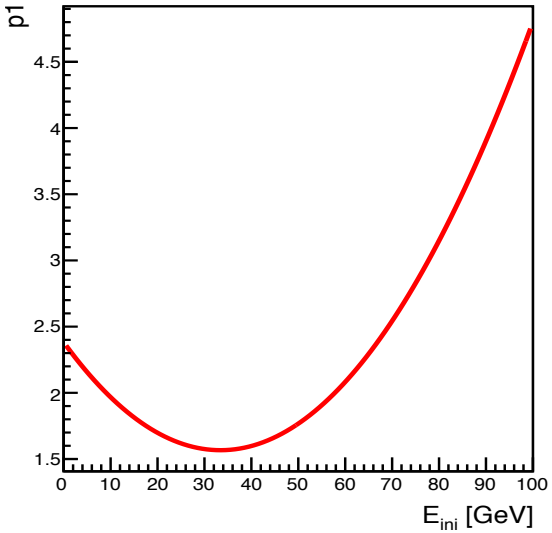
$$p_2 = p_{20} + p_{21} \times E_{ini} + p_{22} \times E_{ini}^2$$

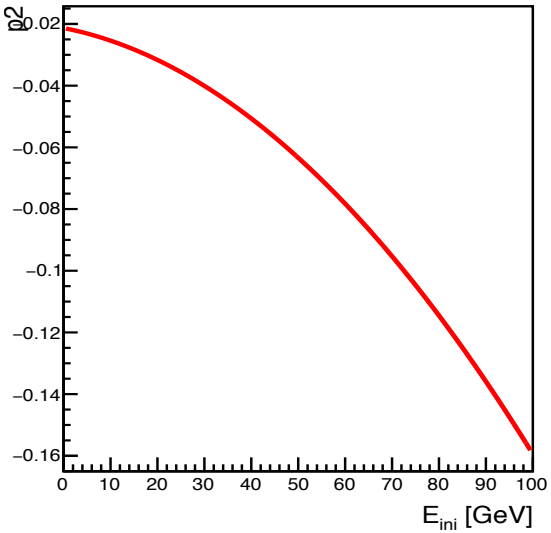
$$p_3 = \frac{p_{30}}{p_{31} + e^{p_{32} \times E_{ini}}}$$

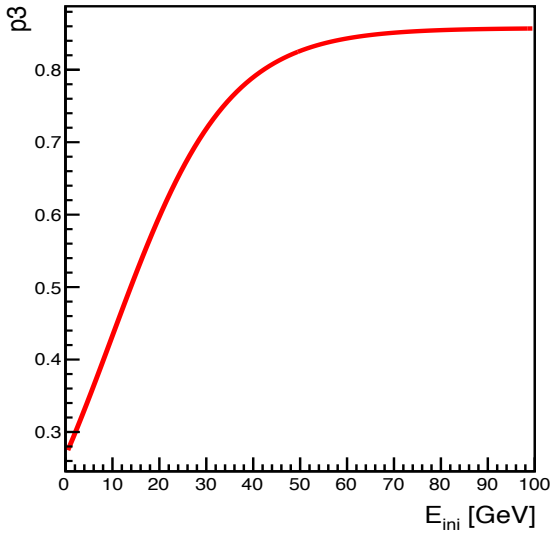
Weight parameters



$$\omega(\rho) = p_1.exp(p_2.\rho) + p_3$$

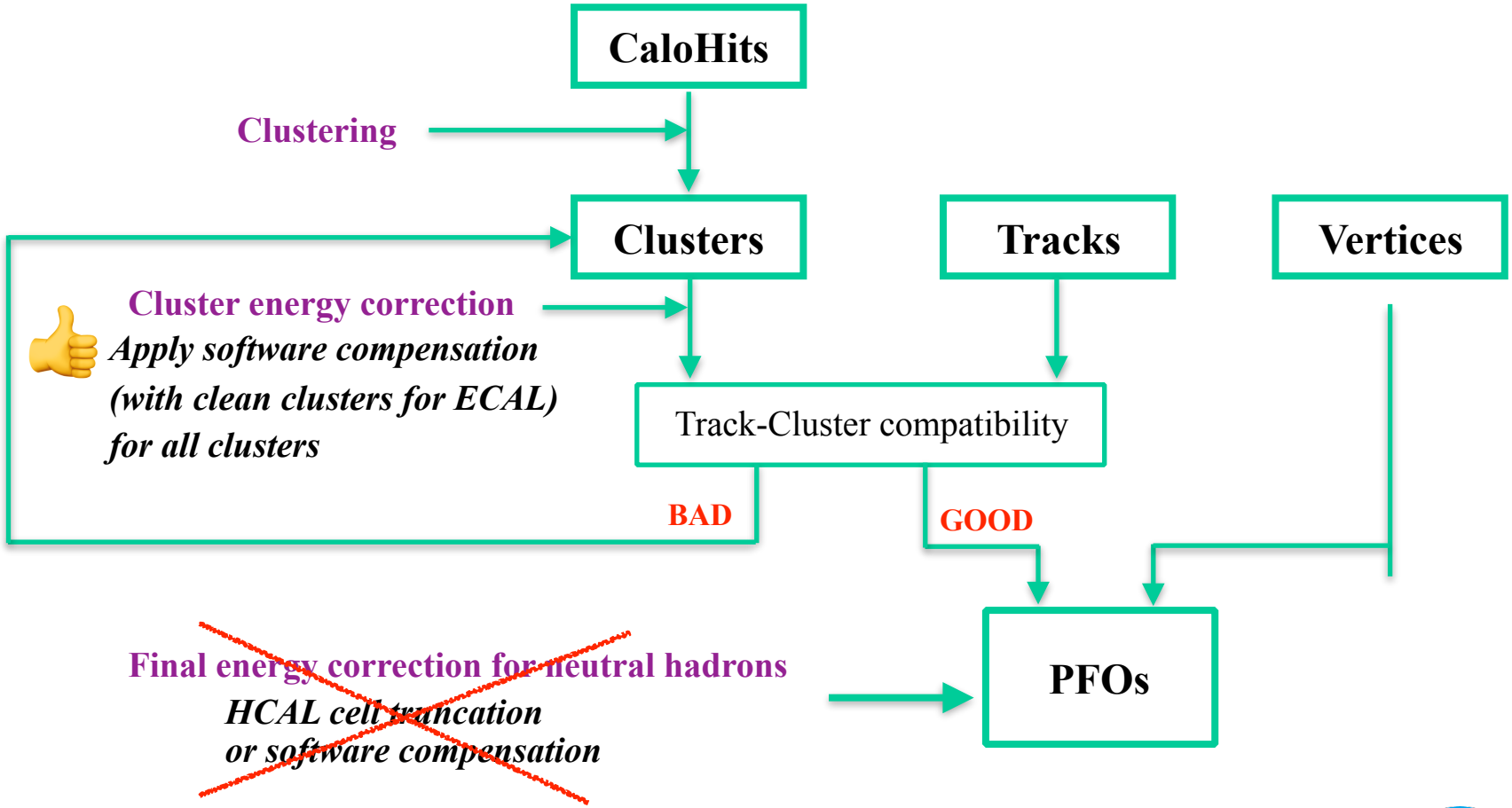






Final software compensation implementation

- Software compensation now applied **all-at-once** in re-clustering step



Software compensation in PFlow reconstruction

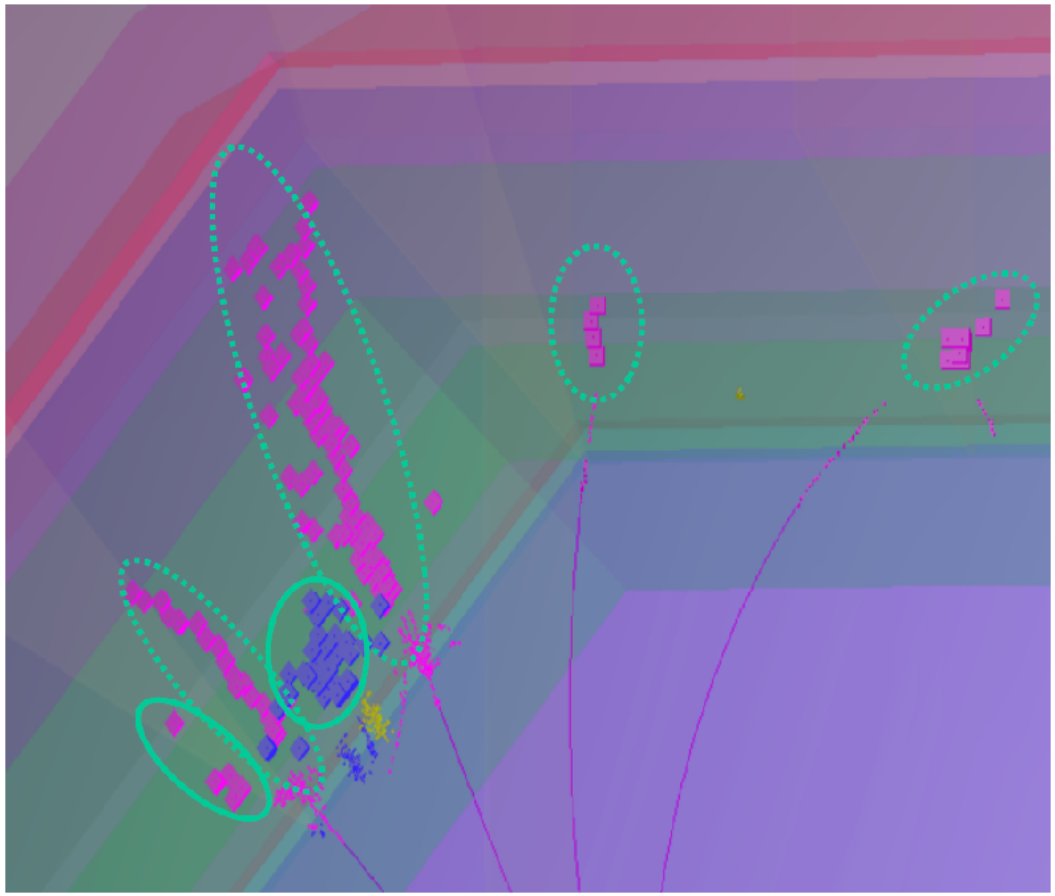
First set of clusters

No associated tracks
- Neutral particles
- Fragments
- To be merged in other clusters

Has associated tracks
- Cluster energy will be compared to track energy re-clustering if not compatible

➢ Software compensation applied for ***only clusters with associated tracks*** for energy comparison

In principle ***can be applied for both type*** of clusters



Software compensation in PFlow reconstruction

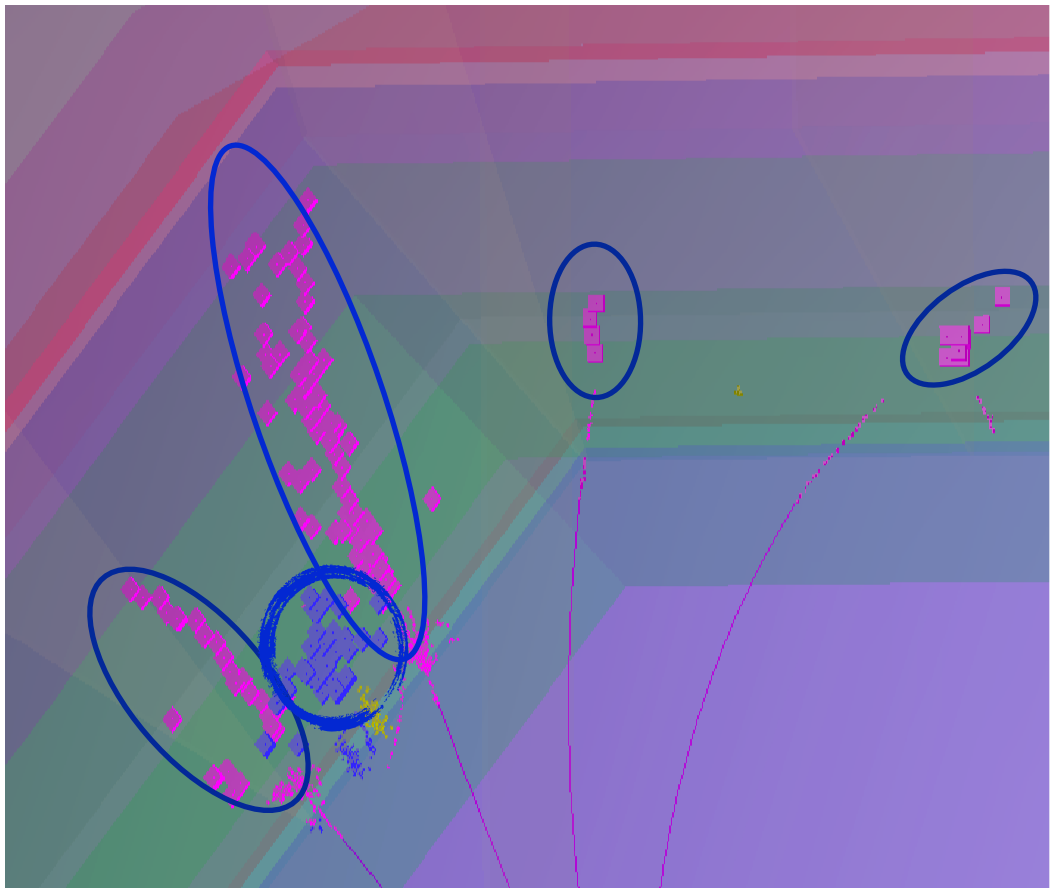
First set of clusters

No associated tracks
- Neutral particles
- Fragments
- To be merged in other clusters

Has associated tracks
- Cluster energy will be compared to track energy re-clustering if not compatible

➢ Software compensation applied for ***only clusters with associated tracks*** for energy comparison

In principle ***can be applied for both type*** of clusters



Particle Flow Objects

➢ Software compensation applied for ***neutral PFOs***

- Stand-alone: sometimes better, sometimes worse compared to Steve's results with truncation
- When combine with application at re-clustering for clusters with associated tracks: improvement at high energies but degradation at small energies

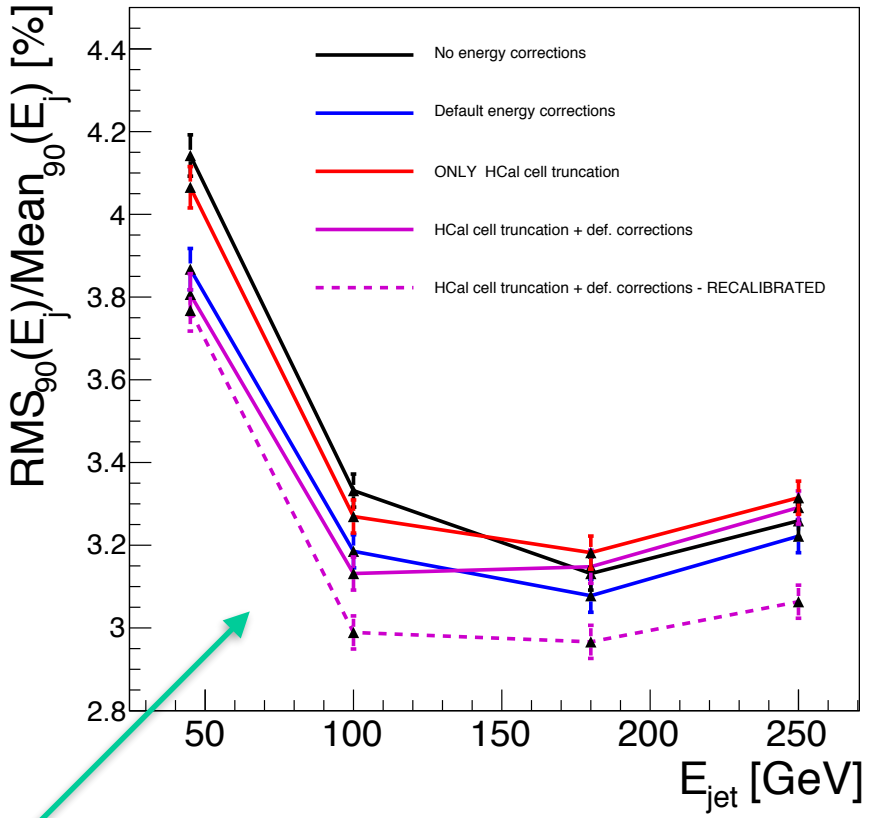
HCAL cell truncation performance

- HCAL cell truncation is not applied ALONE:

  Two default energy correction plugins are turned on

  - ***CleanClusters***: clean hot hits in ECAL track, which is quite effective in *low energy range* for clusters which are largely contained in ECAL
  - ***ScaleHotHadrons***: some sort of simple software compensation for clusters that have up to 100 hits (affects low energy range)

- Study to separate the effect of CleanClusters+ScaleHotHadrons and HCAL cell truncation



CleanClusters energy correction

- CleanClusters mainly affects ECAL clusters by changing energy significantly (remove hot cell)

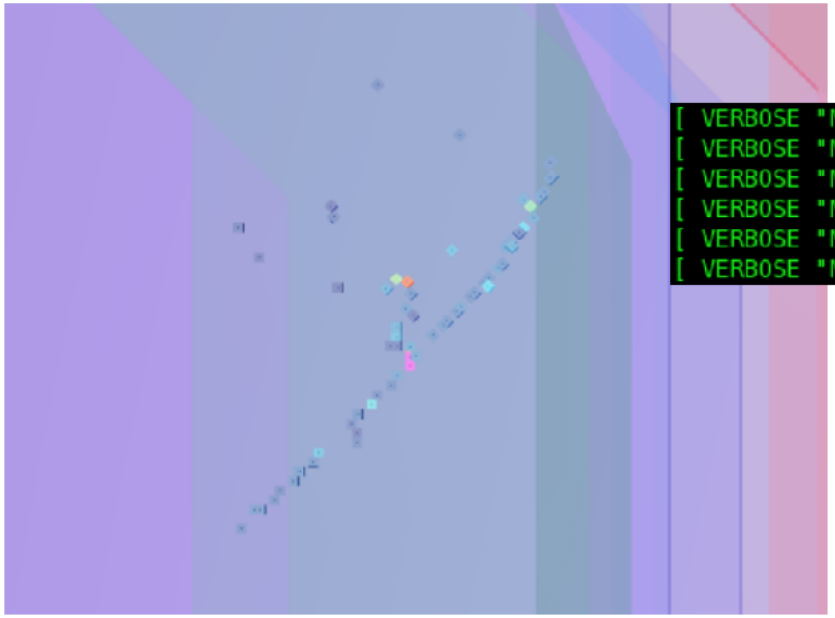
```
[ VERBOSE "MyMarlinPandoraDefault"] Software compensation changing energy : 1
[ VERBOSE "MyMarlinPandoraDefault"] Number of hits in cluster   : 40
[ VERBOSE "MyMarlinPandoraDefault"] Hadronic Energy of Cluster  : 3.79469
[ VERBOSE "MyMarlinPandoraDefault"] Corrected Energy of Cluster : 1.74793
[ VERBOSE "MyMarlinPandoraDefault"] NECalHits                   : 40
[ VERBOSE "MyMarlinPandoraDefault"] NHCalHits                   : 6
```

Clean Cluster Changing Energy Significantly

```
[ VERBOSE "MyMarlinPandoraDefault"] 0x1c6a140
[ VERBOSE "MyMarlinPandoraDefault"] energyInPreviousLayer            : 0.0160862
[ VERBOSE "MyMarlinPandoraDefault"] energyInNextLayer                : 0.0199764
[ VERBOSE "MyMarlinPandoraDefault"] energyInCurrentLayer             : 2.45802
[ VERBOSE "MyMarlinPandoraDefault"] energyInAdjacentLayers           : 0.0180313
[ VERBOSE "MyMarlinPandoraDefault"] hitHadronicEnergy                : 1.06995
[ VERBOSE "MyMarlinPandoraDefault"] Min Clean Hit Energy             : 1
[ VERBOSE "MyMarlinPandoraDefault"] Fraction of cluster energy in hit : 0.281959
[ VERBOSE "MyMarlinPandoraDefault"] m_minCleanHitEnergyFraction      : 0.2
[ VERBOSE "MyMarlinPandoraDefault"] newHitHadronicEnergy(energyInAdjacentLayers + energyInCurrentLayer + hitHadronicEnergy) : 0.2
[ VERBOSE "MyMarlinPandoraDefault"] energy change (newHitHadronicEnergy - hitHadronicEnergy)                               : -0.869948
[ VERBOSE "MyMarlinPandoraDefault"] Changing the energy...
[ VERBOSE "MyMarlinPandoraDefault"] energyInPreviousLayer            : 0.0160862
[ VERBOSE "MyMarlinPandoraDefault"] energyInNextLayer                : 0.0199764
[ VERBOSE "MyMarlinPandoraDefault"] energyInCurrentLayer             : 2.45802
[ VERBOSE "MyMarlinPandoraDefault"] energyInAdjacentLayers           : 0.0180313
[ VERBOSE "MyMarlinPandoraDefault"] hitHadronicEnergy                : 1.37682
[ VERBOSE "MyMarlinPandoraDefault"] Min Clean Hit Energy             : 1
[ VERBOSE "MyMarlinPandoraDefault"] Fraction of cluster energy in hit : 0.362827
[ VERBOSE "MyMarlinPandoraDefault"] m_minCleanHitEnergyFraction      : 0.2
[ VERBOSE "MyMarlinPandoraDefault"] newHitHadronicEnergy(energyInAdjacentLayers + energyInCurrentLayer + hitHadronicEnergy) : 0.2
[ VERBOSE "MyMarlinPandoraDefault"] energy change (newHitHadronicEnergy - hitHadronicEnergy)                               : -1.17682
[ VERBOSE "MyMarlinPandoraDefault"] Changing the energy...
[ VERBOSE "MyMarlinPandoraDefault"] This cluster requires an energy correction according to the CLEAN CLUSTERS logic.
[ VERBOSE "MyMarlinPandoraDefault"] Number of hadronic plugins registered: 2
[ VERBOSE "MyMarlinPandoraDefault"] 0x1c6a0a0
```

CleanClusters energy correction

- CleanClusters mainly affects ECAL clusters by changing energy significantly (remove hot cell)



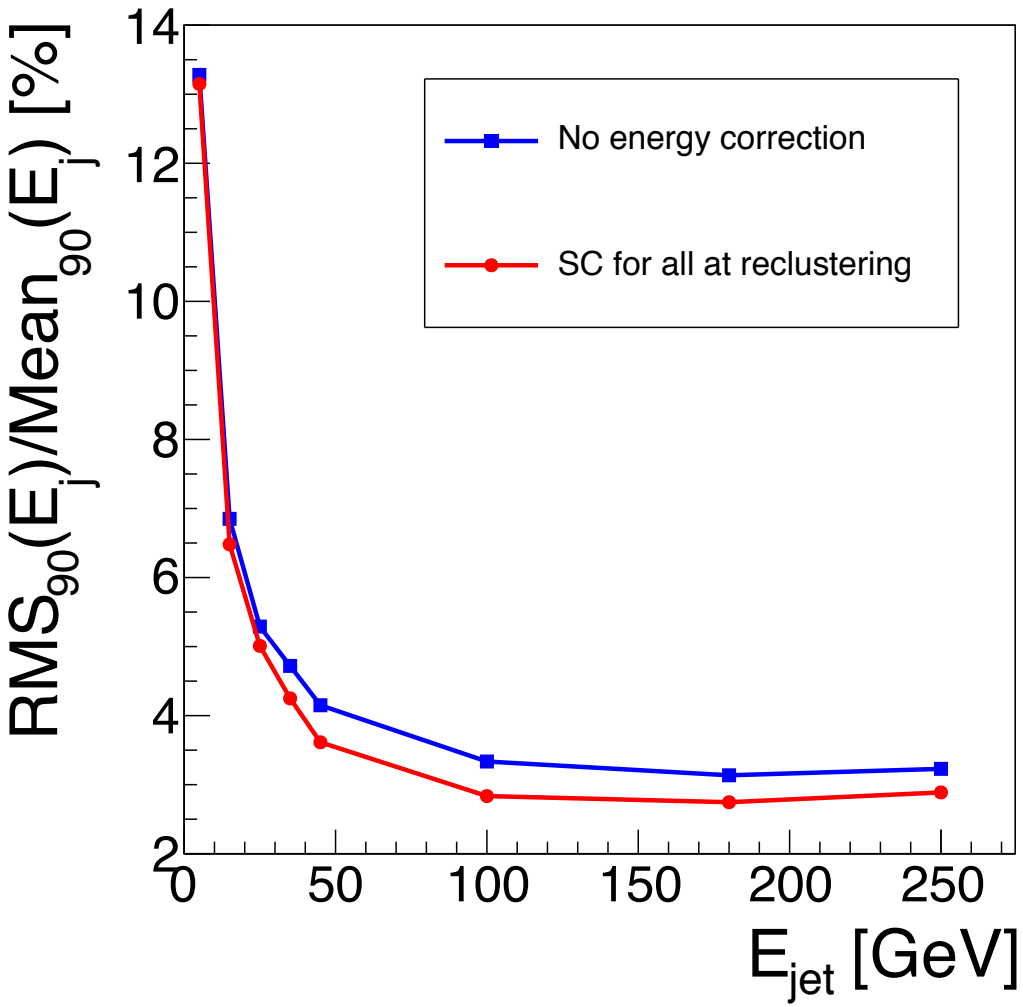
```
[ VERBOSE "MyMarlinPandoraDefault"] Software compensation changing energy : 1
[ VERBOSE "MyMarlinPandoraDefault"] Number of hits in cluster    : 59
[ VERBOSE "MyMarlinPandoraDefault"] Hadronic Energy of Cluster   : 3.67985
[ VERBOSE "MyMarlinPandoraDefault"] Corrected Energy of Cluster : 1.96347
[ VERBOSE "MyMarlinPandoraDefault"] NECalHits                    : 70
[ VERBOSE "MyMarlinPandoraDefault"] NHCalHits                    : 0
```

Clean Cluster Changing Energy Significantly

➢ **Use CleanClusters for ECAL clusters**

```
VERBOSE "MyMarlinPandoraDefault"] energyInPreviousLayer              : 0.151975
VERBOSE "MyMarlinPandoraDefault"] energyInNextLayer                  : 0.170483
VERBOSE "MyMarlinPandoraDefault"] energyInCurrentLayer               : 2.29877
VERBOSE "MyMarlinPandoraDefault"] energyInAdjacentLayers             : 0.161229
VERBOSE "MyMarlinPandoraDefault"] hitHadronicEnergy                  : 1.91638
VERBOSE "MyMarlinPandoraDefault"] Min Clean Hit Energy               : 1
VERBOSE "MyMarlinPandoraDefault"] Fraction of cluster energy in hit : 0.520776
VERBOSE "MyMarlinPandoraDefault"] m_minCleanHitEnergyFraction        : 0.2
VERBOSE "MyMarlinPandoraDefault"] newHitHadronicEnergy(energyInAdjacentLayers - energyInCurrentLayer + hitHadronicEnergy) : 0.2
VERBOSE "MyMarlinPandoraDefault"] energy change (newHitHadronicEnergy - hitHadronicEnergy)                                : -1.71638
```

JER with small energies (3x3cm2 HCAL)



Software compensation and semi-digital reconstruction

- Semi-digital reconstruction is particularly
- successful at low energies
  - Counting hits at 3 thresholds N_1, N_2, N_3

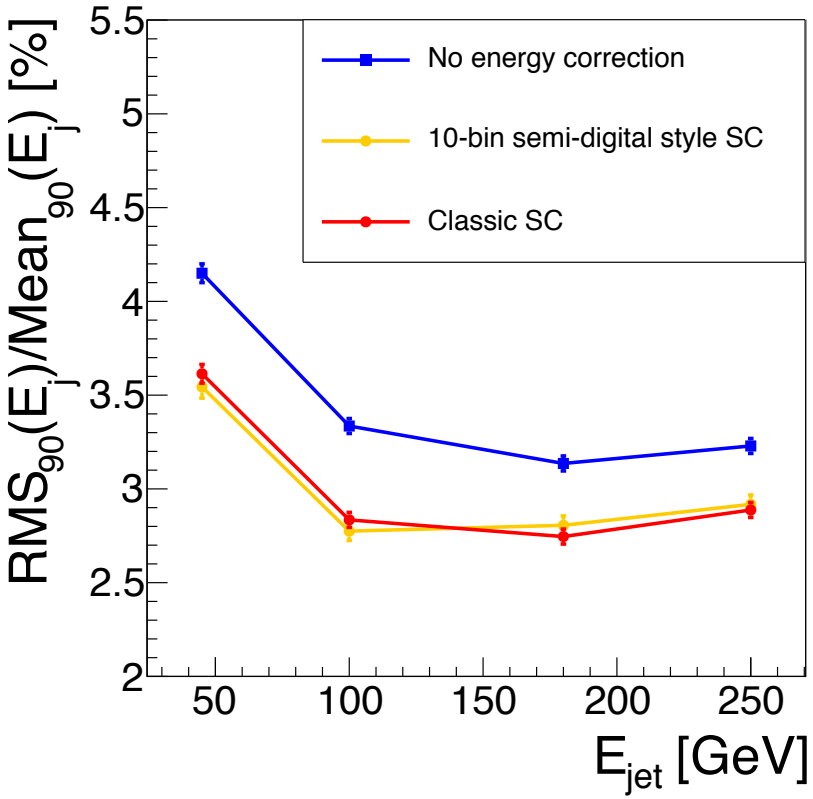
- Reconstructed energy: $E_{SD} = \sum_{bins} \alpha_i . N_i$

or

$$E_{SD} = \sum_{hits} \alpha_i . \frac{E_j}{E_j} = \sum_{hits} \omega_j . E_j \text{ with } \omega_j = \frac{\alpha_i}{E_j}$$

- Software compensation can also apply the **same formalism** keeping **10 bin definition** of classic SC:

$$E_{SC} = \sum_{hits} E_{ECAL} + \sum_{bin} (\alpha + \beta E_{sum} + \gamma E_{sum}^2) \times E_{HCAL}^{bin}$$



- Give compatible results to classic software compensation
  - Number of bin and binning definition steerable
  - Allow semi-digital reconstruction in the same framework for direct comparison