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High Granularity Calorimetry and Particle Flow for the CMS Phase 2 Upgrade

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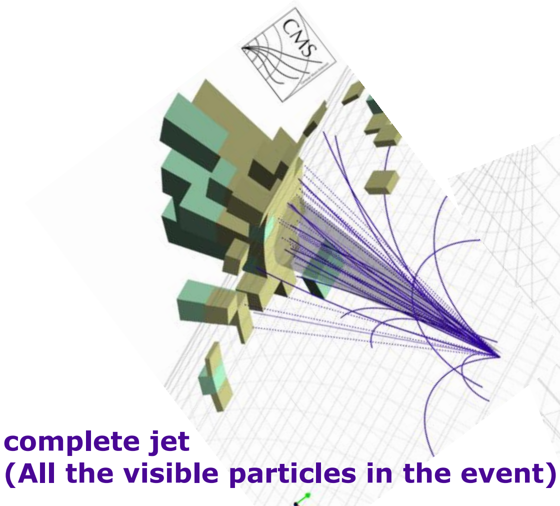
HEP 2015 - Conference on Recent Developments in High Energy Physics and Cosmology 15-18 April 2015, Athens, Greece

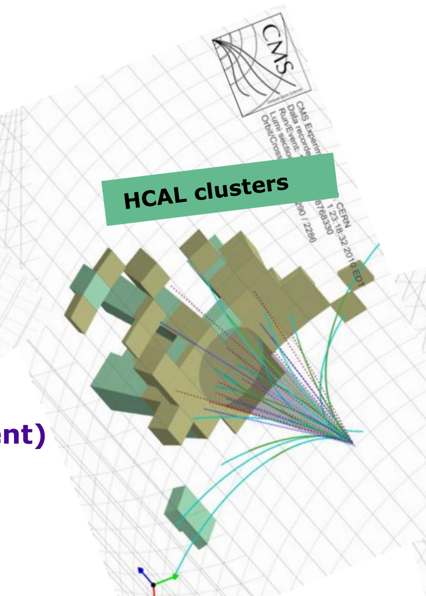
What is Particle Flow

Particle Flow (PF) algorithms aims at reconstructing all stable particles within an event: Photons, charged hadrons, neutral hadrons, muons, electrons.

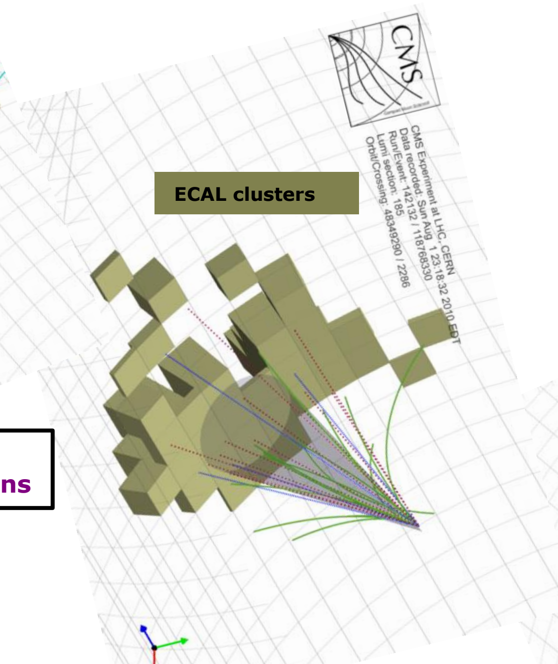


complete jet
(All the visible particles in the event)

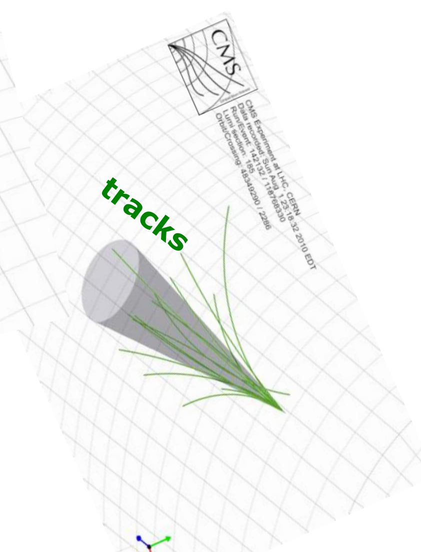
HCAL+ECAL+Tracker info
μ, $e^{\pm}$, γ, $\pi^{\pm}$, $K^{\pm}$, p, K^0, π^0,…



HCAL info
Charged and neutral hadrons



ECAL info
$e^{\pm}$, γ and neutral and charged hadrons



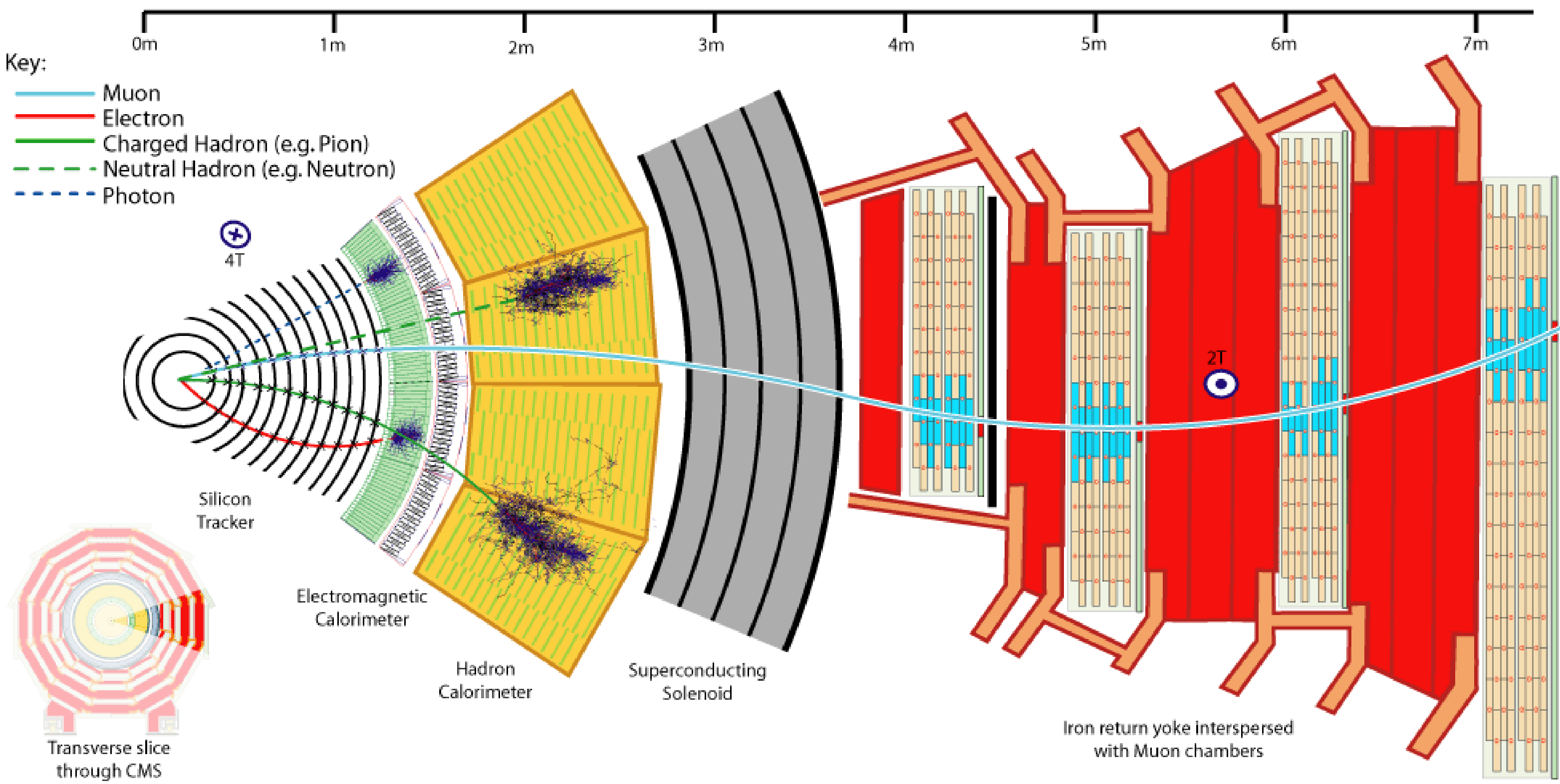
Silicon Tracker info
μ, $e^{\pm}$, and all charged hadrons

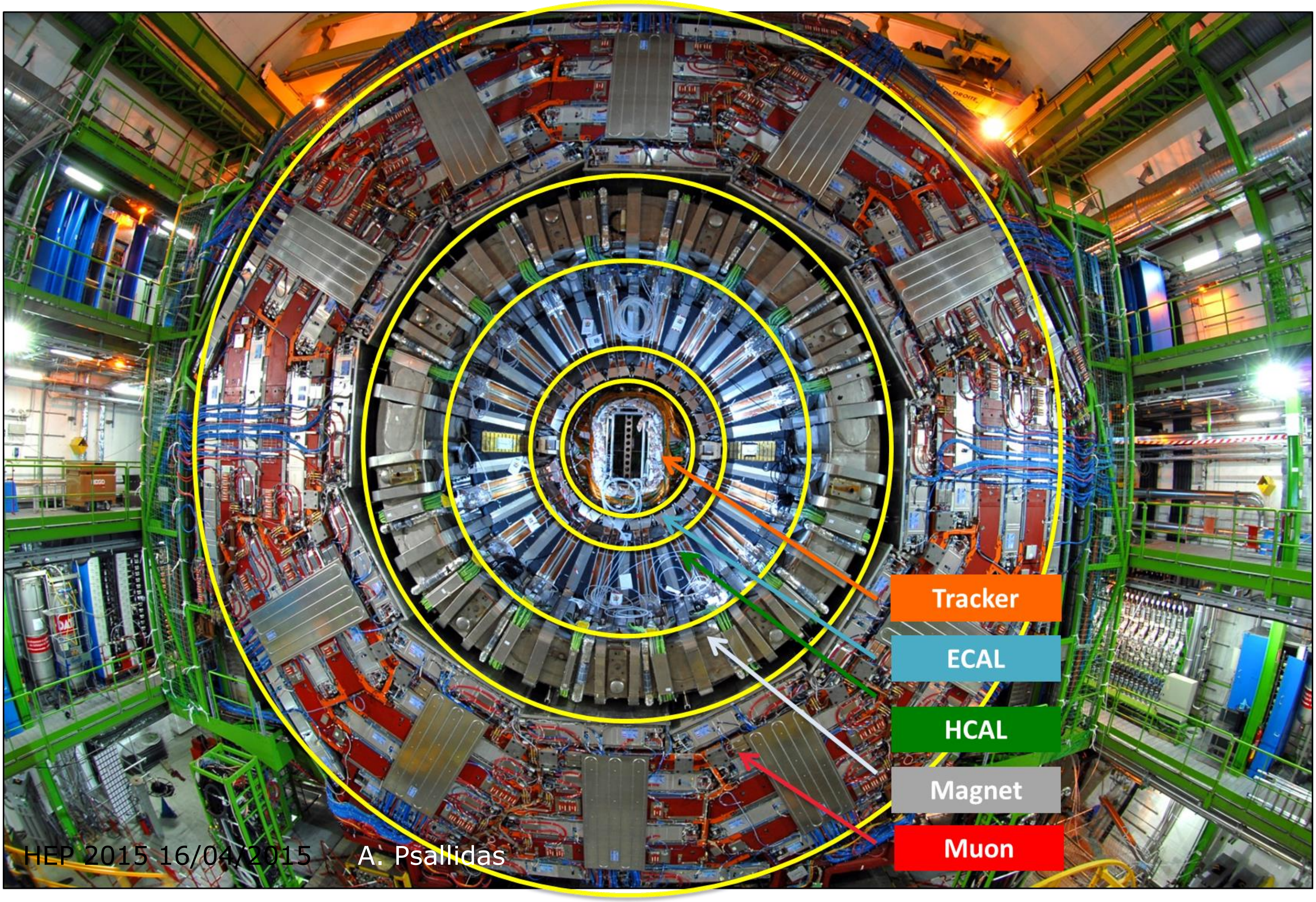
Particle Flow Algorithm combines all information from several sub-detector systems

- Tracker+Ecal+HCAL= charged hadrons ($\pi^{\pm}$,$K^{\pm}$, p,..)
- Tracker+Ecal = $e^{\pm}$
- Tracker+Muon Chambers = μ
- Ecal+HCAL = neutral hadrons
- Ecal = photons

Particle Flow in CMS

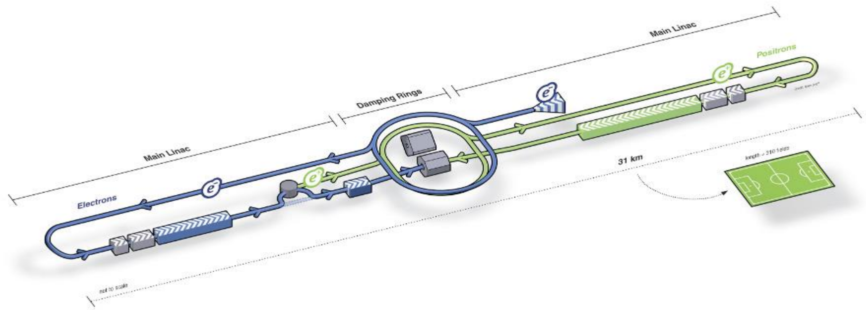
- Particle flow reconstruction has been applied in the Compact Muon Solenoid (CMS) experiment and now nearly all analyses use it.




Tracker
ECAL
HCAL
Magnet
Muon

Particle Flow for ILC - PandoraPFA

The International Linear Collider (ILC) is a proposed concepts that will collide electrons to positrons. Almost all ILC studies have been done using PandoraPFA.



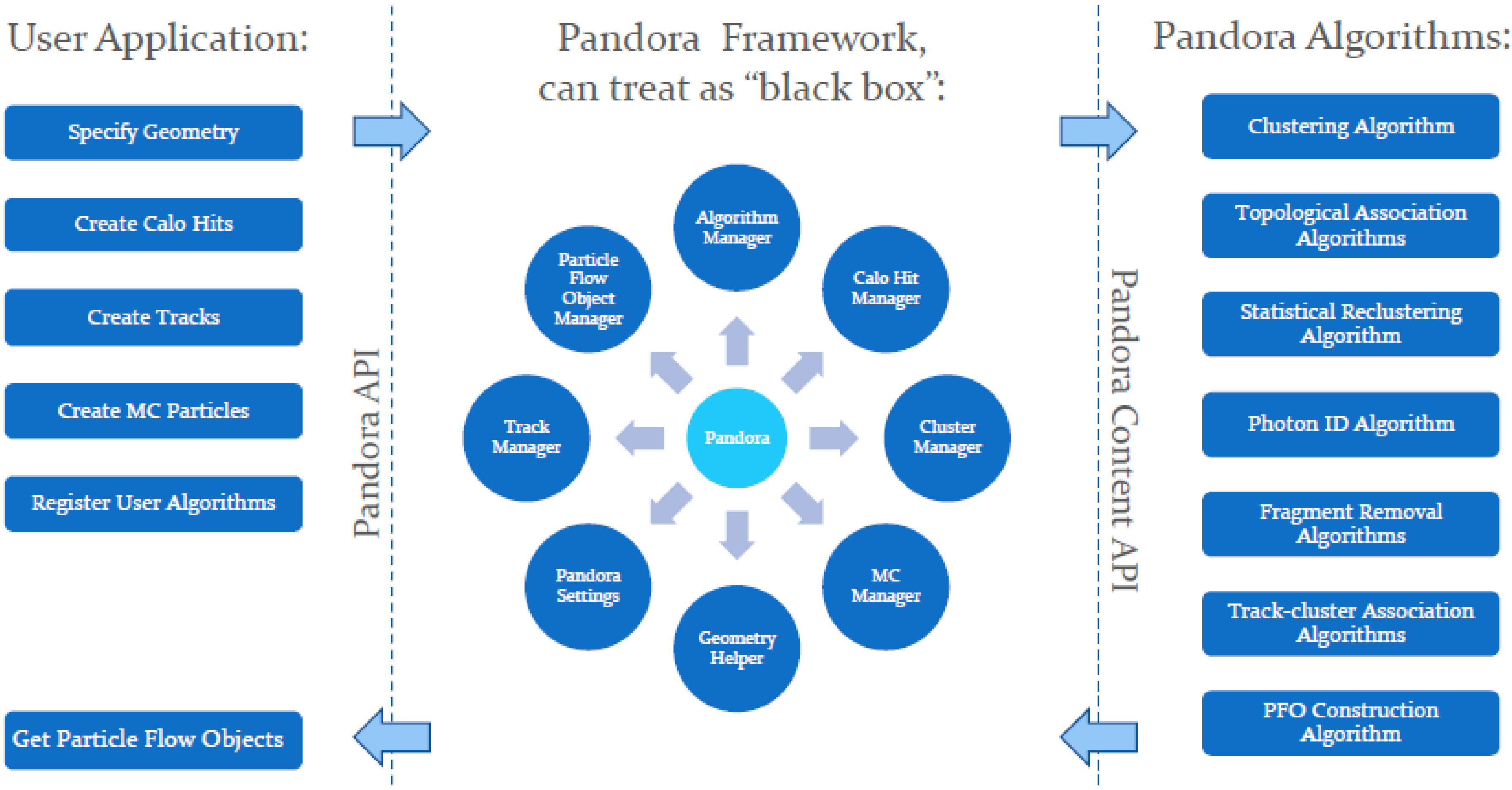
PandoraPFA is a very elaborate reconstruction package using the particle – flow technique / idea. It is developed and maintained by the Cambridge Group (M. Thomson, J. Marshall et al):

http://www.hep.phy.cam.ac.uk/~thomson/pandoraPFA/

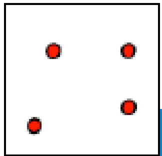
- It is a very well developed and documented package that is widely now used in HEP experiments:
  - CALICE collaboration (Particle flow calorimetry)
  - MicroBOONE (neutrino experiment)
  - ATLAS (internally only, not public yet)

PandoraPFA

- It is a generic software package, extremely flexible (a separate library with no dependencies), independent from any specific software frameworks. The user must write an application that will access this library with a simple c++ API.

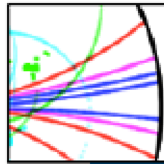


PandoraPFA - Input



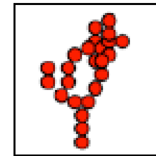
Calo Hit

- Position + normal vectors
- Calorimeter cell size
- Absorber material in front of cell
- Time of first energy deposition
- Calibrated energy (mip equivalent, EM, Had)
- Layer + pseudolayer
- Hit type + detector region
- Density weight
- Surrounding energy
- IsDigital, IsIsolated + IsPossibleMip flags
- Associated MC particle
- Associated user object



Track

- 2D impact parameters
- Momentum at d.c.a
- Particle mass
- Charge sign
- Start track state
- End track state
- ECal track state
- ReachesECal flag
- List of track state projections to calorimeter surfaces
- Associated cluster
- Associated MC particle
- Associated user object
- PFO formation flag
- "Clusterless" PFO formation flag

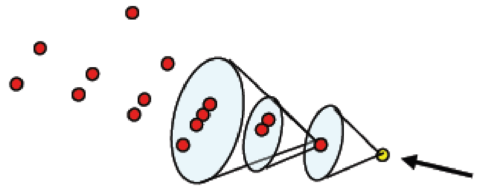


Cluster

- List of constituent calo hits, ordered by pseudolayer
- Mip fraction
- EM energy measure
- Had energy measure
- Initial direction
- Current direction
- Result of linear fit to all hits in cluster
- Energy-weighted centroid
- ShowerStart layer
- Shower profile properties
- List of associated tracks

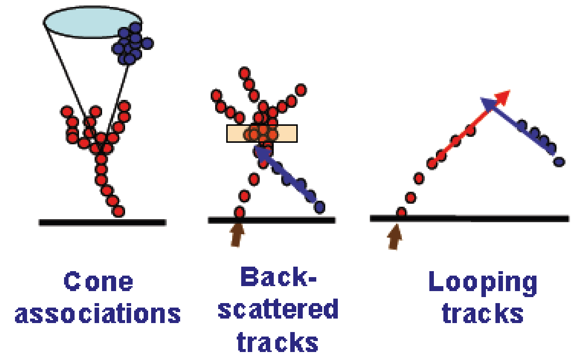
plus some lightweight geometry information about the detector

PandoraPFA – Algorithms

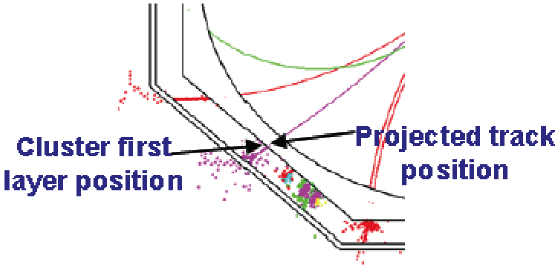


ConeClustering Algorithm

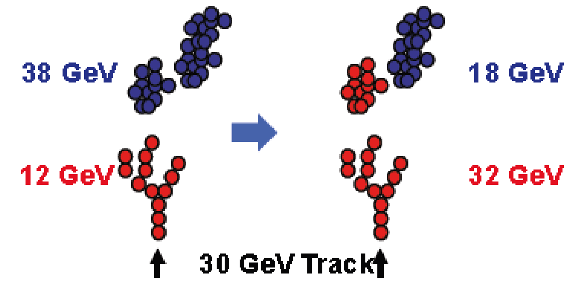
Topological Association Algorithms



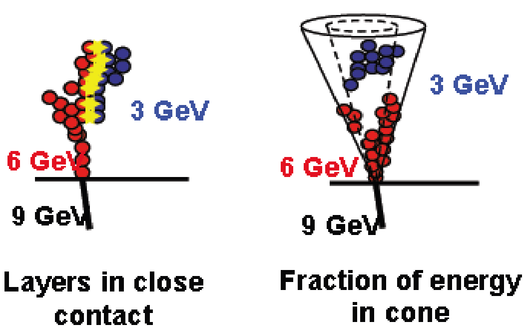
Track-Cluster Association Algorithms



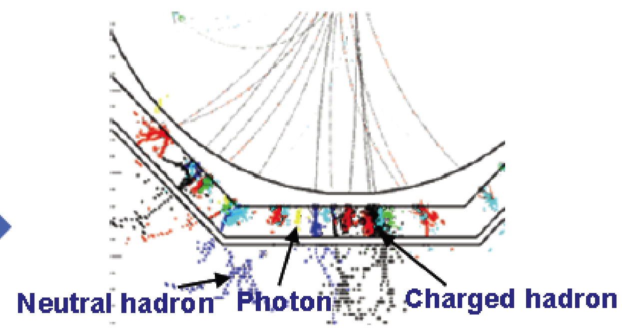
Reclustering Algorithms



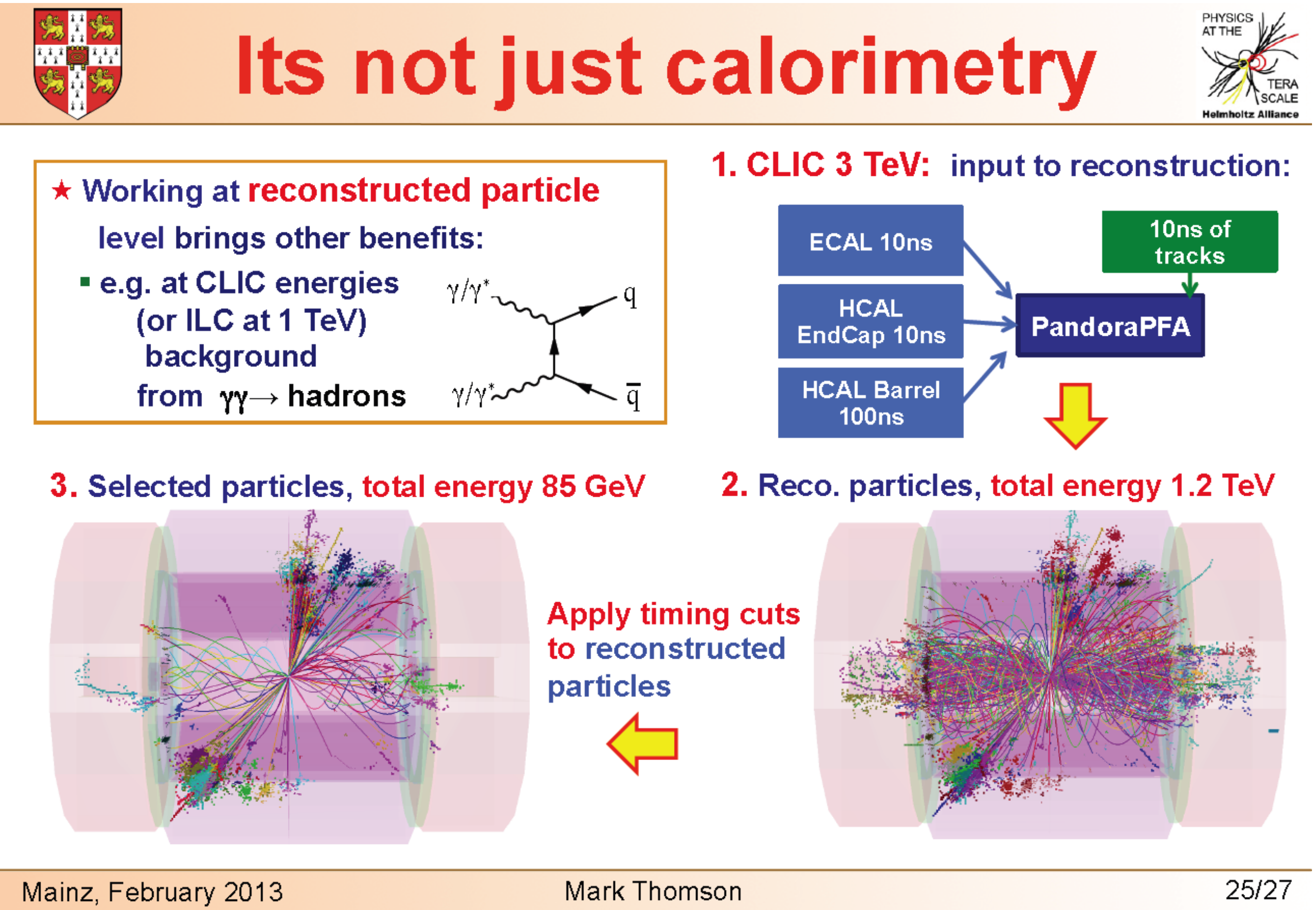
Fragment Removal Algorithms



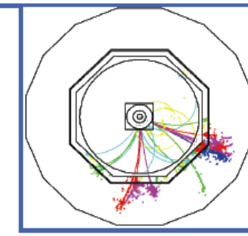
PFO Construction Algorithms



Pandora PFA : Performance

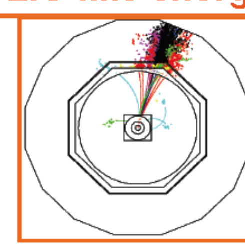


ILC-like energies



Clear separation of W/Z di-jet mass peaks

CLIC-like energies



W and Z still resolved from monojet invariant mass

- Very powerful tool!!

PandoraPFA in HGCAL

In order to see and test the performance of PandoraPFA in the high-granularity calorimeter designed for the High Luminosity LHC (HL-LHC) we firstly tested it in the current detector.

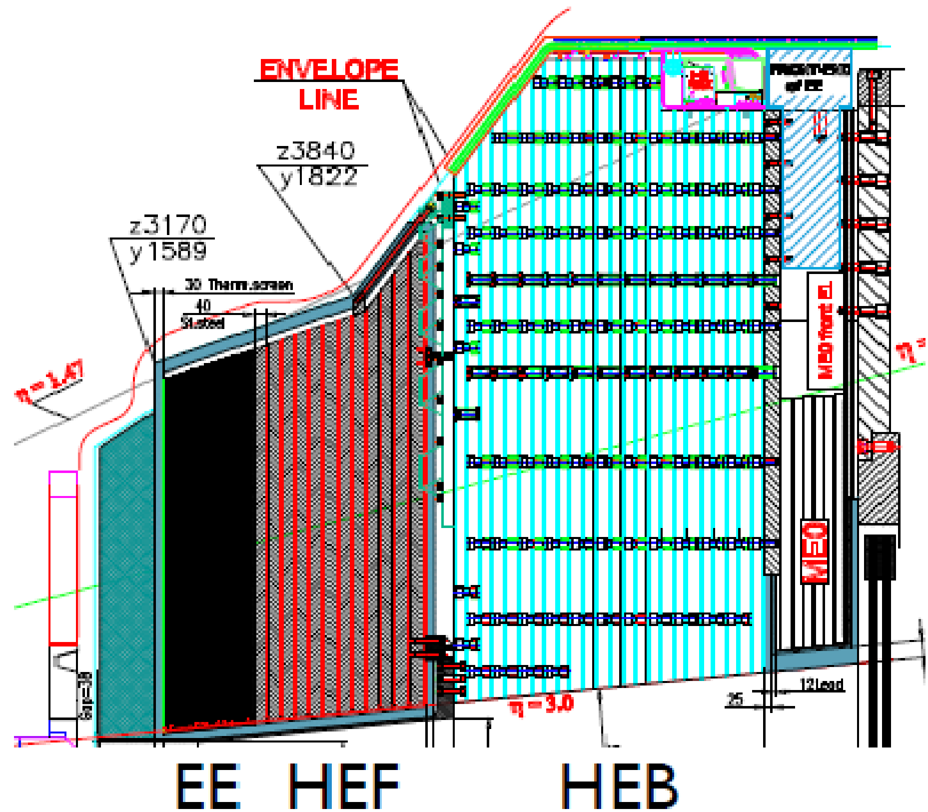
Taking advantage of the flexibility of the PandoraPFA software we incorporated it in the CMS software framework.

The PandoraAPI has been provided for the current CMS detector with:

- Track input: The official local reconstruction of the tracker is used and the extrapolation of the track to the ECAL front face is done using tools of the CMS software framework.
- Calorimeter input: The official reconstructed ECAL and HCAL hit objects is used. The current geometry information is used for the relevant input (cell position, size etc.)
- Geometry input: A very primitive information of the detector is used with one barrel and one endcap layer for each subdetector.

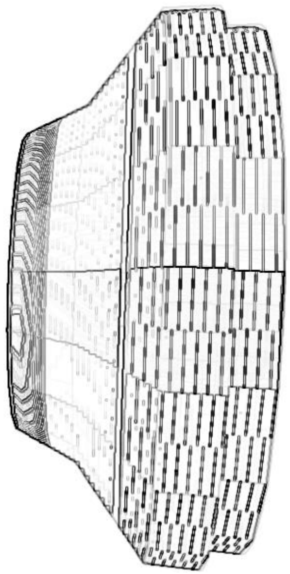
CMS Upgrade – HGCAL (I)

- One future phase that is planned for the Large Hadron Collider (LHC) is referred to as High Luminosity LHC (HL-LHC).
- Aims to record an integrated luminosity of $3000\ fb^{-1}$.
- A solution for electromagnetic and hadronic calorimetry at that era: High Granularity Calorimeter (HGCAL).
- Integrated Silicon ECAL+HCAL sampling calorimeter and a Backing Calorimeter
- For the backing hadronic calorimeter Athens, Demokritos, Annecy and Saclay cooperate in an R&D to promote the Micromegas option.
- The decision will be taken in the next days (Shashlik vs. HGCal)



CMS Upgrade – HGCAL (II)

- $26X_0$ for EE and 5λ for EE + HEF
- 1.5λ for EE and 3.5λ for HEF
- HEB adds 5λ
- HGCAL: 10 λ
- Full 4D (5D?) shower reconstruction
  - x, y, z & Energy
  - With potentially also high resolution cell timing. Studies ongoing: feasibility & physics impact of the timing

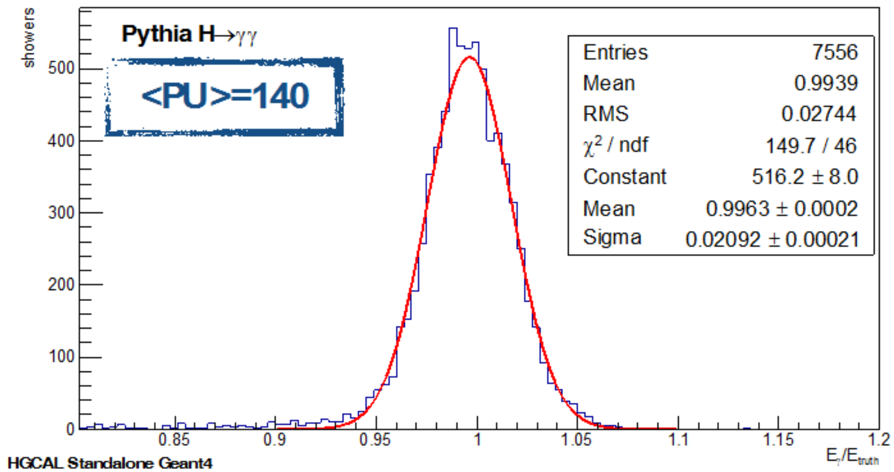


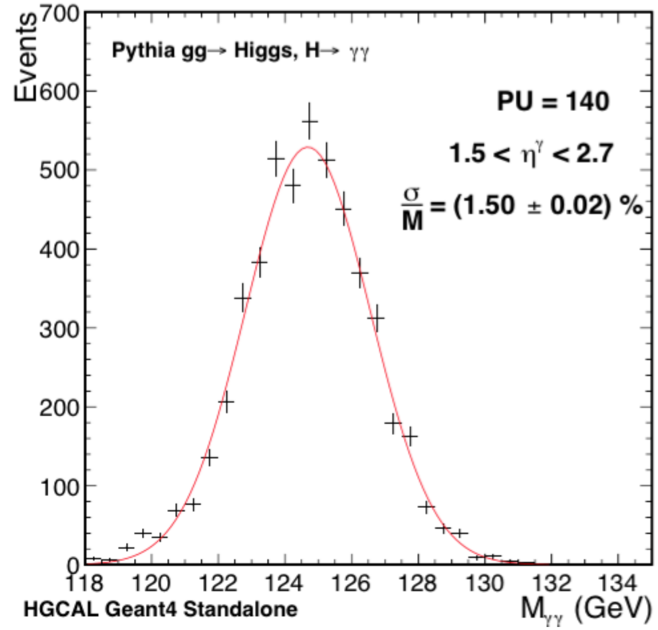
Sub-detector	# layers	Structure	Cell size [mm²]	Cell thickness [mm]
HGCEE	1	0.5mm Cu + 2mm Air + 1.2mm FR4 + 0.3mm Si + 3.0mm Cu + 1mm Pb	10x10	0.2
	5	1.75mm W + 0.5mm Cu + 2mm Air + 1.2mm FR4 + 0.3mm Si + 3mmCu + 1.0mm Pb + 3.0mm Cu + 0.3mm Si + 1.2mm FR4 + 2.0mm Air + 0.5mm Cu	10x10	0.2
	5	2.8mm W + 0.5mm Cu + 2mm Air + 1.2mm FR4 + 0.3mm Si + 3mm Cu + 2.1mm Pb + 3mm Cu + 0.3mm Si + 1.2mm FR4 + 2mm Air + 0.5mm Cu	10x10	0.2
	4	4.2mm W + 0.5mm Cu + 2mm Air + 1.2mm FR4 + 0.3mm Si + 3mm Cu + 4.4mm Pb + 3mm Cu + 0.3mm Si + 1.2mm FR4 + 2mm Air + 0.5mm Cu	10x10	0.2
	1	4.2mmW + 0.5mm Cu + 2mm Air + 1.2mm FR4 + 0.3mm Si + 3.0mm Cu + 1mm Pb	10x10	0.2
HGCEF		15mm Stainless steel		
	12	40mm Brass + 0.5mm Cu + 2mm Air + 1.2mm FR4 + 0.3mm Si + 3.0mm Cu + 1mm Pb	10x10	0.3
		2mm Al + 2mm Foam + 2mm Al (thermal shielding) + 65mm Air gap		
HGCEB	12	34.5mm Brass + 9.0mm Scintillator or 9.0mm Brass	20x20mm	43.5

e/γ Performance

Photon and H→γγ resolution

H→γγ PU140 (p_T>40 GeV)

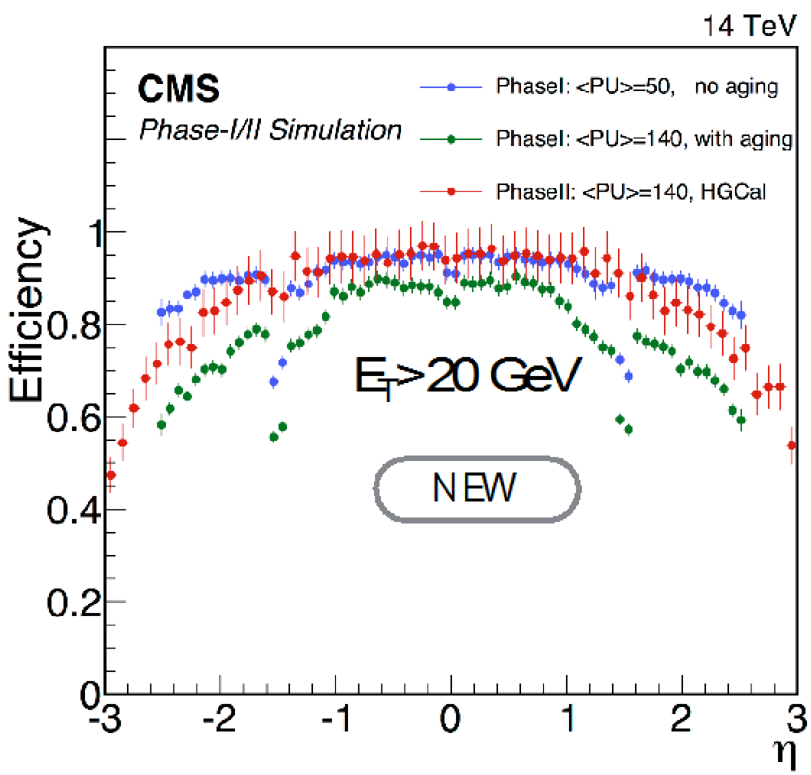




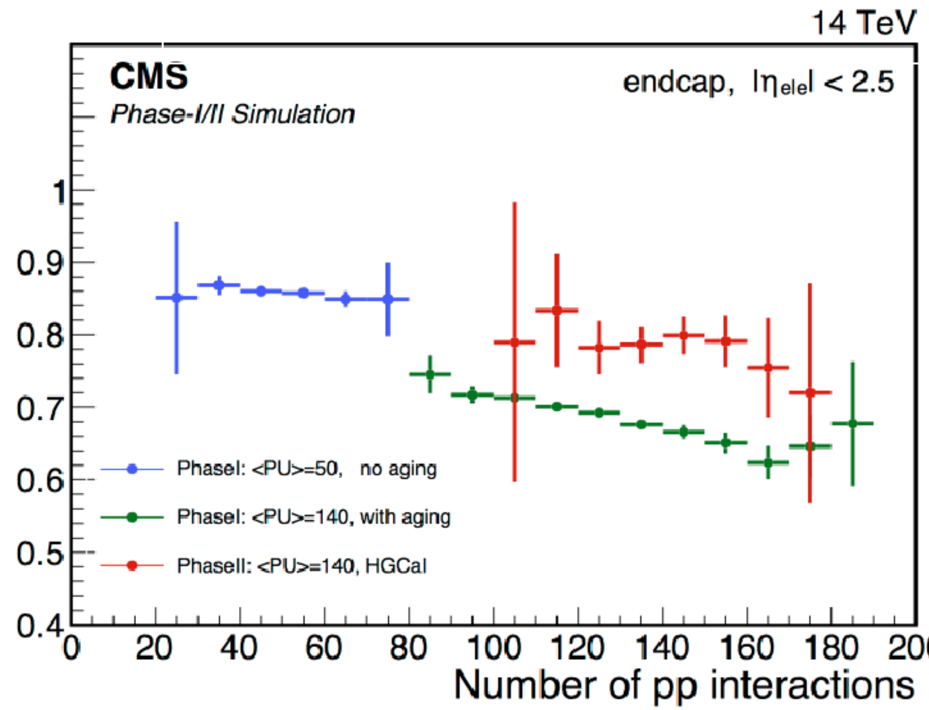
PU/Resolution	HGCal	HGCal
PU0	**0.020**	**1.45%**
PU140	**0.021**	**1.50%**

Electrons (I)

Reconstruction efficiency, without isolation cuts; but indirect isolation via H/E requirement.

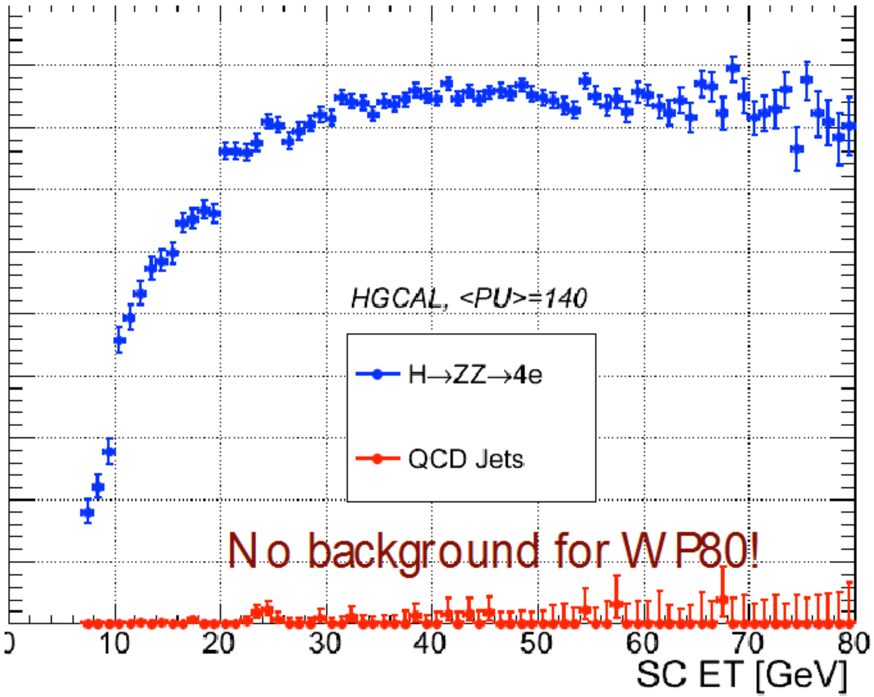


Dependence on pileup, E_T>10 GeV

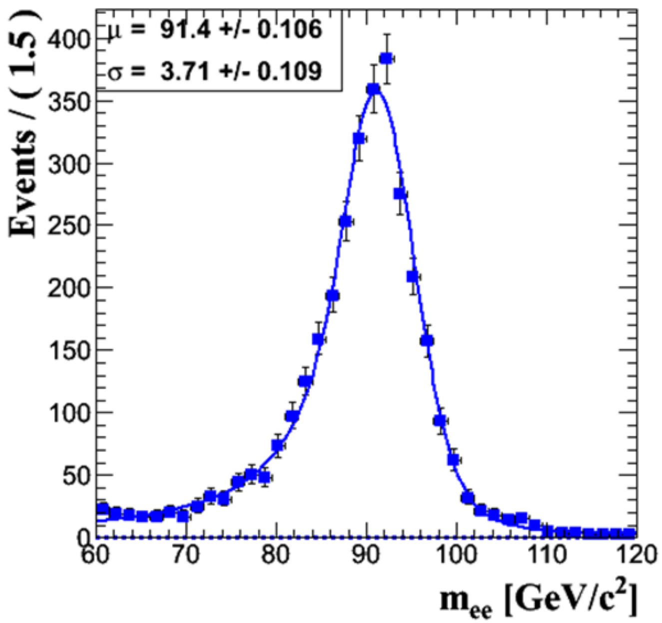


Electrons (II)

Full MVA developed. Uses longitudinal info.



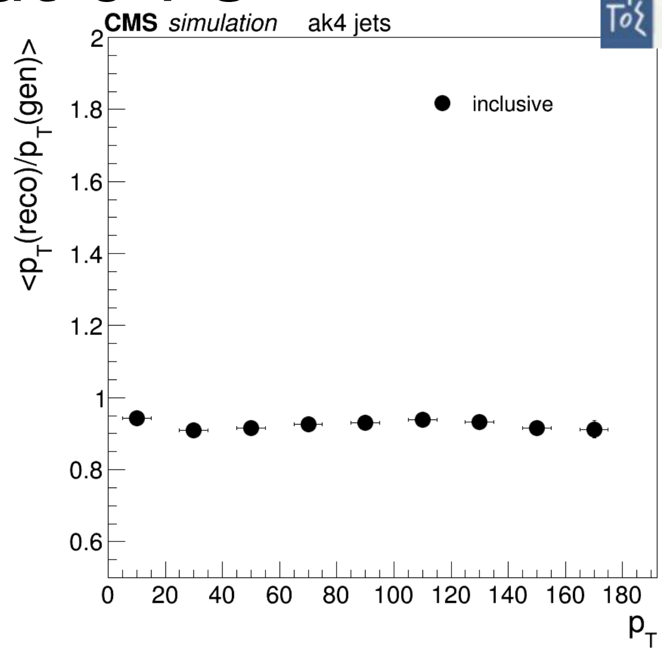
Z→ee mass resolution: 3.71/91.4 = 4.1%

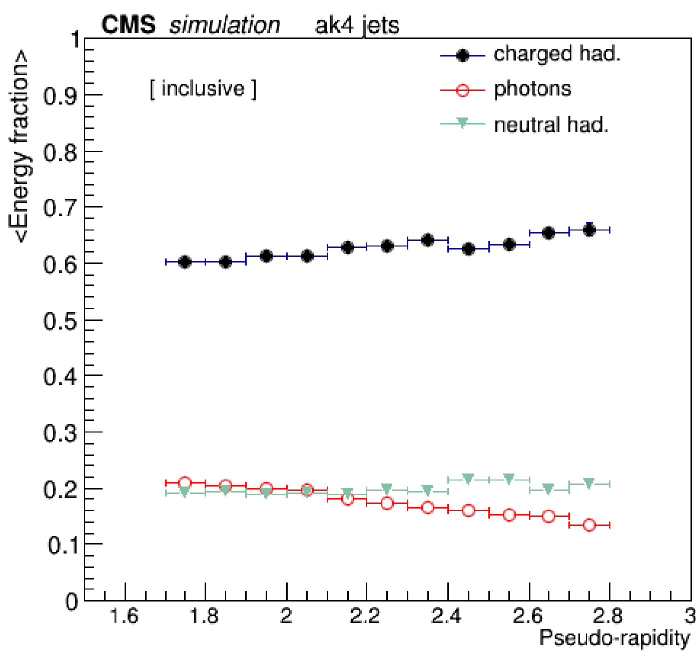


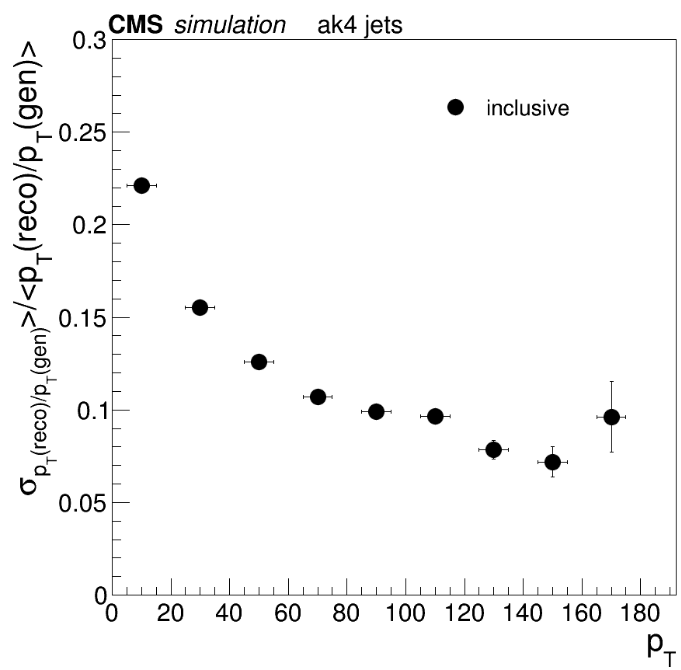
Jets Performance

Jet Performance at 0 PU

- Promising first results for jet energy performance at 0 PU.
- Scale and resolution look reasonable.
- Problem in Jet constituent energy fractions. Expect 65% charged hadrons, 25% γ, 10% neutral hadron
- Jet Energy Corrections have not been applied



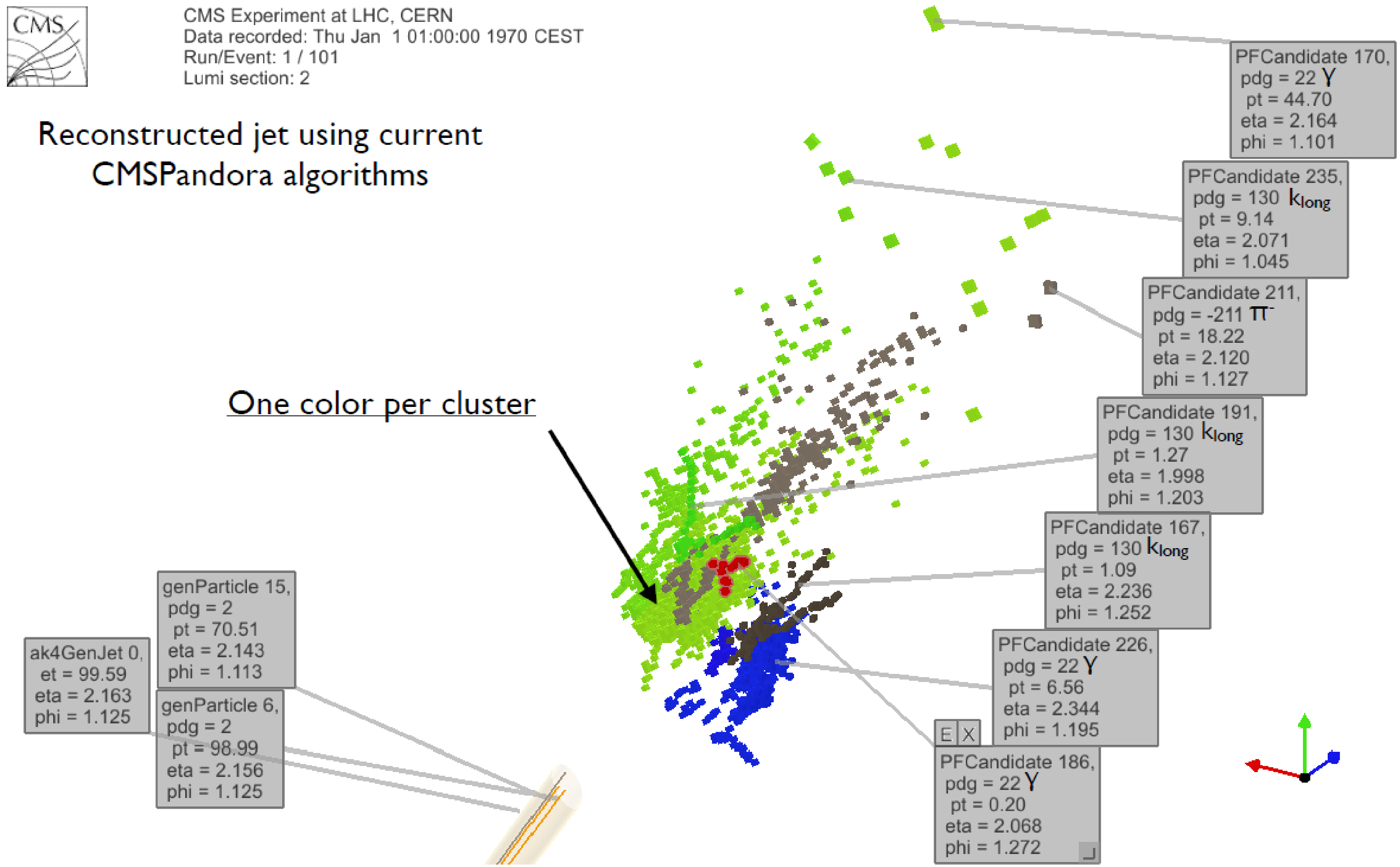




Cluster Reconstruction in HGCal (I)

Reconstructed jet using current CMSPandora algorithms

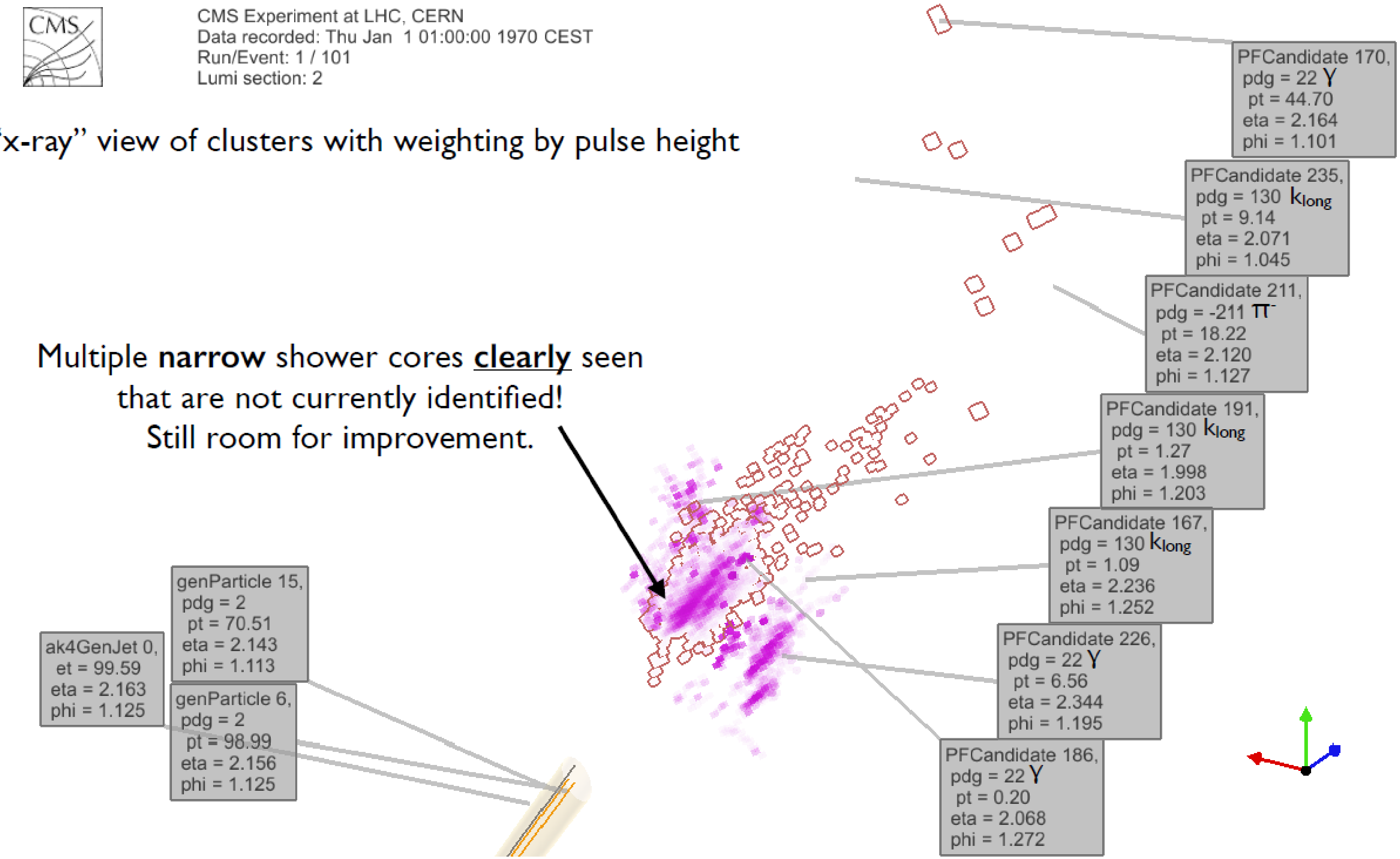
One color per cluster



Cluster Reconstruction in HGCal (II)

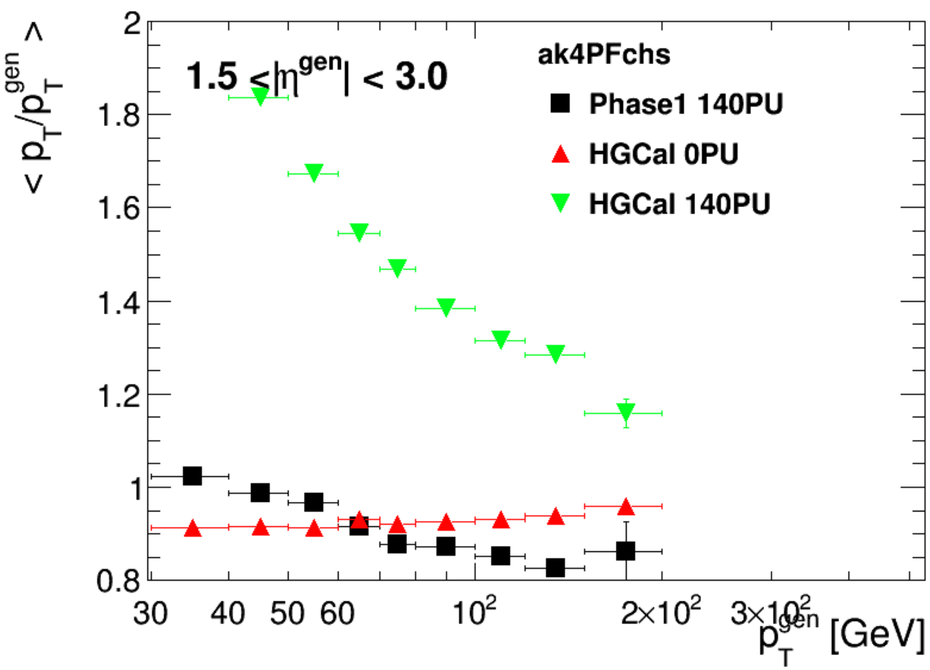
"x-ray" view of clusters with weighting by pulse height

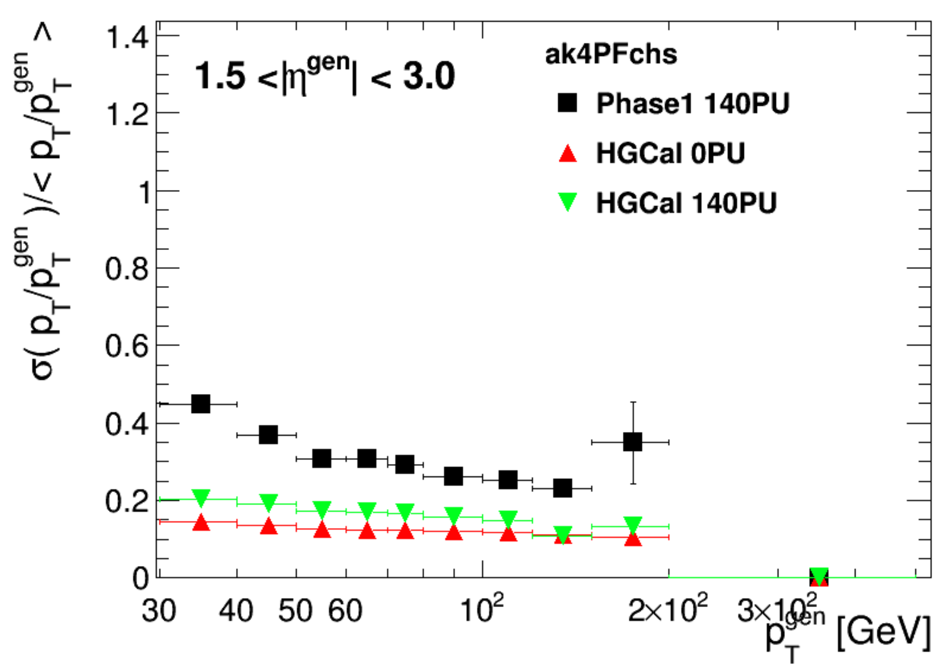
Multiple **narrow** shower cores <u>**clearly**</u> seen that are not currently identified! Still room for improvement.



Jet Performance in 140 PU

- Good performance in 140 PU. Algorithms are making good decisions with available information. Room for improvement.





Summary

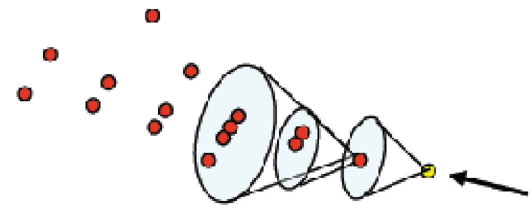
- PandoraPFA is in the official software framework of CMS with good results.
- Good electron performance and γγ mass resolution (stand-alone).
- Uncorrected jet energy resolution 20% at low pT in 140 PU.
- Jet resolution and composition close to expected performance.
- Room for improvement if the option is selected over the next 10 years.

Back-Up

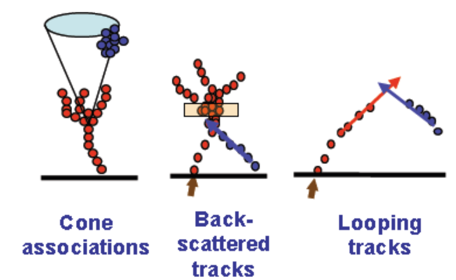
PandoraPFA – Algorithms (I)

In PandoraPFA the algorithms perform the actual particle flow reconstruction.

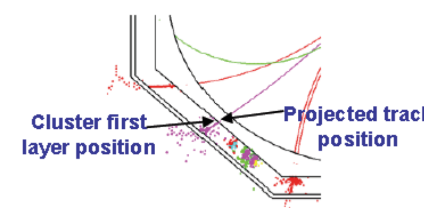
- Cone Clustering Algorithm: The clustering algorithm starts at inner layers and work outward. Hits are added to clusters or are used to seed new clusters. Clusters can be seeded by the projection of inner detector tracks to the front face of the calorimeter.



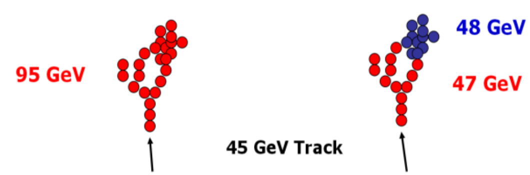
- Topological Association Algorithms: Clusters associated using a number of topological rules.



- Track-Cluster Association Algorithms: Calorimeter clusters are associated to inner detector tracks, by comparing the properties of the clusters (linear fits, helix fits, etc.) to the projected track states at the front face of the calorimeter.

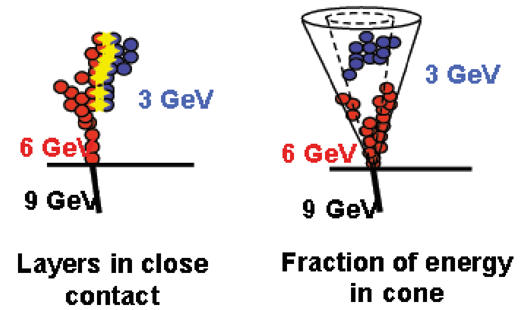


- Reclustering Algorithms: If the track momentum and the cluster energy are inconsistent recluster. That is, change the clustering parameters until the cluster splits, or merged with nearby fragments, and end up with sensible track-cluster match.

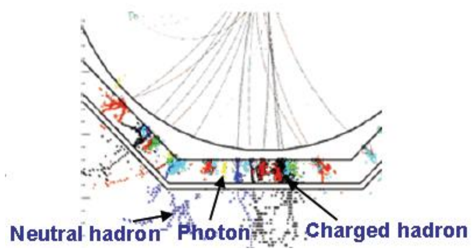


PandoraPFA – Algorithms (II)

- Fragment Removal Algorithms: They look for neutral clusters (no track-association) that are actually fragments of nearby charged clusters (with track-associations). If they find evidence of association between them, they merge them and see the changes in track-cluster compatibility.



- PFO Construction Algorithms: If a particle contains tracks and associated clusters, the particle properties are extracted from the tracks. For neutral particles, the calorimeter information is used.



- Particle identification algorithms: The reconstructed particles are flagged with PDG codes, identifying charged leptons. Photon identification is performed throughout the reconstruction, but can be finalized at this stage.

Pandora PFA - Working with it (I)

Content	Description
Algorithms	Responsible for performing reconstruction; make use of all information provided by objects, helper functions, calculators, etc. to make decisions and create PFOs.
PseudoLayer calculator	Responsible for dividing hits into layers that broadly follow structure of detector; helps to isolate algorithms from need to know specific geometry.
B-field calculator	Responsible for providing signed B-field value for given Cartesian coordinates; often a wrapper for a full field map in client software framework.
Shower-profile calculator	Responsible for examining longitudinal and transverse profile of cluster energy deposits and performing comparison with expectation for EM shower.
Particle id functions	Responsible for providing ("fast" or "full") particle id information to algorithms, which may want to avoid certain particle-types, or simply apply results to PFOs.
Energy corrections	Responsible for applying corrections, improvements or custom calibrations to reported hadronic or electromagnetic cluster energy values.
Geometry	Optional detector description, which can be used by an algorithm if necessary.
Objects	Self-describing properties for tracks, hits and optional MC particles.

Pandora PFA - Working with it (II)

Algorithms for fine granularity detectors

4 clustering algorithms, forward and reverse cone-based, *k*-means and 2D Hough transform

5 algorithms for removing cluster fragments, including charged hadron fragments and photon fragments

2 standalone algorithms for reconstruction of muons and photons, **2** for performing particle id after reconstruction

4 algorithms for PFO creation and selection

7 reclustering algorithms, **15** topological association algorithms, **5** track-cluster association algorithms

6 algorithms for monitoring reconstruction between algorithms or providing event display functionality

3 list management algorithms, **2** algorithms for reading/writing Pandora binary files and **5** 'perfect' PFA algorithms

Helper functions & calculator classes for fine granularity detectors

Pseudo layer calculator

Longitudinal and transverse shower profile characterisation functions

EM shower, photon, electron and muon identification functions

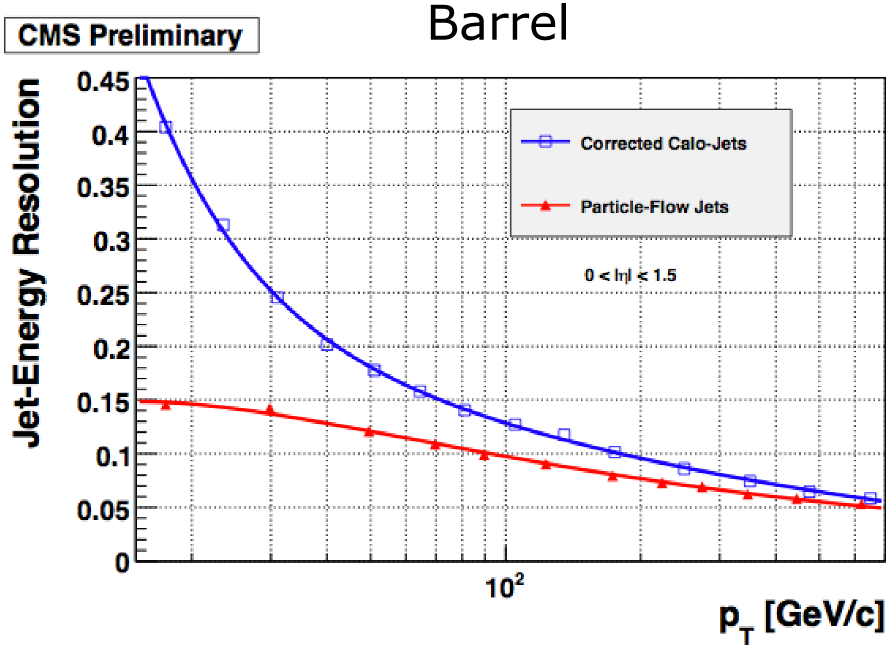
Energy correction functions for addressing energy fluctuations in hadronic showers and energy loss in coil

PF and Jet Energy Resolution

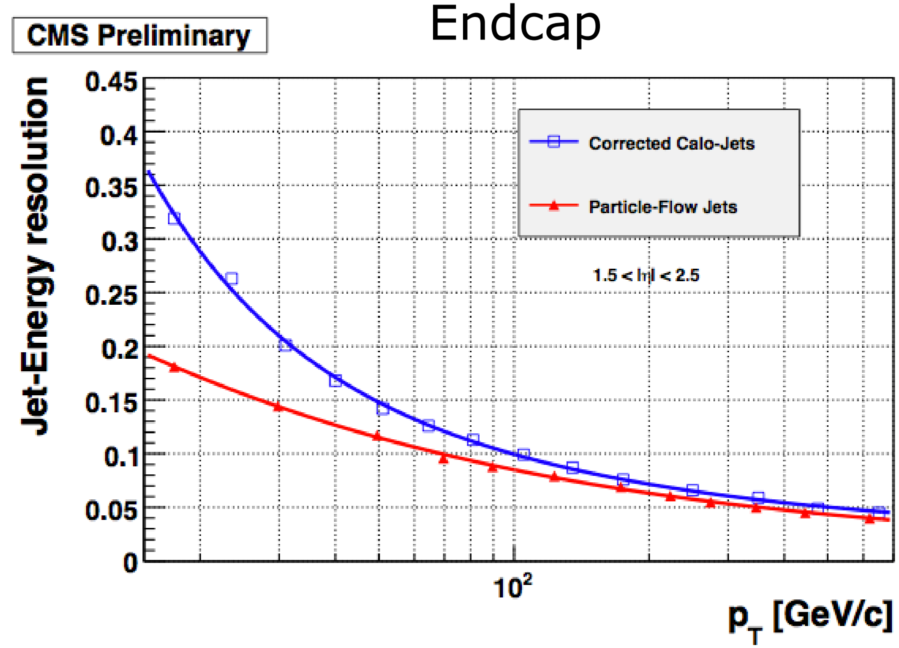
Using simulated QCD events compare:

- Calo-Jets: Jets produced from CaloTowers, that is combination of ECAL and HCAL cells into projective towers corresponding to HCAL granularity.
- Particle-Flow Jets: Jets produced from Particle Flow candidates.

Barrel



Endcap

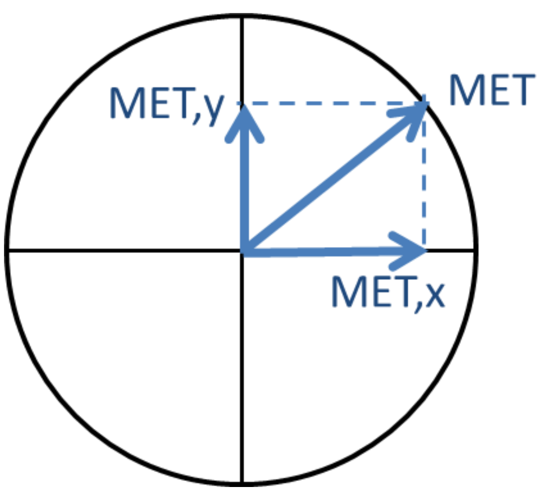


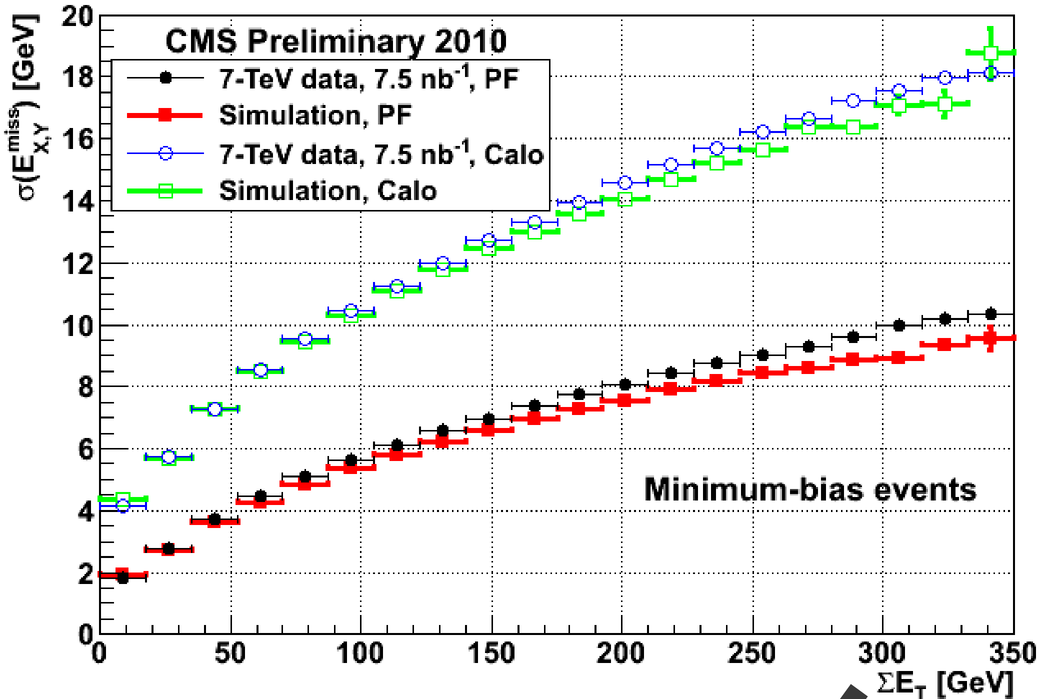
Factor of 2 gain in low pt.

PF and Missing Transverse Energy

Using Minimum-bias events:

- $E_{X,Y}^{miss}$ $\rightarrow$ distributions fit to a Gaussian.
- Plot the resulting width $\sigma(E_{X,Y}^{miss})$ vs $\sum E_T$
- Factor of 2 gain for simulation and data.

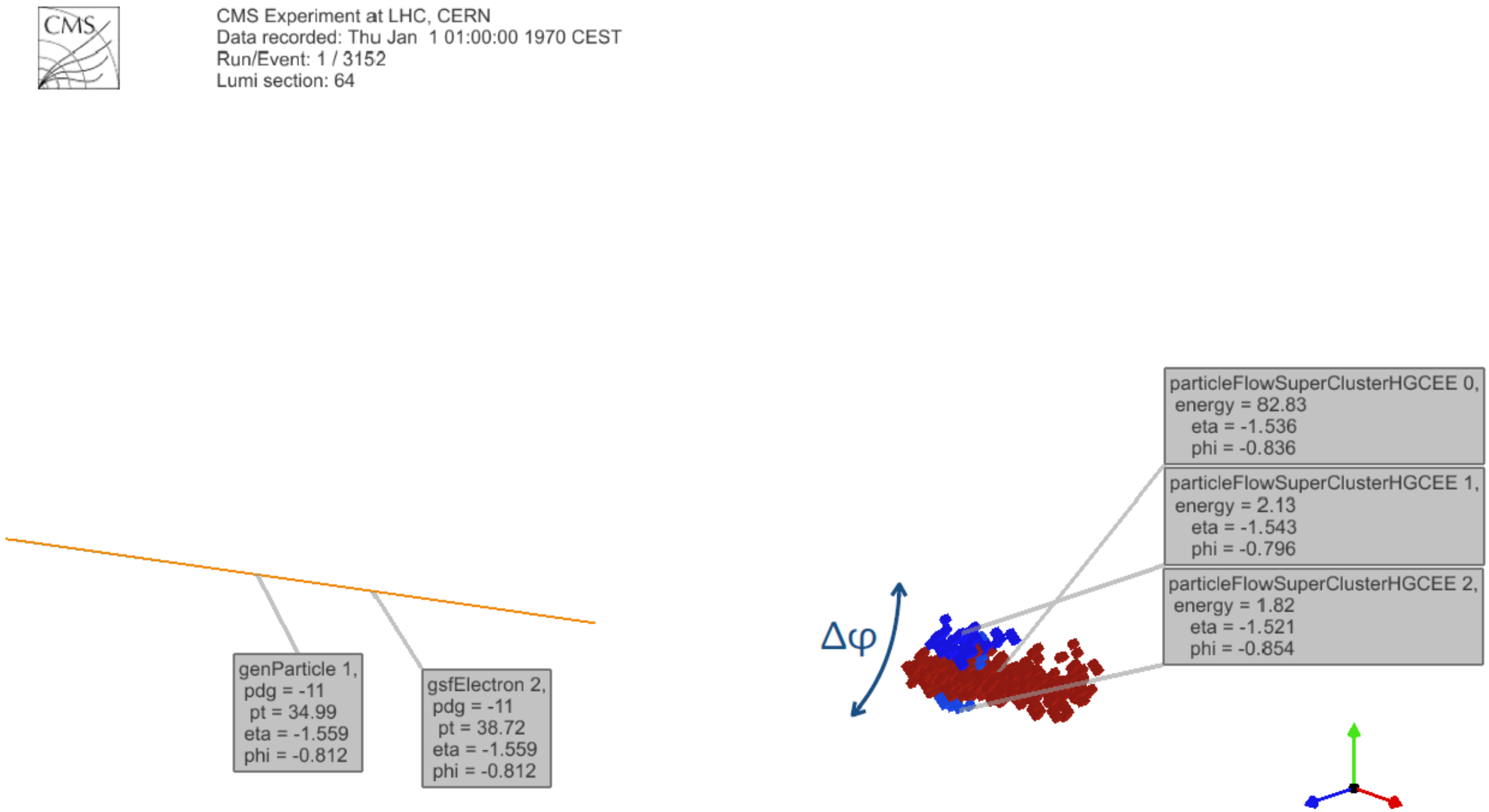




Sum of the transverse energies of all reconstructed particles.

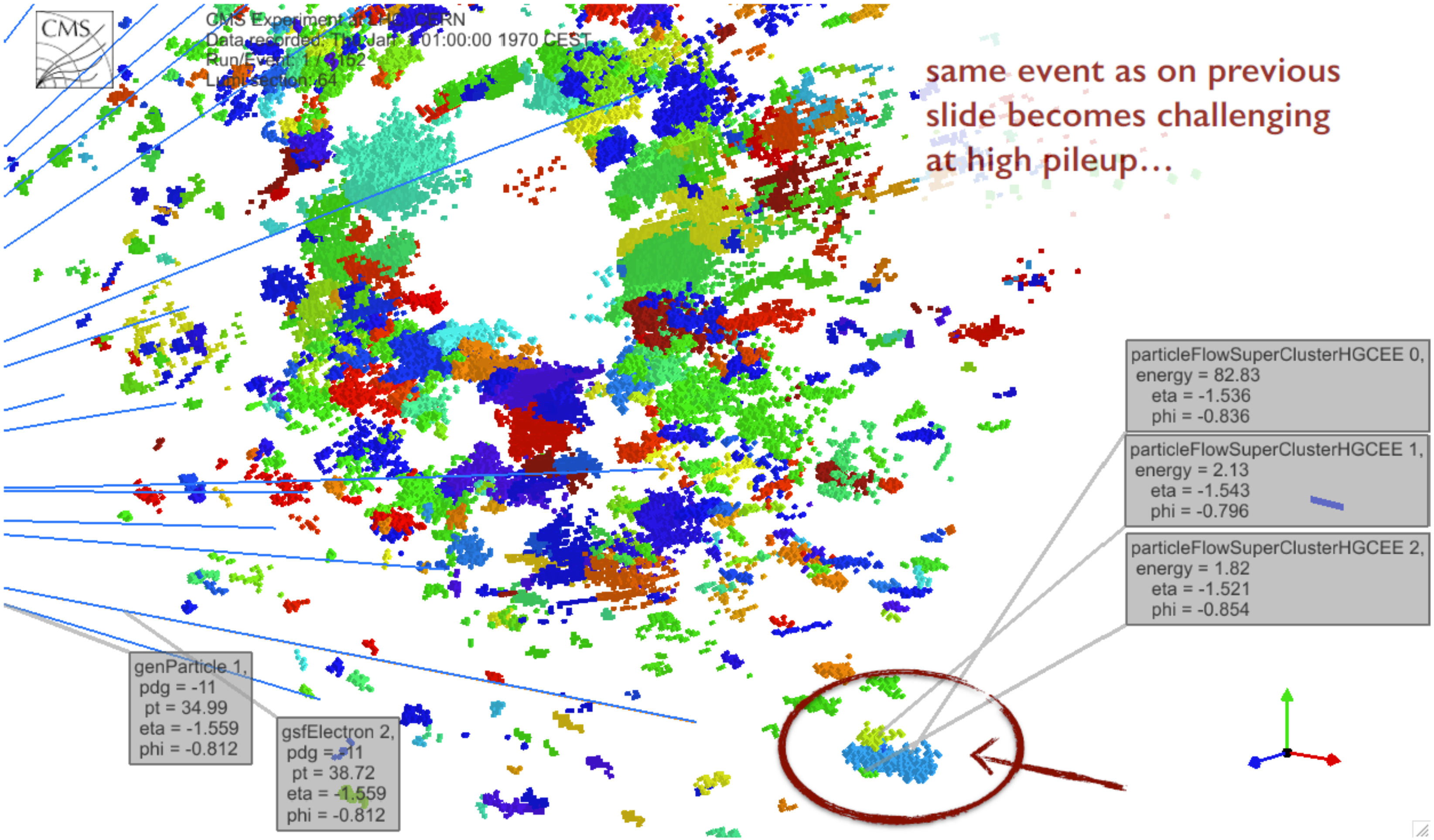
Electron energy measurement at 140 PU

Key issue: Recovery of Bremsstrahlung



Electron energy measurement at 140 PU

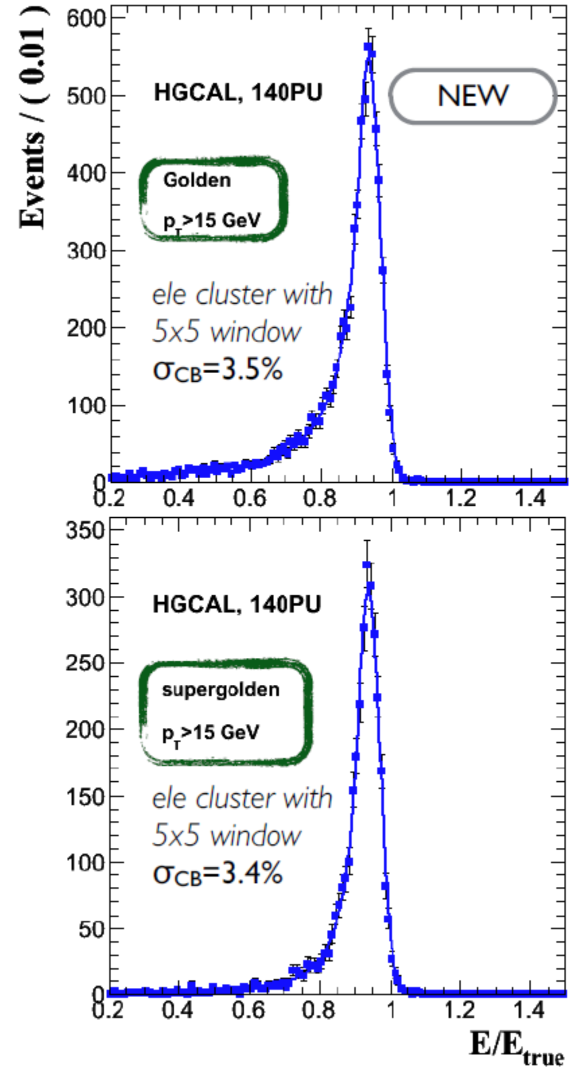
Key issue: Recovery of Bremsstrahlung



same event as on previous slide becomes challenging at high pileup…

Electron energy resolution

- Electrons reconstructed in HGC fiducial region ($1.5<|\eta|<3$). Electron categories are:
  - Golden electrons: $f_{brem}<0.2$ and $|\Delta\varphi(\text{ele,tk out})|<8$ mrad
  - Showering: $0.5<f_{brem}<0.8$
  - Super-golden: Golden + #clusters=1

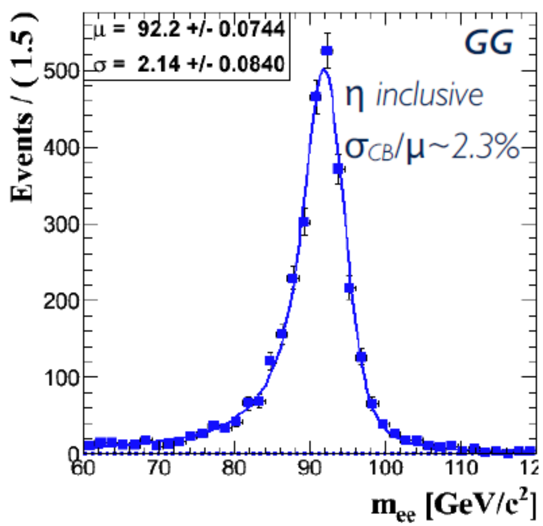


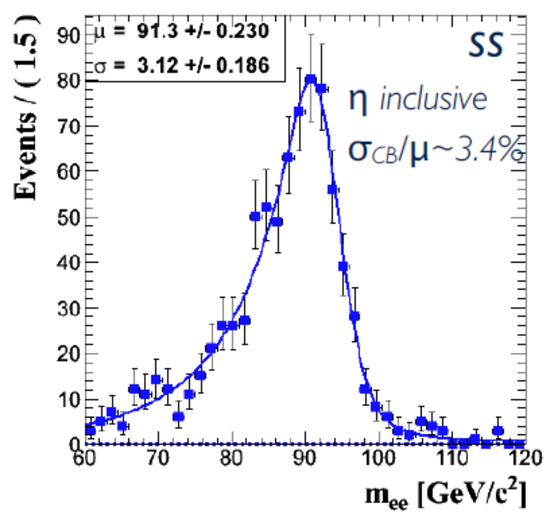
	Peak		σ_{CB}		σ_{eff}	
p_T threshold [GeV]	15	30	15	30	15	30
Golden (e cl energy)	0.935	0.936	3.5%	3.1%	7.4%	6.5%
Golden (cleaned SC)	0.998	0.994	5.4%	4.9%	6.9%	6.3%
Golden (ele cl 5x5)	**0.935**	**0.936**	**3.5%**	**3.1%**	**8.4%**	**6.5%**
Supergolden (cleaned SC)	0.987	0.986	4.7%	4.0%	5.8%	5.0%
Supergolden (ele cl, 5x5)	**0.938**	**0.939**	**3.4%**	**3.0%**	**5.1%**	**4.4%**
Showering	0.991	0.994	6.3%	5.4%	9.7%	8.5%

Z→ee mass resolution

- Electrons reconstructed in HGC fiducial region (1.5<|η|<3). Momentum from ECAL energy + tracker direction. Further improvements expected from full energy/momentum corrections.

	σ/m		σ_{eff}/m		% events	
	Run I	HGC	Run I	HGC	Run I	HGC
All	2.2%	2.9%	2.5%	4.6%	100%	100%
BG x BG	1.2%	1.6%	1.3%	2.2%	4.4%	13.8%
BS x BS	2.1%	2.3%	2.4%	4.2%	15.5%	1.5%
BG x **EG**	2.1%	**3.0%**	2.3%	**4.1%**	2.2%	**7.9%**
BS x **ES**	2.9%	**4.2%**	3.2%	**7.0%**	11.5%	**3.0%**





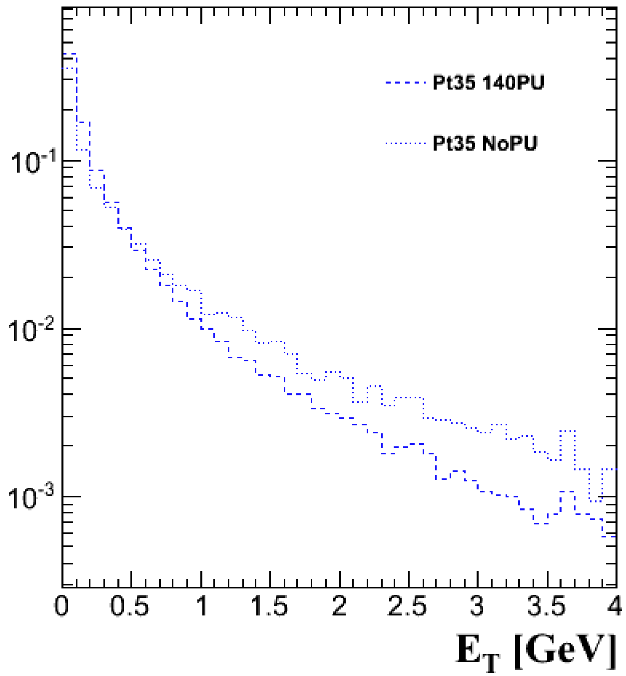
Run I (40 PU, based on 2 regressions)
B - barrel;
E - endcaps
G - golden;
S - showering or bigbrem or cracks

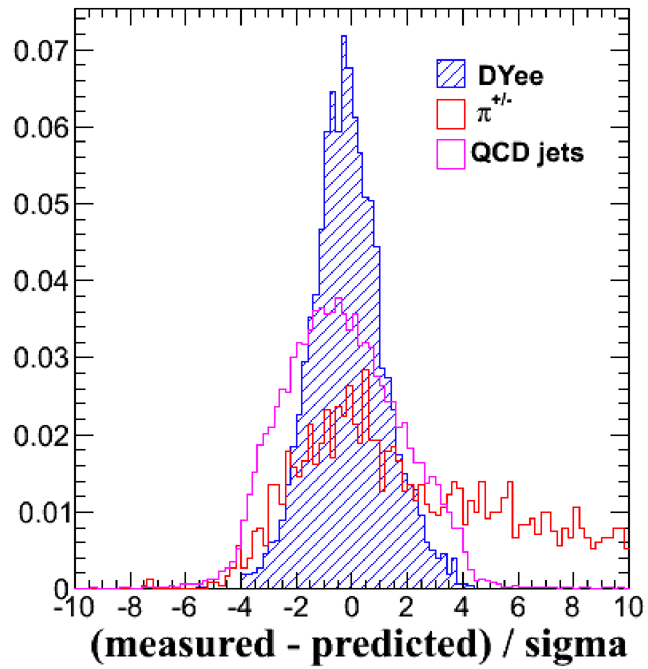
HGC (140 PU, simple weighting + PU cleaning
B - barrel;
E - endcaps
G - golden;
S - showering or badtrack or cracks

Natural width subtracted

Pileup contamination

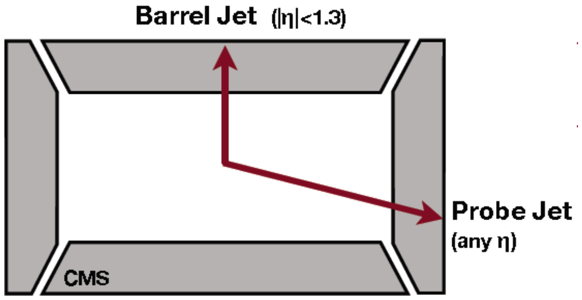
- Supercluster is filled with in average 4-5 additional sub-clusters mostly from PU.
  - Low p_T neutrals γ are resolved using transverse granularity.
  - Charged hadron will in average interact later in the calorimeter and using the longitudinal segmentation of the detector and the shower length the extra pions that are overlapping can be removed.

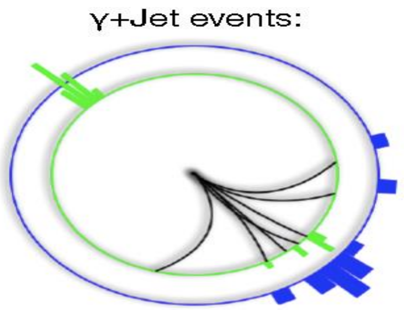




Jet Corrections

- Jets are corrected at CMS following a factorized scheme, where three corrections are applied sequentially:
- *Offset: pile up and noise correction*
- *Relative: jet response vs η relative to barrel found using dijet balance*
- *Absolute: jet response vs pT found in barrel using γ/Z+jet*





$$p_T^{corrected} = Abs(p_T \cdot Rel(\eta, p_T)) \times Rel(\eta, p_T) \times p_T - \text{offset}$$

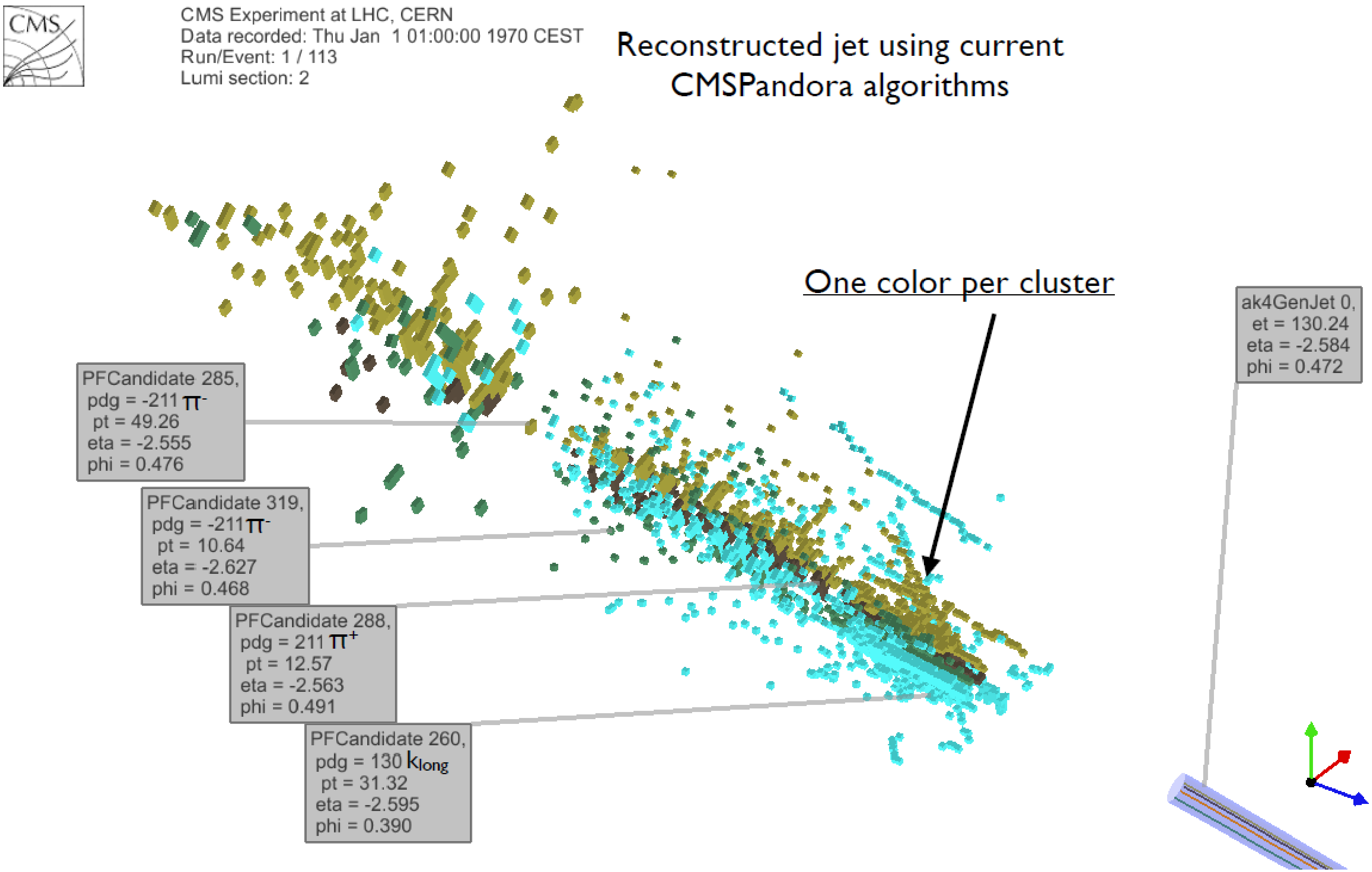
Absolute correction is applied to the jets which have already been corrected for η dependence

Relative correction is applied to the jets which have already been "offset" corrected

Offset correction is applied to the uncorrected jets

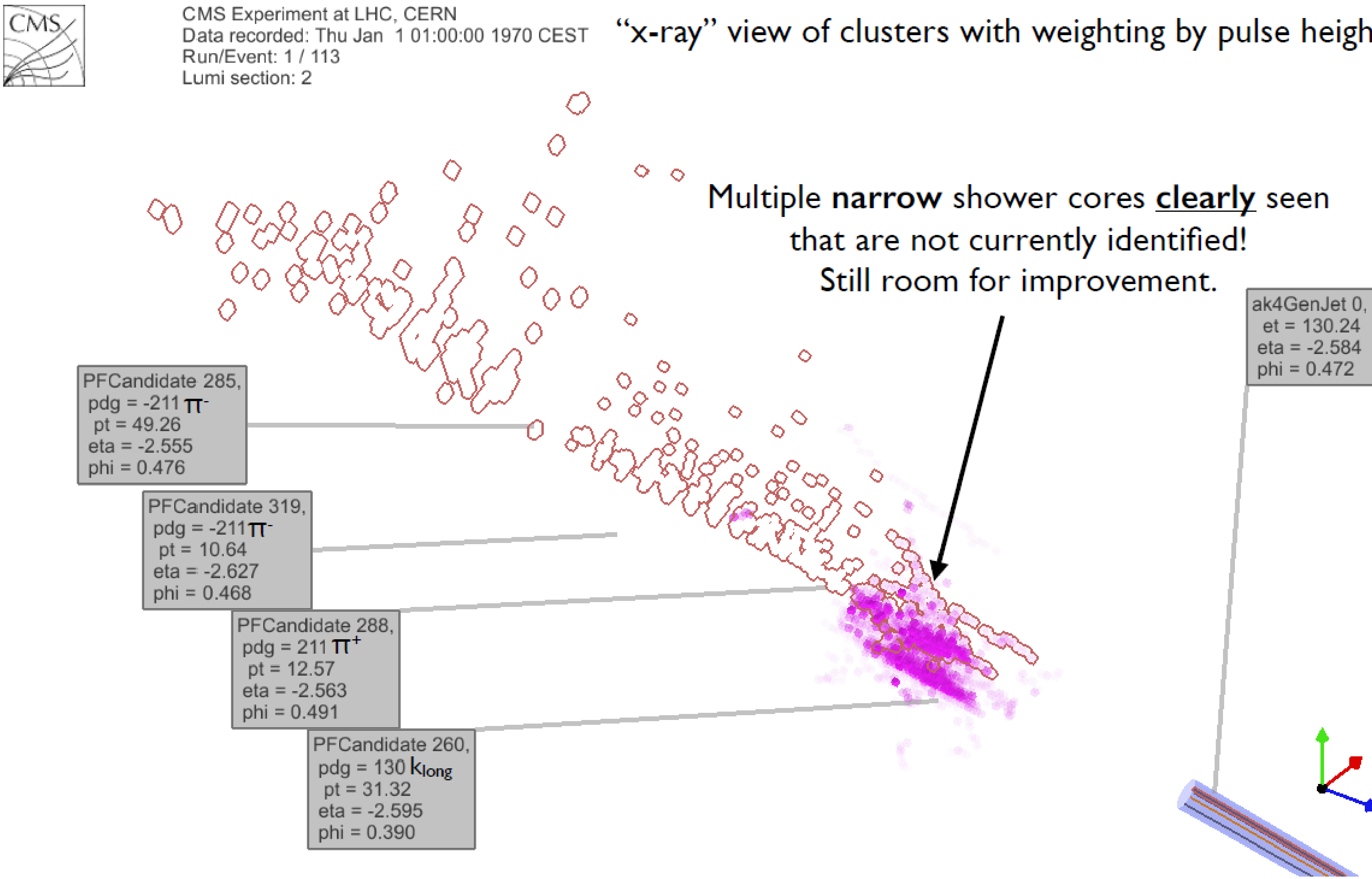
Combined correction brings back the jet to the particle level

Cluster Reconstruction in HGCal (III)



Cluster Reconstruction in HGCal (IV)

"x-ray" view of clusters with weighting by pulse height



Multiple **narrow** shower cores **clearly** seen that are not currently identified! Still room for improvement.