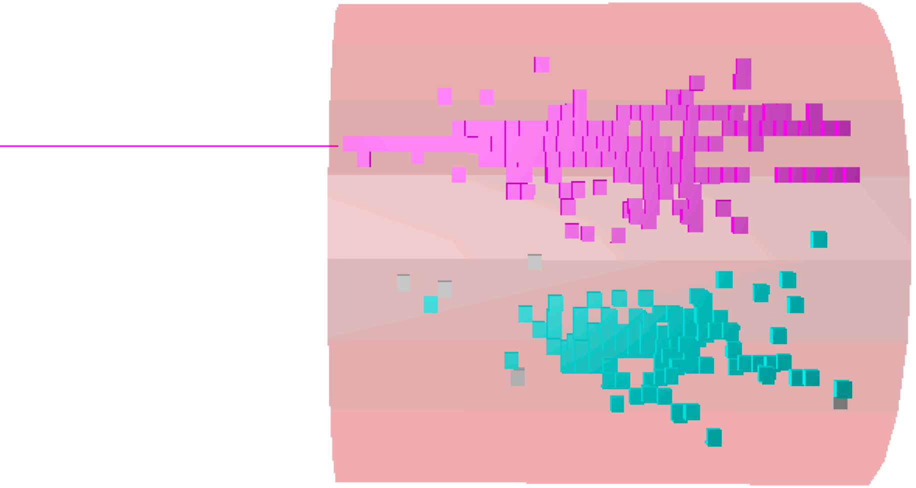
Pandora Particle Flow Algorithm Studies

On CALICE Analog Hadron Calorimeter 2018 Beam Test Data



Magenta: Charged Hadron
Cyan: Neutral Hadron
Grey: Unclustered Hits

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Outline

For this Talk

- Concept of Particle Flow
- Analog Hadron Calorimeter 2018 Prototype

- Applying Pandora Particle Flow Algorithm on Beam Test Data
  - ➡ Results of Single & Double Particle Event Reconstruction

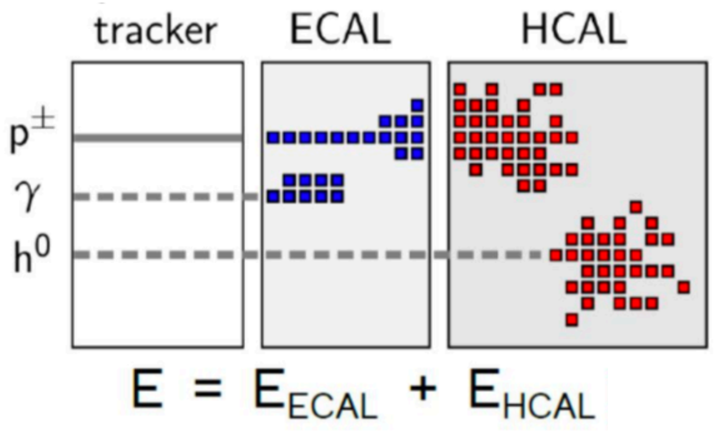
- Summary & Outlook

The Concept of Particle Flow Reconstruction

Reaching Highest Precision

- High precision experiments at future e^+e^- colliders e.g. proposed International Linear Collider (ILC)
  - ➡ One goal: Unprecedented jet energy resolution of 3-4% (jet energies 40-500 GeV)
- Not achievable with classical calorimetry due to poor hadronic calorimeter resolution

Classical



The Concept of Particle Flow Reconstruction

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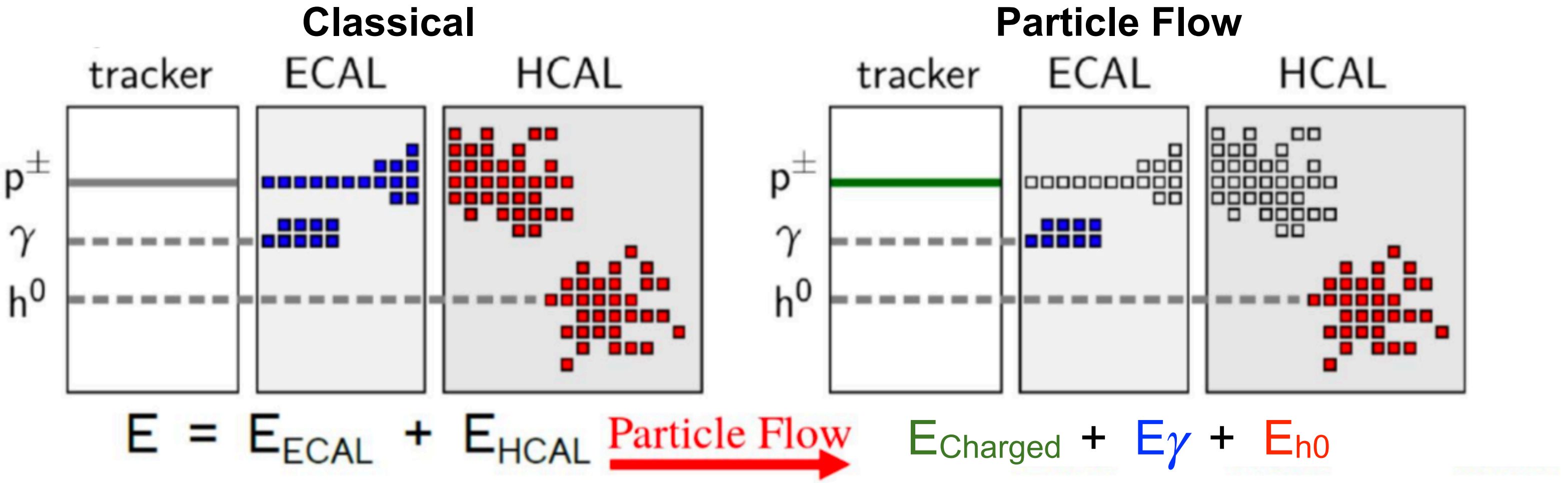
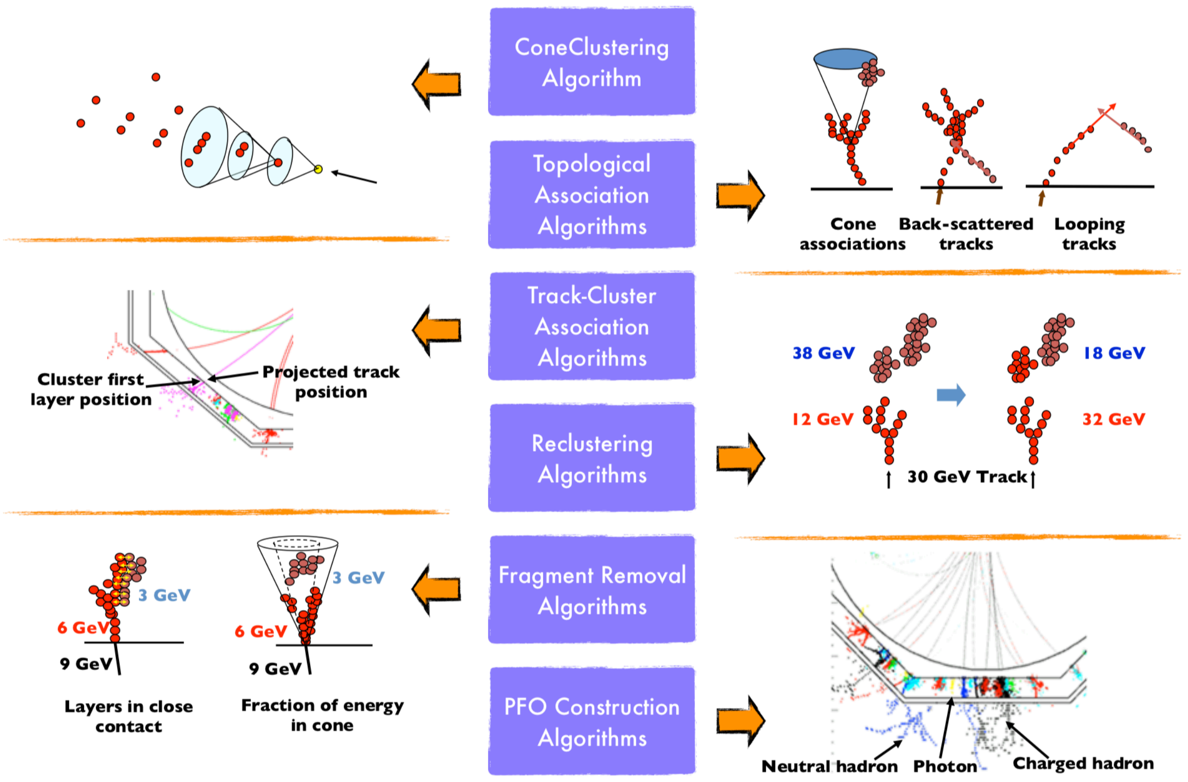
  - ➡ One goal: Unprecedented jet energy resolution of 3-4% (jet energies 40-500 GeV)
- Not achievable with classical calorimetry due to poor hadronic calorimeter resolution
- **Concept of Particle Flow: Follow each particle through the whole detector system**
  - ➡ Use energy measure of sub-detector providing best resolution
    - ➡ Excellent momentum resolution of tracker for ~60% charged particles in jets
    - ➡ Use calorimeter measure only for neutral particles



The Pandora Particle Flow Algorithm (PandoraPFA)

A Multi-Algorithm Pattern Recognition Tool

Illustration of Key Steps of PandoraPFA



J. S. Marshall: https://indico.in2p3.fr/event/7691/contributions/42712/attachments/34375/42344/3_john_marshall_PFA_marshall_24.04.13.pdf

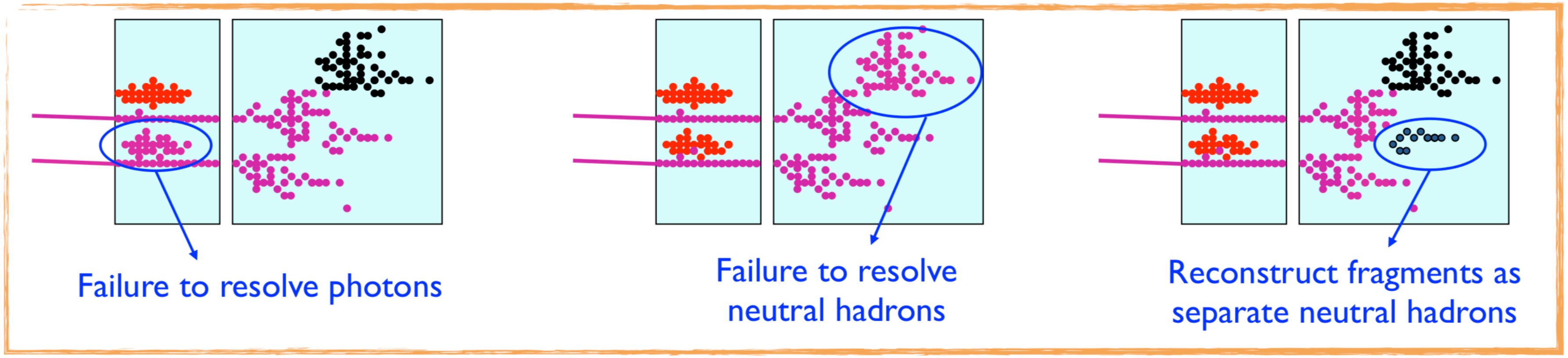
- PandoraPFA: Complex multi-algorithm chain using pattern recognition for event reconstruction
  - ➡ Performs calorimeter hit clustering, topological associations, …
  - ➡ Highly recursive: Find most accurate reconstruction scenario
  - ➡ Overall goal: Distinguish energy depositions originating from charged and neutral particles in calorimeters and avoid **confusion** among this

Confusion Scenarios

The Limit of Particle Flow Reconstruction

- **Topologically or energetically confusing** events could cause problems for PFA reconstruction:
  - ➡ Missing or double counted energy limiting jet energy resolution

Types of confusion



Missing energy | **Missing energy** | **Double counted energy**

J. S. Marshall: https://indico.in2p3.fr/event/7691/contributions/42712/attachments/34375/42344/3_john_marshall_PFA_marshall_24.04.13.pdf

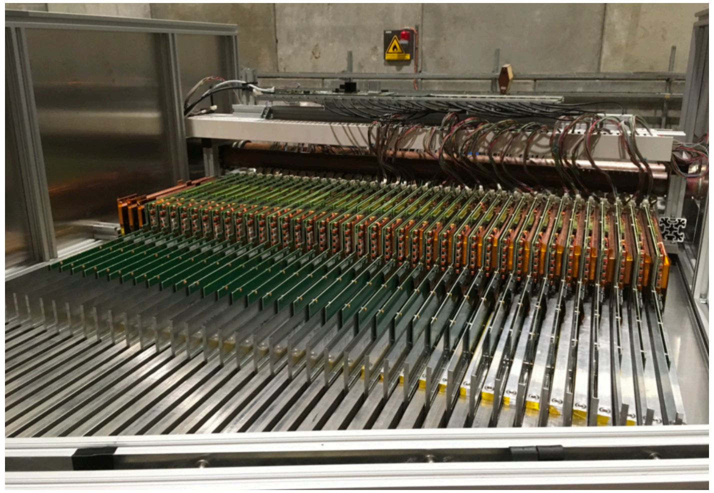
- Crucial requirements for Particle Flow designed detector systems keeping confusion on considerable level:
  - ➡ Calorimeters within magnetic coil for proper track-cluster associations
  - ➡ **High granularity calorimeters** to fully exploit pattern recognition algorithms

The Analog Hadron Calorimeter Prototype 2018

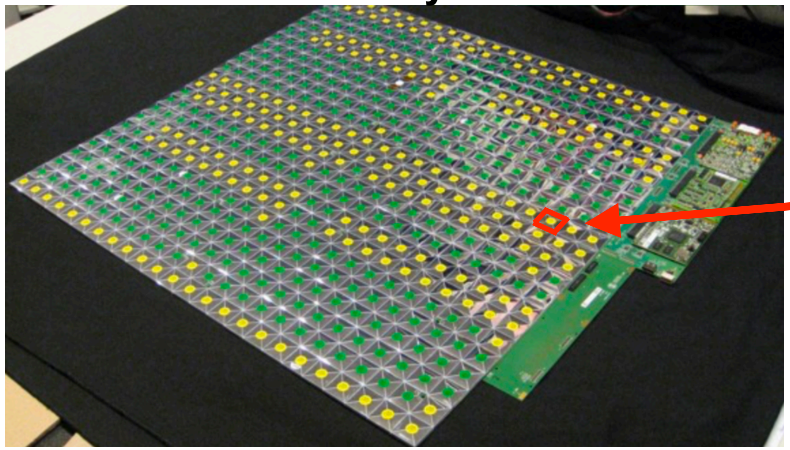
A Highly Granular SiPM-on-tile Sampling Calorimeter

- 38 layer steel sampling calorimeter (~4 λ_n) featuring a total of **~22k channels**
- Active layers ($72 \cdot 72$ cm^2) consisting of 576 channels
  - ➡ One channel: Silicon-Photomultiplier (SiPM) coupled to wrapped scintillating tile
- **Compact design**: Fully integrated front-end readout electronics, no active cooling
- In 2018: Three successful test beam campaigns at SPS CERN collecting electron/muon/**pion data**

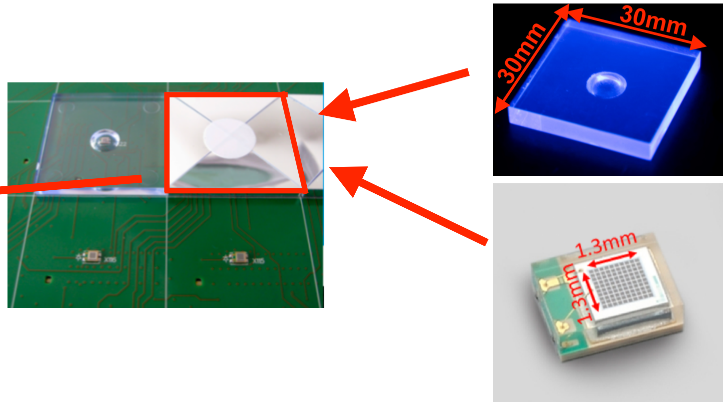
38 layers within steel absorber stack



One layer



One channel: Scintillating tile + SiPM

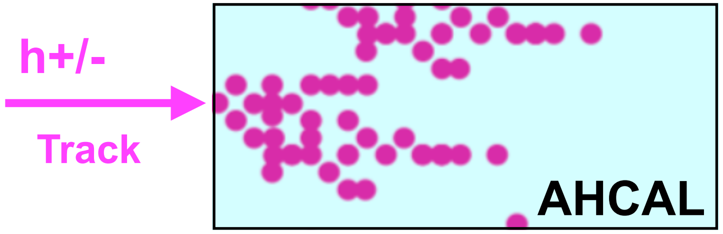


Motivation and Goals of Studies

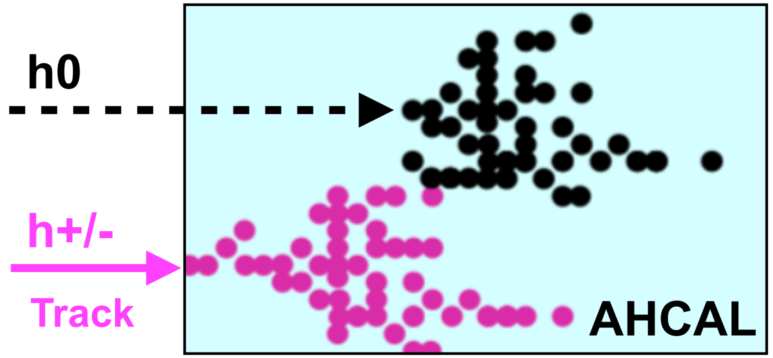
PandoraPFA on AHCAL 2018 Prototype Data

- Over the last years significant developments on software (PandoraPFA) & hardware side (AHCAL)
- Apply PandoraPFA on AHCAL 2018 beam test data and simulated events
  - ➡ Evaluate simulated algorithm performance for standalone application & **provide feedback on real data**
  - ➡ Compare performance on data and simulated events
  - ➡ Study degree of confusion for different scenarios (particle energies, shower separation, etc.)

Scenario 1 (Single Charged Hadron Event)



Scenario 2 (Charged Hadron + Neutral Hadron Event)

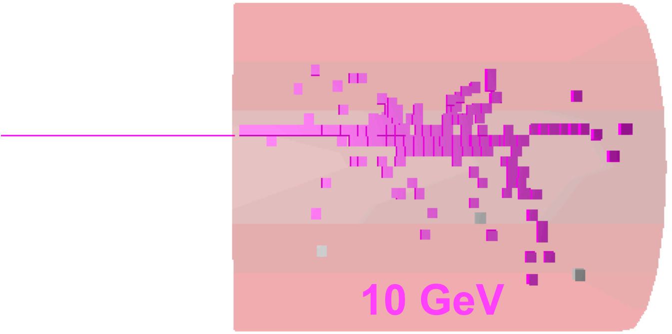


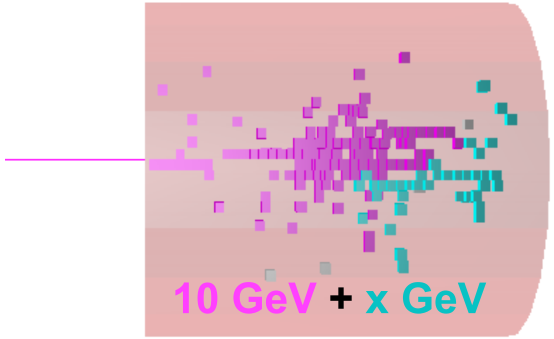
Note: No magnetic field during beam test

Results: Single Particle Reconstruction I

Note: PFO = Particle Flow Object

How many Particles are Reconstructed by PandoraPFA?





Magenta: Charged Hadron
Cyan: Neutral Hadron
Grey: Unclustered Hits

- Confusion: Part of charged hadron shower reconstructed as separate neutral hadron
  - ➡ Scenario is sensitive to double counted energy

Results: Single Particle Reconstruction I

Note: PFO = Particle Flow Object

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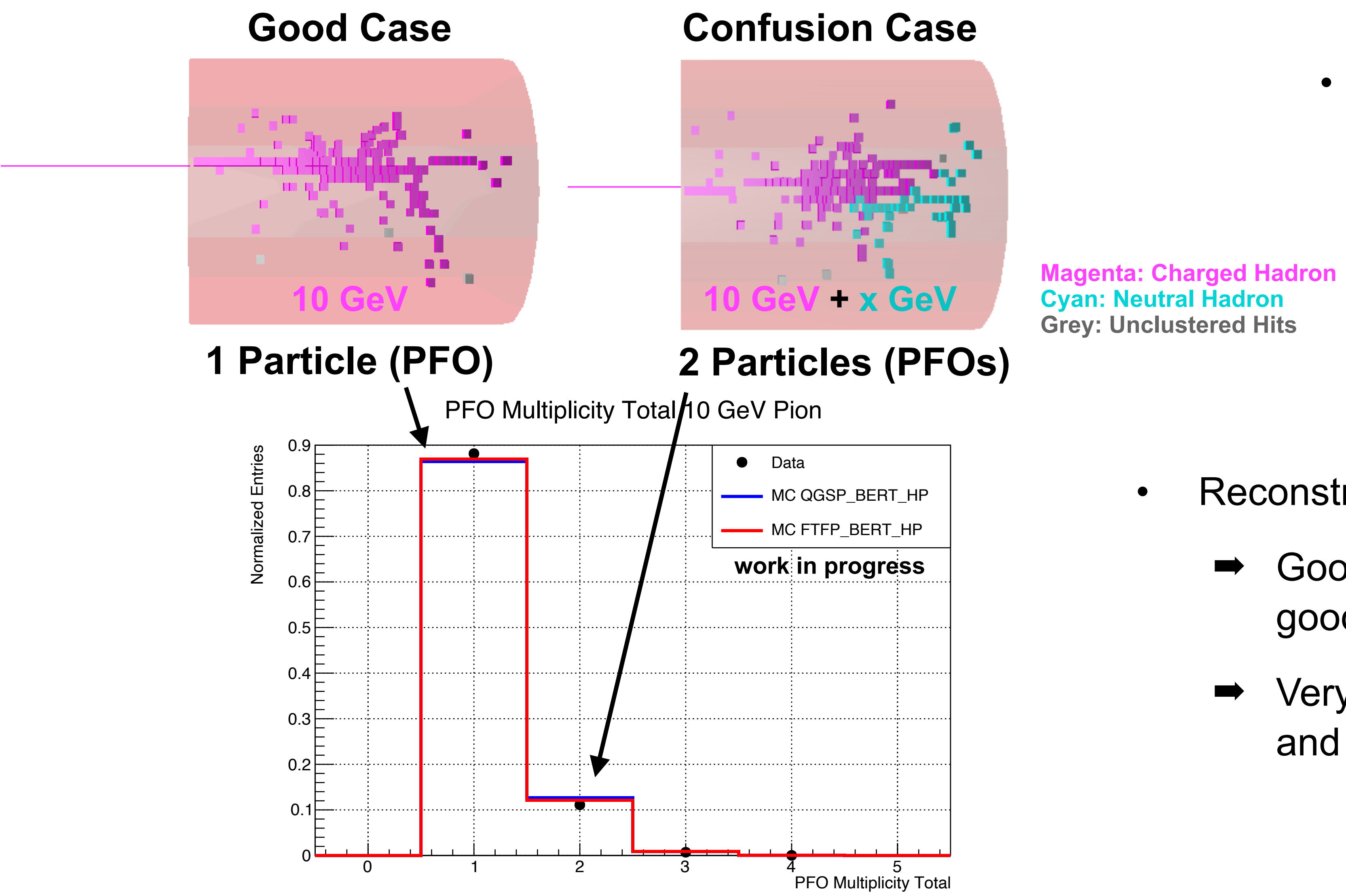
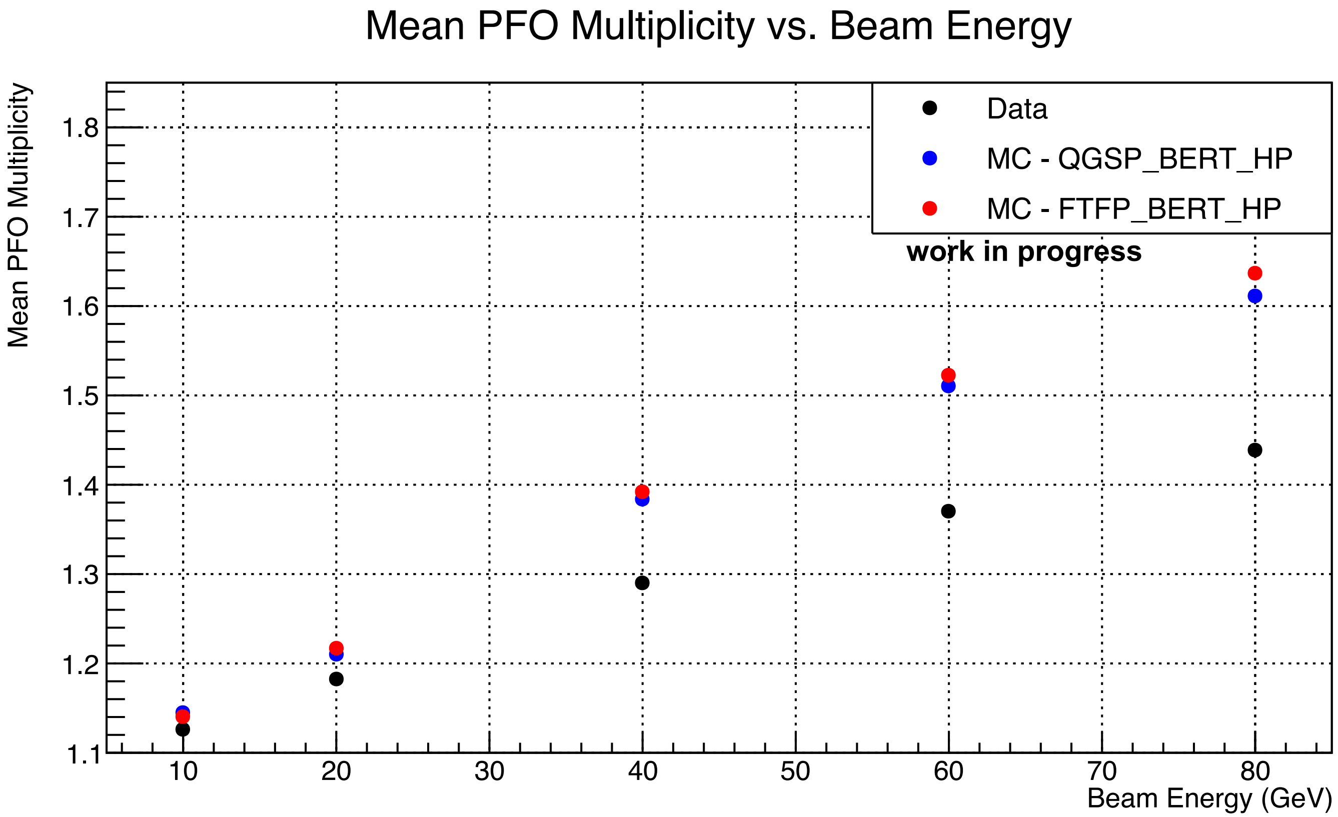


- Confusion: Part of charged hadron shower reconstructed as separate neutral hadron
  - ➡ Scenario is sensitive to double counted energy

- Reconstruction of many 10 GeV pion events
  - ➡ Good case: ~90% of events showing good reconstruction performance
  - ➡ Very good agreement between data and simulated events

Results: Single Particle Reconstruction II

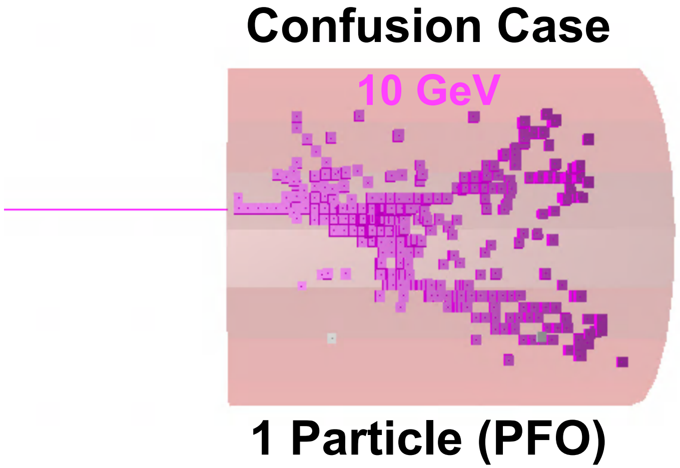
How many Particles are Reconstructed by PandoraPFA on Average?

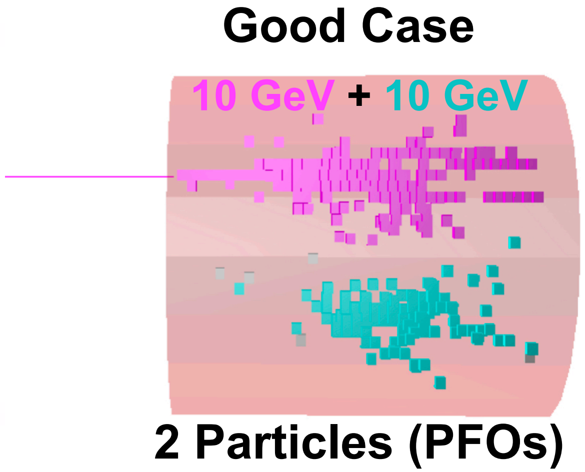


- Number of events with confusion is increasing with energy (higher energy -> more complex event topology)
- Discrepancy between data and simulation grows with energy: Confusion appears more often in simulated events

Results: Double Particle Reconstruction I

How many Particles are Reconstructed by PandoraPFA?





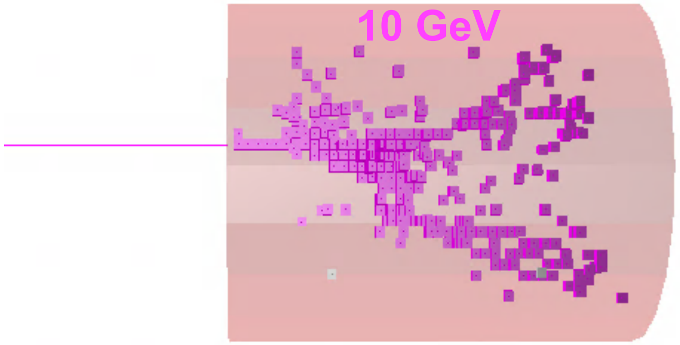
Magenta: Charged Hadron
Cyan: Neutral Hadron
Grey: Unclustered Hits

- Confusion: Neutral hadron hits are fully or partly reconstructed as part of the charged hadron
  - ➡ Scenario is sensitive to missing energy

Results: Double Particle Reconstruction I

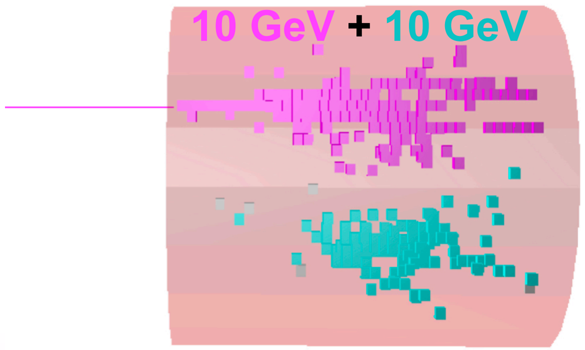
How many Particles are Reconstructed by PandoraPFA?

Confusion Case



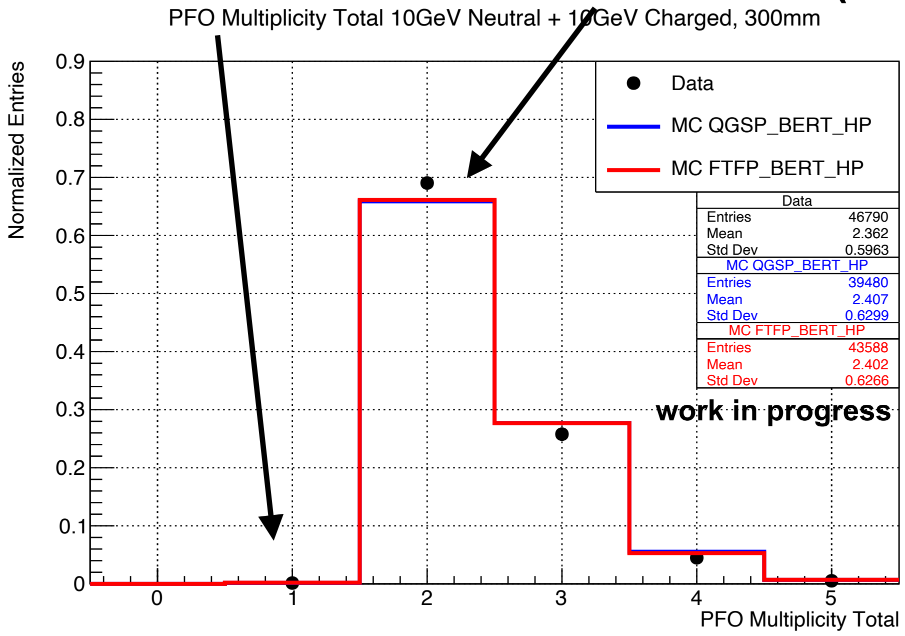
1 Particle (PFO)

Good Case



2 Particles (PFOs)

Magenta: Charged Hadron
Cyan: Neutral Hadron
Grey: Unclustered Hits

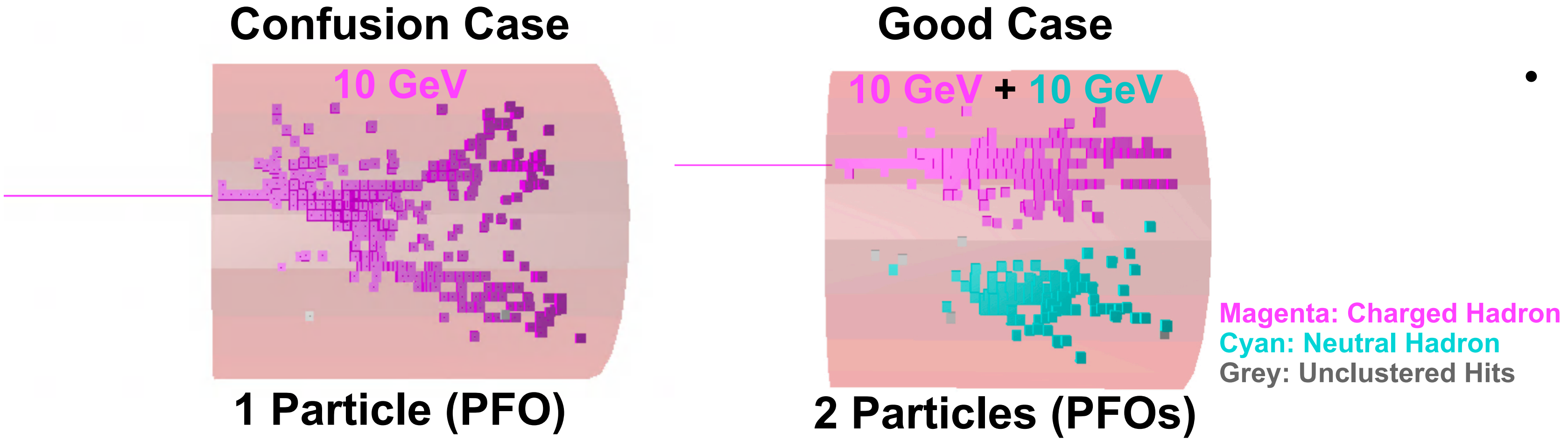


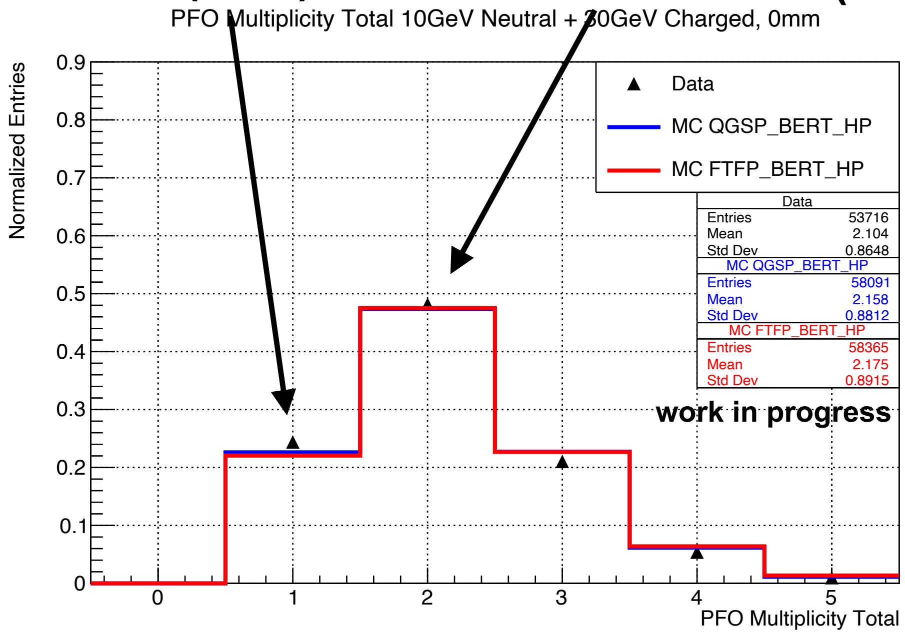
- Confusion: Neutral hadron hits are fully or partly reconstructed as part of the charged hadron
  - ➡ Scenario is sensitive to missing energy

- PFO multiplicity for 10 GeV charged hadron overlaid with a 10 GeV neutral hadron at 300mm distance:
  - ➡ Clean shower separation: Almost no full confusion events
  - ➡ Good data to simulation agreement

Results: Double Particle Reconstruction I

How many Particles are Reconstructed by PandoraPFA?





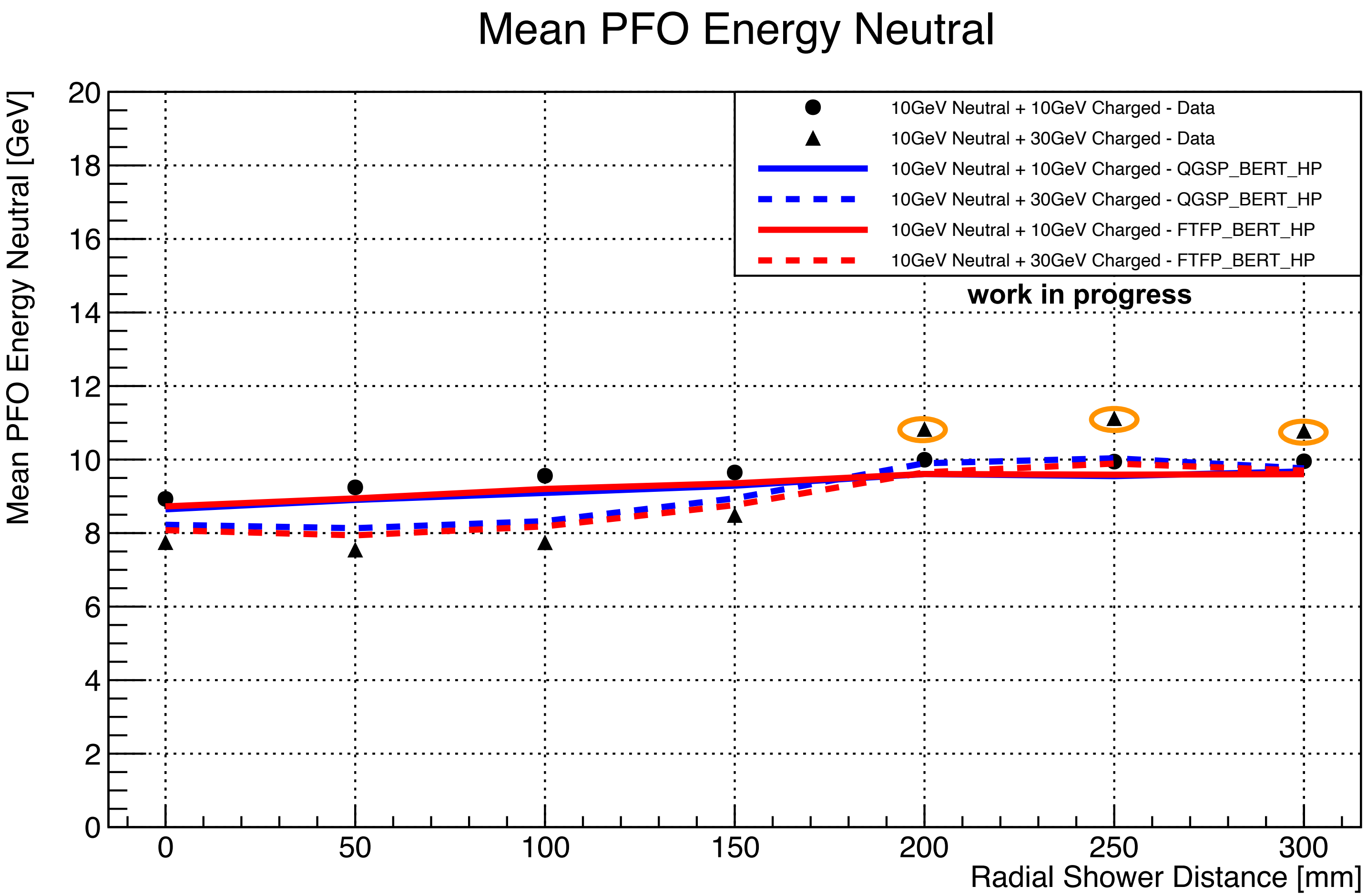
- Confusion: Neutral hadron hits are fully or partly reconstructed as part of the charged hadron
  - ➡ Scenario is sensitive to missing energy

- PFO multiplicity for 30 GeV charged hadron overlaid with a 10 GeV neutral hadron at same spot:
  - ➡ More difficult shower separation - but still only 22-24% full confusion events
  - ➡ Good data to simulation agreement

Results: Double Particle Reconstruction II

How well is the Neutral Hadron Energy Reconstructed in the Vicinity of the Charged Hadron?

- Mean energy of neutral hadron (10 GeV) reconstructed by PandoraPFA for different shower distances to 10/30 GeV charged hadrons:
  - ➡ With growing distance between showers on average less confusion: Closer to 10 GeV input energy
  - ➡ Shower separation more difficult in vicinity of 30 GeV charged hadron
  - ➡ Good data to simulation agreement
  - ➡ Slight overestimation for large distance data points currently under investigation



Summary & Outlook

- Particle Flow reconstruction is the key to high precision: Reach unprecedented jet energy resolution in experiments at future e^+e^- colliders like proposed ILC
- Crucial requirements: High granularity calorimeters (like CALICE AHCAL) within magnetic coil
- Applied PandoraPFA on AHCAL 2018 prototype data to reconstruct single and double hadron events
  - ➡ Reasonable algorithm performance for standalone application
  - ➡ Good agreement between data and simulated events
  - ➡ Expected trends for different types of confusion observed in investigated scenarios

- PFA parameter tuning: Comparison of confusion in AHCAL standalone scenarios & full detector jets
- Confusion studies for different granularities/hit energy thresholds

Backup

Particle Flow Approach

Reaching High Precision

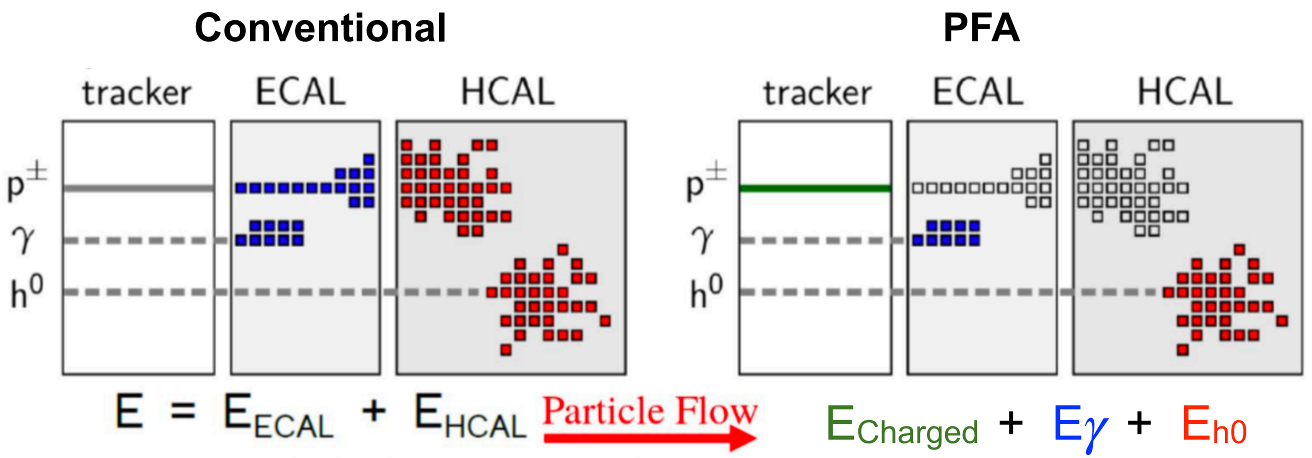
- Goal at the ILC: Jet energy resolution of 3-4% for jet energies between 40-500 GeV
- Typical jet composition of 72% hadrons measured with poor hadronic energy resolution ~60%/√E

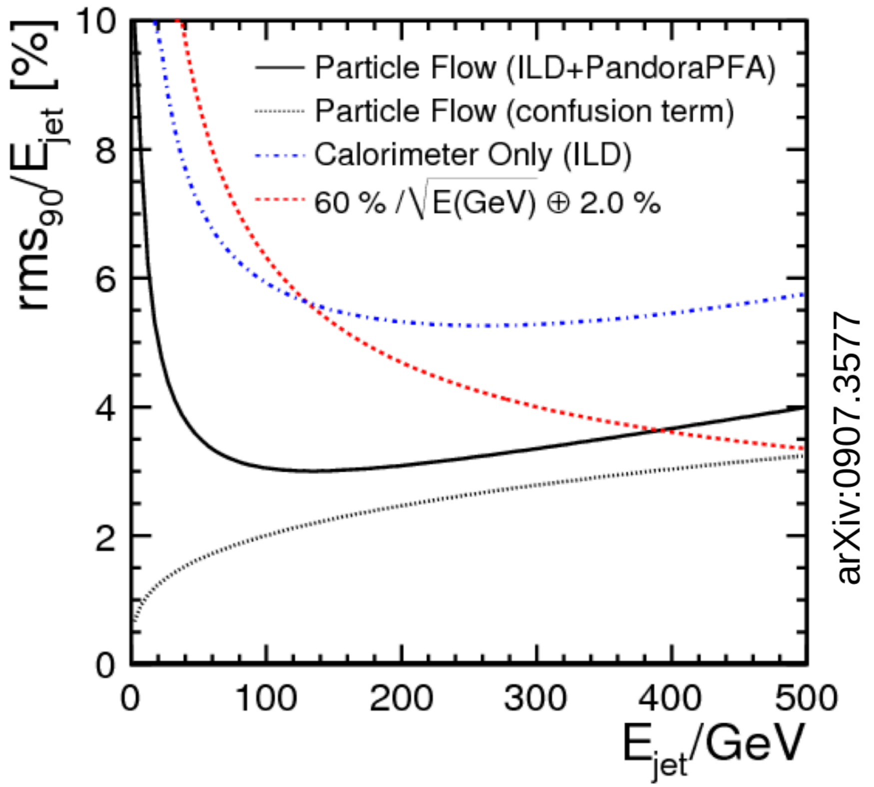
➡ PFA: Measure energy/momentum of each particle with detector providing best resolution

  ➡ 62% charged particles ➙ tracker

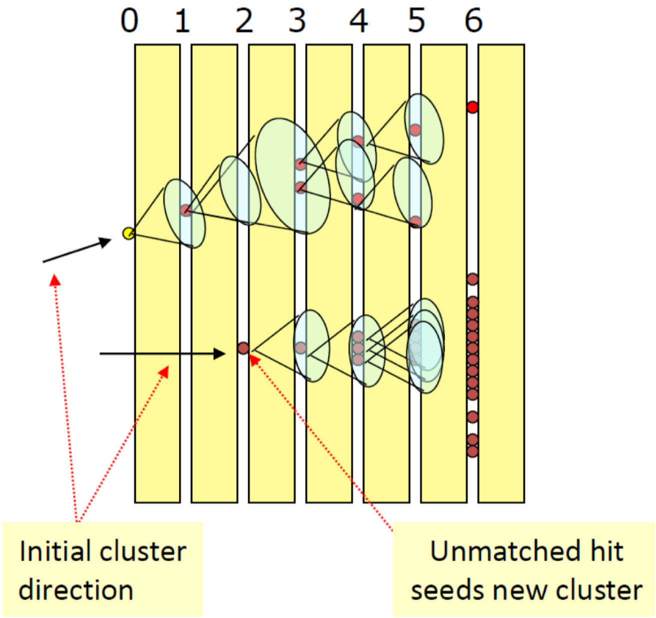
  ➡ 27% photons ➙ ECAL

  ➡ 10% neutral hadrons ➙ ECAL + HCAL



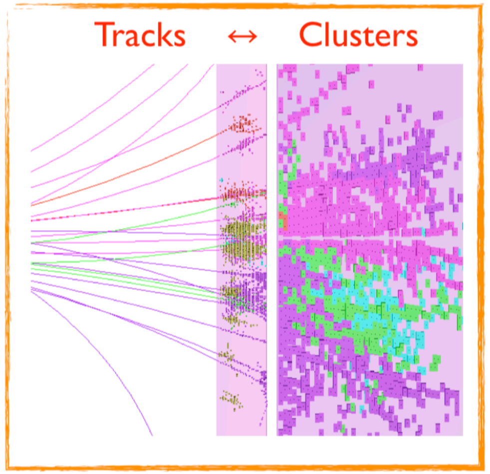


Clustering



Track to Cluster Association

- Track-cluster association algs match cluster positions and directions with helix-projected track states at calorimeter.
- In very high-density jets, reach limit of "pure" particle flow: can't cleanly resolve neutral hadrons in hadronic showers.
- Identify pattern-recognition problems by looking for significant discrepancies between cluster E and track p.
- Choose to recluster: alter clustering parameters or change alg entirely until cluster splits and consistent E/p achieved.



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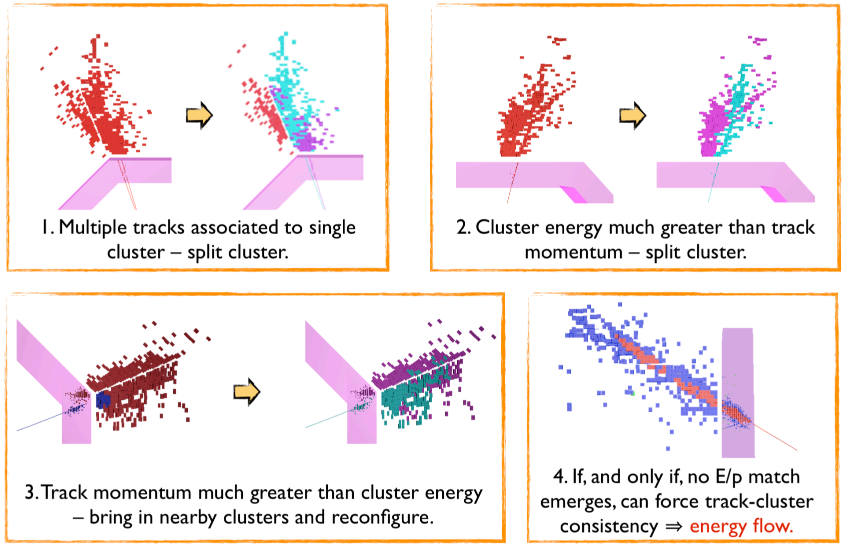
Re-Clustering



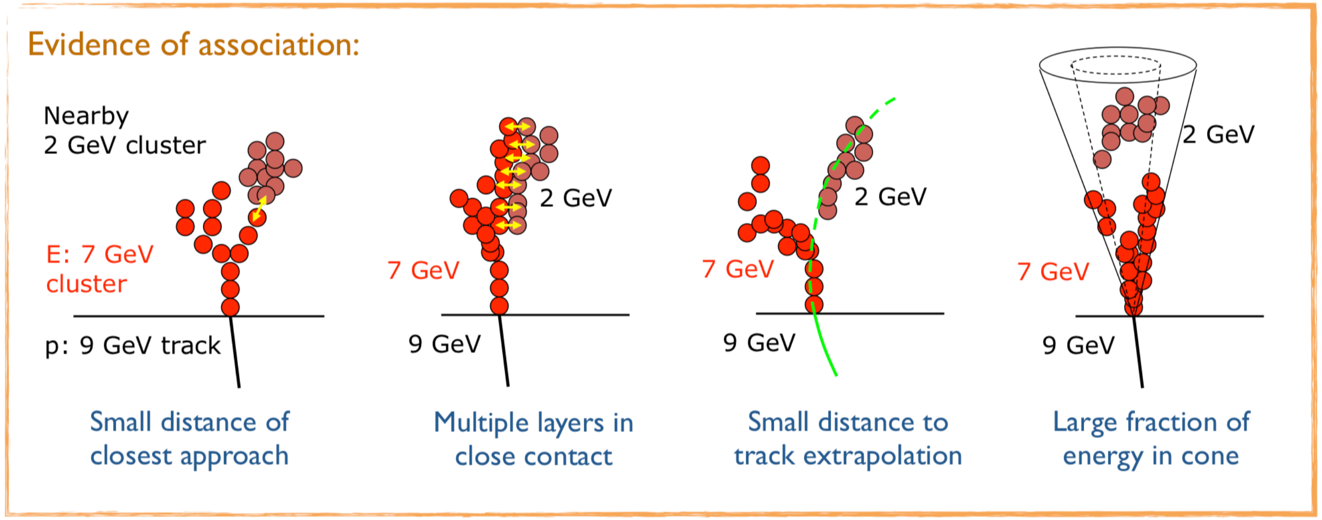
1. Multiple tracks associated to single cluster – split cluster.

2. Cluster energy much greater than track momentum – split cluster.

3. Track momentum much greater than cluster energy – bring in nearby clusters and reconfigure.

4. If, and only if, no E/p match emerges, can force track-cluster consistency ⇒ energy flow.

Fragment Removal



The Confusion Term

The Limit of Particle Flow Reconstruction

- **Topologically or energetically confusing** events can cause problems for PFA reconstruction:
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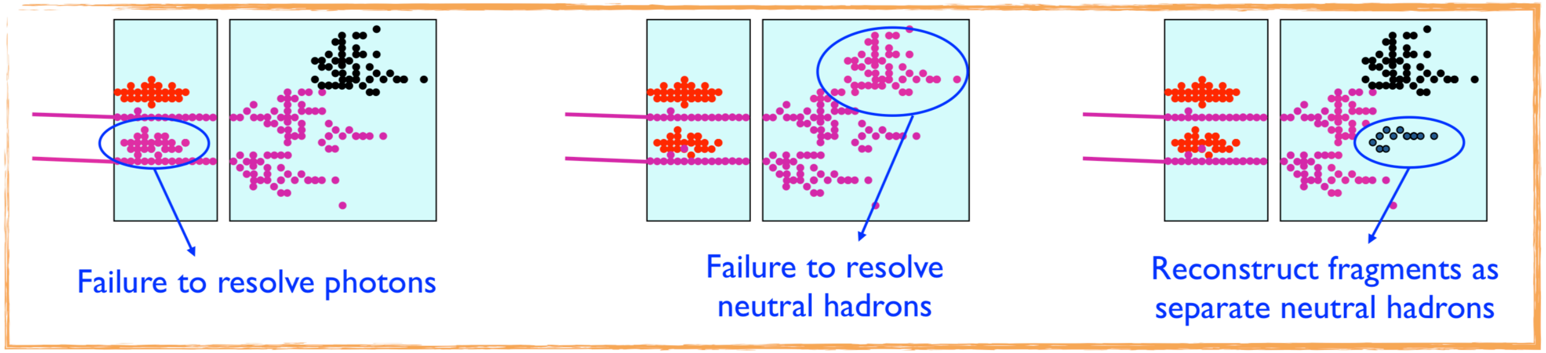
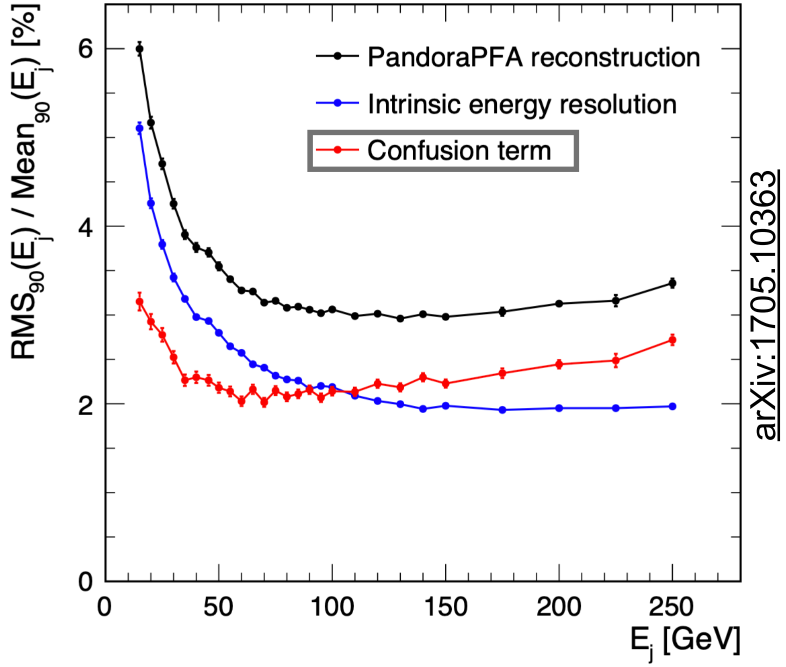
Types of confusion



Missing energy | **Missing energy** | **Double counted energy**



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  - ➡ **High granularity calorimeters** to fully exploit pattern recognition algorithms

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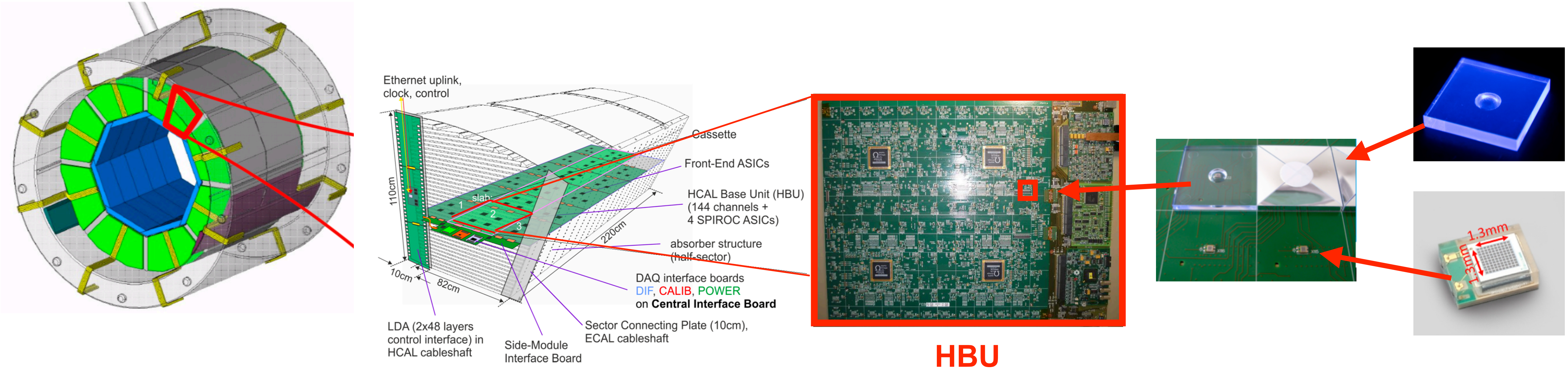
The Analog Hadron Calorimeter (AHCAL) @ ILD

Designed for Particle Flow Reconstruction

- Highly granular sampling calorimeter for the International Large Detector
  - ➡ Total of ~8 million single channels: Wrapped scintillator tile coupled to SiPM readout
- **H**CAL **B**ase **U**nit: 36 · 36 cm² featuring 4 ASICs reading out 144 channels
- Fully integrated detector design to octagonal cylinder
  - ➡ Front-end readout electronics, internal LED calibration system, no cooling within active layers

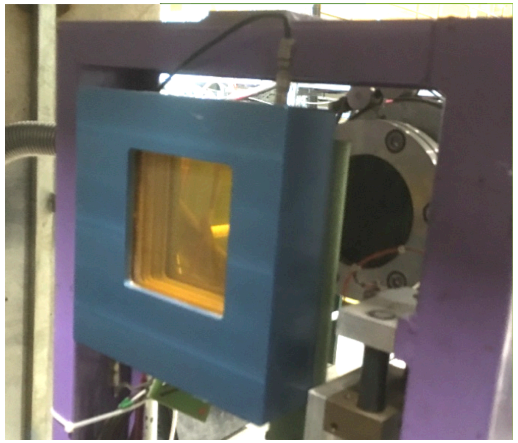


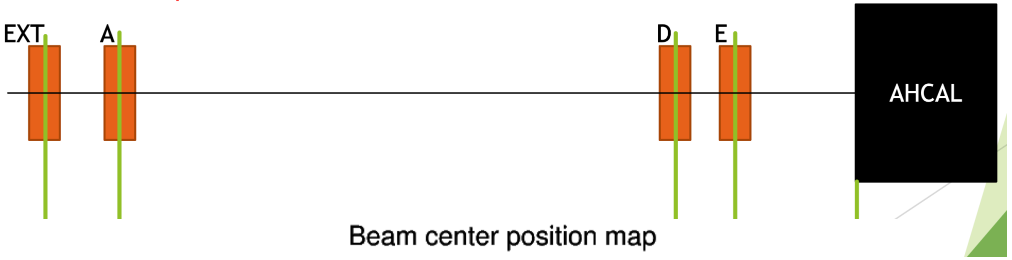
Delay Wire Chambers (DWC)

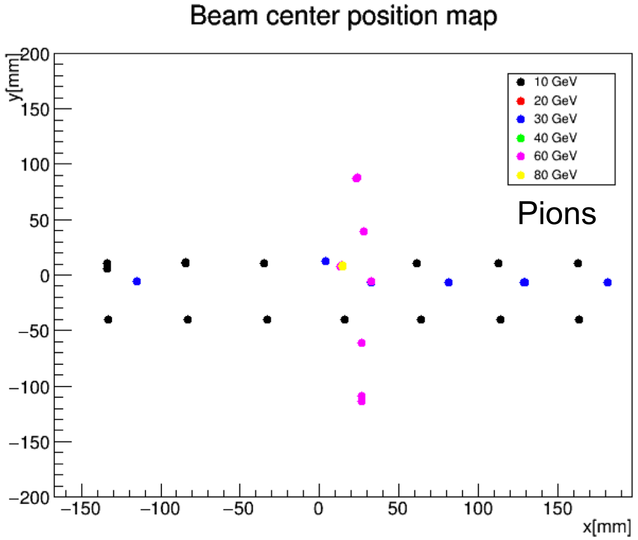
Providing Tracks for Beam Test Events

Work done by Linghui Liu (U. Tokyo)
(https://agenda.linearcollider.org/event/8368/contributions/44971/attachments/35214/54544/LL_AHCALmain_2019.pdf)

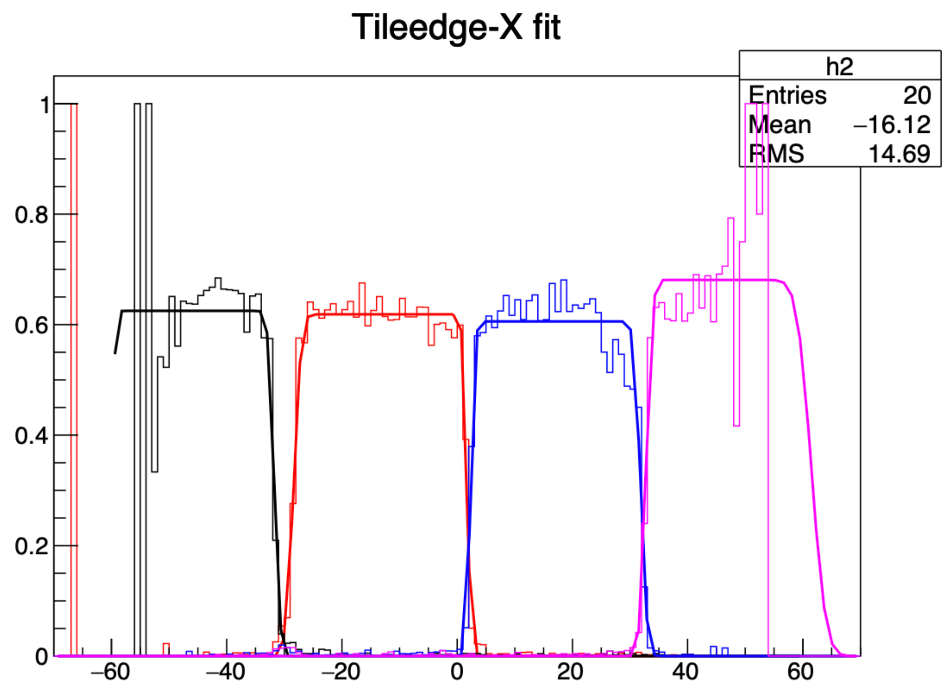
- Beam Test June 2018 at SPS CERN: Four 100 x 100 mm^2 delay wire chambers (MWPCs)
- Position resolution of each chamber: ~600 μm
  - ➡ **Sub-mm resolution at AHCAL**
- Information extracted:
  - ➡ **Reconstructed track for each event**
  - ➡ Position calibration (Prototype moved on X-Y stage during beam test for position scans)
  - ➡ Measurement of scintillator tile gaps

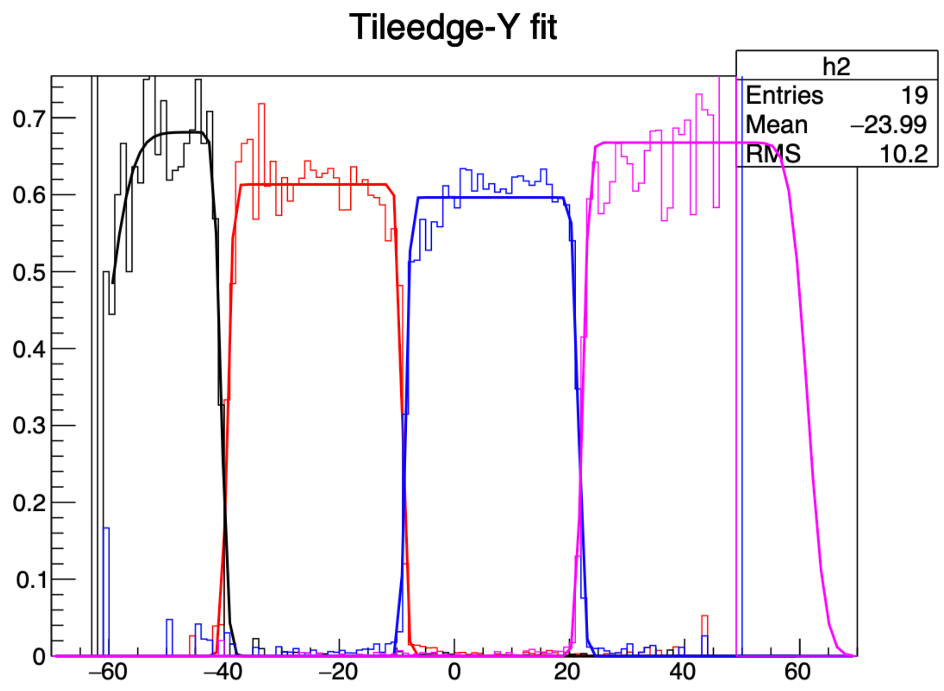






Scintillator Tile Gaps Measurements DWC Example

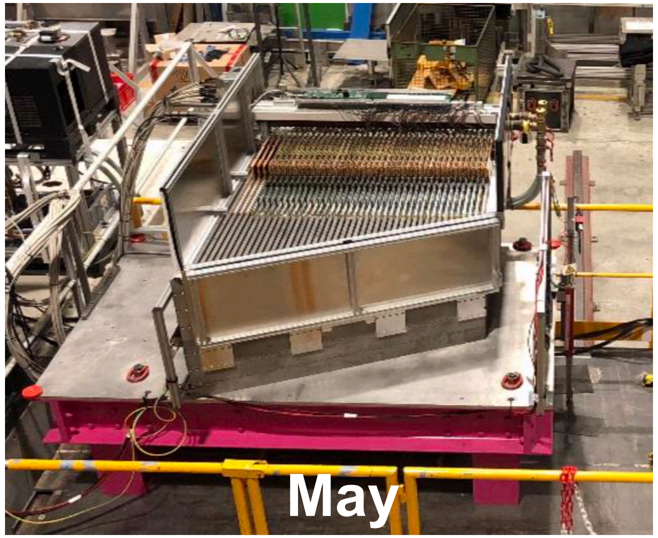


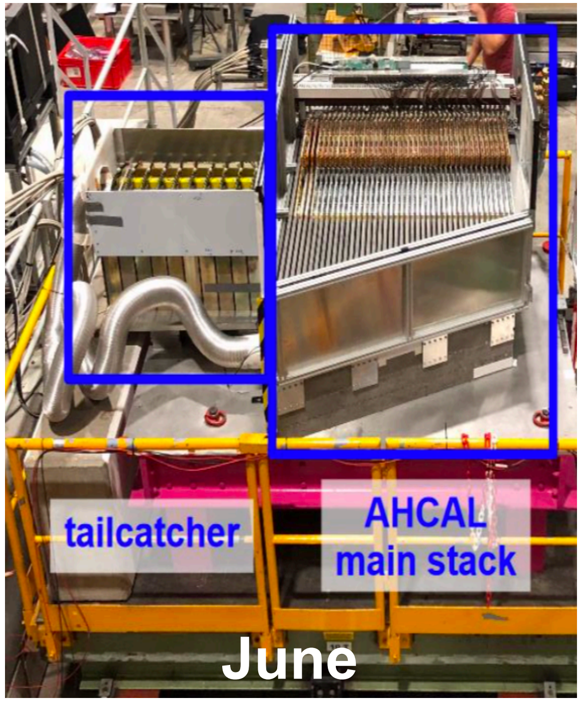


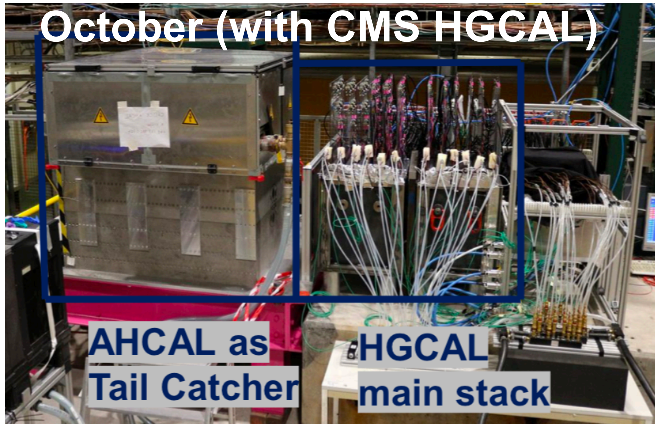
The CALICE AHCAL Beam Test Campaigns 2018

May, June and October @ SPS Cern

- Three successful beam test campaigns at SPS CERN in 2018
- Data sets:
  - ➡ Muons, electrons, **pions**
  - ➡ Energies: 10 - 200 GeV
  - ➡ Events: Multiple 10 million, also at different detector positions
- For this studies: June 2018 beam test data







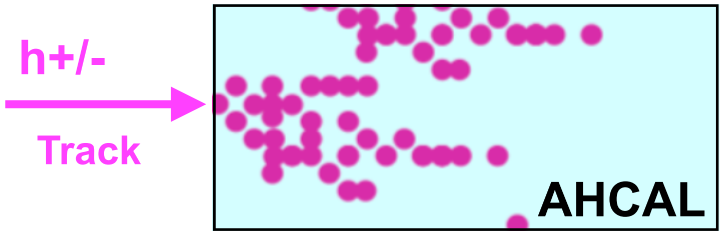
Motivation and Goals of Studies

PandoraPFA on AHCAL 2018 Prototype Data

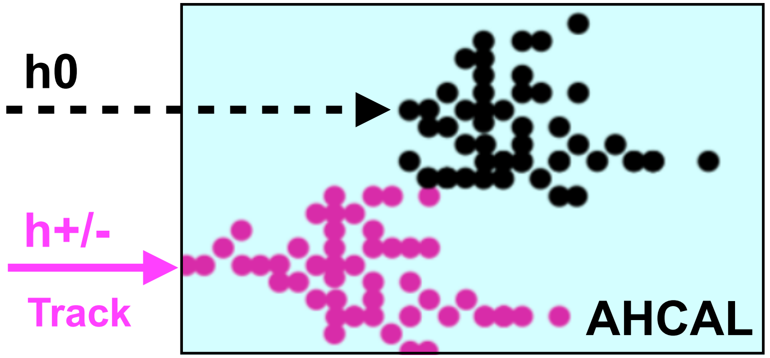
- Over the last years significant developments on software (PandoraPFA) & hardware side (AHCAL)
  - ➡ PandoraPFA: Algorithm tuning, modular application possible instead of full collider detector
  - ➡ AHCAL 2018 prototype: High and uniform granularity, reduction of noise (SiPMs), timing capabilities,…

- Apply PandoraPFA on AHCAL 2018 beam test data and simulated events (+ tracks)
  - ➡ Evaluate simulated algorithm performance for standalone application & provide feedback on real data
  - ➡ Compare performance on data and simulated events
  - ➡ Study degree of confusion for different scenarios (particle energies, shower separation, etc.)

Scenario 1 (Single Charged Hadron Event)



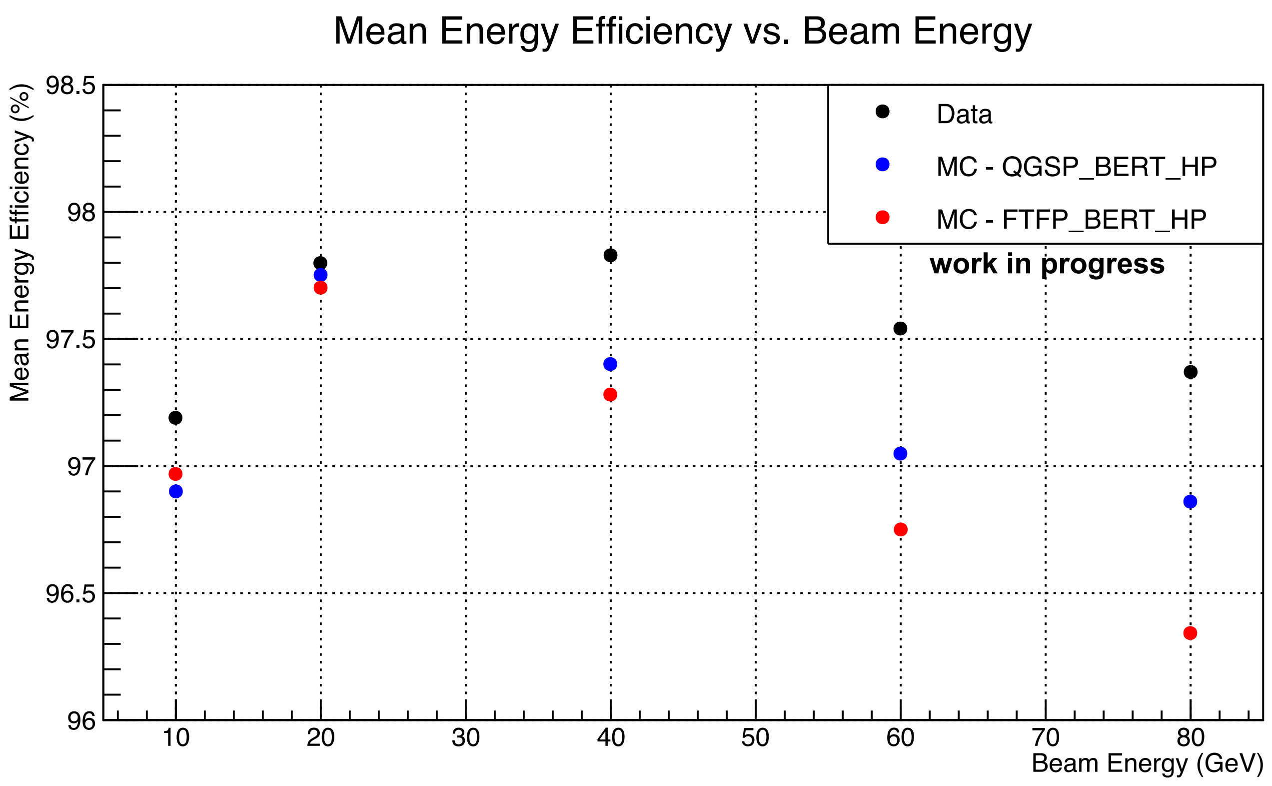
Scenario 2 (Charged Hadron + Neutral Hadron Event)



Note: No magnetic field during beam test

Results: Single Particle Reconstruction III

How much Energy is Reconstructed by PandoraPFA?



- **Energy efficiency:** $\frac{E_{reco,charged}}{E_{input,charged}}$
- Mean energy efficiency > 96% for all scenarios showing good performance in general
  - ➡ On average < 4% double counted energy
- Except for 10 GeV, mean energy efficiency decreasing with energy due to increasing amount of confusion events
  - ➡ More dominant for simulated events

Overview

Sample Preparation & Analysis Strategy

AHCAL data & MC →

Unselected charged pion events

→ **Event preparation & selection**

Selected charged pion events

→ **Primary track removal & event overlay**

Selected events with overlaid charged and pseudo-neutral hadron

Selected charged pion events ↓ **PandoraPFA** ↓ **Scenario 1: Single particle reconstruction studies**

Selected events with overlaid charged and pseudo-neutral hadron ↓ **PandoraPFA** ↓ **Scenario 2: Two-particle separation studies**

Analysis inspired by first CALICE PFA Paper: https://arxiv.org/abs/1105.3417
&
Remi Ete's ArborPFA Studies on SDHCAL Data
CAN: http://cds.cern.ch/record/2669487/files/fulltext.pdf

Sample Preparation & Selection Tools

Sample Preparation & Selection Tools

Overview & Status

- Event Selection:
  - ➡ Shower start finder algorithm: Implemented and optimised in cooperation with Jonas Mikhaeil
  - ➡ PID (Boosted Decision Tree): Talk by V. Bocharnikov
  - ➡ Event filter: Implemented with selection criteria on shower start layer, shower position, track quality, etc.

- Event Preparation for PandoraPFA:
  - ➡ MIP to GeV conversion**:** Implemented for EM and HAD scale
  - ➡ Event overlay: Implemented and validated
  - ➡ **Data tracks from DWC and MC tracks**: Implemented and validated
  - ➡ **Primary track removal (based on shower start layer):** Implemented and validated

Illustration of implemented tracks

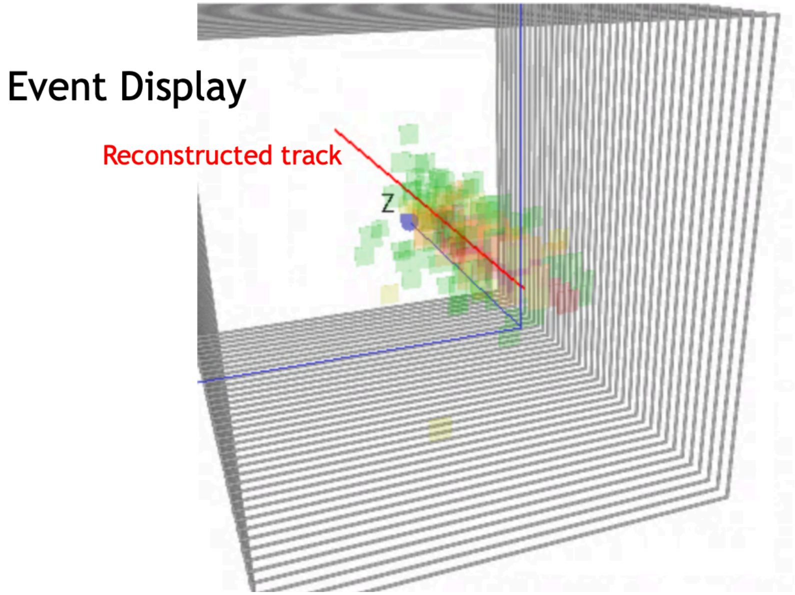
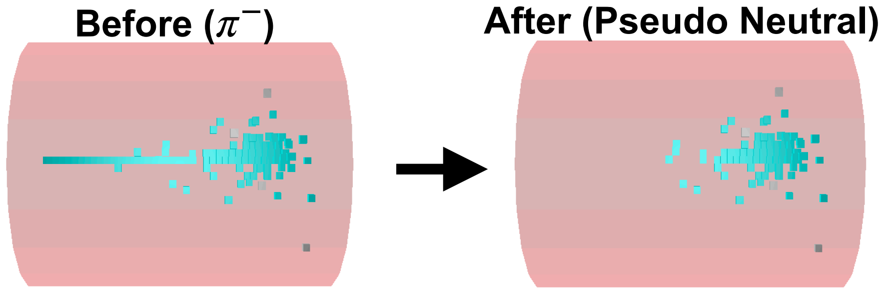


Illustration of pseudo neutral generation



Track Quality Check

Implemented MC and Data Tracks for PandoraPFA Studies

Note: Tracks almost completely straight since no B-field present and particles almost only with p_z

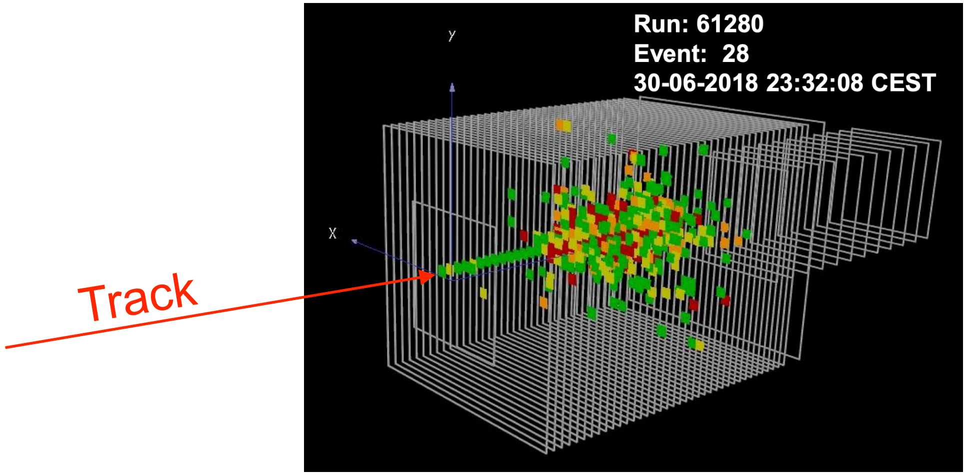
- Data tracks: Reconstructed from DWC of beam test
- MC tracks: MC primary particle endpoint position X/Y extrapolation

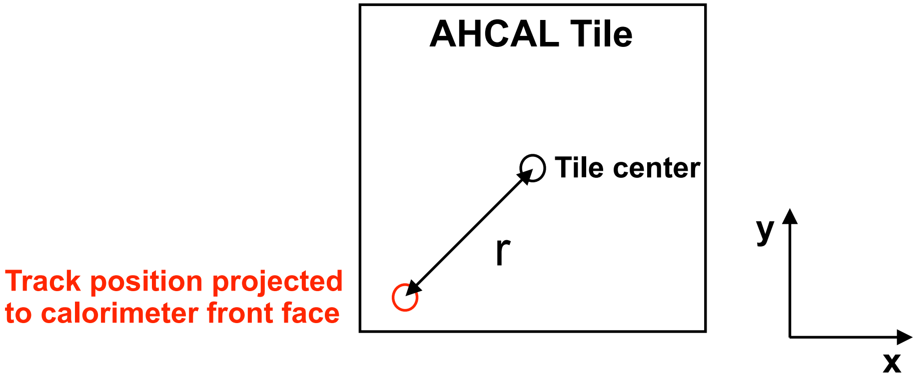
➡ **Track quality?**

How well does track position at calorimeter front face agree with cog in X/Y of event (central shower axis)?

How well does track hit first triggered channel of primary track in layer 1?

Does track hit any triggered channel in layer 1 at all?

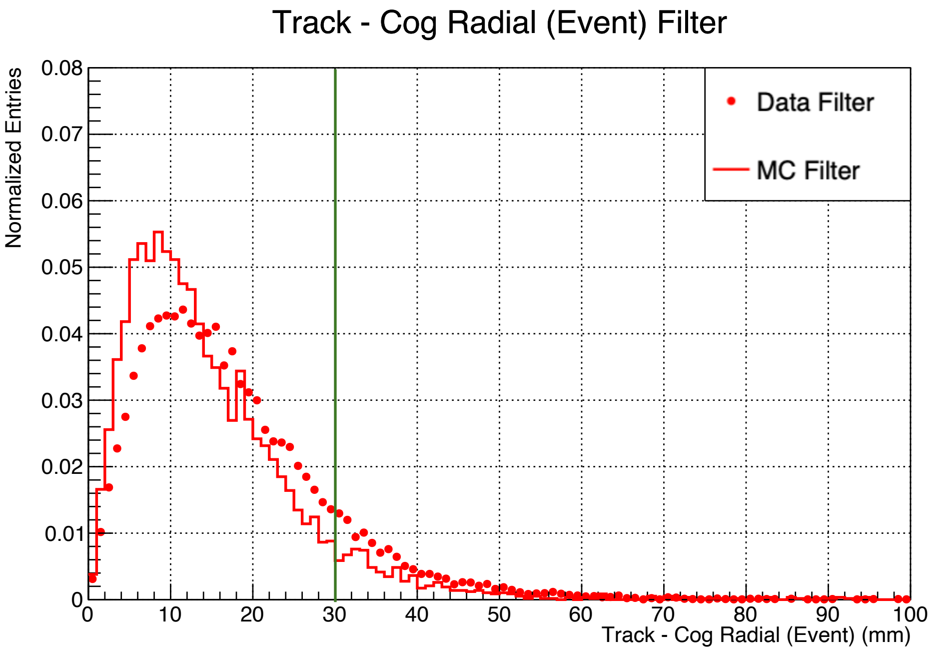




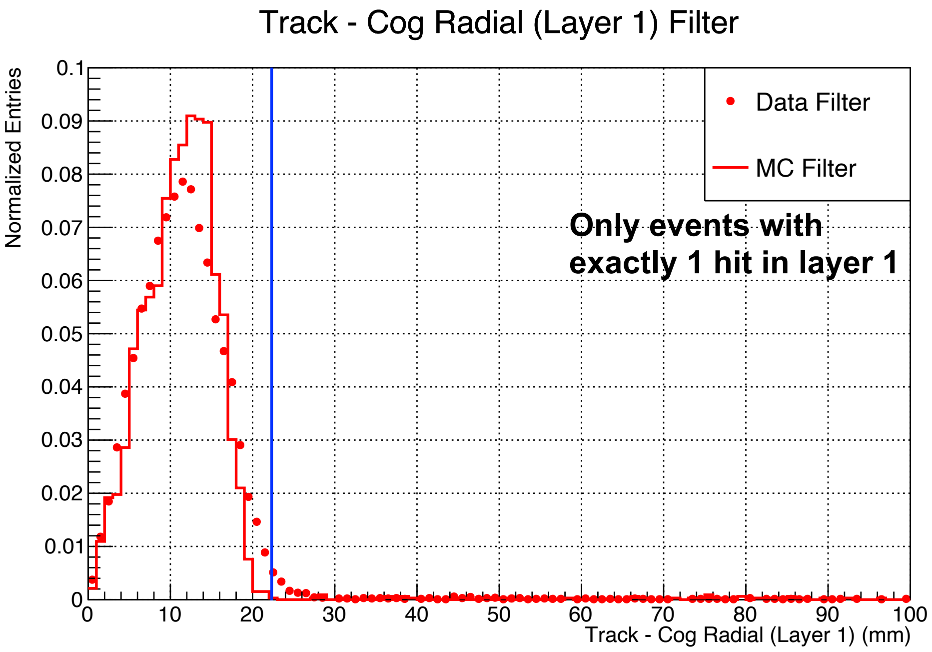
Track Quality Results 20 GeV π^-

Precise Tracks for PandoraPFA Reconstruction

Definition Filter: Applied BDT-PID, Shower start layer < 20, Hit in layer 1+2+3



$$r = \sqrt{(x_{track} - x_{cog})^2 + (y_{track} - y_{cog})^2}$$



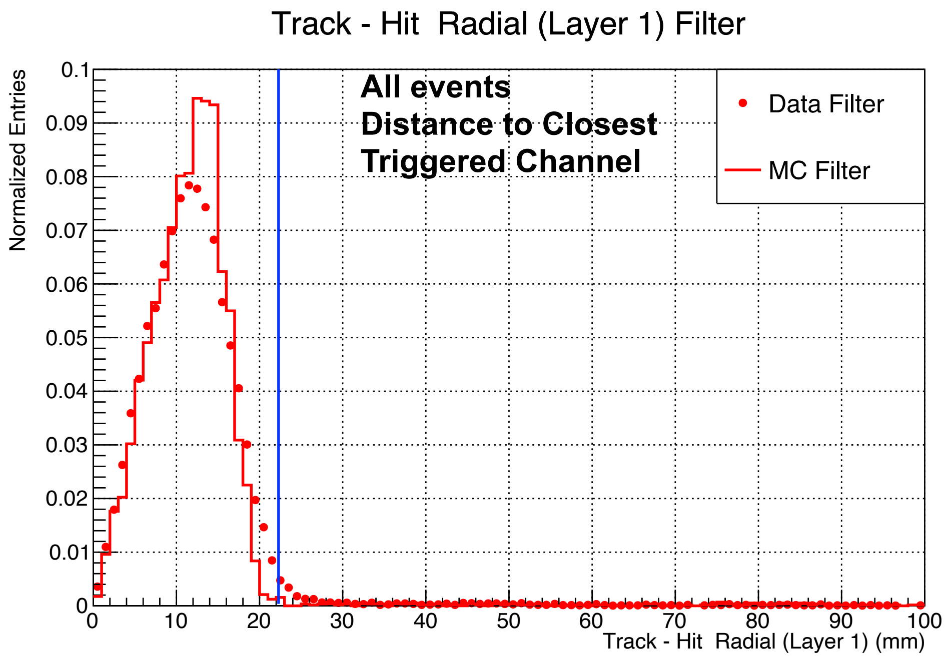
$$r = \sqrt{(x_{track} - x_{hit})^2 + (y_{track} - y_{hit})^2}$$

- Excellent agreement of track and cog (central shower axis) position:
  - ➡ 88.5% (data) and 93% (MC) of events within 30 mm distance (one tile length)
- Most of the tracks hit triggered channel of primary track in layer 1:
  - ➡ 98.2% (data) and 99% (MC) of events within 22 mm radius (tile center - corner distance)

Track Quality Results 20 GeV π^-

Precise Tracks for PandoraPFA Reconstruction

Definition Filter: Applied BDT-PID, Shower start layer < 20, Hit in layer 1+2+3



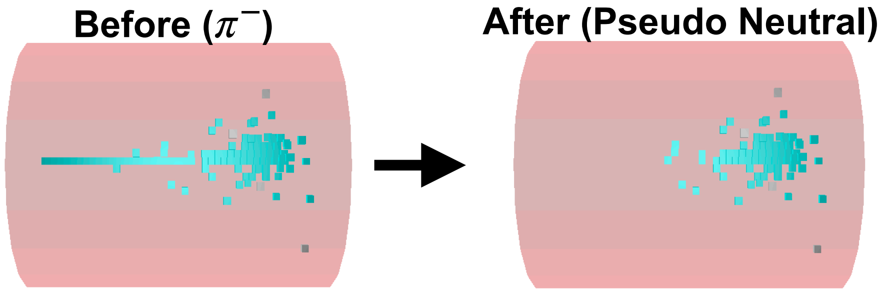
$$r = \sqrt{(x_{track} - x_{hit})^2 + (y_{track} - y_{hit})^2}$$

- Most of the tracks hit a triggered channel in layer 1:
  - ➡ 97.5% (data) and 98.5% (MC) of events within 22 mm radius (tile center - corner distance)
- Similar results achieved for:
  - ➡ Less strict filter options in terms of hit requirements in first layers
  - ➡ Lowest energy scenario of 10 GeV π^-

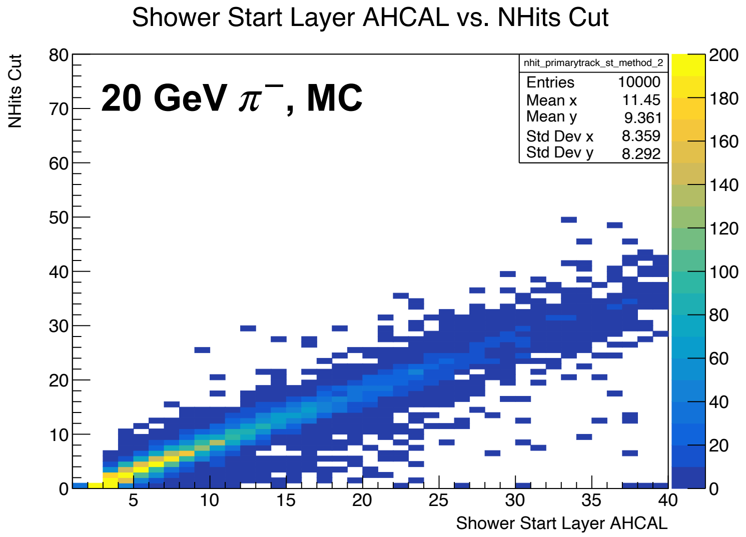
➡ **Excellent track quality validated for data and MC**

Finding and Removing Primary Track

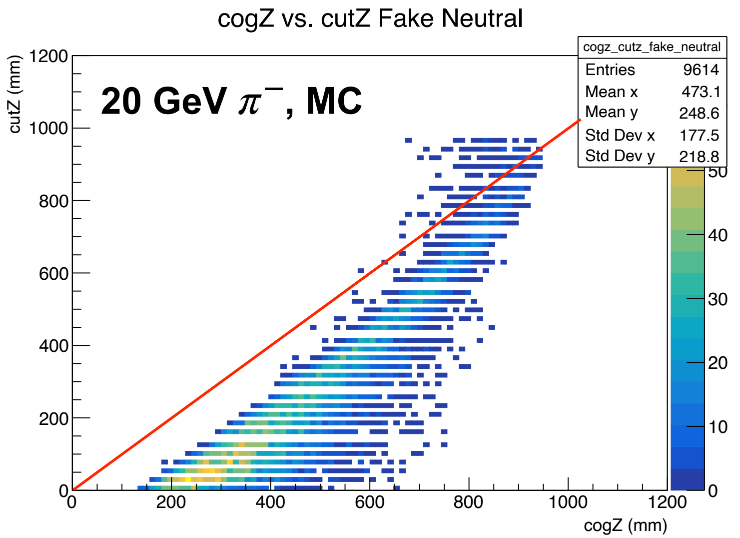
The Method for Creating Pseudo Neutral Hadrons



- Conditions for hit to be considered as primary track hit and being removed:
  - ➡ Hit located in layer before shower start layer - 1
  - ➡ Hit position within r = 60mm to cogX/Y of shower (central shower axis)
  - ➡ Hit energy < 3 MIP

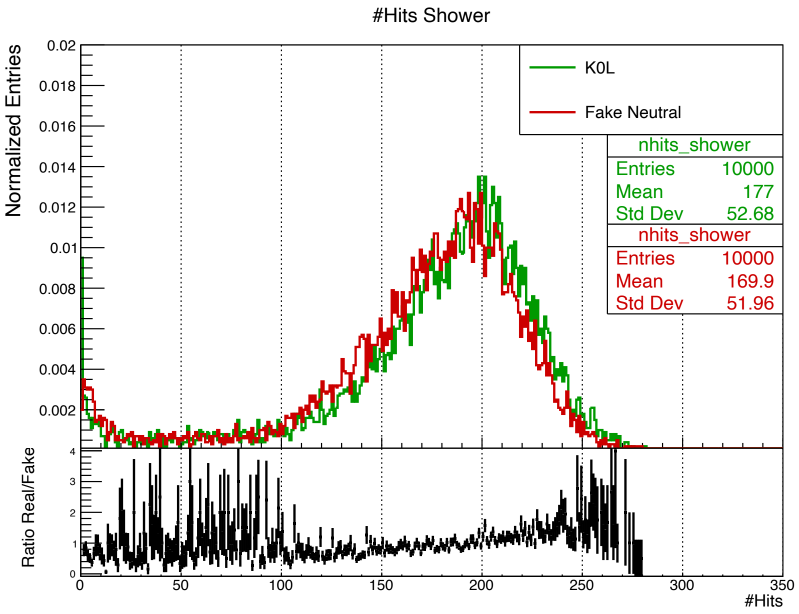


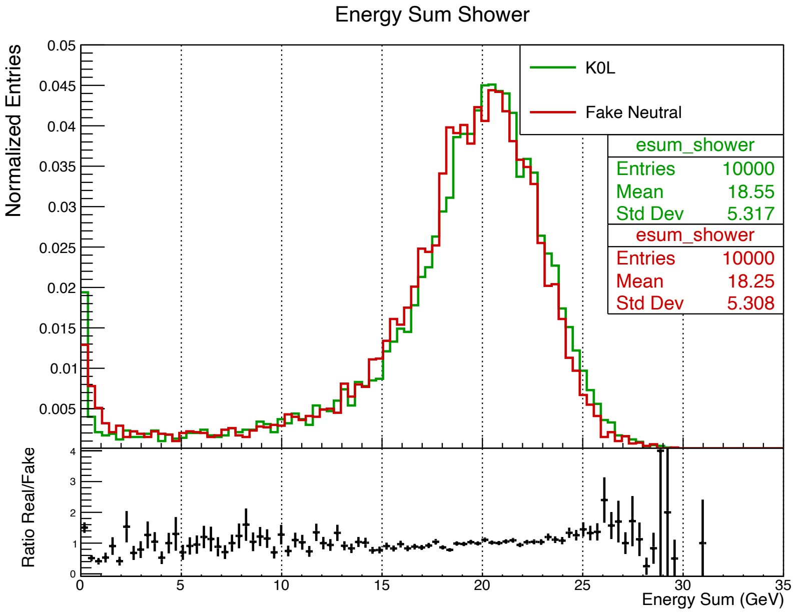
- Method robust and working well:
  - ➡ # cut hits (primary track) well correlated with shower start layer
  - ➡ Z position of potentially last cut hit well before cogZ for most events

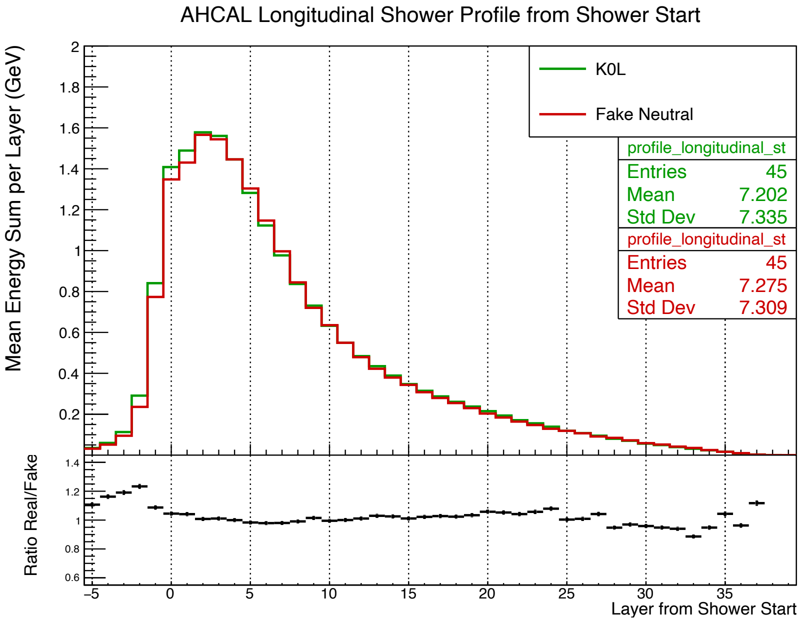


Comparison: Real vs. Pseudo Neutrals 20 GeV (MC)

Validation of Primary Track Removal Algorithm







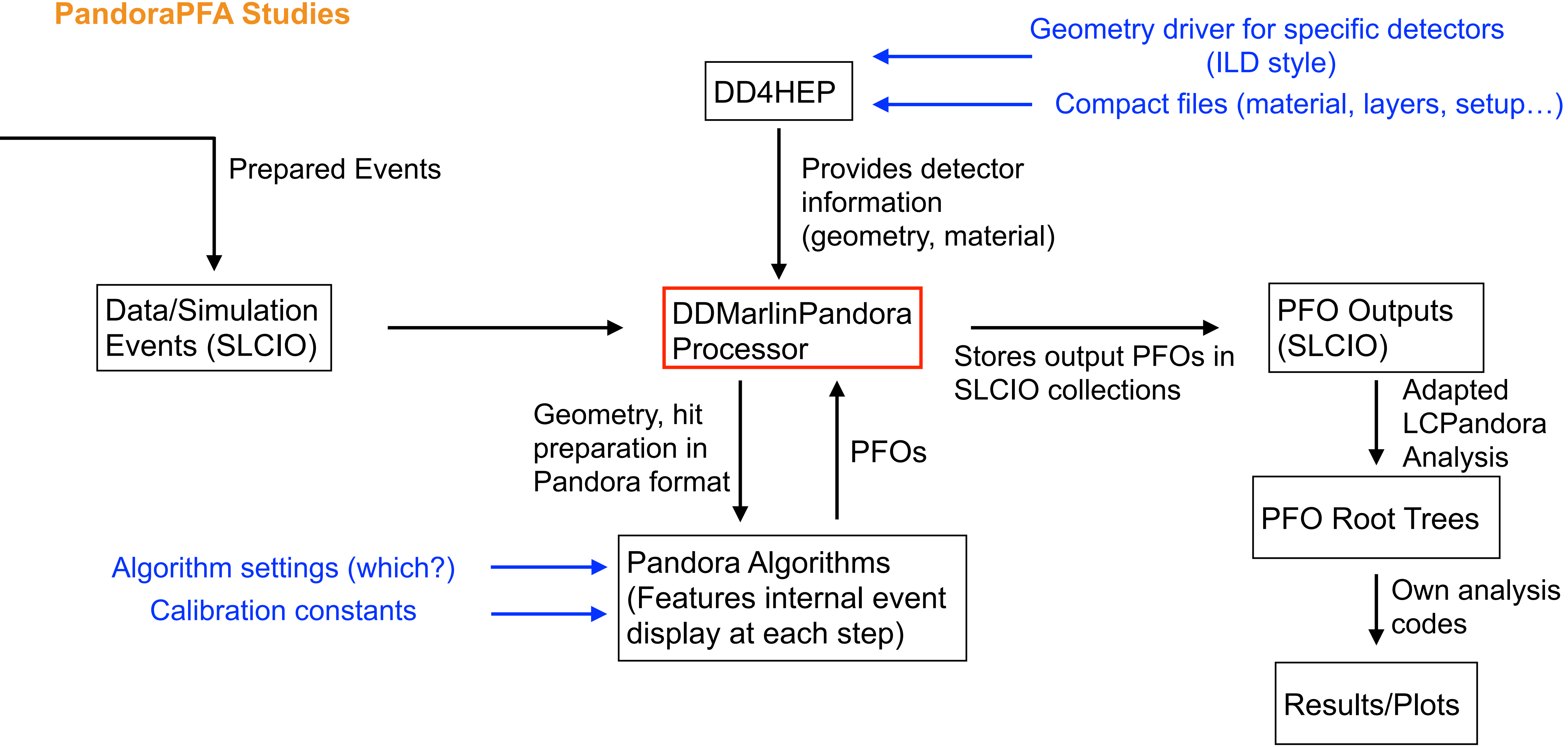
- In general **good agreement** between real neutrals (K0L) and pseudo neutrals (cut π^-) in number of hits, energy sum and longitudinal shower profile

➡ **Pseudo-neutrals validated for charged-neutral separation studies (response and topology)**

The PandoraPFA Framework: Implementation, Calibration & Basic Checks

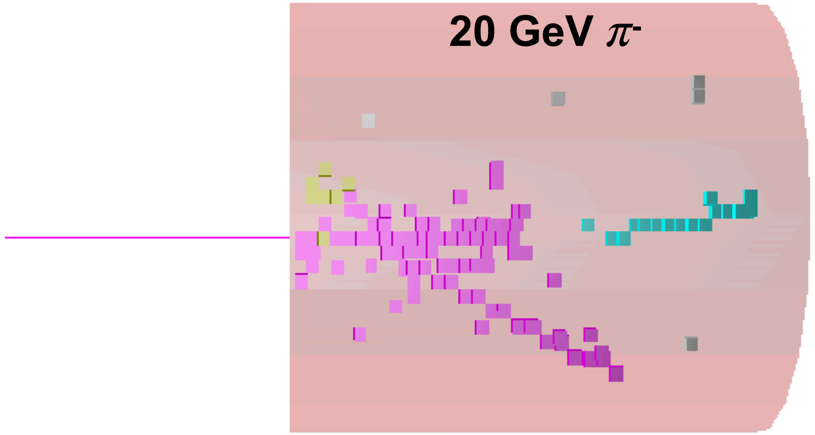
Framework / Data Flow Diagram

PandoraPFA Studies



Pandora Visual Monitoring

Hits, Clusters & PFOs

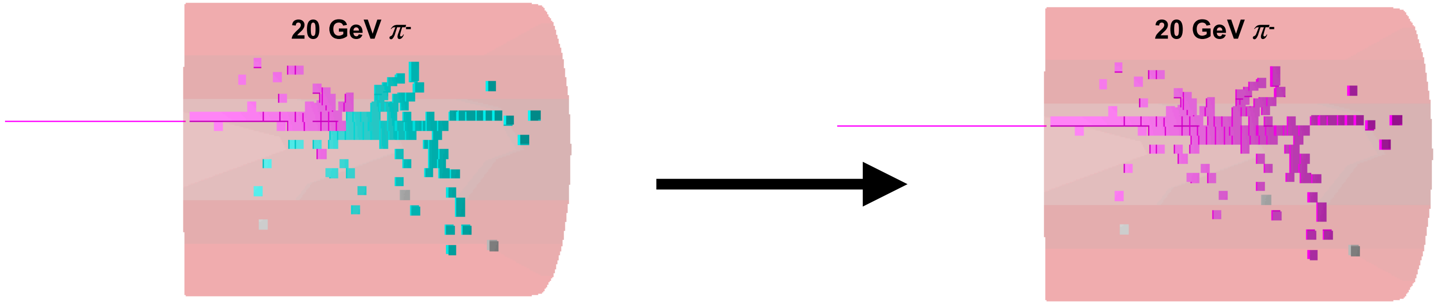


Magenta: Charged Hadron
Cyan: Neutral Hadron
Yellow: Photon
Grey: Unclustered Hits

- Cylinder: Existing HCAL end-cap class used for our setup
- Pandora visual monitoring displaying hits, clusters, tracks and PFOs at different reconstruction steps

  ➡ Great tool to precisely track down technical problems and problematic events

Solved: Non working Track-Cluster association for few events

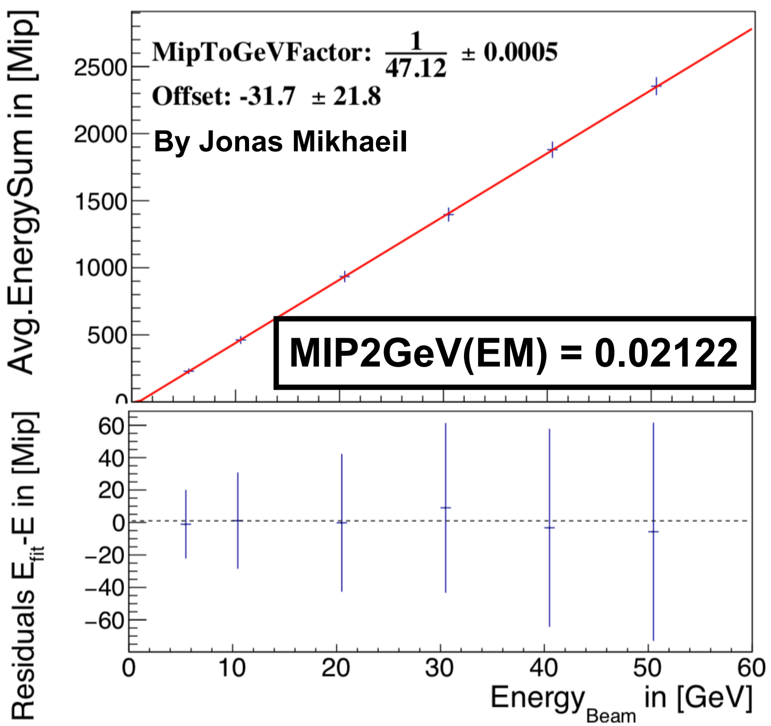


MIP to GeV Conversion

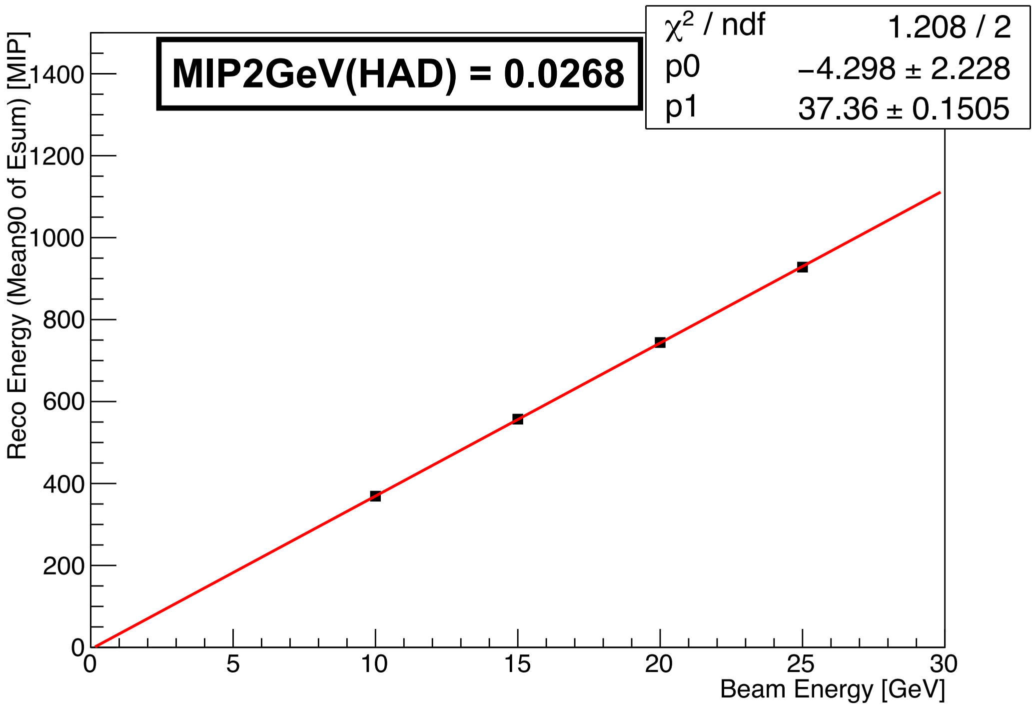
Calibration to EM and HAD Scale

- PandoraPFA framework requires energy depositions in units of GeV
  - ➡ MIP to GeV calibration done on MC samples for EM and HAD energy scale
    - ➡ Extract slope of beam energy vs calorimeter MIP response scan

EM Response Determination (e-)



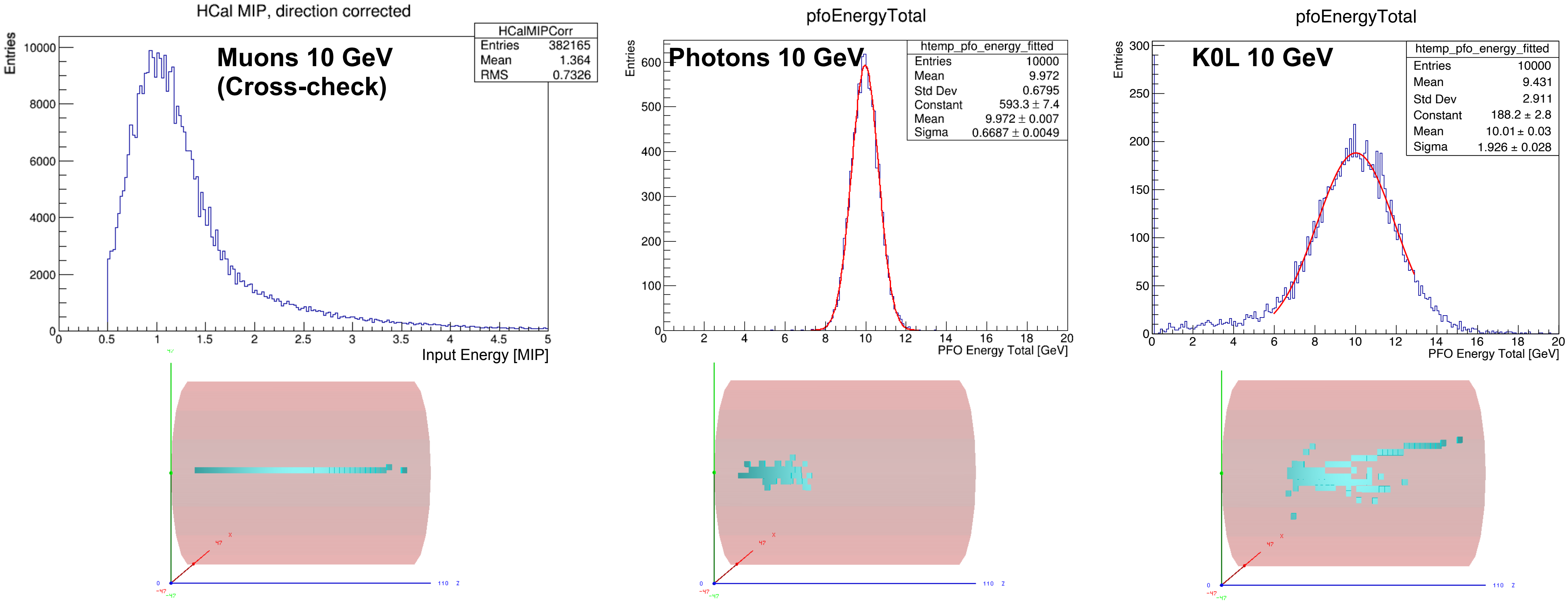
HAD Response Determination (K0L)



Pandora Energy Calibration

MC Muons, Photons, K0L

Note: Without tracks and ECAL everything classified as neutral hadrons at this step

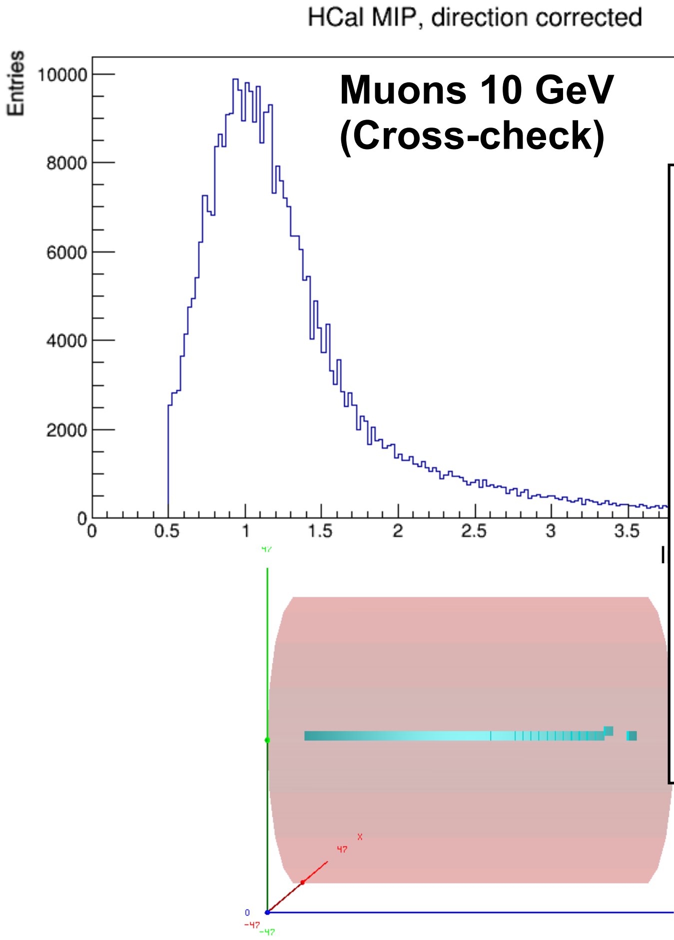


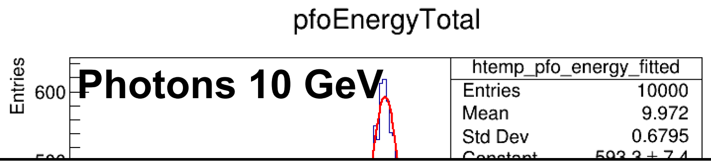
- **Muons**: AHCAL energy GeV -> MIP with negligible angle correction since straight TB tracks
- **Photons and K0L's**: Used to determine EM and HAD response, PFO energy tuned to peak at 10 GeV

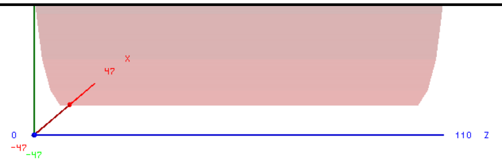
Pandora Energy Calibration

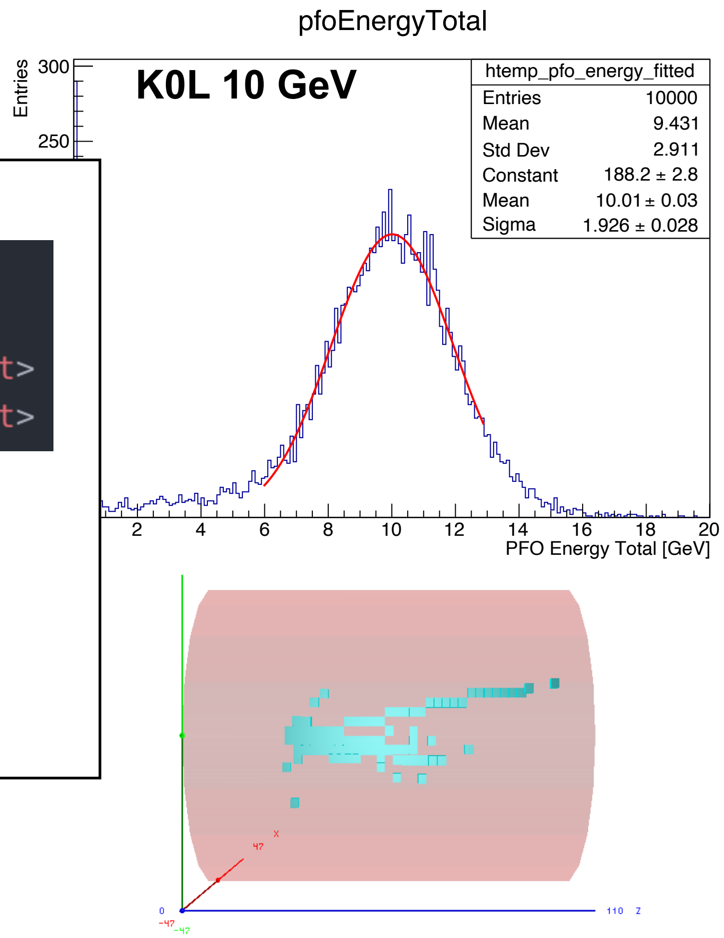
MC Muons, Photons, K0L

Note: Without tracks and ECAL everything classified as neutral hadrons at this step









Results:

```
<constant name="PandoraHcalToMip">37.36</constant>

<constant name="PandoraHcalToEMScale">1.005</constant>
<constant name="PandoraHcalToHadScale">1.03</constant>
```

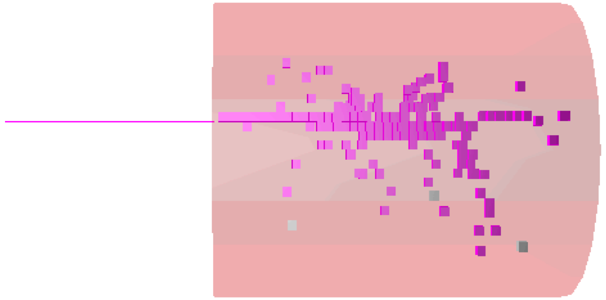
- Both factors a bit higher than for raw AHCAL response (= 1.0)
  - ➡ Pandora clustering isolation cuts

- **Muons**: AHCAL energy GeV -> MIP with negligible angle correction since straight TB tracks
- **Photons and K0L's**: Used to determine EM and HAD response, PFO energy tuned to peak at 10 GeV

Data & MC Pion Samples Overview

PandoraPFA Single Particle Reconstruction

- **Charged pions** events **(10, 20, 40, 60, 80, 120, 160, 200 GeV) with fixed track momentum in PandoraPFA**
  - ➡ Data: **June Beam Test 2018 @ SPS CERN**
  - ➡ MC: **GEANT4 v.10.03, QGSP_BERT_HP & FTFP_BERT_HP**



- Applied BDT-PID for hadrons (remove beam contamination)
- Event selection:
  - ➡ At least one hit in layer 1 or 2 or 3 & corresponding track - hit match (for proper track-cluster assignment)
  - ➡ Track to detector crack rejection +- 2mm
  - ➡ Shower start layer < 20 (reject leakage events)
  - ➡ Rejection of remaining events with complete failure of track-cluster association (<1%)
    - ➡ Technical reason within PandoraPFA algorithms: No ECAL before - missing first track association

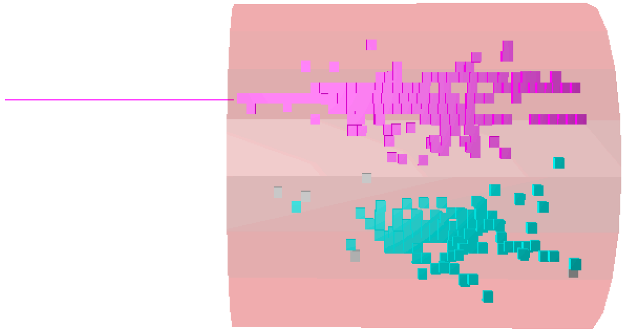
Data & MC Pion Samples Overview

PandoraPFA Two Particle Reconstruction

- 10 GeV (pseudo-) neutral hadrons overlaid with 10 GeV or 30 GeV charged hadrons
- Distances: 0, 50, 100, 150, 200, 250, 300 mm with ±25 mm acceptance range

➡ **Now all 10 & 30 GeV charged runs centralised, except for data 30 GeV (200, 250 & 300 mm)**

  ➡ **MC samples all centralised!**



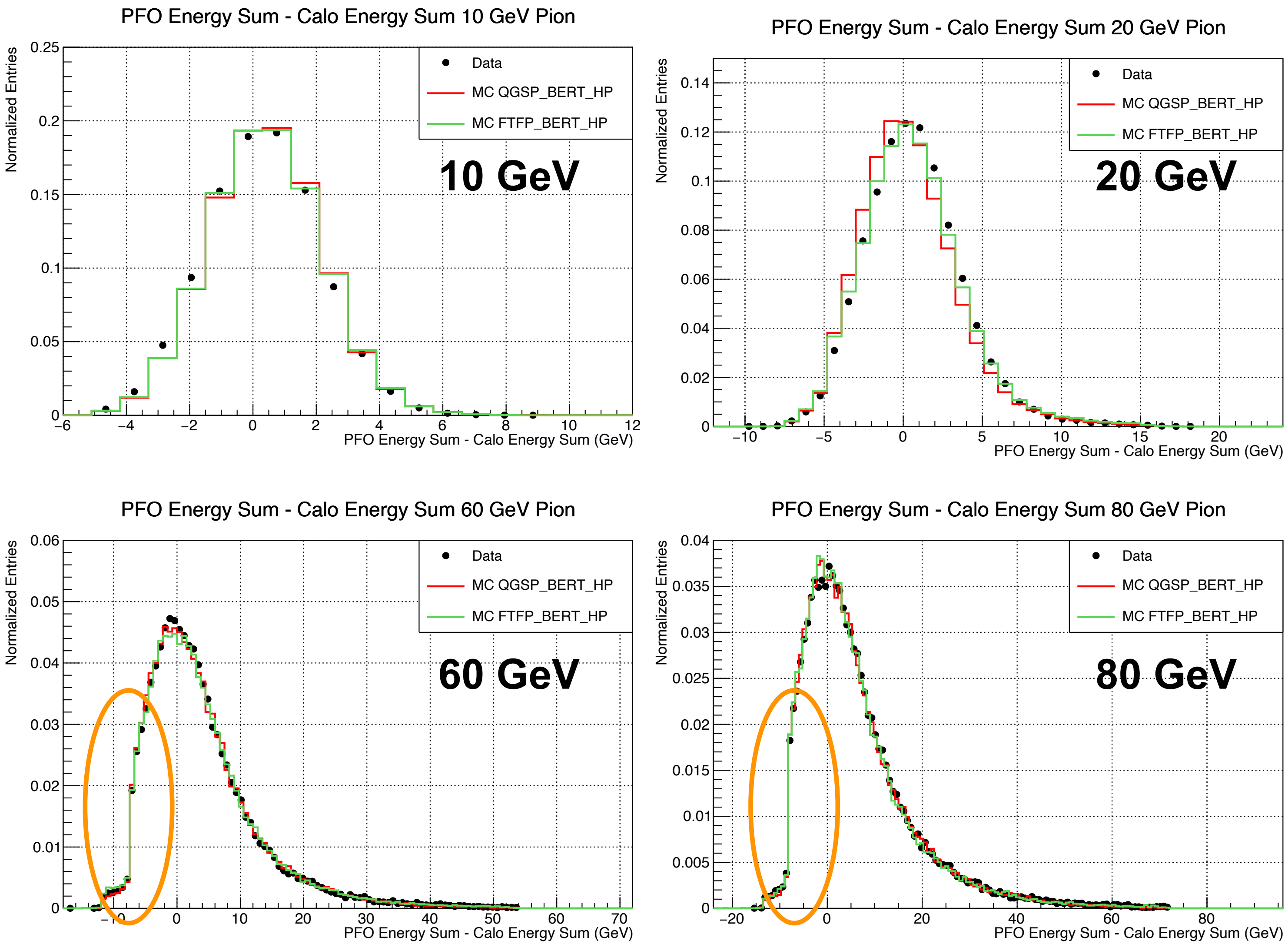
➡ Data: June Beam Test 2018 @ SPS CERN

➡ MC: GEANT4 v.10.03, QGSP_BERT_HP & FTFP_BERT_HP

- Applied latest BDT-PID for hadrons (remove beam contamination)
- Event selection:
  - ➡ Punch trough rejection & no cut on shower start layer (allow long. separation)
  - ➡ Charged hadron: track-hit match layer 1||2||3, track-to-gap rejection
  - ➡ „Diagonal rejection“ by requiring at least 10% of charged hadron energy associated to track (IsoHitMerging)

PFO Energy Sum - Calorimeter Energy Sum

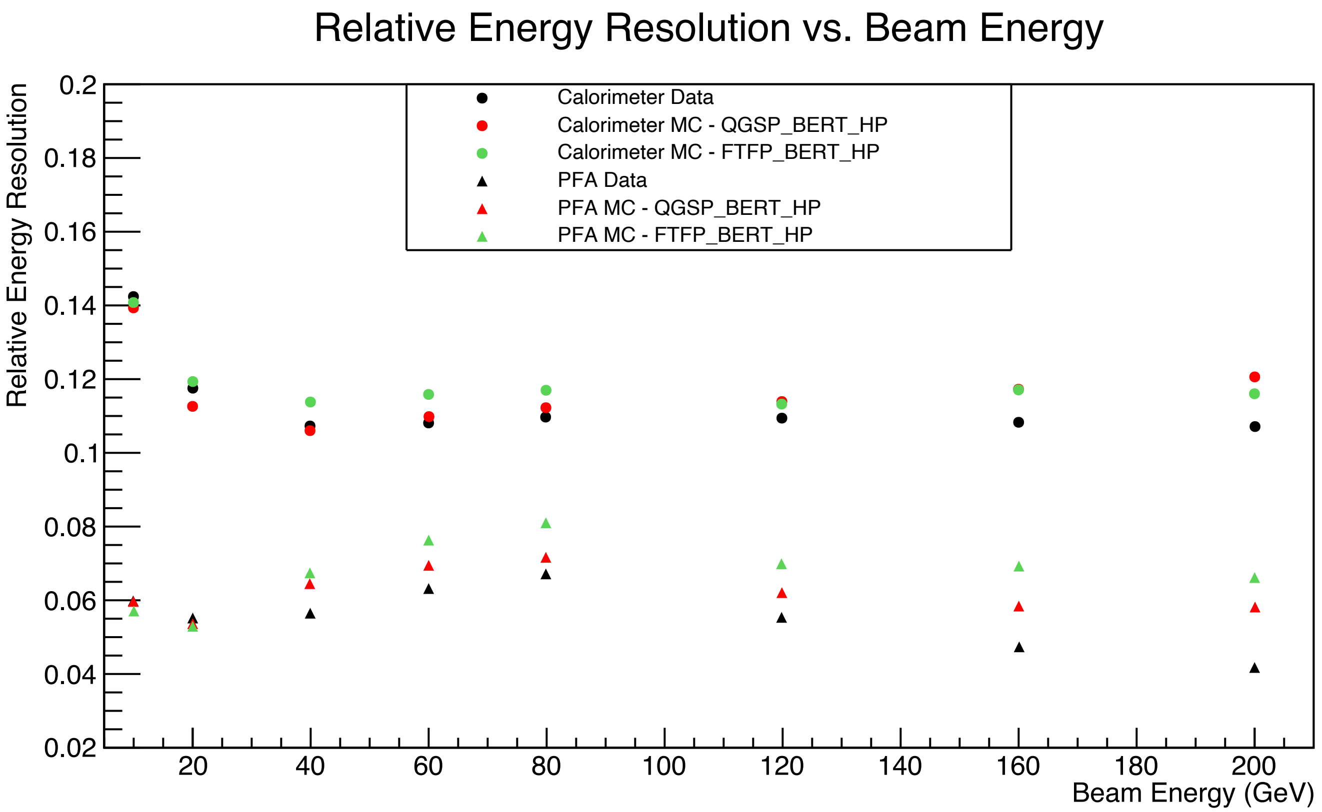
10, 20, 60 & 80 GeV Data and MC



- Overall good agreement between data and MC
- Sharp edge at **-8.8 GeV**
  - ➡ Internal PandoraPFA cut?
  - ➡ John Marshall had few ideas what it might be within PandoraPFA code: Probably related to internally assumed hadronic energy resolution of 60%/sqrt(E)

Relative Energy Resolution vs. Beam Energy

Data and MC



Classical: Mean90 and RMS90

PFA: Full Mean and RMS

- **PFA energy resolution factor of 2 better than classical energy resolution**
- PFA reconstruction performance on data best, at low energies same level as MC

➡ Up to 80 GeV: Growing confusion - degrading of energy resolution

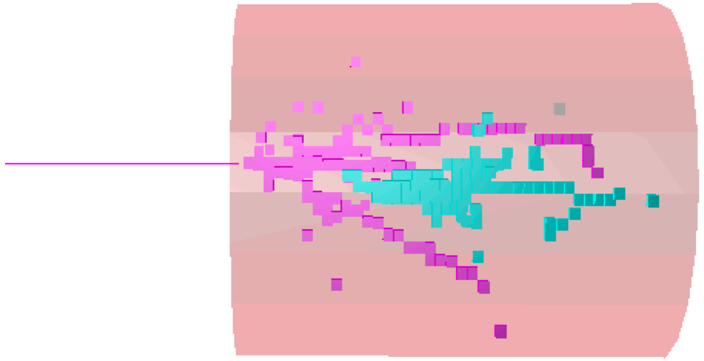
➡ From 120 GeV onwards: Artificial improvement of energy resolution due to remaining leakage

Total PFO Multiplicity - How many Particles Reconstructed?

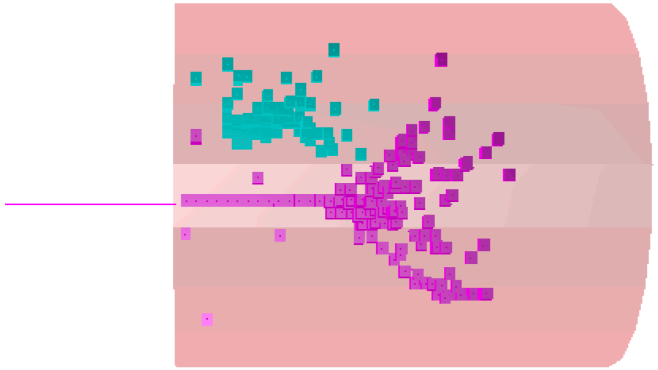
Different Scenarios

Examples of good case: Two PFO’s

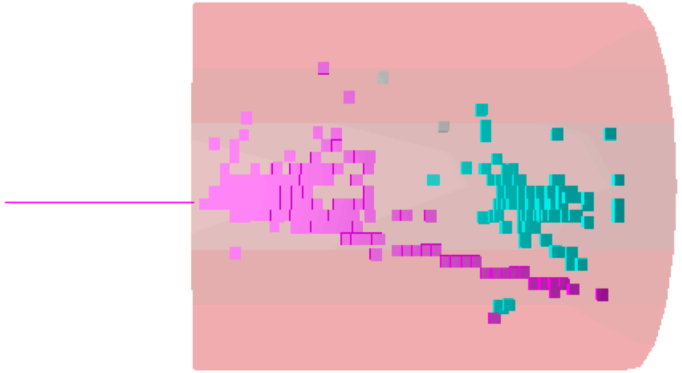
10GeV Neutral + 10 GeV Charged Distance: 50mm



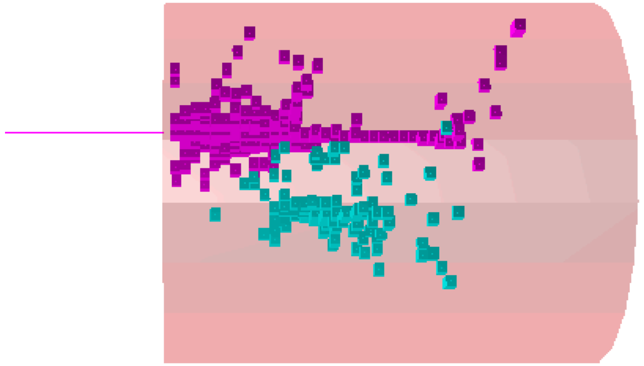
10GeV Neutral + 10 GeV Charged Distance: 200mm



10GeV Neutral + 30 GeV Charged Distance: 50mm



10GeV Neutral + 30 GeV Charged Distance: 200mm

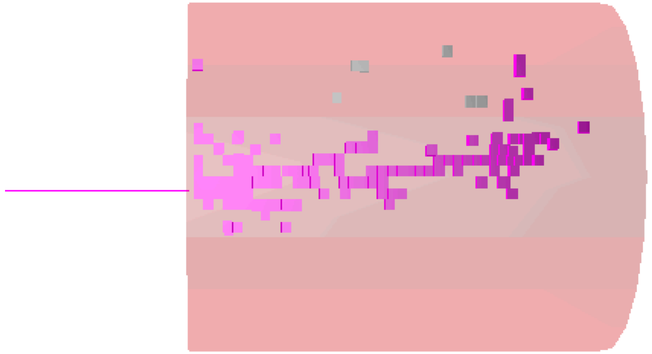


Total PFO Multiplicity - How many Particles Reconstructed?

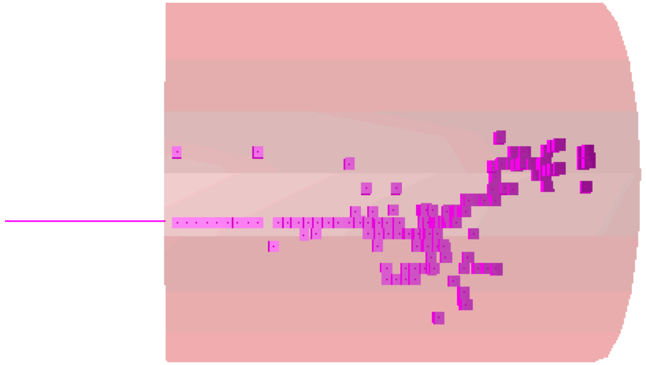
Different Scenarios

Examples of bad case: Only one PFO

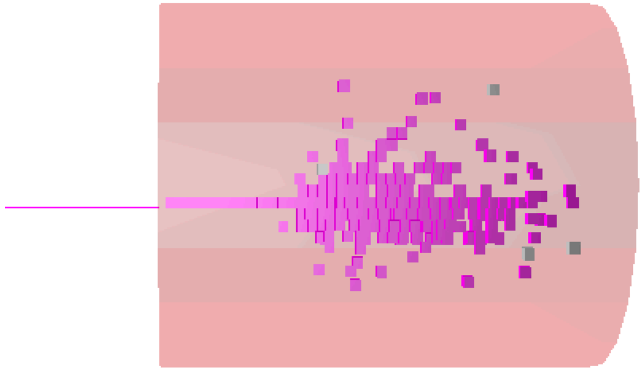
10GeV Neutral + 10 GeV
Charged Distance: 50mm



10GeV Neutral + 10 GeV
Charged Distance: 200mm



10GeV Neutral + 30 GeV
Charged Distance: 50mm



10GeV Neutral + 30 GeV
Charged Distance: 200mm