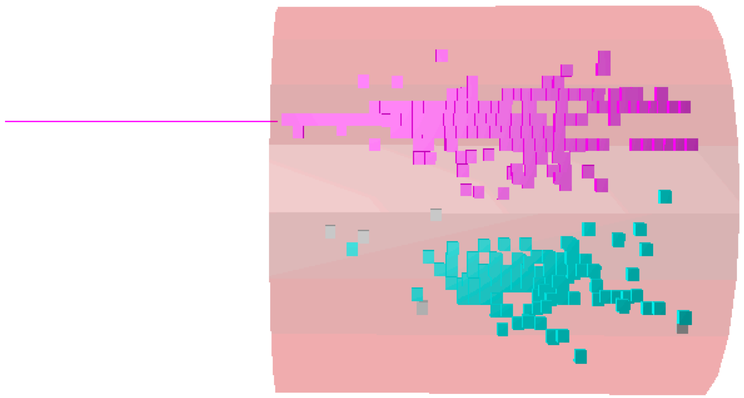
PandoraPFA Studies on AHCAL 2018 Data

Update

PandoraPFA Visual Monitor



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

Daniel Heuchel (DESY)
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CALICE Collaboration Meeting
30th September 2020

Work done in cooperation with
Linghui Liu (The University of Tokyo)

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386
HGSFP
CALICE
DESY.

Outline

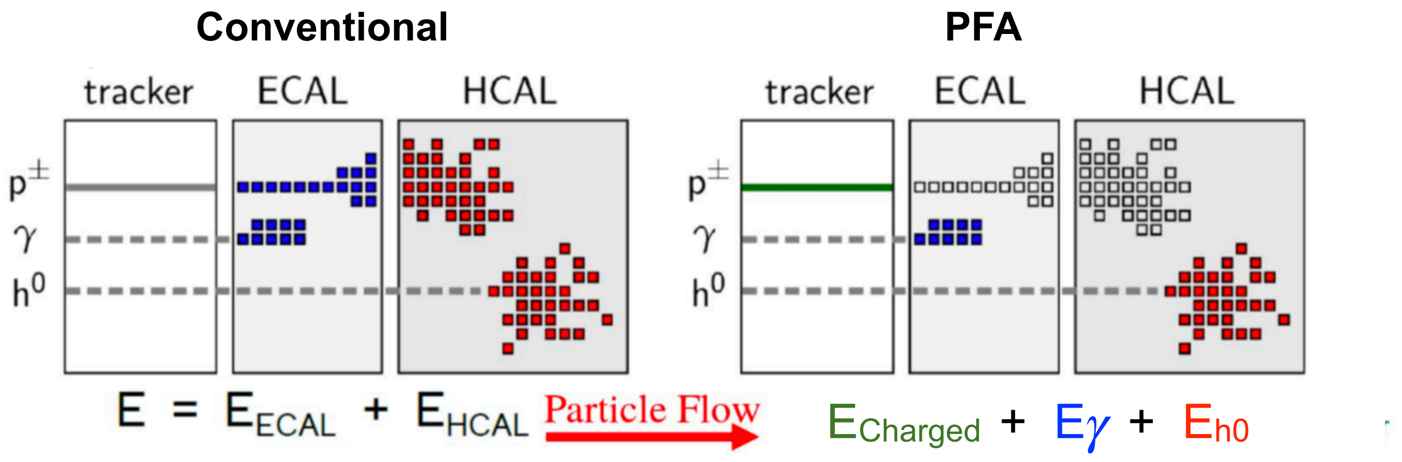
For this Talk

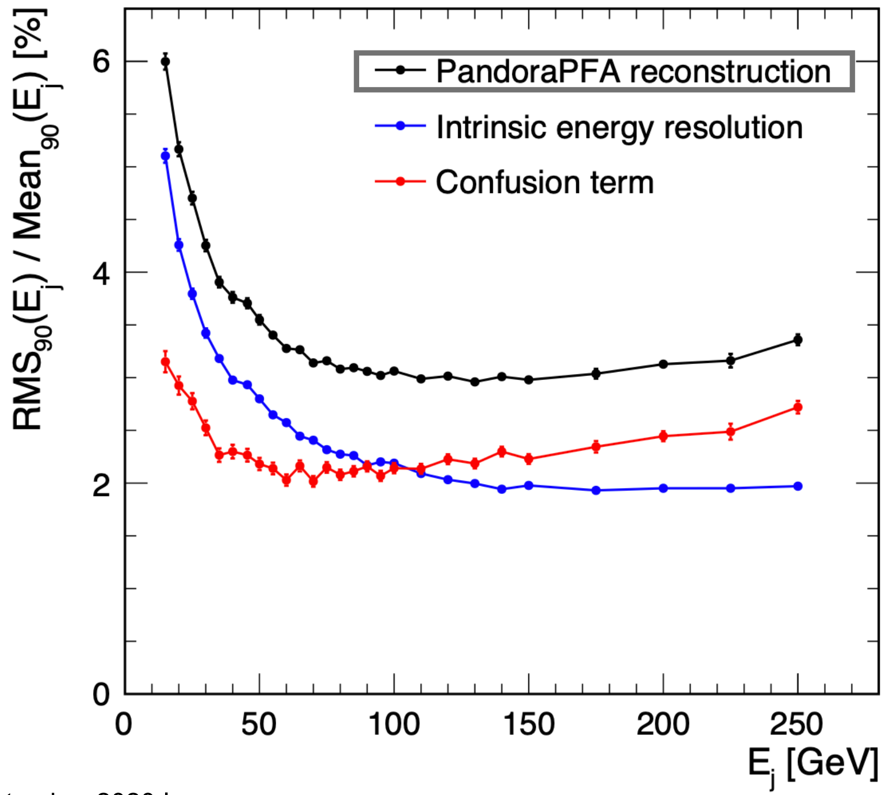
- Concept of Particle Flow & PandoraPFA
- Idea & Goals of Study
- Sample Preparation and Selection Tools
  - ➡ Validation of Tracks
  - ➡ Validation of Pseudo Neutral Hadrons
- Second Look into PandoraPFA Single Particle Reconstruction
- Summary & Outlook

Particle Flow Approach

Reaching High Precision

- Goal at the ILC: Jet energy resolution of 3-4% for jet energies between 40-500 GeV
  - ➡ PFA: Measure energy/momentum of each particle with detector providing best resolution
    - ➡ Make use of excellent resolution of tracker (for ~60% charged particles in jets)



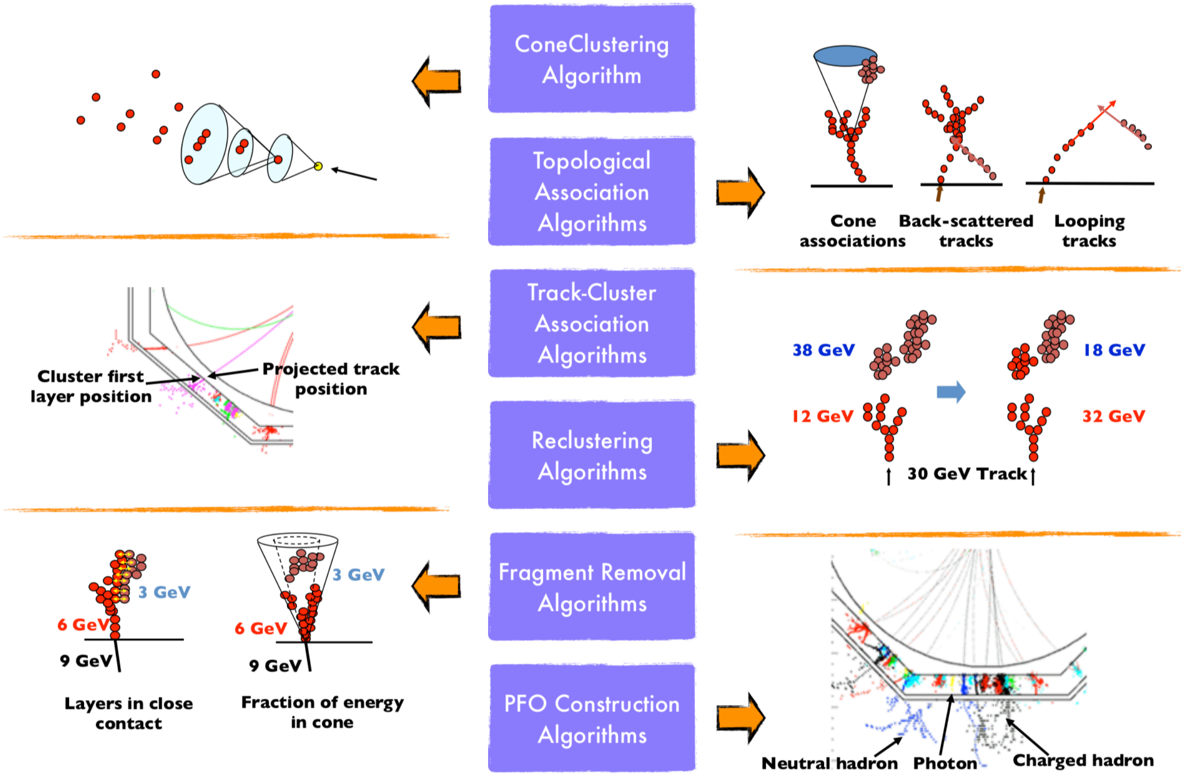


arXiv:1705.10363

The Pandora Particle Flow Algorithm

Multi-Algorithm Pattern Recognition

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

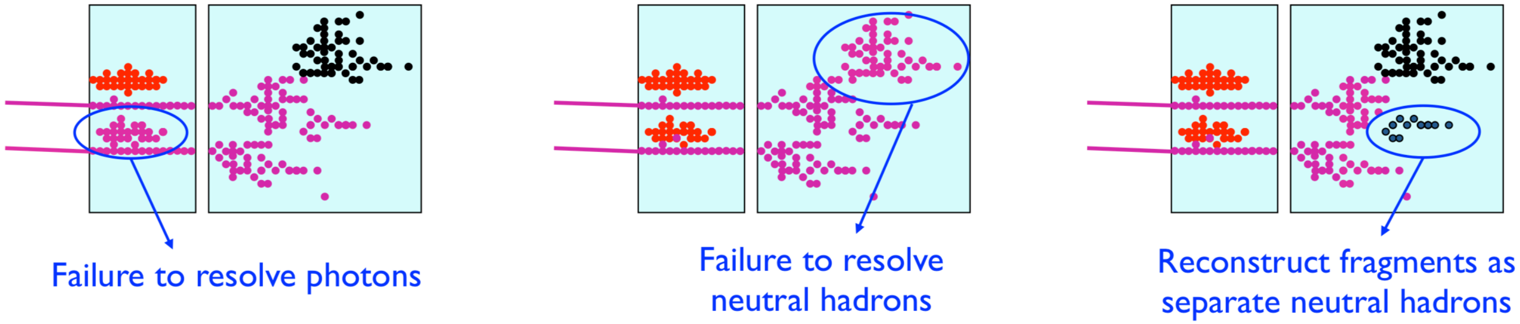
- PandoraPFA: Complex multi-algorithm chain for pattern recognition
  - ➡ Fully reconstruct the path of individual particles through the full detector including their shower substructure
    - ➡ **Correctly** identify charged and neutral particles corresponding energy depositions and take best energy measure for this **Particle Flow Objects (PFOs)**
    - ➡ Charged PFO: Calorimeter cluster + track
    - ➡ Neutral PFO: Calorimeter cluster

The Confusion Term

The Limit of PFA Reconstruction

- **Topologically or energetically confusing** scenarios might appear in specific events limiting jet energy resolution:

Types of confusion



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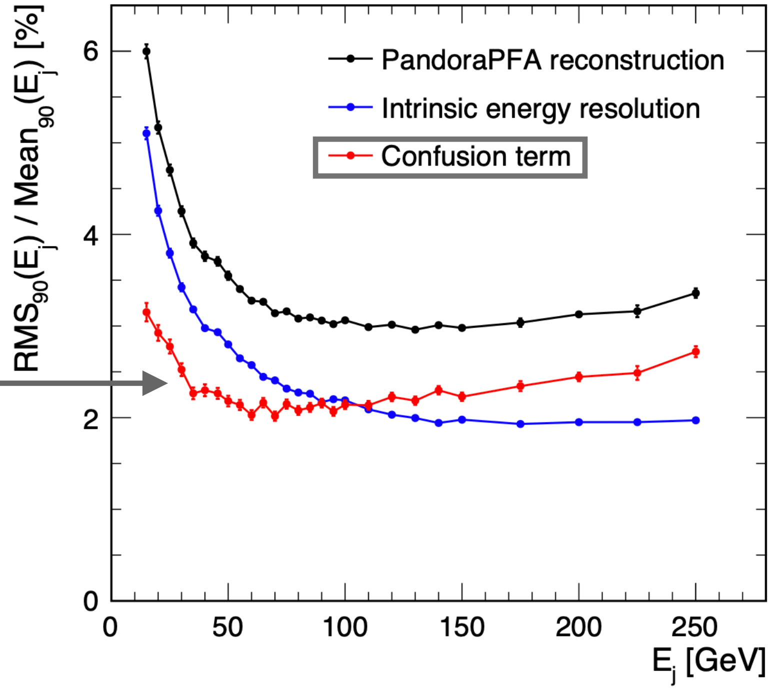

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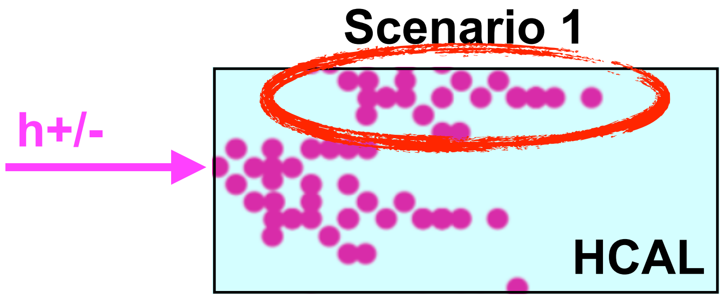
Idea and Goals of Studies

PandoraPFA on AHCAL 2018 Prototype Data

- **Evaluate PandoraPFA on beam test data:** AHCAL 2018 prototype standalone + tracks
  - ➡ Study of **single and two particle reconstruction performance** with regard to **confusion**
    - ➡ Different conditions (energies, transversal/longitudinal separation, amount of leakage, etc.)

- **Scenario 1**: **Single Particle Event (Charged Hadron)**
  - ➡ Confusion: Fragment of charged hadron shower reconstructed as separate neutral hadron
    - ➡ Sensitive to double counted energy



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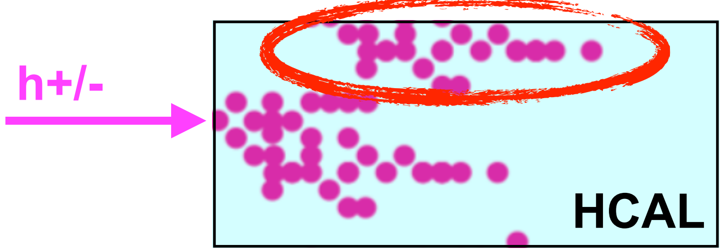
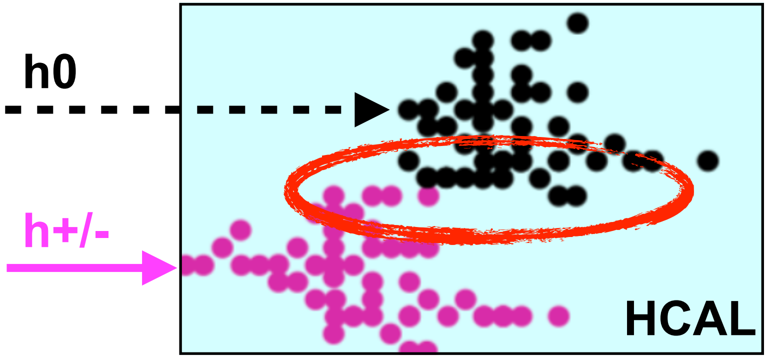
Scenario 1



- **Scenario 2**: **Two Particle Event (Charged + Neutral Hadron)**
  - ➡ Confusion: Failure to resolve neutral hadron; Neutral hadron hits fully or partly added to charged hadron cluster
    - ➡ Sensitive to missing energy

Scenario 2



Overview

Sample Preparation & Analysis Strategy

Note: No neutral hadron beam in beam tests therefore primary track removal on charged hadrons required to create pseudo-neutrals

AHCAL data & MC → Unselected charged pion events → **Event preparation & selection** → Selected charged pion events → **<u>Primary track removal</u> & 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
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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: Work in progress - talk by Linghui Liu
  - ➡ **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

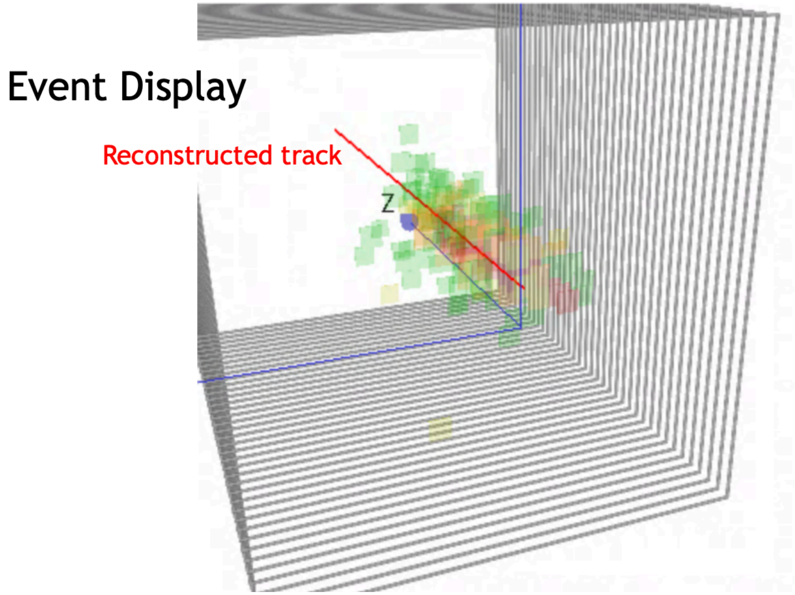
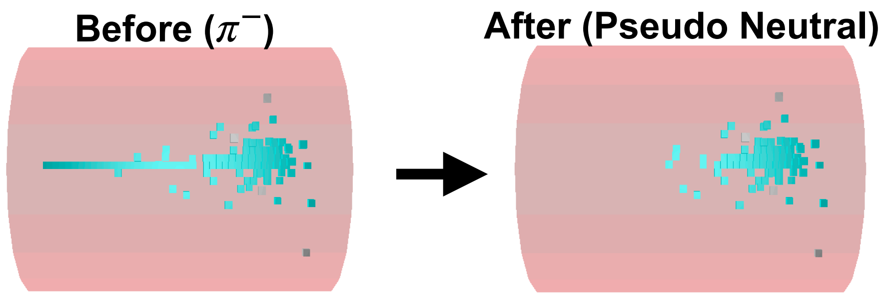


Illustration of pseudo neutral generation

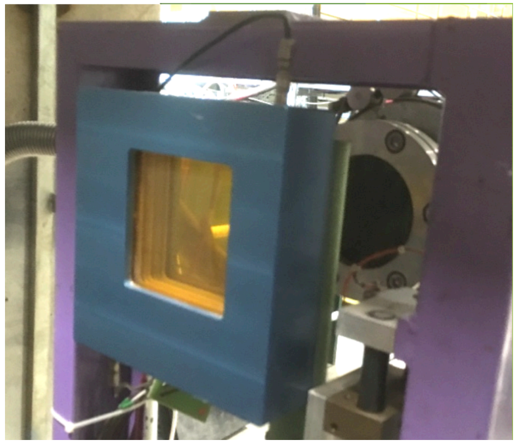


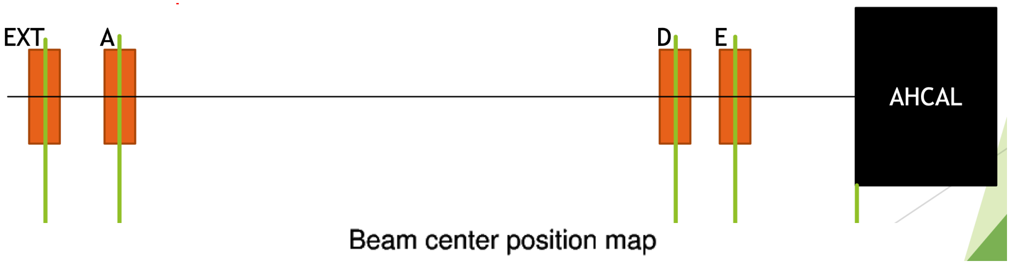
Delay Wire Chambers (DWC)

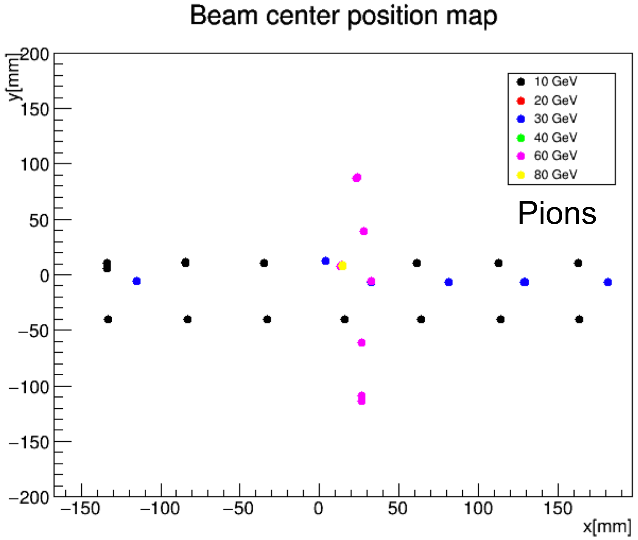
Providing Tracks for Beam Test Events

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







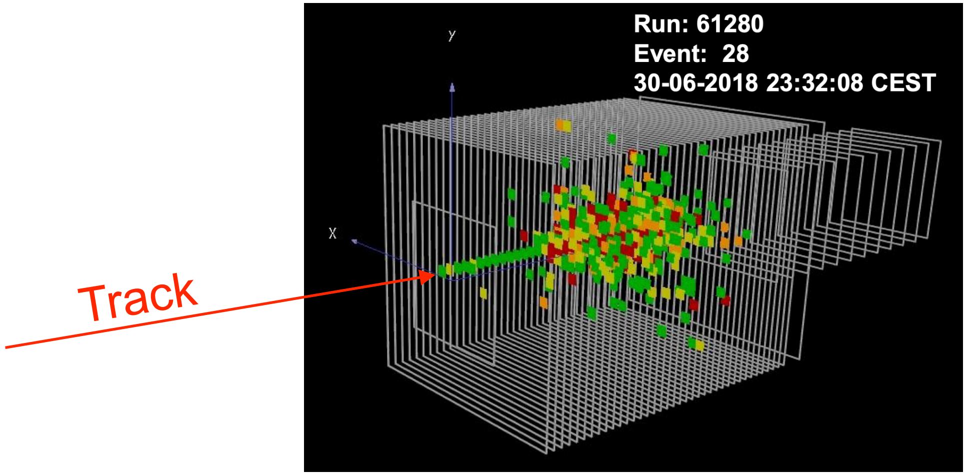
Track Quality Check

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

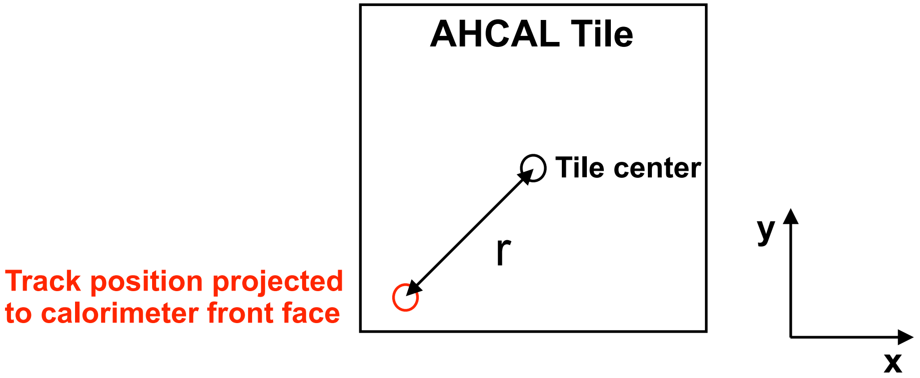
➡ **Track quality?**



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?

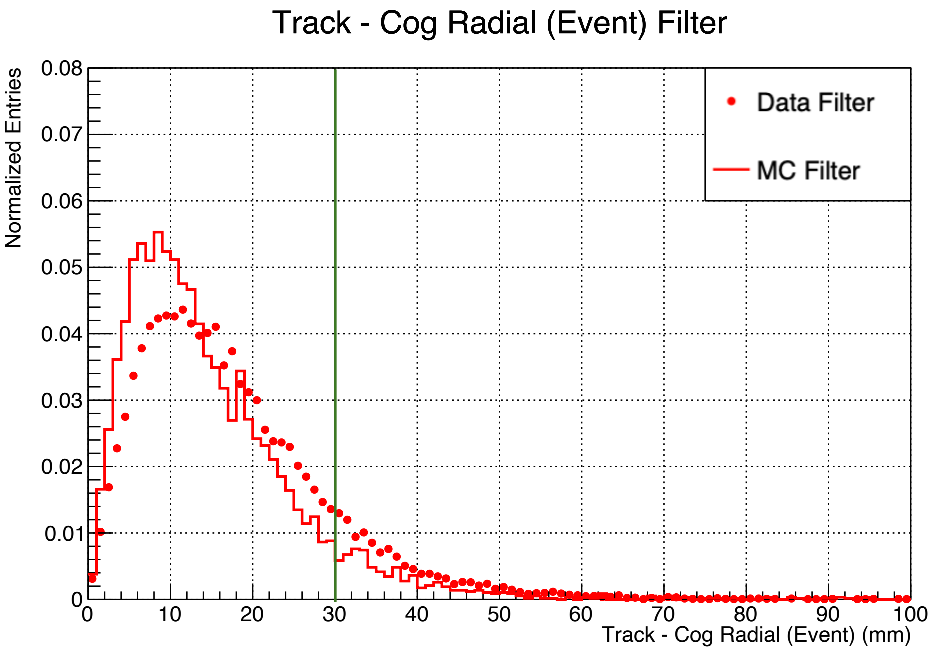
Does track hit any triggered channel in layer 1 at all?



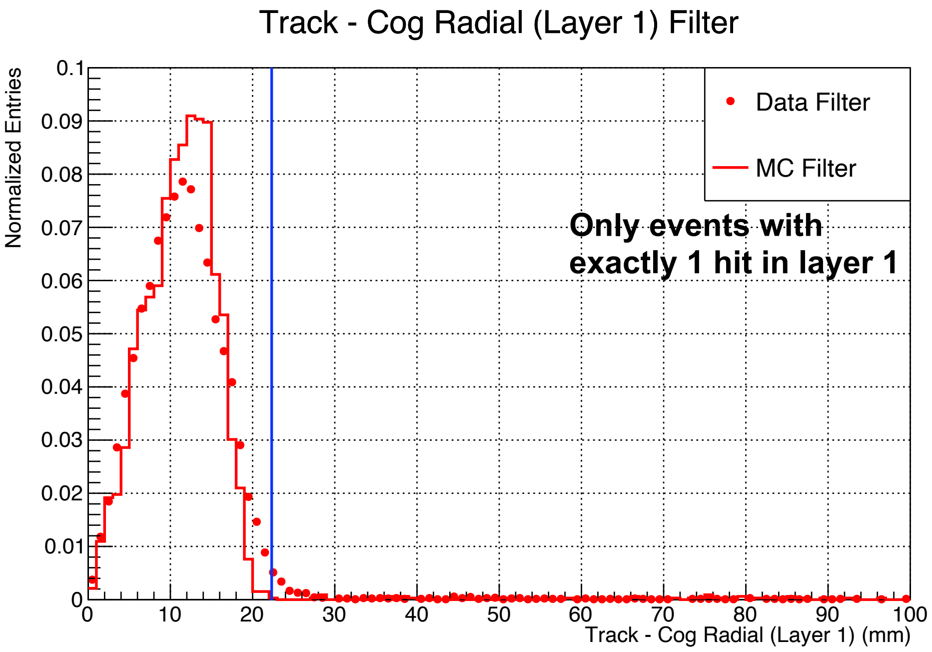
Track Quality Results 20 GeV π^-

Precise Tracks for PandoraPFA Reconstruction

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



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



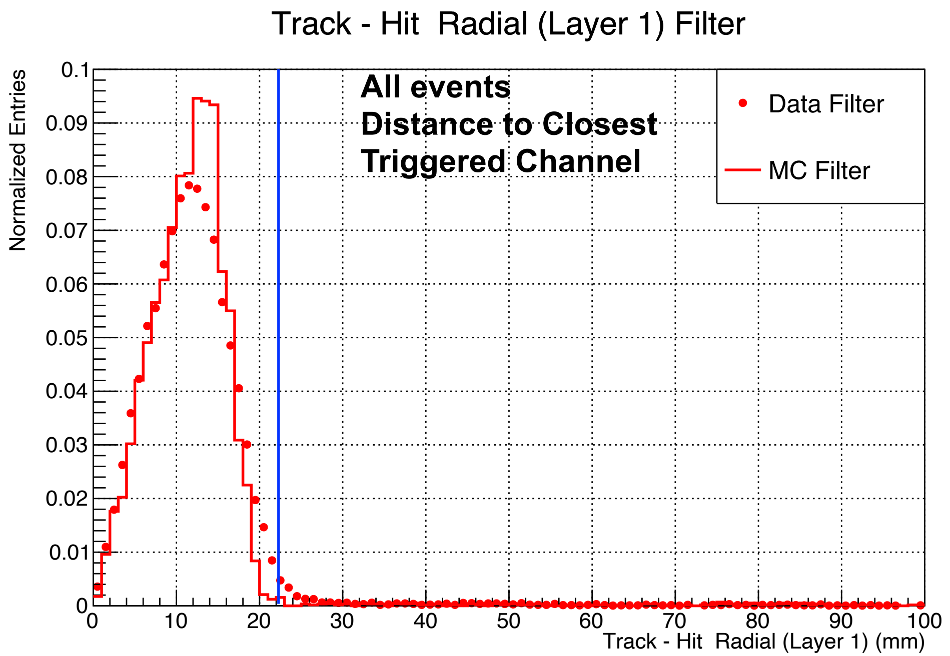
$$r = \sqrt{(x_{track} - x_{hit})^2 + (y_{track} - y_{hit})^2}$$

- 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^-

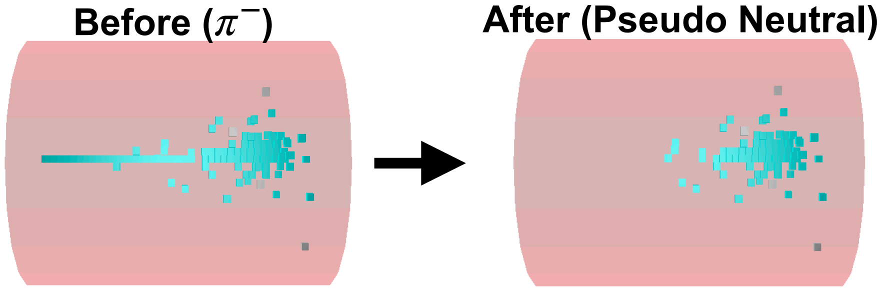
➡ **Excellent track quality validated for data and MC**

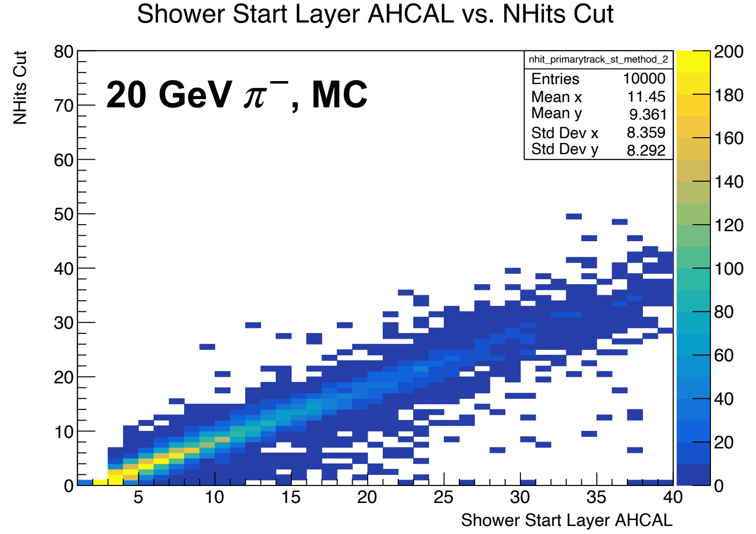
Finding and Removing Primary Track

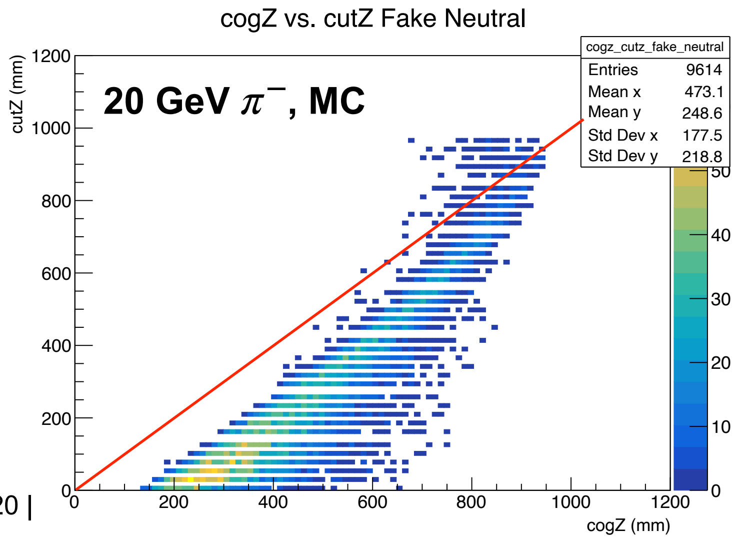
The Method for Creating Pseudo Neutral Hadrons

- 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

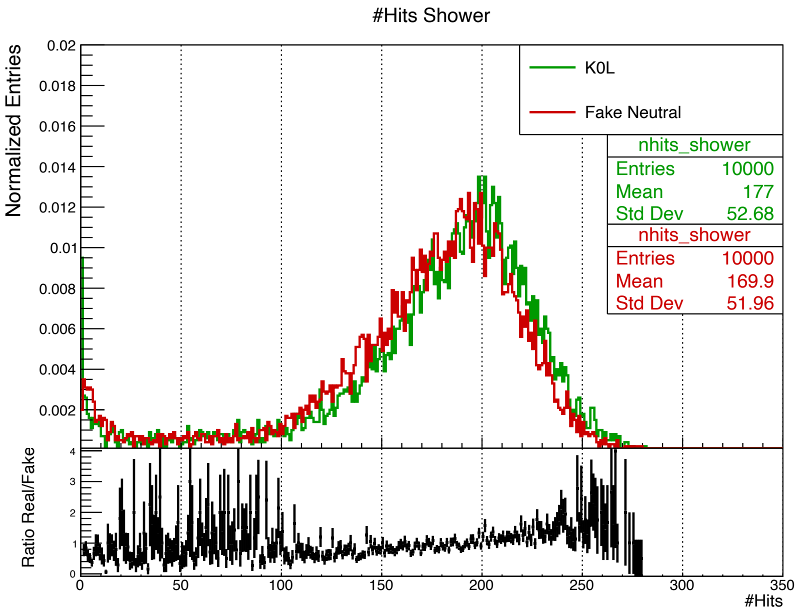


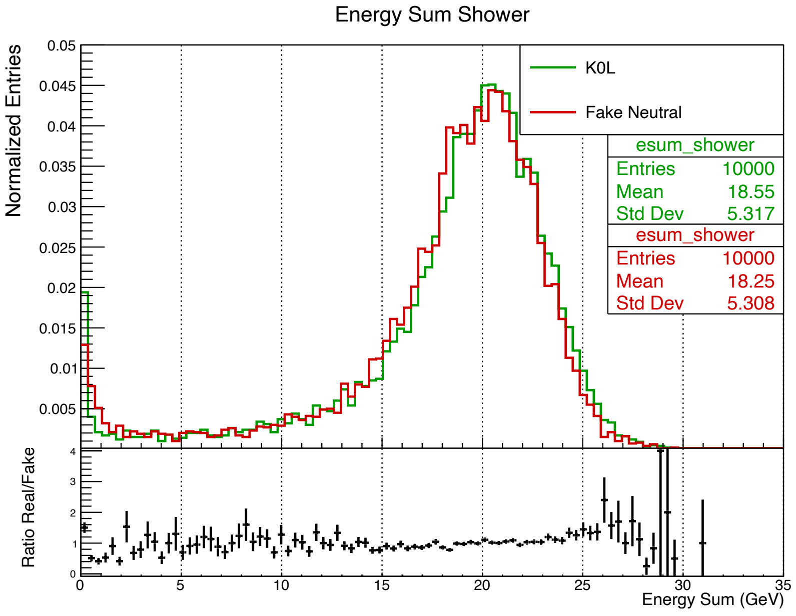


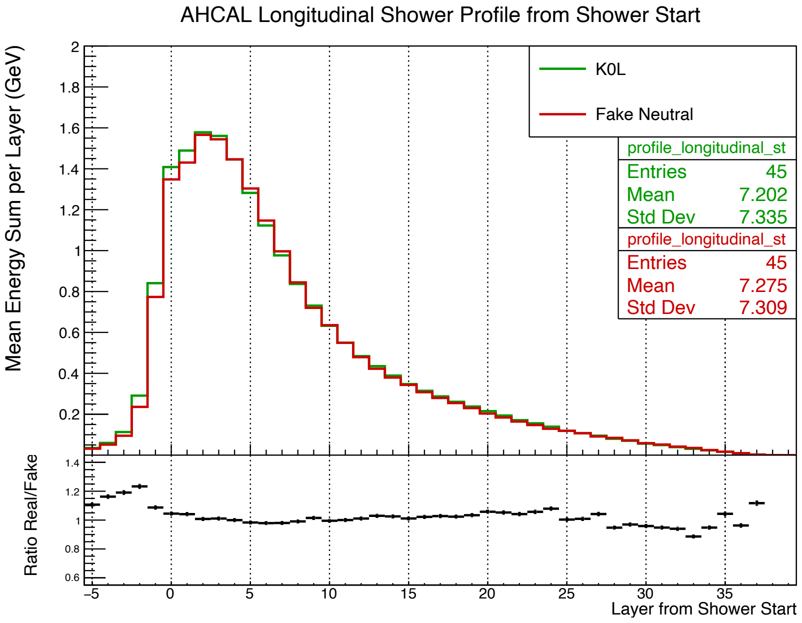


Comparison: Real vs. Pseudo Neutrals 20 GeV (MC)

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)**

Overview

Sample Preparation & Analysis Strategy

AHCAL data & MC →

Unselected charged pion events

→ **Event preparation & selection**

Selected charged pion events

→ **<u>Primary track removal</u> & 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
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PandoraPFA on Single Particles

(Charged π^- , Work in Progress)

Data & MC Pion Samples

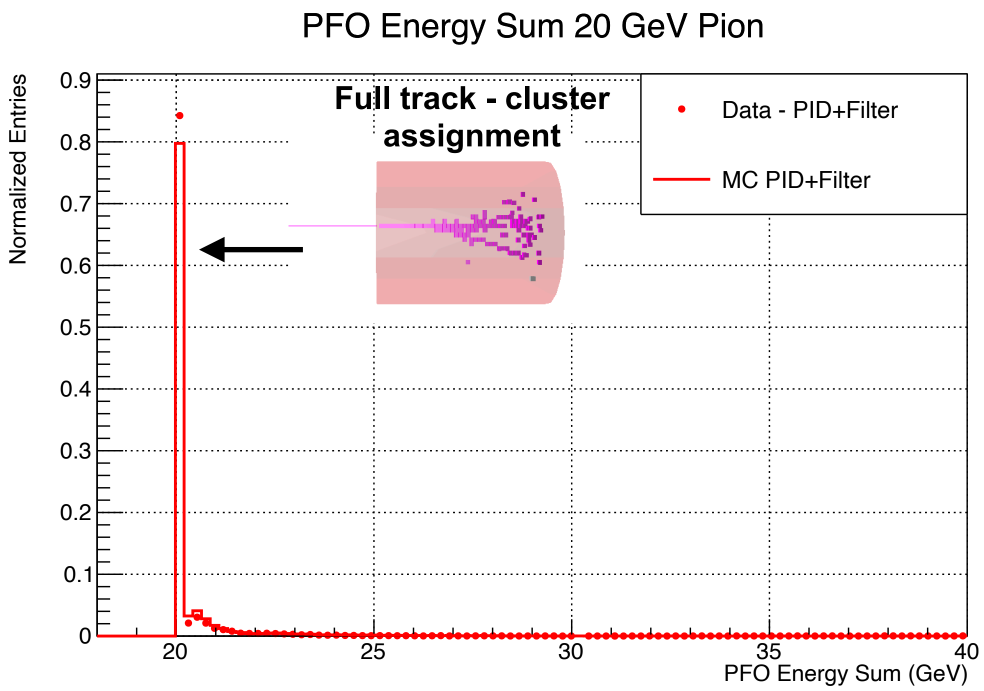
Pandora Single Particle Reconstruction

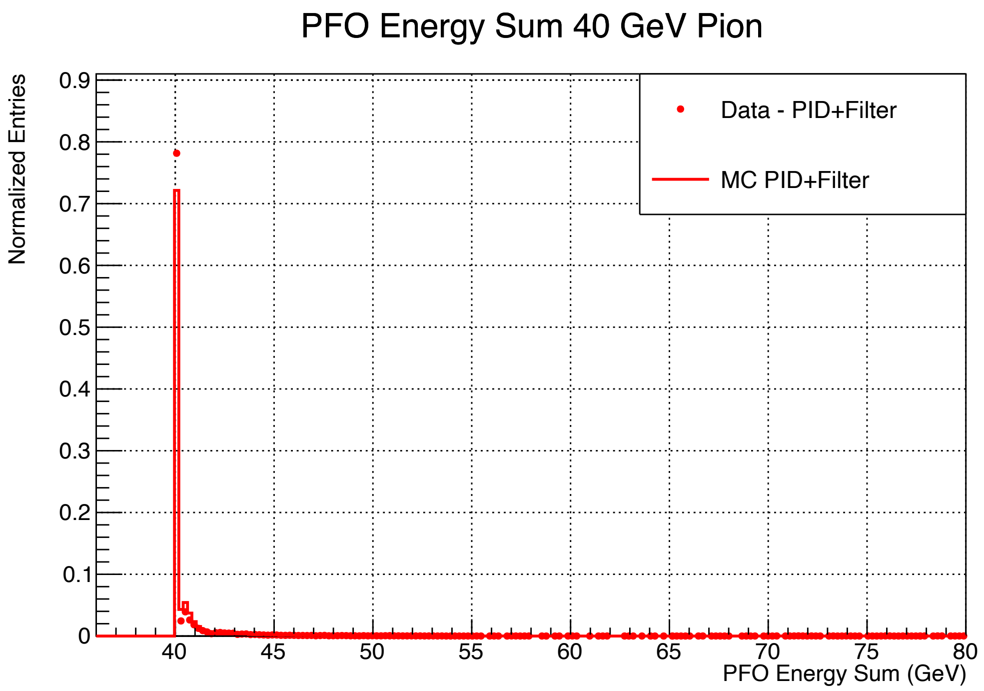
- **50k charged pions** events (**20 & 40 GeV)** simulated (**Geant4 v.10.03, QGSP_BERT_HP)** and data from **June Beam Test 2018**
  - ➡ For data and MC: Fixed **track momentum of 20/40 GeV in Pandora**

- Applied BDT-PID for hadrons (to remove beam contamination)
- Applied simple event filter:
  - ➡ At least one hit in layer 1 or 2 or 3 & track - hit match in layer 1 or 2 or 3 (for proper track-cluster assignment)
  - ➡ Track to detector crack rejection (avoiding most events with particle propagating through central crack of detector before showering)
  - ➡ Shower start layer < 20 (reject leakage events)

Results: PFO Energy Sum

20 & 40 GeV Pions Data & MC

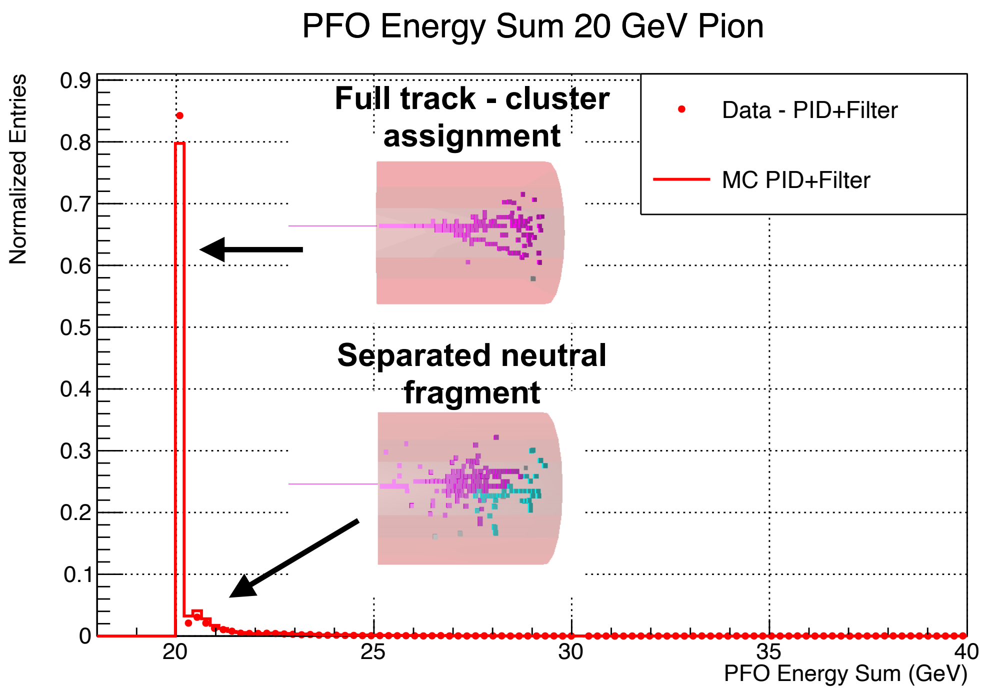


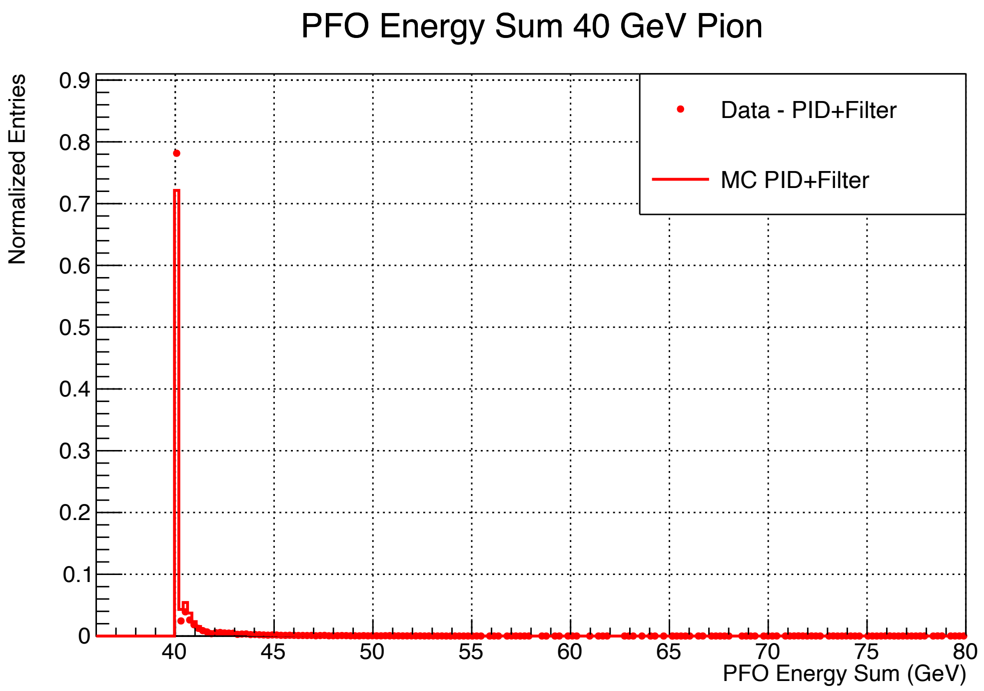


- Three types of reconstruction cases:
  - ➡ Most events with proper track - full cluster assignment: 20 and 40 GeV (first bin)

Results: PFO Energy Sum

20 & 40 GeV Pions Data & MC





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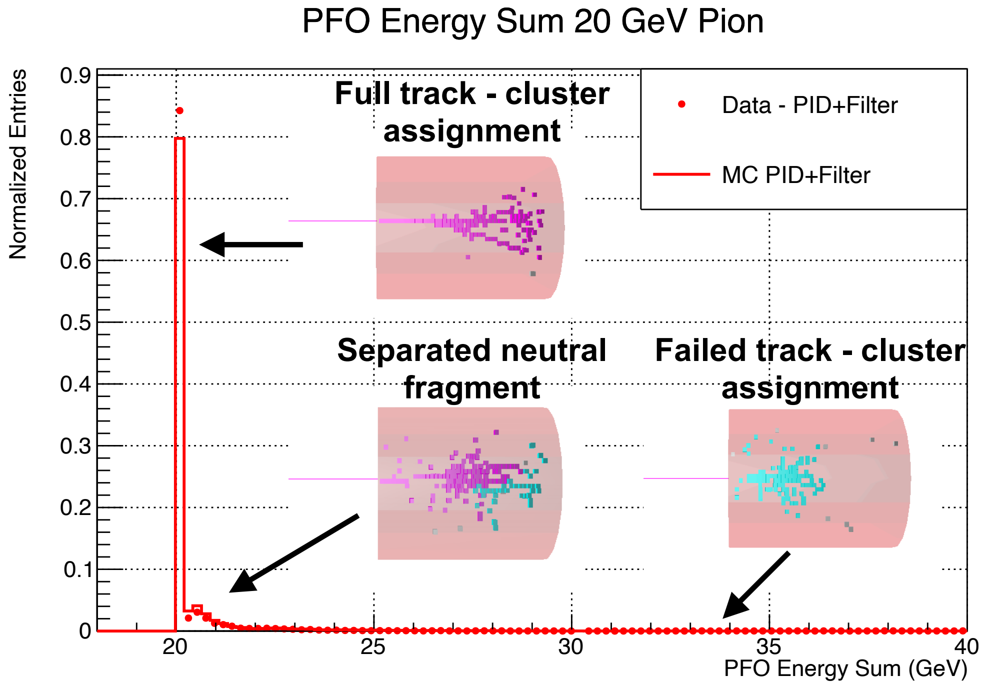
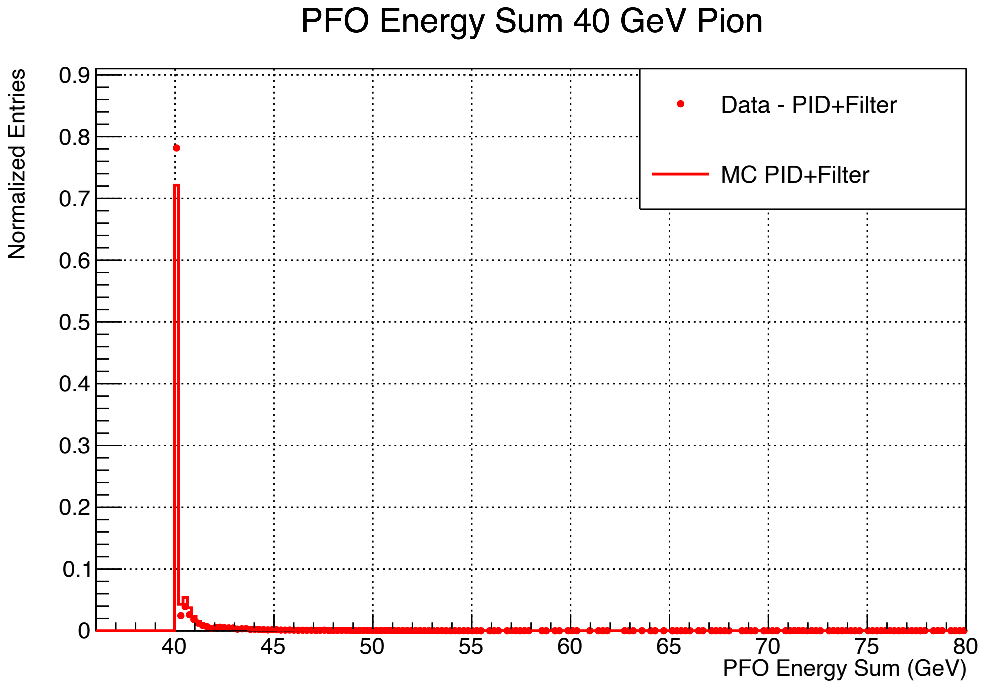




- Three types of reconstruction cases:
  - ➡ Most events with proper track - full cluster assignment: 20 and 40 GeV (first bin)
  - ➡ Tail to higher energies: Events with identified separated neutral hadron fragment
  - ➡ Far right tail events: Failed track-cluster assignment due to topological gap in shower development or particles hitting central detector crack in first layers

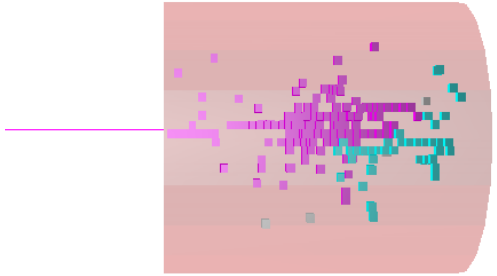
Results: PFO Multiplicity Total

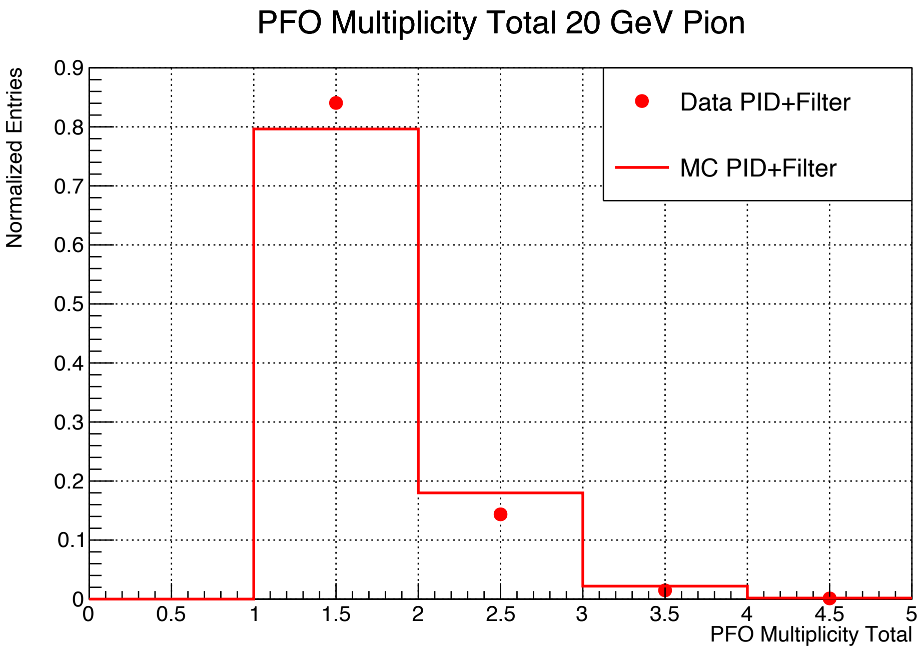
20 & 40 GeV Pions Data & MC

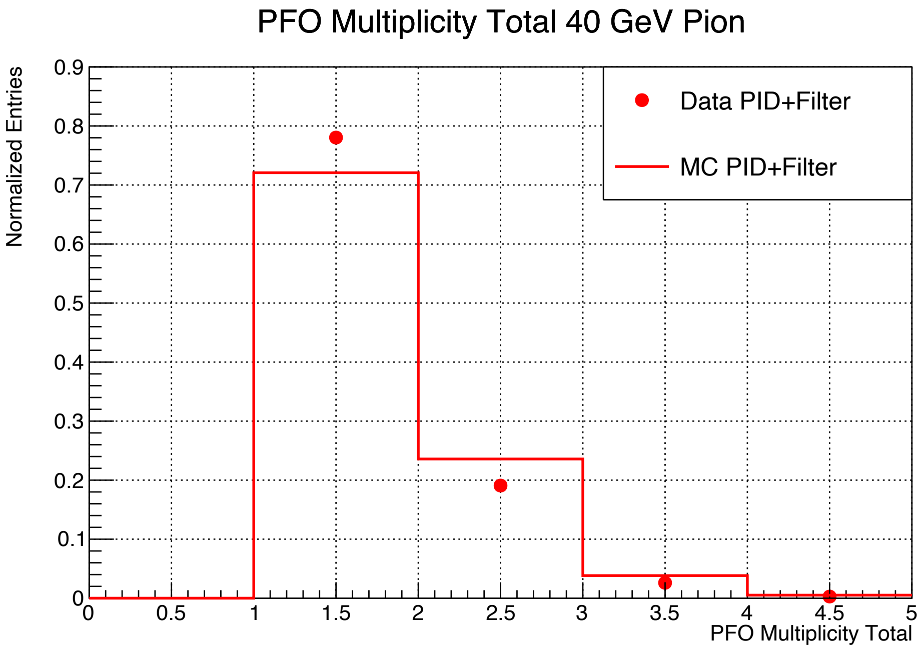
- Reasonable agreement between data and MC for both energies (~4-6% difference)

- For 40 GeV: ~10% less events in first bin (best case) than for 20 GeV

  ➡ The higher the energy, the higher the probability for PandoraPFA to „see" separated neutral hadron fragments within the shower sub-structure of the charged hadron shower

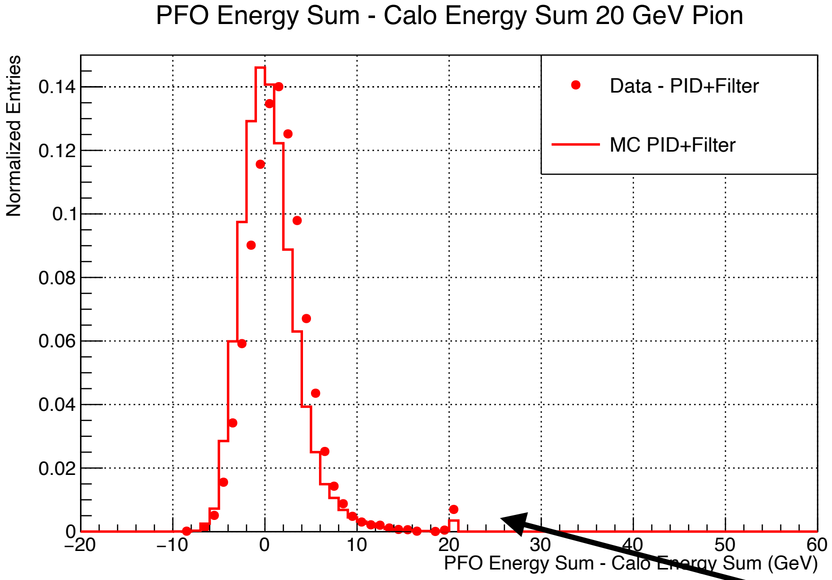


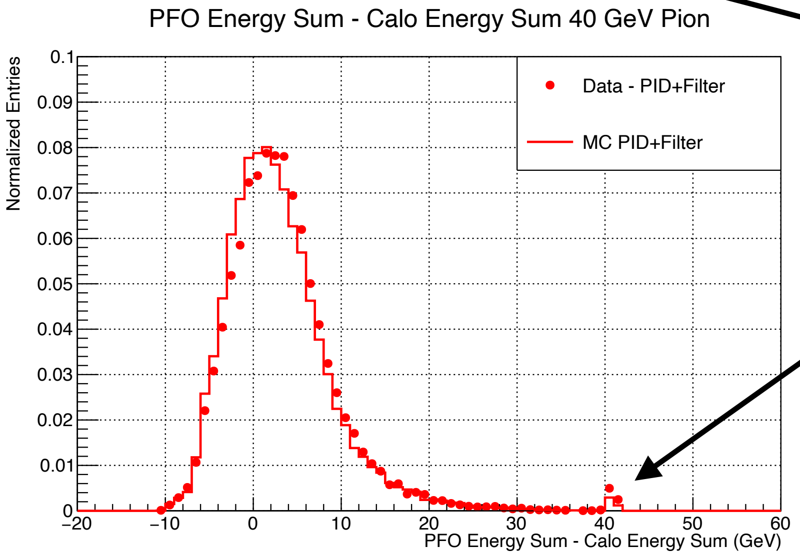




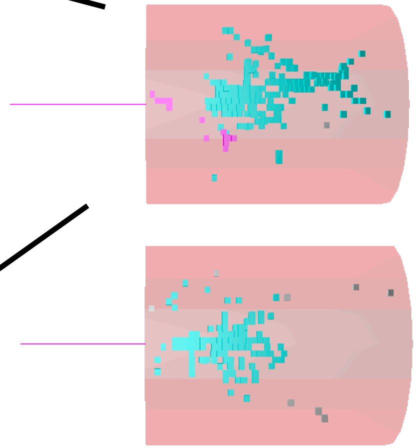
Results: PFO Energy Sum - Calorimeter Energy Sum

20 & 40 GeV Pions Data & MC





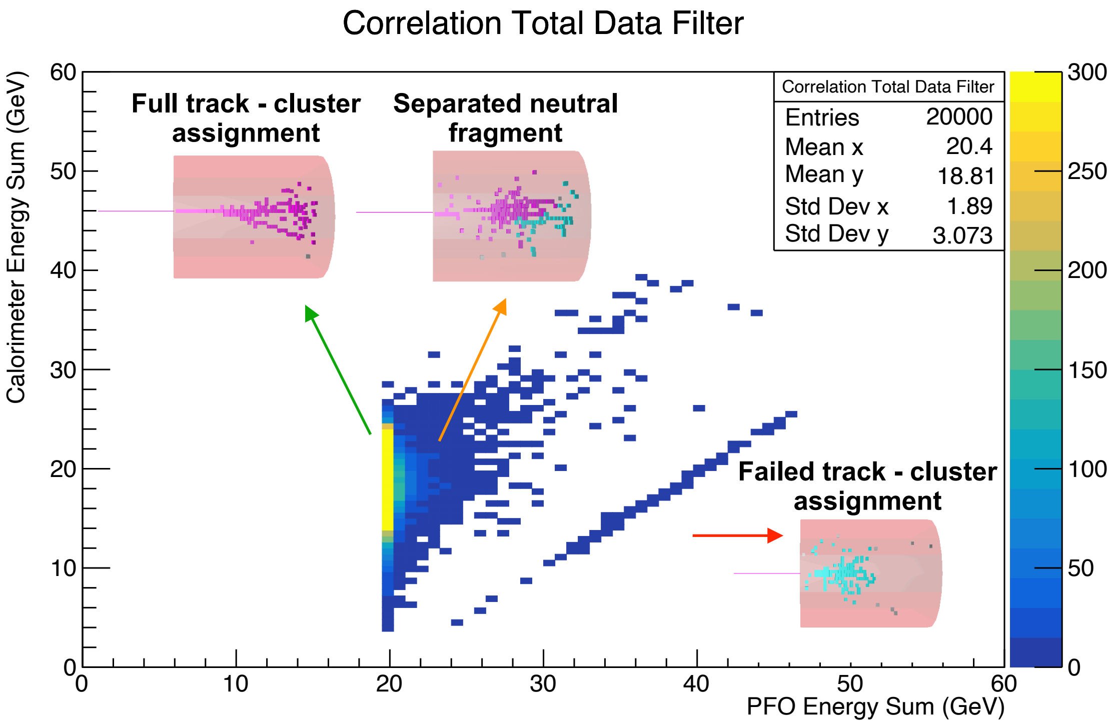
Failed track - cluster assignment

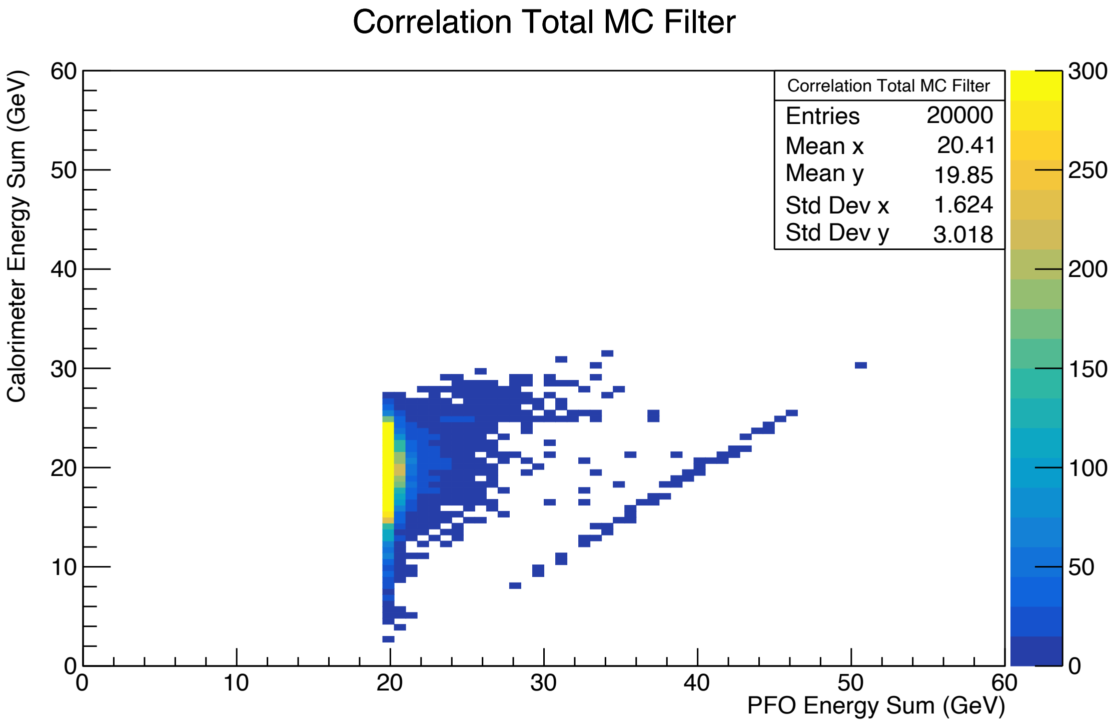


- Most events around 0 GeV: Best reconstruction case
  - ➡ Slight offset for data due to MC MIP2GeV calibration and general discrepancy in energy sum between data and MC
- Tail to the right due to remaining leakage and multi-PFO events
- Few per-mille remaining events with failed track - cluster assignment

Result: PFO Energy Sum to Calorimeter Energy Sum Correlation

20 GeV Pions Data & MC Filtered

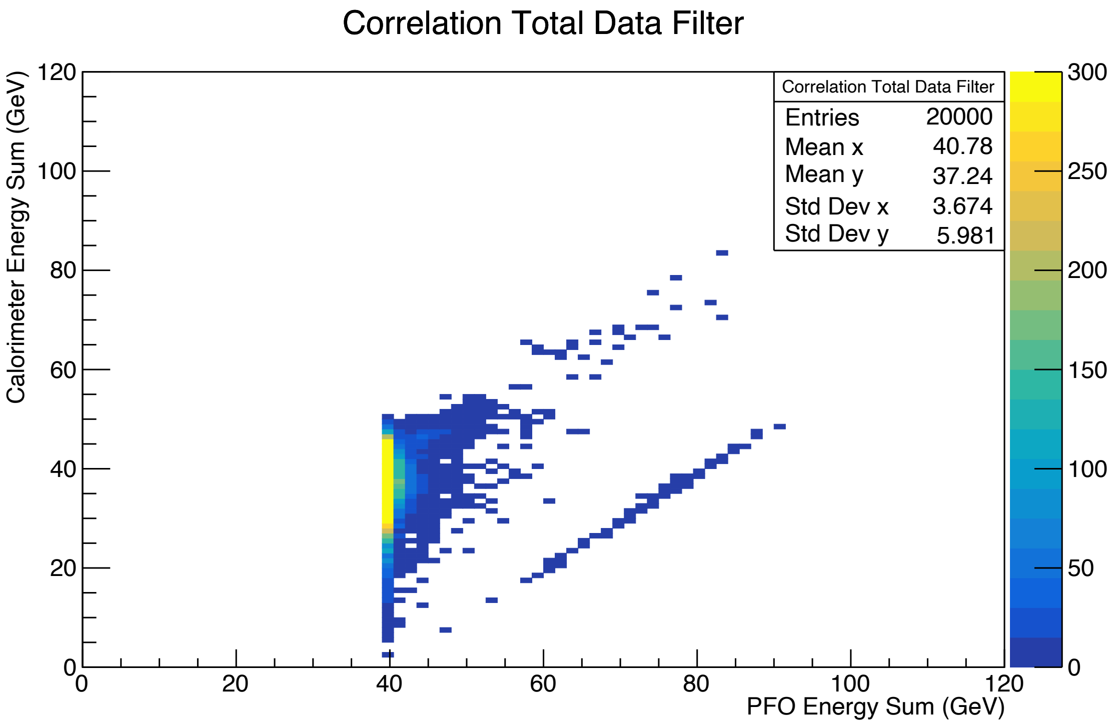


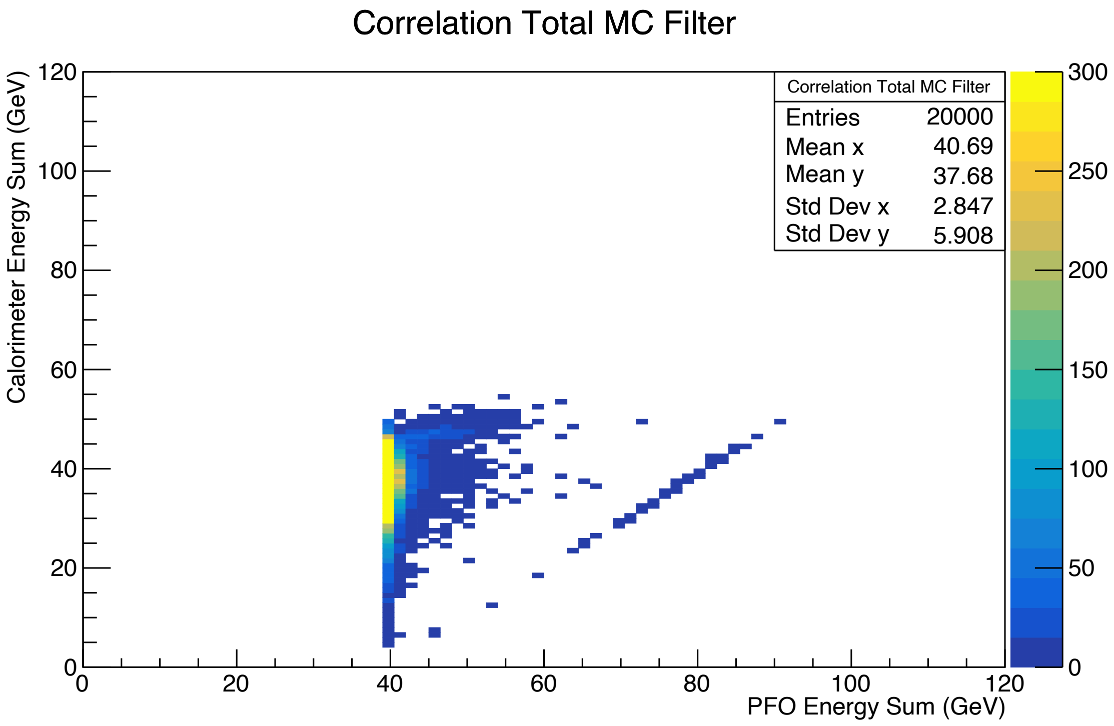


- Again 3 categories: Good reconstruction region, "cloud" region (20-30 GeV PFO energy sum), diagonal
- In general rather similar for data & MC
  - ➡ **To be investigated in more detail** with potential detector crack implementation in PandoraPFA

Result: PFO Energy Sum to Calorimeter Energy Sum Correlation

40 GeV Pions Data & MC Filtered





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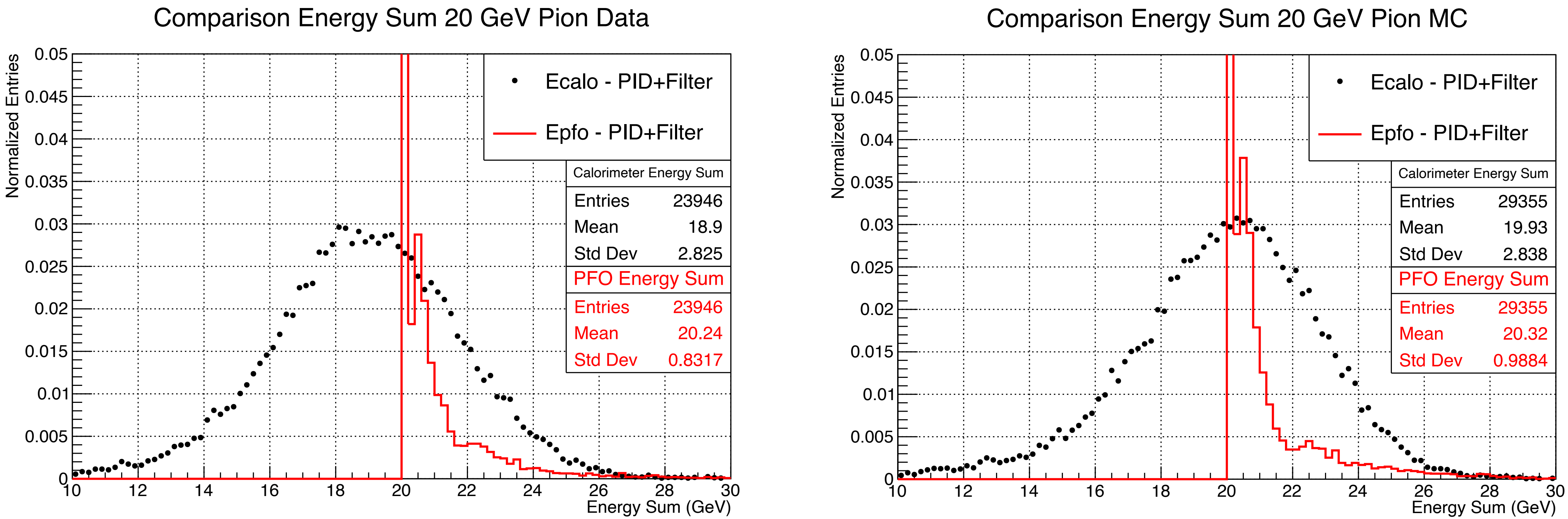
Result: Comparison Calorimeter and PFO Energy Sum

20 GeV Pions Data & MC Filtered

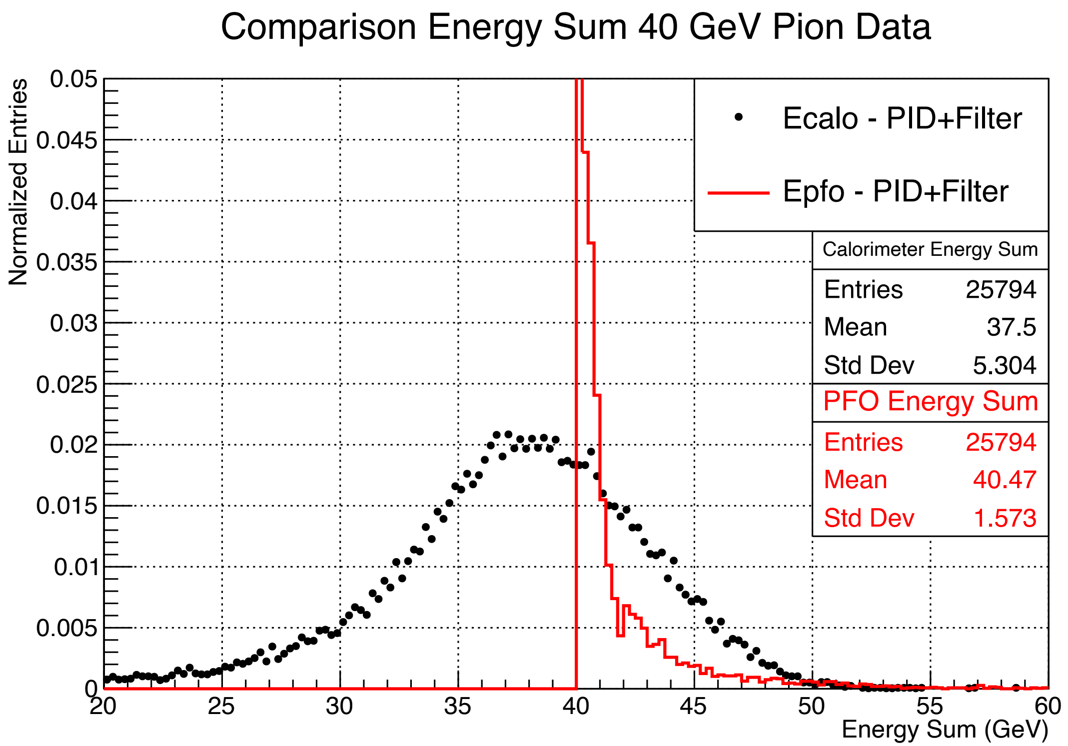


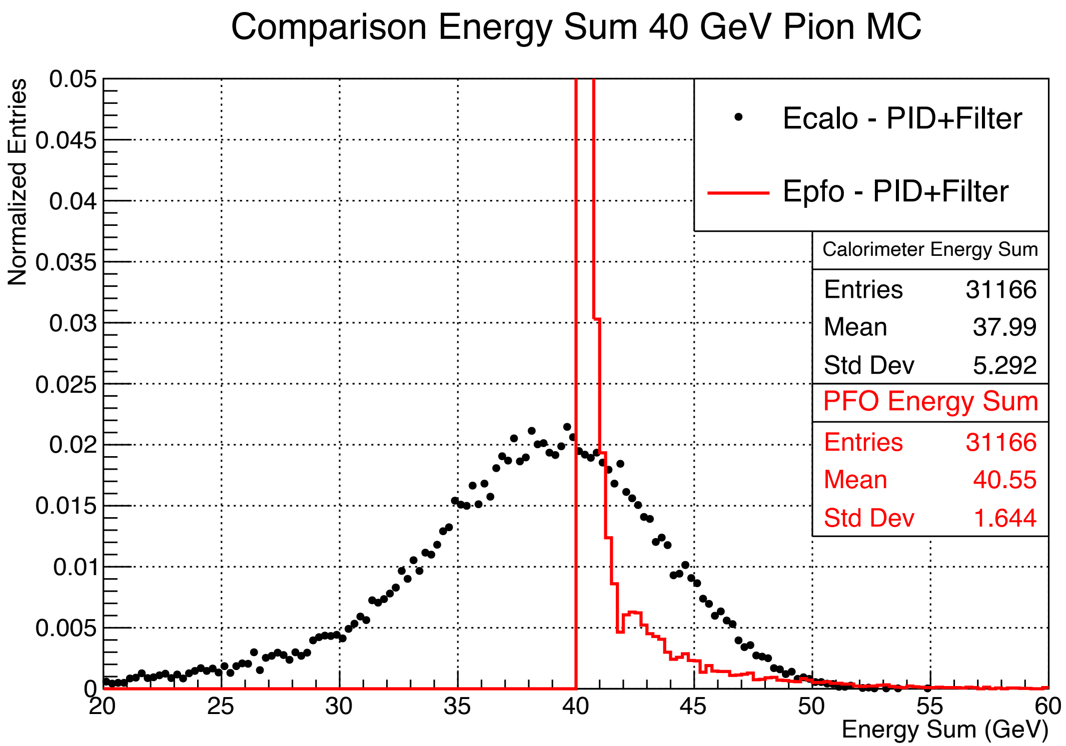
- Now comparing projections of correlation plots of previous slides
    - ➡ Events with no proper track-cluster assignment and high energy events excluded

➡ PandoraPFA reconstruction improves resolution by ~ factor 3 for both, data and MC

Result: Comparison Calorimeter and PFO Energy Sum

40 GeV Pions Data & MC Filtered





- Now comparing projections of correlation plots of previous slides
    - ➡ Events with no proper track-cluster assignment and high energy events excluded

➡ PandoraPFA reconstruction improves resolution by ~ factor 3 for both, data and MC

Summary & Outlook

- Established well working PandoraPFA environment for reconstruction of AHCAL standalone events
- Far advanced sample preparation and well working event selection tools
  - ➡ Quality of individual objects (tracks, pseudo neutral hadrons) validated
- Second more quantitative look into PandoraPFA single particle reconstruction:
  - ➡ General trends as expected
  - ➡ Reasonable agreement between data and MC

Further Plans:

- Last technical checks (central detector crack implementation and event overlay procedure)
- Detailed quantitative studies of data vs. MC (single & double particle PandoraPFA reconstruction)
- Leakage correction energy-plugin in PandoraPFA

Summary & Outlook

- Established well working PandoraPFA environment for reconstruction of AHCAL standalone events
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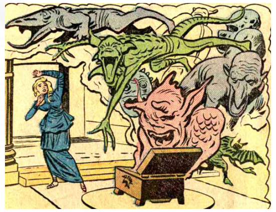
Thank you!

(And special thanks to J. Marshall for his continuous feedback so far!)



Pandora's box is almost open!

Further Plans:

- Last technical checks (central detector crack implementation and event overlay procedure)
- Detailed quantitative studies of data vs. MC (single & double particle PandoraPFA reconstruction)
- Leakage correction energy-plugin in PandoraPFA

Backup

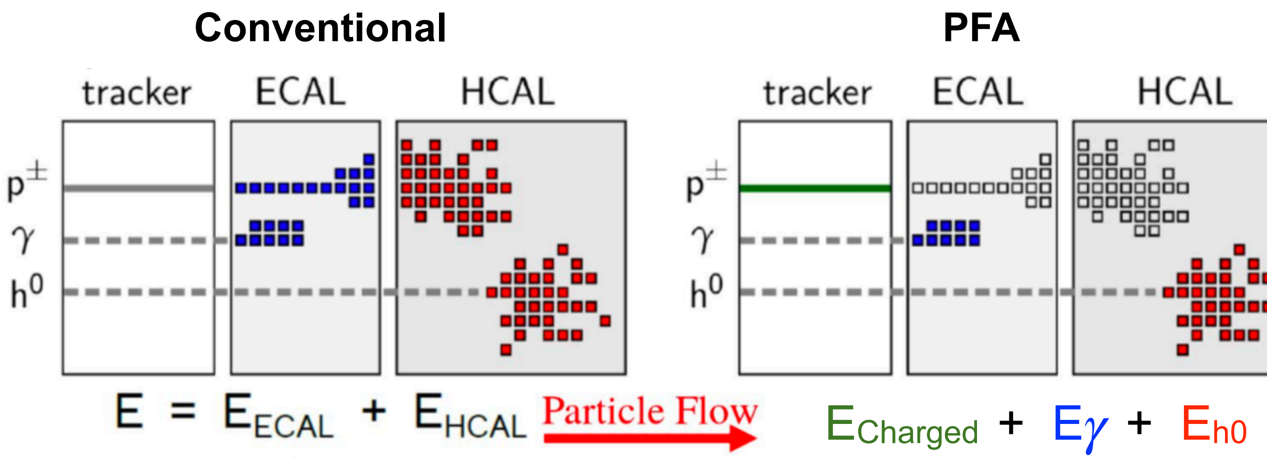
Particle Flow Approach

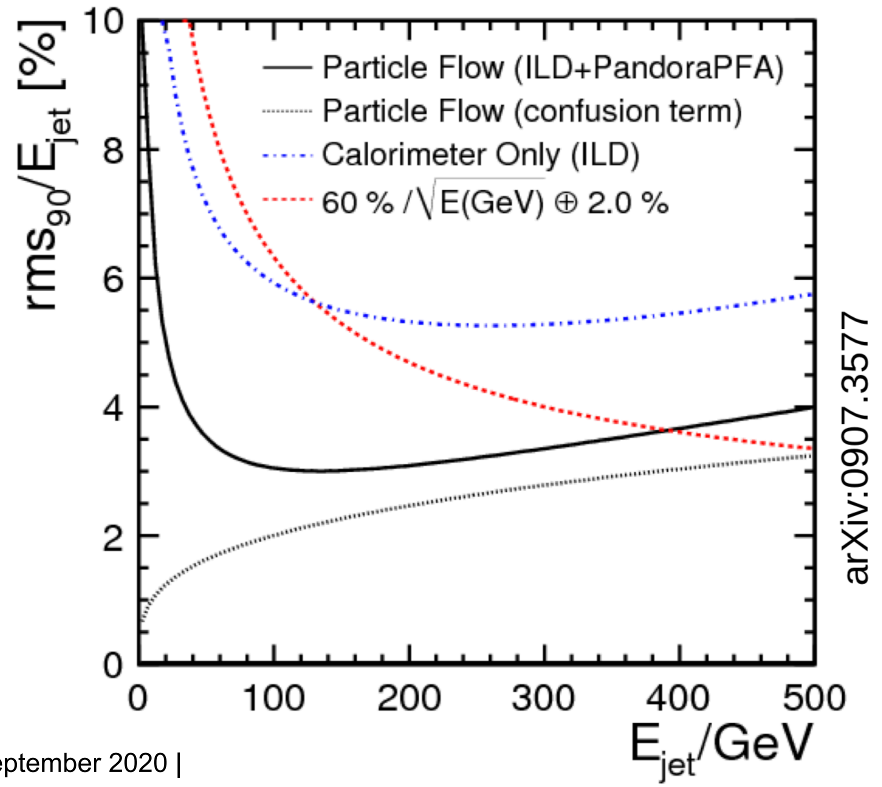
Reaching High Precision

- 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

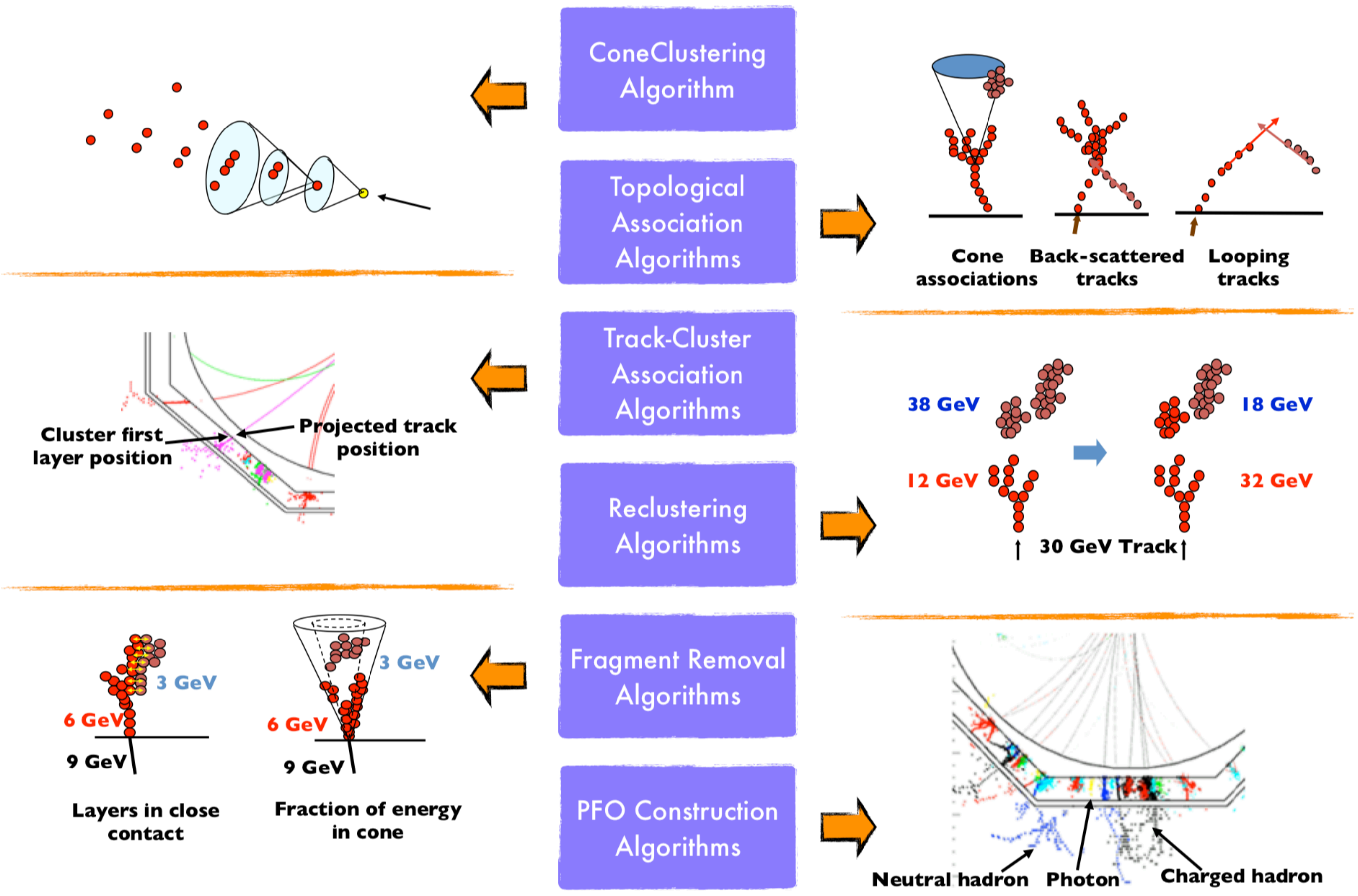




The Pandora Particle Flow Algorithm

Multi-Algorithm Pattern Recognition

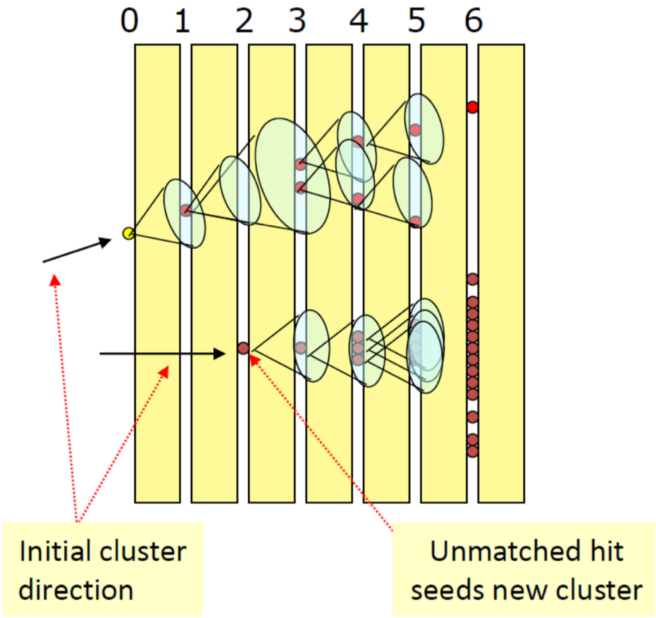
Key Steps of PandoraPFA



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

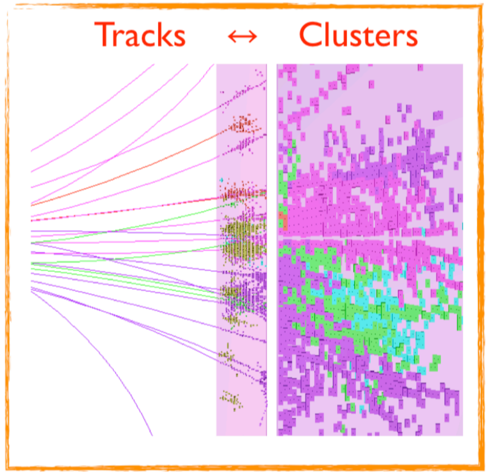
- PandoraPFA: Complex multi-algorithm chain for pattern recognition developed at Cambridge
  - ➡ Fully reconstruct the path of individual particles through the detector including shower substructure
- The goal: Correctly reconstruct charged and neutral particles in detectors as charged and neutral particle flow objects (**PFOs**)
  - ➡ Charged PFO: Calorimeter cluster + track
  - ➡ Neutral PFO: Calorimeter cluster

Clustering



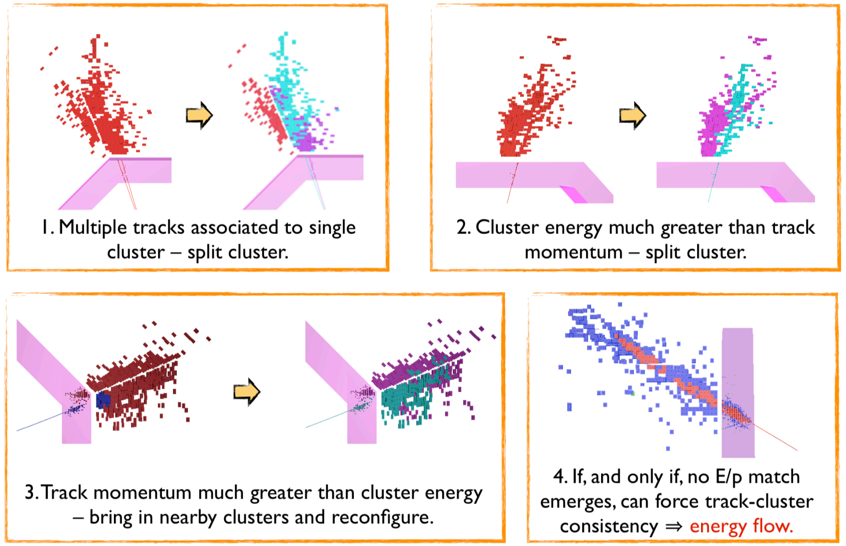
Track to Cluster Association

- 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.



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

Re-Clustering



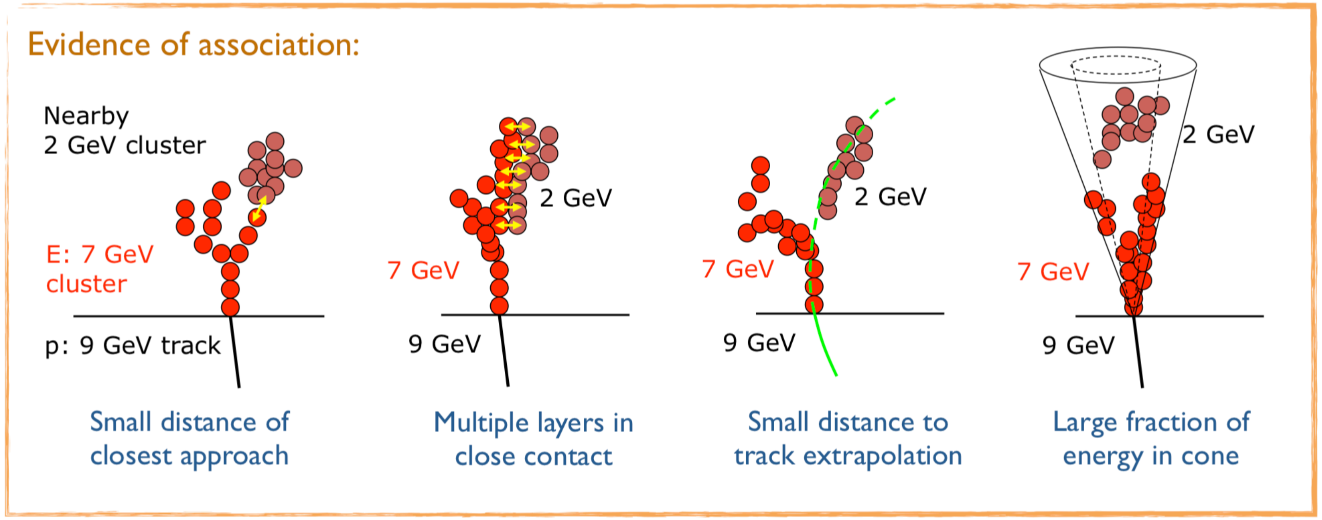
1. Multiple tracks associated to single cluster – split cluster.

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

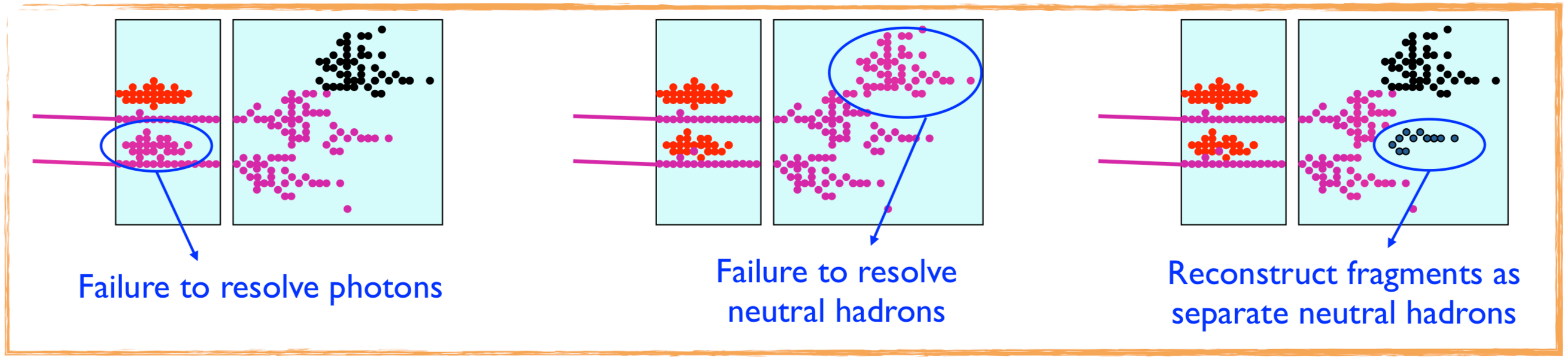


The Confusion Term

The Limit of PFA Reconstruction

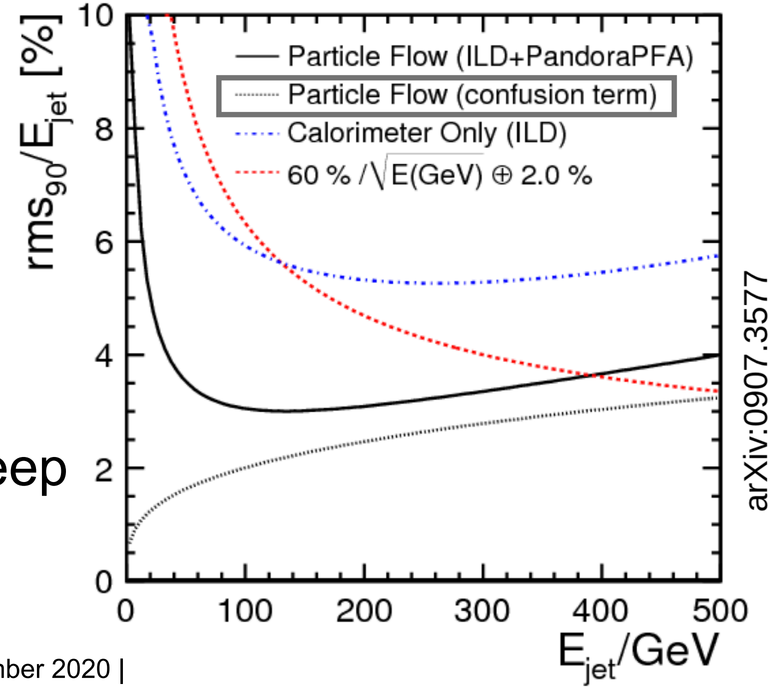
- **Topologically + energetically confusing** scenarios might appear in specific events:

Types of confusion



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

  - ➡ Photons close to a charged particle track
  - ➡ Neutral particle calorimeter hits right next to charged particle calorimeter hits
  - ➡ Neutral fragments in charged hadron shower topologically separated

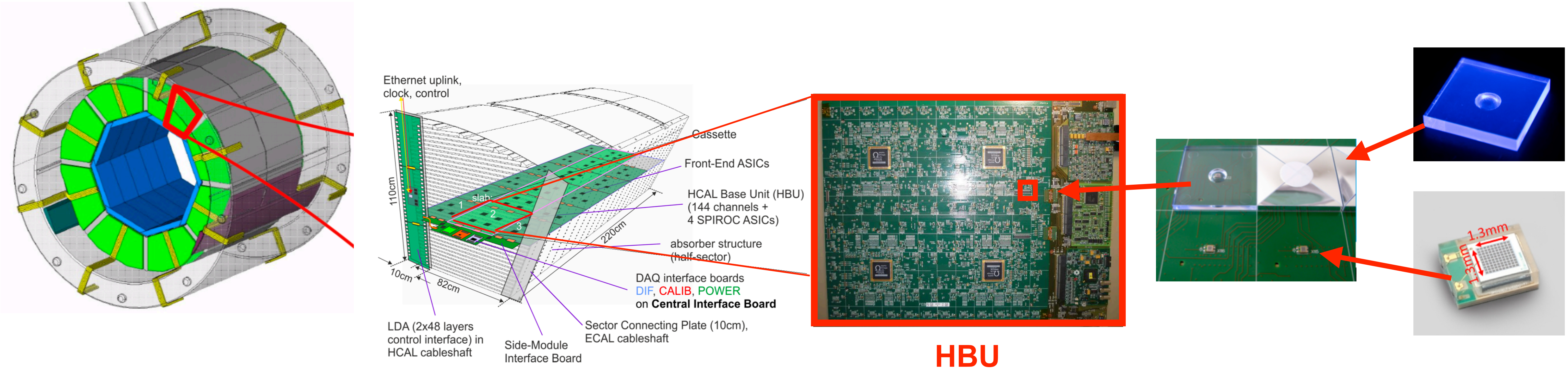


- To be able to assign track to charged particle cluster and keep confusion level low: **High granularity calorimeters with good energy resolution required**

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 cm^2 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



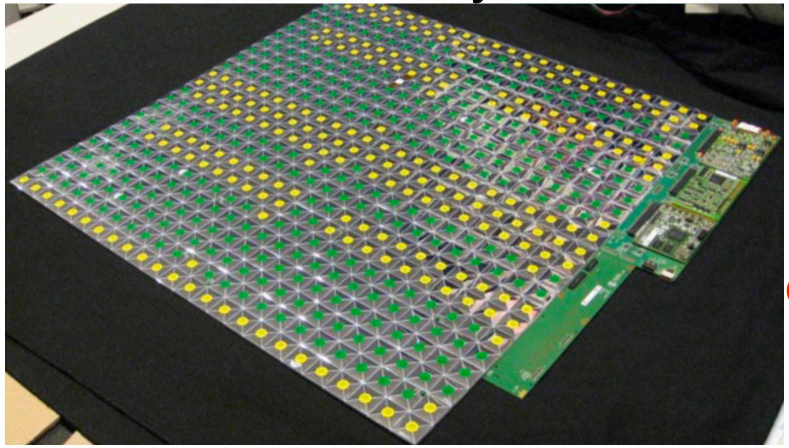
The CALICE AHCAL Technological Prototype 2018

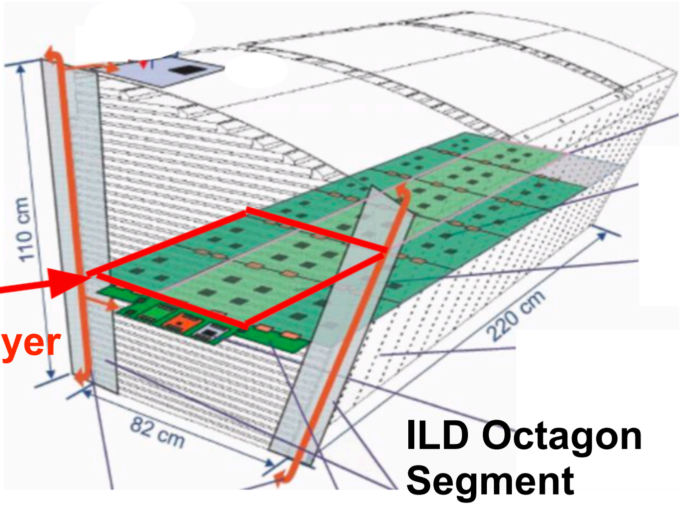
Hardware and Goals

- 38 active layers of 72 · 72 cm^2 alternating with ~1.72 cm thick steel absorbers (~4 λ_n)
- 1 layer = 4 HBU's = 16 ASICS (SPIROC2E) = 576 SiPM-on-tile channels
  - ➡ Total of 608 ASICS, ~22k channels
- **Goals:** Scalability of SiPM-on-tile calorimetry, reliable detector operation and studies on energy linearity, resolution and shower shapes/separation (PFA)

- SiPM (Hamamatsu S13360-1325PE):
  - ➡ 2668 pixels
  - ➡ Operated at ~5 V overvoltage

1 AHCAL layer

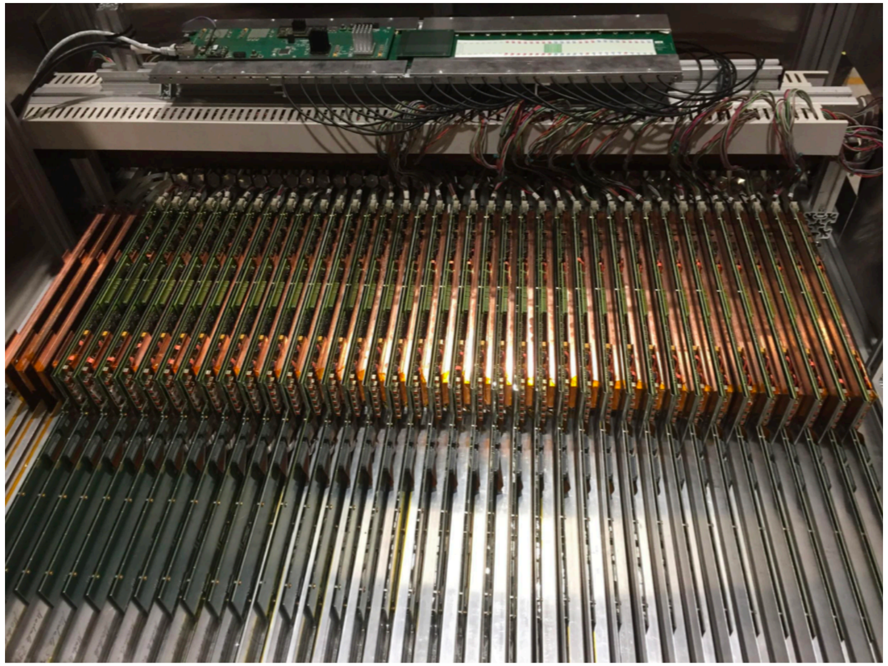




One layer

ILD Octagon Segment

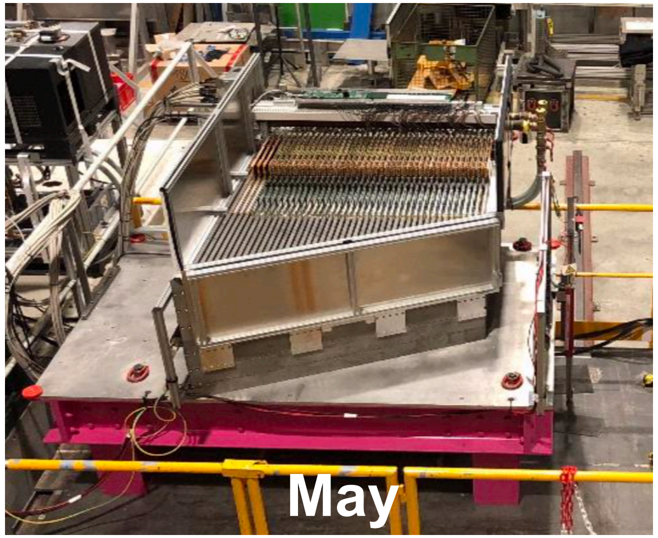
38 layers within steel absorber stack

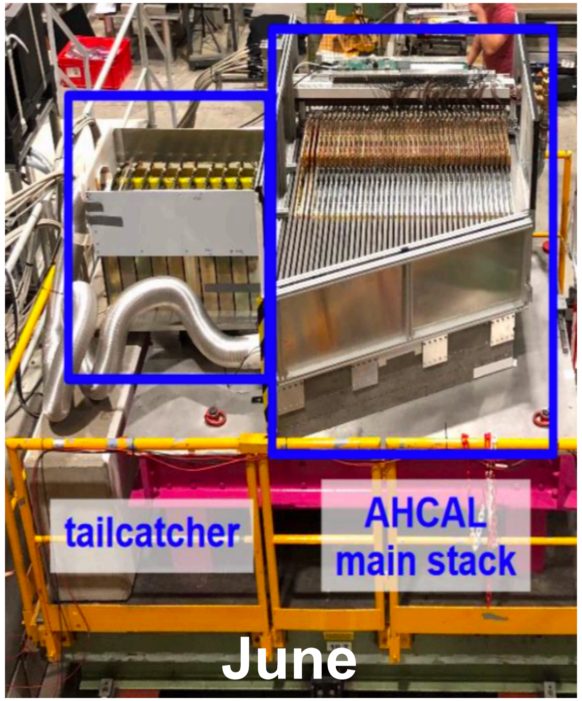


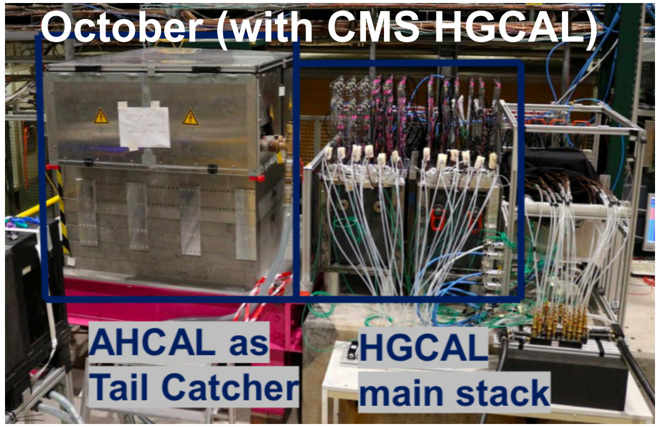
The CALICE AHCAL Beam Test Campaigns 2018

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







Analysis Examples

PandoraPFA on AHCAL 2018 Prototype Data

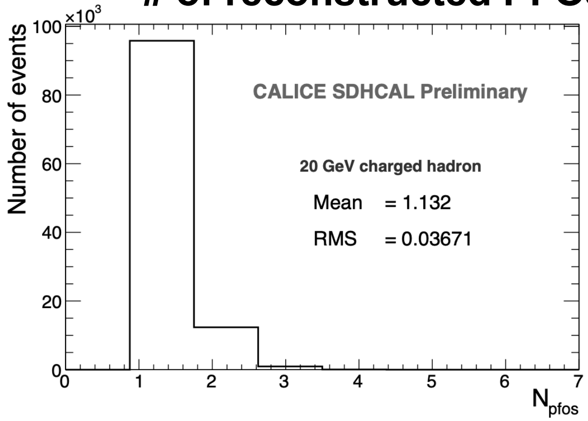
PandoraPFA

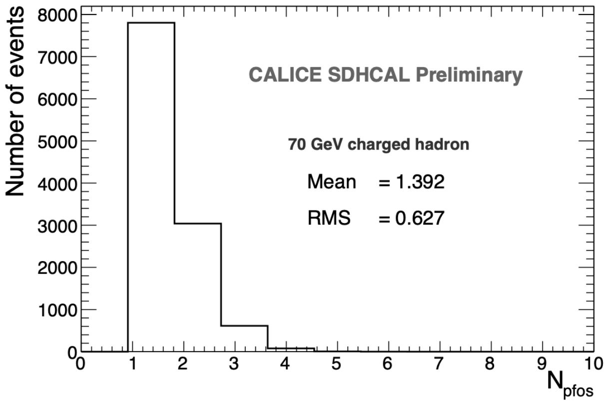
Scenario 1: Single particle reconstruction studies

PandoraPFA

Scenario 2: Two-particle separation studies

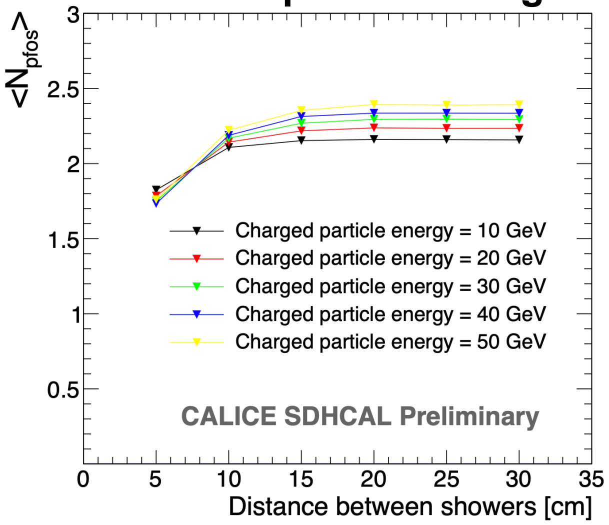
of reconstructed PFOs for different particle energies



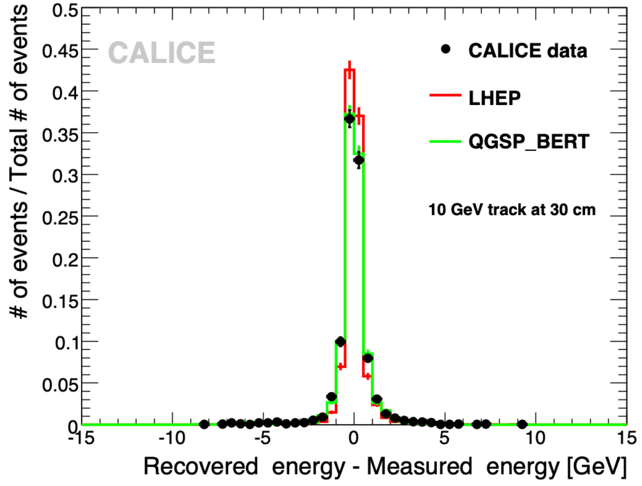


http://cds.cern.ch/record/2669487/files/fulltext.pdf

Mean # of reconstructed PFOs for different particle energies



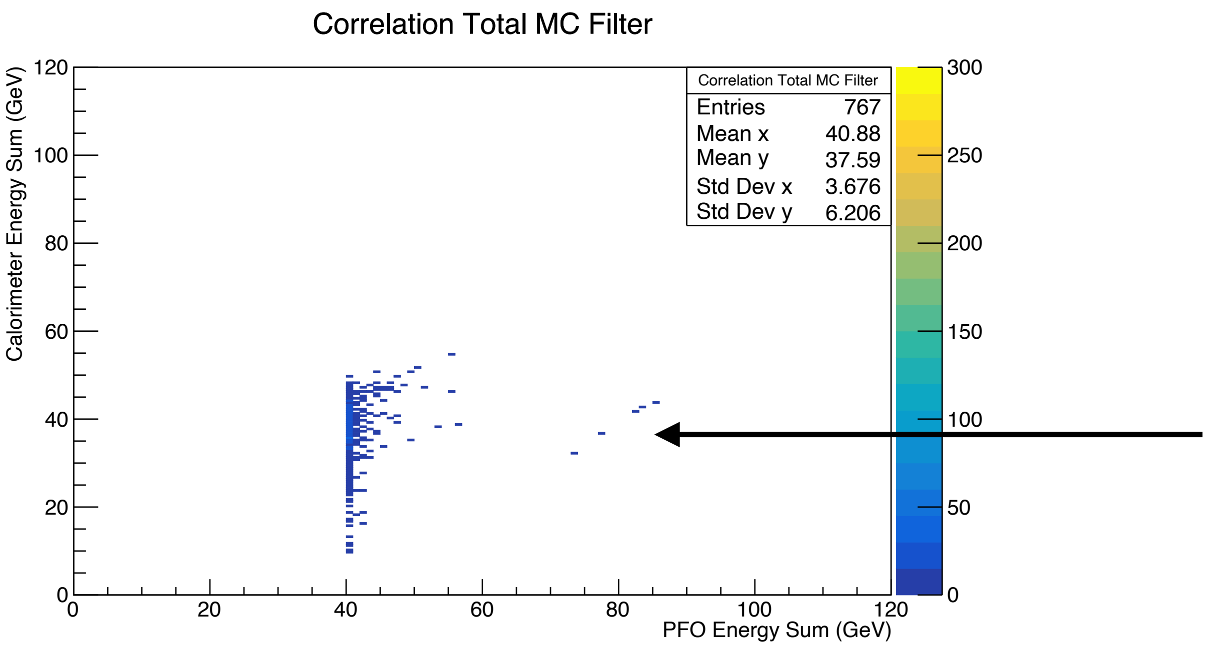
Energy difference of calorimeter pure & PFO reconstruction

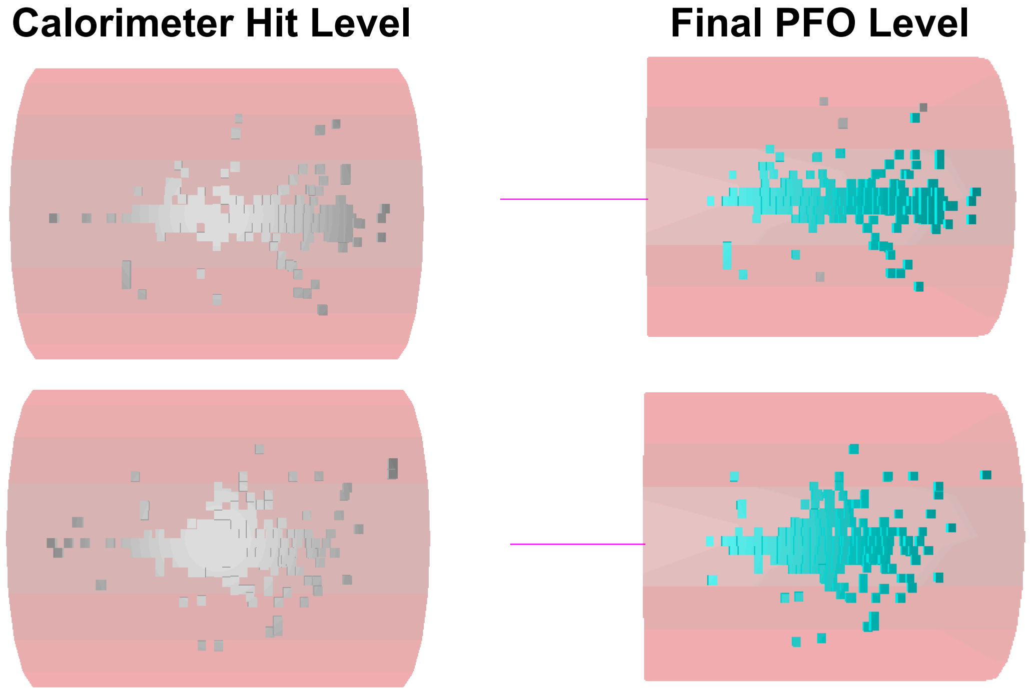


https://arxiv.org/abs/1105.3417

Isolated Hit Merging Algorithm - PandoraPFA

Diagonal „Gap" Events

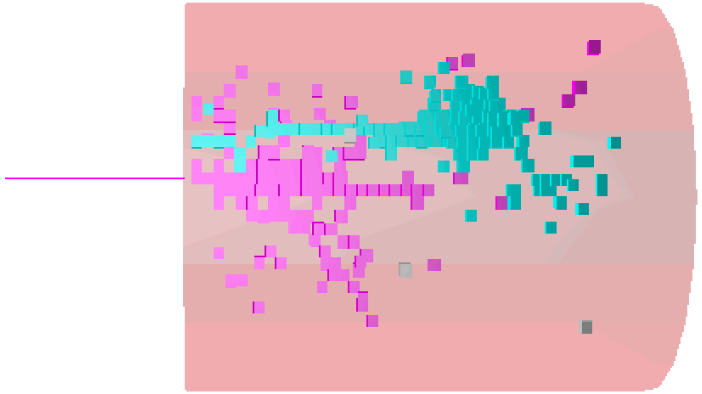




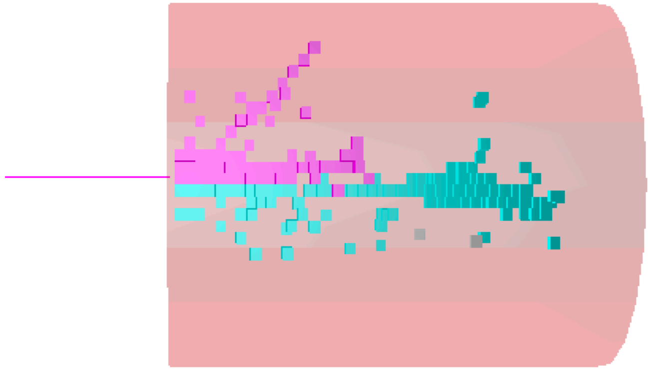
- 98% of diagonal events (non working track-cluster assignment) caused by PandoraPFA's "Isolated Hit Merging“ algorithm
  - Topological gap in primary track of first layers causes algorithm to „cut off“ hits which makes track-cluster assignment impossible
  - ➡ Fine granularity of ECAL in front missing allowing first assignment of track before AHCAL

High Energy Events in 20 GeV Pion Beam Test Data

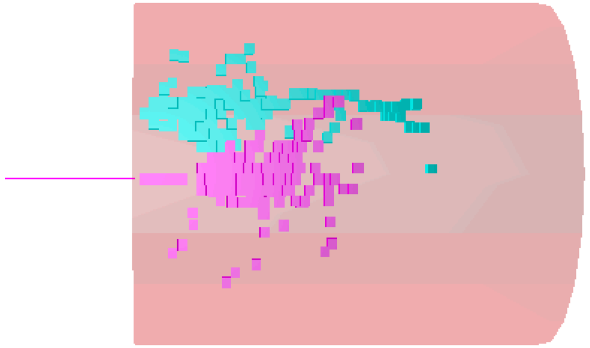
Examples - Multi Particle Events?



Energy in Calorimeter: ~40 GeV

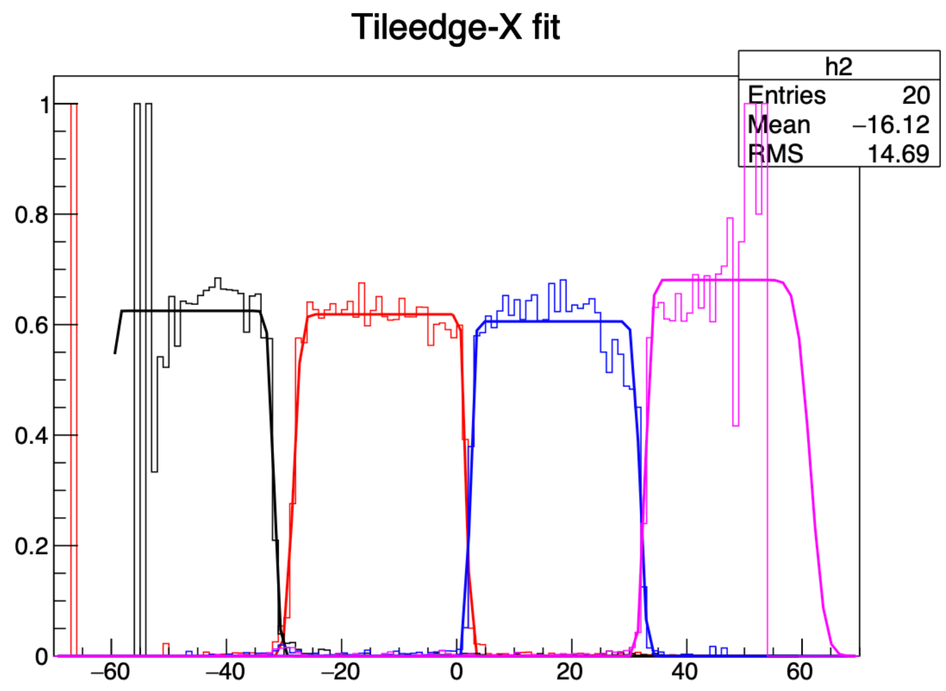


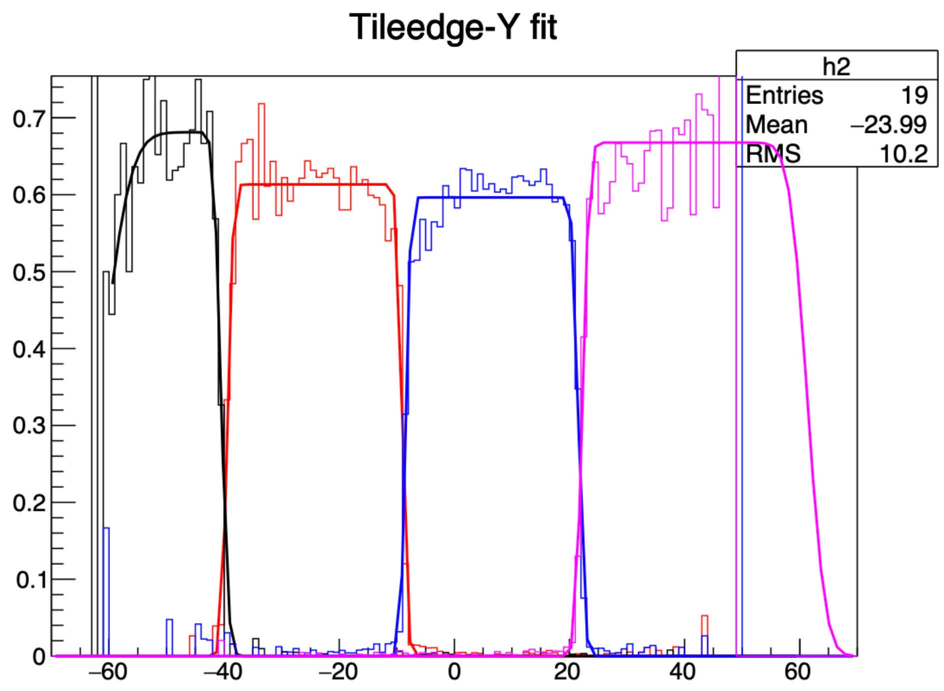
Energy in Calorimeter: ~42 GeV



Energy in Calorimeter: ~38 GeV

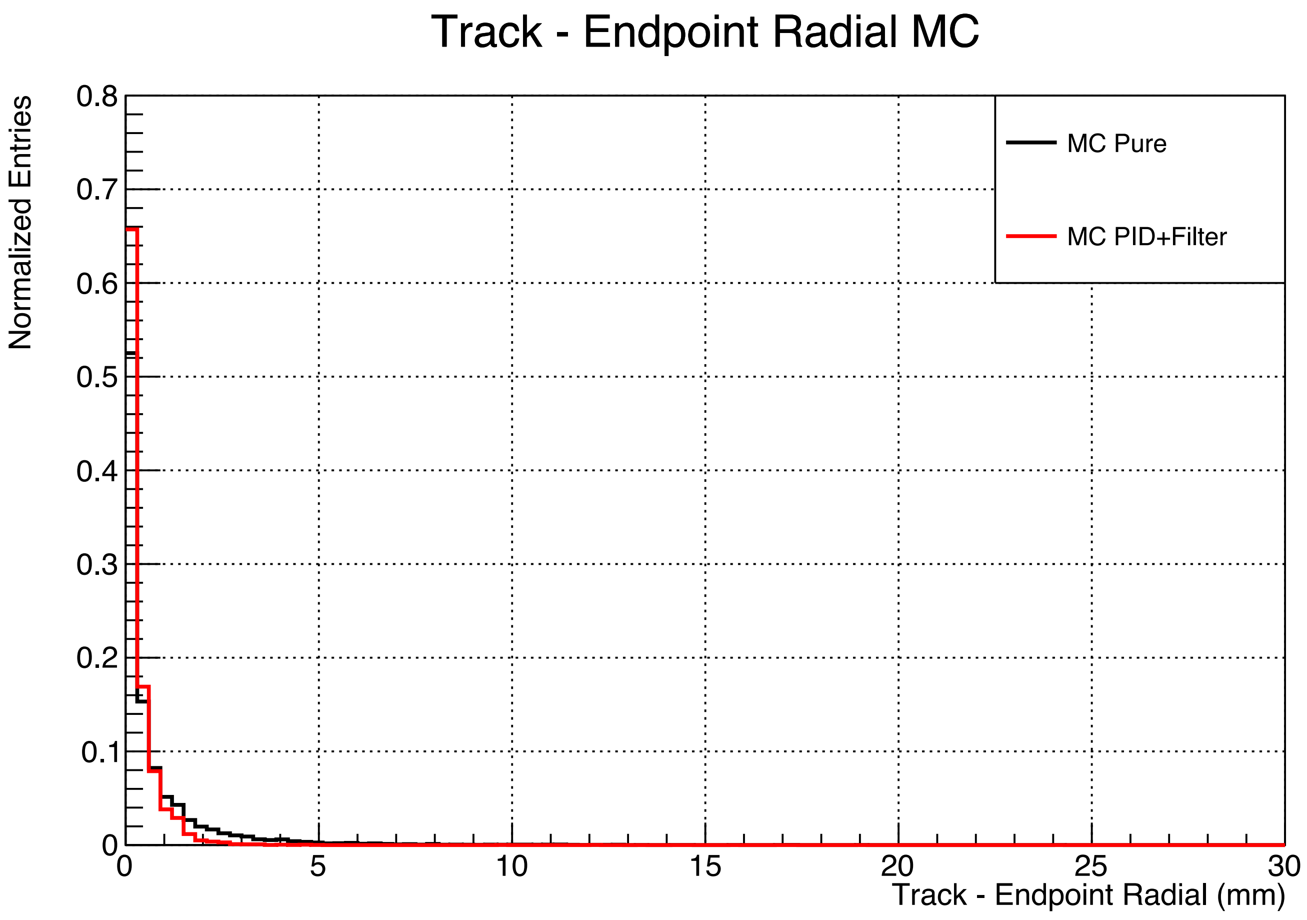
Scintillator Tile Gaps Measurements DWC Example





MC: Track to MC Endpoint Position Comparison

Track Quality Study



r

- Only events with primary particle endpoint z within calorimeter
- Radial distance in x-y plane:

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

- Very good agreement between implemented MC track and „truth MC track“
  ➡ 100% of events within 10 mm distance

Results: Track Agreement 20 GeV Pions

Overview

Data

Agreement [% of events]	Pure (36.6k)	Hit1+2+3 (22.5k)	Hit1or2or3 (25.4k)	Hit1 (23.9k)
Track - Event CoG (within 30mm)	89.8	88.5	88.6	88.6
Track - Primary Track Hit Layer 1 (within 22mm)	98.4	98.2	98	98
Track - Closest Hit Layer 1 (within 22mm)	97.4	97.5	97.5	97.5

MC

Agreement [% of events]	Pure (47k)	Hit1+2+3 (29.2k)	Hit1or2or3 (31.5k)	Hit1 (30.3k)
Track - Event CoG (within 30mm)	88.9	93	93.1	93.2
Track - Primary Track Hit Layer 1 (within 22mm)	90.9	99	99	99
Track - Closest Hit Layer 1 (within 22mm)	92.6	98.5	98.4	98.4

- Most of 11.5% MC events with endpoint $z < 0$ get rejected by PID+filter not depending on hit criterium
- Less strict hit criteria in filter options do not influence fraction of events with good track agreement
  - ➡ Overall good agreement for all filter options and between data and MC
  - ➡ MC tracks on average a bit preciser after PID + Filter for 20 GeV pions

Results: Track Agreement 10 GeV Pions

Overview

Data

Agreement [% of events]	Pure (32k)	Hit1+2+3 (18.7k)	Hit1or2or3 (21.1k)	Hit1 (20k)
Track - Event CoG (within 30mm)	76.3	72.2	72.4	72.3
Track - Primary Track Hit Layer 1 (within 22mm)	98.2	98.2	98	98
Track - Closest Hit Layer 1 (within 22mm)	97.1	97.5	97.4	97.4

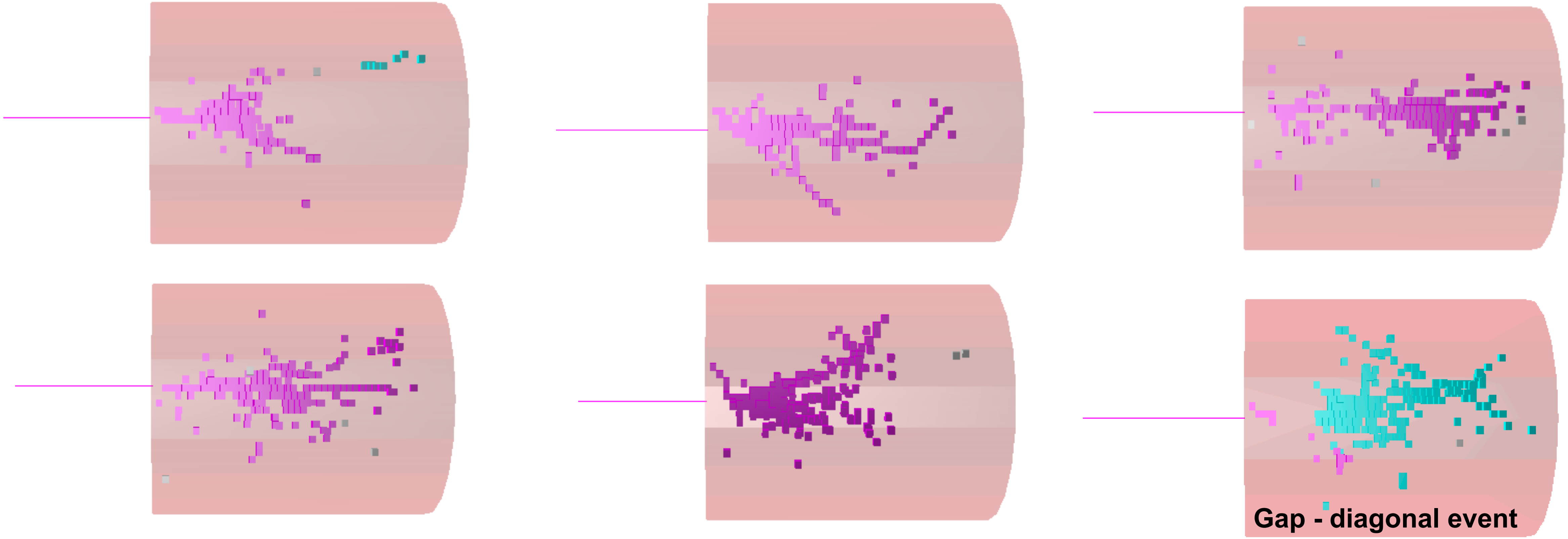
MC

Agreement [% of events]	Pure (46.8k)	Hit1+2+3 (26.7k)	Hit1or2or3 (28.5k)	Hit1 (27.5k)
Track - Event CoG (within 30mm)	72.9	77.2	77.3	77.3
Track - Primary Track Hit Layer 1 (within 22mm)	86.7	99.4	99.2	99.2
Track - Closest Hit Layer 1 (within 22mm)	89.5	98.7	98.6	98.6

- Most of 17.4% MC events with endpoint z < 0 get rejected by PID+filter not depending on hit criterium
- Less strict hit criteria in filter options do not influence fraction of events with good track agreement
  - ➡ Track to CoG (event) agreement worse for 10 GeV pions
  - ➡ Overall good agreement for all filter options and between data and MC
  - ➡ MC tracks on average a bit preciser after PID + Filter also for 10 GeV pions

Track to COG (layer 1) Position Comparison Outliers

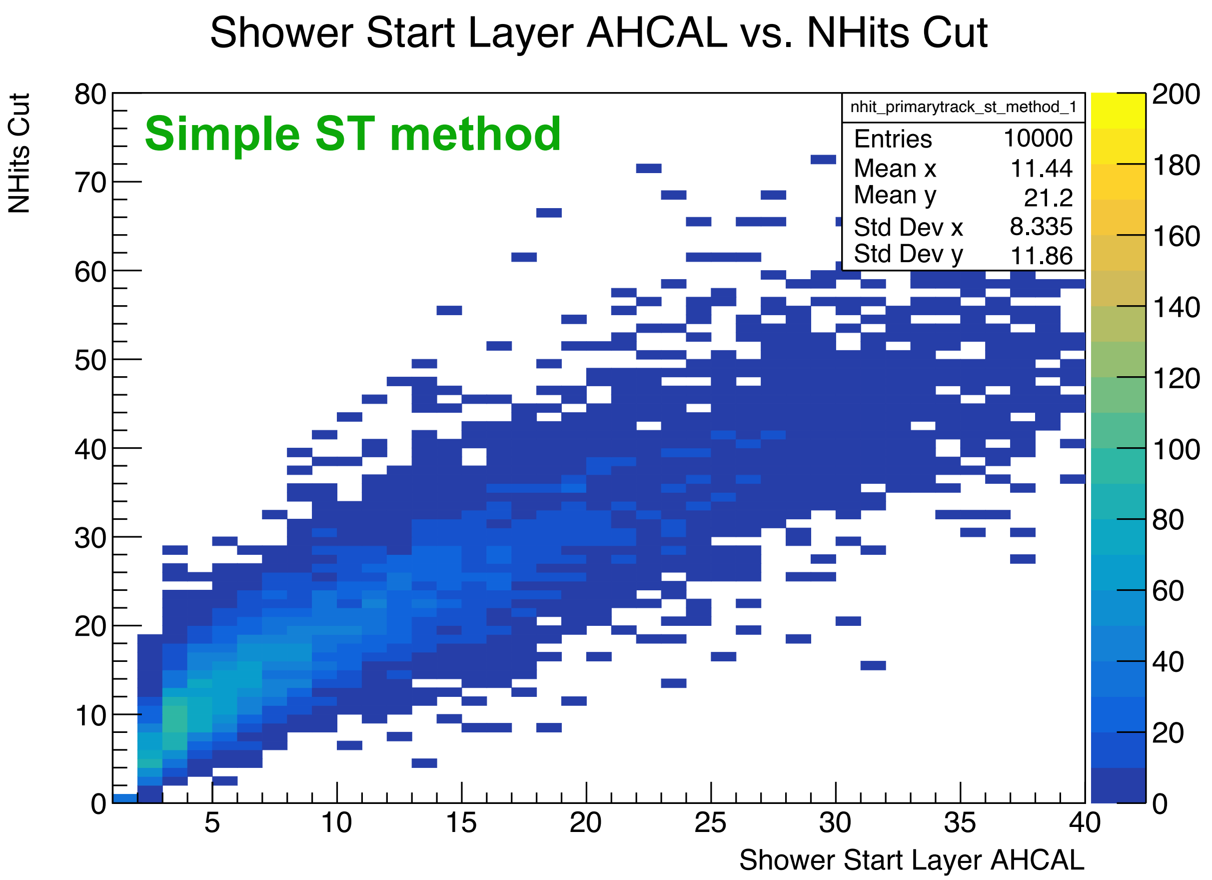
Examples

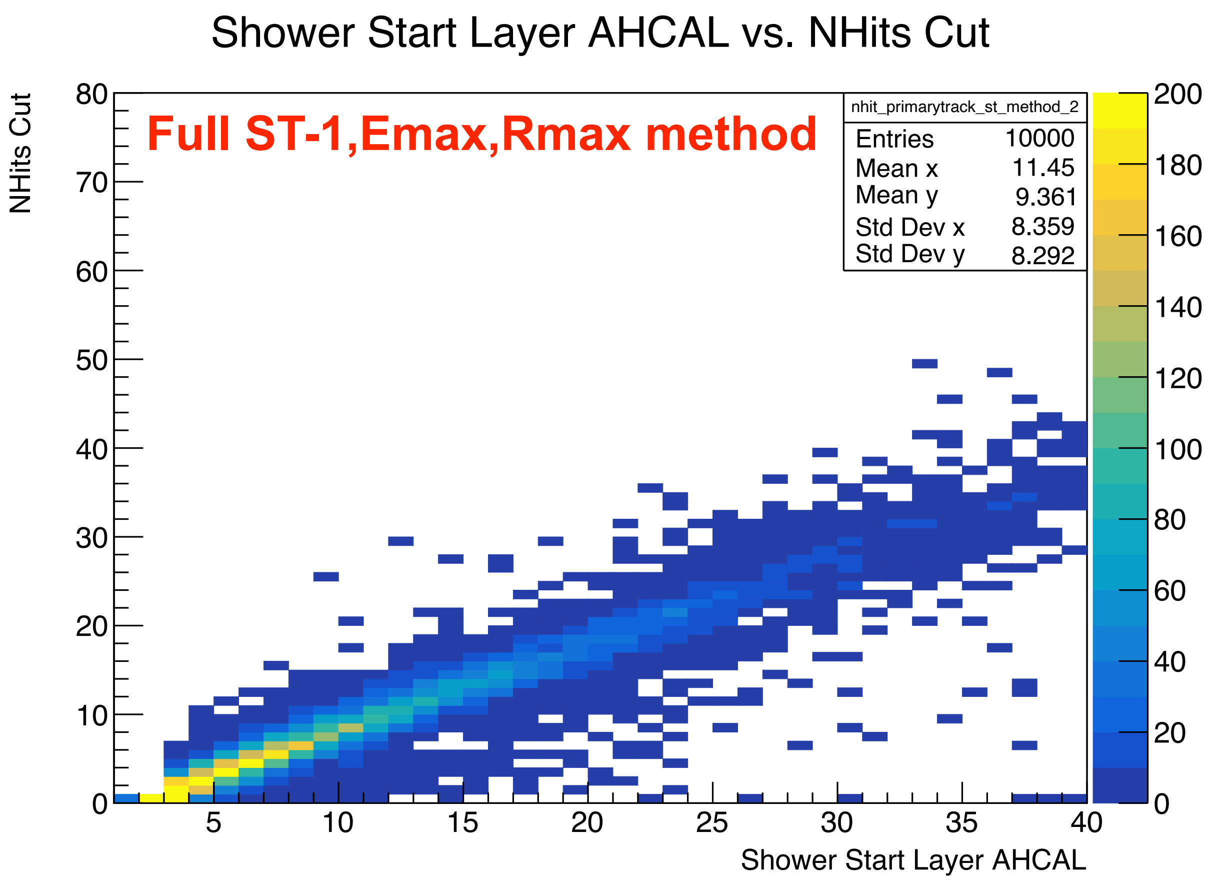


- Checked **outliers with r > 22.0 mm** of pure and filtered data and MC events
  - ➡ Simple gap like events (hits missing in 1-2 layers), most of them reconstructed well by Pandora (even without gap implementation)
  - ➡ Few badly reconstructed events (with more missing hits) remaining, gap implementation might help

Number of Hits (Primary Track) vs. Shower Start Layer

Validation of Method

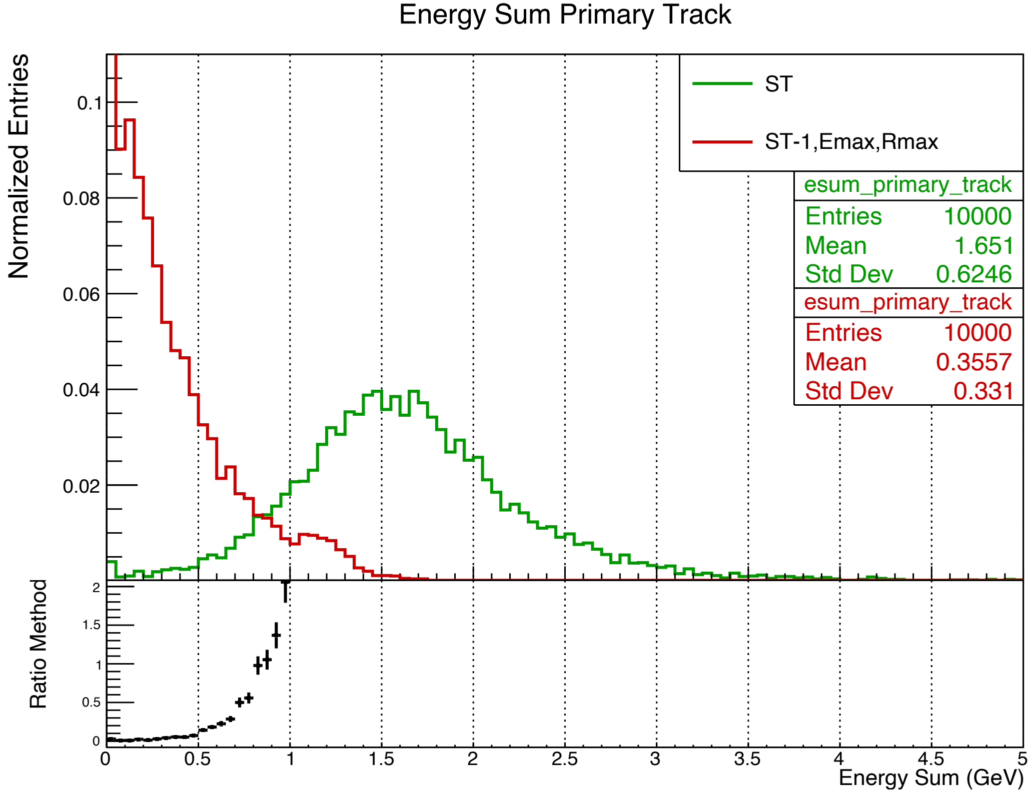


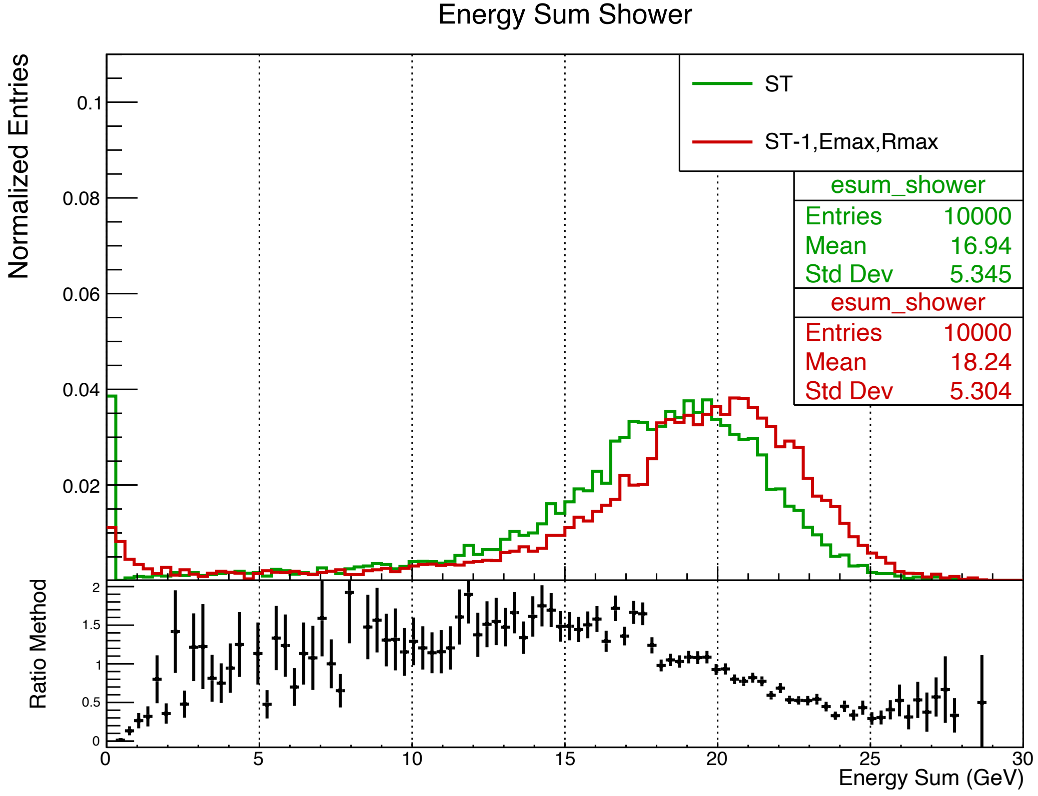


- Too many hits cut away for simple ST method
- Much better correlation of shower start layer and cut nHits of classified primary track for advanced method (#Cut hits ≈ #shower starter layer)

Energy Sum: Primary Track and Shower Hits

Validation of Method

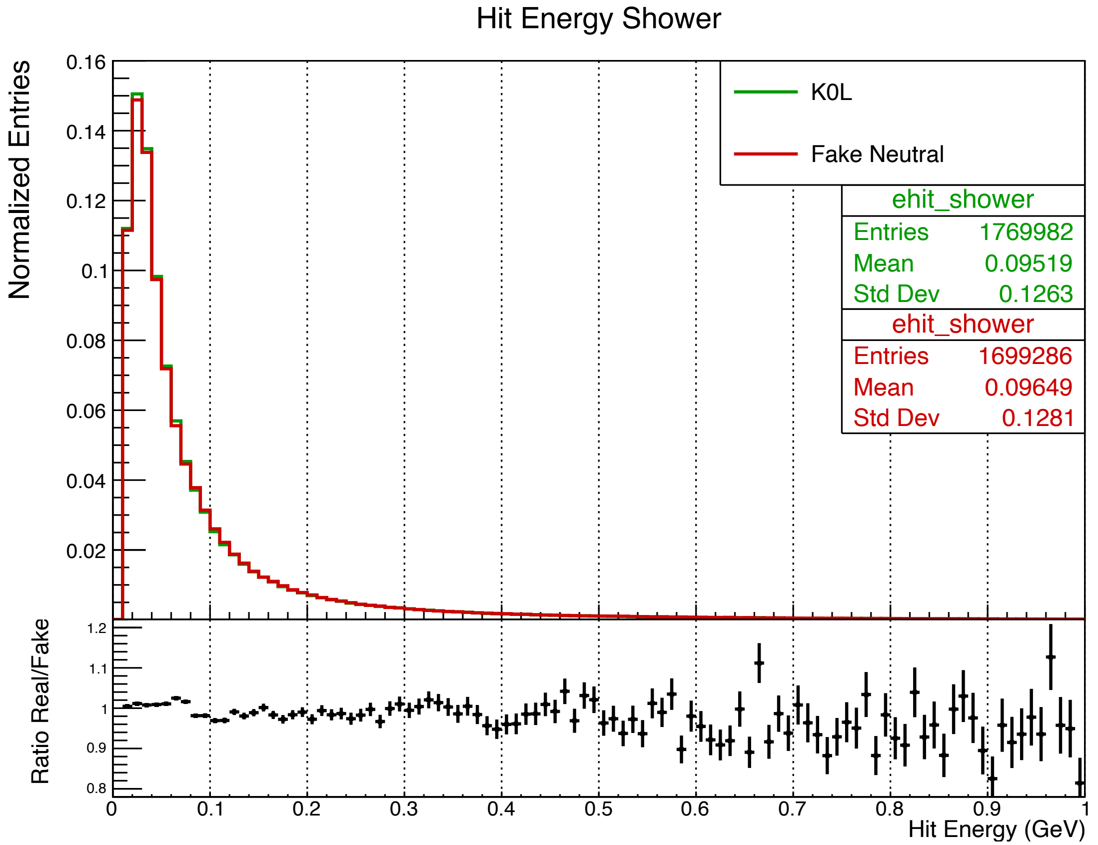


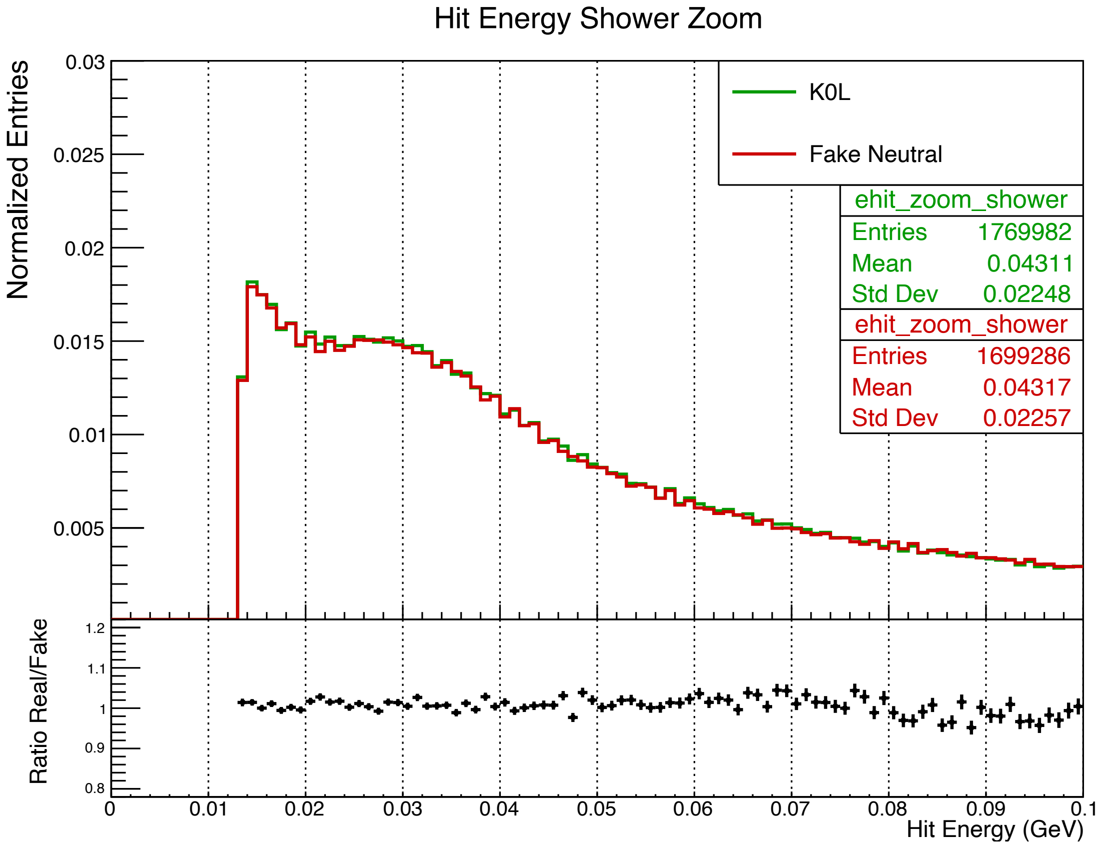


- Shower energy sum much closer to 20 GeV for advanced method
  - ➡ Too much hits and therefore energy cut away with simple method
  - ➡ Simple estimate: Upper primary track energy sum expected for perfect 40 hit MIP track: 0.0268 GeV (1 MIP) * 40 (layers) * 1.4 (landau-gaussian mean) = **~1.5 GeV**

Hit Energy

Real vs. Pseudo Neutrals



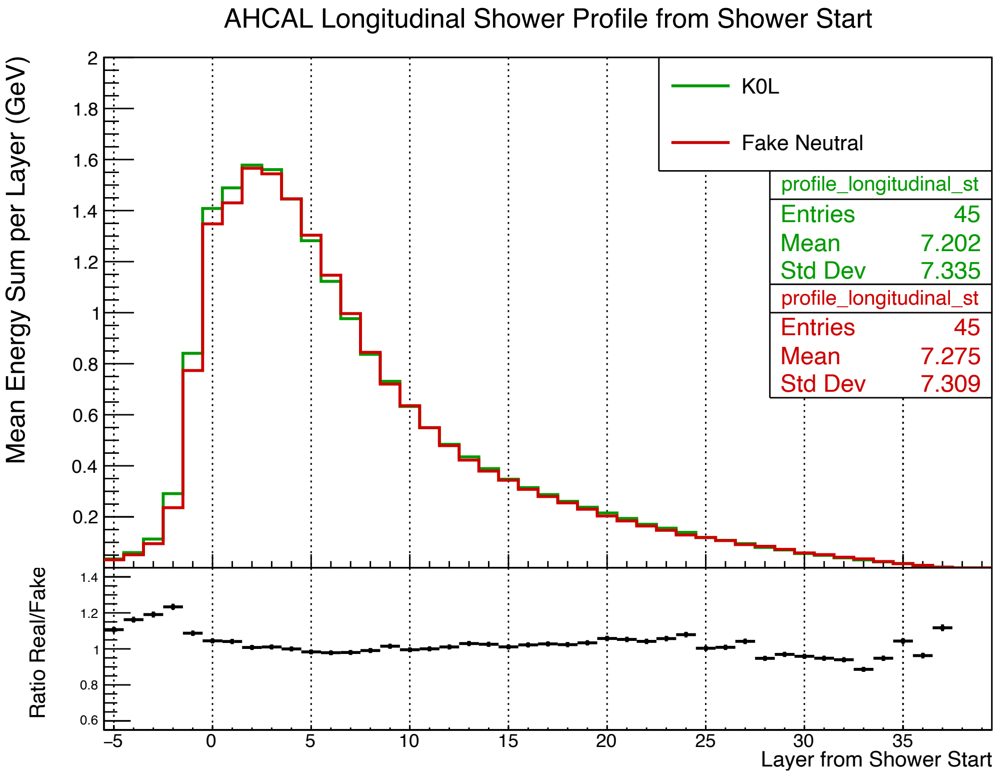


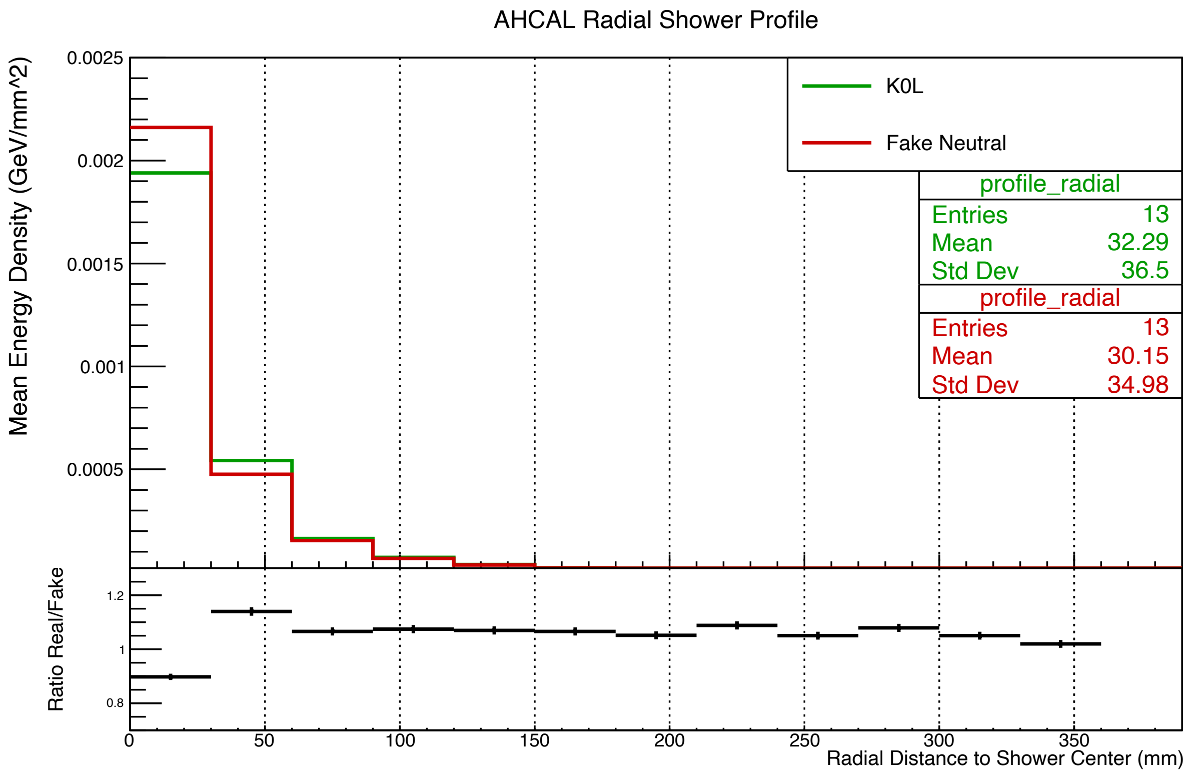
- Very good agreement, even for low energy hits (within 2%)

Shower Profiles: Longitudinal & Radial

Real vs. Pseudo Neutrals

Simple radial profile code:
13 concentric circle areas, no fractional sharing of tile energy between two circle areas if overlap at edge





- Reasonable agreement for shower profiles:
  - ➡ Longitudinal: ~20% discrepancy ±2 layer around shower start layer
  - ➡ Radial: ~10-15% discrepancy for first two bins / innermost two circles

Data vs. MC
Pseudo Neutral Comparison

Test samples:

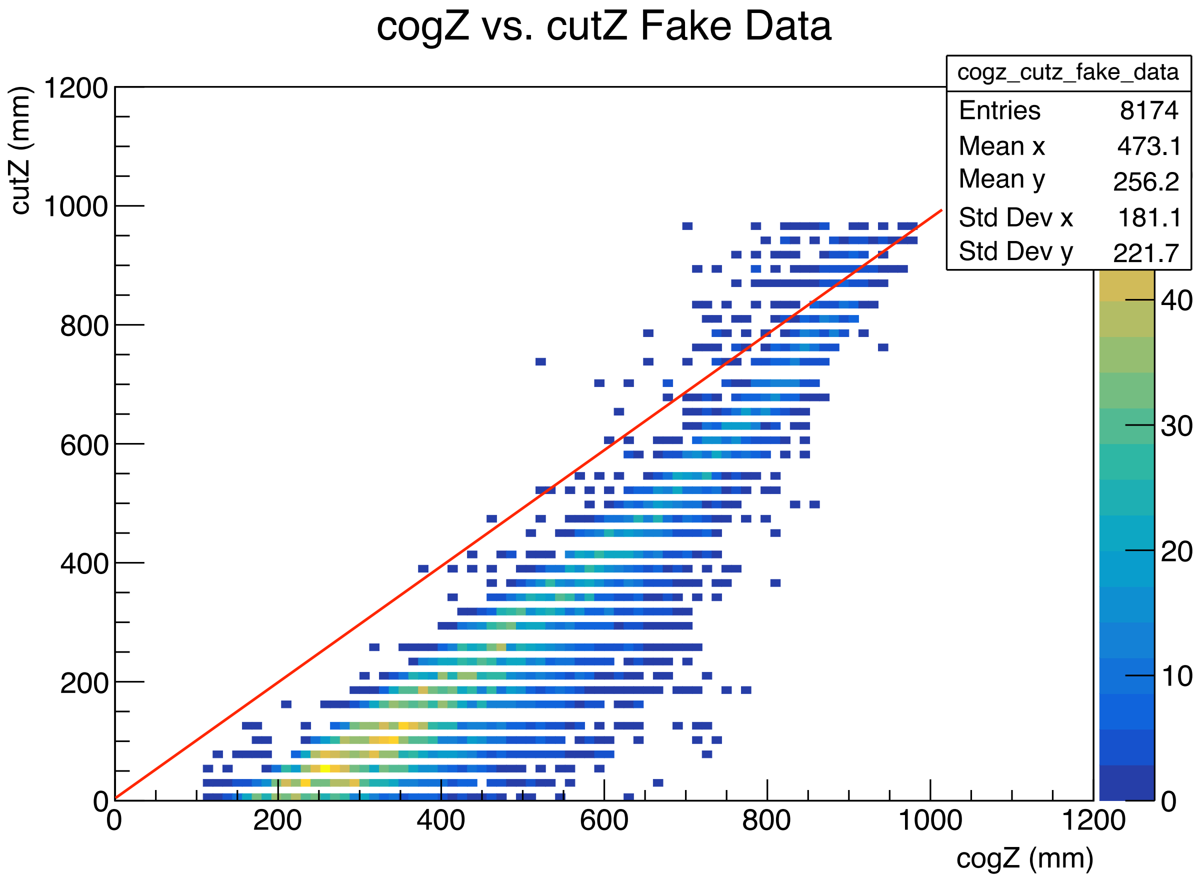
MC: 10k pi-, 20 GeV, June 2018 TB, QGSP_BERT_HP, 0.1 MIP ROC Threshold, No Gaussian Smearing in Digitisation

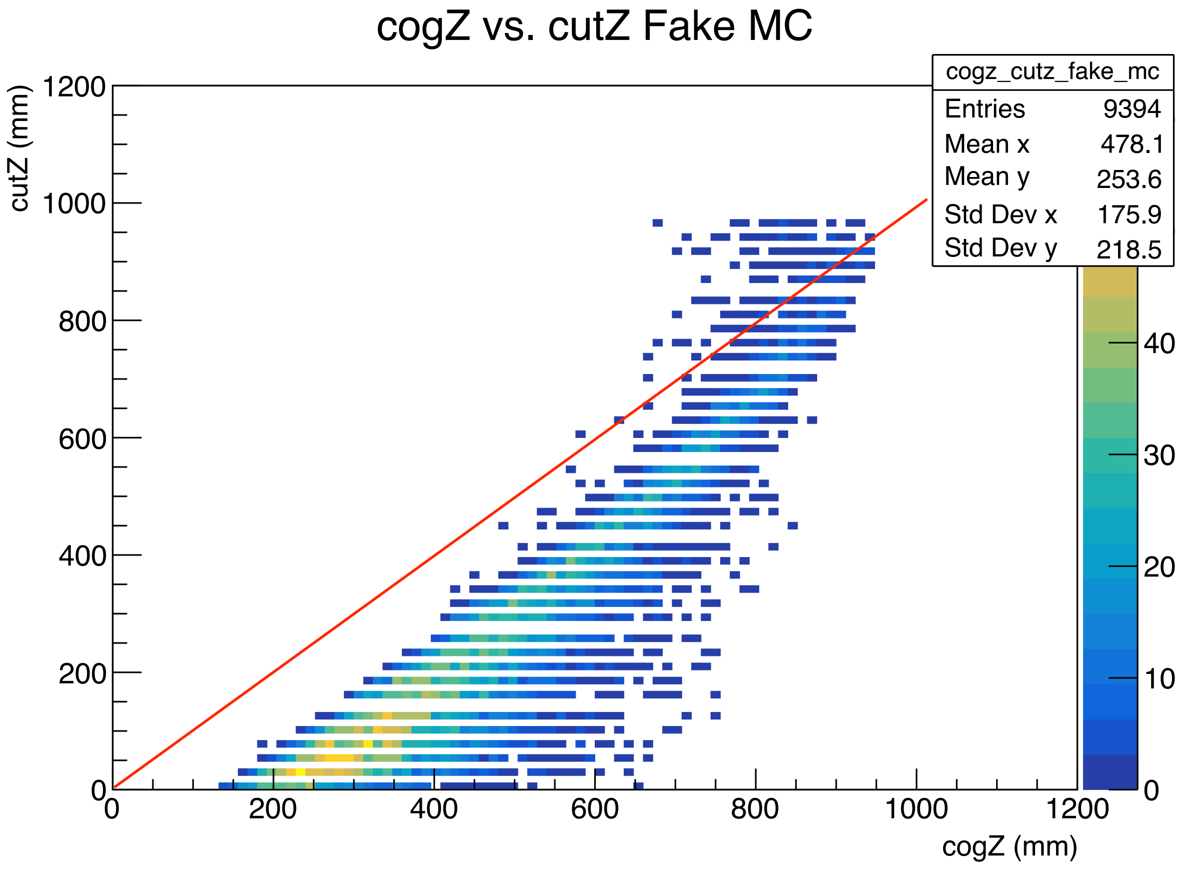
Data: 10k events of Run 61270, pi-, 20 GeV, June TB

Common: 0.0268 MIP to GeV conversion, Latest Beam Profiles, Default Cut Based PID Applied

Cross-check: CogZ vs. CutZ

Pseudo Neutrals Data vs. MC

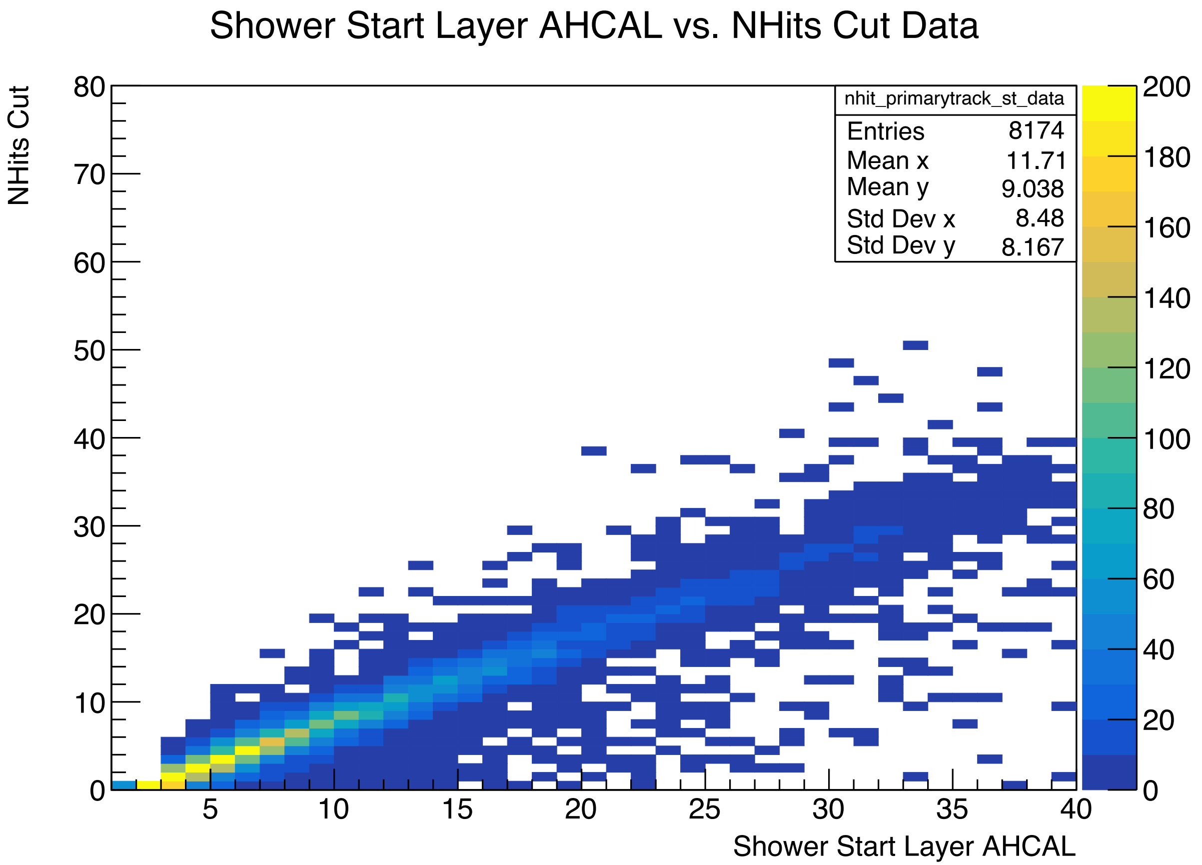


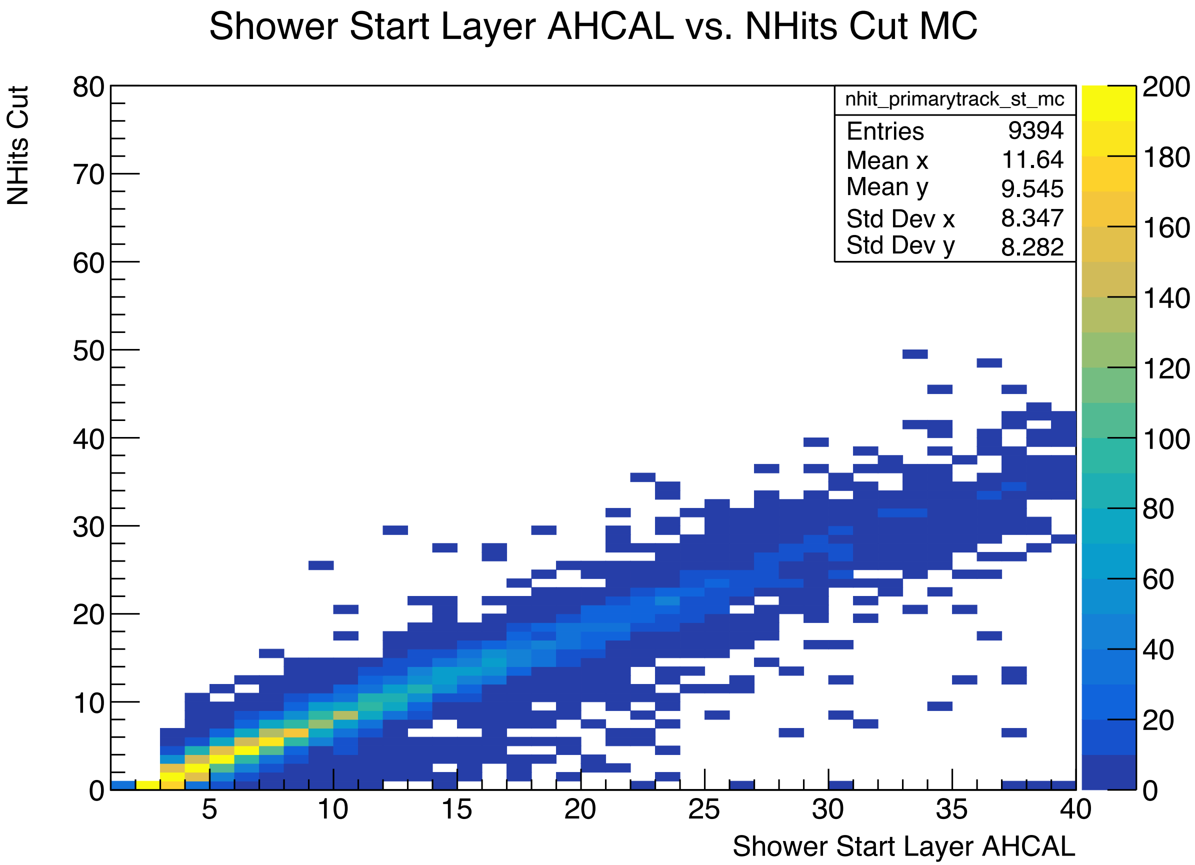


- In general very good agreement and hits of most of events potentially cut before cogZ

Number of Hits (Primary Track) vs. Shower Start Layer

Pseudo Neutrals Data vs. MC

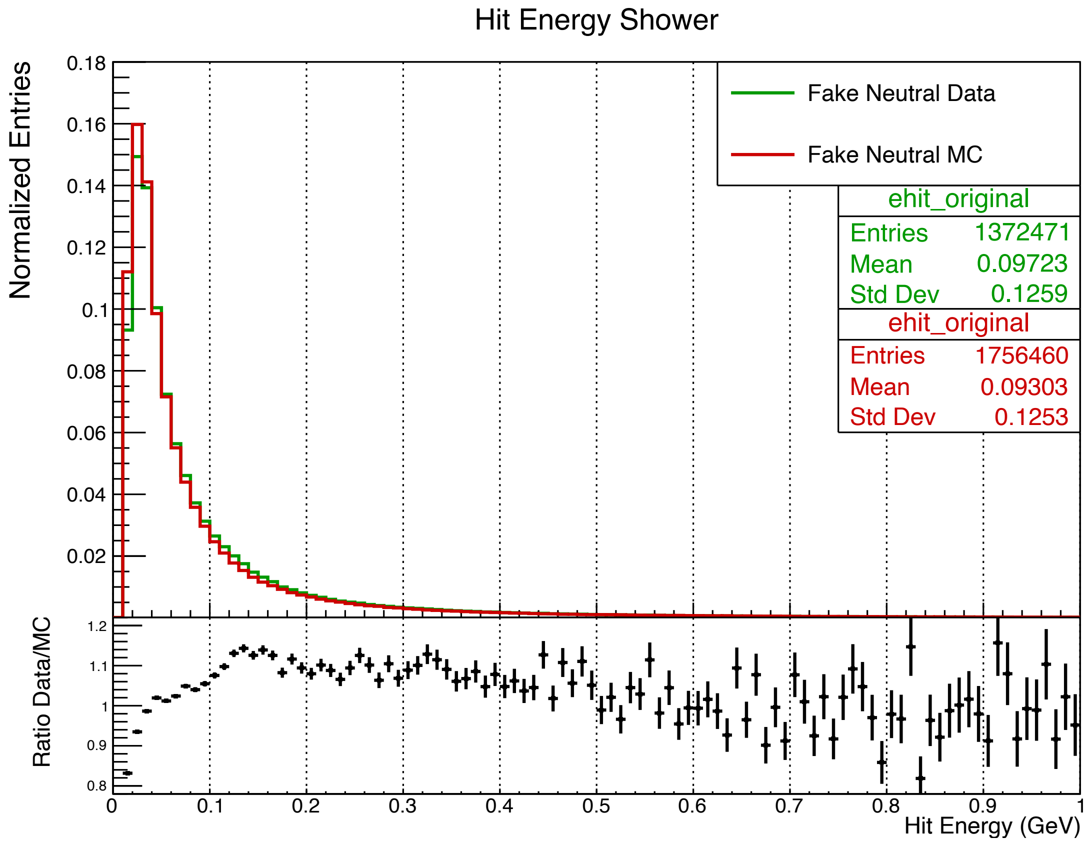


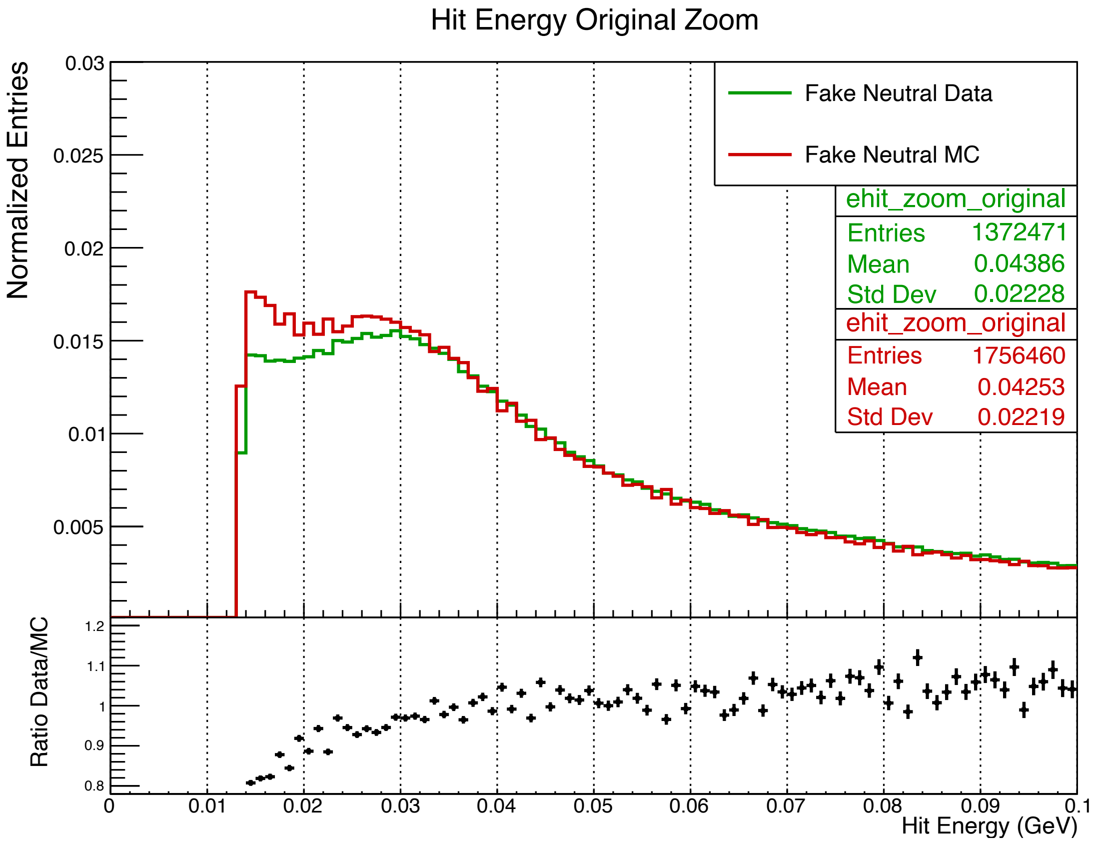


- For both: Correlation of shower start layer and nHits of classified primary track quite good and comparable

Hit Energy

Pseudo Neutrals Data vs. MC

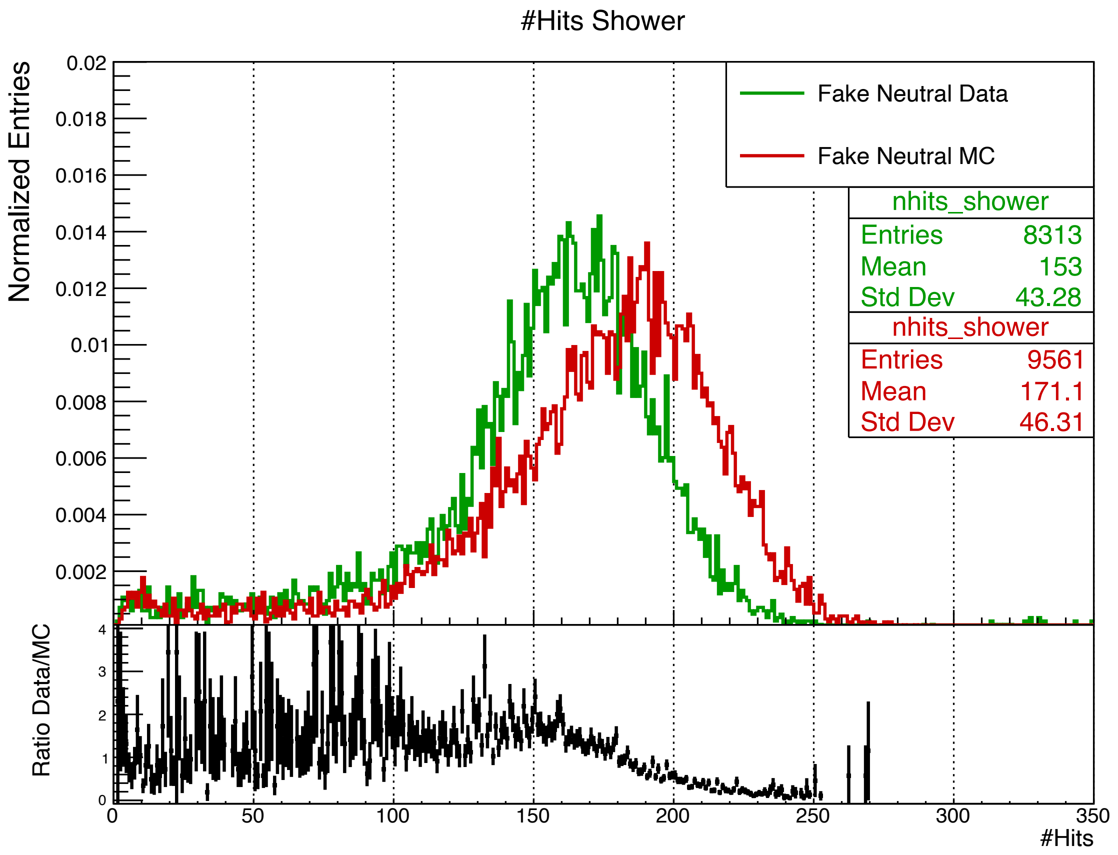


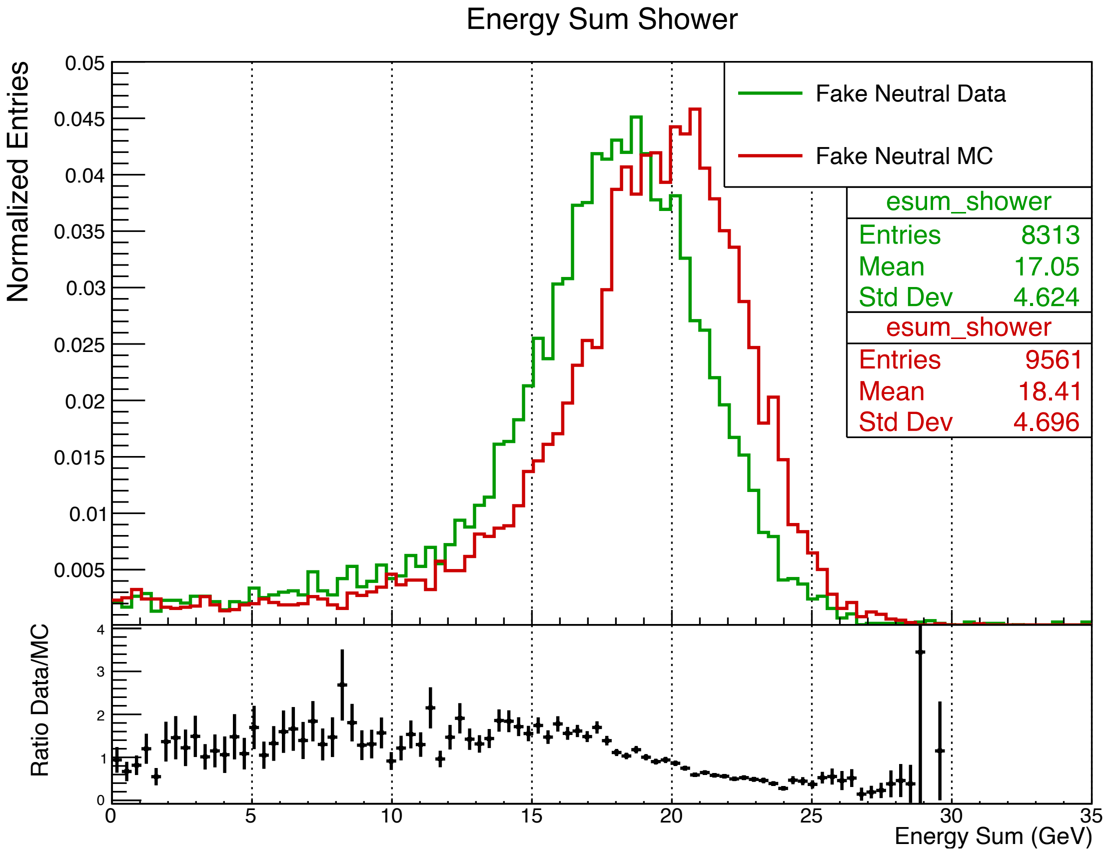


- Discrepancy for low energy hits: Same trends as observed in studies done by Olin Pinto

Number of Hits and Energy Sum

Pseudo Neutrals Data vs. MC

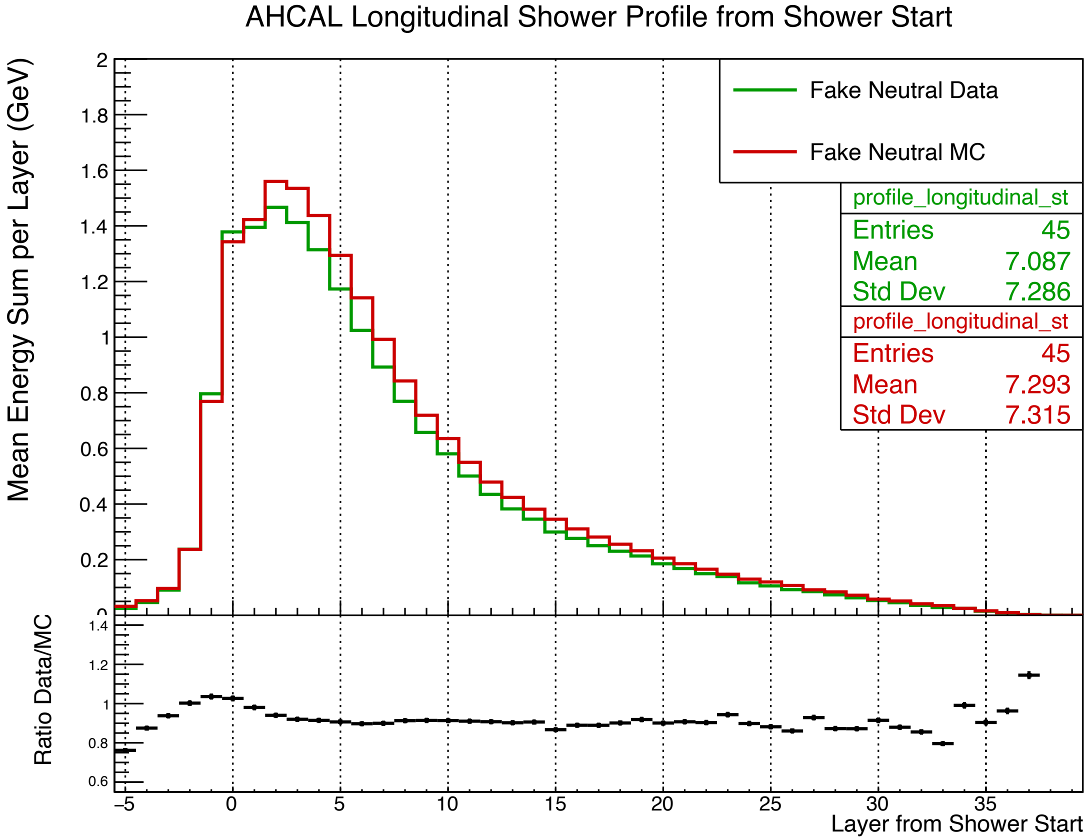


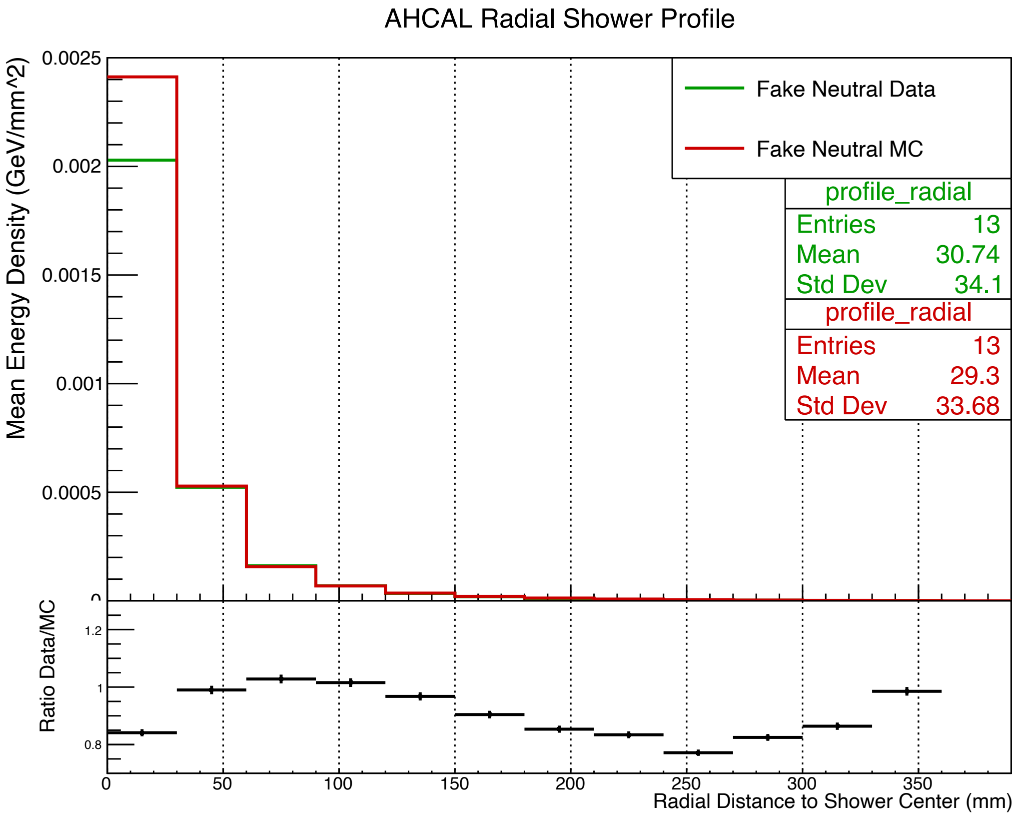


- Confirmation: ~10% shift of nHits and energy sum for 20 GeV data vs. MC pions

Shower Profiles: Longitudinal & Radial

Pseudo Neutrals Data vs. MC



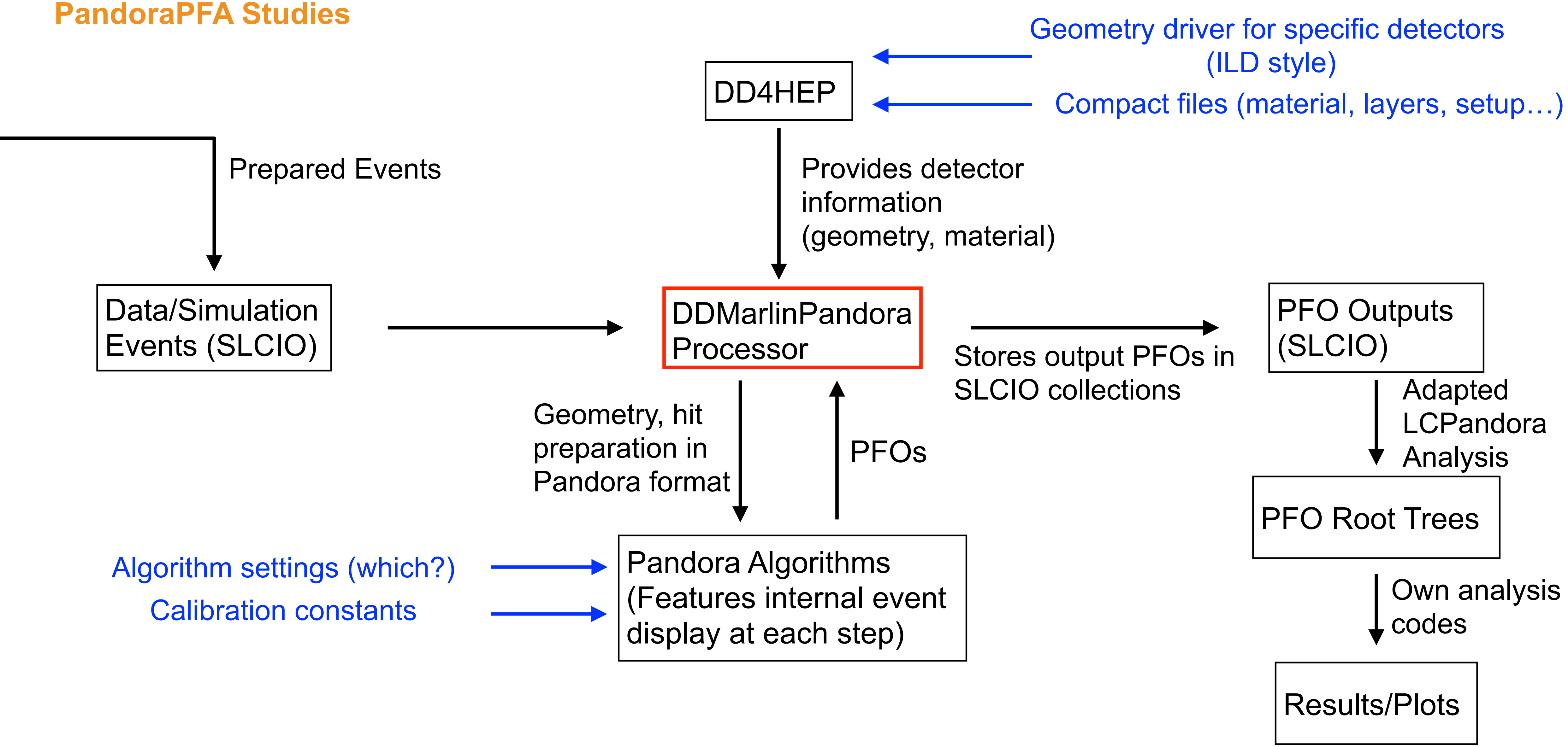


- As seen in energy sum and number of hits: More energy deposited in MC showers
  - ➡ Extra energy seems to appear in later layers after shower start and closer to shower core

The PandoraPFA Framework: Implementation, Calibration & Basic Checks

Framework / Data Flow Diagram

PandoraPFA Studies



Setting up the PandoraPFA Framework

Technical Challenges & Solutions

Many aspects considered while implementing PandoraPFA from a 4π detector setup (like ILD) to our AHCAL standalone (+tracks) scenario:

- Simplified detector geometry and related geometry drivers
  - ➡ Careful implementation
- No real tracker, ECAL, muon detector, no B-field
  - ➡ Disable/Re-write related parts code in interface processor
  - ➡ Re-define so-called pseudo layer plugin
  - ➡ Enable algorithm chain step-by-step and check for dependencies, internal cuts & problems (# sub-algorithms/event ~65-90)
- Detector gap implementation
- Internal Pandora energy calibration
- Check available plugins (PID, software compensation,…)

Typical algorithm chain for 1 event

```
[ VERBOSE "MyDDHCALPandora"] > Running Algorithm: Alg0001, CaloHitPreparation
[ VERBOSE "MyDDHCALPandora"] > Running Algorithm: Alg0002, EventPreparation
[ VERBOSE "MyDDHCALPandora"] > Running Algorithm: Alg0003, ClusteringParent
[ VERBOSE "MyDDHCALPandora"] ----> Running Algorithm: Alg0004, ConeClustering
[ VERBOSE "MyDDHCALPandora"] ----> Running Algorithm: Alg0005, TopologicalAssociationParent
[ VERBOSE "MyDDHCALPandora"] --------> Running Algorithm: Alg0006, LoopingTracks
[ VERBOSE "MyDDHCALPandora"] --------> Running Algorithm: Alg0007, BrokenTracks
[ VERBOSE "MyDDHCALPandora"] --------> Running Algorithm: Alg0008, ShowerMipMerging
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[ VERBOSE "MyDDHCALPandora"] --------> Running Algorithm: Alg0010, BackscatteredTracks
[ VERBOSE "MyDDHCALPandora"] --------> Running Algorithm: Alg0011, BackscatteredTracks2
[ VERBOSE "MyDDHCALPandora"] --------> Running Algorithm: Alg0012, ShowerMipMerging3
[ VERBOSE "MyDDHCALPandora"] --------> Running Algorithm: Alg0013, ShowerMipMerging4
[ VERBOSE "MyDDHCALPandora"] --------> Running Algorithm: Alg0014, ProximityBasedMerging
[ VERBOSE "MyDDHCALPandora"] ------------> Running Algorithm: Alg0015, TrackClusterAssociation
[ VERBOSE "MyDDHCALPandora"] --------> Running Algorithm: Alg0016, ConeBasedMerging
[ VERBOSE "MyDDHCALPandora"] ------------> Running Algorithm: Alg0015, TrackClusterAssociation
[ VERBOSE "MyDDHCALPandora"] --------> Running Algorithm: Alg0017, MipPhotonSeparation
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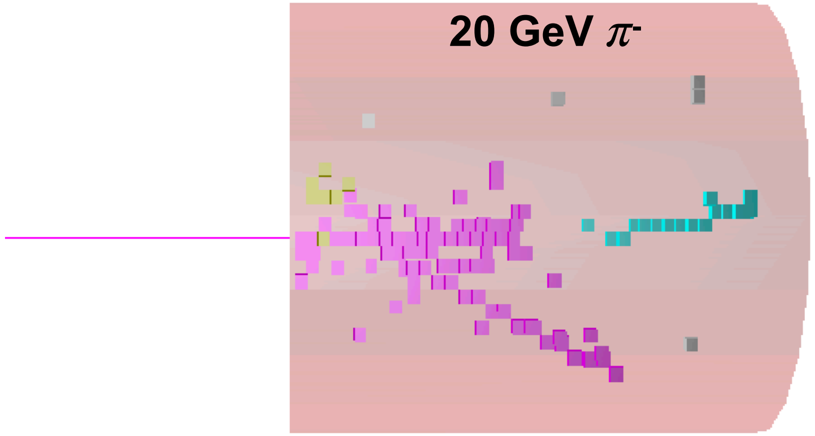
Pandora Visual Monitoring

Hits, Clusters & PFOs

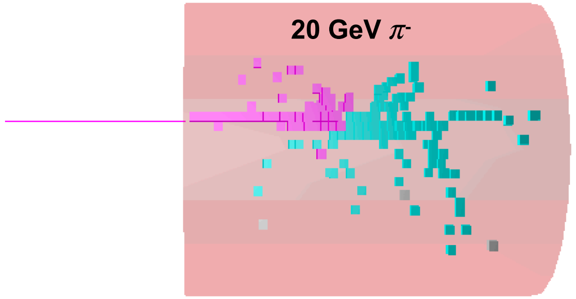


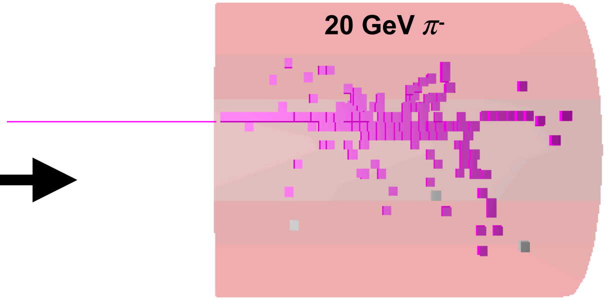
Magenta: Charged Hadron
Cyan: Neutral Hadron
Yellow: Photon
Grey: Unclustered Hits

- 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



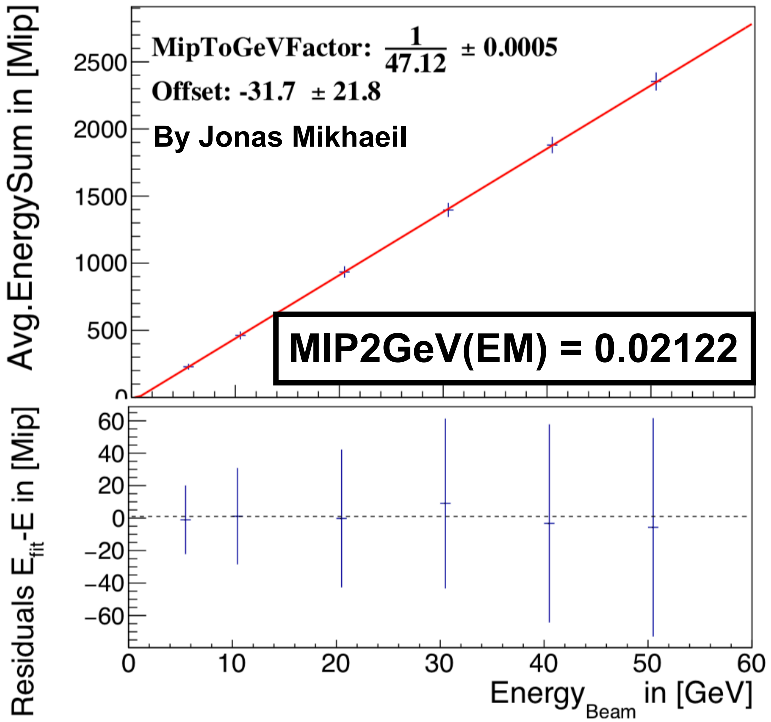


MIP to GeV Conversion

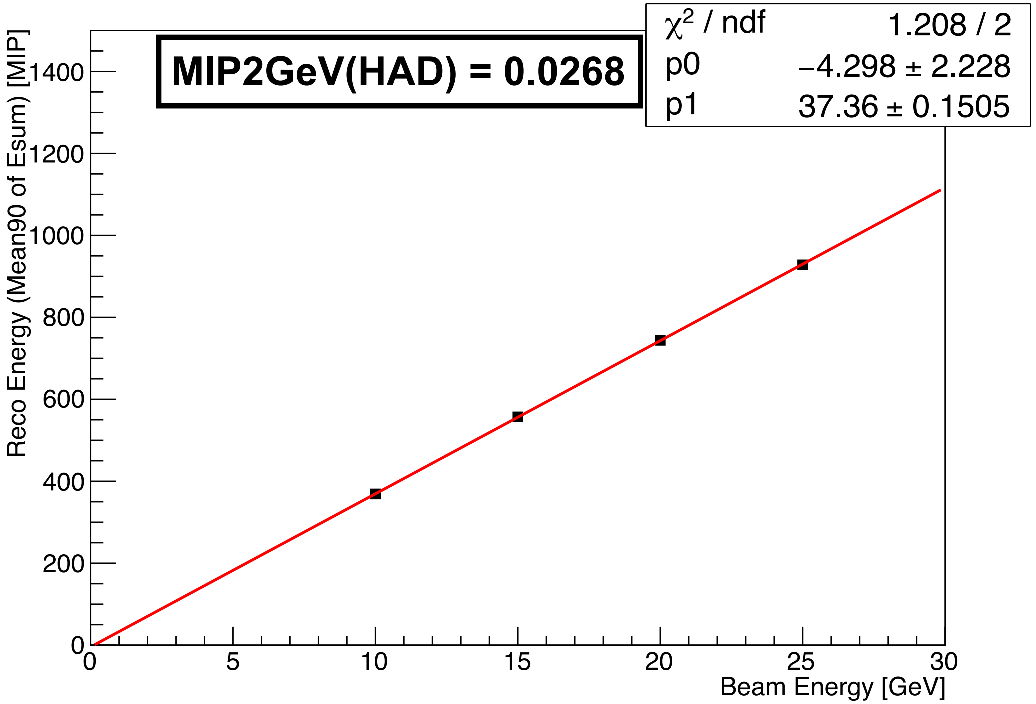
Calibration to EM and HAD Scale

- 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-)



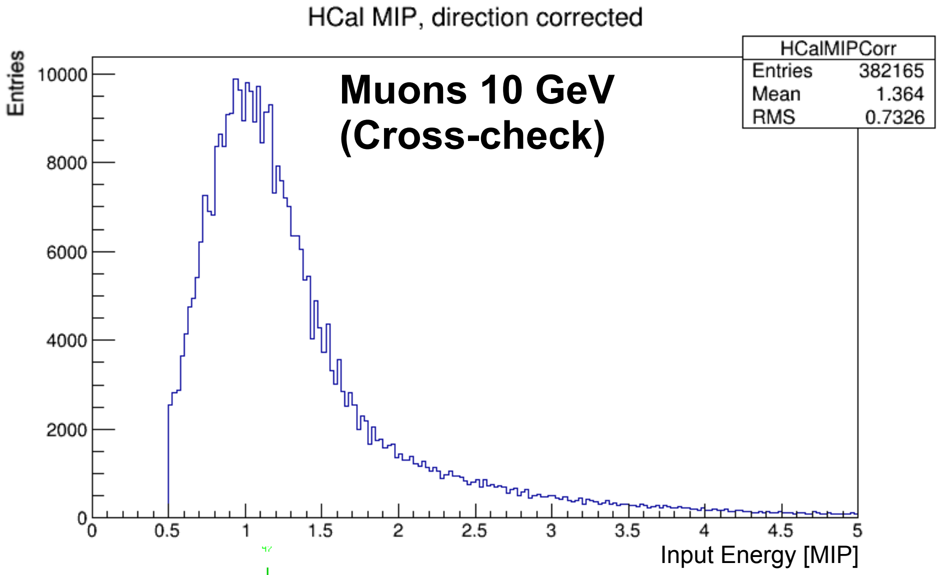
HAD Response Determination (K0L)

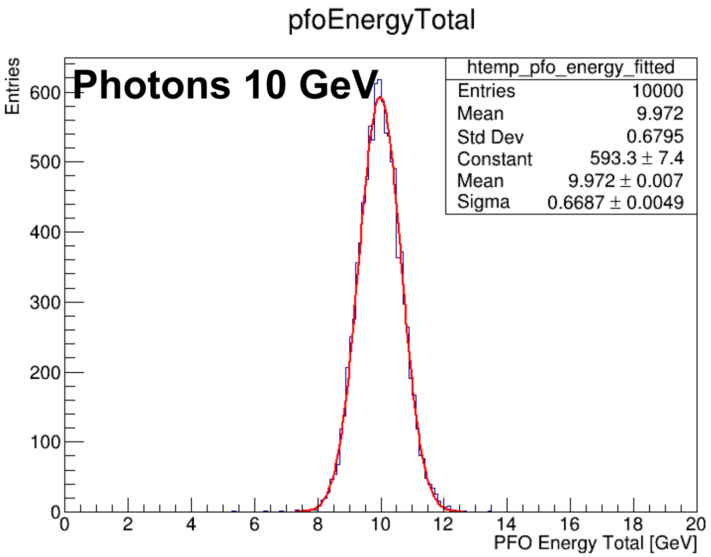


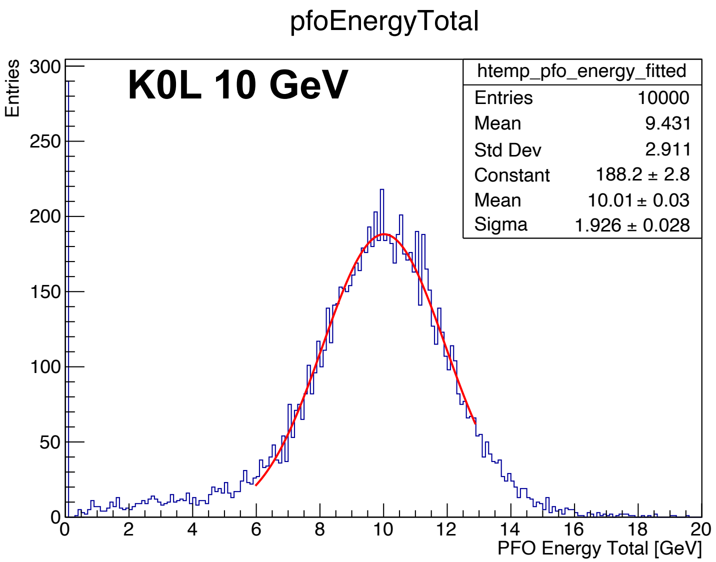
Pandora Energy Calibration

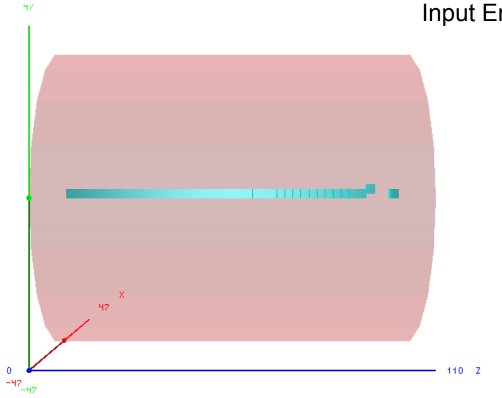
MC Muons, Photons, K0L

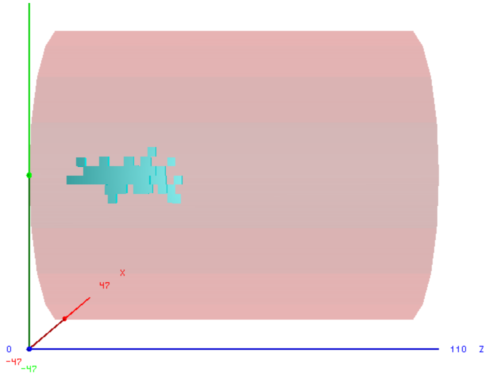
Note: Without tracks and ECAL everything classified as neutral hadrons at this step

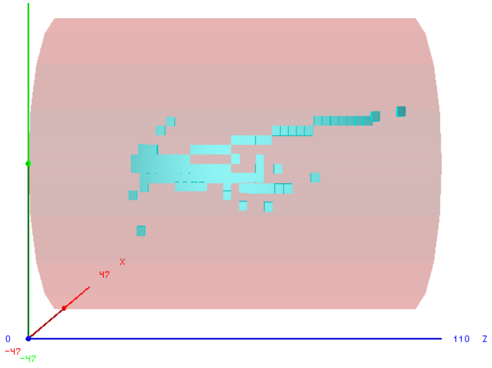










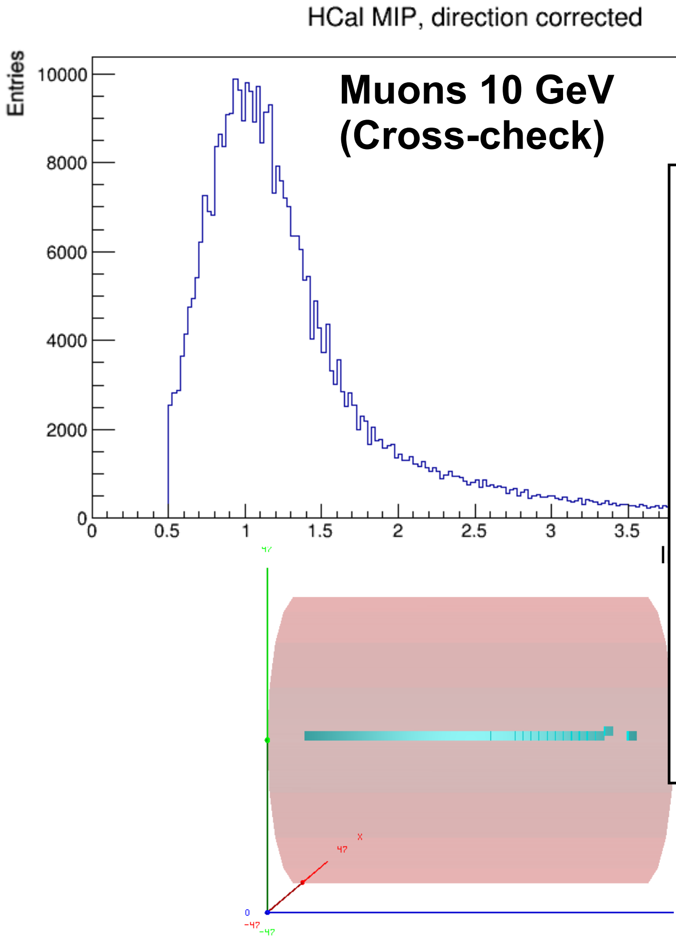


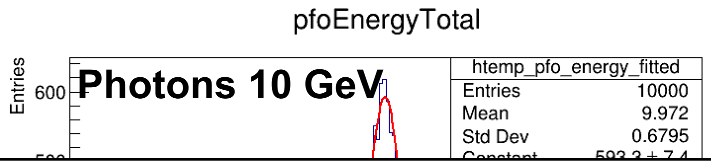
- **Muons**: AHCAL energy GeV -> MIP with negligible angle correction since straight TB tracks
- **Photons and K0L's**: Used to determine EM and HAD response, PFO energy tuned to peak at 10 GeV

Pandora Energy Calibration

MC Muons, Photons, K0L

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





Results:

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

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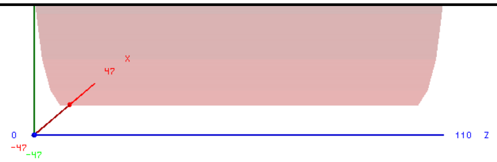
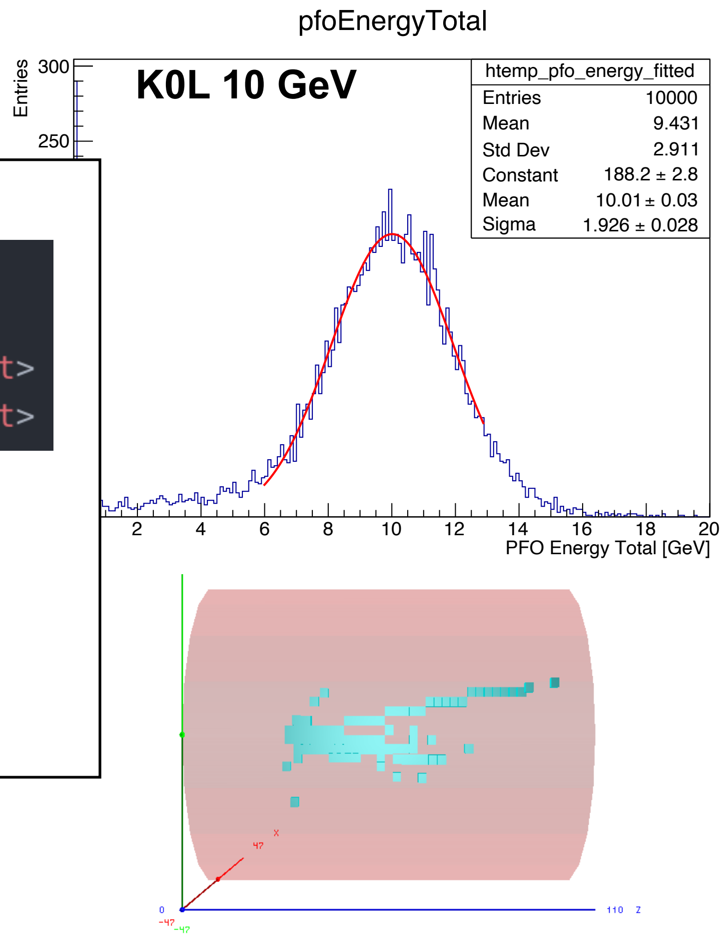

- Both factors a bit higher than for raw AHCAL response (= 1.0)
  - ➡ Pandora clustering isolation cuts





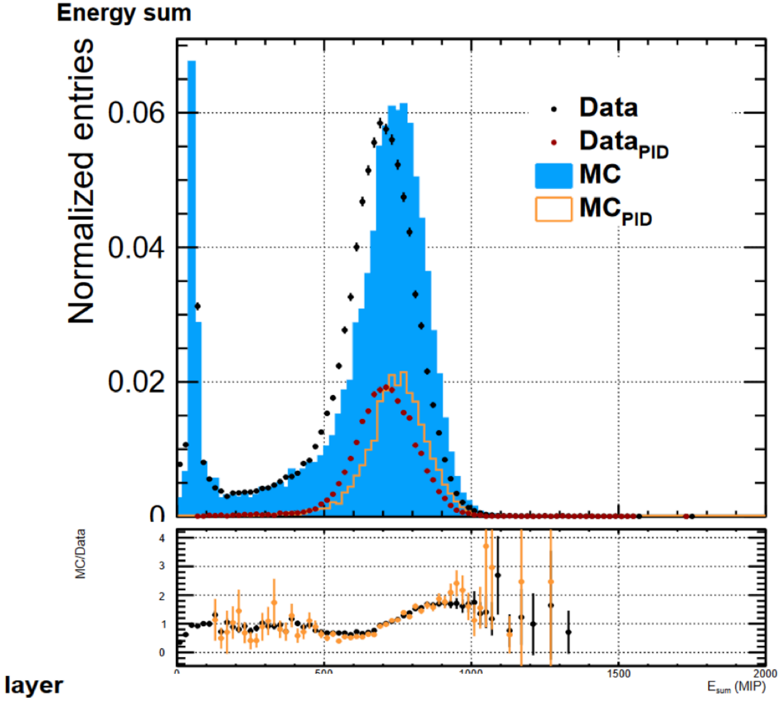
- **Muons**: AHCAL energy GeV -> MIP with negligible angle correction since straight TB tracks
- **Photons and K0L's**: Used to determine EM and HAD response, PFO energy tuned to peak at 10 GeV

Energy Sums Data and MC

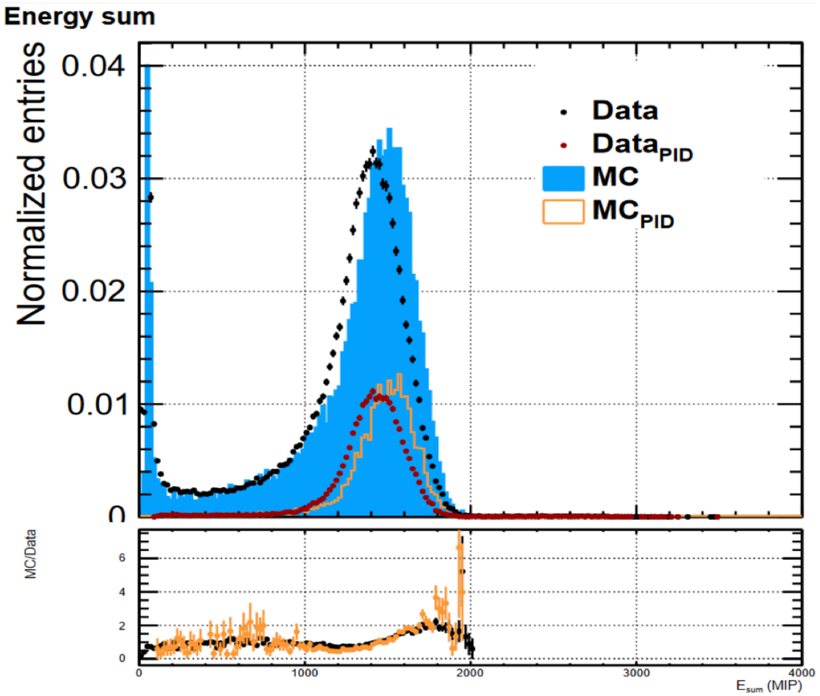
By Olin Pinto

20, 40 & 60 GeV

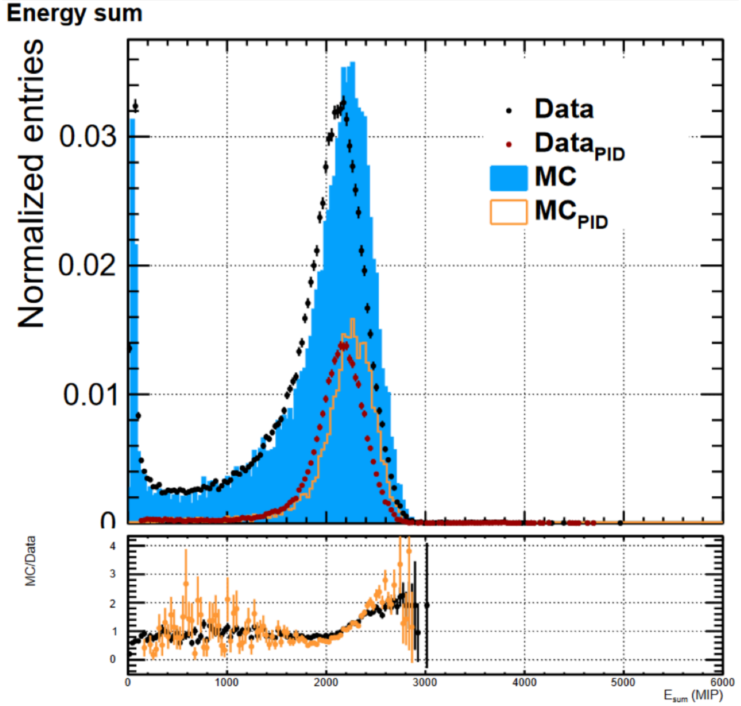
20 GeV



40 GeV



60 GeV



https://indico.desy.de/indico/event/25091/session/7/contribution/19/material/slides/0.pdf