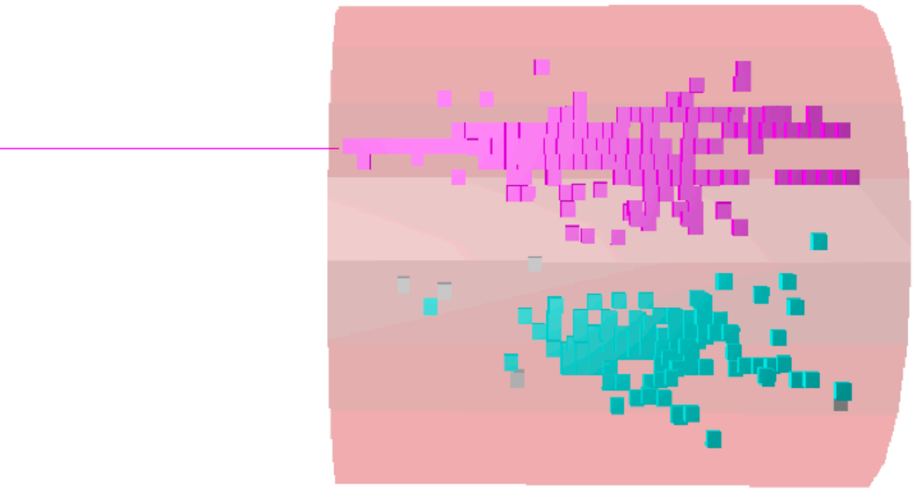
PandoraPFA Confusion Studies

Two Particle Events - AHCAL 2018 Beam Test Data



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

Daniel Heuchel (DESY)
daniel.heuchel@desy.de
CALICE Analysis Meeting
30th June 2021

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

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

Outline

For this Talk

- Brief Recap: Concept of Particle Flow & Confusion
- Motivation & Goals of Study
- Results: PandoraPFA Two Particle Reconstruction (AHCAL 2018 Data)

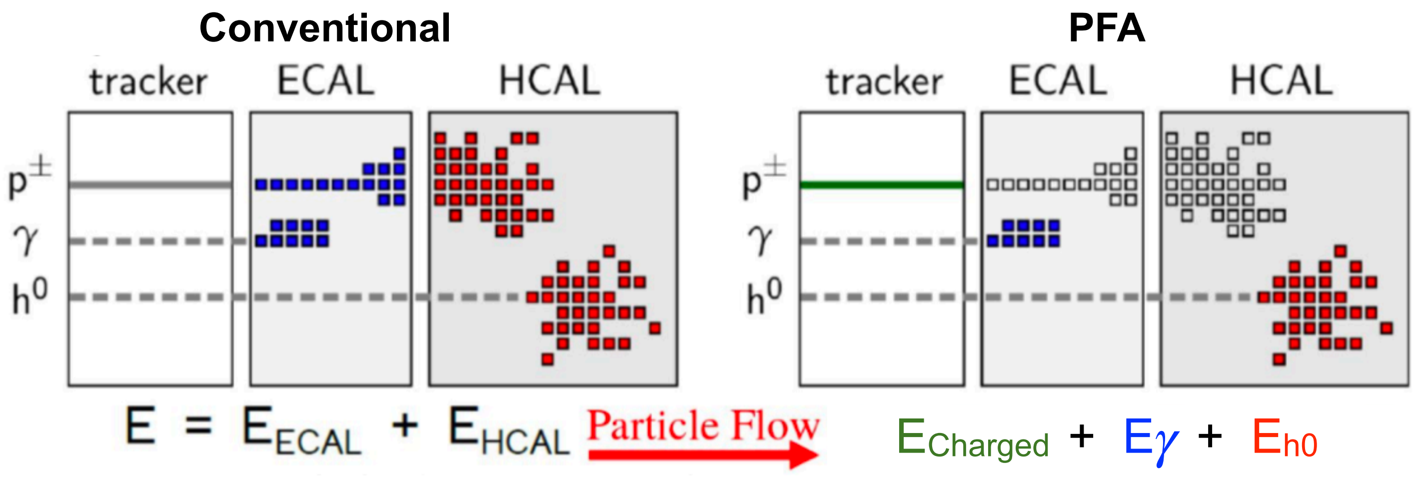
- Summary & Conclusion
- Outlook: Confusion Studies with ILD Jets

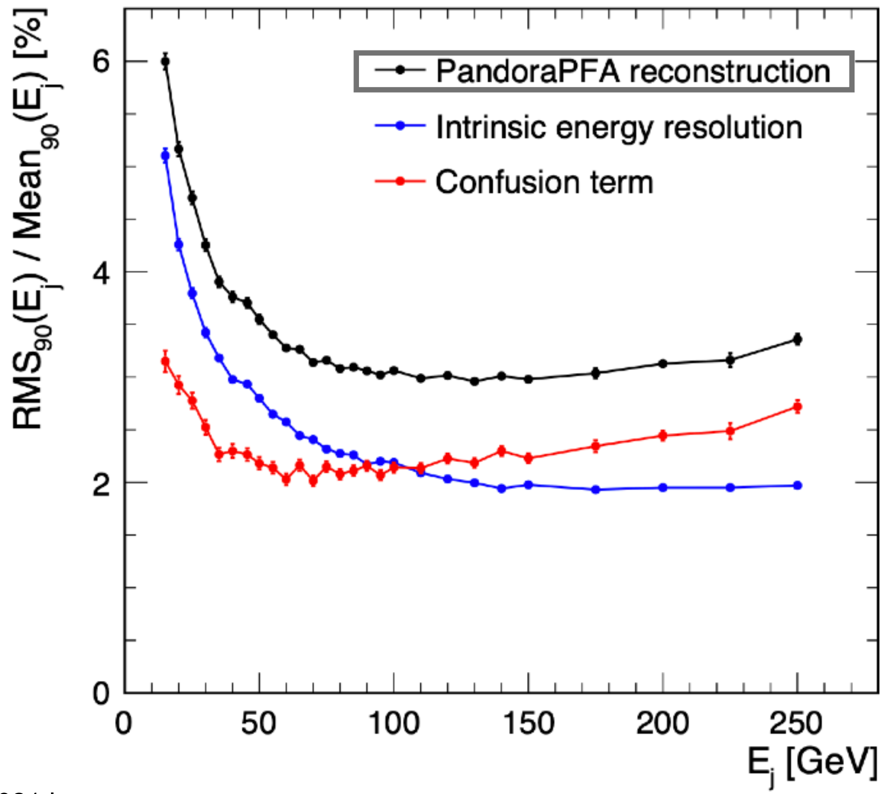
Particle Flow Reconstruction
&
Confusion

Particle Flow Approach

The Key to Highest Precision

- Goal at future e^+e^- collider experiments: 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)





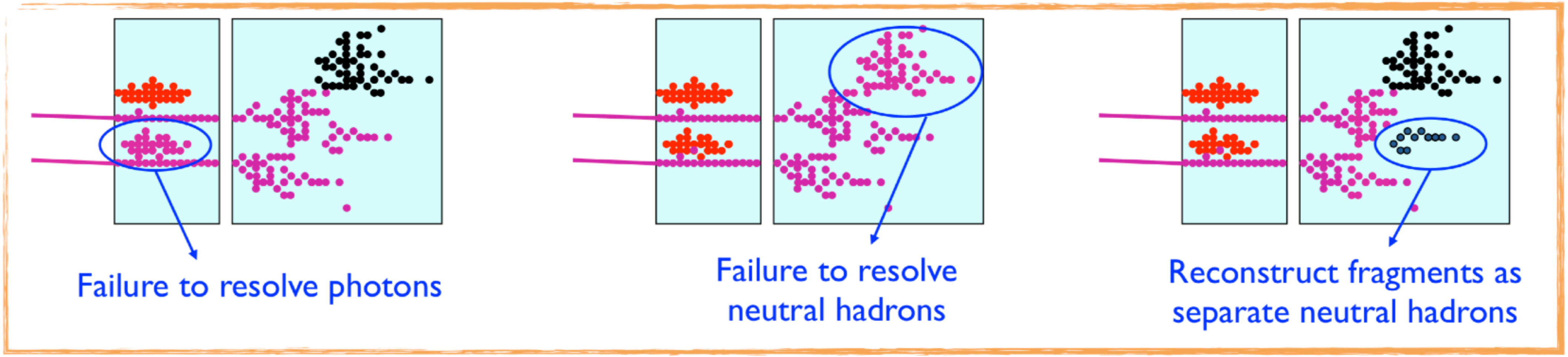
arXiv:1705.10363

Confusion Scenarios

The Limit of Particle Flow Reconstruction

- **Topologically or energetically confusing** events could cause problems for PFA reconstruction:

Types of confusion



Missing energy

Missing energy (Confusion Type 1)

Double counted energy (Confusion Type 2)

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

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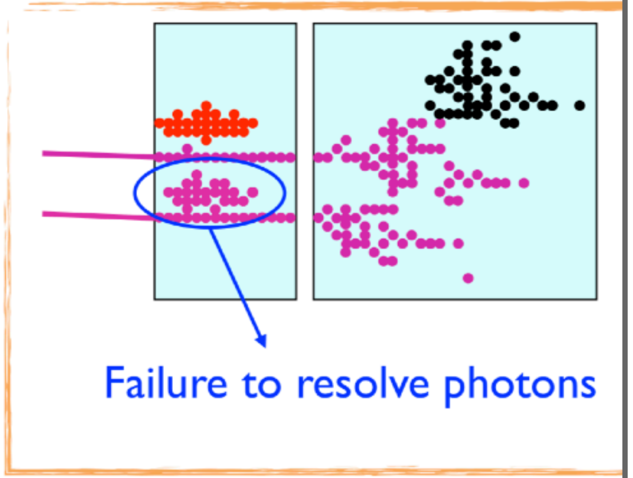

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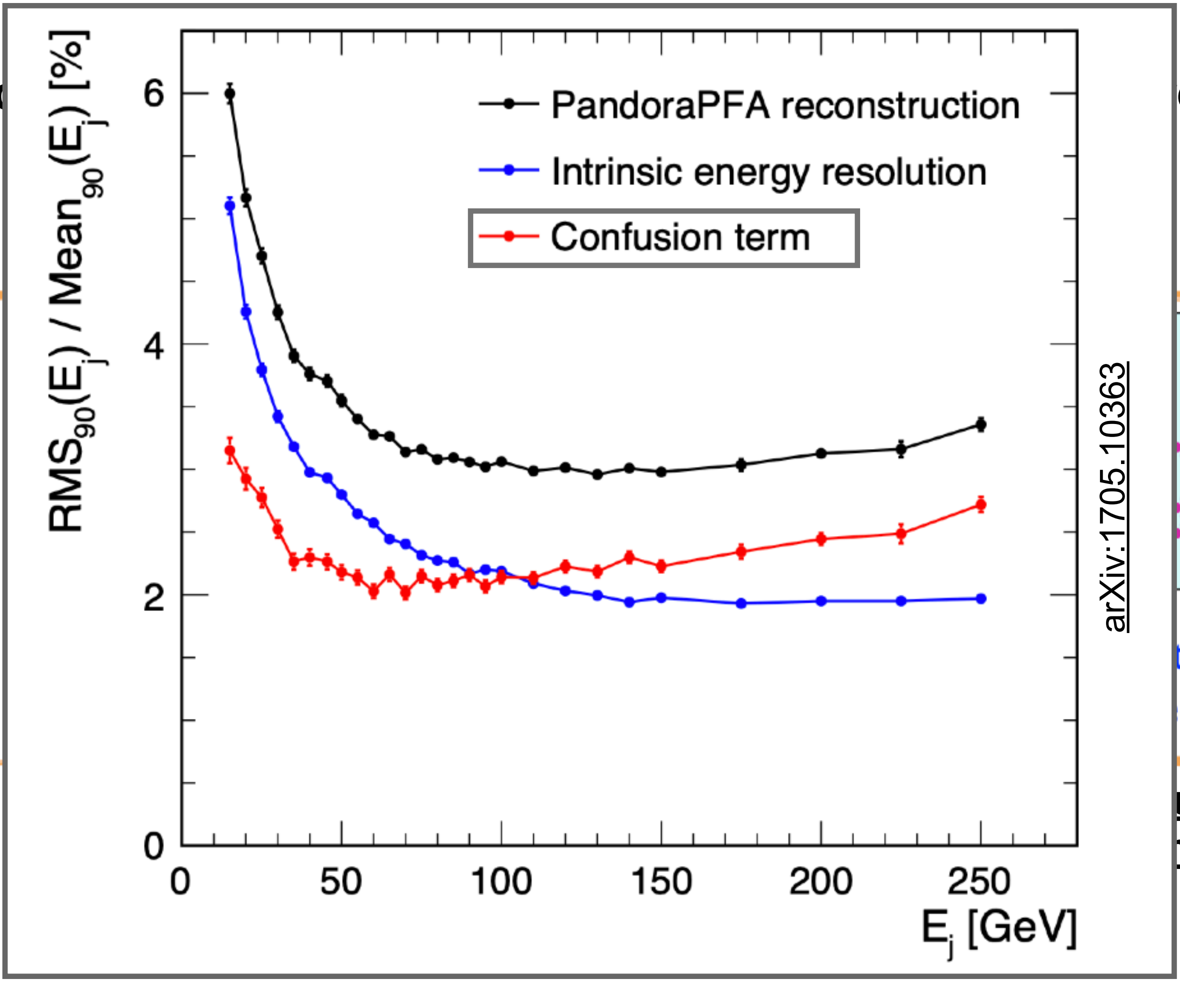

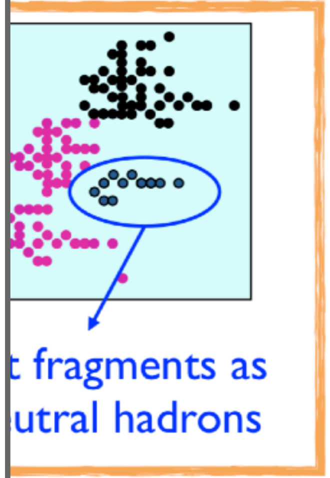

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➡ Missing or double counted energy limiting jet energy resolution at high energies

Motivation & Goals

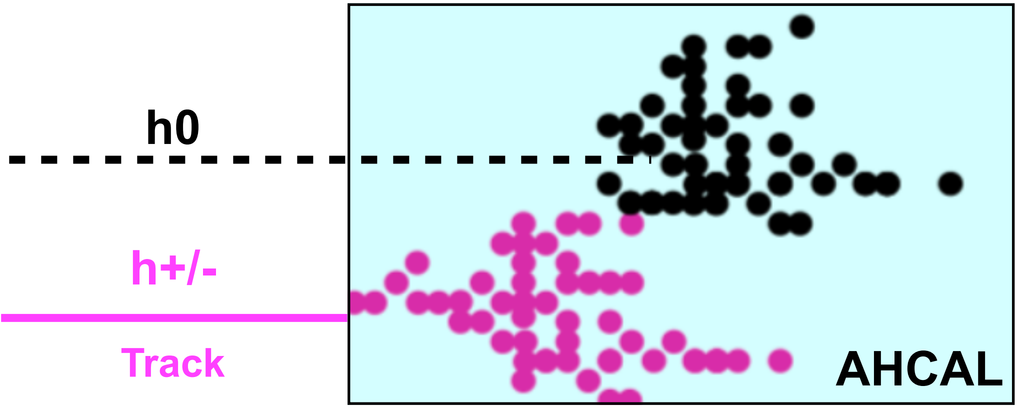
Motivation and Goals of Studies I

PandoraPFA on AHCAL 2018 Prototype Data

- General question: How accurate are details of simulations (e.g. for full collider detector jets) to be able to predict improvement in energy resolution by exploiting shower sub-structure information?
  - ➡ Study limiting effects of PFA in detail with beam test data of a simplified setup

- Apply PandoraPFA on AHCAL 2018 beam test data
  - ➡ Evaluate simulated algorithm performance for standalone application (presented previously)
  - ➡ **Systematically study confusion types and degree for different scenarios & provide feedback on beam data in comparison to simulations**

Baseline Scenario: Charged + Neutral Hadron Event



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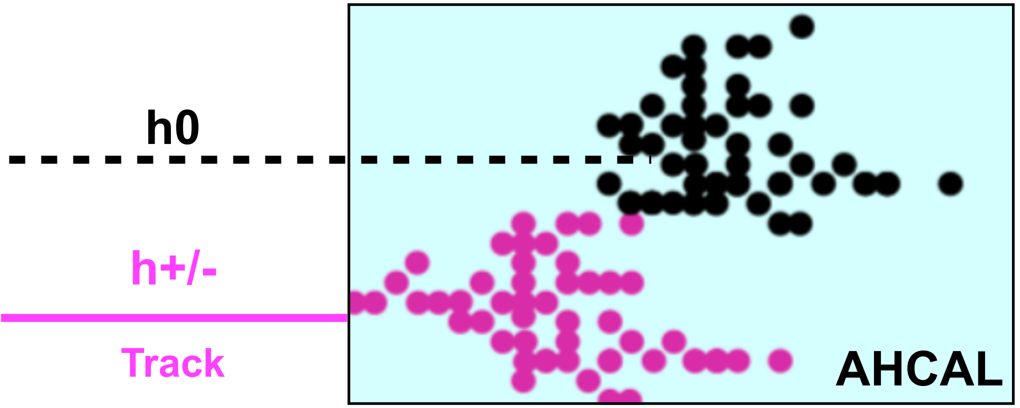


Main Questions Two Particle Study:

- **How well can PandoraPFA separate and resolve the neutral from the charged hadron (hits & energy)?**
- **Total energy reconstruction performance?**
- **How does confusion scale with energy and distance?**
- **Confusion type 1 vs. type 2 - balanced?**
- **Confusion sensitive PFA parameters/algorithms?**

Motivation and Goals of Studies II

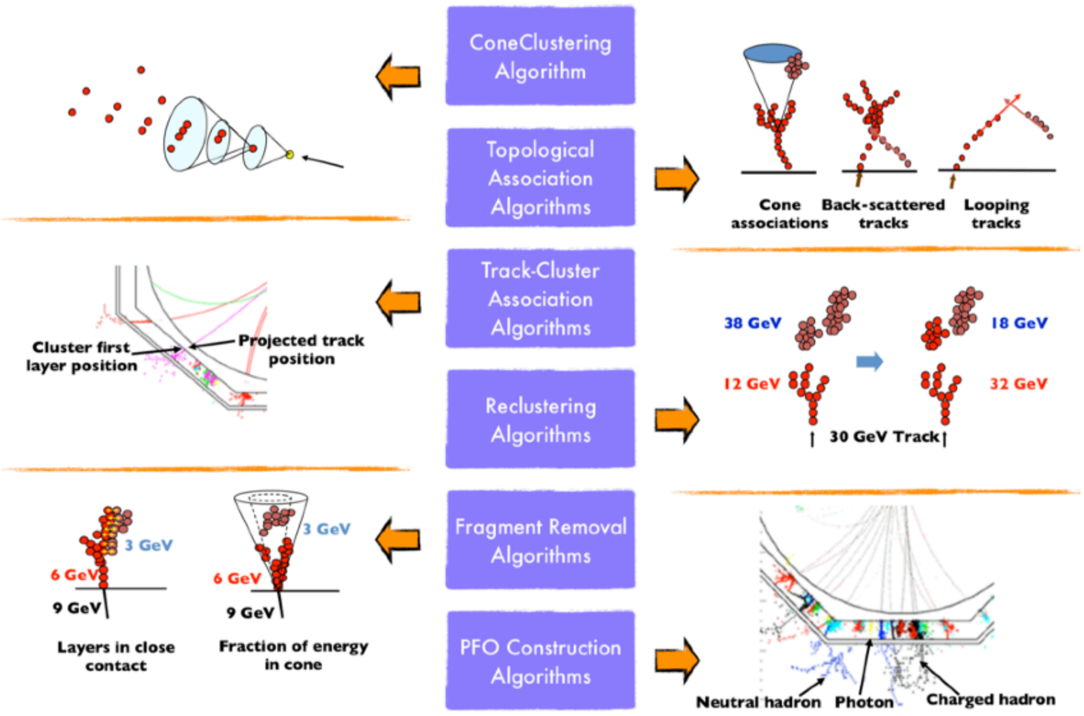
PandoraPFA on AHCAL 2018 Prototype Data

Parts of this study were done for the AHCAL 2007 prototype (https://arxiv.org/abs/1105.3417)

Why do it again on AHCAL 2018 prototype data?

- **Significant developments of PandoraPFA**
  - ➡ Modular setup and drivers allow standalone application (instead of projection of data to ILD)
  - ➡ Relative easy plugin initialisation and interface for changes/adaptions, etc.
- Latest AHCAL 2018 prototype:
  - ➡ Significant reduction of noise (SiPMs)
  - ➡ Very high and uniform granularity (22k channels)
  - ➡ Timing capabilities for potential use
- Single particle studies new (presented previously)

Illustration of Key Steps of PandoraPFA



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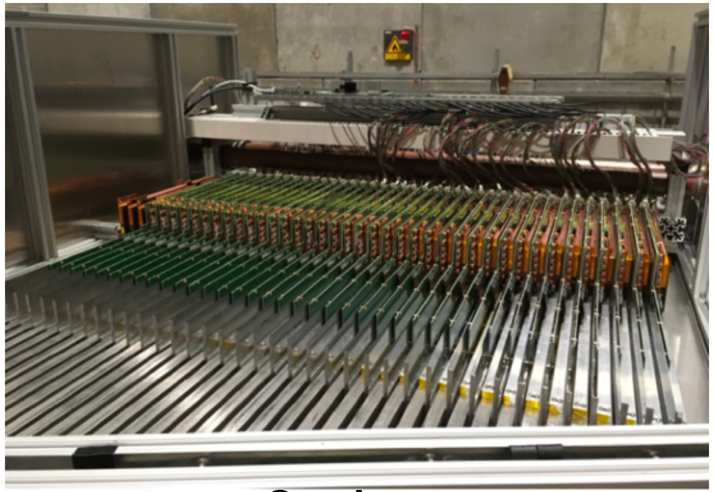
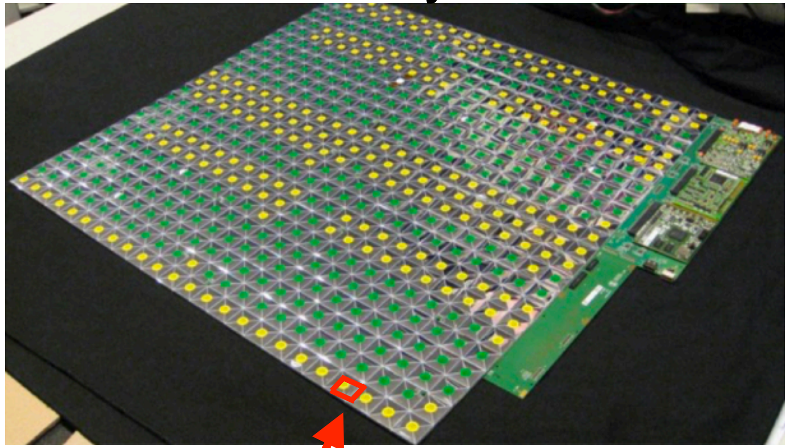
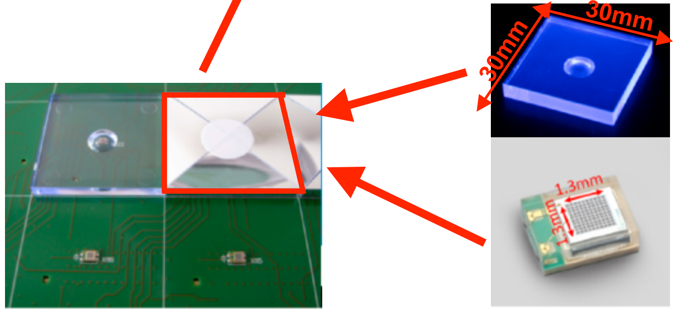
AHCAL 2018 Prototype: 38 layers within steel stack



One layer



One channel: Scintillating tile + SiPM



Analysis Strategy
&
Sample Selection

Overview

Sample Preparation & Analysis Strategy

Note: Preparation and selection tools finished and validated (https://agenda.linearcollider.org/event/8585/contributions/45938/attachments/35663/55351/DH_pandora_calice_200730.pdf)

AHCAL data & MC → Unselected charged pion events → **Event preparation & selection** → Selected charged pion events → **Primary track removal & event overlay** → Selected events with overlaid pseudo-neutral and charged hadron

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

Selected events with overlaid pseudo-neutral and charged hadron → **PandoraPFA** → **Scenario 2: Two-particle reconstruction 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

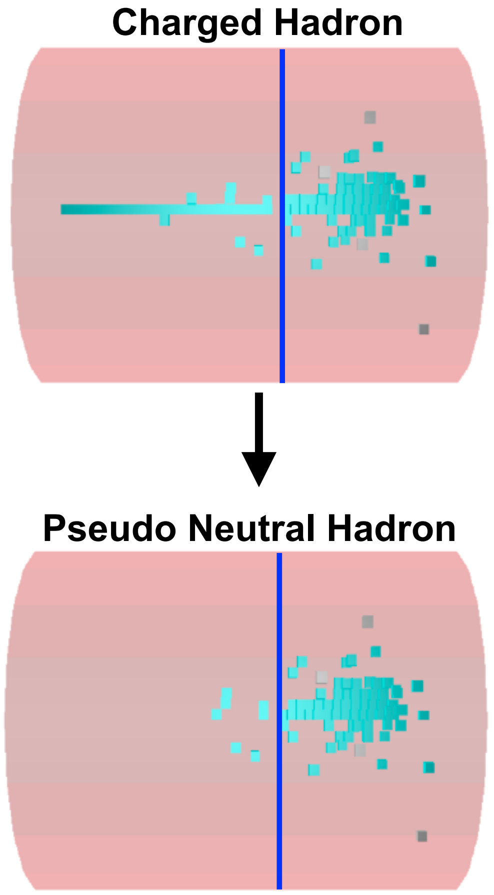
Intermezzo: Pseudo-Neutrals & Event Overlay

Creation of Two Particle Events (Pseudo-Neutral + Charged Hadron)

- No neutral hadrons @ beam tests: Creation of pseudo-neutral hadrons

  ➡ Take charged hadron event and remove MIP track before shower start

  ➡ Hit classified as part of MIP track if located in layers before **shower start layer**, hit position within radius of 60mm around central shower axis and hit energy < 3 MIP



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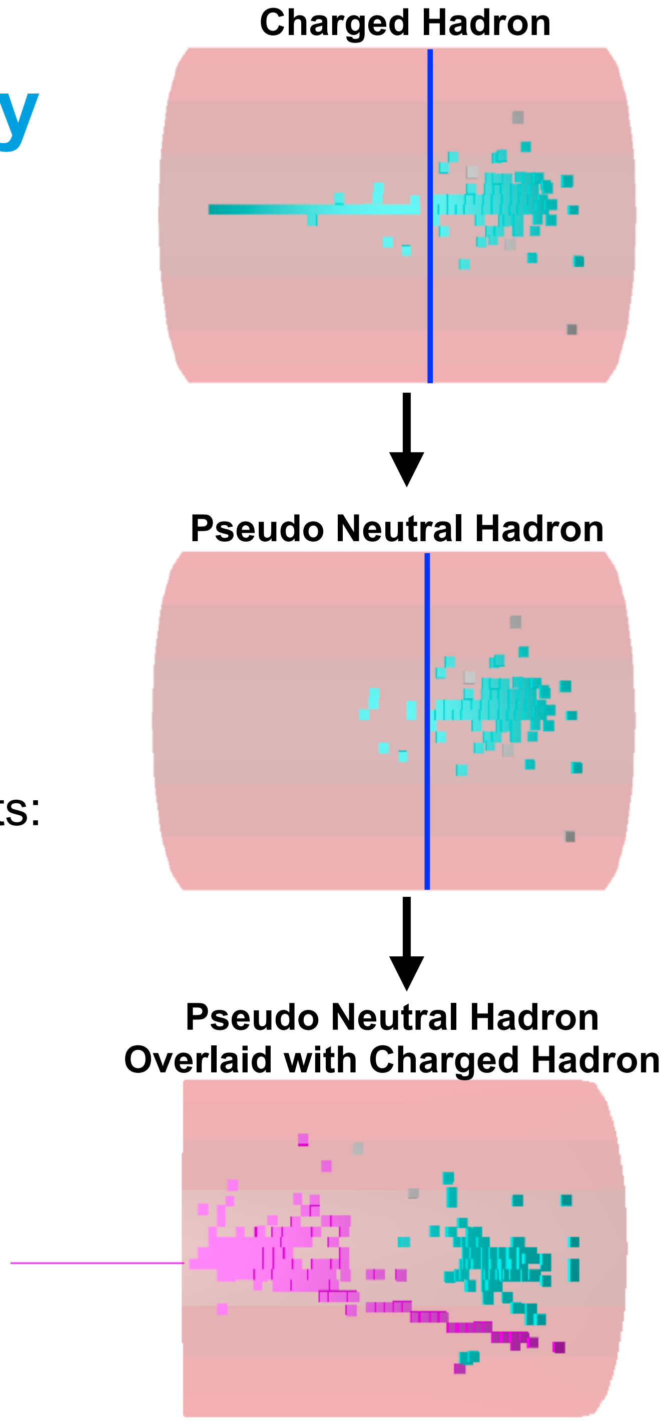
- Subsequent overlay with charged hadron to create desired two particle events:
  - ➡ Channel by channel overlay of hit information (+ origin flagging)
  - ➡ Energy threshold considerations
  - ➡ Control parameters: Energy of overlaid charged hadron, transversal shower distance, longitudinal shower separation (shower starts)



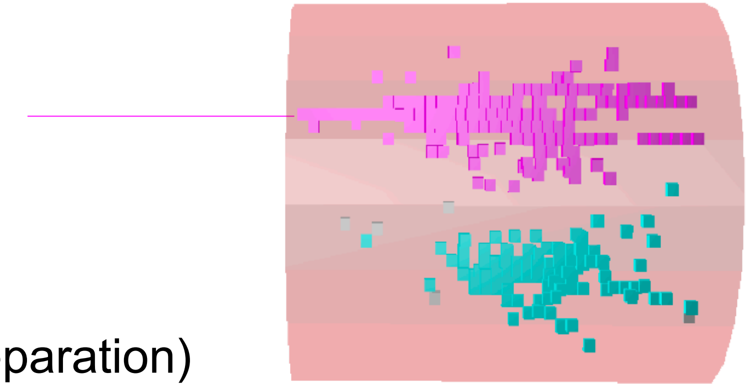
Sample Selection Overview

PandoraPFA Two Particle Reconstruction

- Event: 10 GeV pseudo-neutral + 10 GeV or 30 GeV charged hadron
- Distances: 0, 50, 100, 150, 200, 250, 300 mm with ±25 mm acceptance range/binning

- 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-detector-gap rejection
  - ➡ Requiring at least 10% of charged hadron energy associated to track (No ECAL, Problems IsoHitMerging)
    - ➡ 20 - 50k events per scenario for data & MC
- PandoraPFA: ILD default settings, AHCAL geometry adaptions

Endcap class only for visualisation

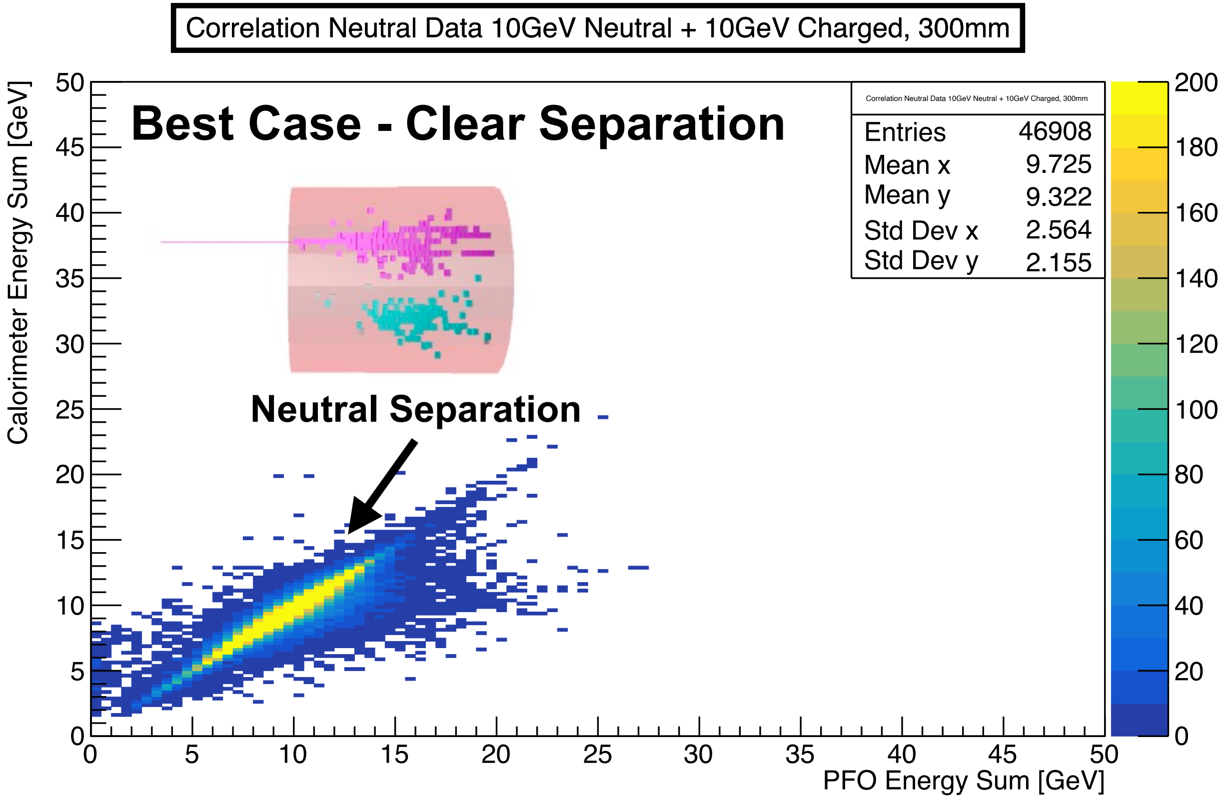


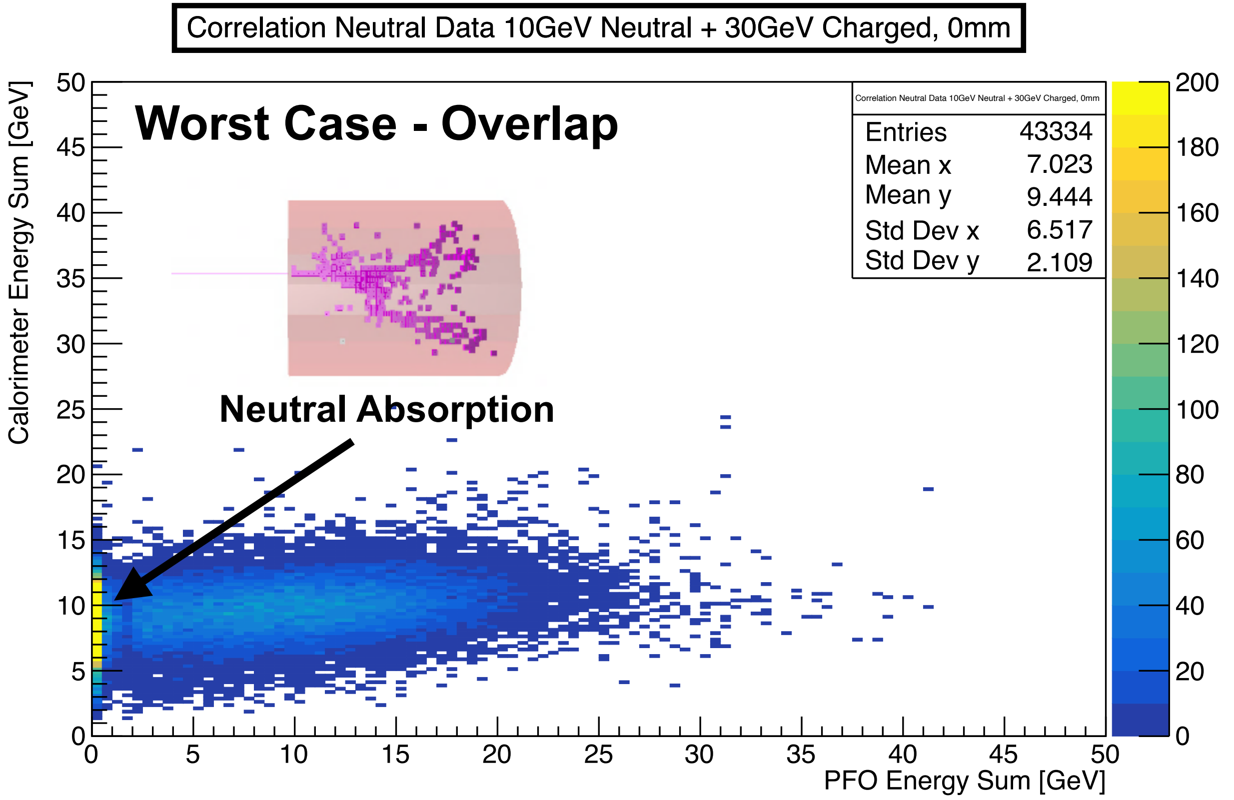
Results:

Neutral Hadron Energy

Neutral Hadron Energy: PFO vs. Calorimeter Energy Correlation

Visualisation Examples for Data - Best vs. Worst Case

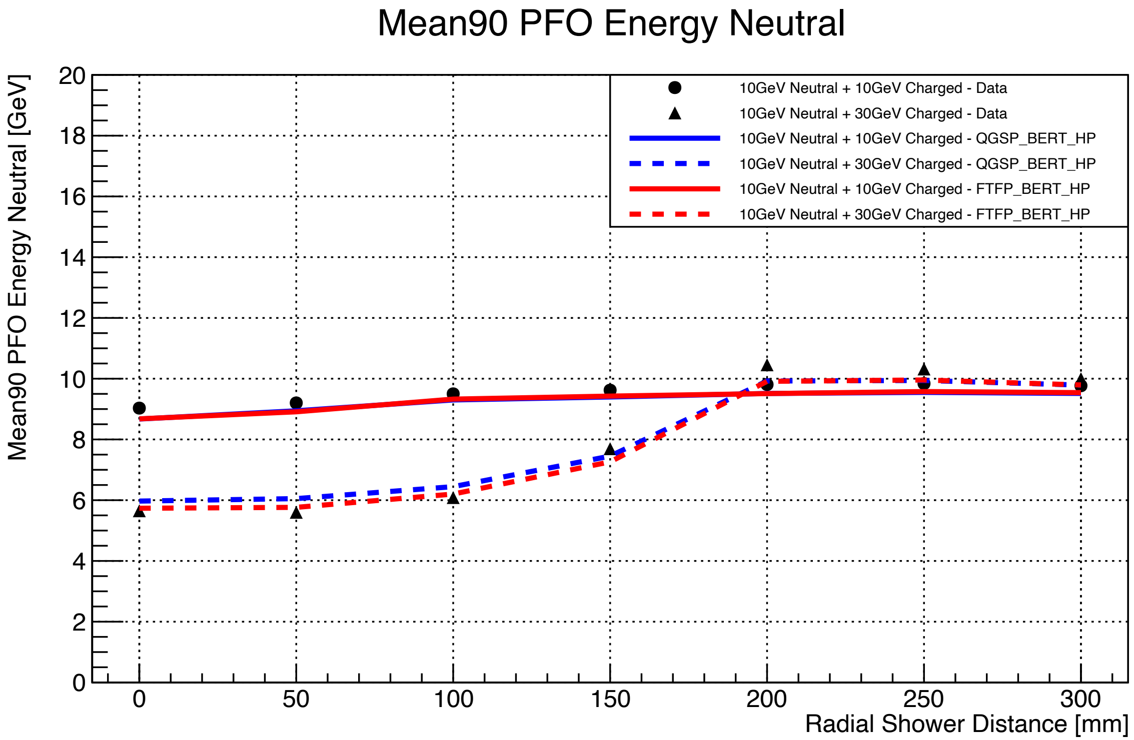


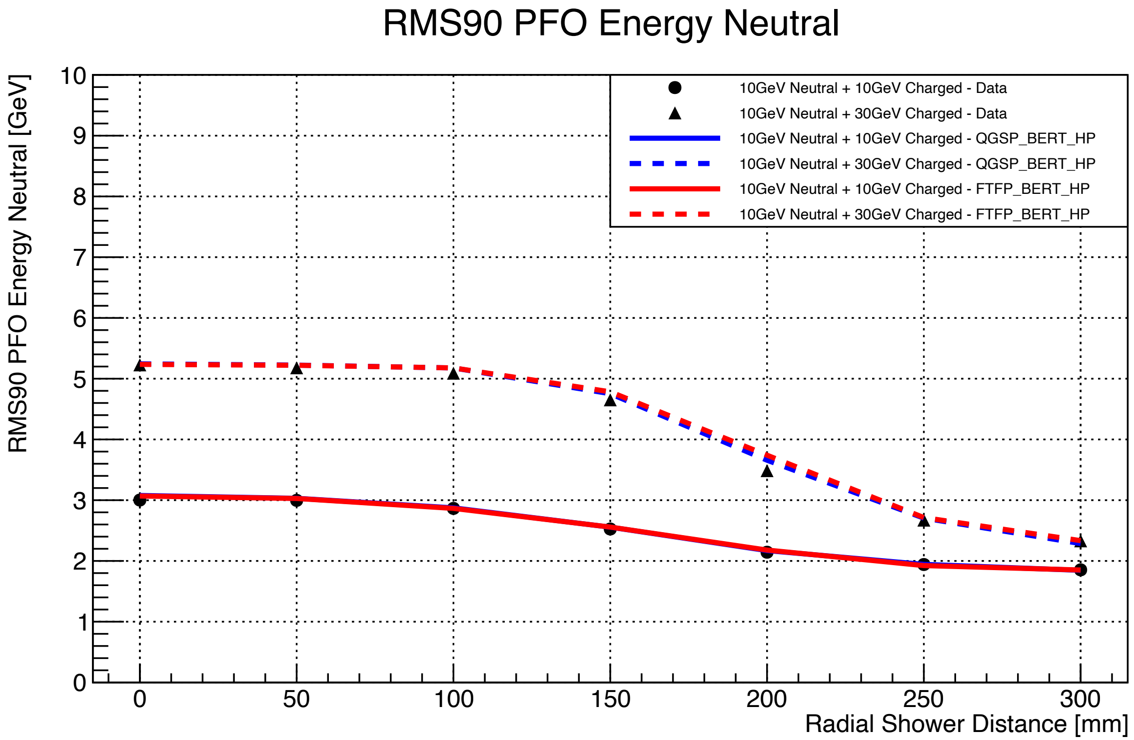


- General expectations: With decreasing shower distance and increasing charged hadron energy the fraction of confusion events (absorption - confusion type 1) is increasing

Mean90 & RMS90: PFO Energy Neutral Hadron

How much Absolute Energy is Reconstructed? How Precise?

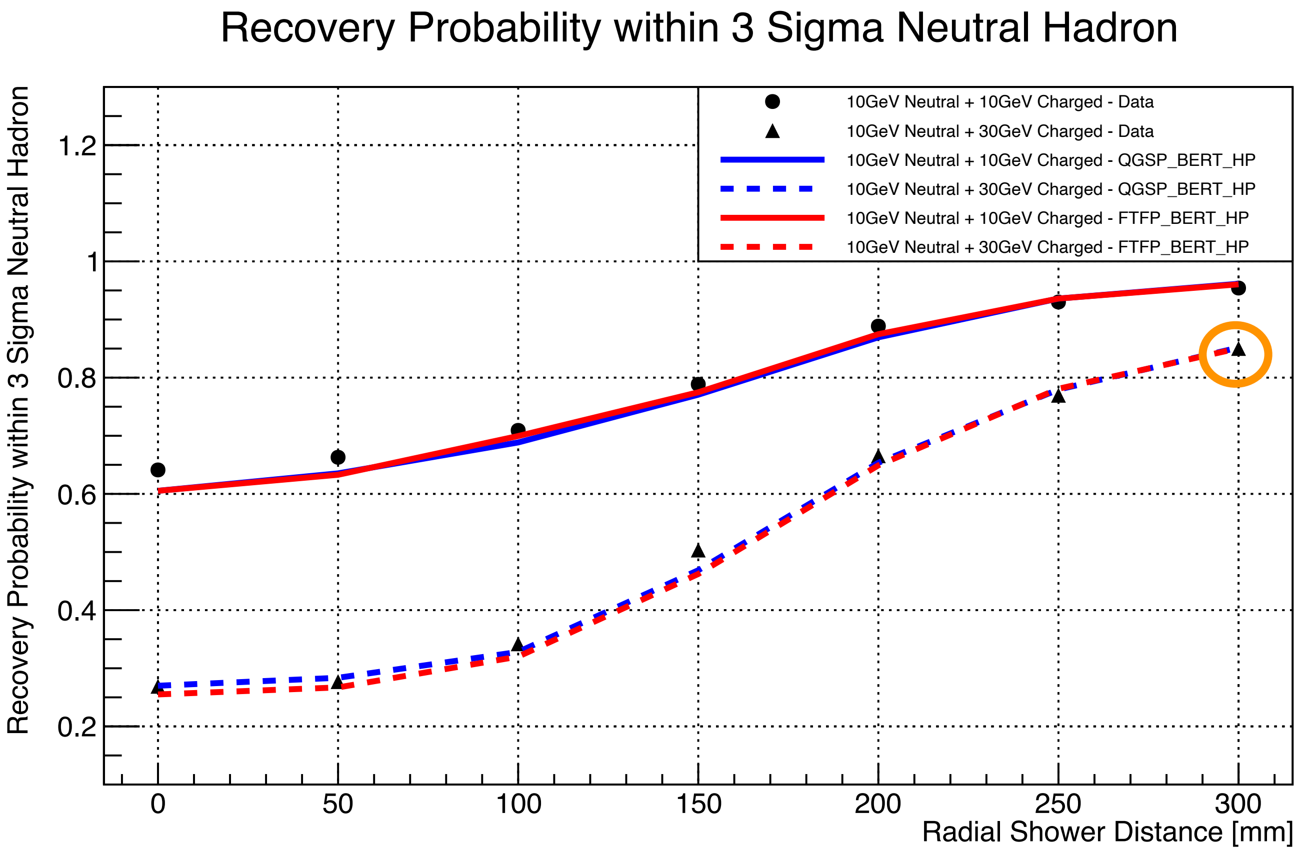


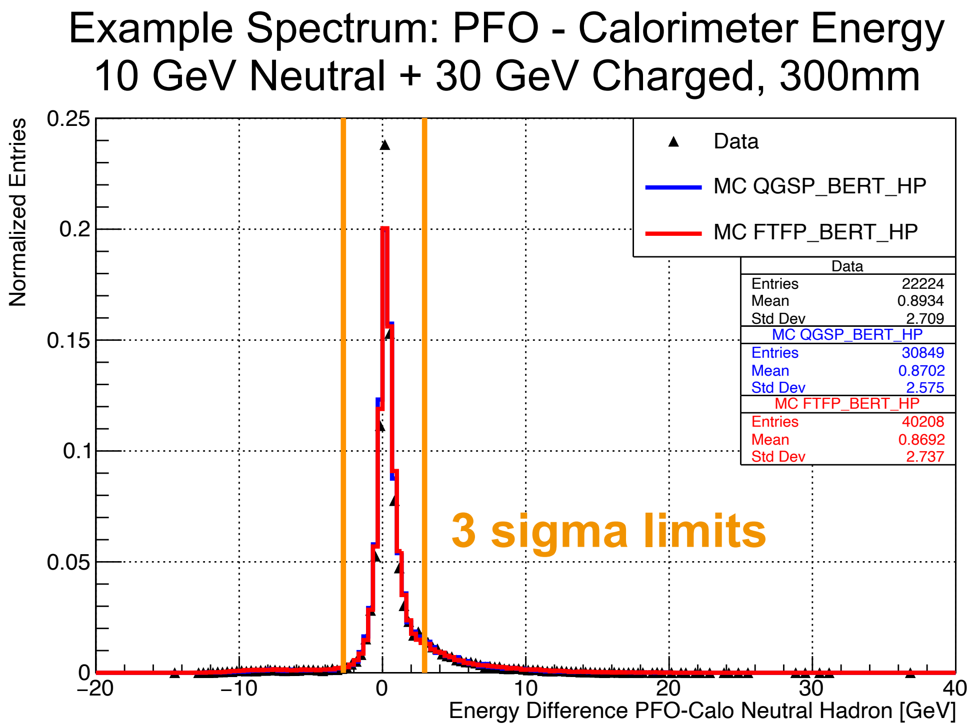


- The larger the shower separation the better and preciser the reconstruction of the 10 GeV neutral hadron
- More difficult in vicinity of 30 GeV charged hadron; good data/MC agreement within 5%
- Slight overestimation for mean at larger shower distances: **No confusion type 1** (absorption) anymore, **but remaining confusion type 2** (additional neutral fragments)

3 Sigma Recovery Probability of Neutral Hadron

How well is the Neutral Hadron Energy Recovered Compared to Input Energy?





- Definition sigma: Width of neutral hadron energy sum of calorimeter measurement
- Rising trend for larger separation due to less confusion; More difficult in vicinity of 30 GeV charged hadron
- Excellent data to MC agreement; Even for largest separations **remaining confusion type 2**

Results:

Efficiency & Purity

Reconstruction on Hit Level: Efficiency & Purity

Definitions

- Study reconstruction performance on hit level event by event: How many charged & neutral hits have been reconstructed as charged or neutral? (Info available from overlay procedure for MC and data!)

- Efficiency Definition: $\frac{Nhit_{reco,correct}}{Nhit_{input,total}}$

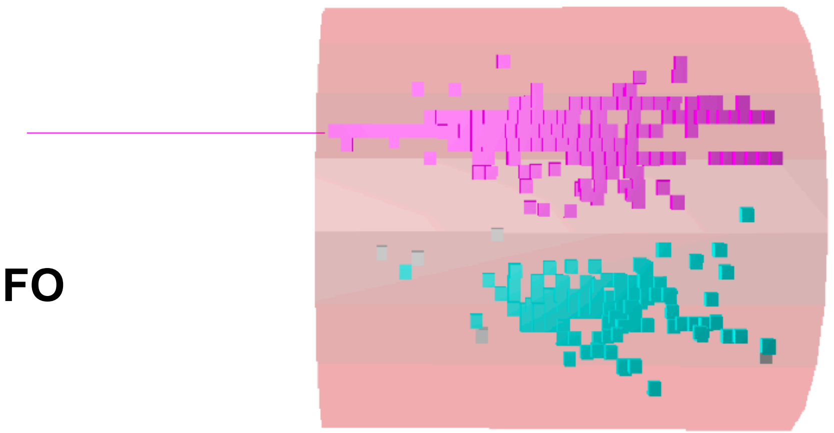
  Hits correctly reconstructed within PFO (numerator)

  All hits of input calorimeter shower (denominator)

- Purity Definition: $\frac{Nhit_{reco,correct}}{Nhit_{reco,total}}$

  Hits correctly reconstructed within PFO (numerator)

  All hits of reconstructed PFO (denominator)

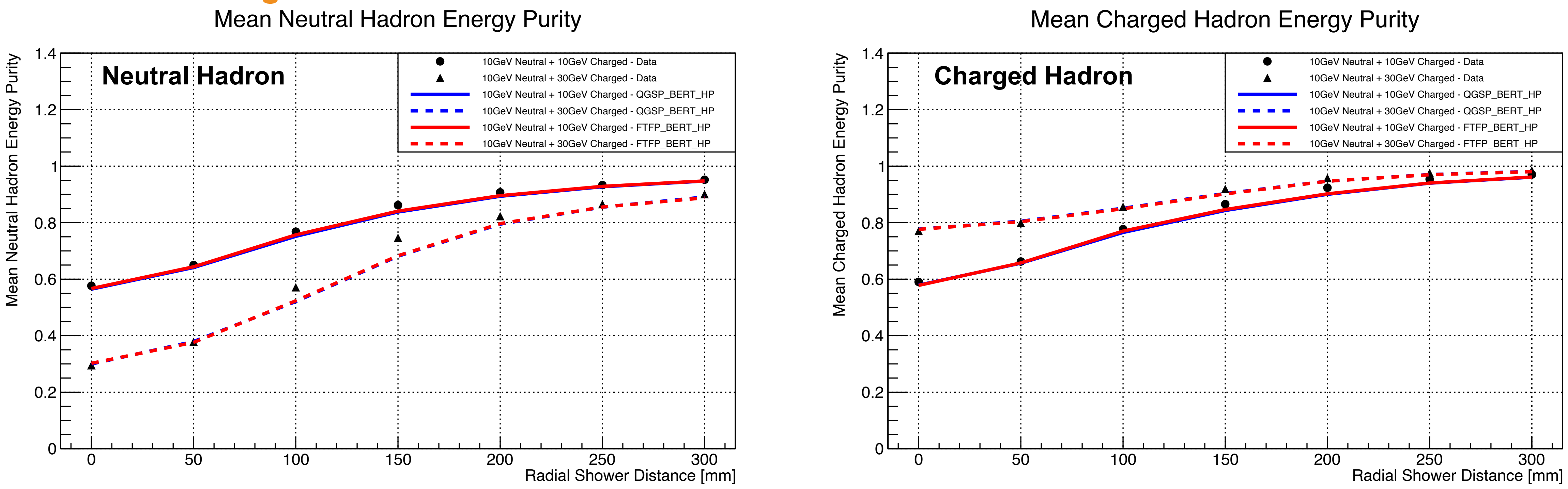


Magenta: Charged Hadron Hits
Cyan: Neutral Hadron Hits
Grey: Unclustered Hits

Same definitions can be made energy-wise

Reconstruction on Hit Level: Mean Energy Purity

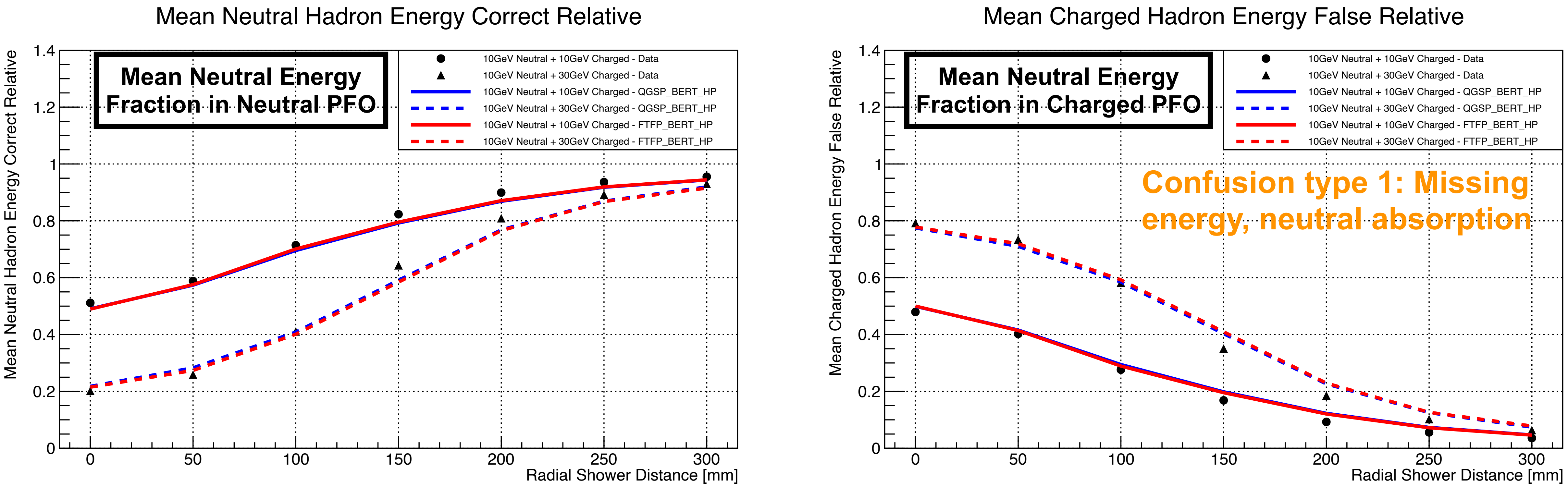
Neutral & Charged Hadron



- The larger the separation, the more pure (in terms of energy) the neutral and charged PFOs get
- Good data/mc agreement within 5%
- Neutral hadron: Remaining neutral fragments even for largest distances - **confusion type 2**
- Charged hadron: Almost non remaining absorption hits at largest distances - **confusion type 1**

Reconstruction on Hit Level: Mean Energy Efficiency

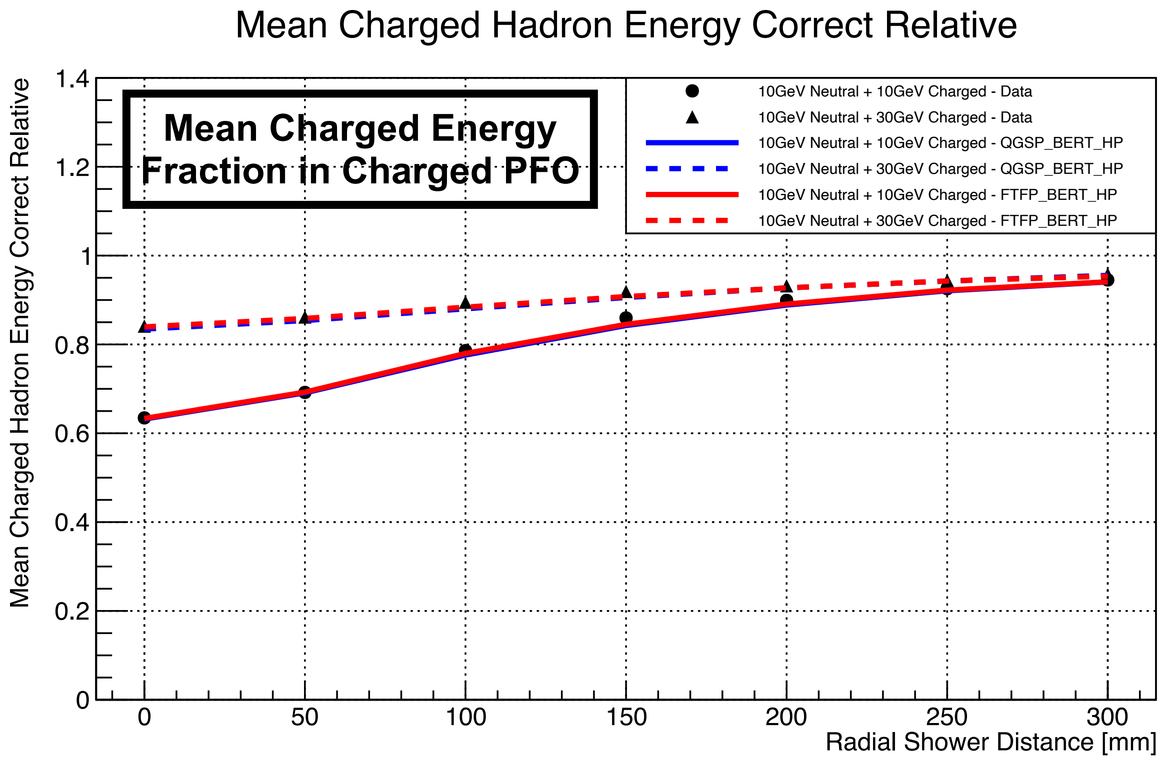
Neutral Hadron - Confusion Matrix Elements

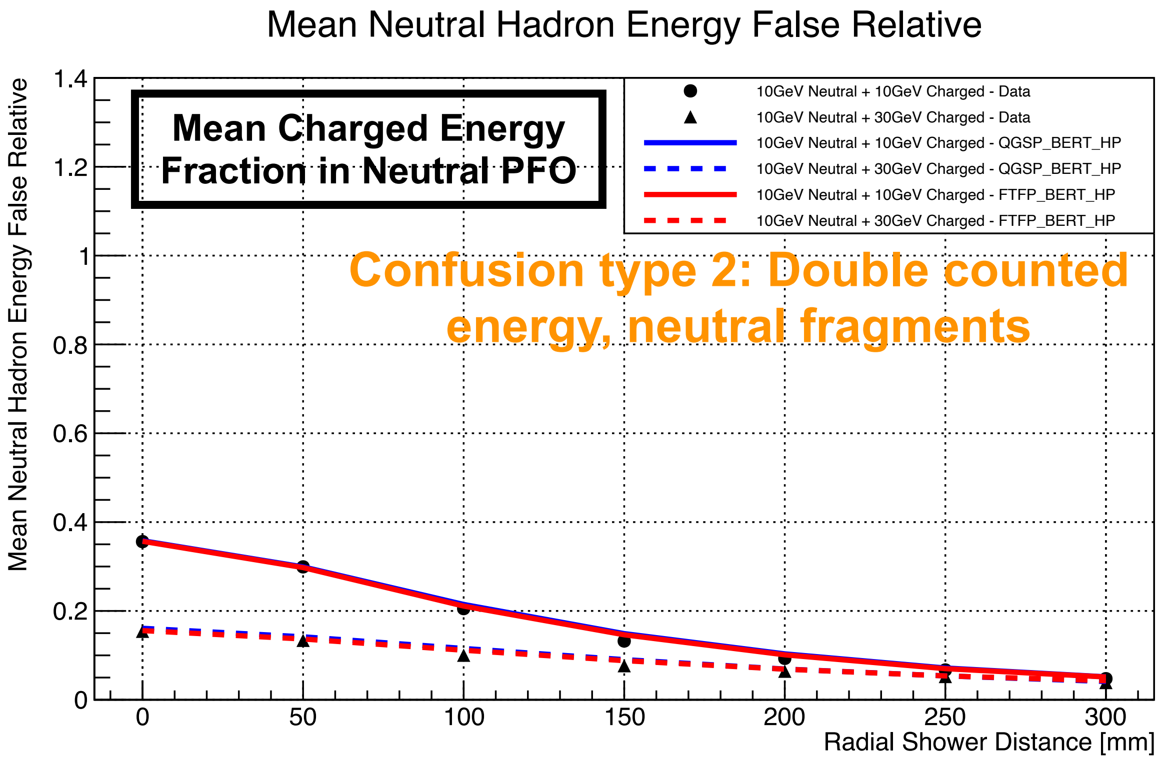


- With increasing shower distance (decreasing charged hadron energy) mean neutral energy efficiency grows
  - ➡ In other words: **Confusion type 1 is decreasing**
  - ➡ Confirmation on hit level and access to confusion matrix elements
- Good data to MC agreement within 5%

Reconstruction on Hit Level: Mean Energy Efficiency

Charged Hadron - Confusion Matrix Elements





- Due to energy difference to neutral hadron: 10 + 30 GeV scenarios better performance
- Confusion type 2 fractionally less dominant than type 1 for lowest, same level for larger distances
- Good data to MC agreement within 5%
- **How balanced are the types of confusion?**

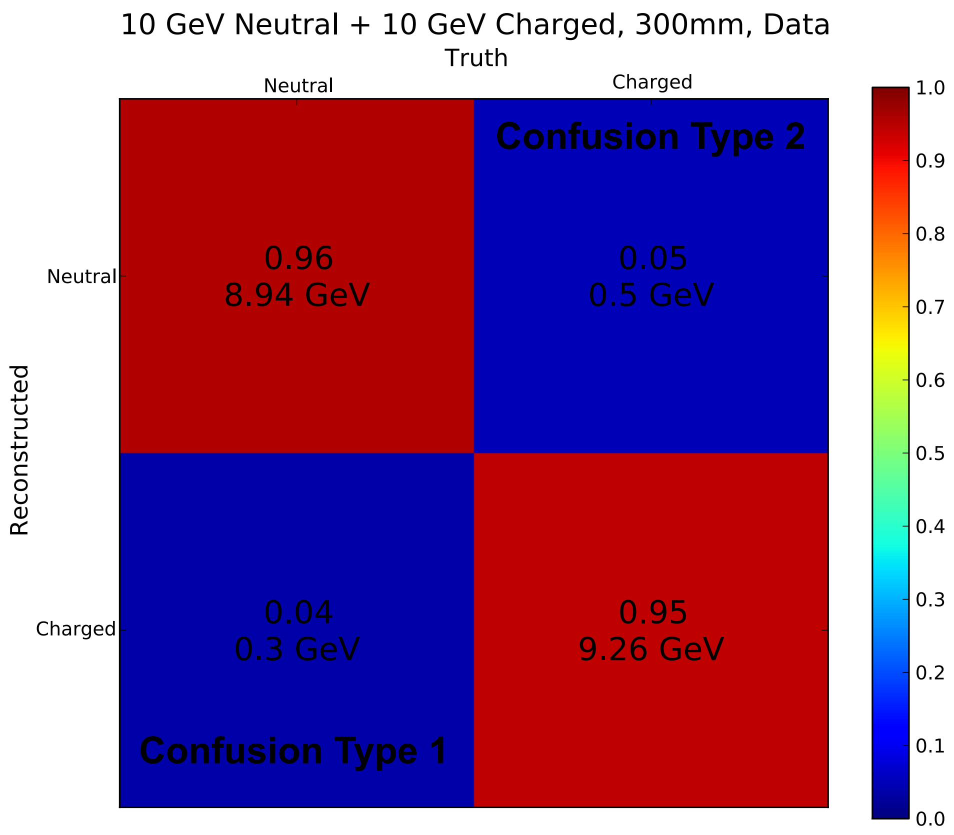
Results:

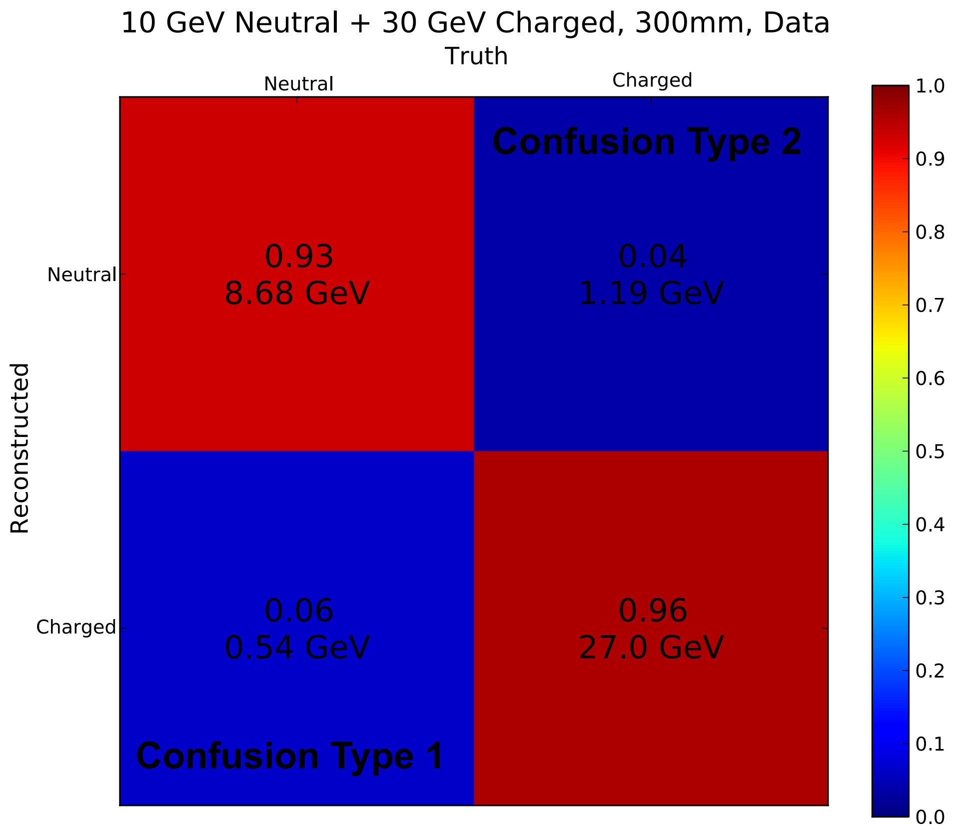
Confusion Matrices

Averaged Confusion Matrices

Separation: 300mm

Summarising the Total Confusion Level - Example Data





- Normalised to truth input energy (~1% missing on average due to isolated, unclustered hits)
- Mean absolute values not 10/30 GeV: Primary track removal (pseudo neutrals) & leakage (charged)
- **The larger the shower separation the less and the more balanced the types of confusion!**

Averaged Confusion Matrices

Separation: 250mm

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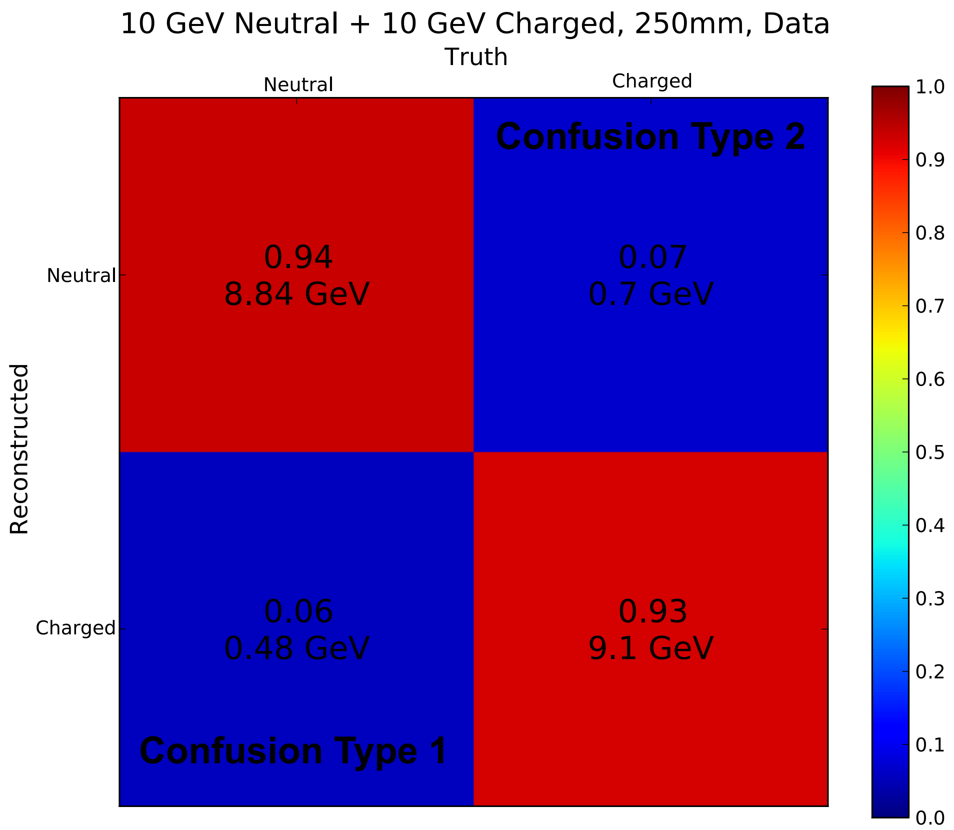

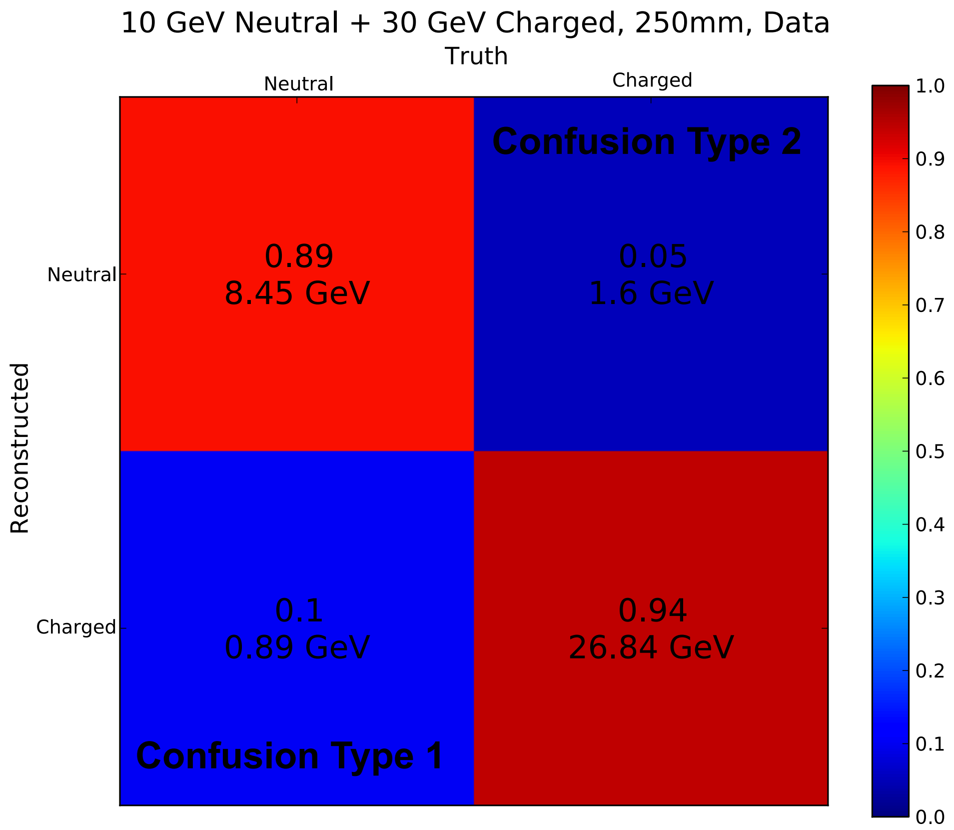

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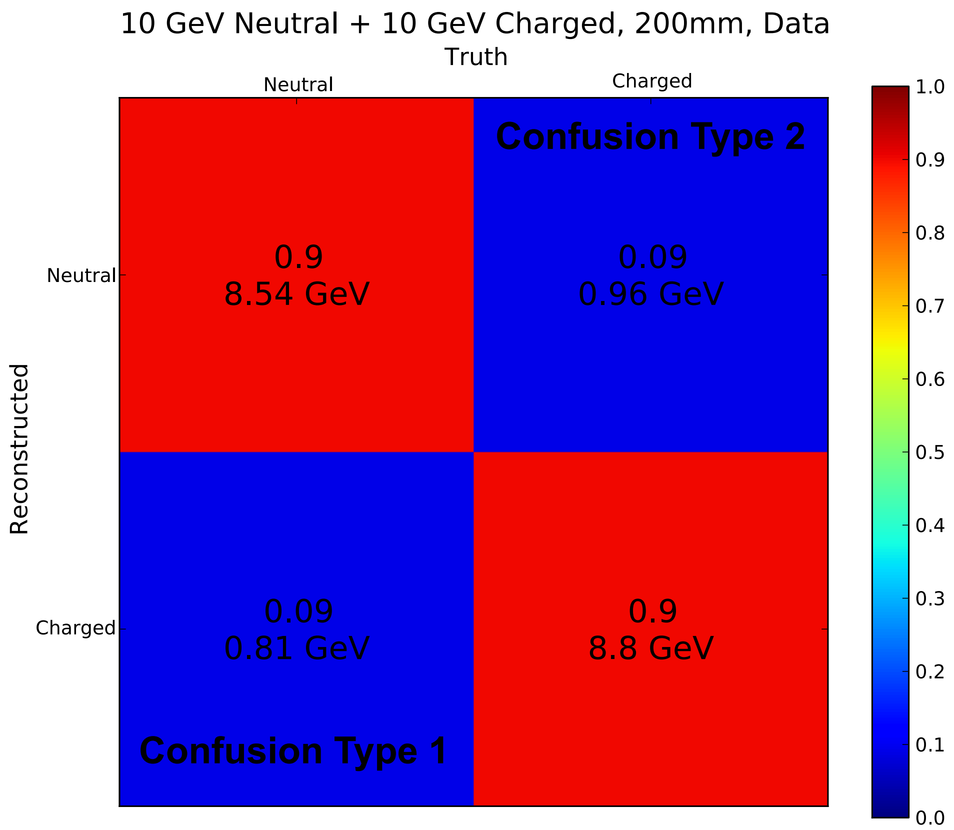
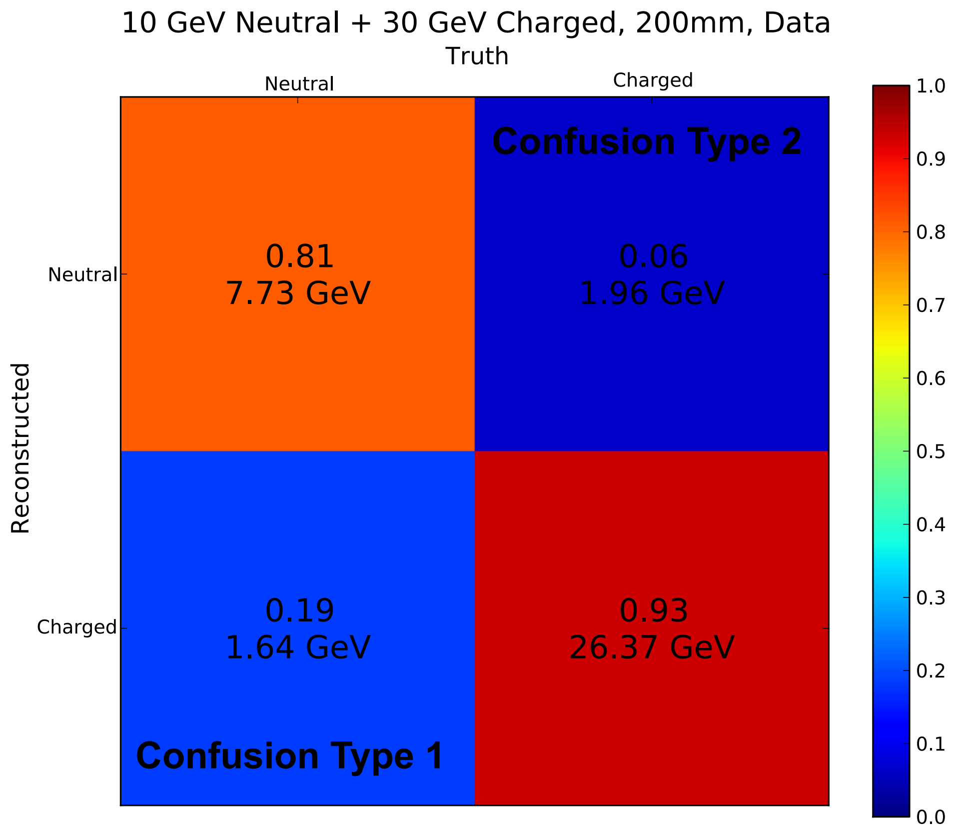
Averaged Confusion Matrices

Separation: 200mm

Summarising the Total Confusion Level - Example Data





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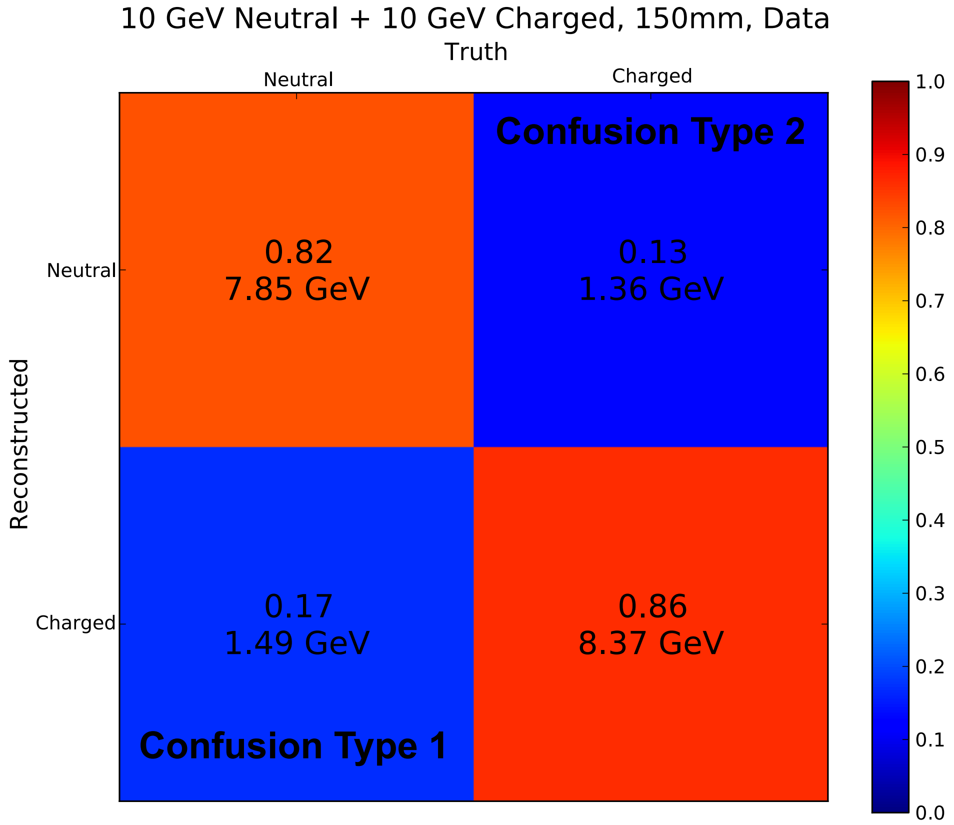
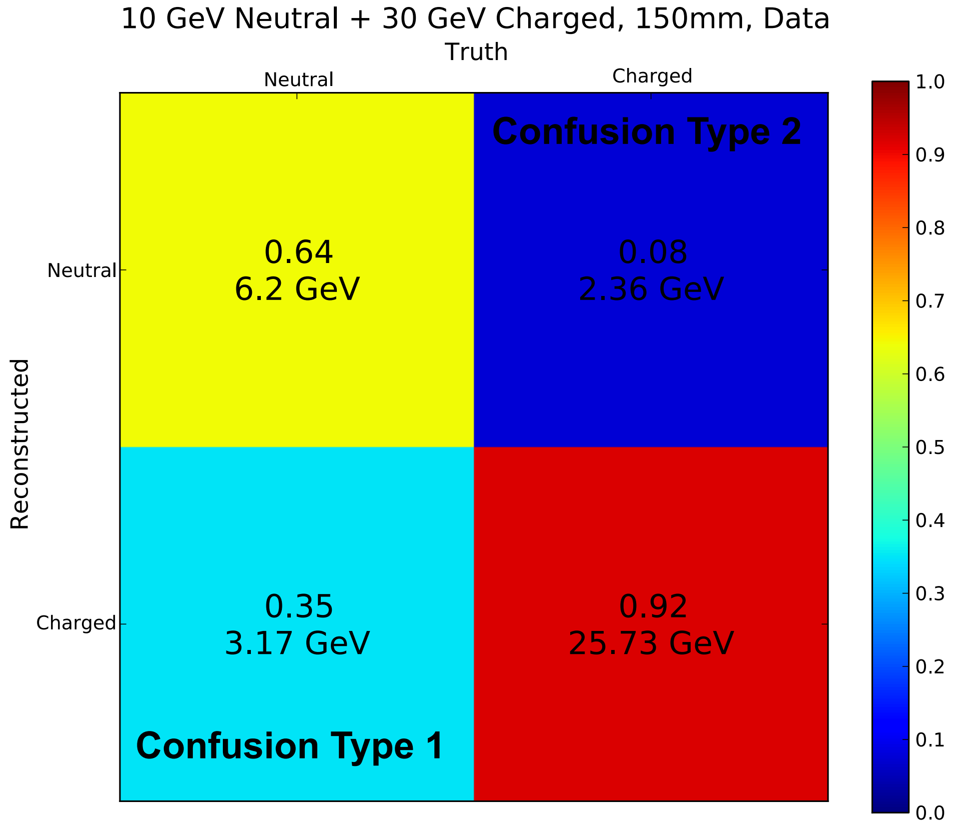
Averaged Confusion Matrices

Separation: 150mm

Summarising the Total Confusion Level - Example Data





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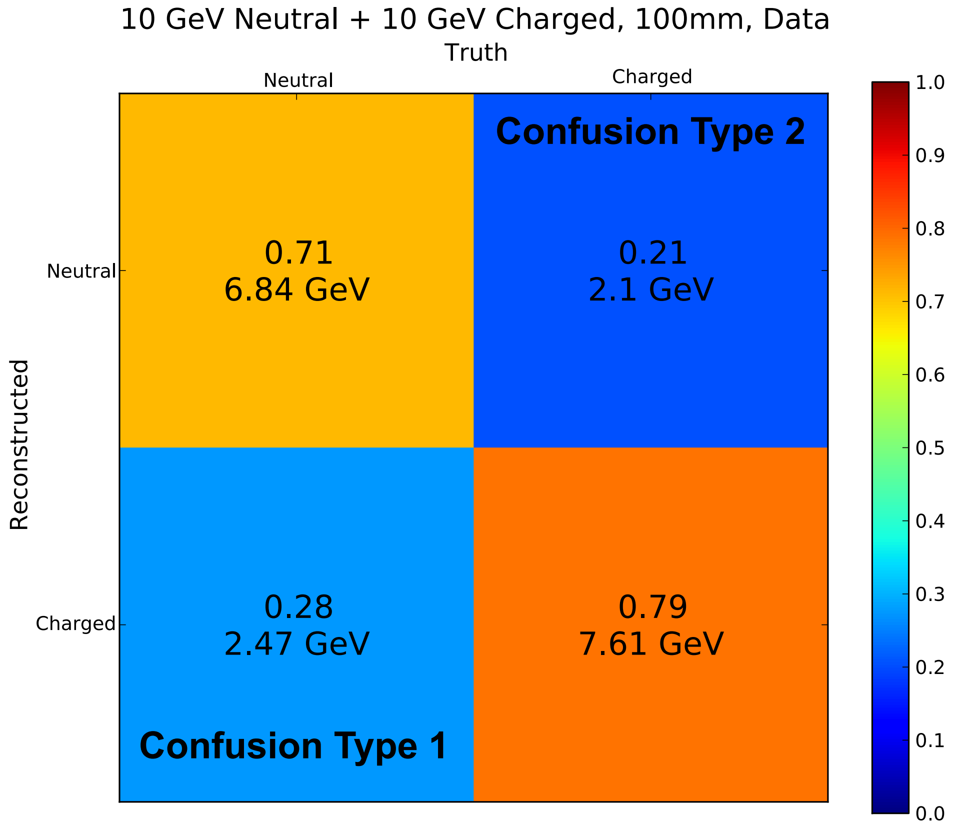
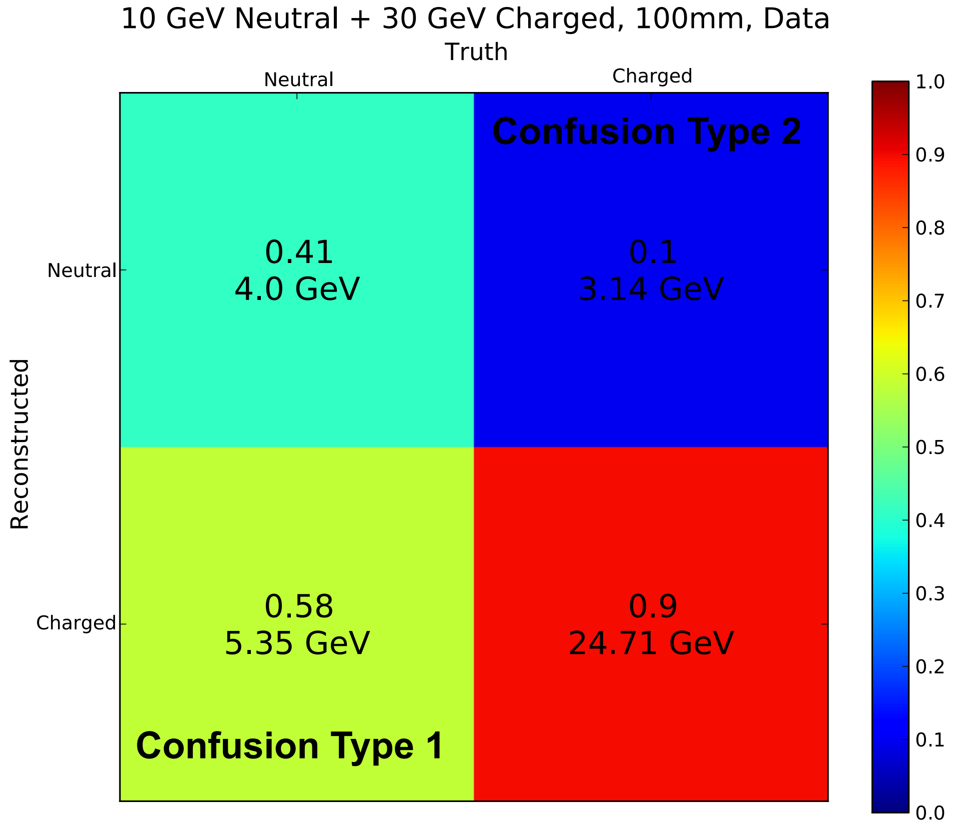
Averaged Confusion Matrices

Separation: 100mm

Summarising the Total Confusion Level - Example Data





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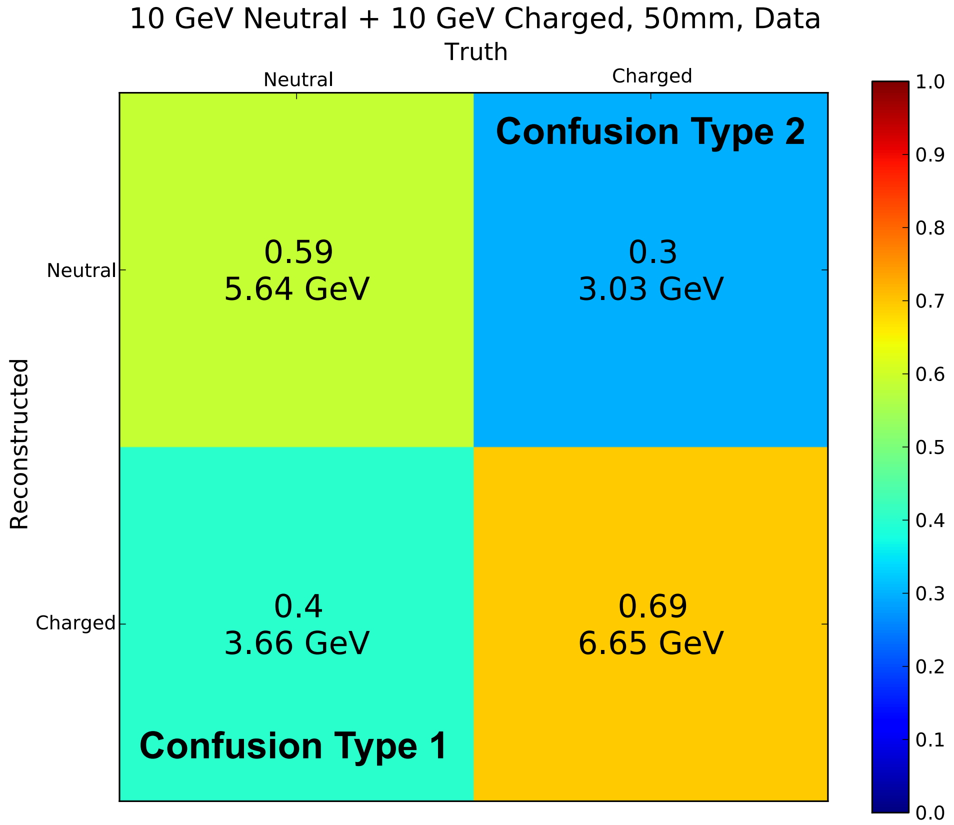
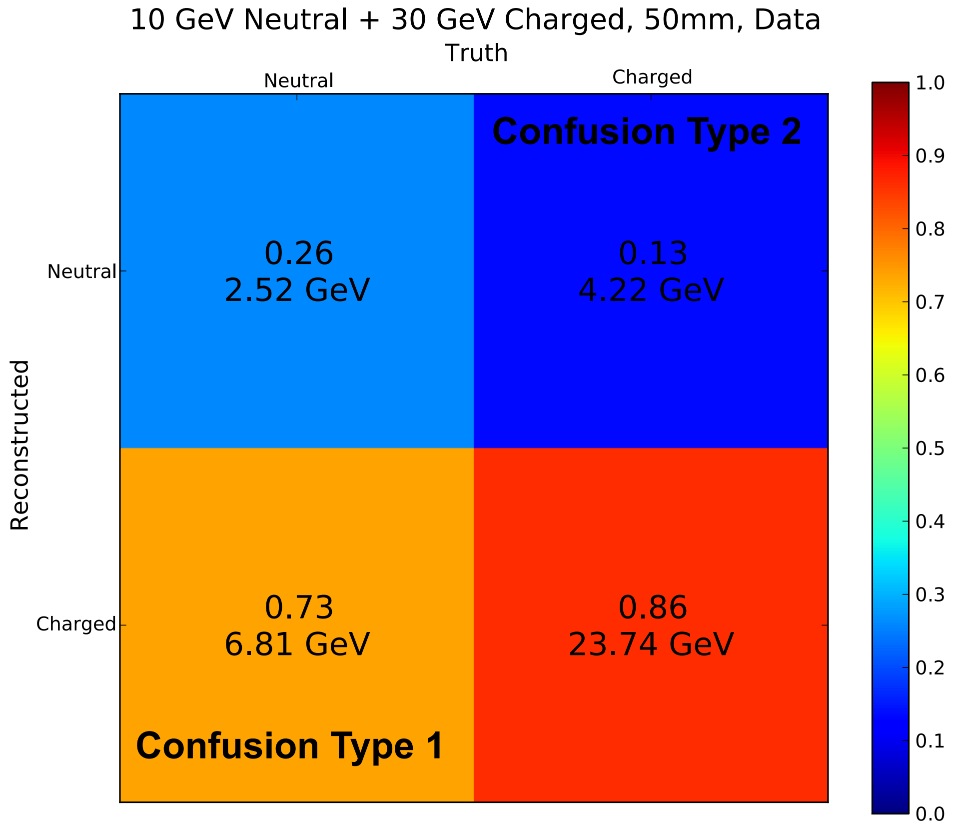
Averaged Confusion Matrices

Separation: 50mm

Summarising the Total Confusion Level - Example Data





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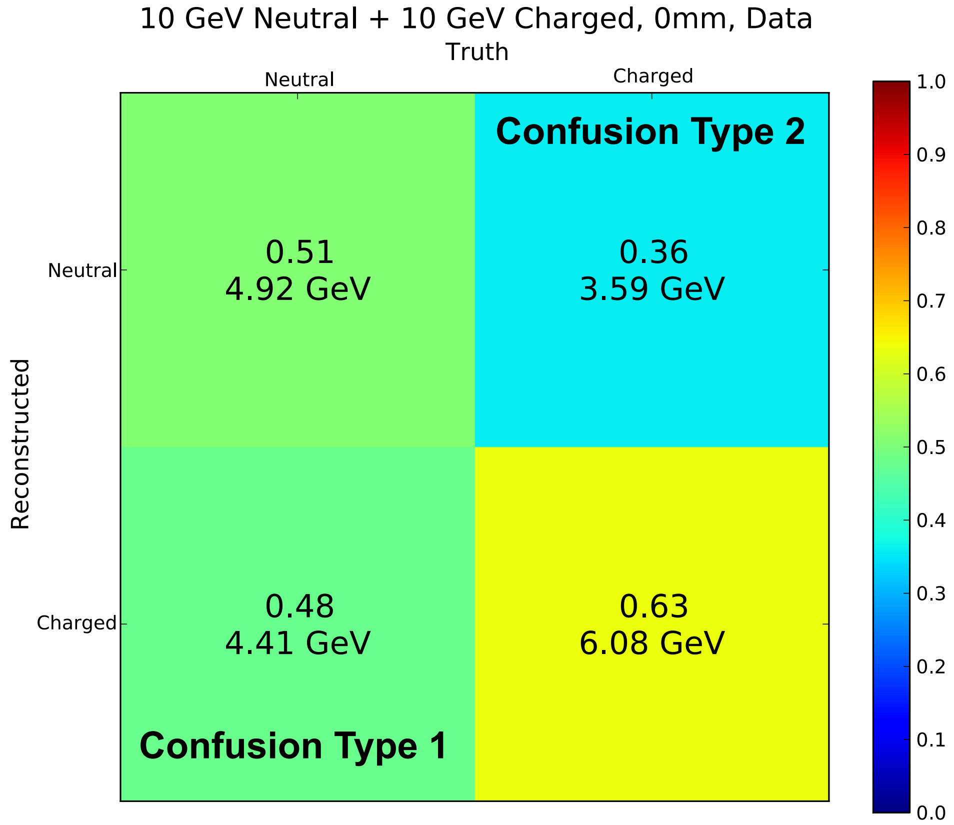
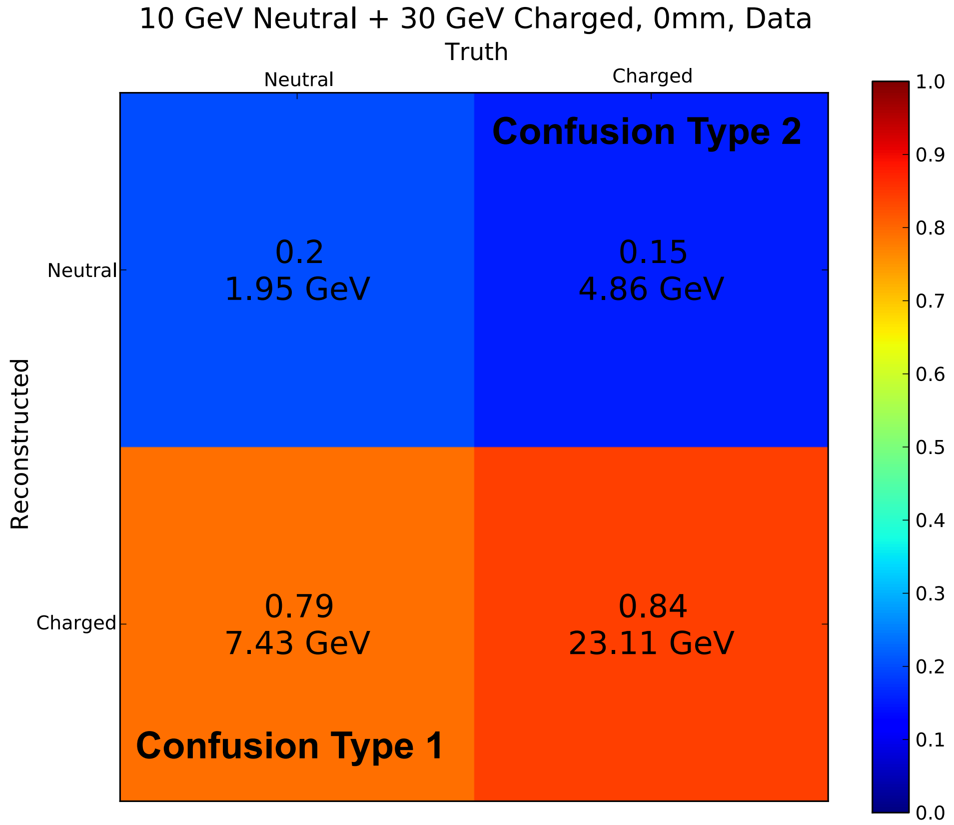
Averaged Confusion Matrices

Separation: 0mm

Summarising the Total Confusion Level - Example Data





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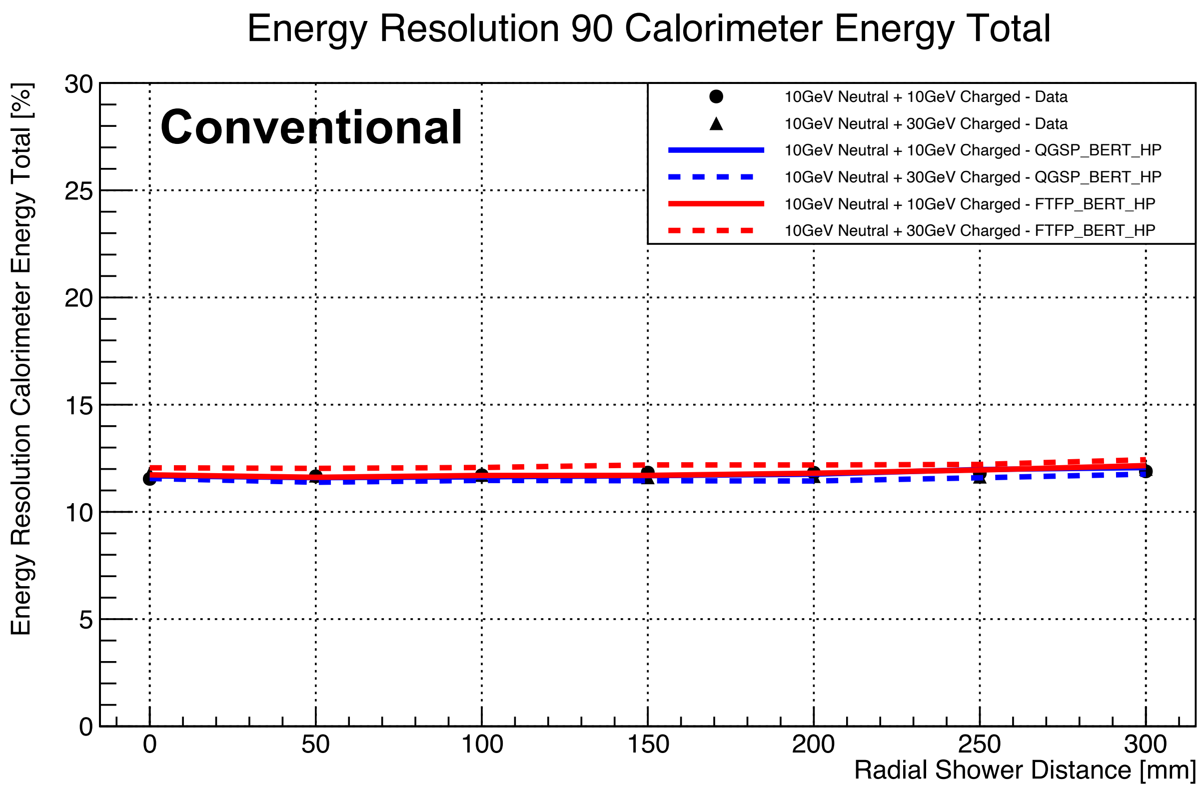
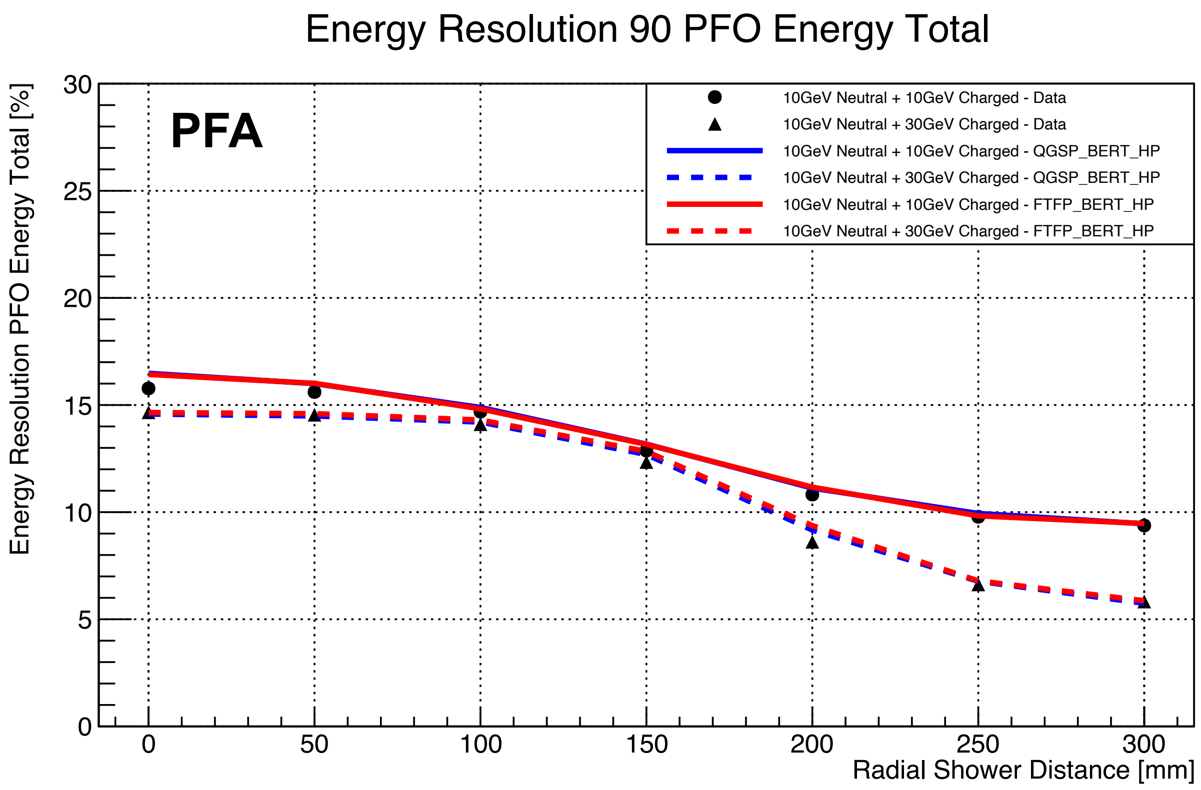
Results:

Total Reconstruction Performance

Total Energy Resolution

AHCAL Two Particle Events - Conventional vs. PFA





- For simple two particle event scenario (AHCAL) PFA pays off for shower distances > 150mm
  - ➡ Confusion gets on a small level and type 1 and 2 are more balanced

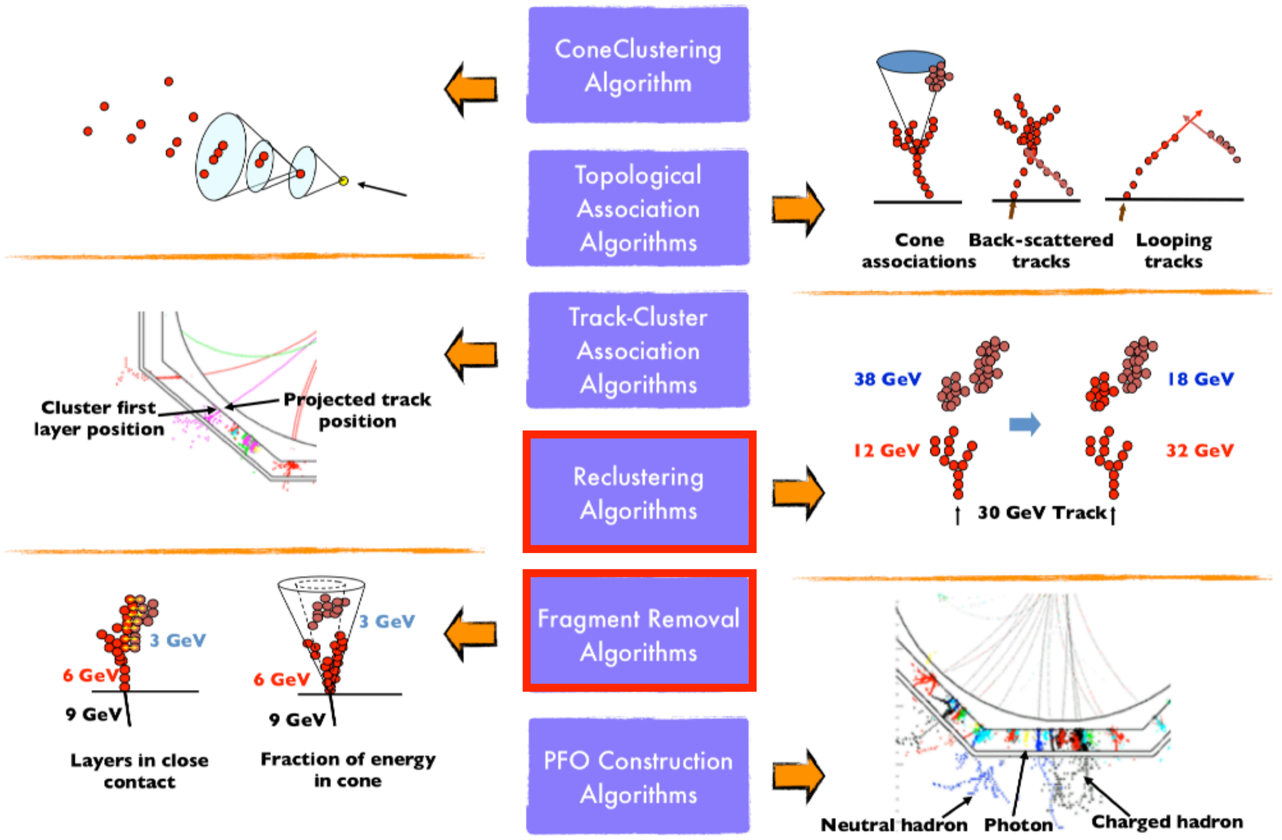
➡ Next: Confusion sensitive PFA parameters/algorithms? Behaviour in a more crowded scenario (ILD Jets)?

Results:

Confusion Sensitive PFA Parameters/Algorithms

Confusion Sensitive PFA Algorithms/Parameters

Investigating & Understanding the Magic of PandoraPFA

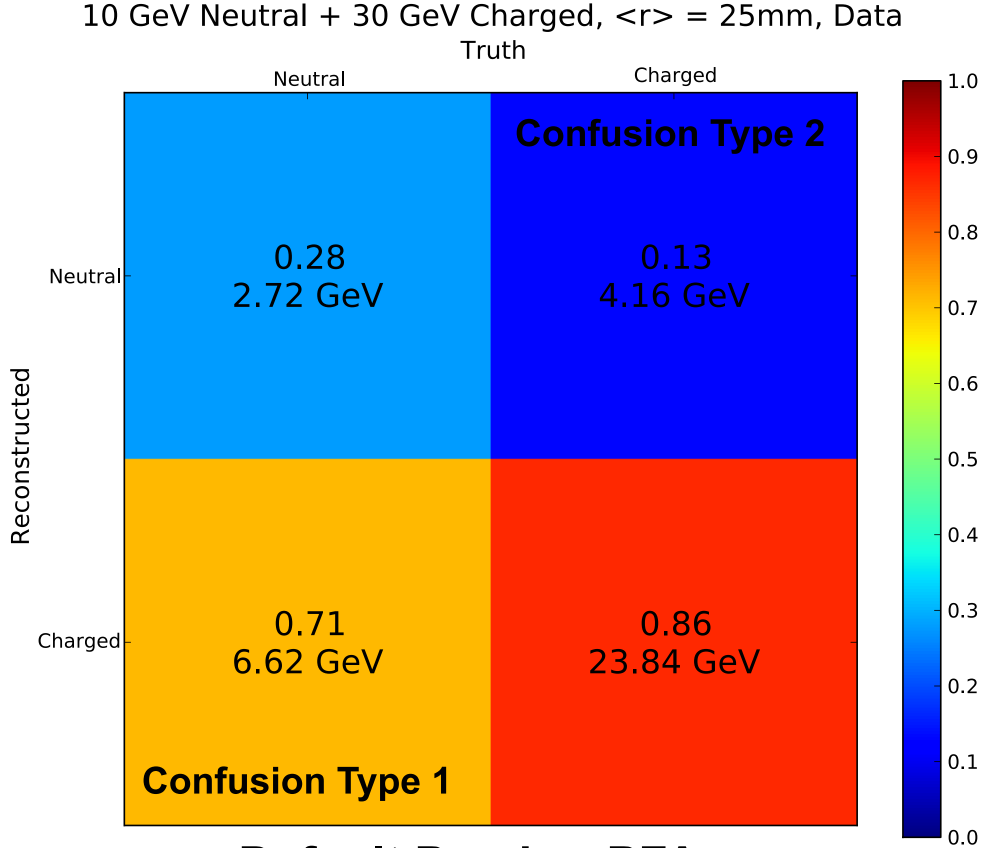


J. S. Marshall: https://indico.in2p3.fr/event/7691/contributions/42712/attachments/34375/42344/3_john_marshall_PFA_marshall_24.04.13.pdf

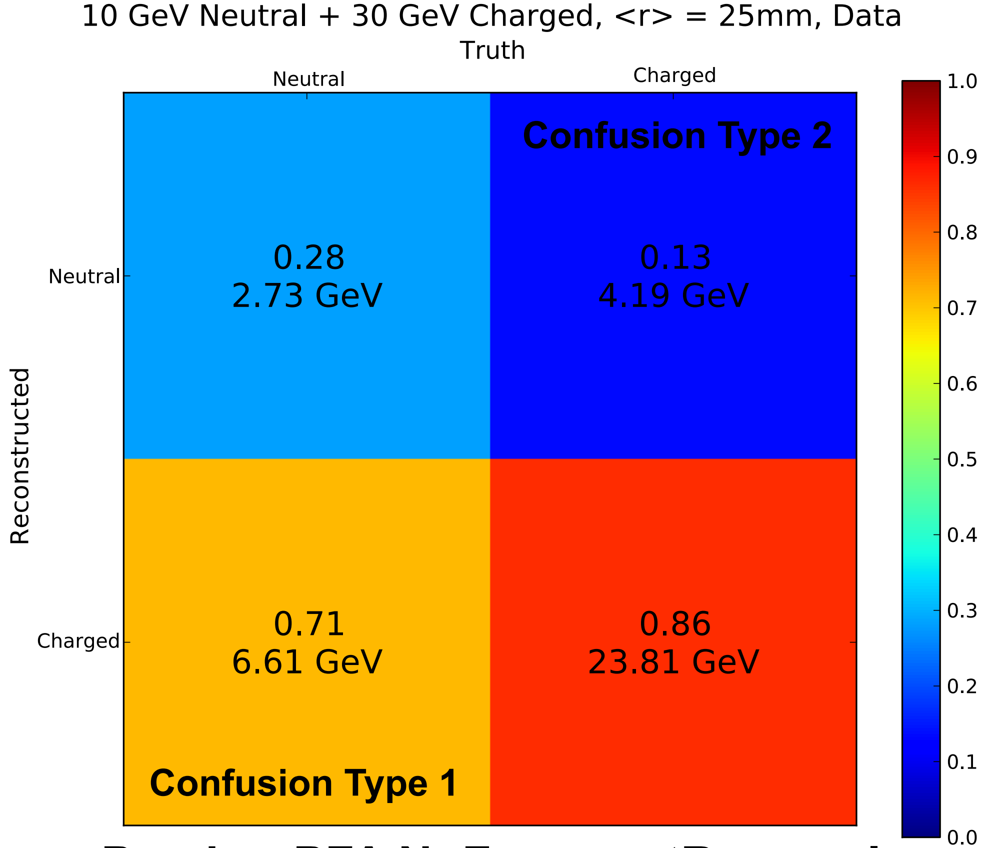
- Basic question: Which algorithms (parameters) within PandoraPFA are the most confusion sensitive?
  - ➡ Disable/change those to study and understand impact on confusion balance/energy resolution

Two Particle Reconstruction: Default vs. NoFragmentRemoval

Finding Confusion Sensitive Parameters/Algorithms, Data, 10 + 30 GeV, Overlapping



Default PandoraPFA

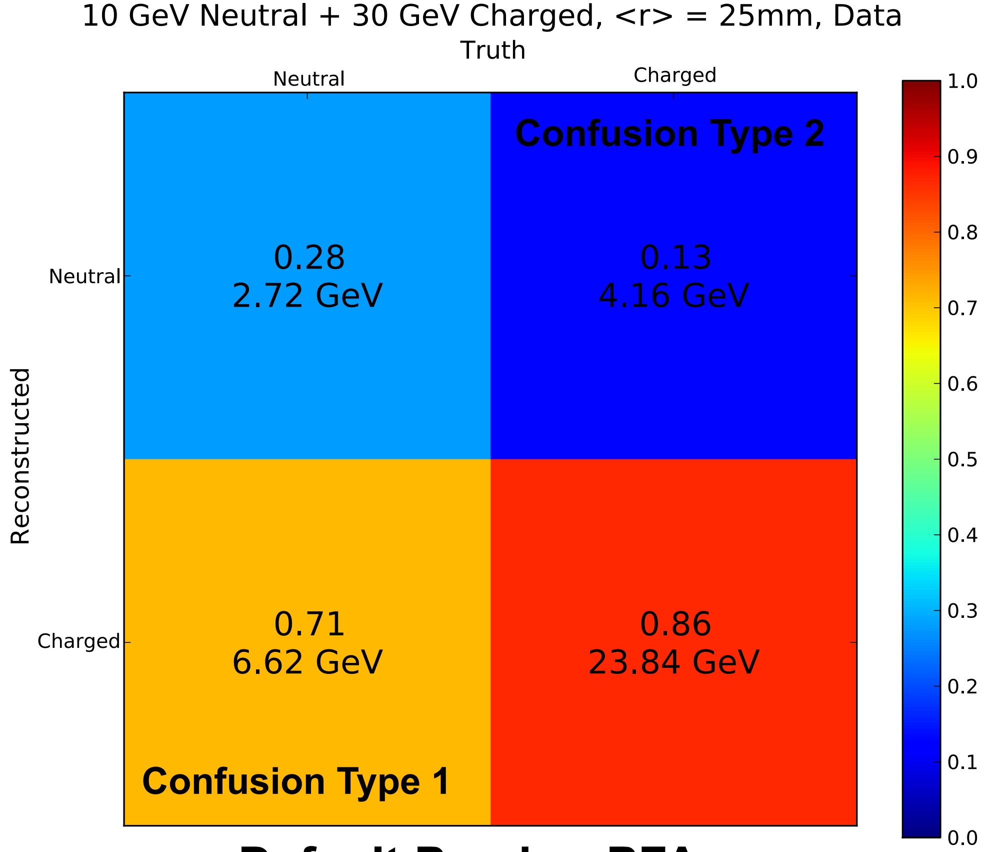


PandoraPFA NoFragmentRemoval

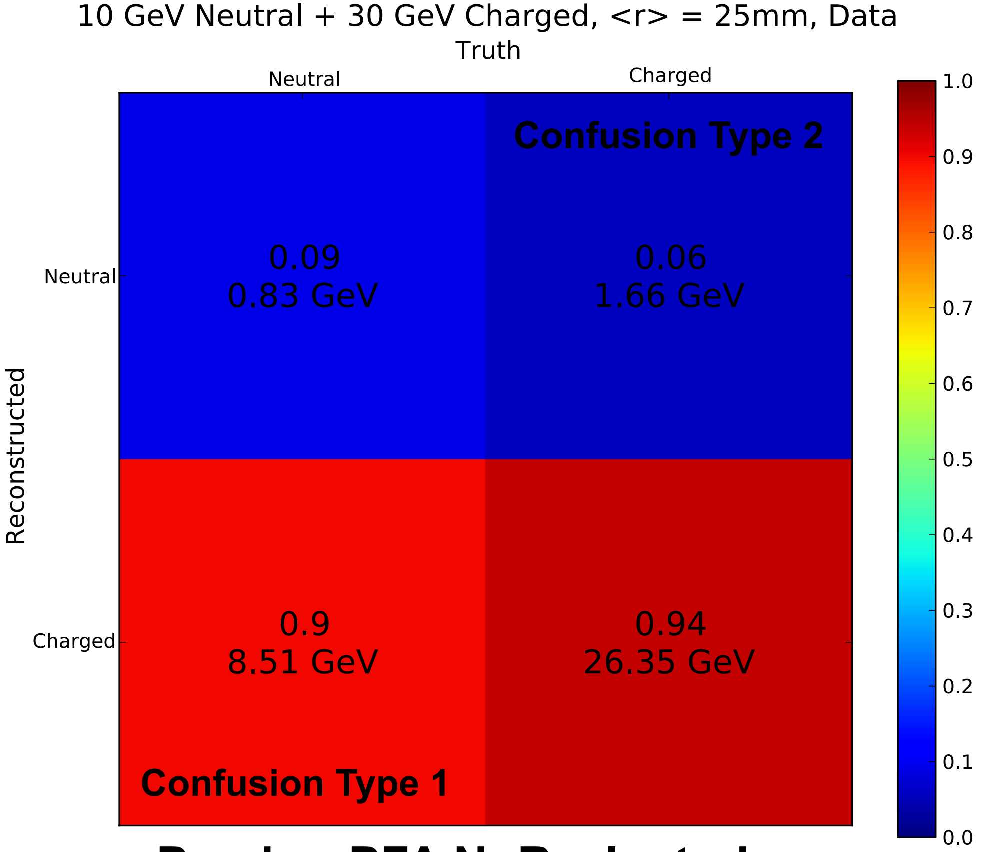
- Basically no difference between default PandoraPFA and PandoraPFA without fragment removal algorithms

Two Particle Reconstruction: Default vs. NoReclustering

Finding Confusion Sensitive Parameters/Algorithms, Data, 10 + 30 GeV, Overlapping



Default PandoraPFA



PandoraPFA NoReclustering

- As expected: Large influence on confusion by disabling full re-clustering iterations within PandoraPFA
  - ➡ Type 1 gets more, type 2 gets less - **large in-balance**
  - ➡ Approach to be studied and compared to ILD jets

Summary & Conclusion

PandoraPFA Two Particle Event Reconstruction

- Established well working PandoraPFA environment for reconstruction of AHCAL 2018 standalone events
- Pseudo-neutral + charged hadron event studies:
  - ➡ Promising performance for standalone application in terms of neutral hadron energy recovery
  - ➡ Overall tendencies of observables (for different shower distances & energies) as expected
  - ➡ Beam Data vs. MC in good agreement (5%)
  - ➡ Disentanglement of confusion type 1 and type 2 (on truth hit level)
  - ➡ Identified confusion sensitive PFA algorithms and parameters for further studies

- Next: Continue detailed ILD jet confusion studies
  - ➡ Trends and balance of confusion types and influence on jet energy resolution
    - ➡ Different PFA algorithm options and parameters
    - ➡ Influence of changing energy thresholds

Outlook:

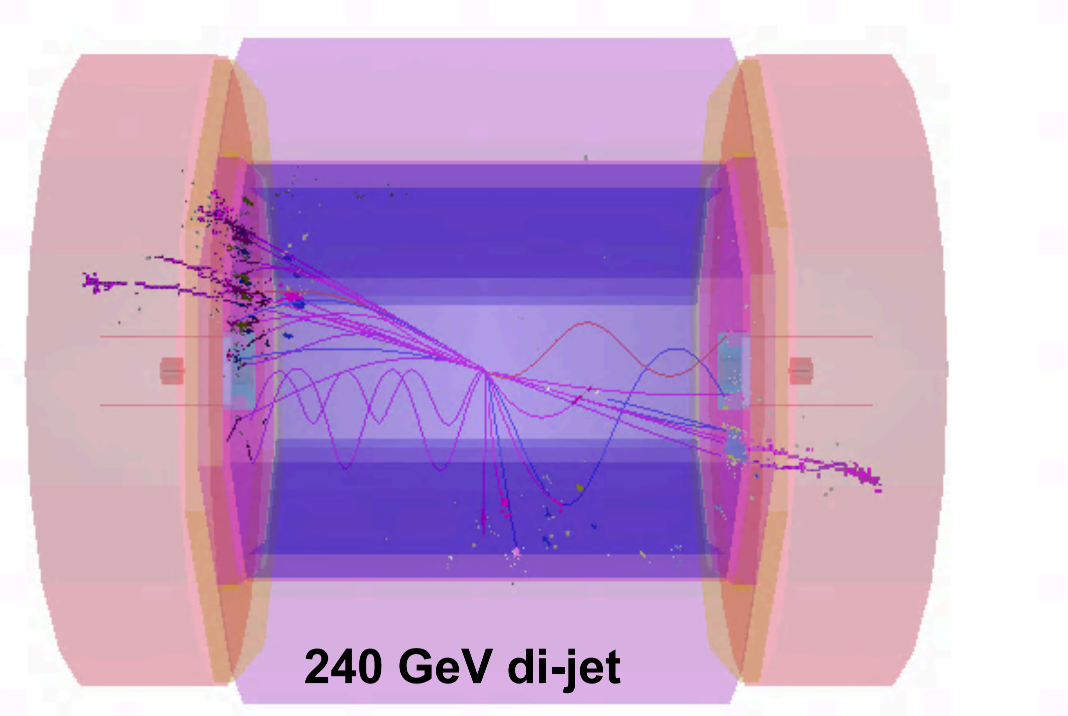
Confusion Studies with ILD Jets

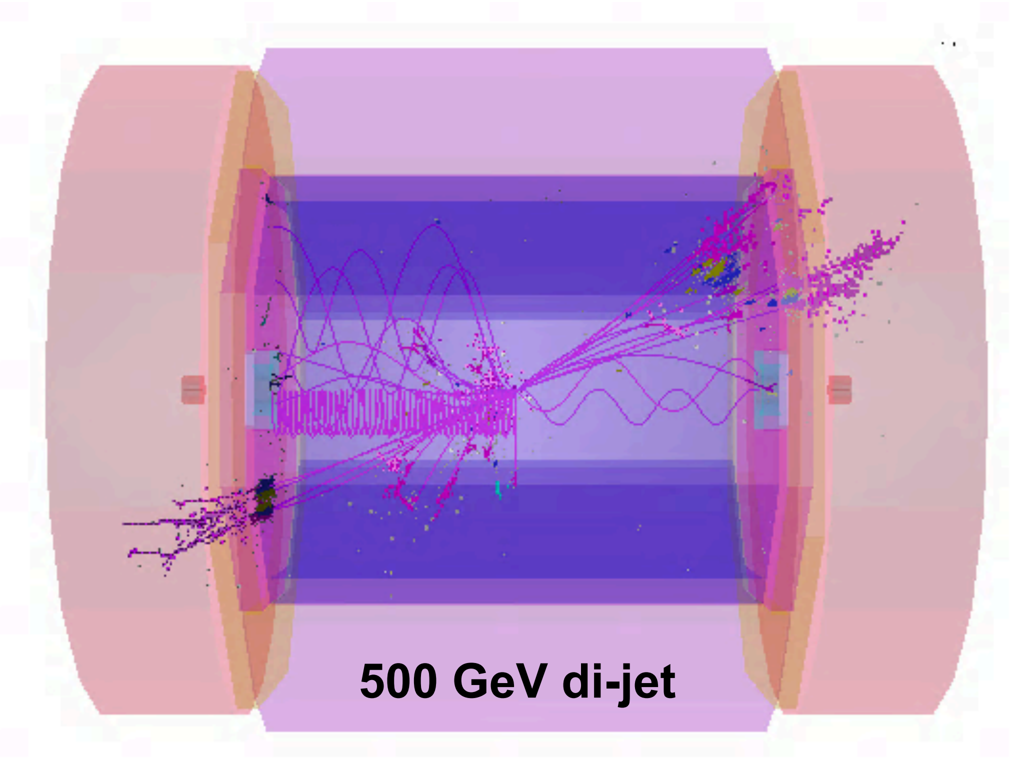
First Look

ILD Jets

Status

PFA Reconstruction, PFO Analysis & Event Displays Running!

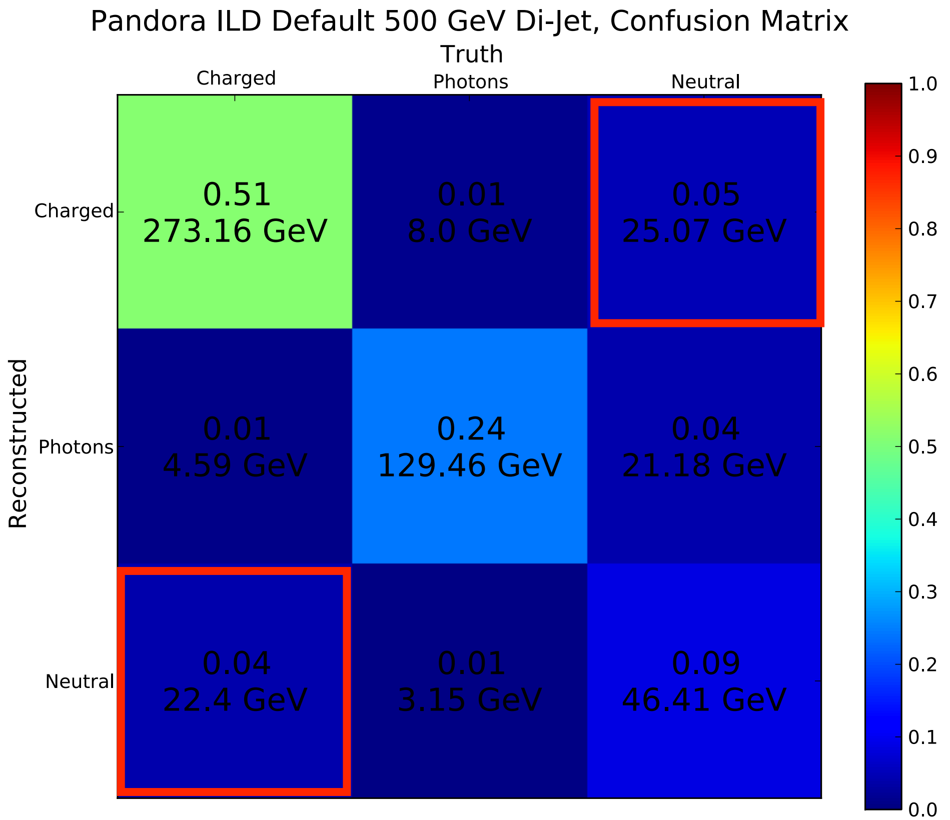




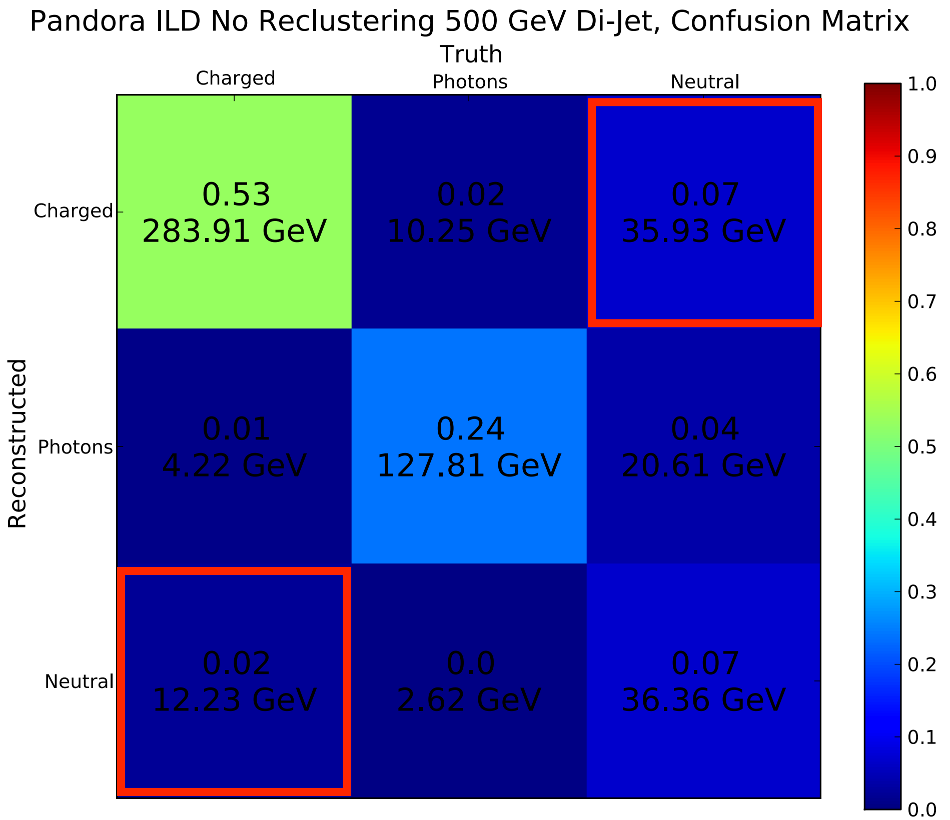
- JER calibration samples for ILD: Di-jet, back to back, light quarks: uds, event energies: 40-500 GeV
- Latest detector models (ILD_l5_o1_v02) and lc_geo versions

ILD Jets - Confusion Matrix - Pandora Default vs. NoReclustering

First Comparison



Default PandoraPFA

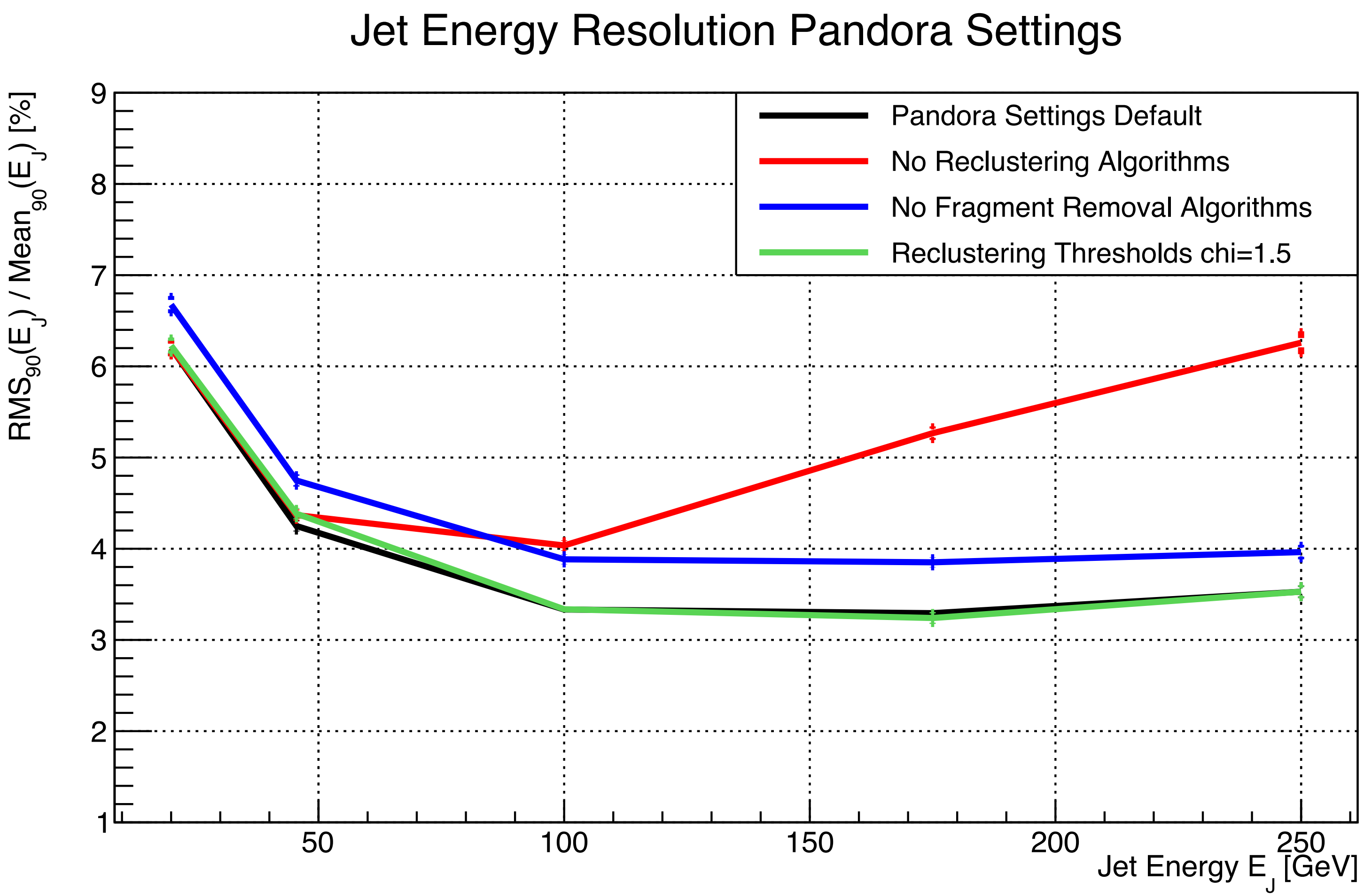


PandoraPFA NoReclustering

- Confusion matrices normalised to full event energy (not to individual MCTruth charged/neutral energy)
- **Same trend as for AHCAL only studies: For no-reclustering reconstruction larger in-balance**

Jet Energy Resolution

First Look for Different PandoraPFA Settings



Caution:
Work in progress

No selection of central jet angles/ jet observables (thrust, etc.) yet

- Default Pandora settings best and optimised as expected
- No Fragment Removal: Constant degradation of JER; No Reclustering: Degradation of JER mostly at higher E

Backup

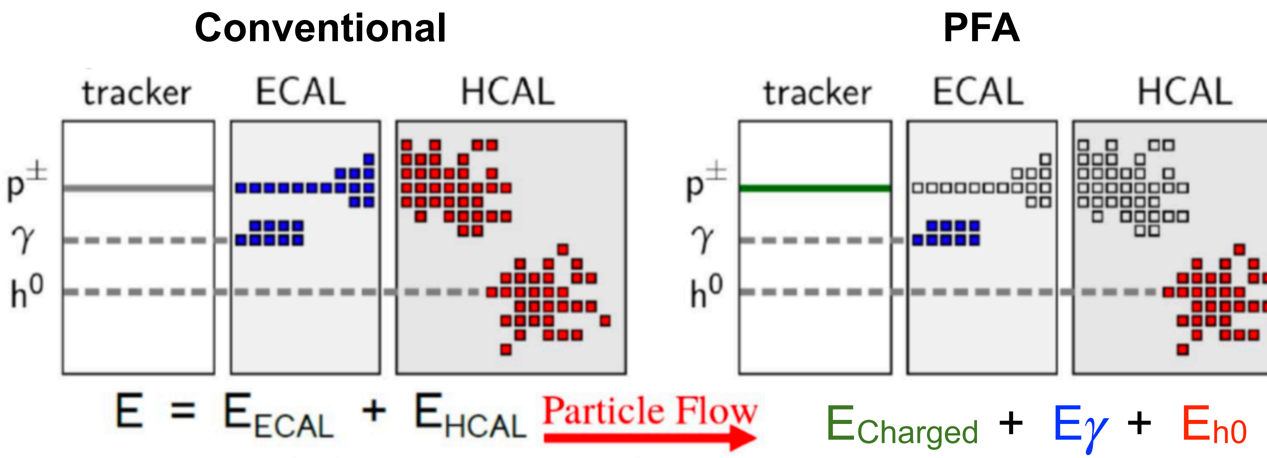
Particle Flow Approach

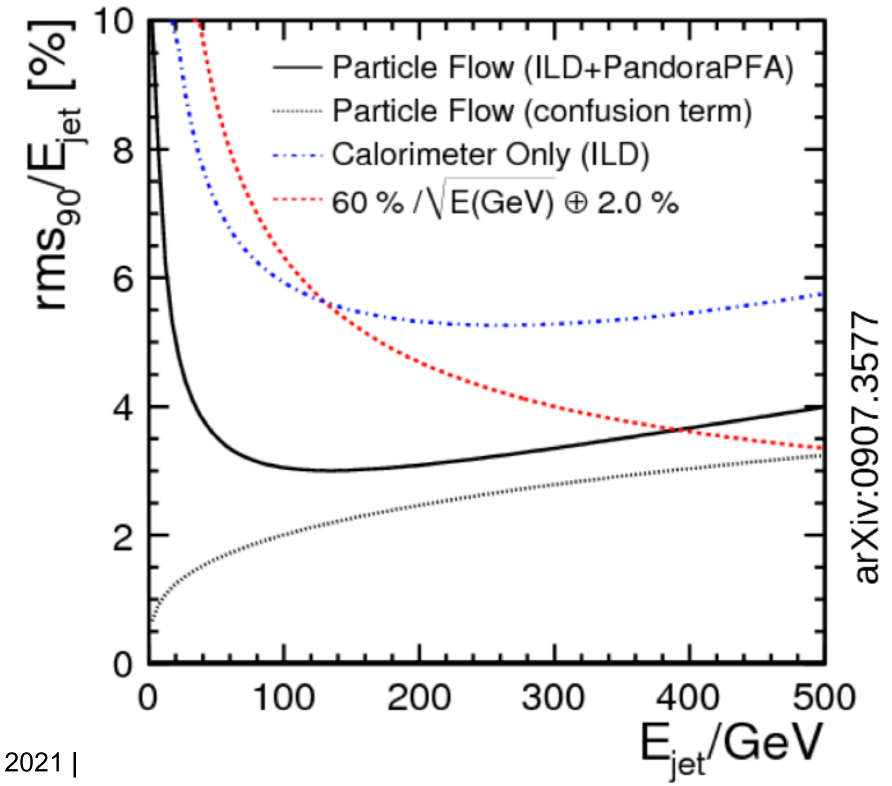
Reaching High Precision

- 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

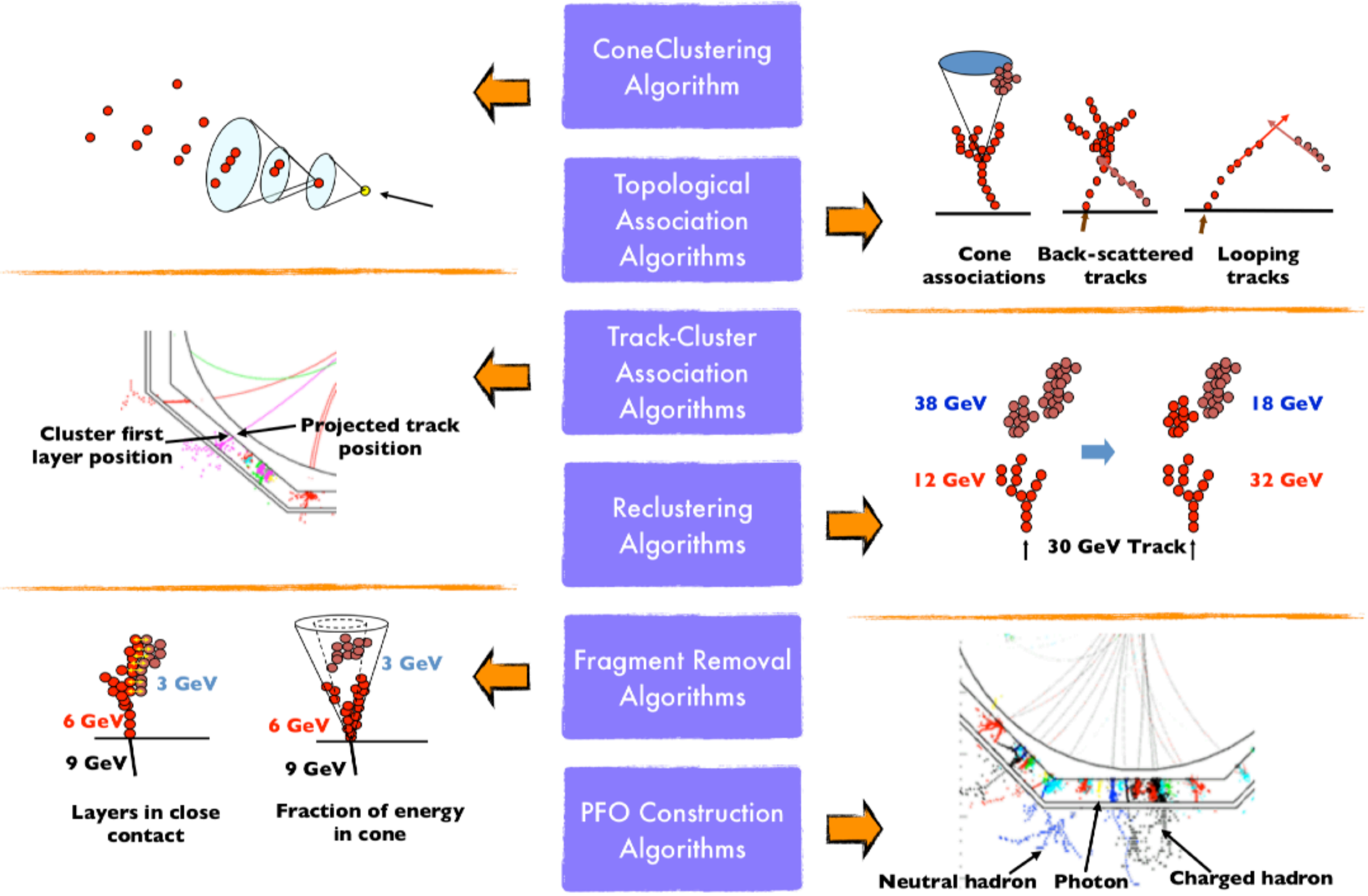




The Pandora Particle Flow Algorithm (PandoraPFA)

A Multi-Algorithm Pattern Recognition Tool

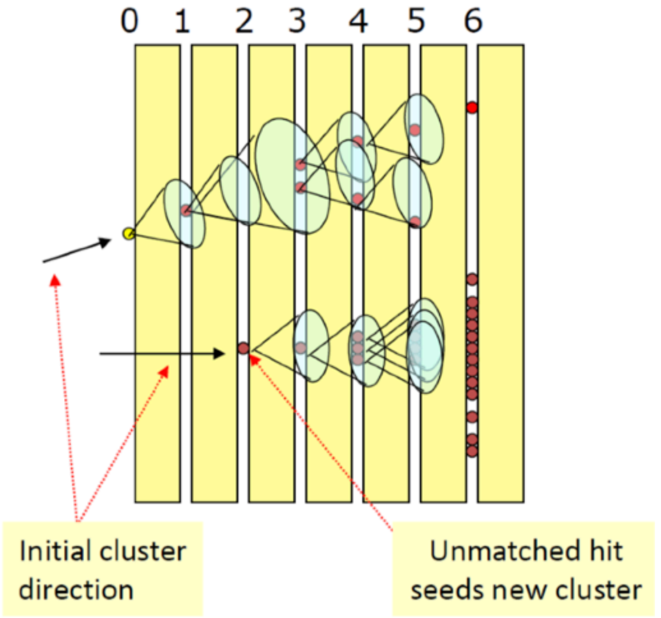
Illustration of Key Steps of PandoraPFA



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

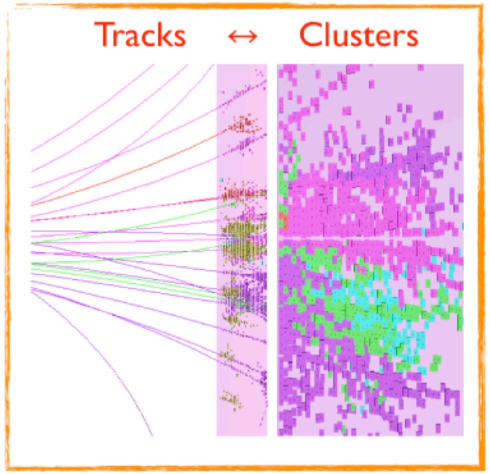
- PandoraPFA: Complex multi-algorithm chain using pattern recognition for event reconstruction
  - ➡ Performs calorimeter hit clustering, topological associations, …
  - ➡ Highly recursive: Find most accurate reconstruction scenario
  - ➡ Overall goal: Distinguish energy depositions originating from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

Clustering



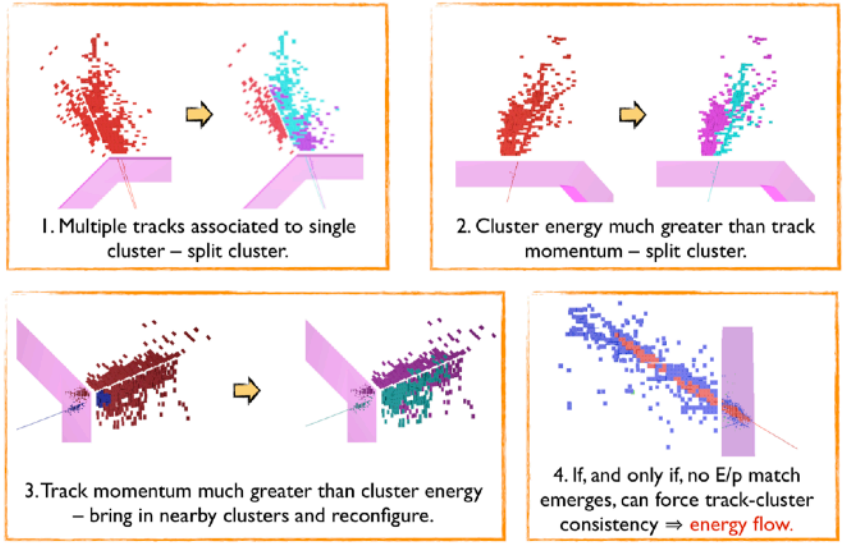
Track to Cluster Association

- 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.

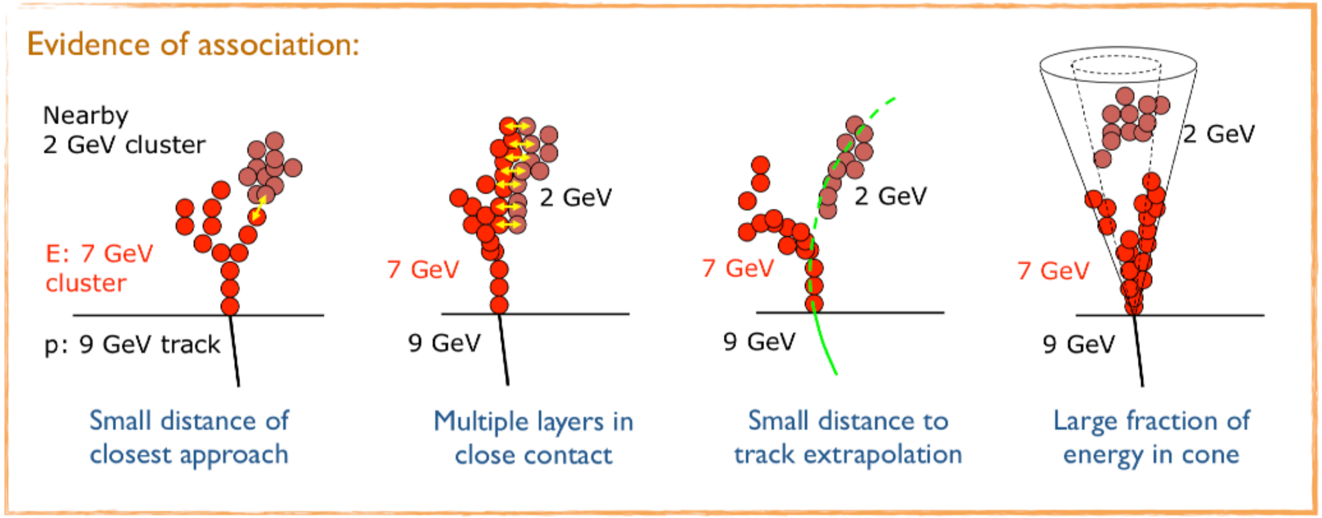


J. S. Marshall: https://indico.in2p3.fr/event/7691/contributions/42712/attachments/34375/42344/3_john_marshall_PFA_marshall_24.04.13.pdf

Re-Clustering



Fragment Removal

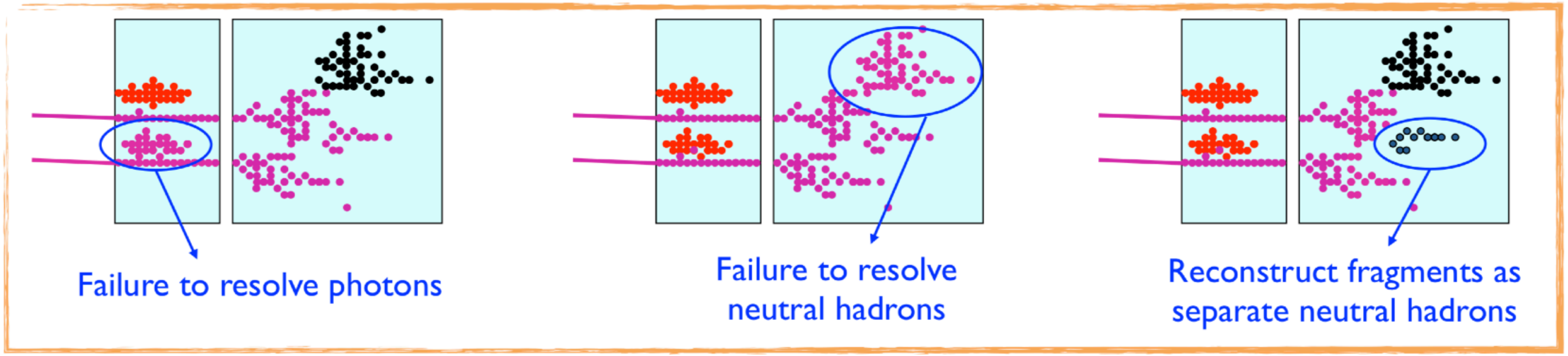


Confusion Scenarios

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 at high energies

Types of confusion



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

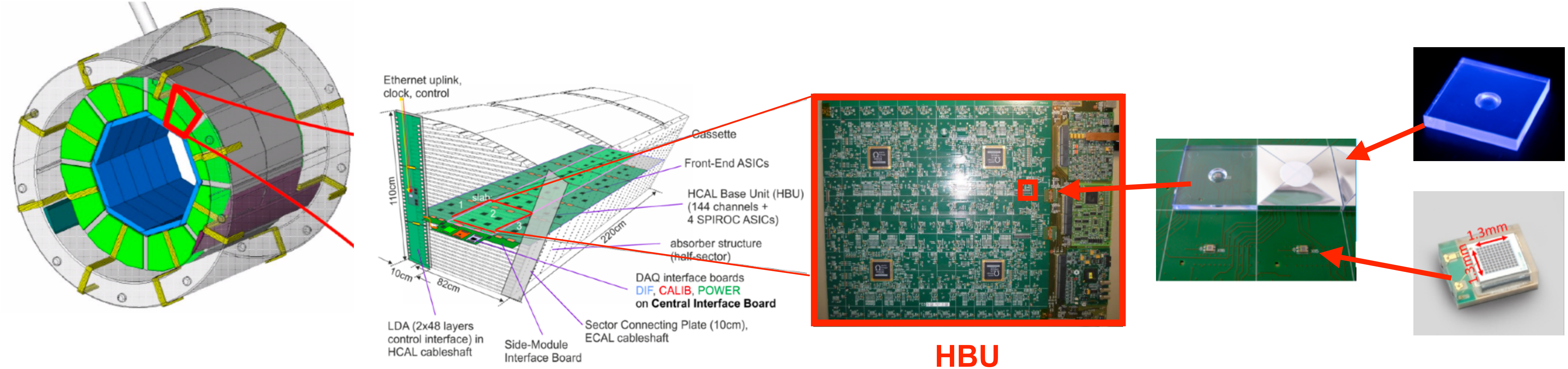
J. S. Marshall: https://indico.in2p3.fr/event/7691/contributions/42712/attachments/34375/42344/3_john_marshall_PFA_marshall_24.04.13.pdf

- 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 (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

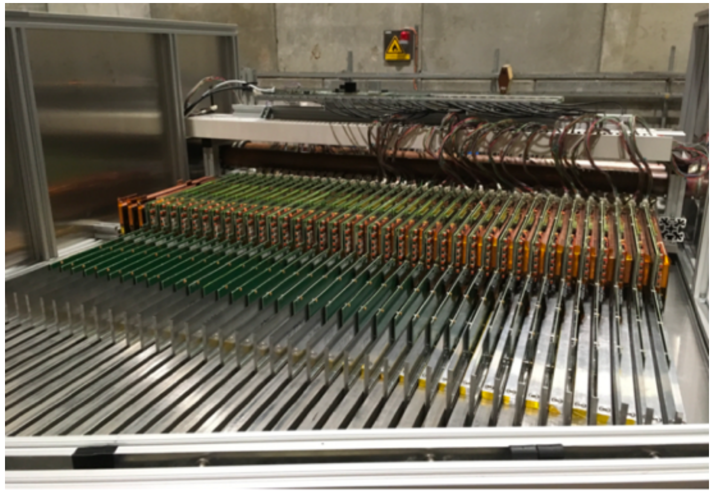


The Analog Hadron Calorimeter Prototype 2018

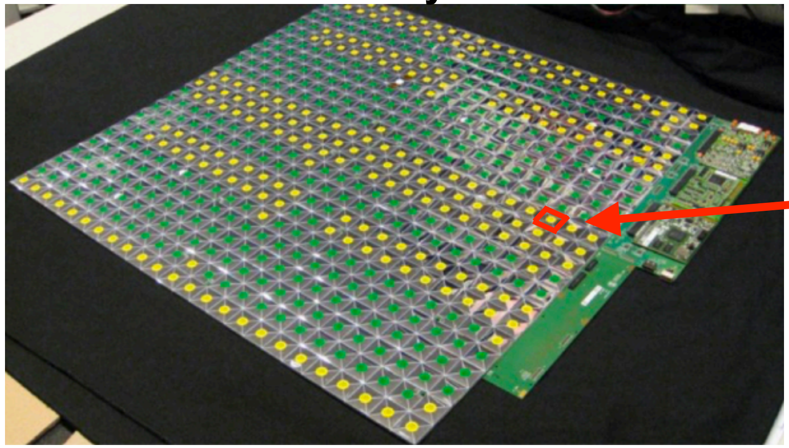
A Highly Granular SiPM-on-tile Sampling Calorimeter

- 38 layer steel sampling calorimeter (~4 λ_n) featuring a total of **~22k channels**
- Active layers (72 x 72 cm^2) consisting of 576 channels
  - ➡ One channel: Silicon-Photomultiplier (SiPM) coupled to wrapped scintillating tile (3 x 3 cm^2)
- **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**

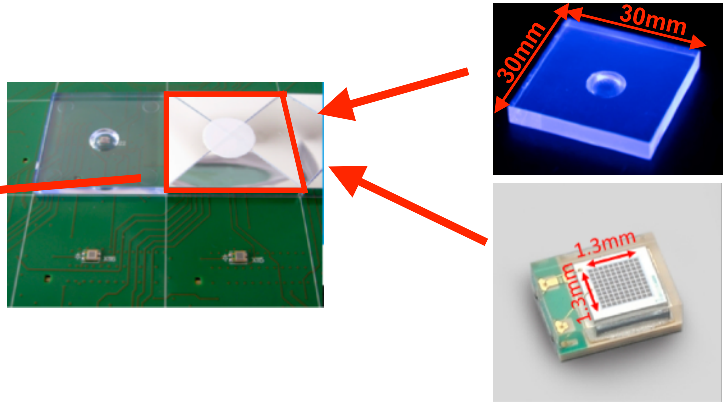
38 layers within steel absorber stack



One layer



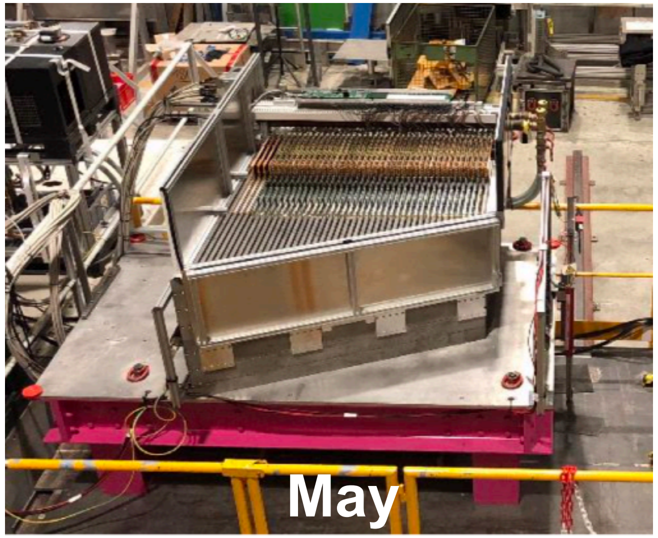
One channel: Scintillating tile + SiPM

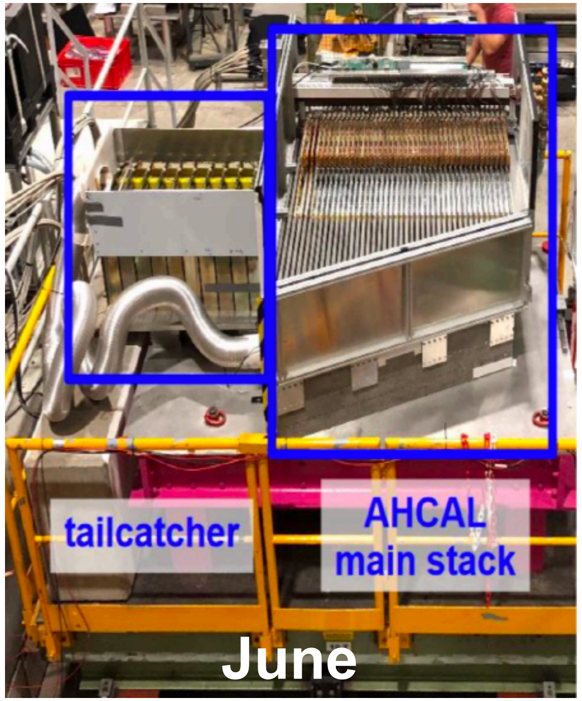


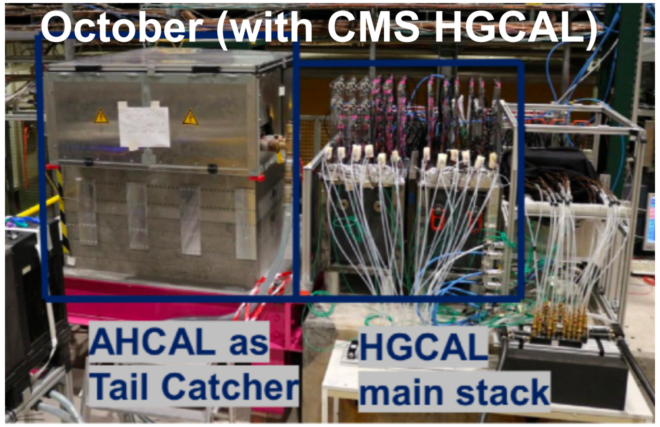
The CALICE AHCAL Beam Test Campaigns 2018

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







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
  - ➡ **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

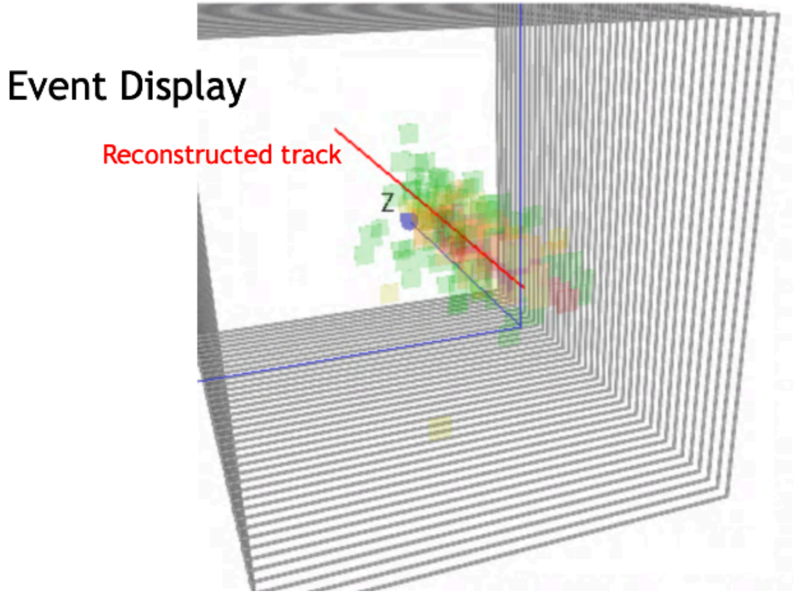
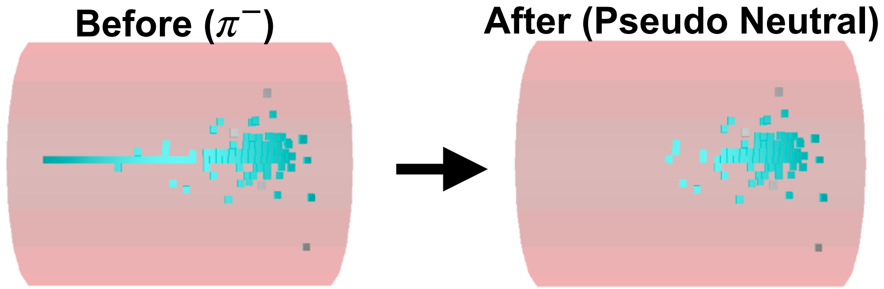


Illustration of pseudo neutral generation

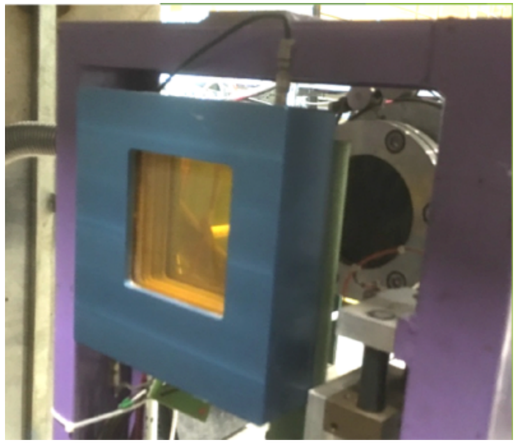


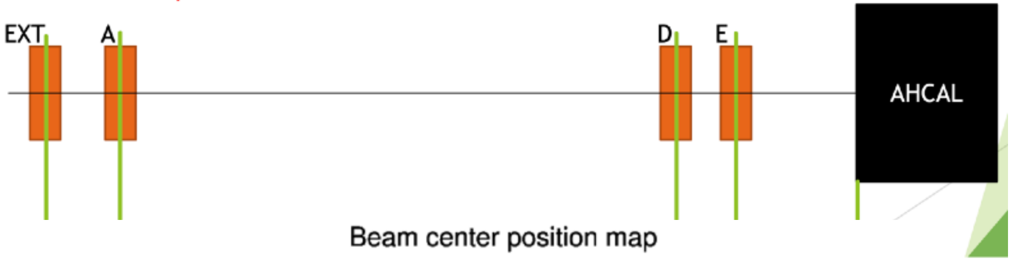
Delay Wire Chambers (DWC)

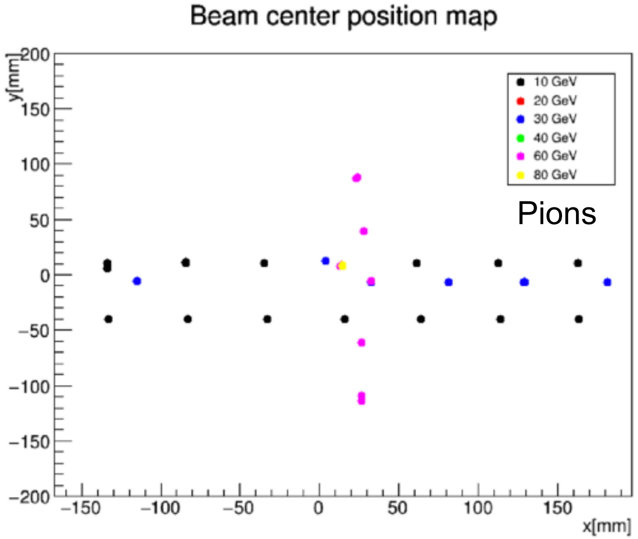
Providing Tracks for Beam Test Events

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

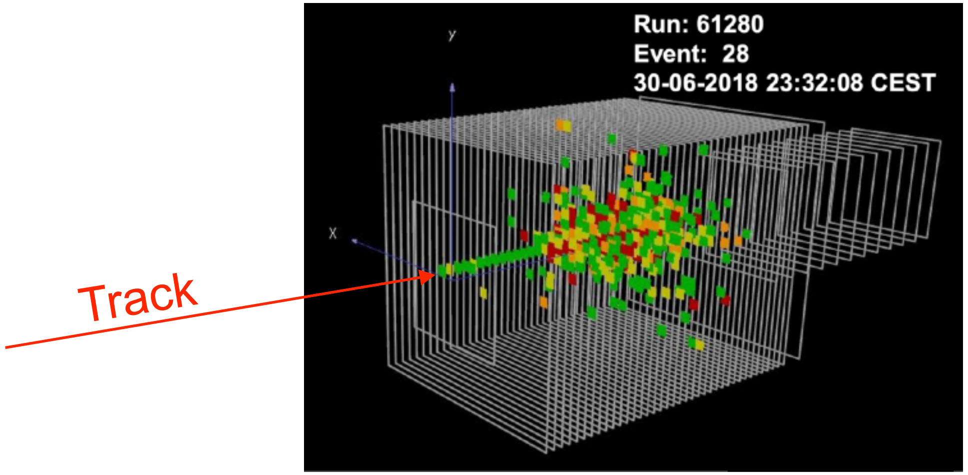
- Data tracks: Reconstructed from DWC of beam test
- MC tracks: MC primary particle endpoint position X/Y extrapolation

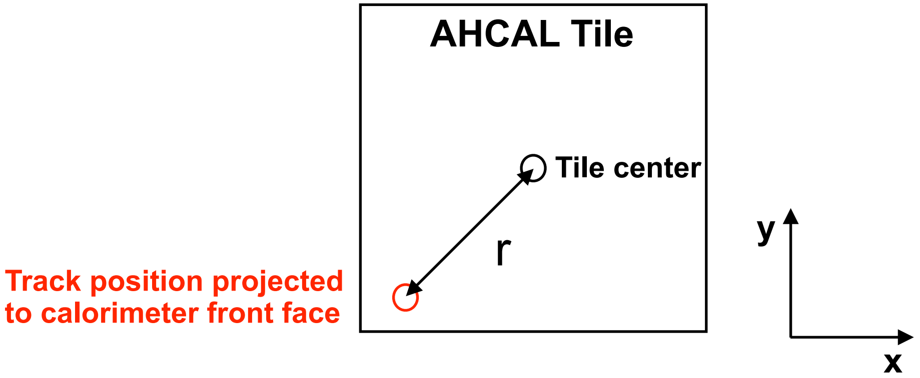
➡ **Track quality?**

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?

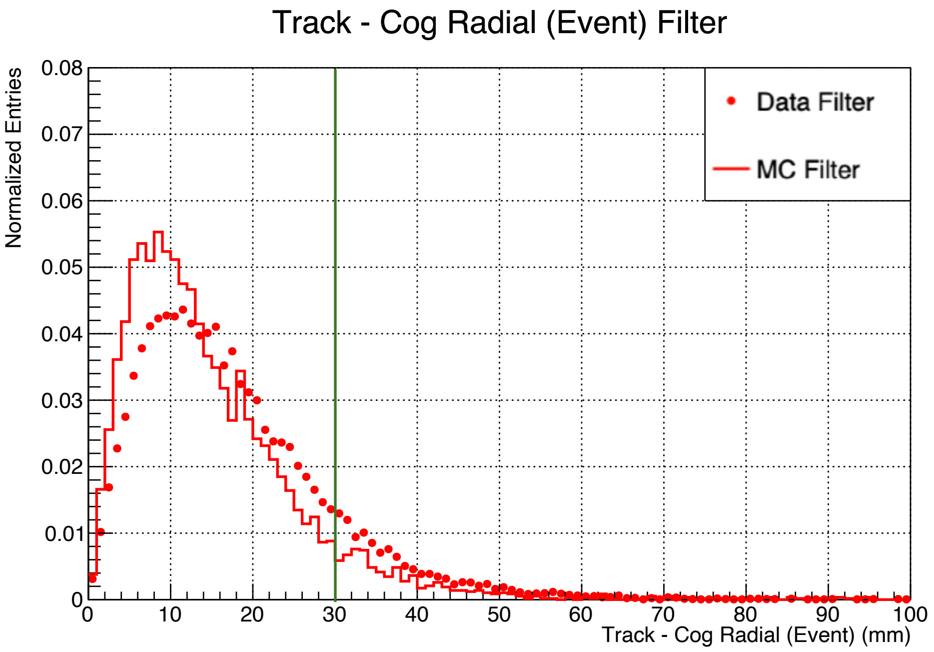




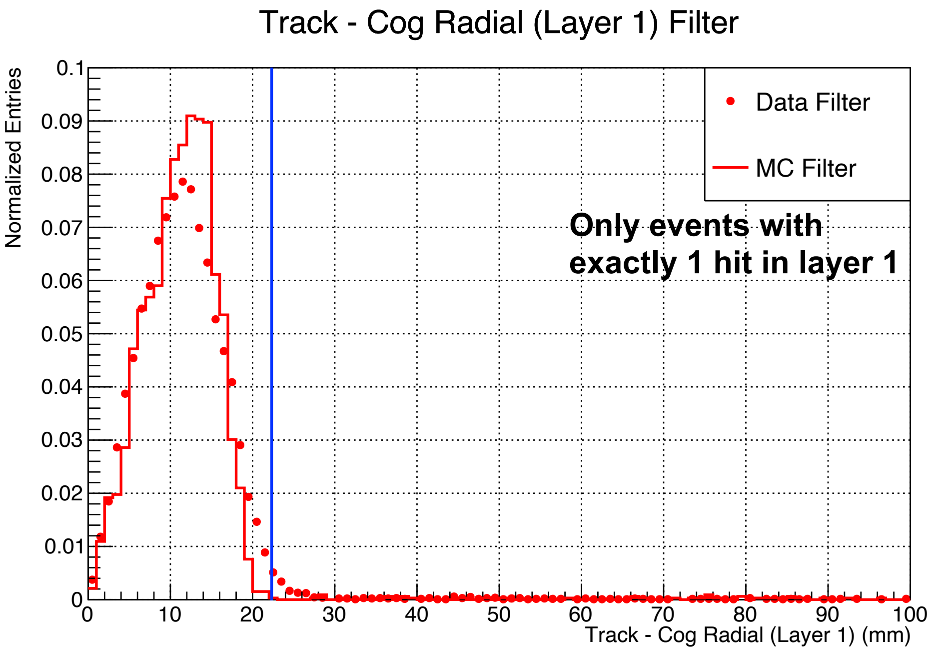
Track Quality Results 20 GeV π^-

Precise Tracks for PandoraPFA Reconstruction

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



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



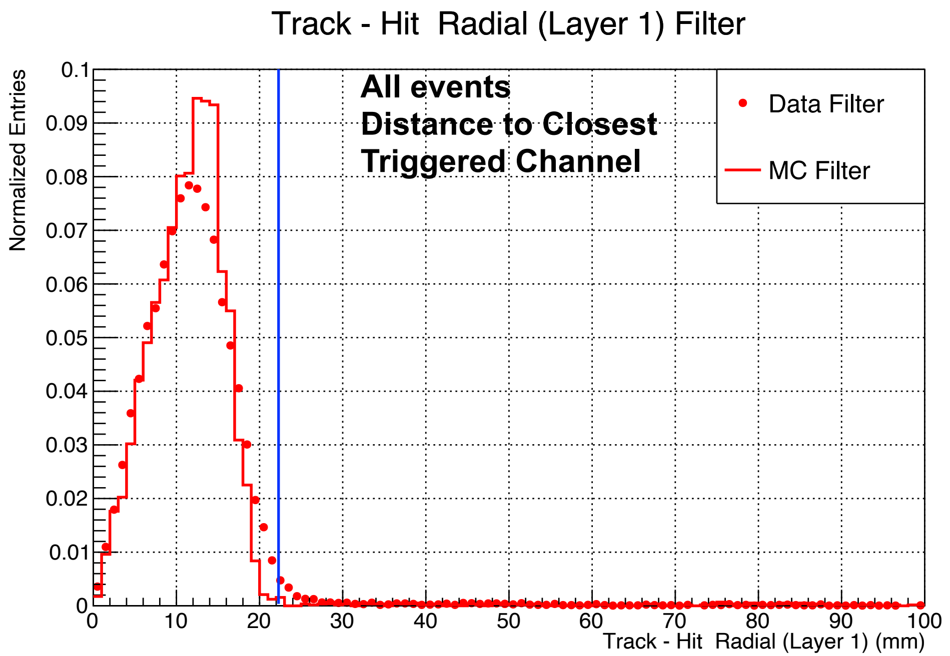
$$r = \sqrt{(x_{track} - x_{hit})^2 + (y_{track} - y_{hit})^2}$$

- 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^-

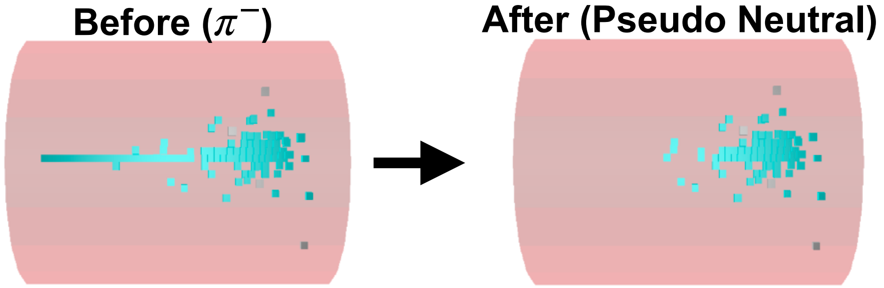
➡ **Excellent track quality validated for data and MC**

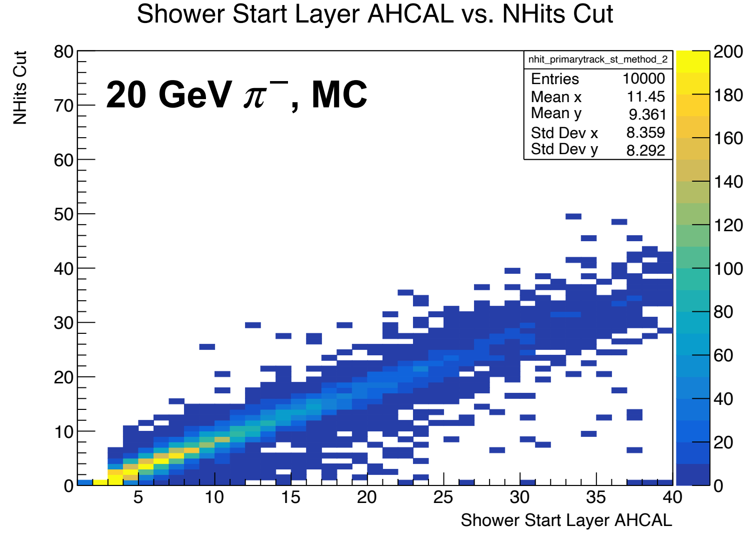
Finding and Removing Primary Track

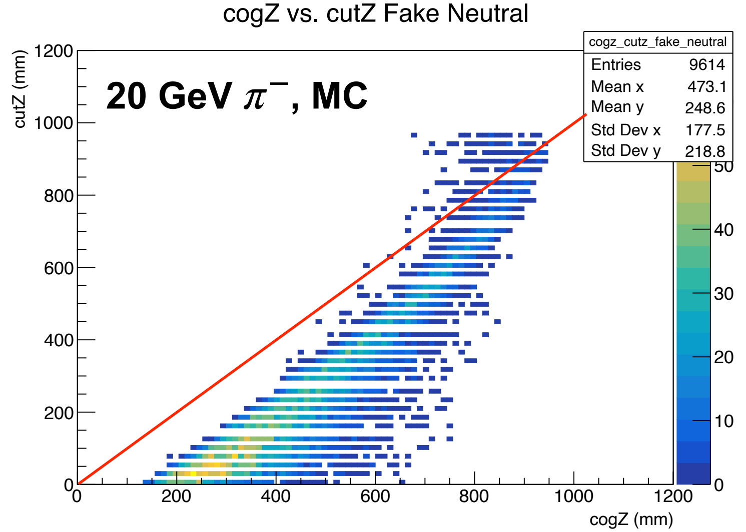
The Method for Creating Pseudo Neutral Hadrons

- 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

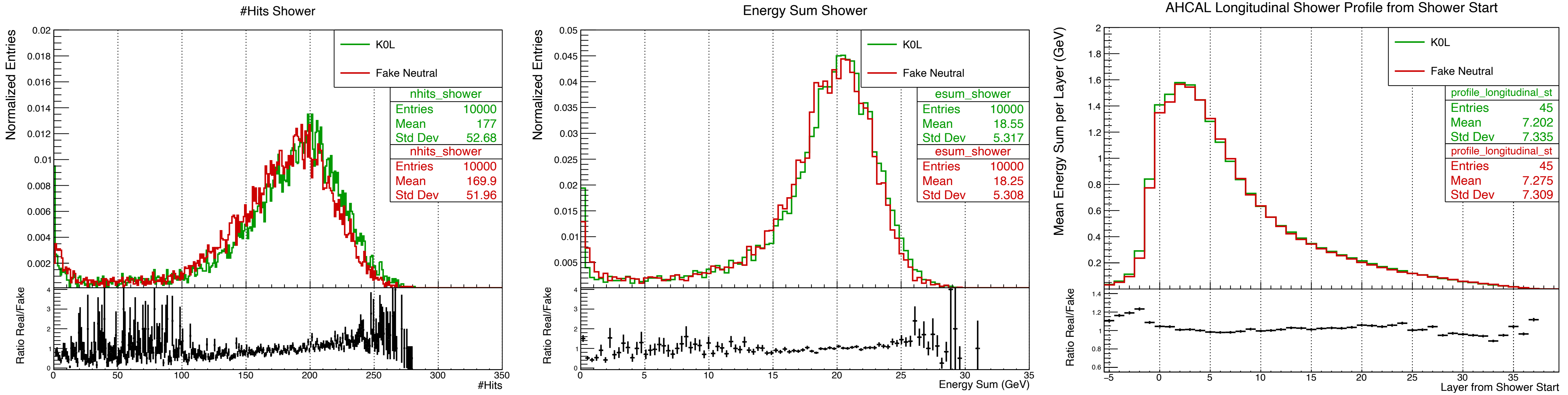






Comparison: Real vs. Pseudo Neutrals 20 GeV (MC)

Validation of Primary Track Removal Algorithm

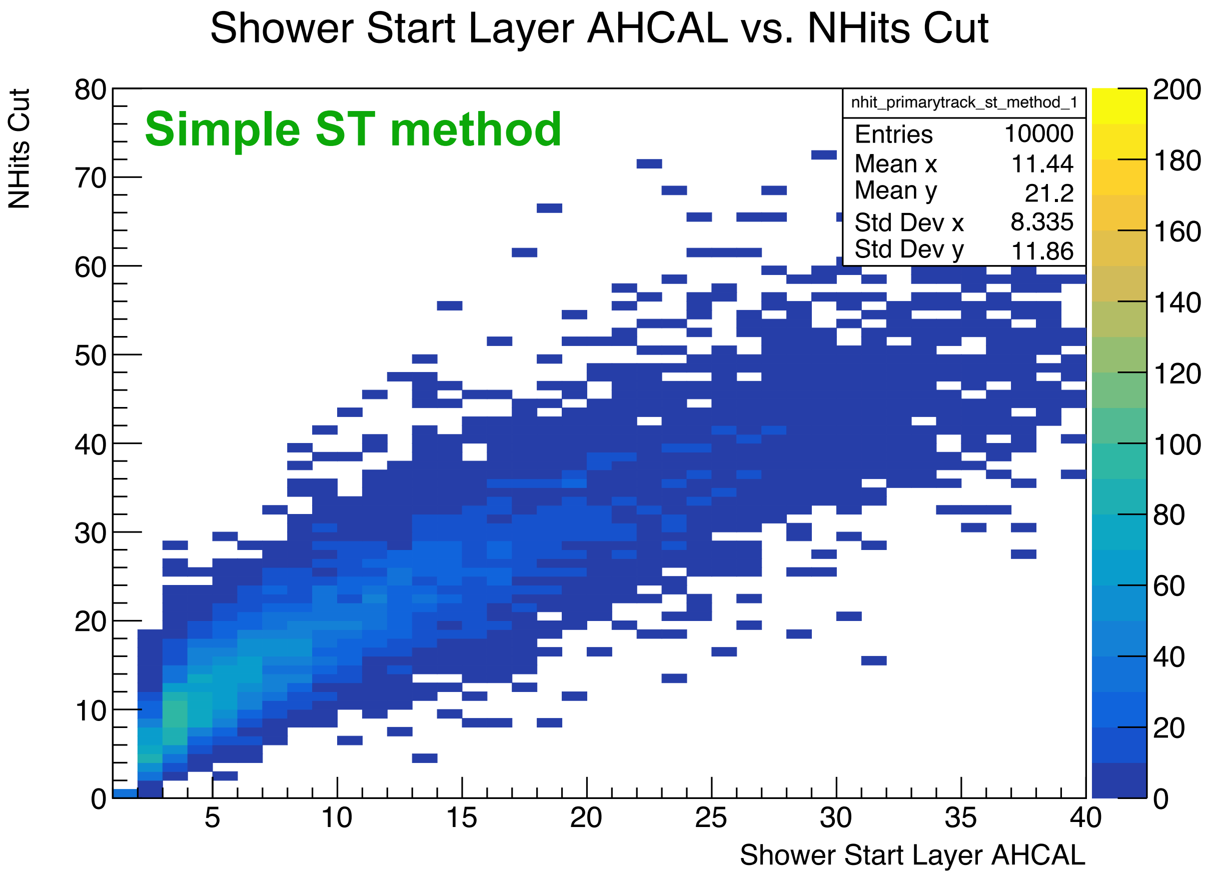


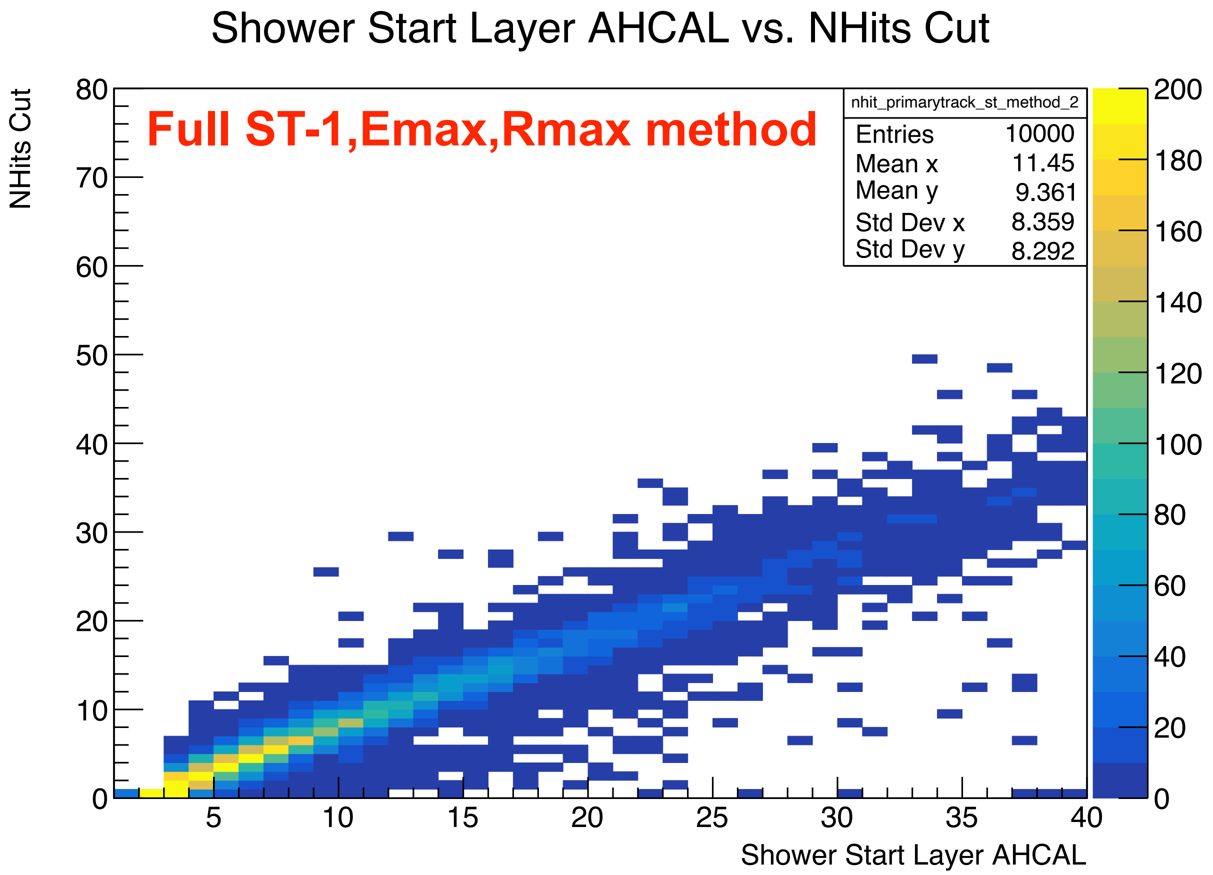
- In general **good agreement** between real neutrals (K0L) and pseudo neutrals (cut π^-) in number of hits, energy sum and longitudinal shower profile

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

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

Validation of Method

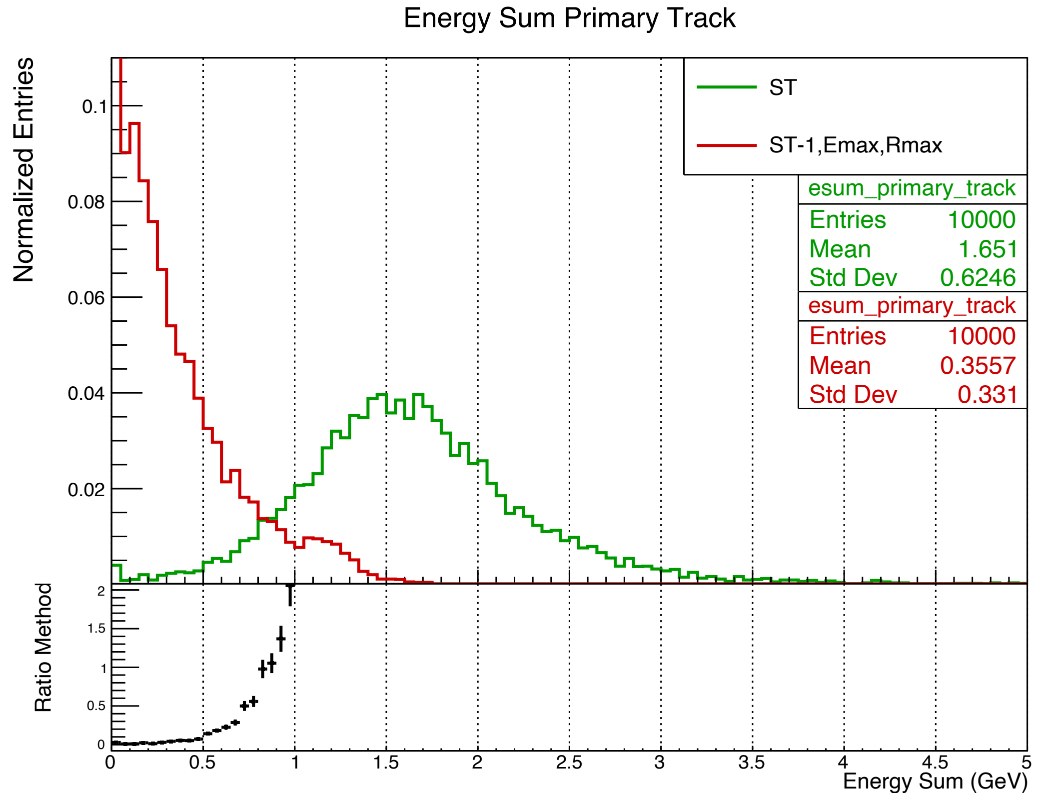


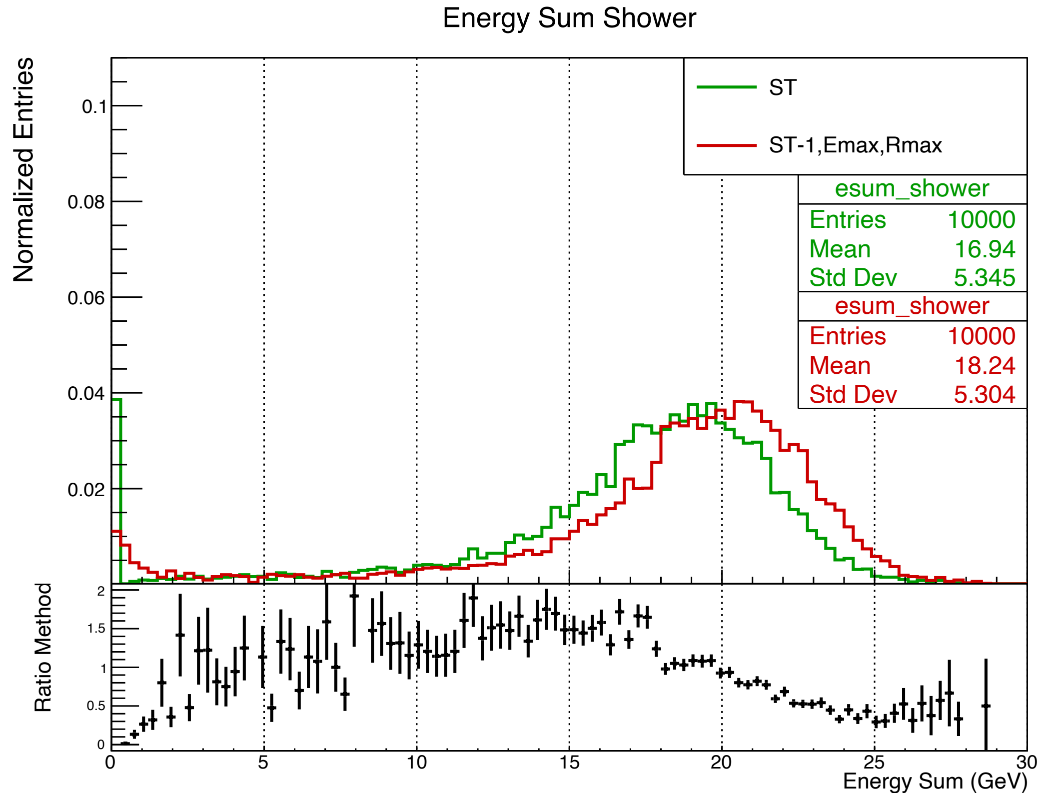


- Too many hits cut away for simple ST method
- Much better correlation of shower start layer and cut nHits of classified primary track for advanced method (#Cut hits ≈ #shower starter layer)

Energy Sum: Primary Track and Shower Hits

Validation of Method

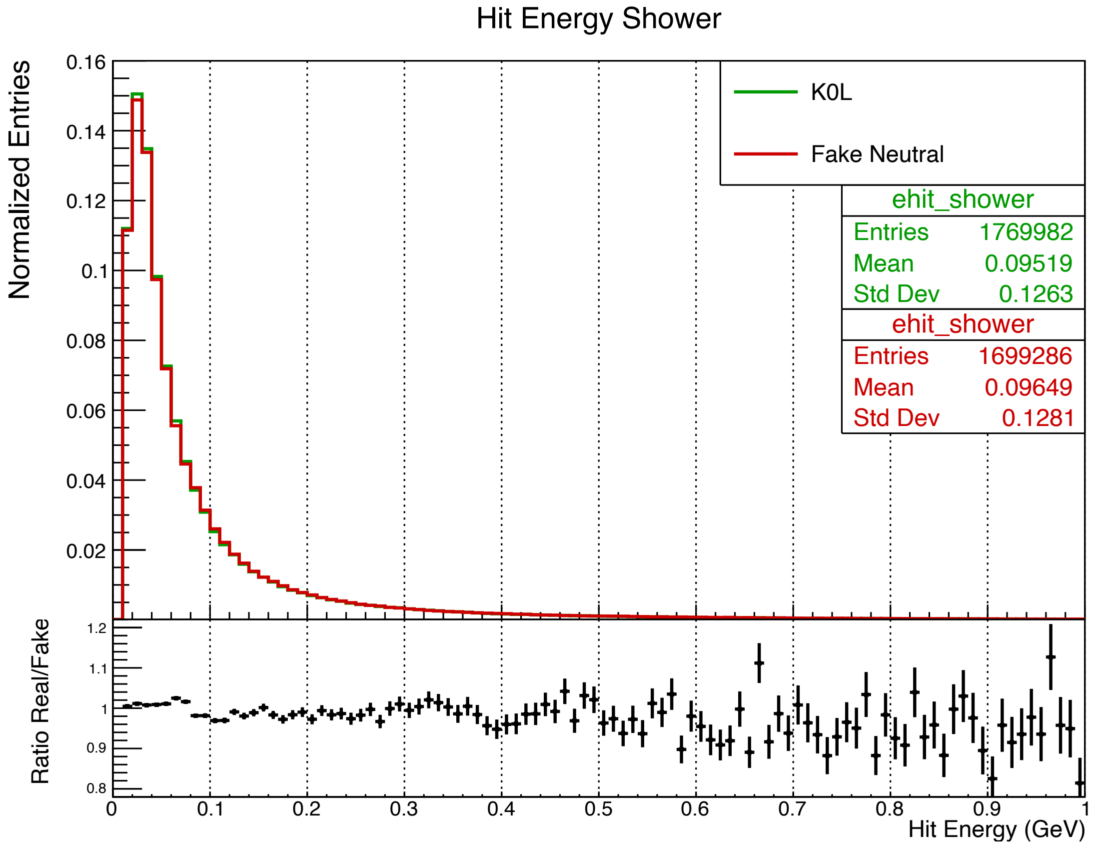


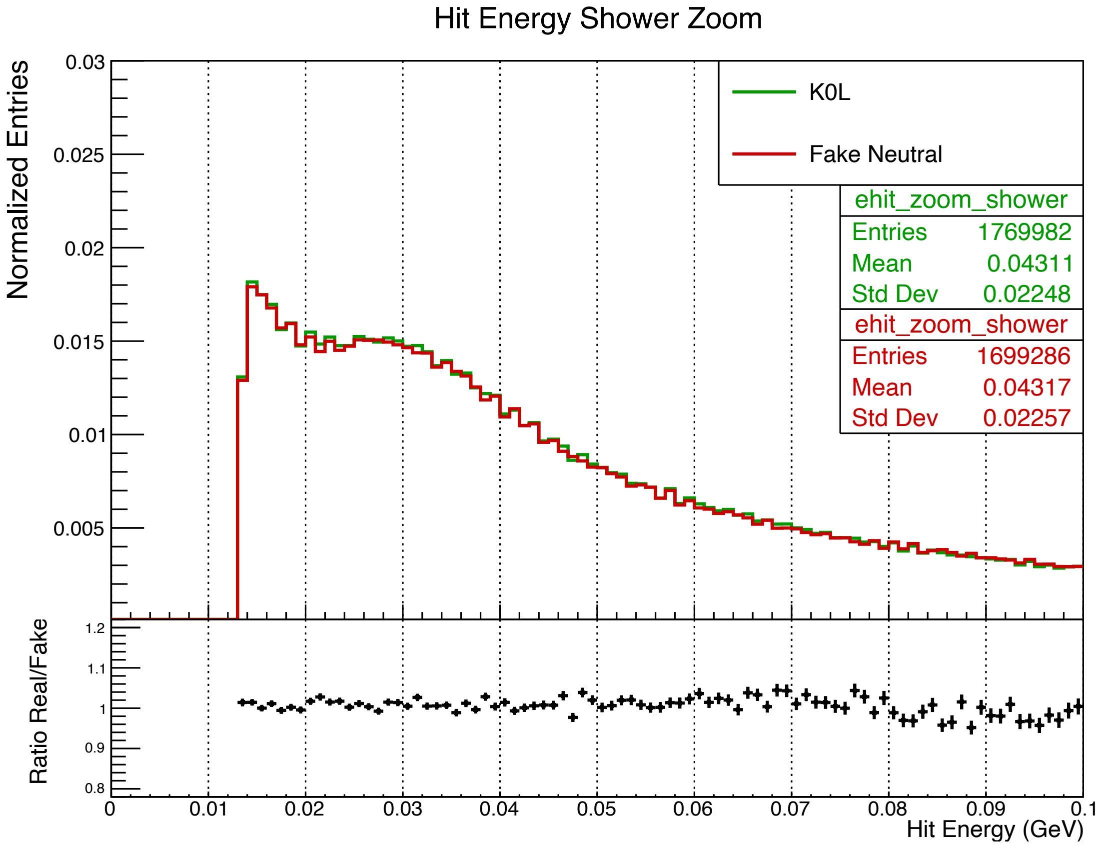


- Shower energy sum much closer to 20 GeV for advanced method
  - ➡ Too much hits and therefore energy cut away with simple method
  - ➡ Simple estimate: Upper primary track energy sum expected for perfect 40 hit MIP track: 0.0268 GeV (1 MIP) * 40 (layers) * 1.4 (landau-gaussian mean) = **~1.5 GeV**

Hit Energy

Real vs. Pseudo Neutrals



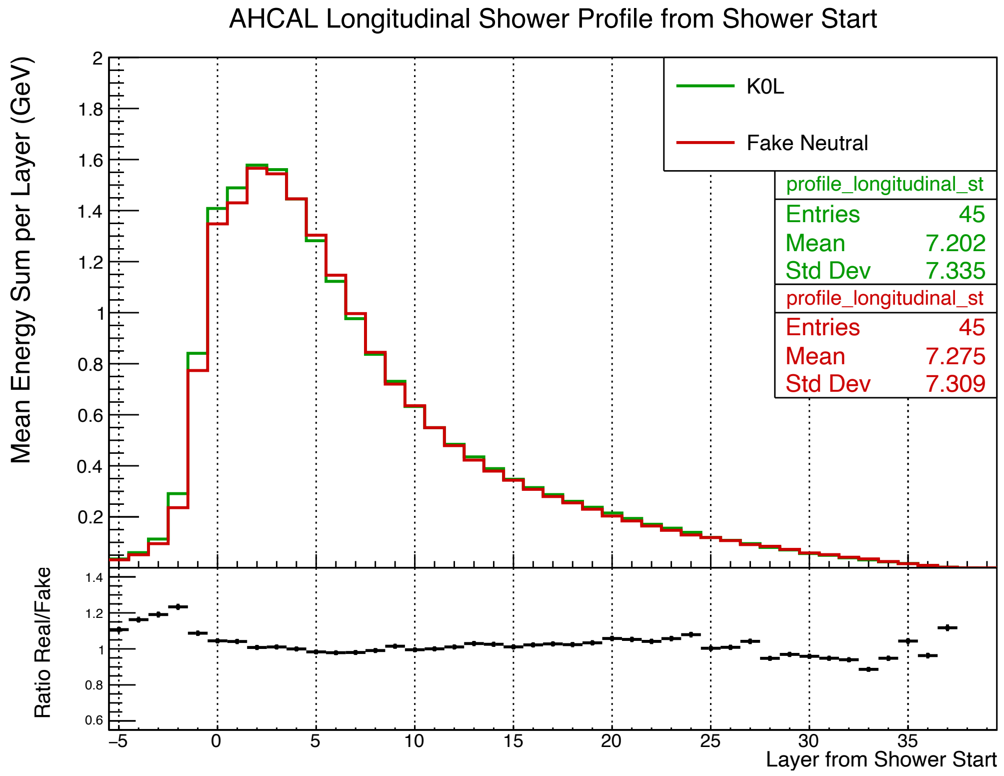


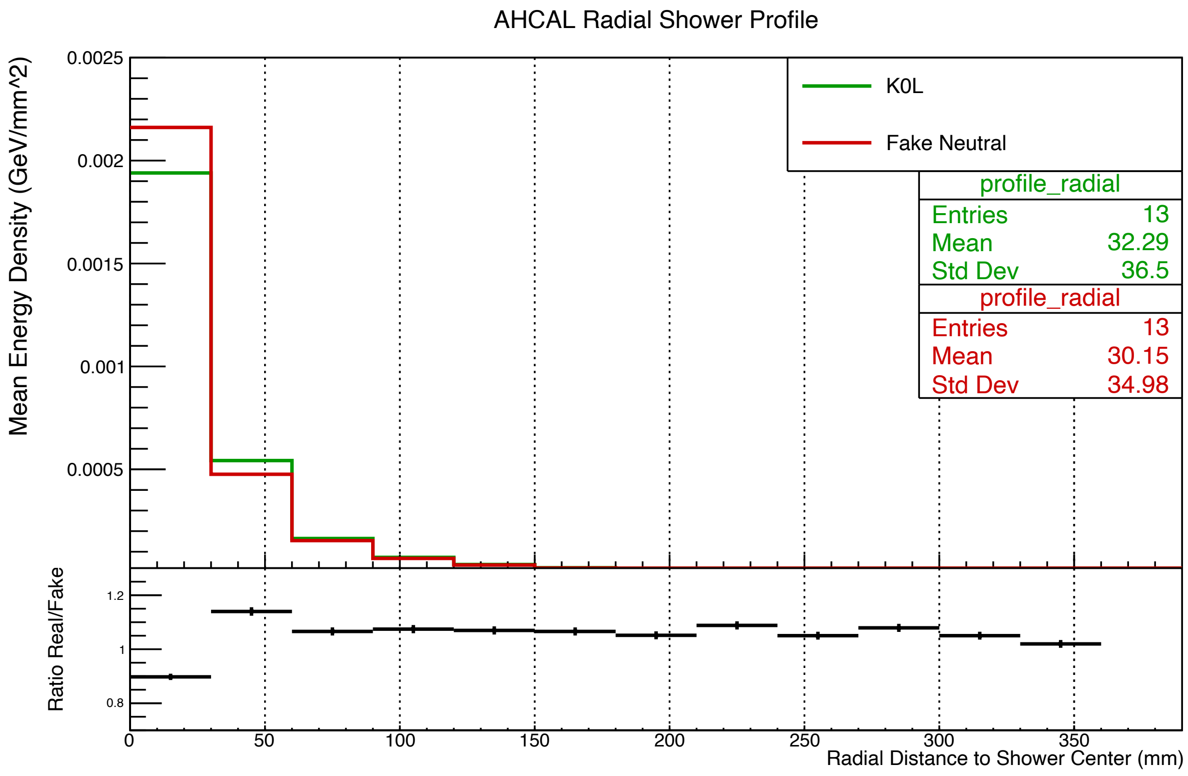
- Very good agreement, even for low energy hits (within 2%)

Shower Profiles: Longitudinal & Radial

Real vs. Pseudo Neutrals

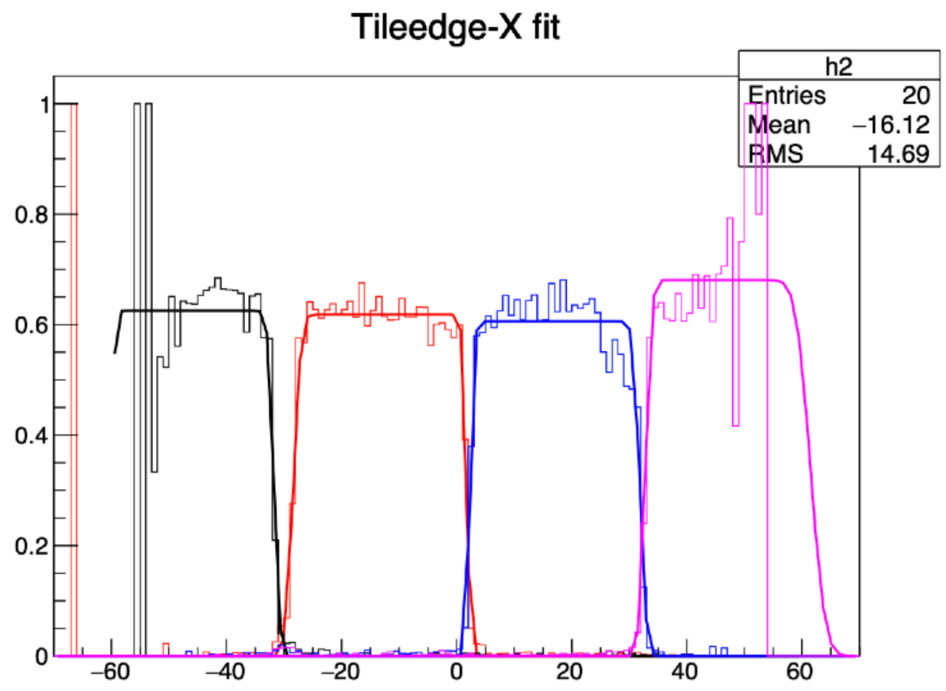
Simple radial profile code:
13 concentric circle areas, no fractional sharing of tile energy between two circle areas if overlap at edge

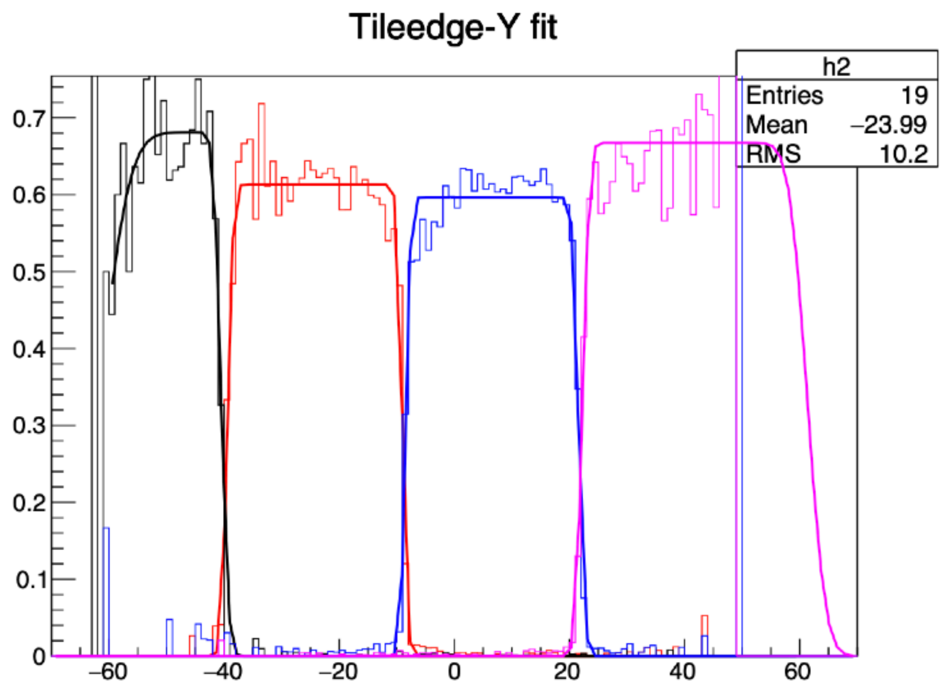




- Reasonable agreement for shower profiles:
  - ➡ Longitudinal: ~20% discrepancy ±2 layer around shower start layer
  - ➡ Radial: ~10-15% discrepancy for first two bins / innermost two circles

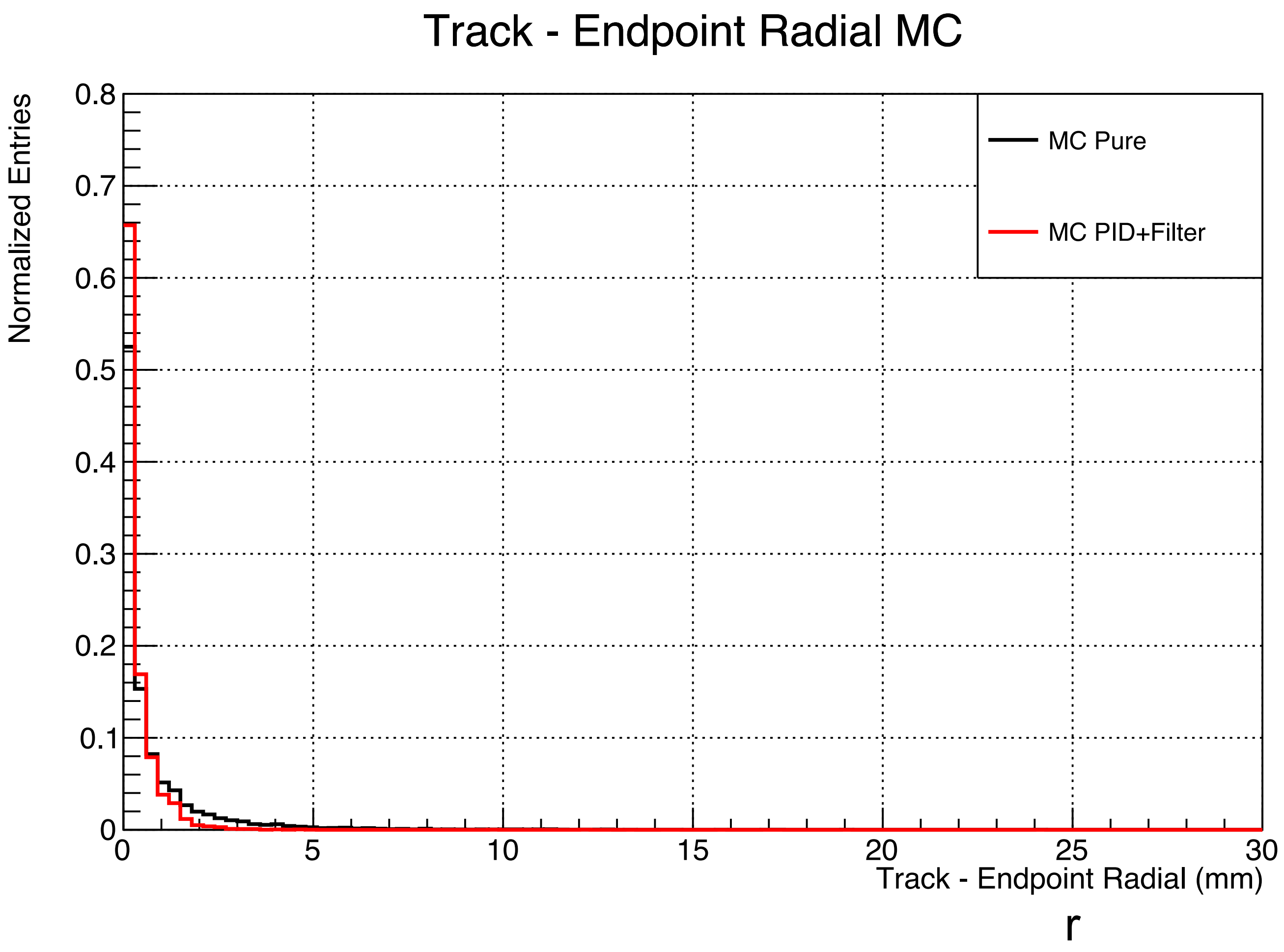
Scintillator Tile Gaps Measurements DWC Example





MC: Track to MC Endpoint Position Comparison

Track Quality Study



- Only events with primary particle endpoint z within calorimeter

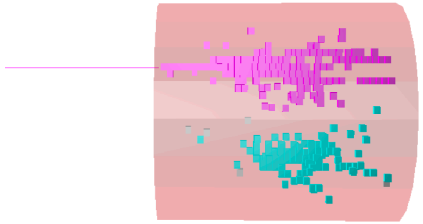
- Radial distance in x-y plane:

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

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

Basics of Overlay Processor

Estimate of Radial Distance Covering



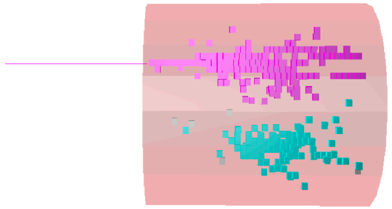
Magenta: Charged Hadron
Cyan: Neutral Hadron
Grey: Unclustered Hits

- **Overlay processor implemented and working well** (https://stash.desy.de/projects/CALICE/repos/calice_analysis/browse/addonProcs/src/MergeProcessor.cc) - **Big thanks to Linghui for great work and synchronisation on that!** ✔

- Requirements (not available in general ILD version):
  - ➡ Proper flagging of merged output hits and saving of individual output collection 1,2 and merged
  - ➡ Proper handling of MIP threshold - Apply 0.5 MIP cut only on overlaid hits ✔
  - ➡ Radial shower distance saving according to cogX,Y of shower pairs
  - ➡ Subsequent event overlay from two input (neutral & charged) LCIO collections

Overlay Processor

Status and Validation



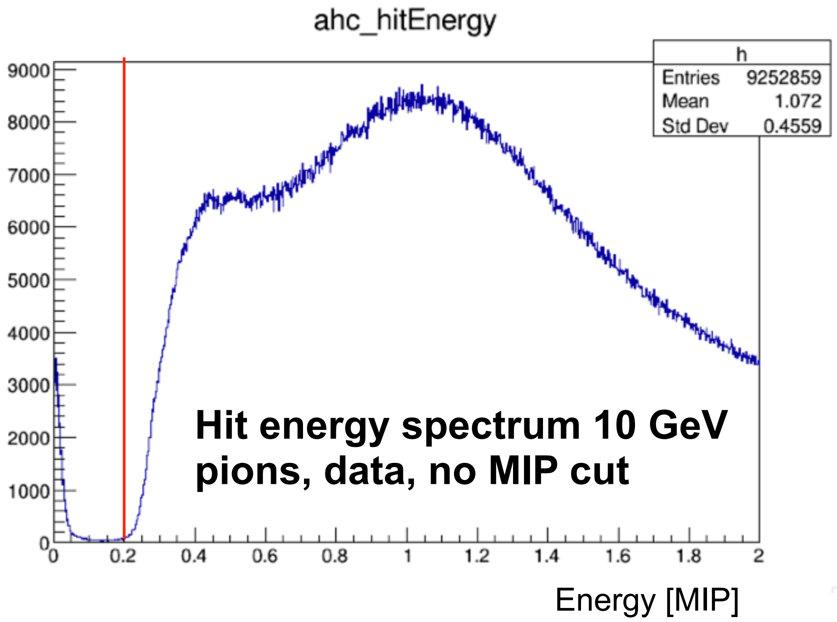
Magenta: Charged Hadron
Cyan: Neutral Hadron
Grey: Unclustered Hits

- What is the lowest MIP cut to use for data and MC before overlay?
  ➡ Hardware MIP cut ~0.2 MIP seems to be a good choice

- Samples used for validation of overlay processor (MC and data):
  ➡ 10 GeV neutral & 10/30 GeV charged pion (50mm & 200mm distance)

- Results:
  - Overlaid event yield (of initial neutral events) > 94%
  - Fraction of cut low energy hits (lower 0.5 MIP threshold) after/before overlay: > 95%
    ➡ Most of low energy hits are cut after overlay
  - Mean #new hits after overlay (reaching 0.5 MIP threshold) < 0.25 hits
    ➡ Negligible for all scenarios

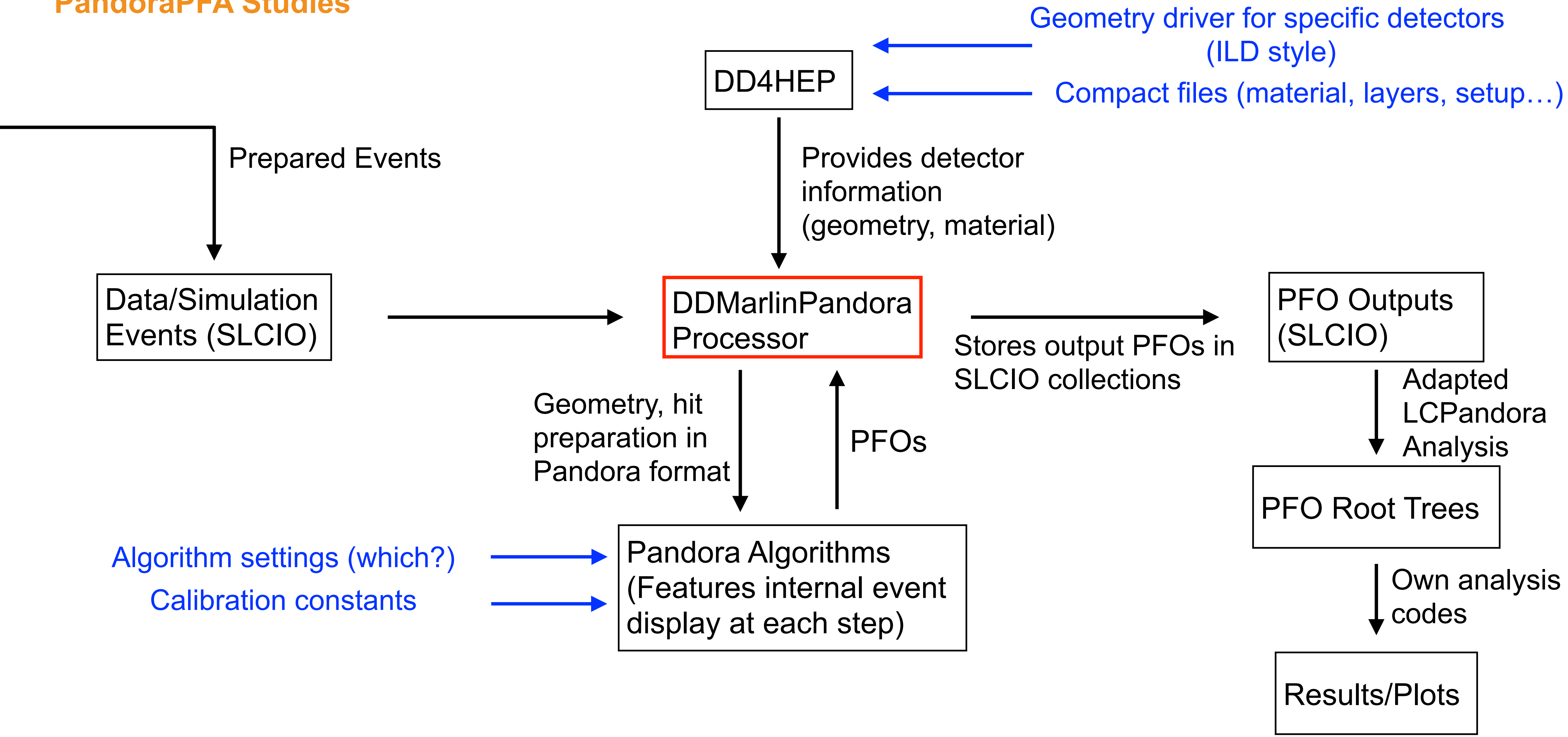
➡ Processor implemented and working well for two particle events



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
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[ VERBOSE "MyDDHCALPandora"] --------> Running Algorithm: Alg0008, ShowerMipMerging
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[ VERBOSE "MyDDHCALPandora"] --------> Running Algorithm: Alg0010, BackscatteredTracks
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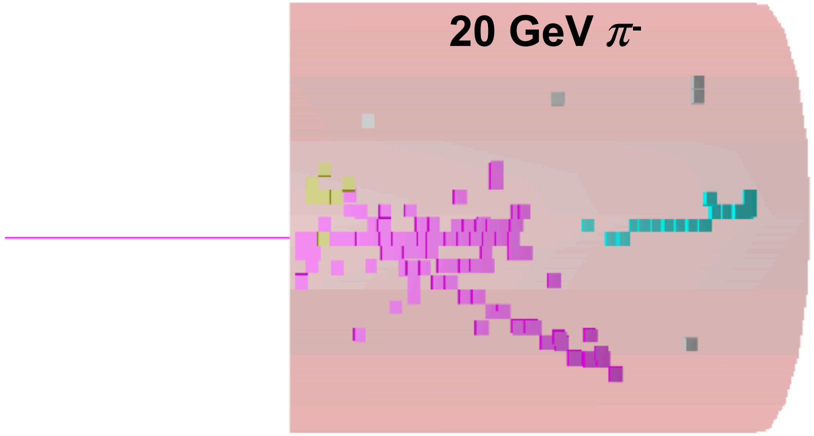
Pandora Visual Monitoring

Hits, Clusters & PFOs

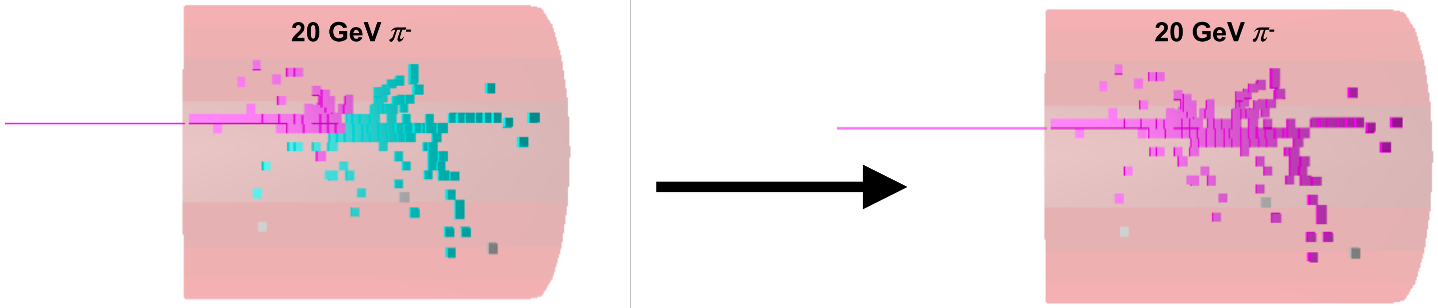


Magenta: Charged Hadron
Cyan: Neutral Hadron
Yellow: Photon
Grey: Unclustered Hits

- 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

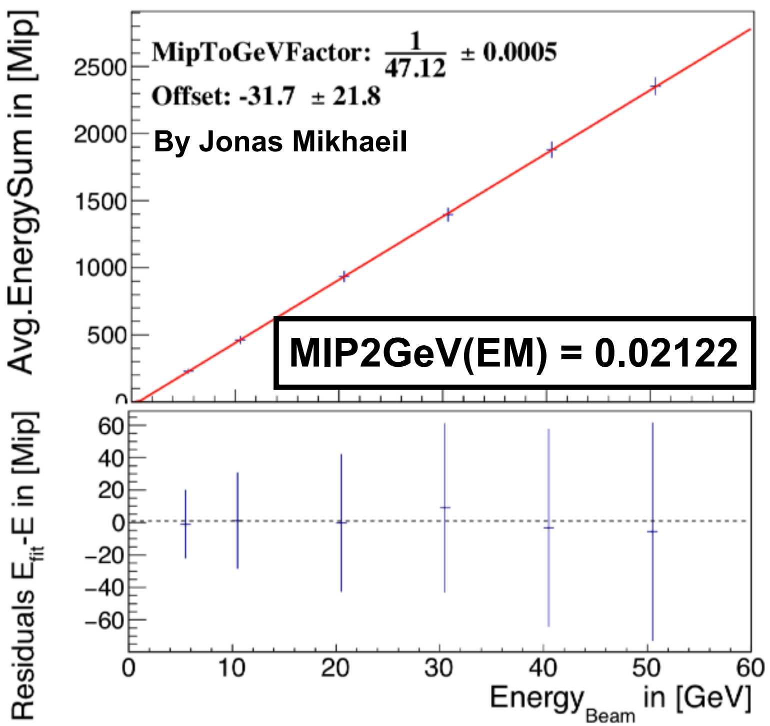


MIP to GeV Conversion

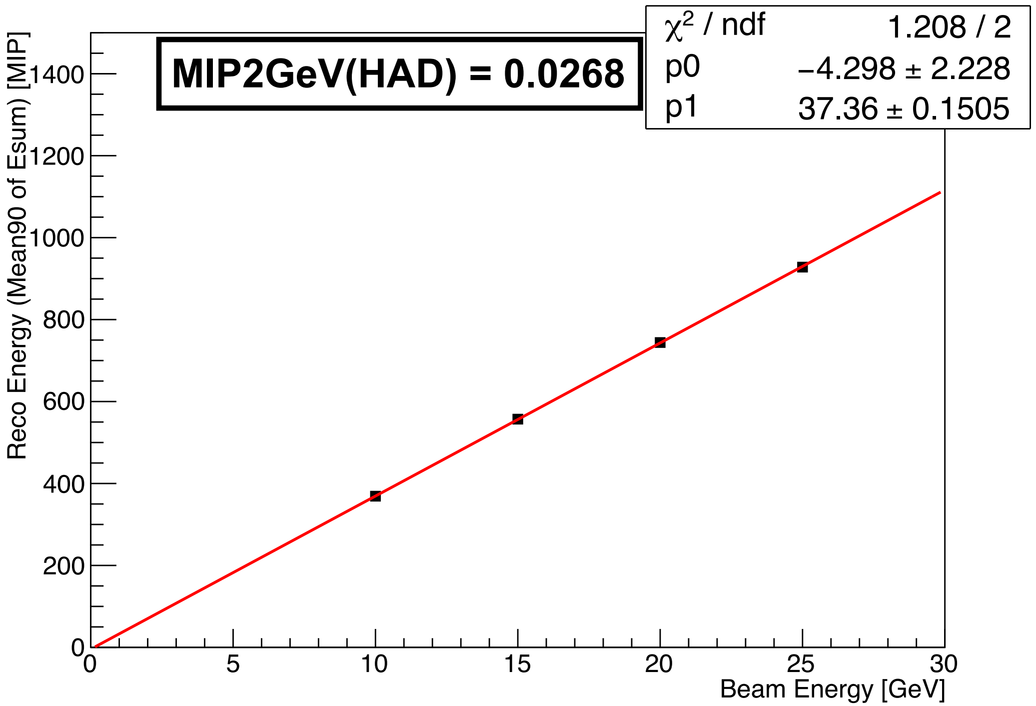
Calibration to EM and HAD Scale

- 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-)



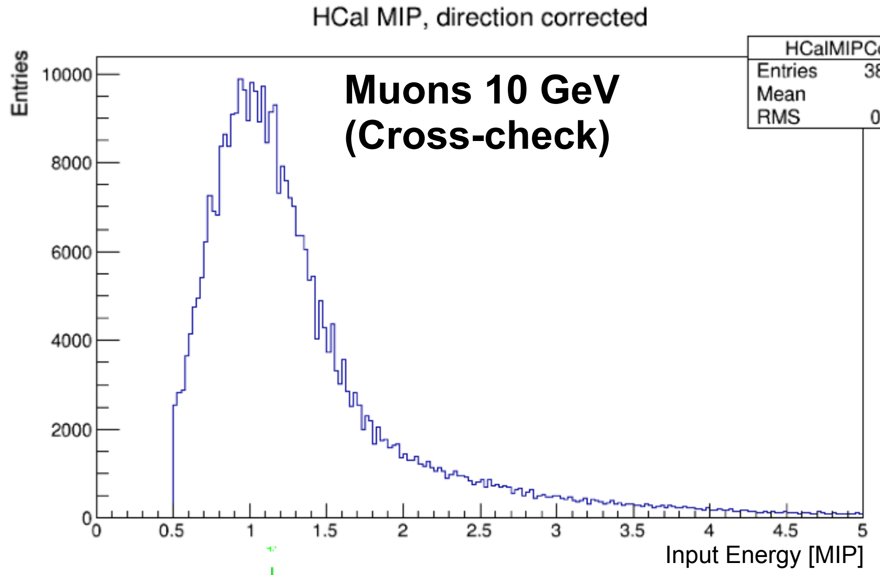
HAD Response Determination (K0L)

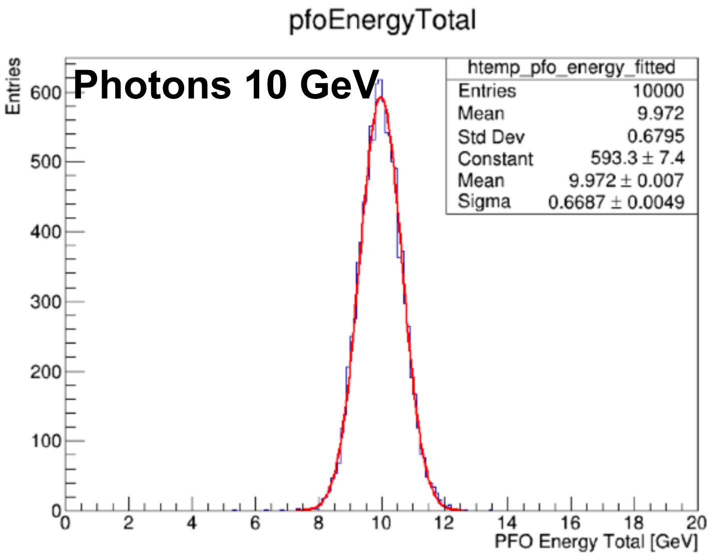


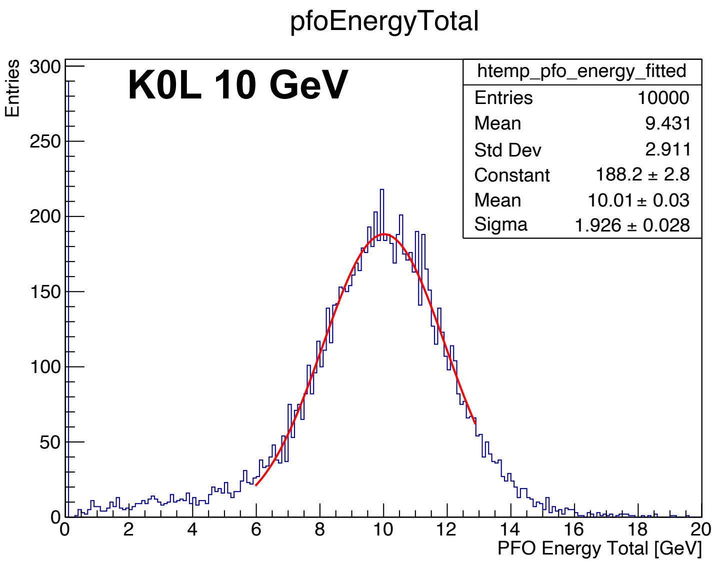
Pandora Energy Calibration

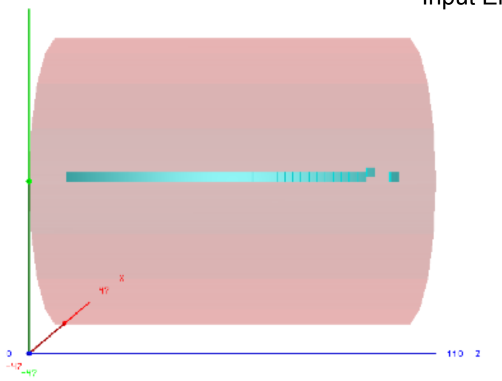
MC Muons, Photons, K0L

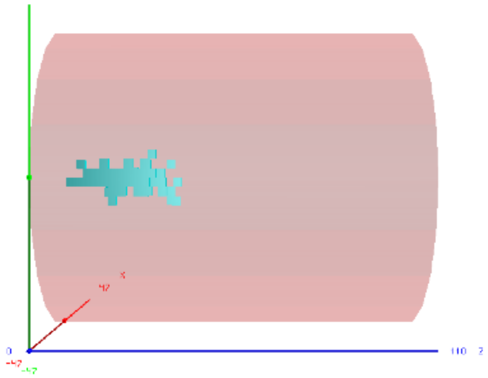
Note: Without tracks and ECAL everything classified as neutral hadrons at this step

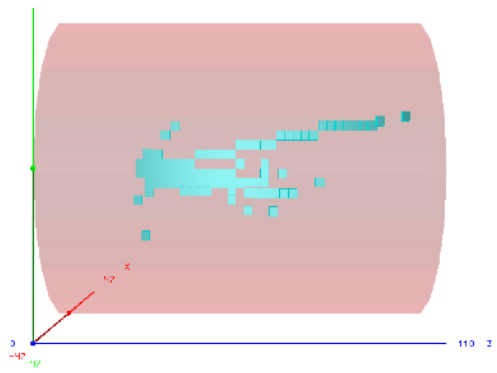










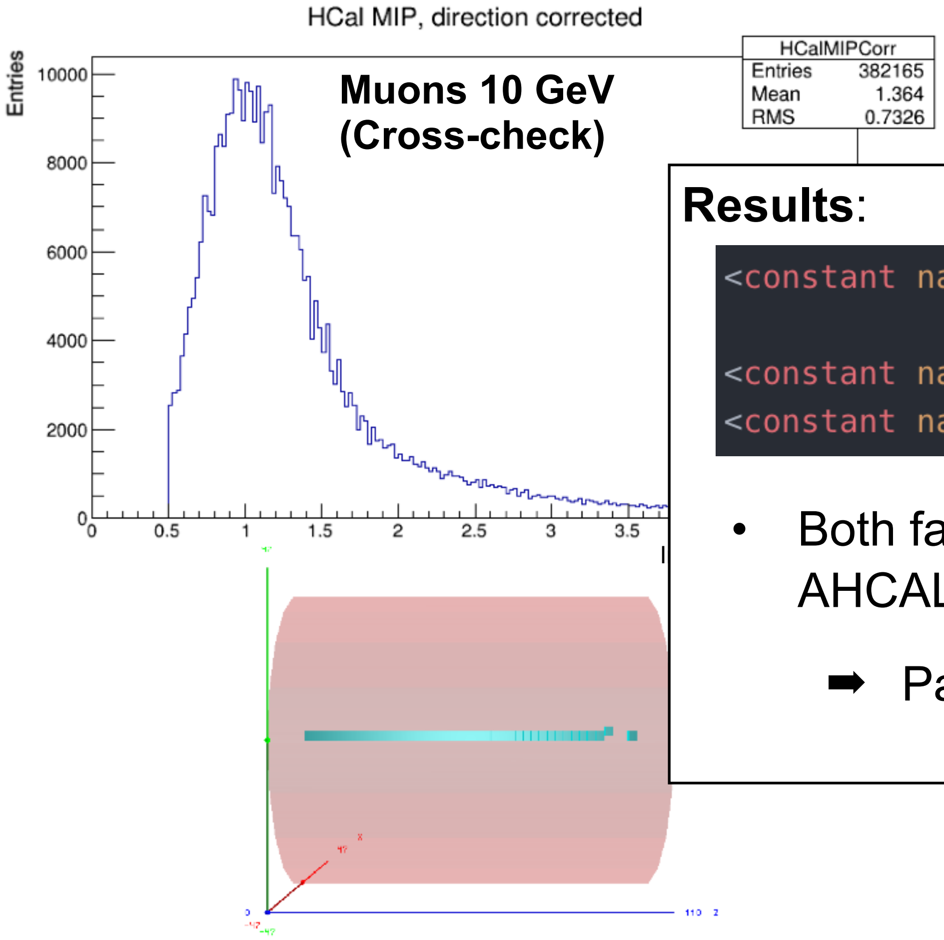


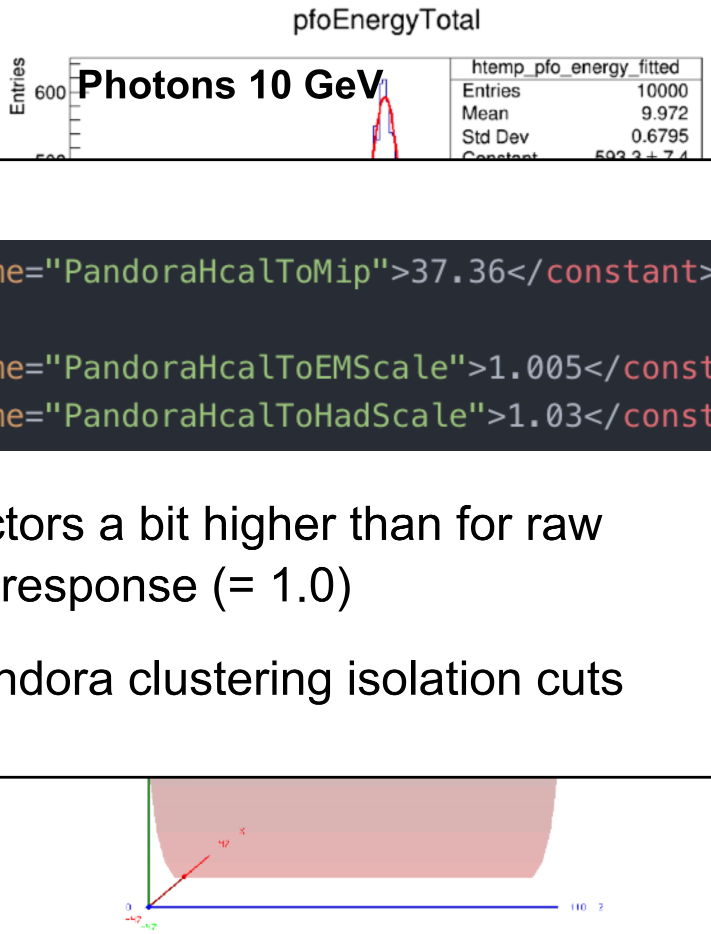
- **Muons**: AHCAL energy GeV -> MIP with negligible angle correction since straight TB tracks
- **Photons and K0L's**: Used to determine EM and HAD response, PFO energy tuned to peak at 10 GeV

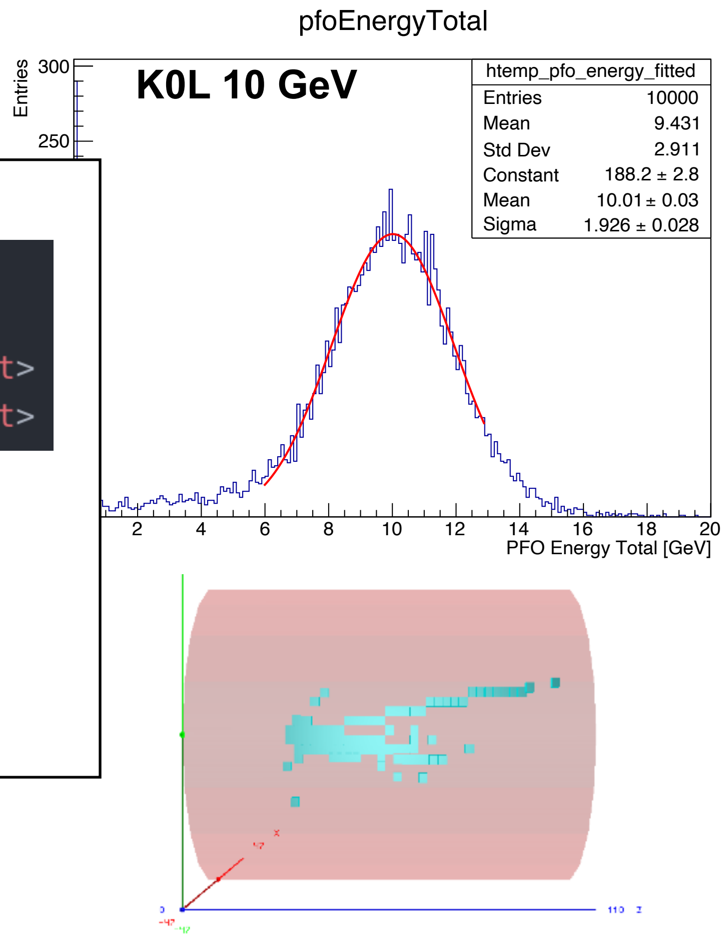
Pandora Energy Calibration

MC Muons, Photons, K0L

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







Results:

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

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

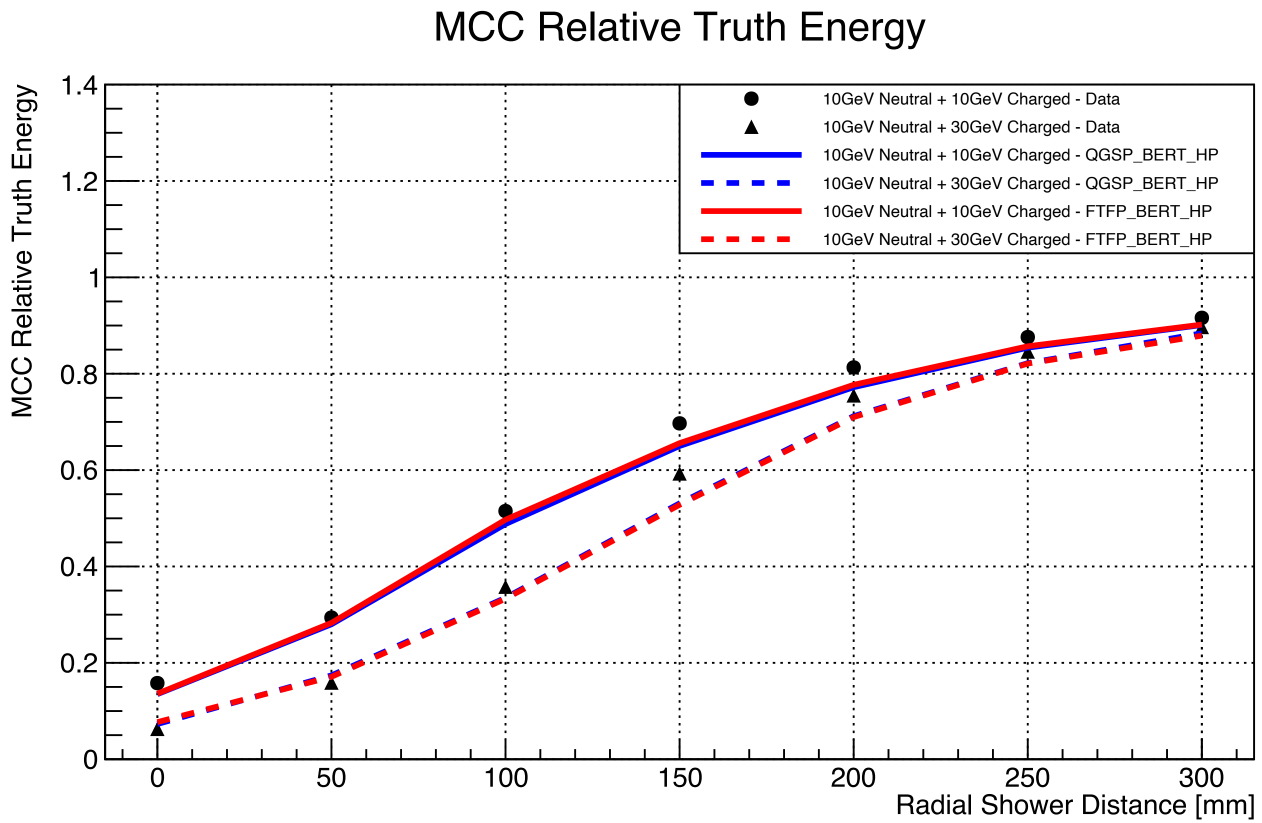
- Both factors a bit higher than for raw AHCAL response (= 1.0)
  - ➡ Pandora clustering isolation cuts

- **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

Additional Results

Matthews (Phi) Correlation Coefficient

Tests to Measure Diagonality of Matrices



TN = True Neutral
TC = True Charged
FN = False Neutral
FC = False Charged

$$MCC = \frac{TN * TC - FN * FC}{\sqrt{(TN + FN) * (TN + FC) * (TC + FN) * (TC + FC)}}$$

MCC = [-1,1]
1: Perfect agreement
0: Not better than random
-1: Total disagreement

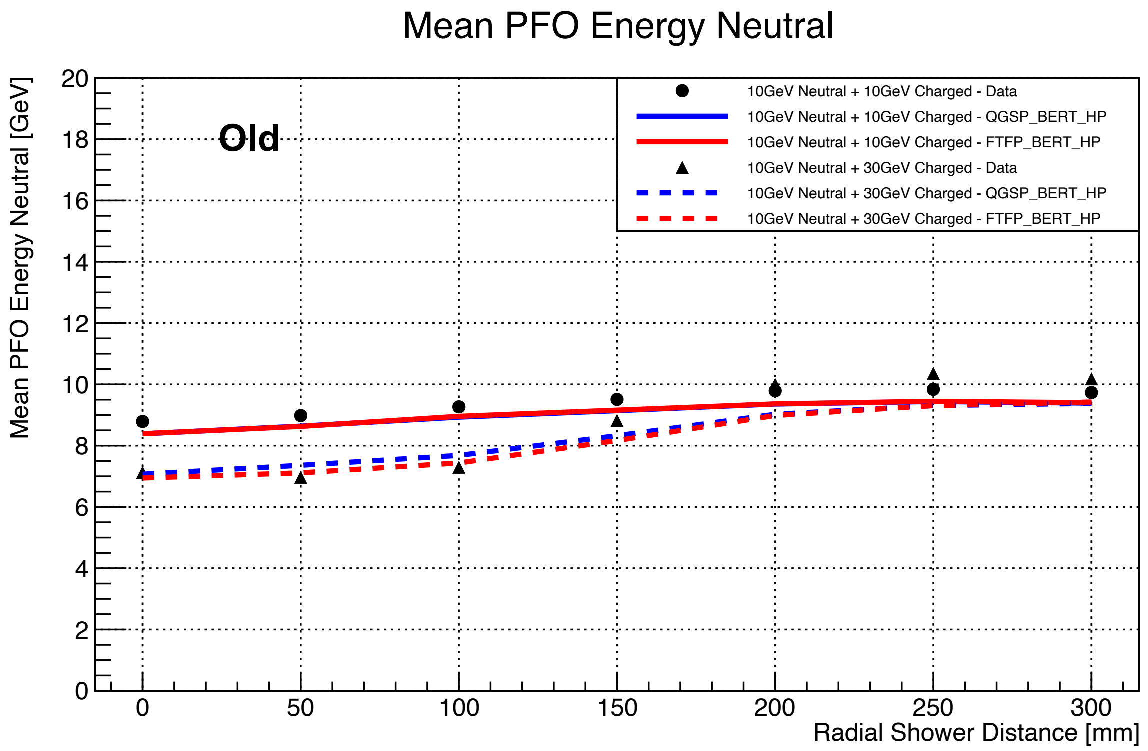
- Idea from world of machine learning (2x2 confusion matrices truth vs. prediction)
  - ➡ Quantifying truth to reconstruction prediction agreement (diagonality of matrix) with a single number

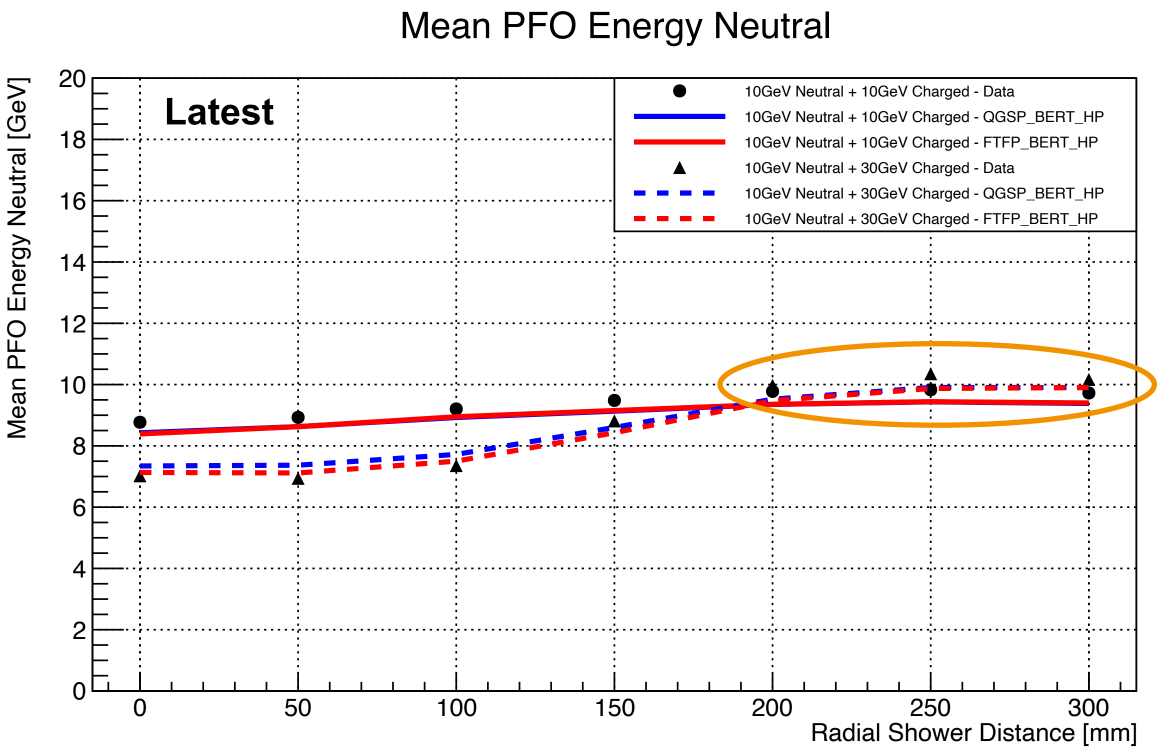
➡ First test: Works quite well for AHCAL standalone confusion scenario: Quantity for comparing to ILD jets?

Mean PFO Energy Neutral Hadron

Previous vs. Adapted Reconstruction

Old: Different position data and MC for high distances
New: Same positions data and MC + higher statistics

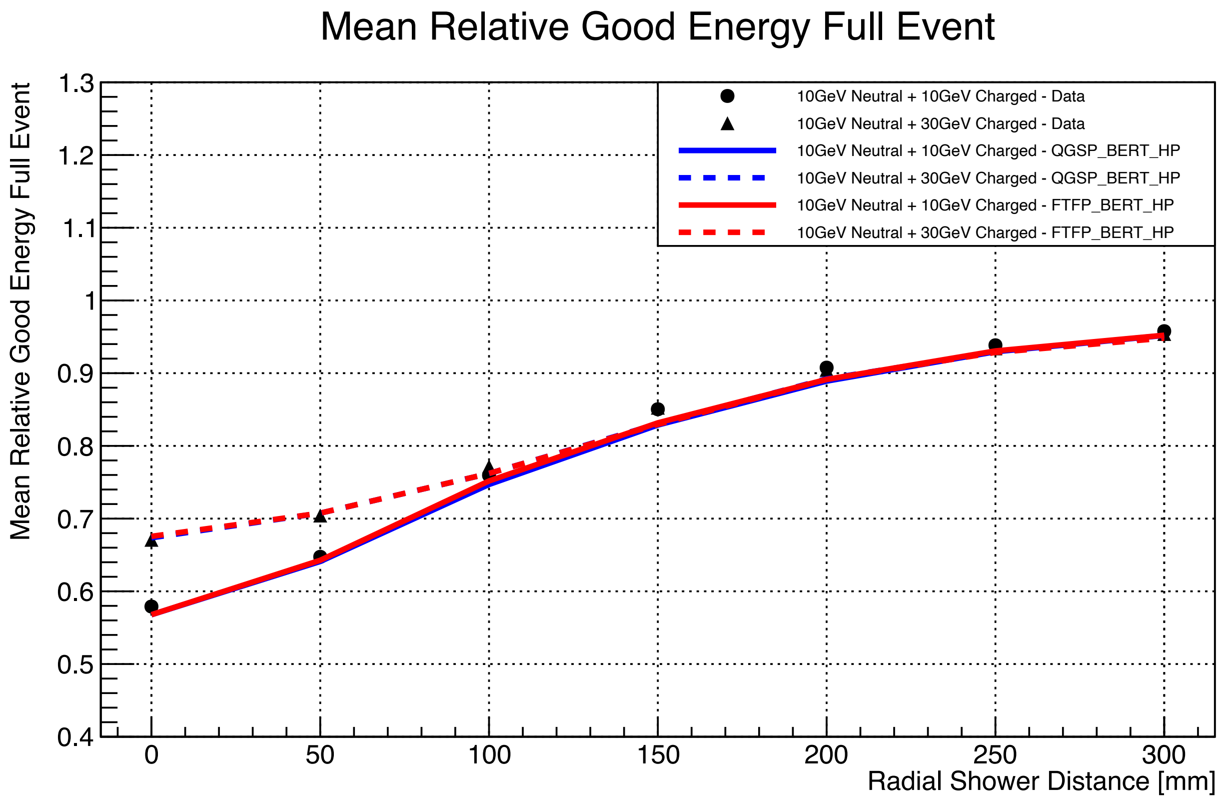


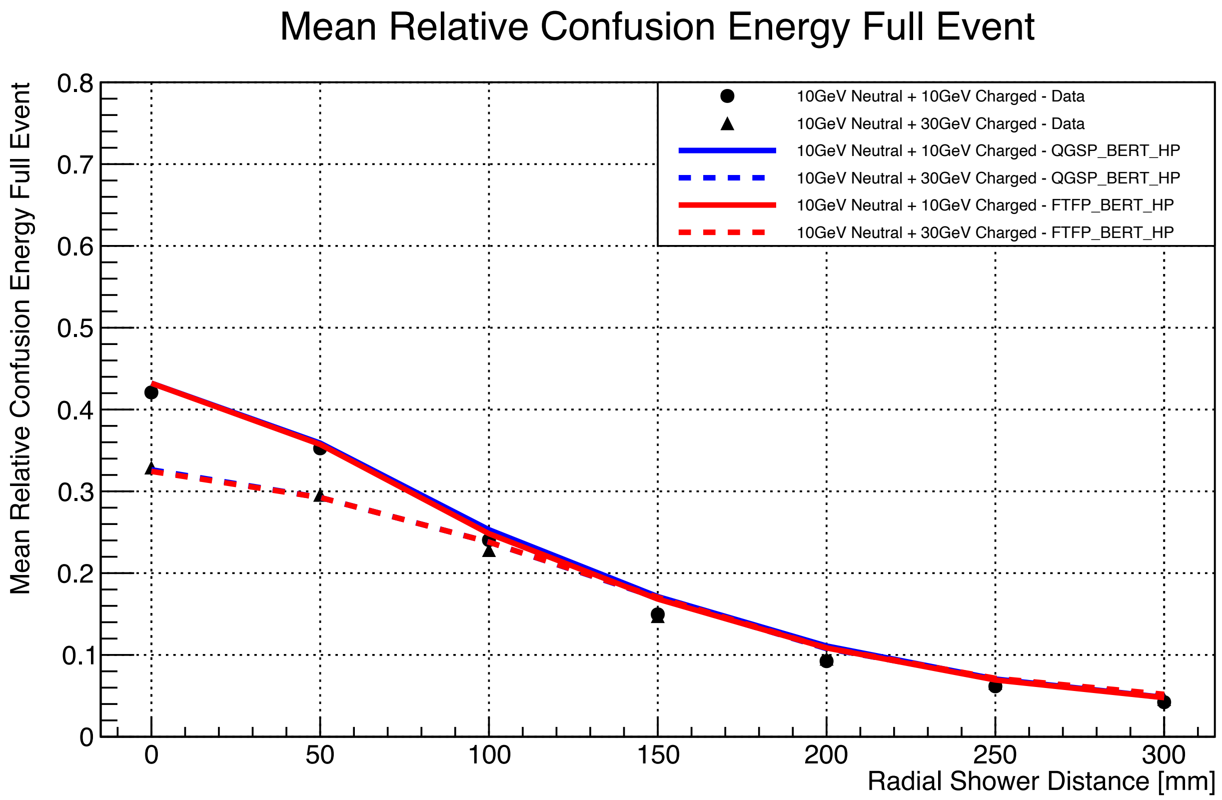


- Better data/MC agreement for largest distances (now same edge effects)
- Only slight overestimation of mean neutral PFO energy due to remaining high energy outliers
  - ➡ Mean & RMS 90/95

Mean Good/Confused Energy per Event

Total Event Energy Efficiency

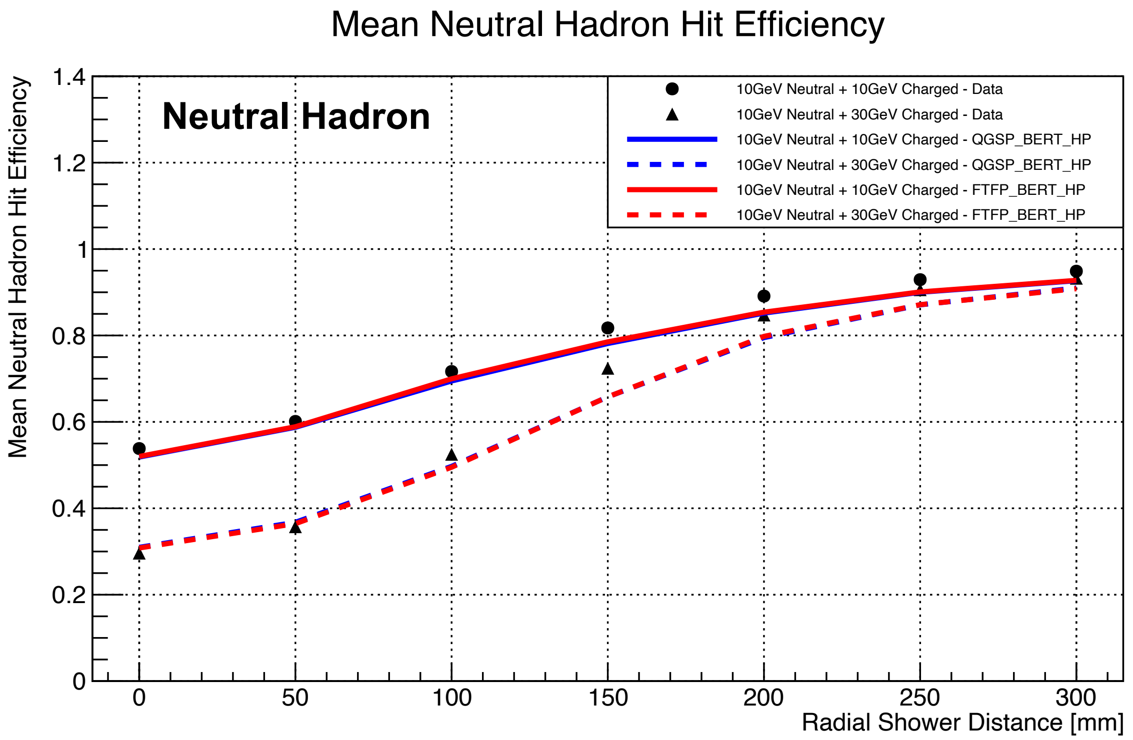


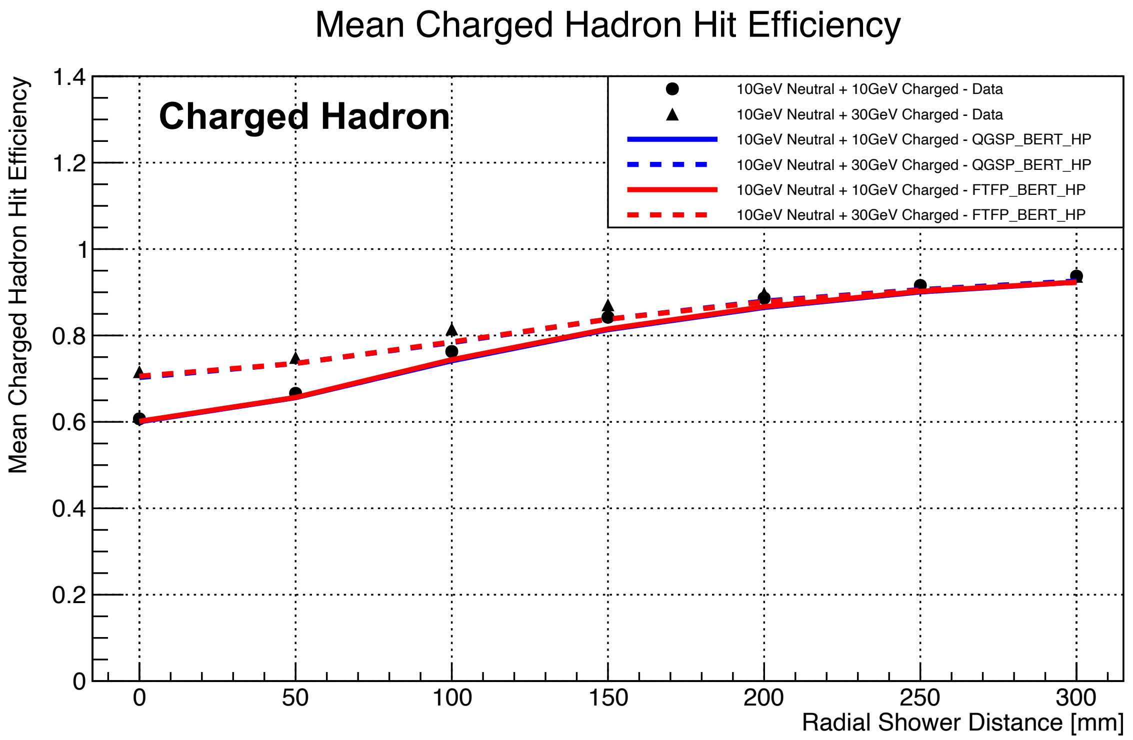


➡ Note: No information which type of confusion present if they might cancel out!

Reconstruction on Hit Level: Mean Hit Efficiency

Neutral & Charged Hadron

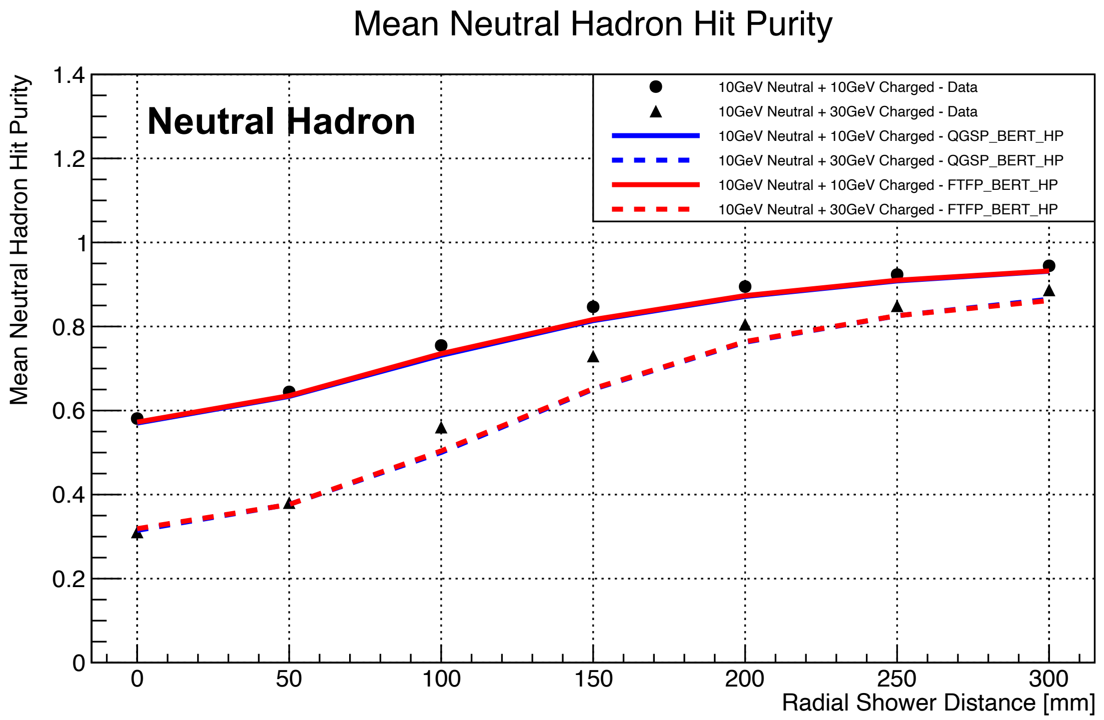


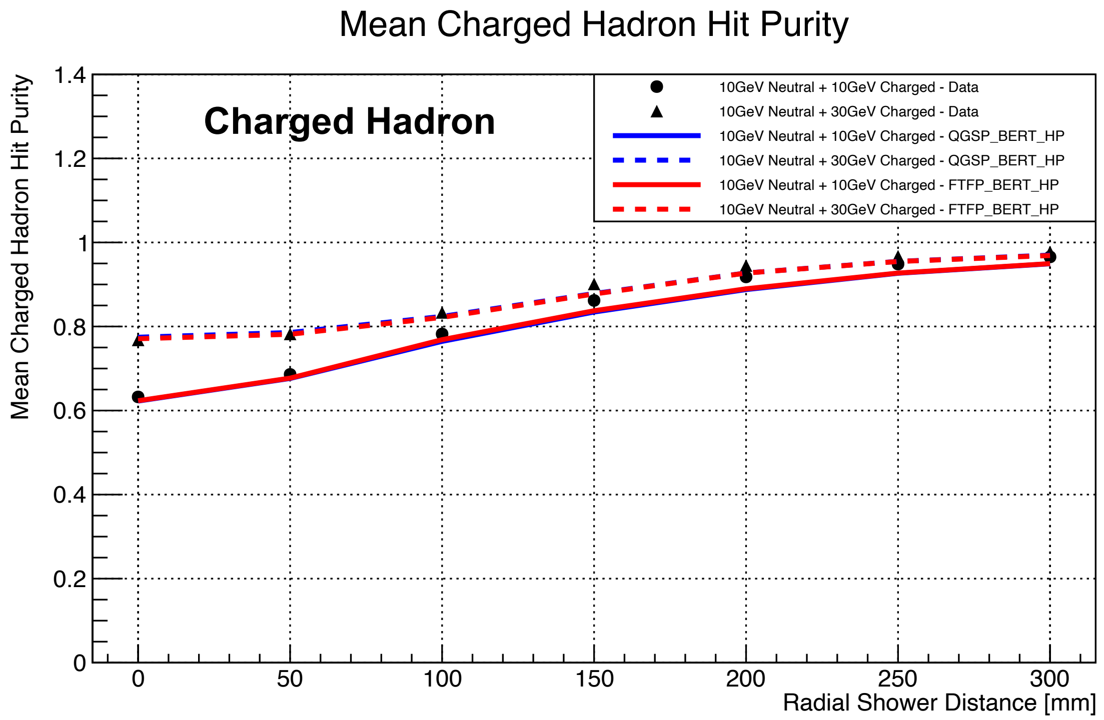


- The larger the separation, the more of the initial input hits are reconstructed correctly as neutral or charged
- Good data/mc agreement; For distances > 100mm data slightly better
- Missing few % for largest distances: Isolated & merged hits

Reconstruction on Hit Level: Mean Hit Purity

Neutral & Charged Hadron

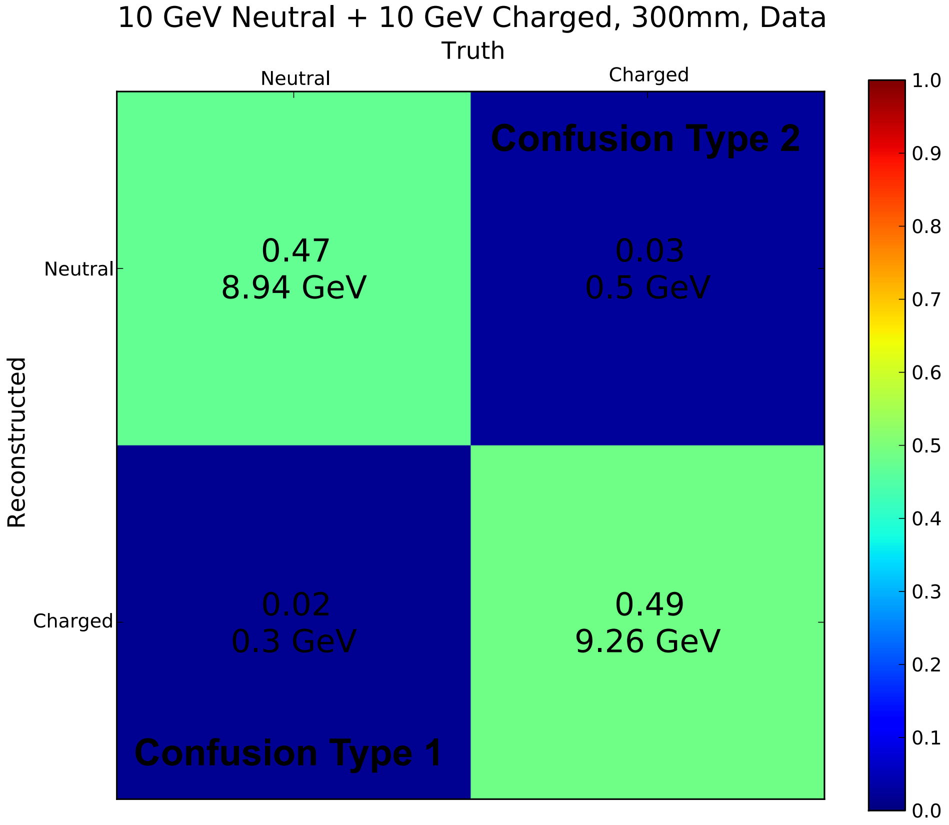


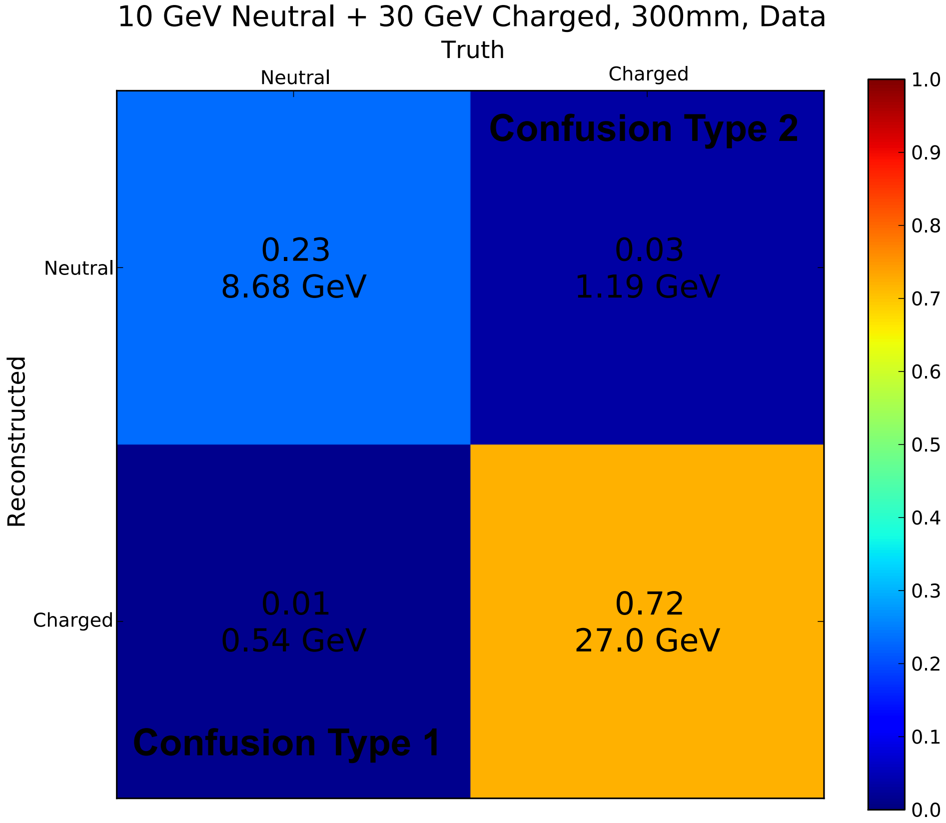


- The larger the separation, the more pure (in terms of hits) the charged and neutral PFOs become
  - ➡ Same observations as for hit efficiencies
- Neutral hadron: Remaining neutral fragments even for largest distances - **confusion type 2**
- Charged hadron: Almost non remaining absorption hits at largest distances - **confusion type 1**

Averaged Confusion Matrices - Event-wise

Summarising the Total Confusion Level - Example Data, 300mm

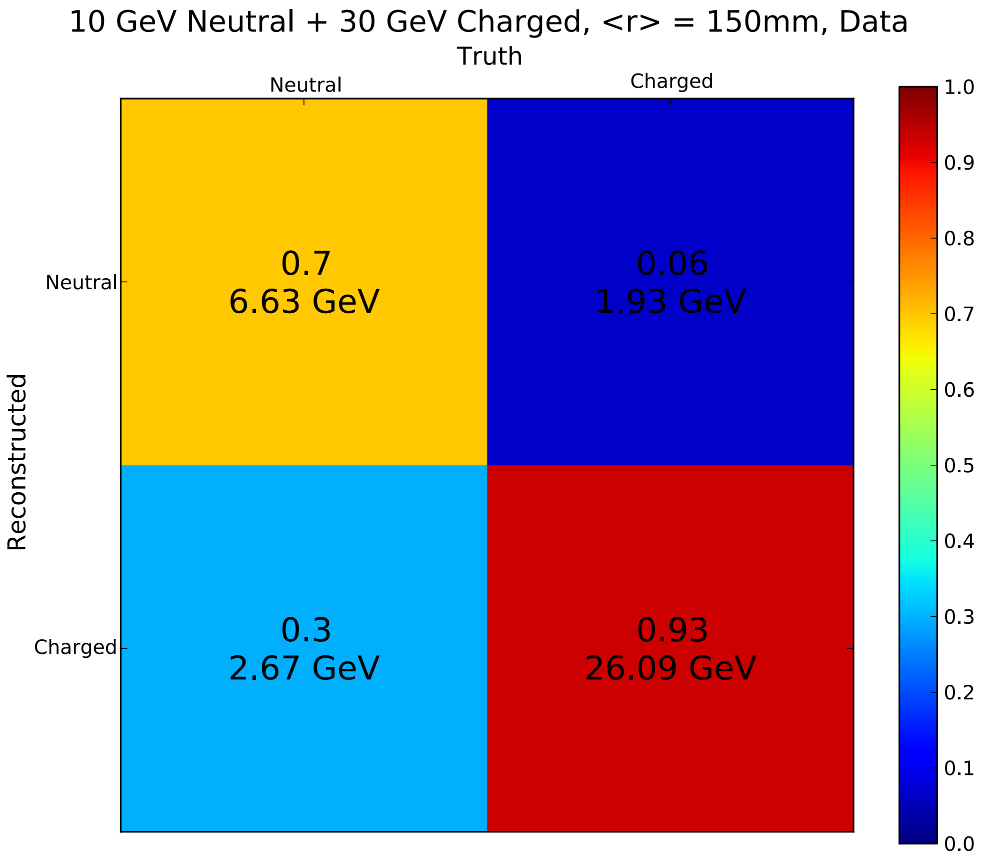


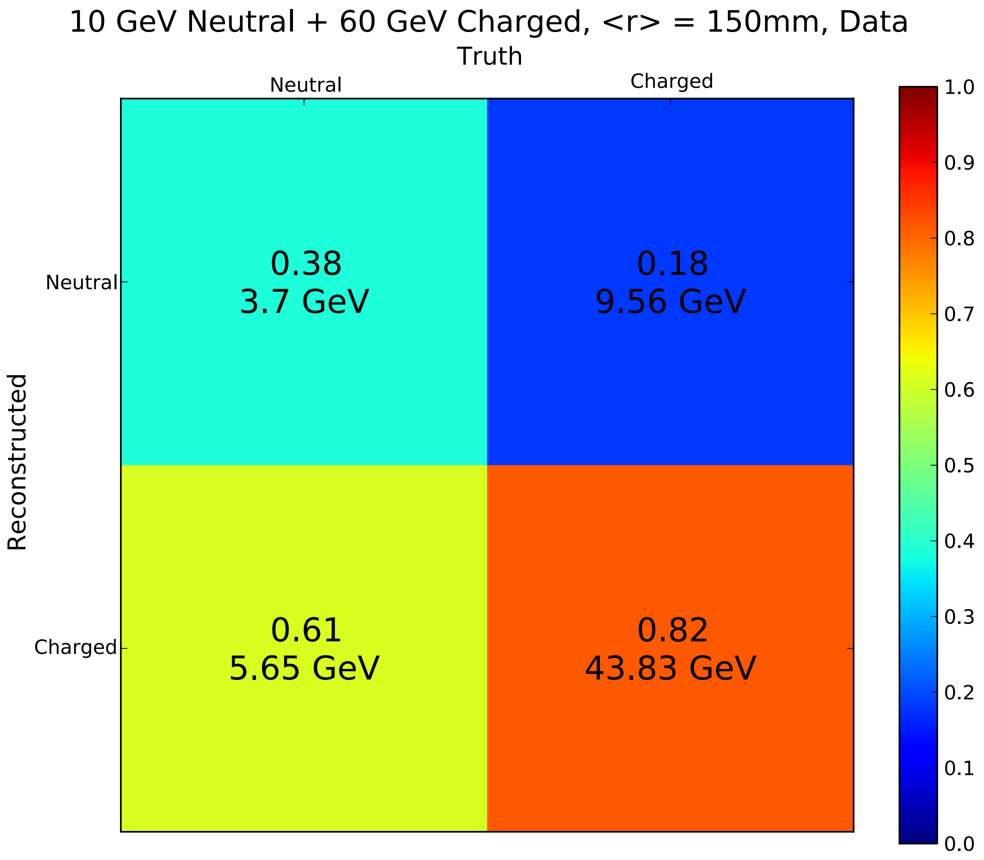


- Normalised to total input event energy (like in ILD confusion matrices)
  - ➡ Not favoured due to difference in total input energy (20 or 40 GeV)
  - ➡ But better for monitoring if confusion type 1 and type 2 are balanced

Two Particle Reconstruction: Default, Separated

Finding Confusion Sensitive Parameters/Algorithms, Data, 10 + 30 & 60 GeV Scenarios

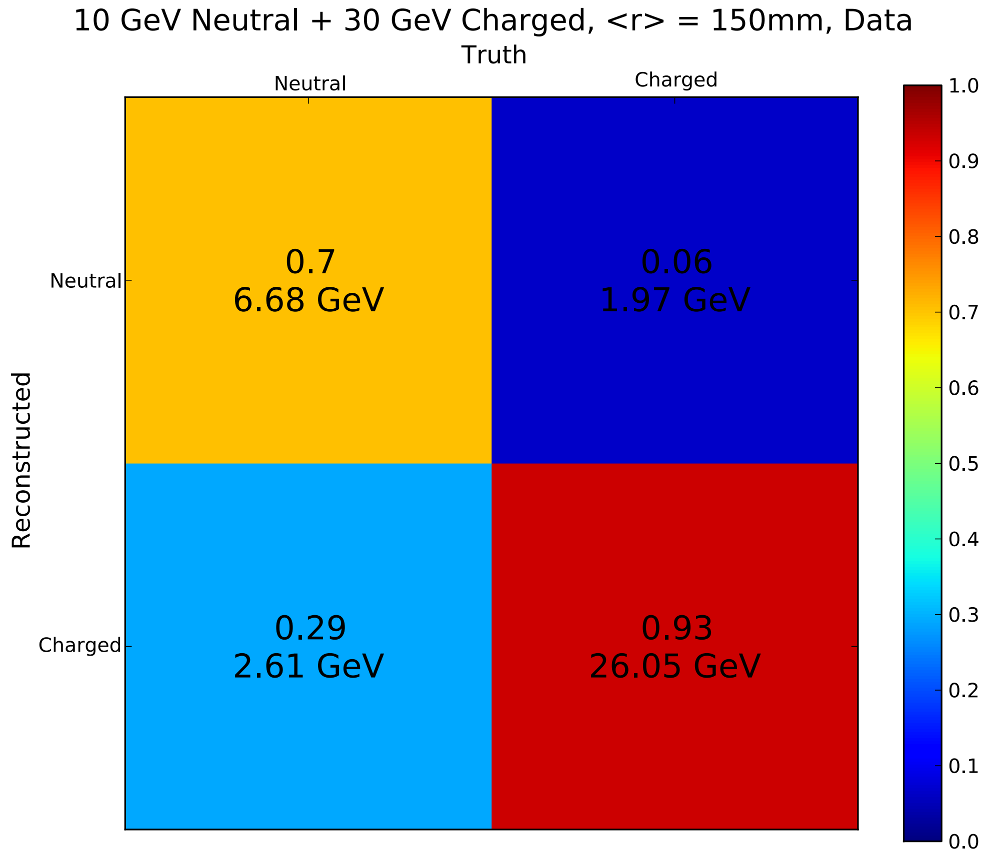


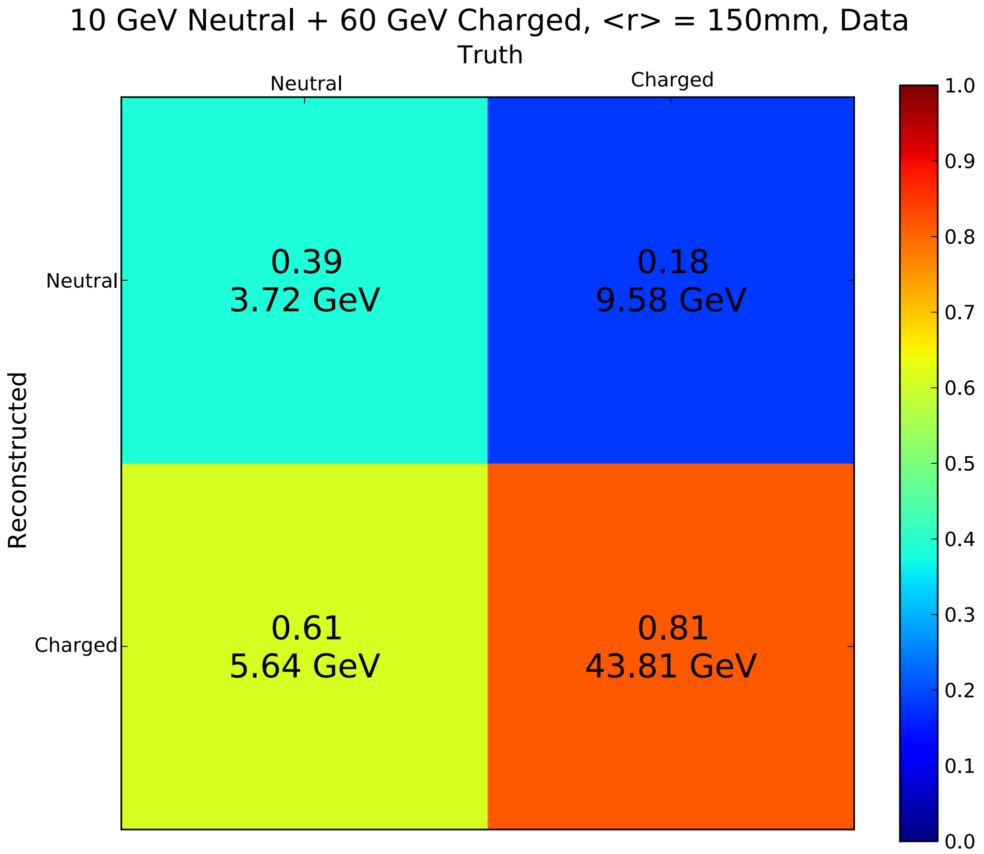


- In general less confusion than for overlapping shower scenario (except type 2 for 60 GeV roughly same)
  - ➡ Improvement less dominant for 60 GeV charged hadron scenario due to richer topology and leakage

Two Particle Reconstruction: TrackDrivenMerging OFF, Separated

Finding Confusion Sensitive Parameters/Algorithms, Data, 10 + 30 & 60 GeV Scenarios

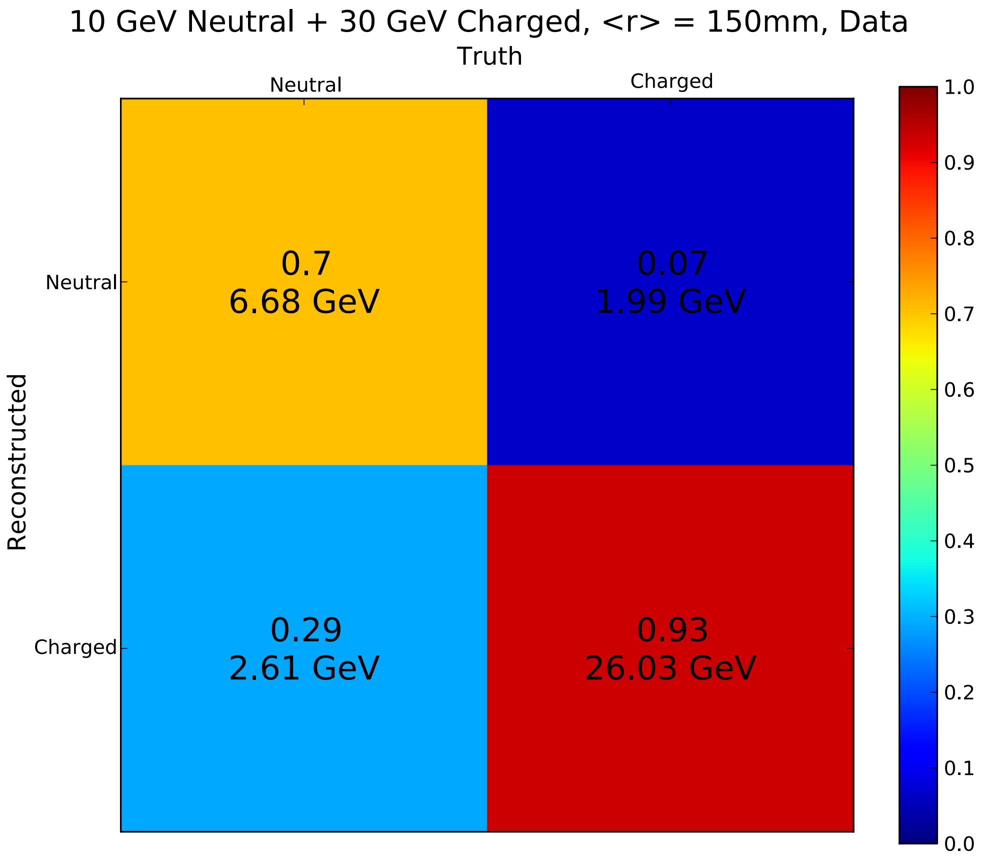


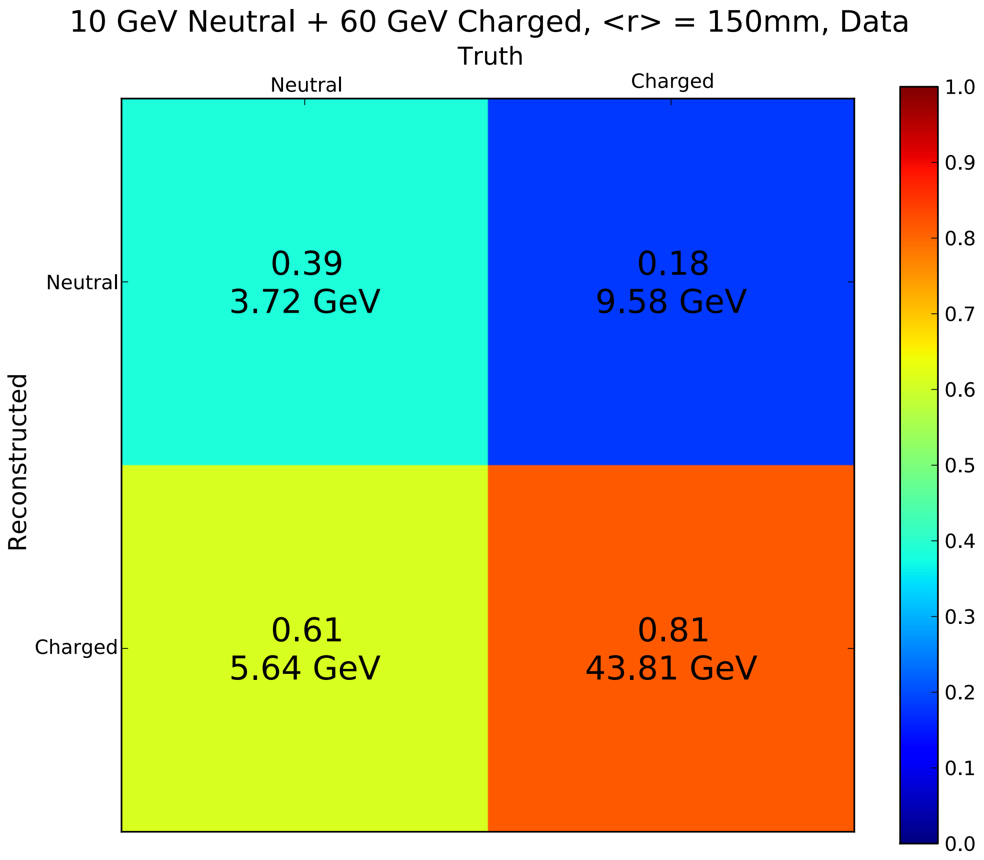


- Negligible difference compared to default Pandora for both energies and separated showers

Two Particle Reconstruction: Fragment Removal OFF, Separated

Finding Confusion Sensitive Parameters/Algorithms, Data, 10 + 30 & 60 GeV Scenarios

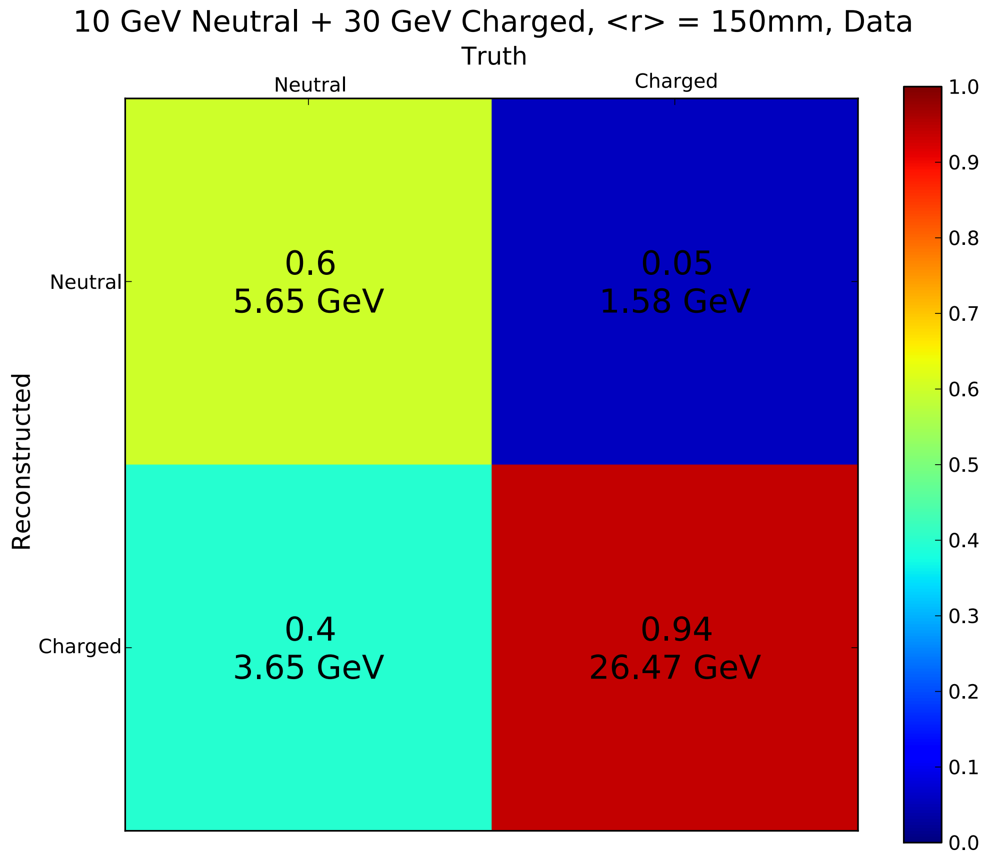


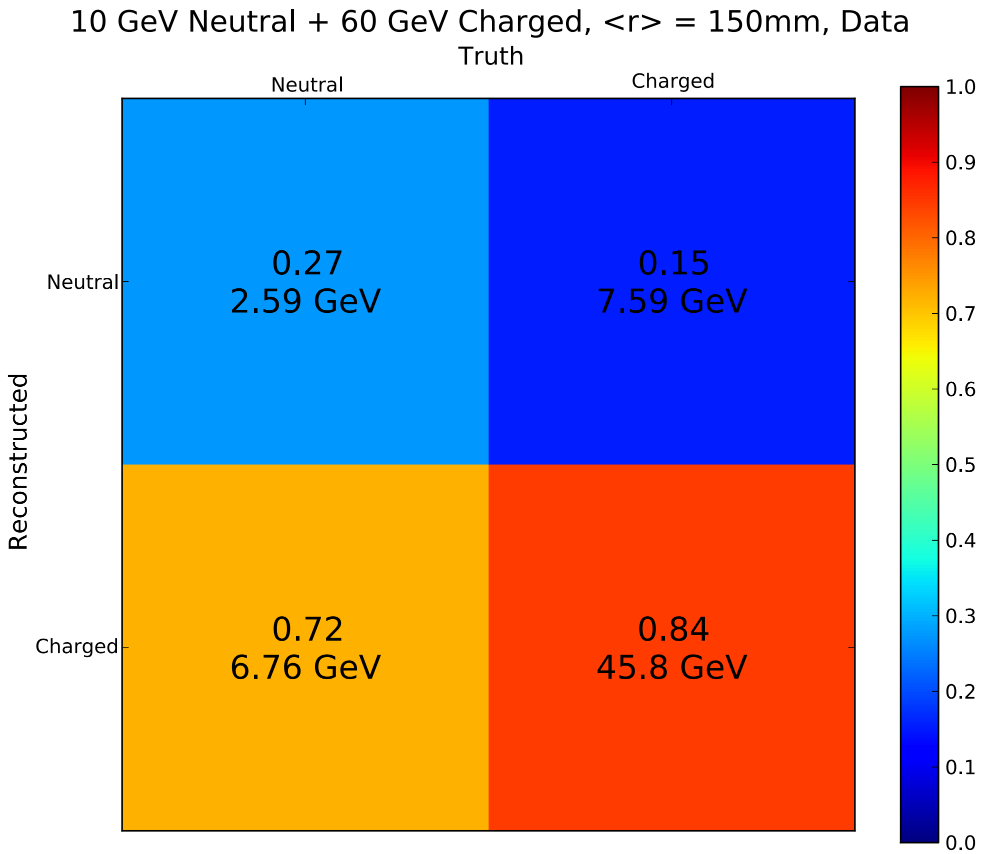


- No difference compared to default Pandora for both energies and separated showers

Two Particle Reconstruction: Full Reclustering OFF, Separated

Finding Confusion Sensitive Parameters/Algorithms, Data, 10 + 30 & 60 GeV Scenarios

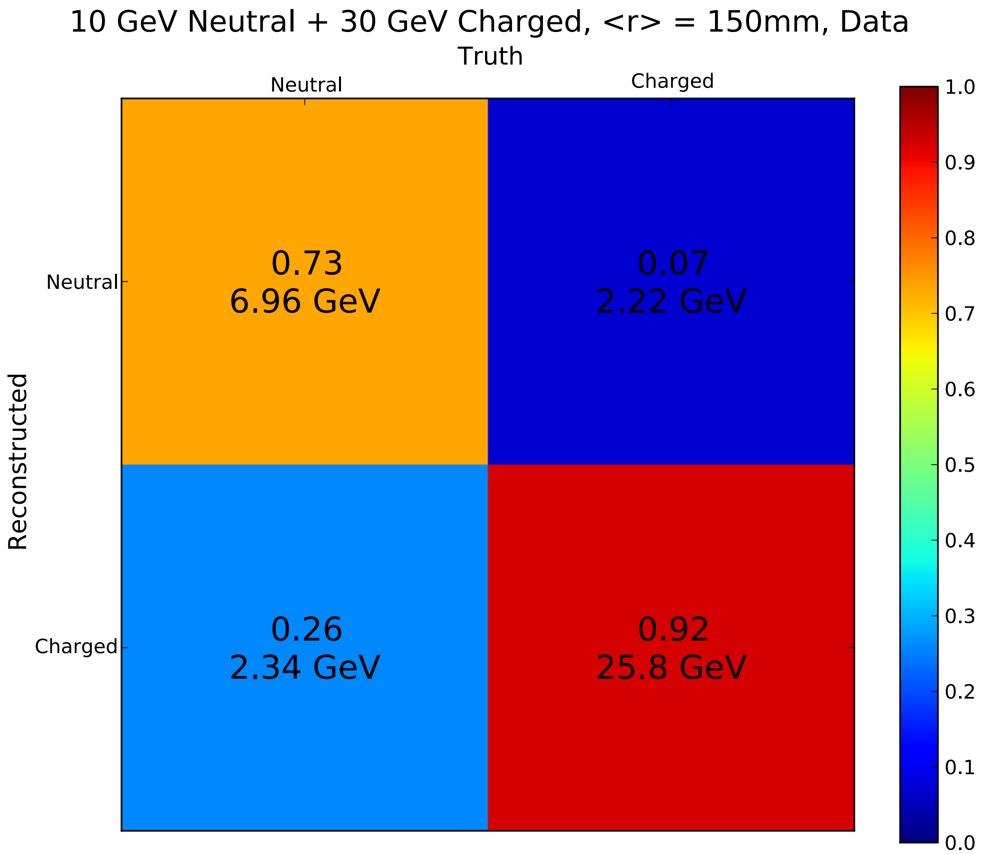


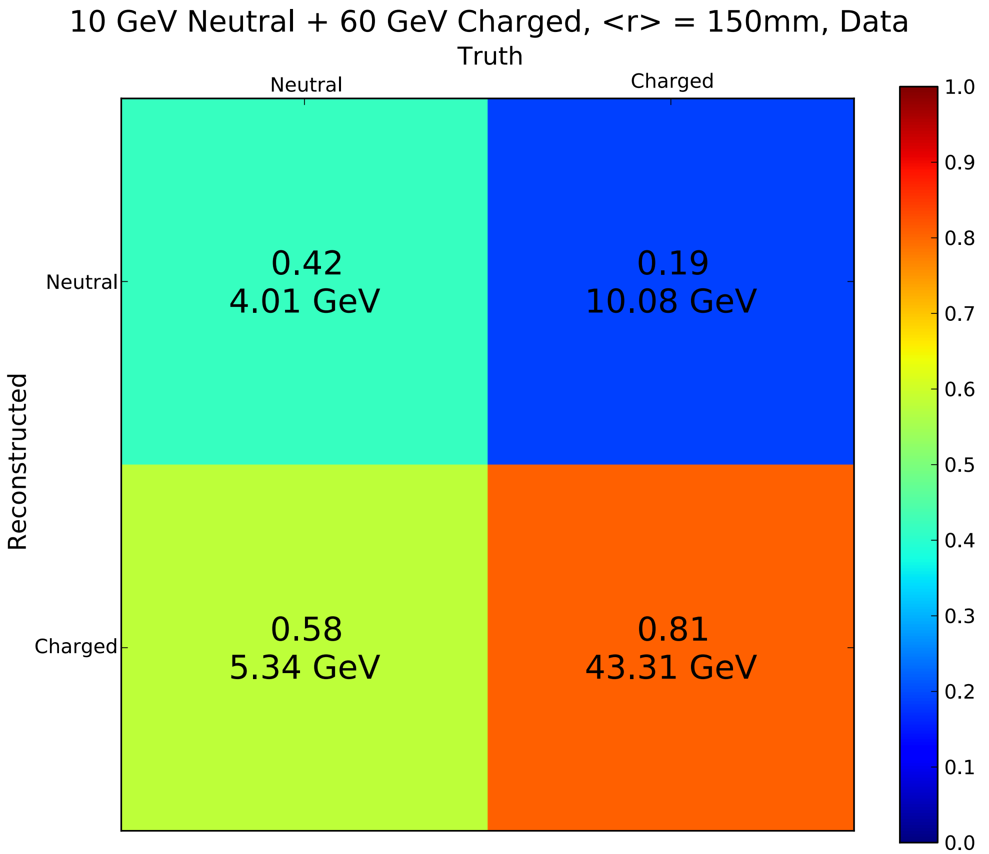


- As expected: Large impact on confusion level for overlap scenarios
  - ➡ Type 1 confusion: 10% more for 30 GeV, **12% more for 60 GeV**
  - ➡ Type 2 confusion gets less: 2% less for 30 GeV, **3% less for 60 GeV**

Two Particle Reconstruction: Reclustering Chi1.5, Separated

Finding Confusion Sensitive Parameters/Algorithms, Data, 10 + 30 & 60 GeV Scenarios





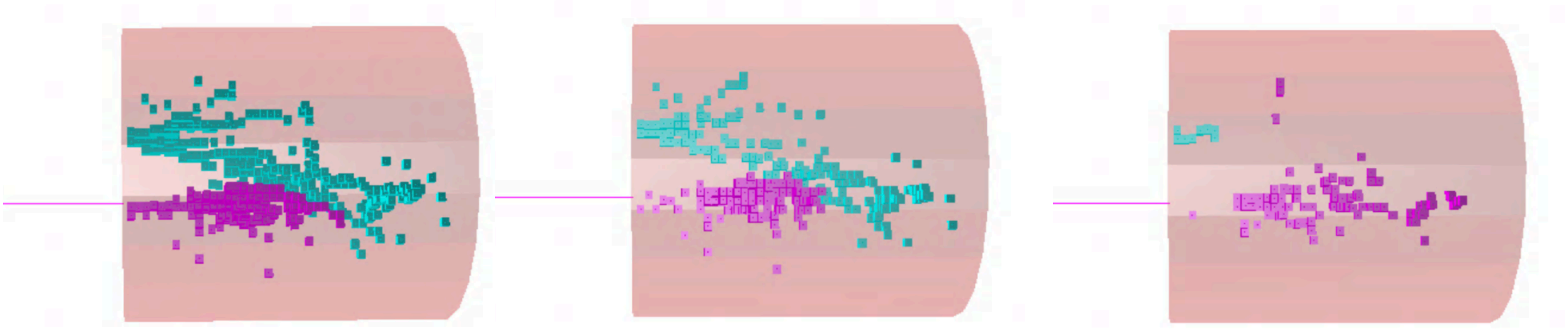
- Small impact on confusion for separated scenarios (towards energy flow)
  - ➡ Type 1 confusion: 3% less for both energies
  - ➡ Type 2 confusion: 1% more for both energies

Other ideas for tests with internal algorithm parameters

Energy Thresholds

Introduction

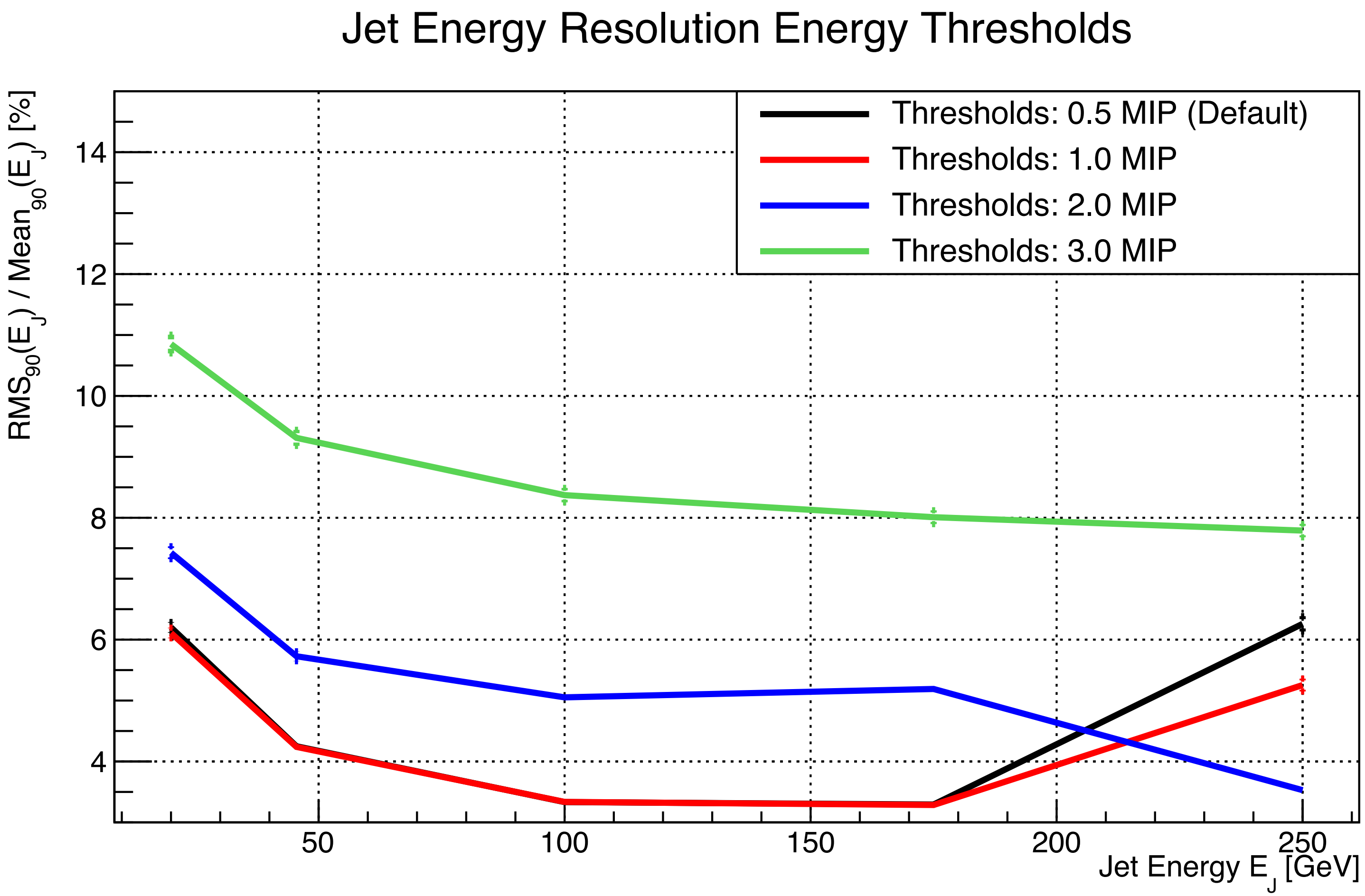
- Internal PandoraPFA energy thresholds are working well
  - ➡ Motivation CMS: Increasing noise levels after exposure in high radiation environment
  - ➡ By changing energy thresholds, shower energy as well as topology dramatically influenced
  - ➡ Study influence on PandoraPFA performance on AHCAL + ILD jet events



0.5 MIP | 1.0 MIP | 3.0 MIP

Jet Energy Resolution

Different Energy Thresholds (ECAL & HCAL)

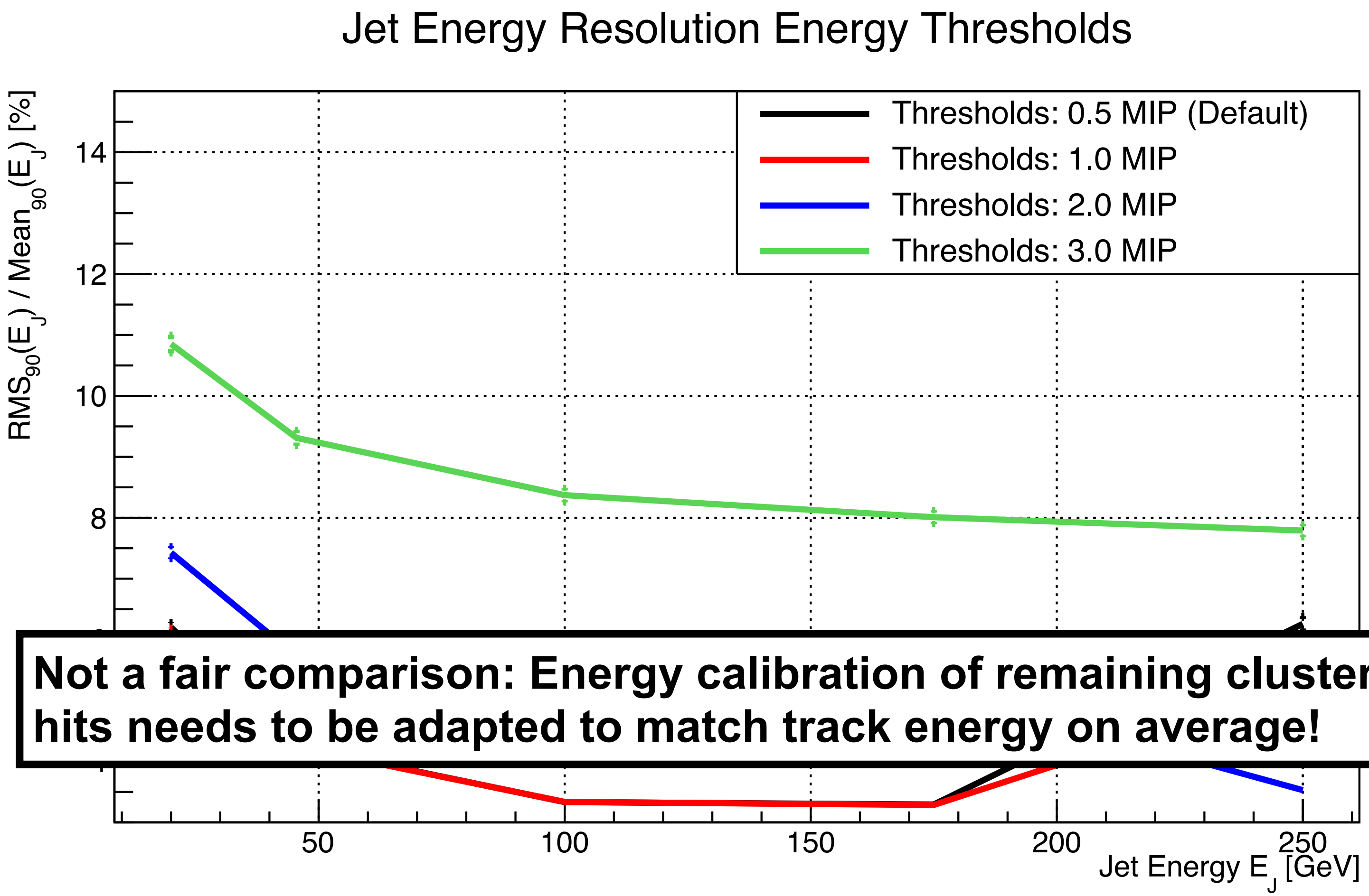


Caution:
Work in progress

- First look: Slightly higher thresholds do not degrade JER at all (helping slightly for lowest/highest energies?)
- Threshold 2.0 MIP and higher: Large degradation of JER (MIP tracks before/within showers,…)

Jet Energy Resolution

Different Energy Thresholds (ECAL & HCAL)



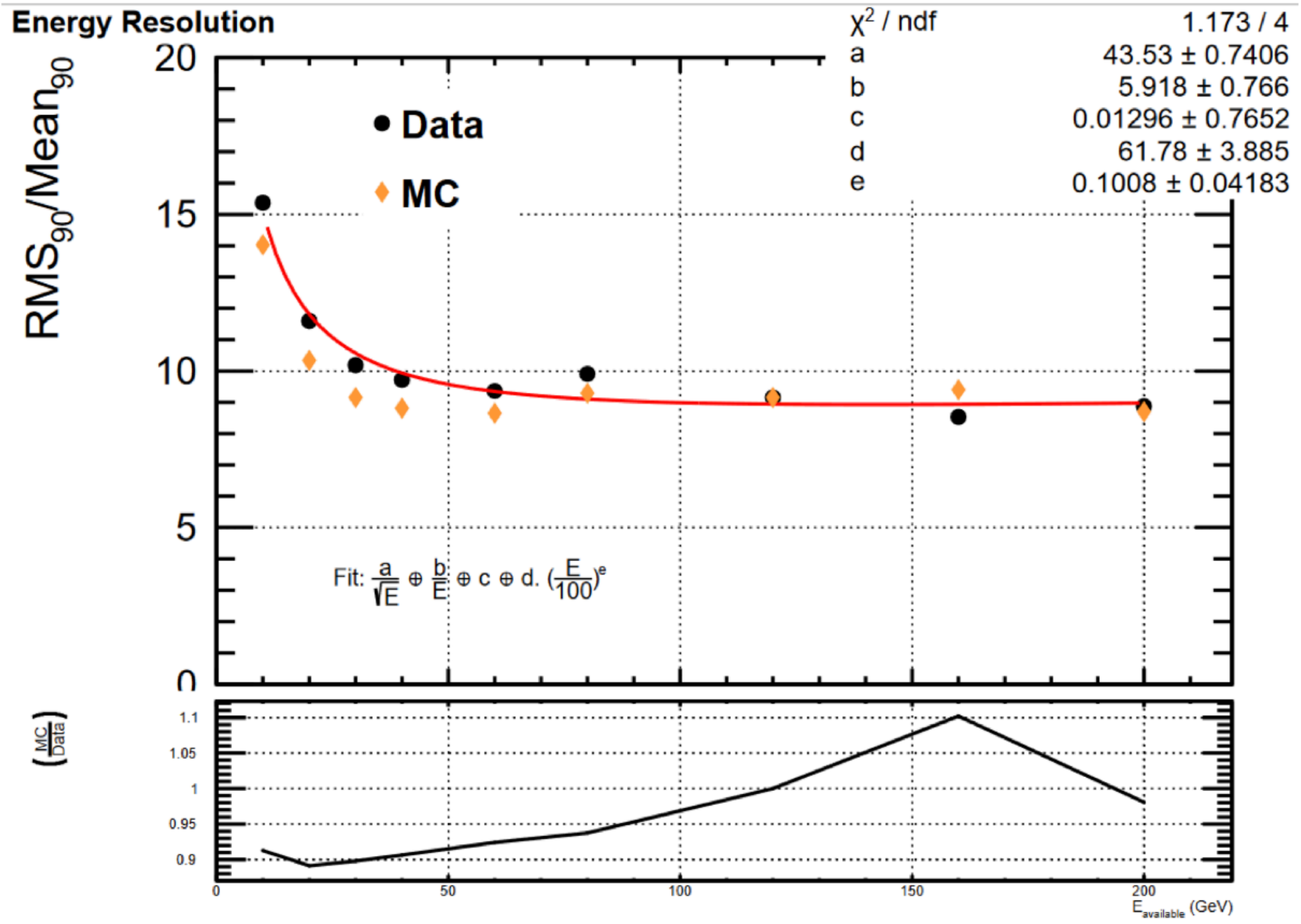
Not a fair comparison: Energy calibration of remaining cluster hits needs to be adapted to match track energy on average!

Caution:
Work in progress

- First look: Slightly higher thresholds do not degrade JER at all (helping slightly for lowest/highest energies?)
- Threshold 2.0 MIP and higher: Large degradation of JER (MIP tracks before/within showers,…)

Conventional Energy Resolution

Comparison



Note: Plot may be outdated!

Conventional Energy Resolution

PandoraPFA Scenarios