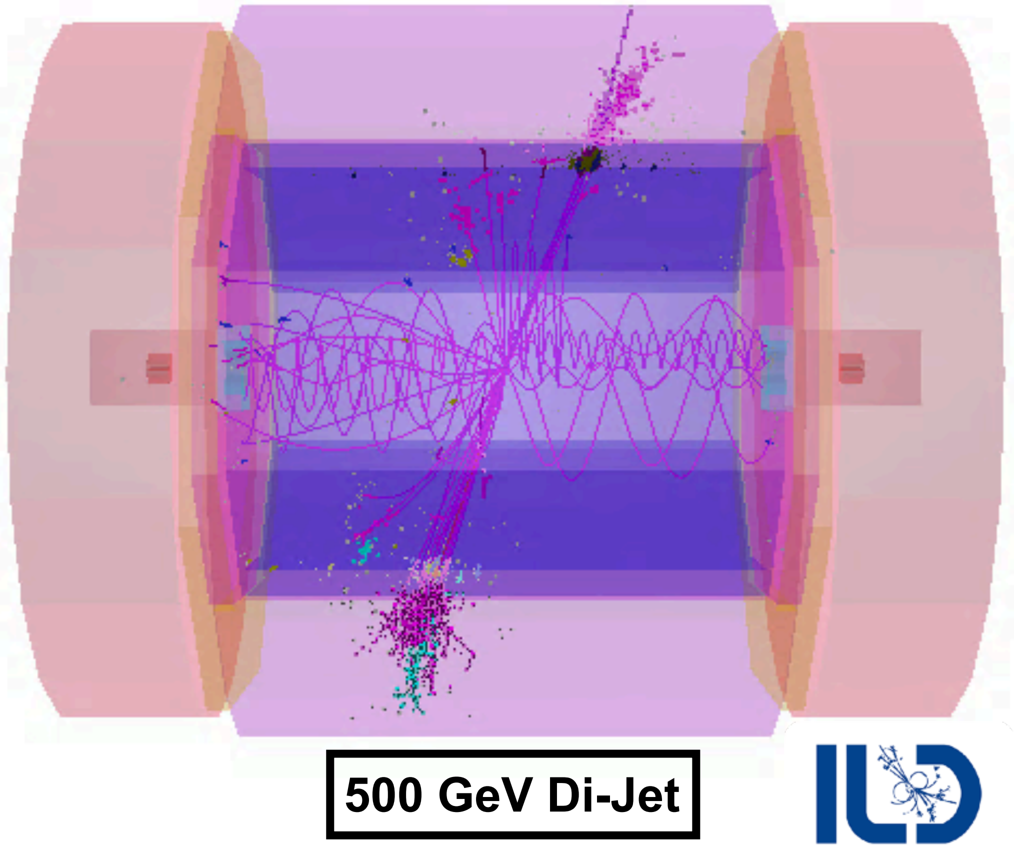
PandoraPFA Studies with AHCAL 2018 Prototype Beam Test Data & ILD Jets



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

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386
HGSFP

Outline

For this Talk

- Concept of Particle Flow & Limiting Effects

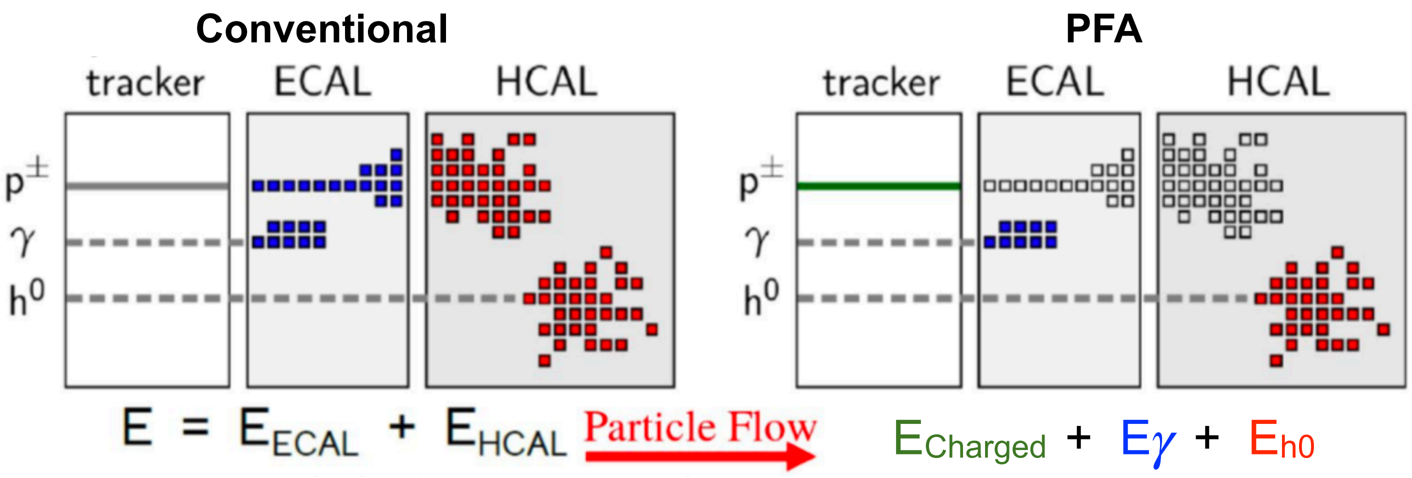
- Two Particle Separation Studies with AHCAL 2018 Data
- Performance Studies on AHCAL 2018 Data & ILD Jets for Different
  - ➡ Algorithm Settings
  - ➡ Energy Thresholds

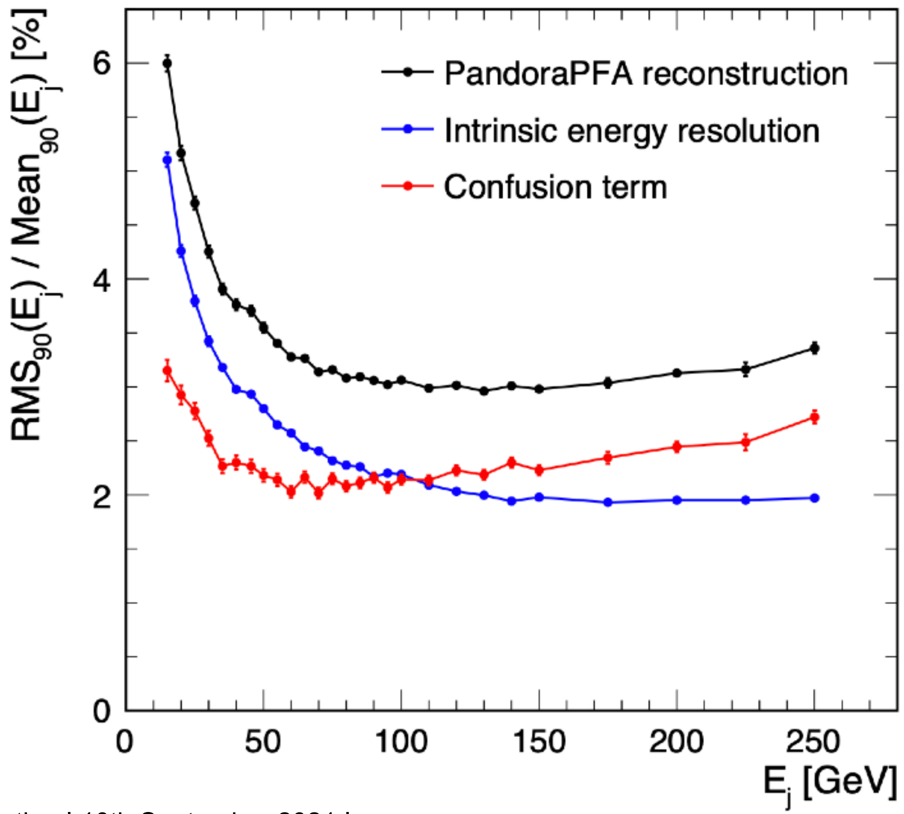
- Summary & Conclusions

Particle Flow Approach

Key to Highest Precision

- Goal at future e^+e^- collider experiments: **Jet energy resolution** of **3-4%** for jet energies of **40-500 GeV**
  - ➡ PFA: Measure energy/momentum of individual particles with sub-detector providing best resolution
    - ➡ Make use of excellent resolution of tracker (for ~60% charged particles in jets)
    - ➡ Calorimeter measure only for neutral particles





arXiv:1705.10363

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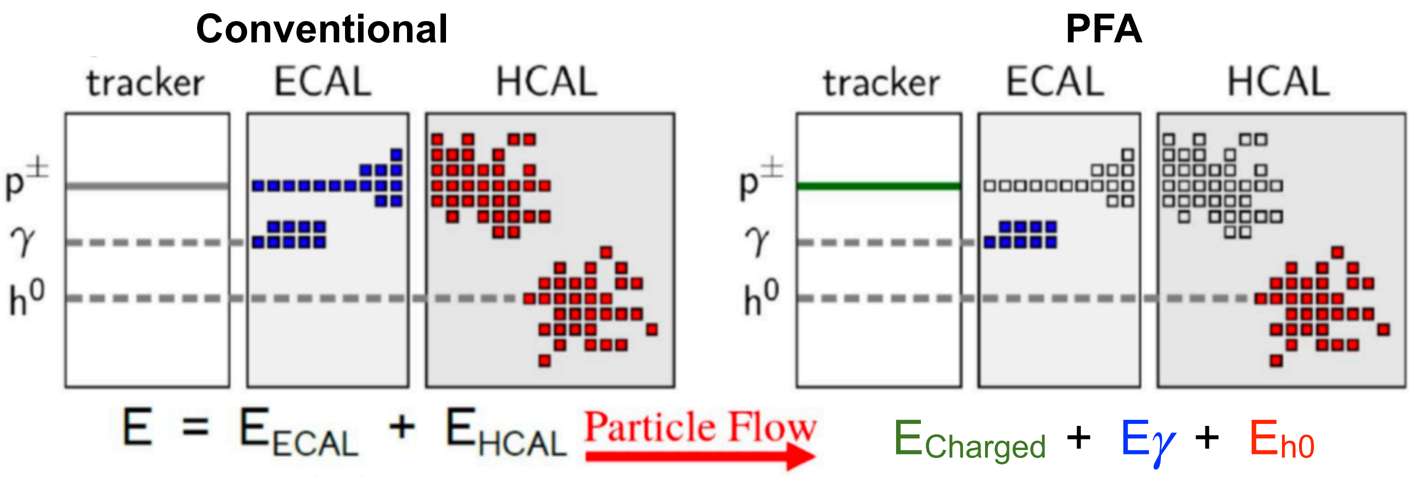

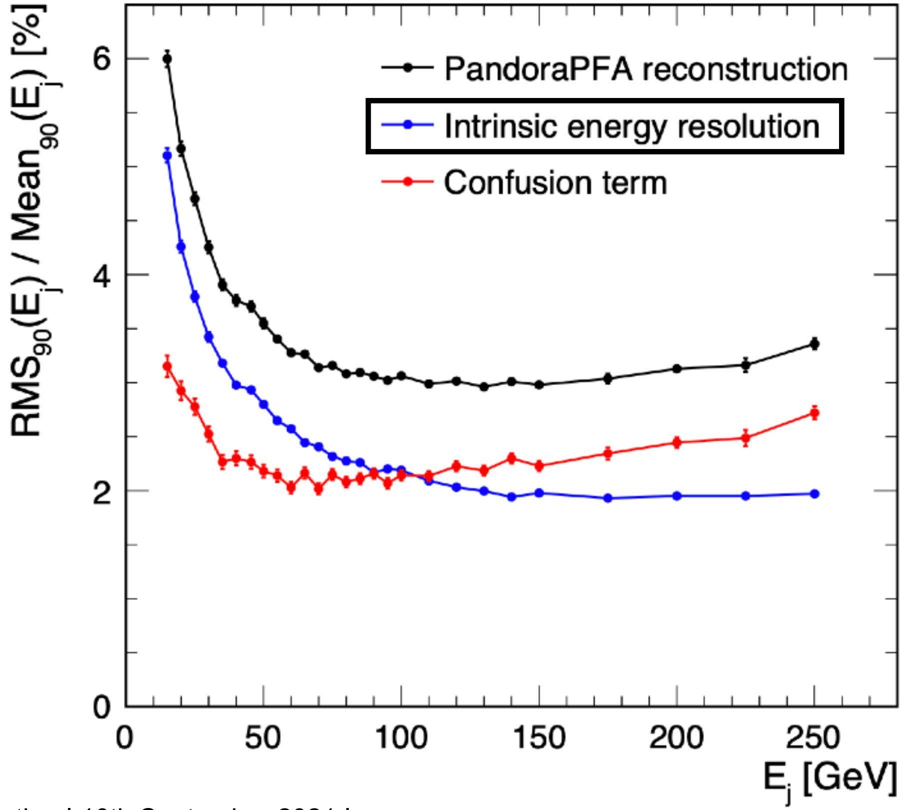

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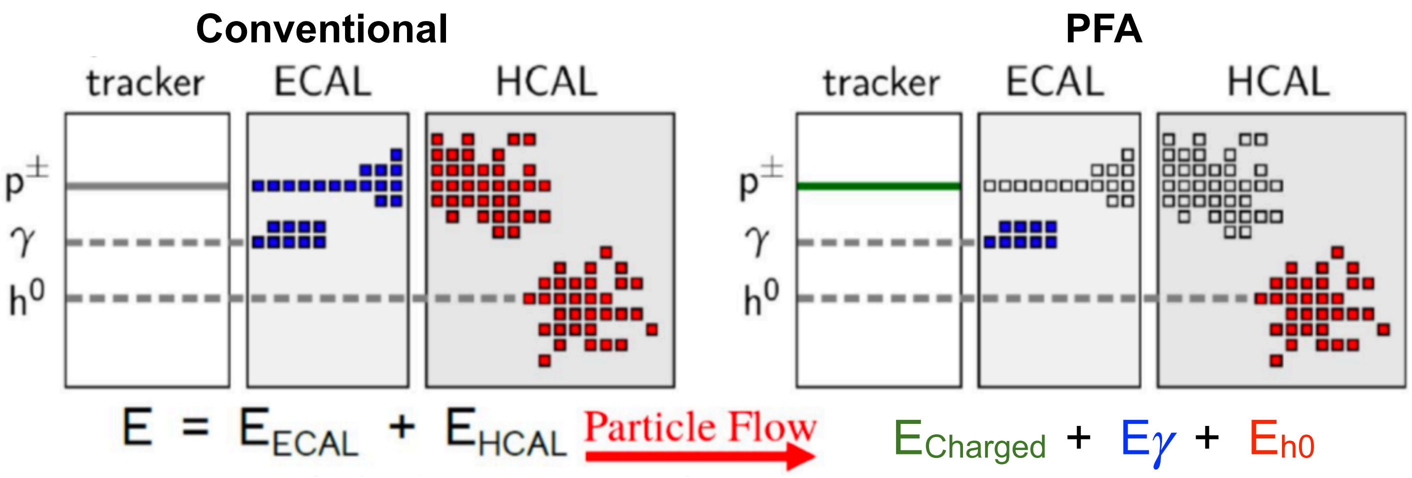

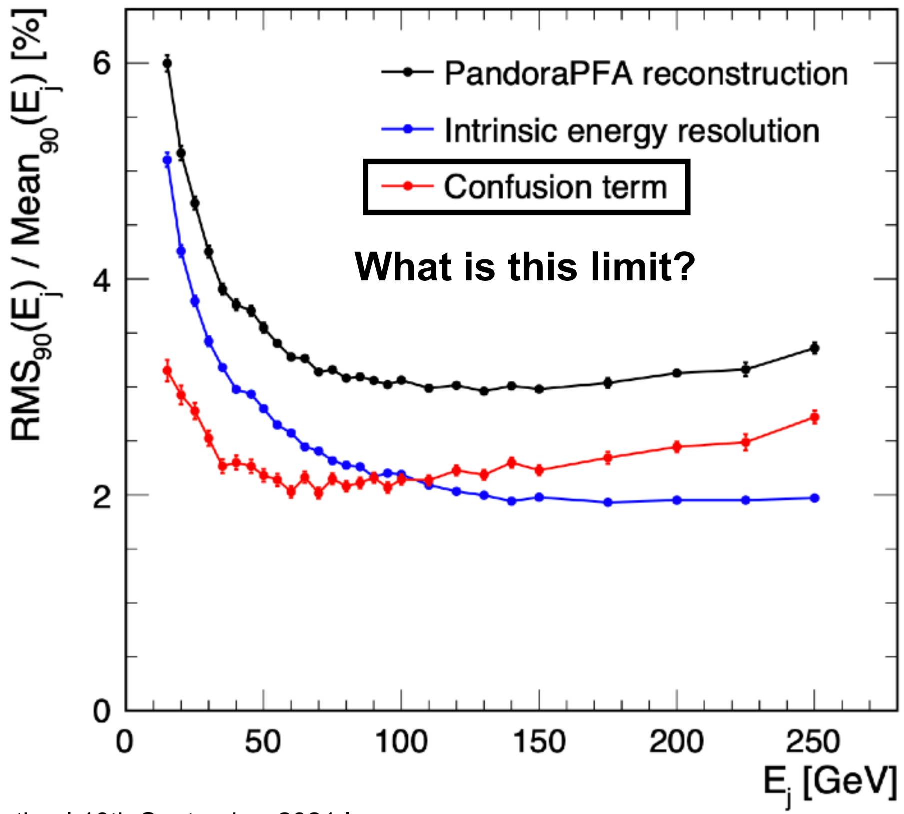

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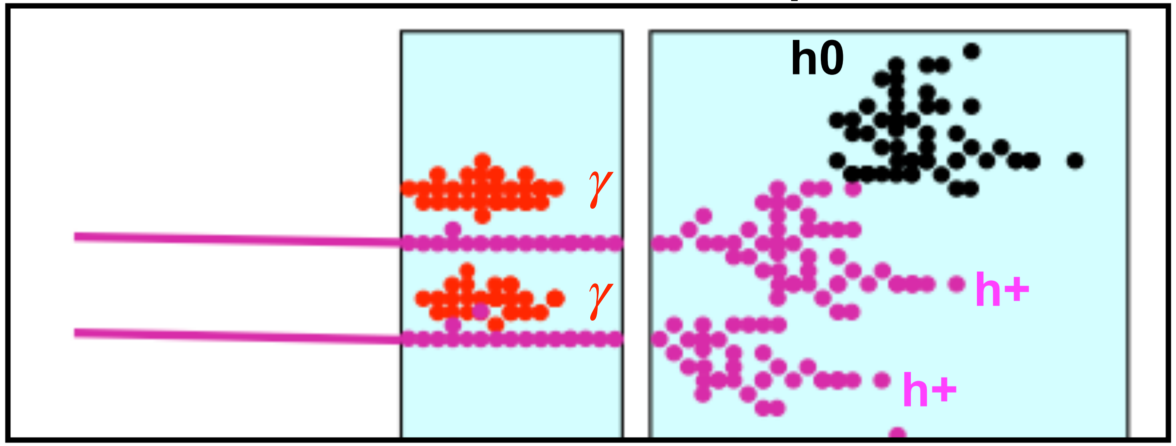
Confusion Types

Limits of Particle Flow Reconstruction

Well Reconstructed Example Event



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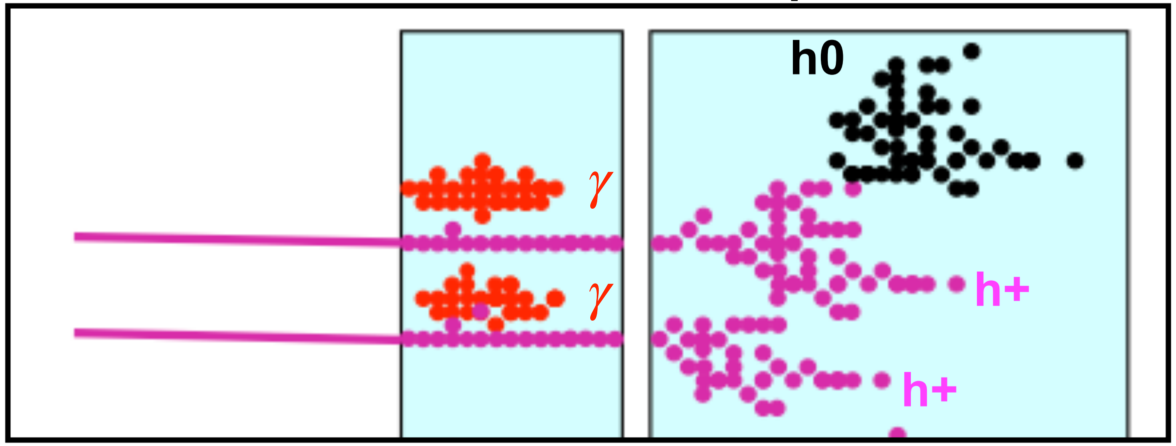

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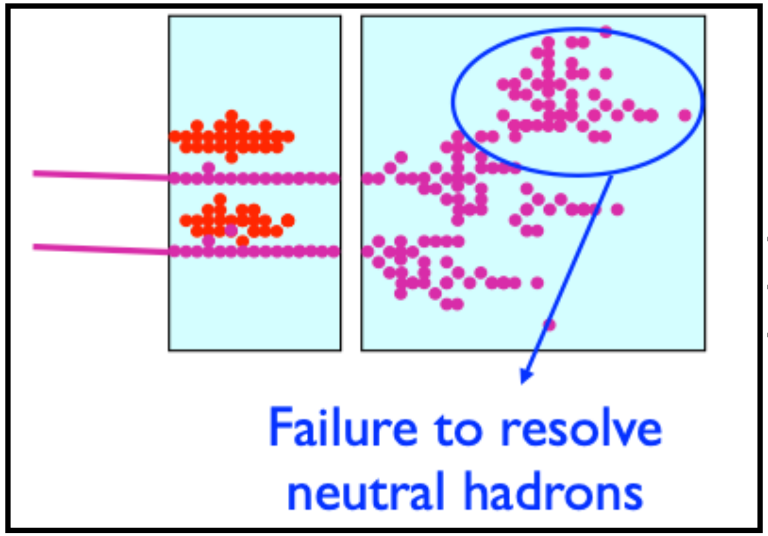
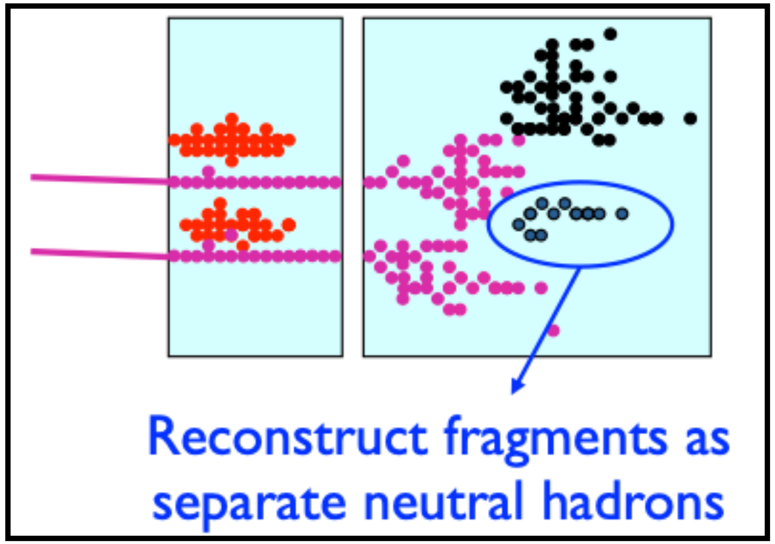
- **Topologically/energetically confusing** events potentially cause problems for PFA reconstruction:
  - ➡ **Two types of confusion**
  - ➡ Level and balance of this "mistakes" **limiting jet energy resolution at high energies**

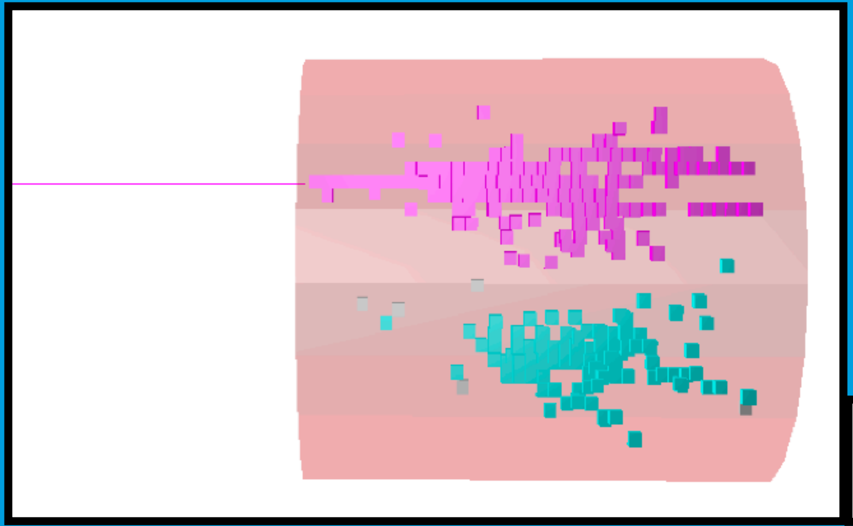


Loss of neutral energy (Confusion Type 1)



Double counting of charged energy (Confusion Type 2)

Two Particle Separation
AHCAL 2018 Beam Test Data & MC



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

Motivation and Goals of Studies

PandoraPFA on AHCAL 2018 Prototype Data

- **General question:** How accurate are details of simulations (e.g. ILD jets) to fully exploit shower sub-structure information for an improvement in energy resolution? Is this dependency predictable?

  ➡ Study limiting effects of PFA in detail for different energies and shower distances

  - Provide **performance** feedback on **real data** in comparison to simulations
  - Apply **PandoraPFA** on a simplified setup (AHCAL 2018 data + tracks)

    ➡ Evaluated simulated algorithm performance for standalone application
    https://agenda.linearcollider.org/event/8608/contributions/46465/attachments/35889/55718/DH_pandora_calice_200930_final.pdf

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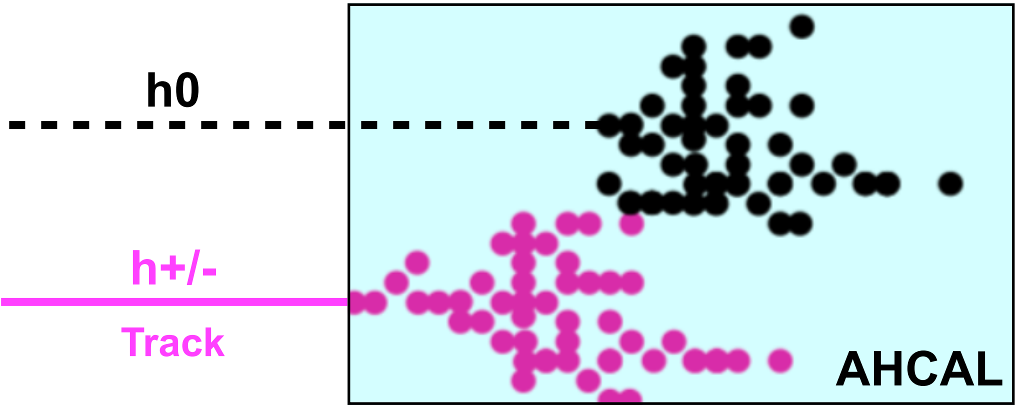
Baseline Scenario: Charged + Neutral Hadron Event



Main Questions to be Answered:

- How well can PandoraPFA separate and resolve the neutral from the charged hadron (energy & hits)?
- How is confusion level scaling with energy & distance?
- How balanced are energy losses & double counting?
- Total energy reconstruction performance?
- Simulation agreeing with best beam data?

Motivation and Goals of Studies II

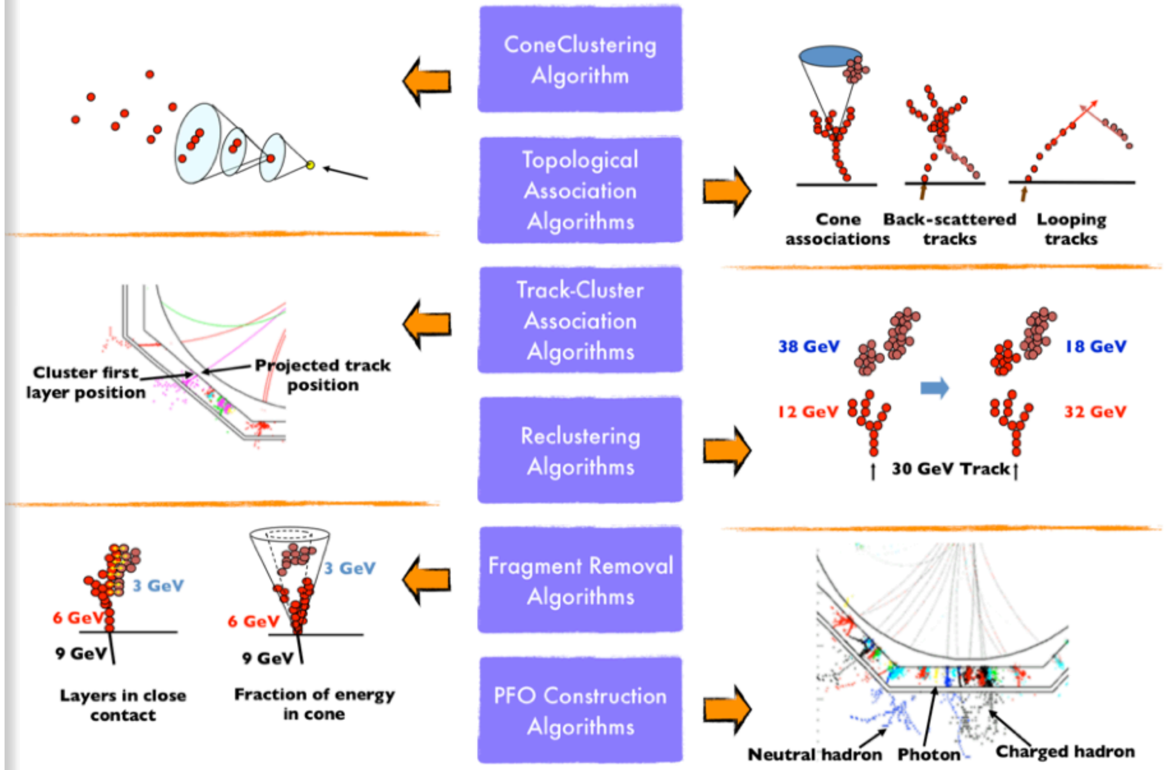
PandoraPFA on AHCAL 2018 Prototype Data

Similar studies were performed for the AHCAL 2007 prototype (https://arxiv.org/abs/1105.3417) and the SDHCAL with ArborPFA (http://cds.cern.ch/record/2669487/files/fulltext.pdf)

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.
- 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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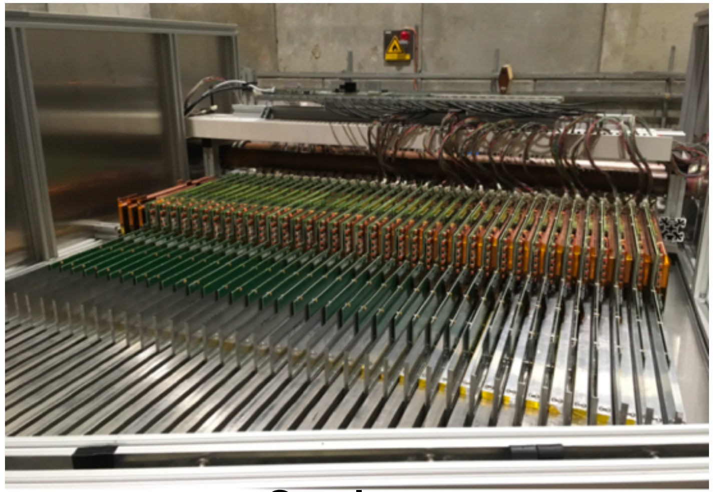
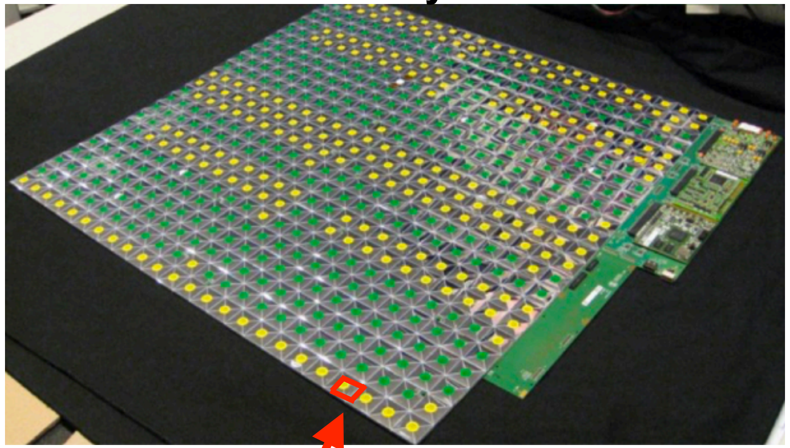
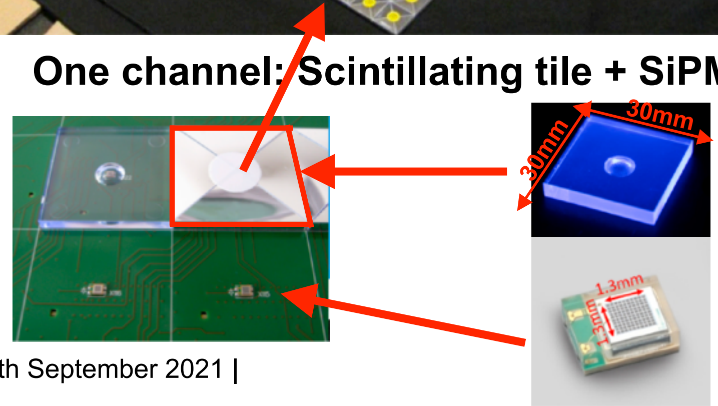
AHCAL 2018 Prototype: 38 layers within steel stack



One layer



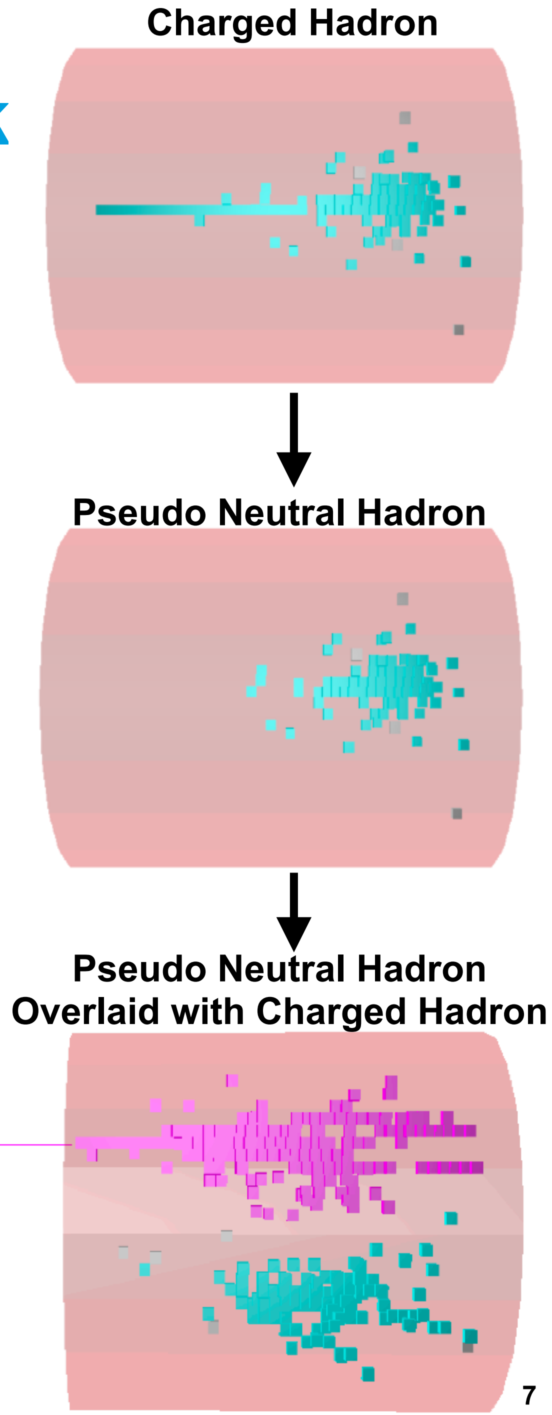
One channel: Scintillating tile + SiPM



Sample Selection, Event Preparation, Framework

PandoraPFA Two Particle Separation - AHCAL 2018 Data & MC

- Data: June beam test 2018 @ SPS CERN + delay wire chamber tracks
- MC: GEANT4 v.10.03, QGSP_BERT_HP & FTFP_BERT_HP + MC truth tracks
- Applied BDT PID for hadrons
- **Event: 10 GeV pseudo-neutral + 10 GeV or 30 GeV charged hadron**
  ➡ Pre-shower MIP track removal + subsequent hit-by-hit event overlay
- **Transversal distances between showers: 0-300 mm**
- Track for charged hadron: Fixed momentum of 10 GeV or 30 GeV



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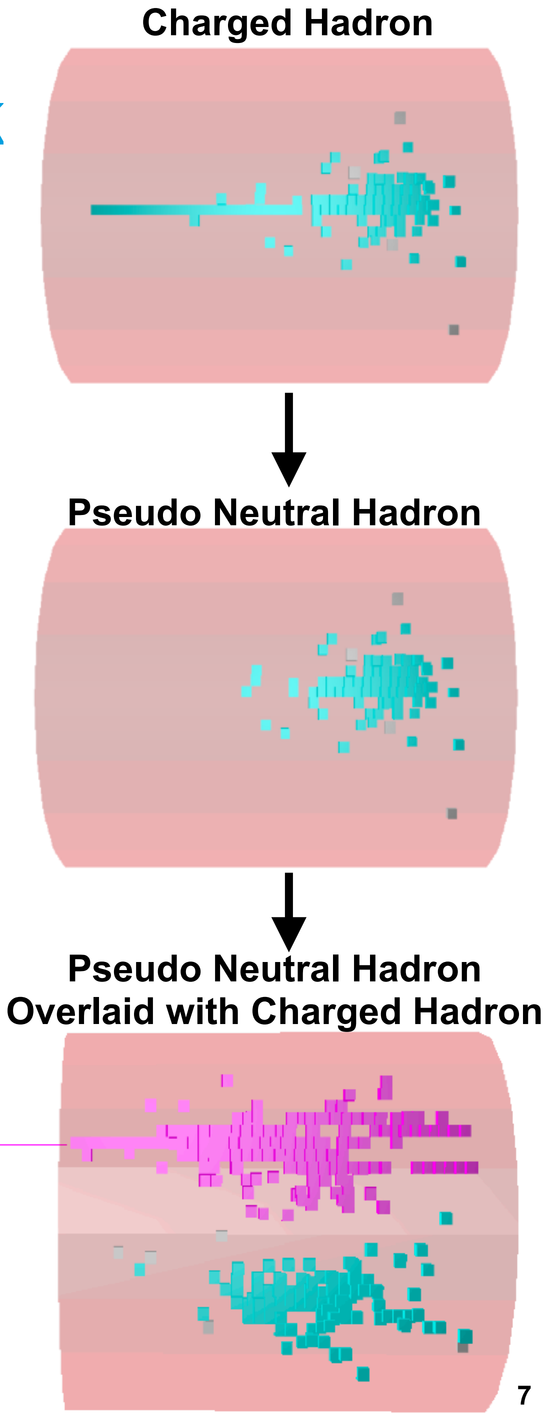
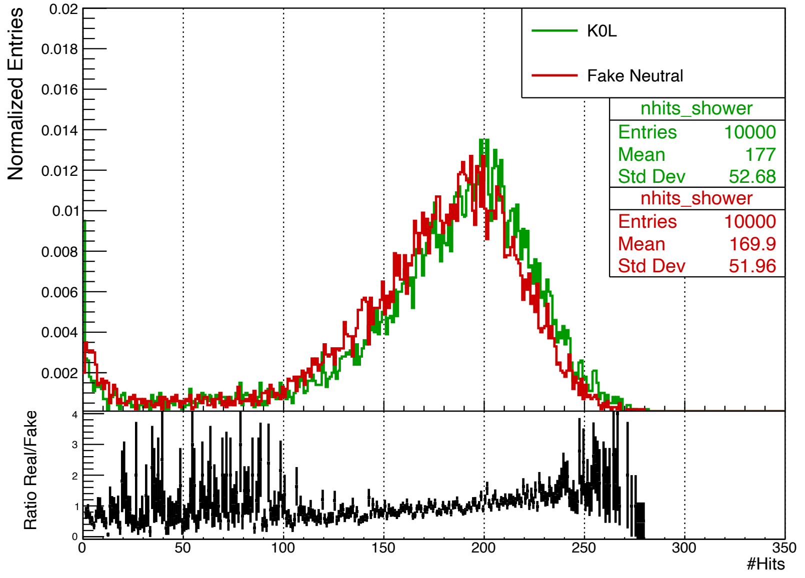
- **Transversal distances between showers: 0-300 mm**
- Track for charged hadron: Fixed momentum of 10 GeV or 30 GeV
- Additional event selection:
  - ➡ Charged hadron: track-hit match layer 1||2||3, track-to-detector-gap rejection
  - ➡ At least 10% of charged hadron energy associated to track (No ECAL)
- PandoraPFA: ILD default settings, AHCAL geometry adaptions, DDMarlinPandora adaptions for standalone application (pseudo layers, etc.)



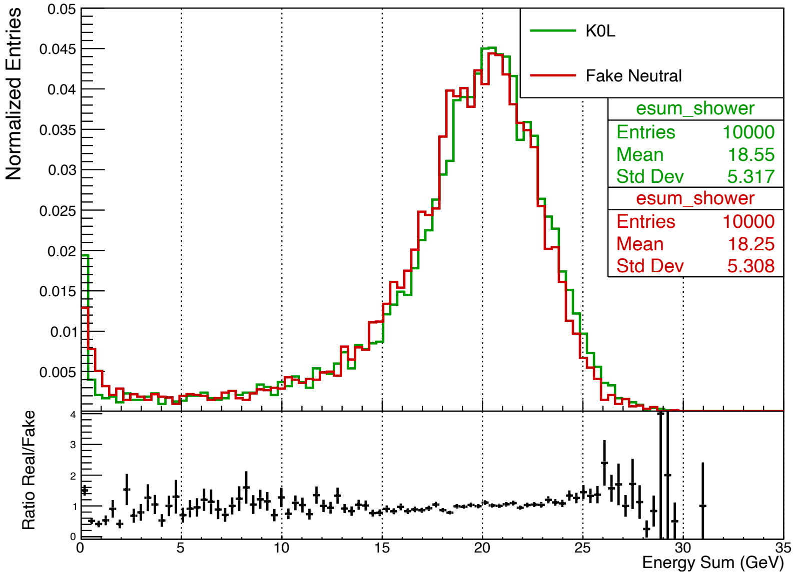
Intermezzo: Validation of Pseudo Neutral Hadrons

Comparison of Real & Pseudo Neutral Hadrons 20 GeV (MC)

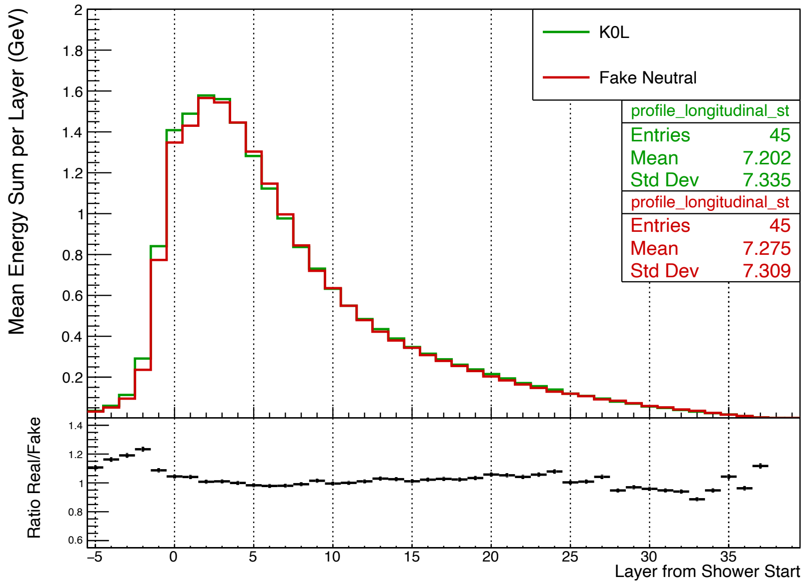
Number of Hits



Energy Sum



Longitudinal Energy Profile



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

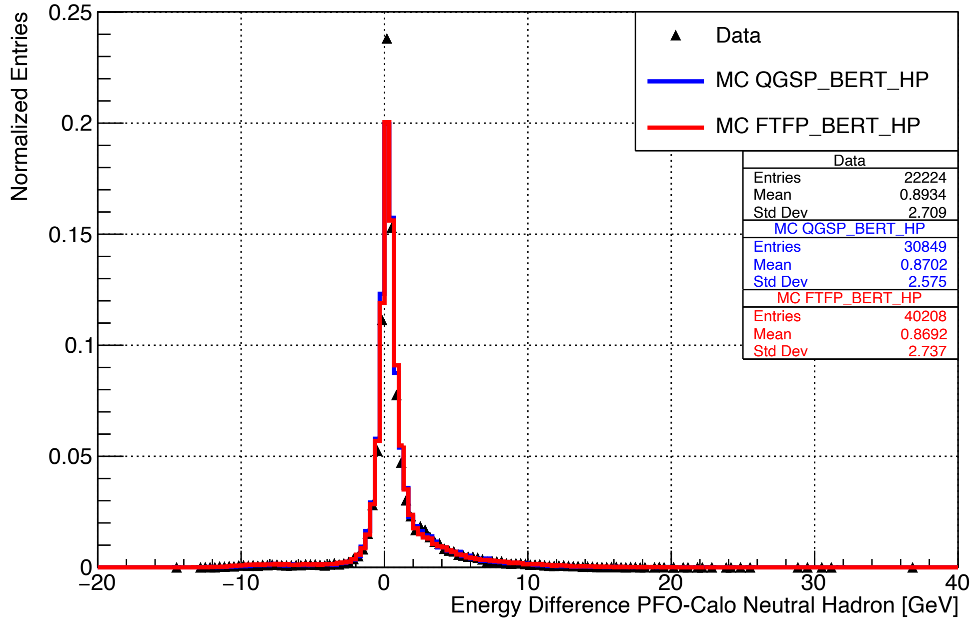
➡ **Pseudo-neutrals validated for charged-neutral separation studies (response and topology)**

Note: "*Generation of Artificial Neutral Hadron Showers in A Highly Granular Calorimeter using Cycle-Consistent Neutral Networks*" proposed paper by J. Rolph, E. Garutti and G. Kasieczka

How well is the (Pseudo-)Neutral Hadron Energy Recovered?

3 Sigma Neutral Hadron Energy Recovery Probability

Example Spectrum: PFO - Calorimeter Energy
10 GeV Neutral Hadron, 300mm to Charged Hadron



Overall excellent data to MC agreement within 5%

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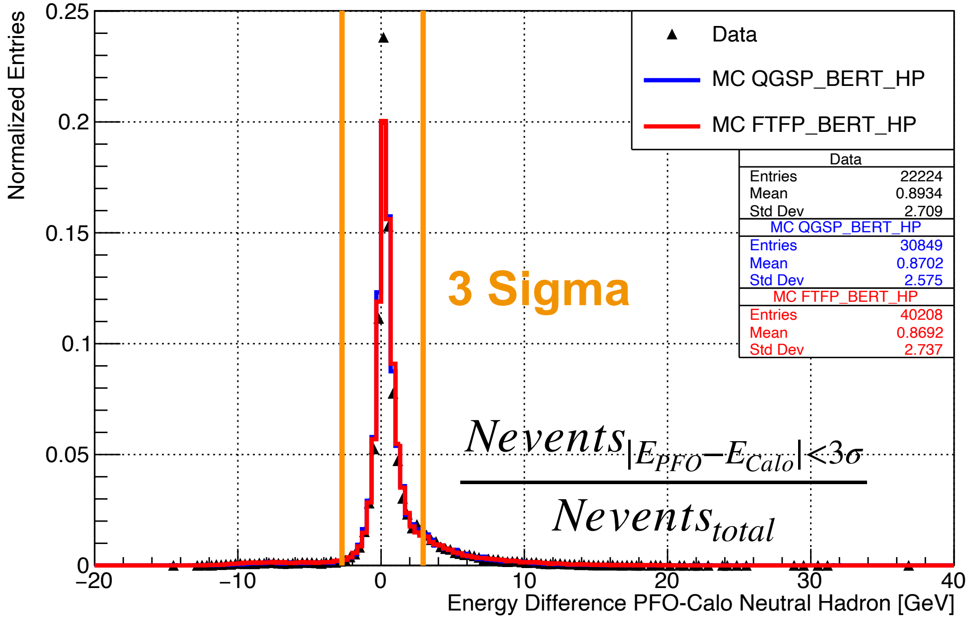

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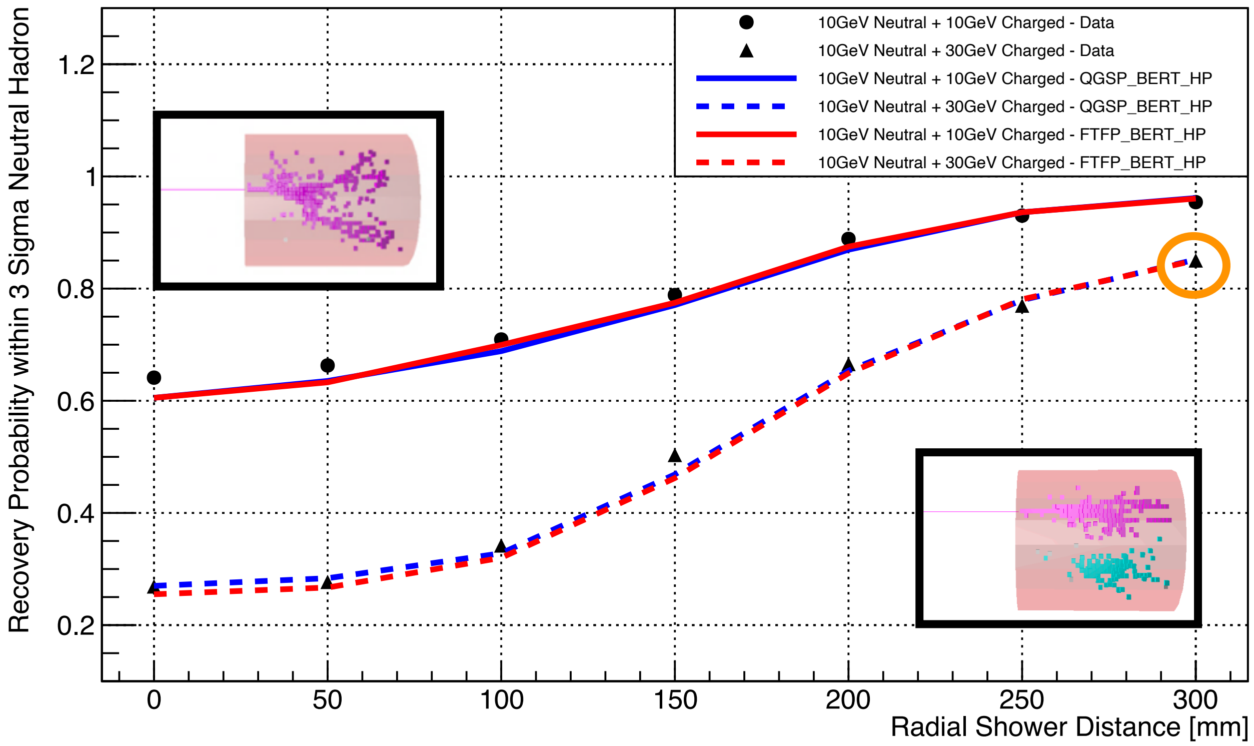

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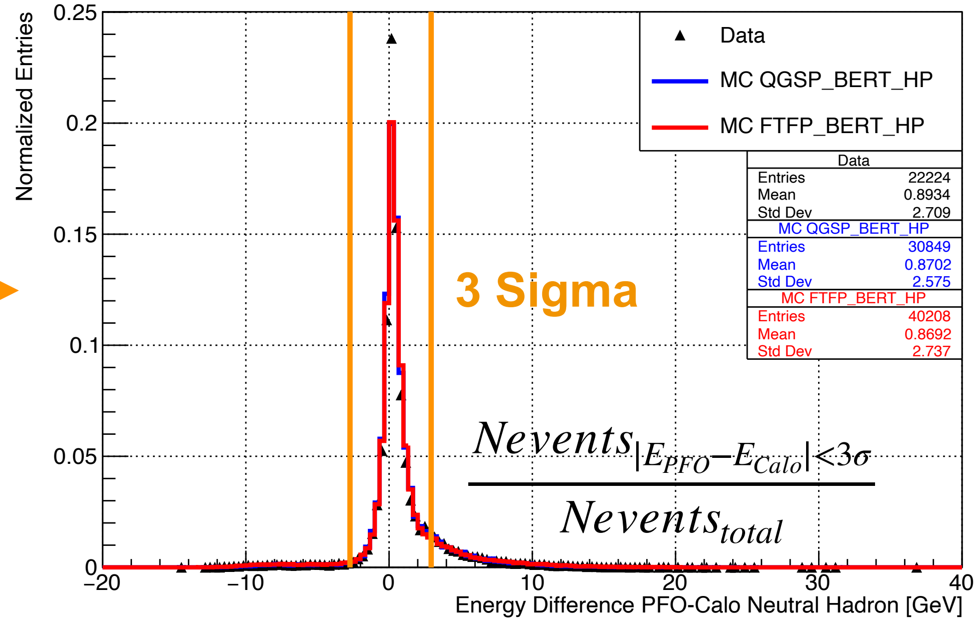
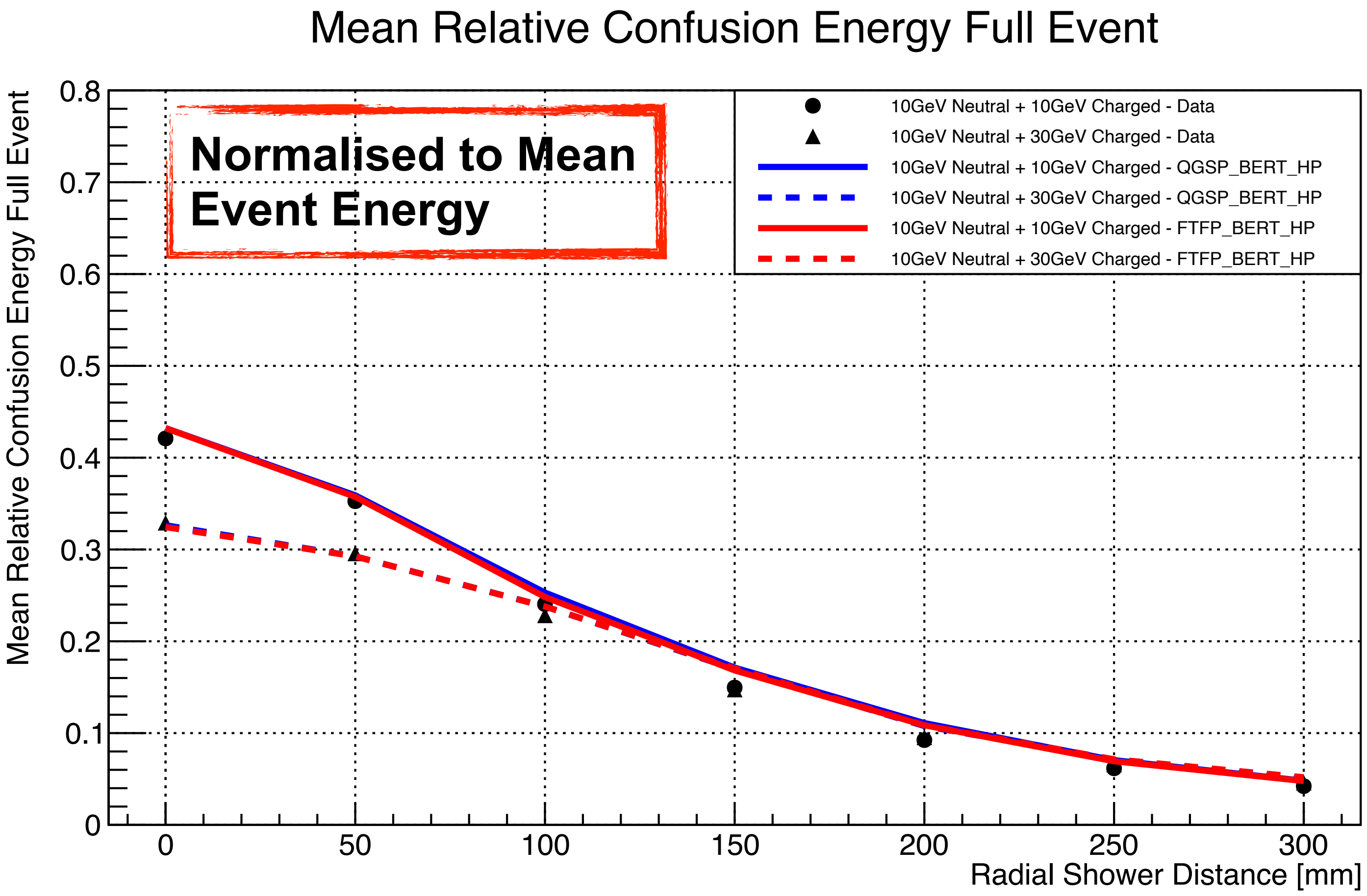


Overall excellent data to MC agreement within 5%

- For largest shower separations: Energy of neutral hadron recovered well on average
- Falling probability for smaller separation due to more events with neutral energy loss
  - ➡ More pronounced for vicinity of 30 GeV charged hadron due to richer topology
- Same observations and trends for reconstruction efficiency on hit level

How is the Total Confusion Level Scaling with Shower Distance?

Mean Fraction of Confusion Energy in Events

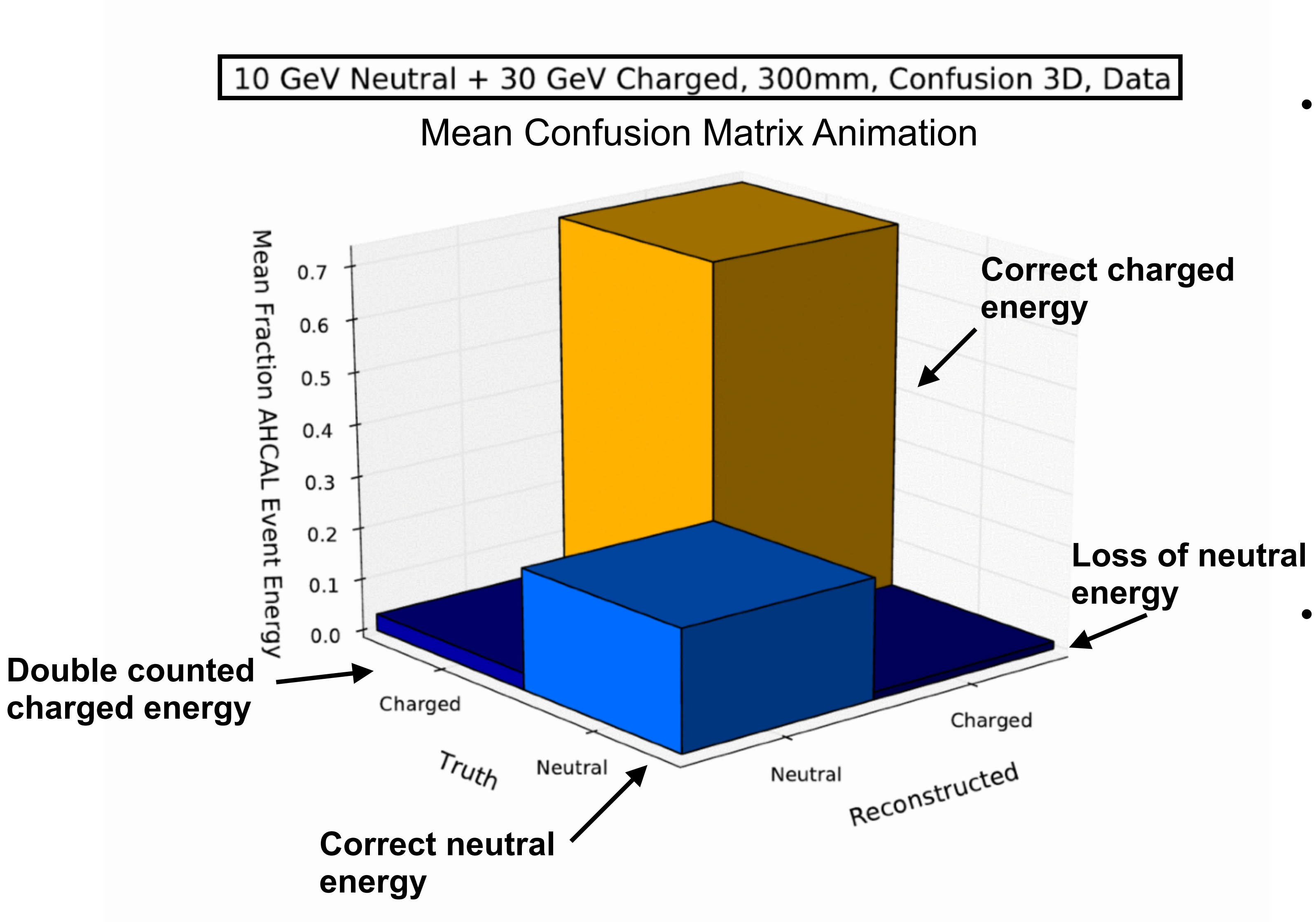


- For large shower distances: Average fraction of confused energy < 10%
- With decreasing shower distance mean fraction of confused energy is increasing
  - ➡ Confusion fractionally higher for 10+10 GeV scenario for lowest distances due to same energy of particles

➡ How are the individual types of confusion scaling with shower distance?

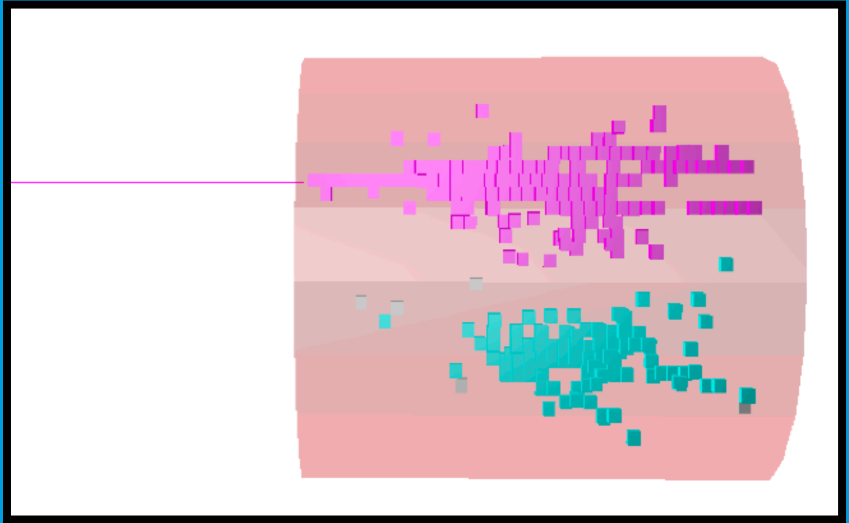
A Closer Look Into Confusion Types - Confusion Matrix

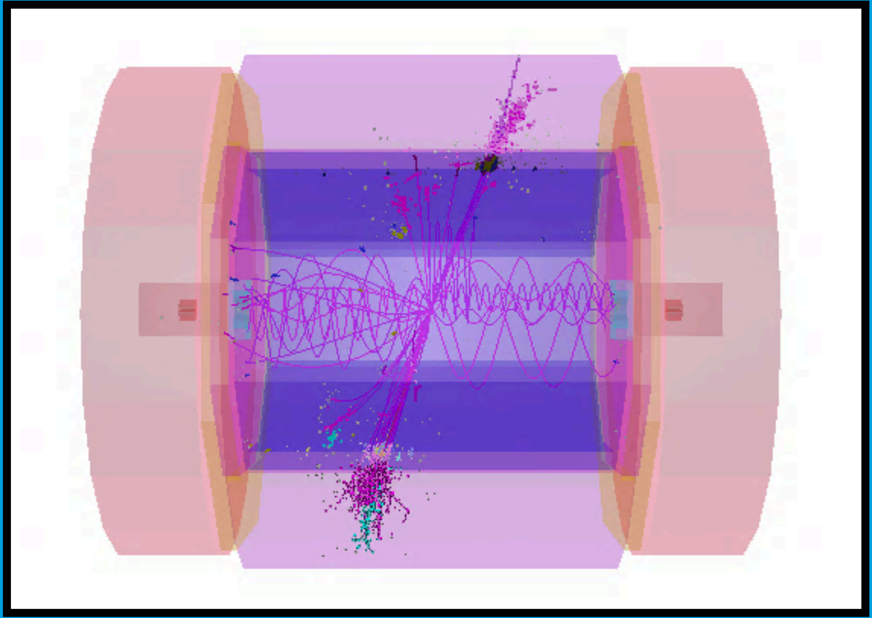
Example: Data, 10 GeV Pseudo Neutral + 30 GeV Charged Hadron



- Exploiting hit information: Check if hit energy was correctly/in-correctly reconstructed as charged/neutral
  - ➡ Access to confusion matrices
  - ➡ Disentanglement of lost neutral energy and double counted charged energy
- With decreasing shower distance:
  - ➡ Both confusion types increasing
  - ➡ In-balance of energy losses and double counted energy increasing

Performance Studies
Different PandoraPFA Settings
AHCAL 2018 Data & ILD Jets

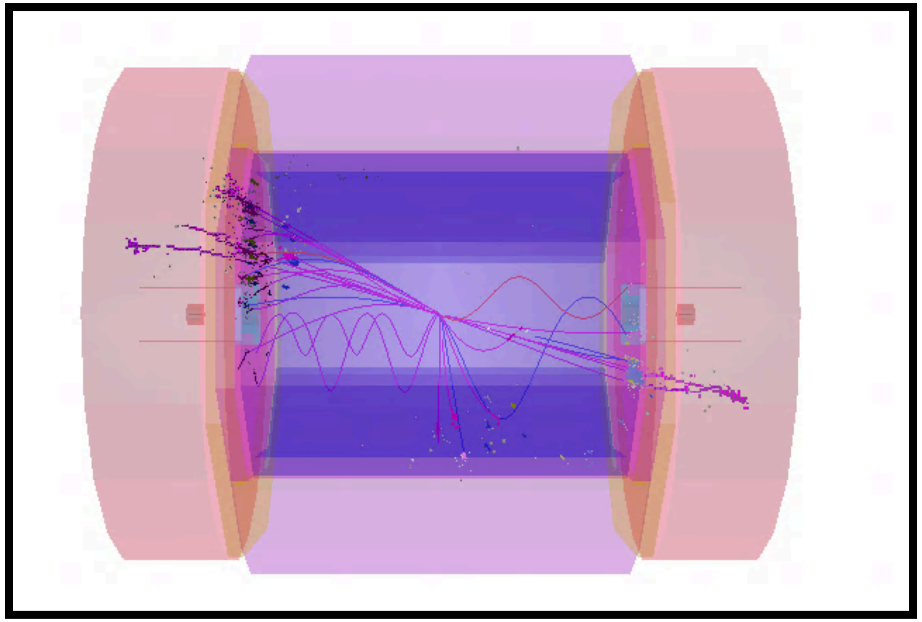




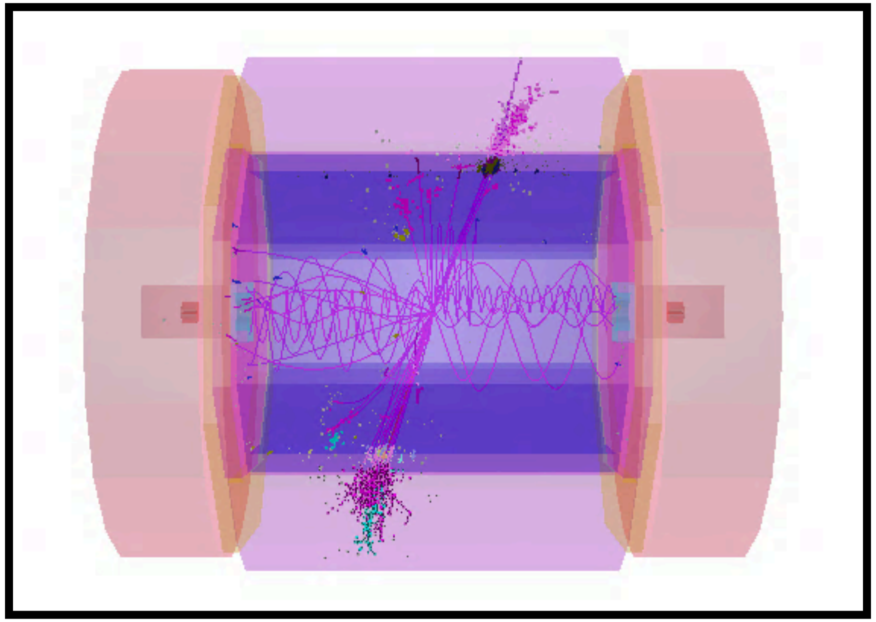
ILD Di-Jets

Input Samples

Big thanks to ILCSoft and ILD analysis experts @ DESY



Example: 200 GeV Di-jet



Example: 500 GeV Di-jet

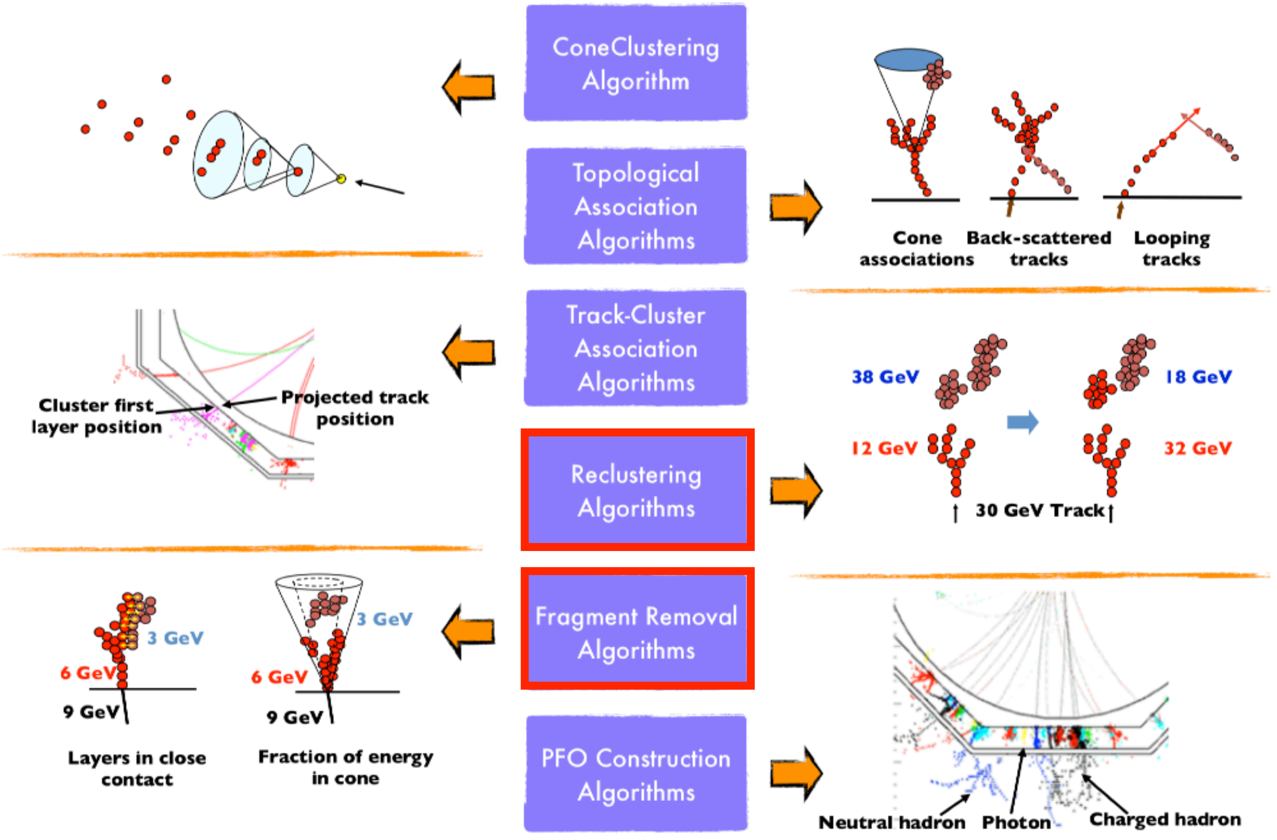
- Jet energy resolution calibration samples for ILD
  - ➡ Di-jet, back to back, light quarks: uds, energies: 40, 91, 200, 350, 500 GeV
- No backgrounds, no BeamCAL reconstruction
- Detector model: ILD_l5_o1_v02, latest ILCsoft

Studies of Different PandoraPFA Settings

Motivation & Goals

- Which algorithms within PandoraPFA are most **sensitive to level of confusion & specific types**?
  - ➡ Gain deeper understanding of PandoraPFA's "magic" and algorithm interplay
  - ➡ Compare impact and trends for more complex and dense ILD di-jet simulations and simpler AHCAL standalone beam data events

- Changes in PFA settings studied:
  - ➡ Re-clustering Algorithms disabled
  - ➡ Fragment Removal Algorithms disabled
  - ➡ Re-clustering Algorithms' Chi Thresholds = 1.5 (Stricter re-clustering towards Energy Flow)



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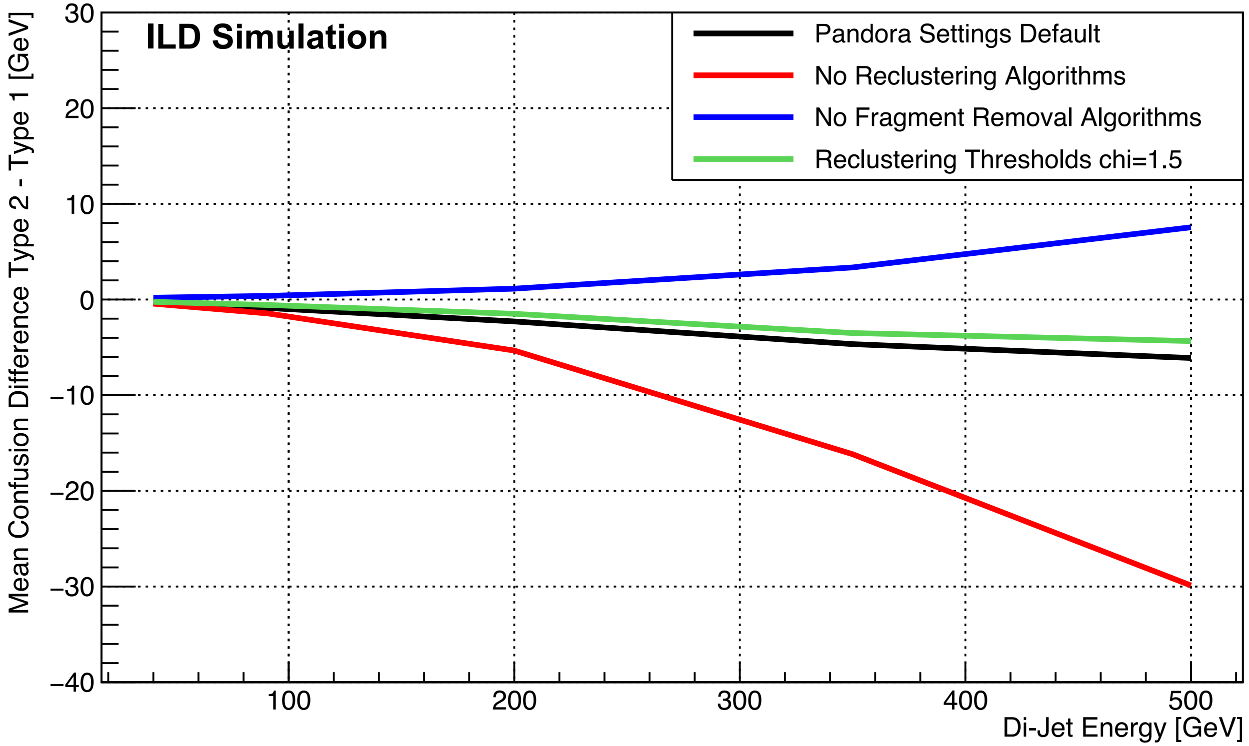
How well are Lost & Double Counted Energy Balanced?

Different PandoraPFA Settings - ILD Di-Jets Simulation & AHCAL 2018 Data

Mean Absolute Confusion Difference:
Double Counted - Lost Energy vs. Di-Jet Energy



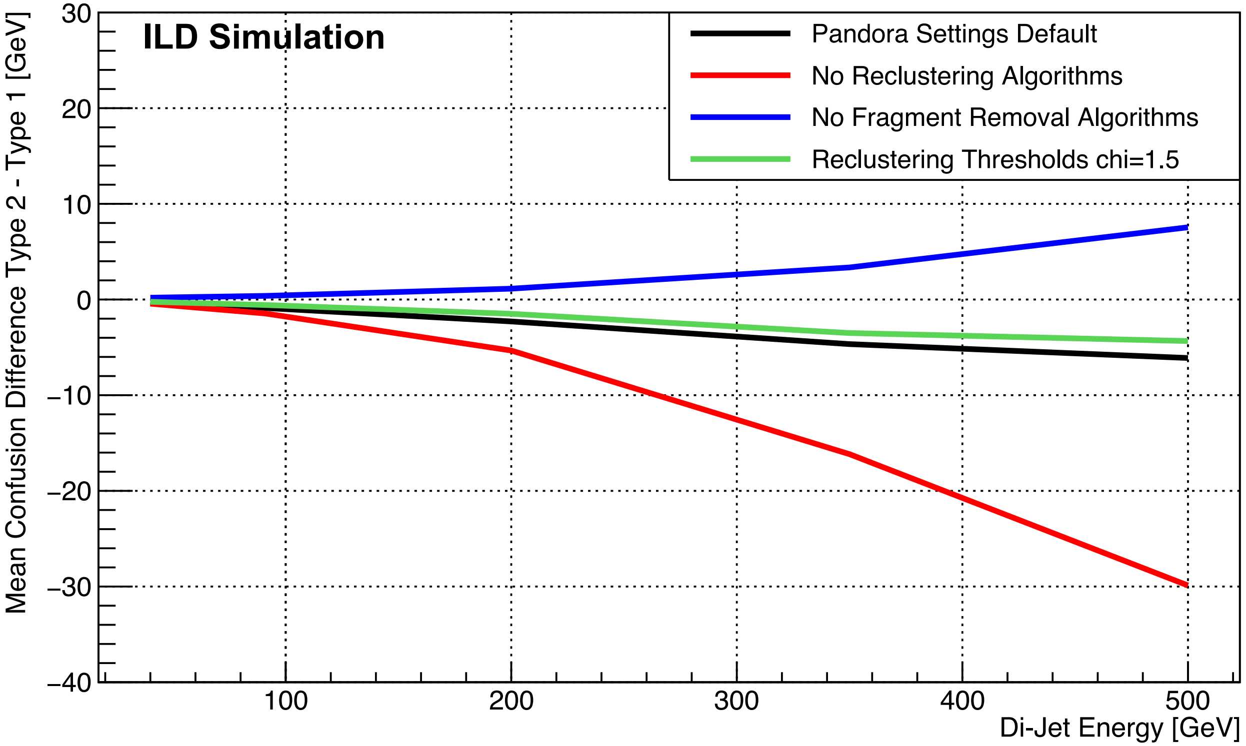
- Loss of neutral energy dominant for no re-clustering algorithms setting
  - ➡ Neutral clusters/hits merged into charged clusters without exploiting track information
- Double counted charged energy more dominant for no fragment removal algorithms & chi=1.5 settings
  - ➡ Parts of charged shower sub-structure (reconstructed as neutral) are not merged into charged hadron clusters and remain neutral

➡ **Do we see the same general trends for different PandoraPFA settings in AHCAL beam test data?**

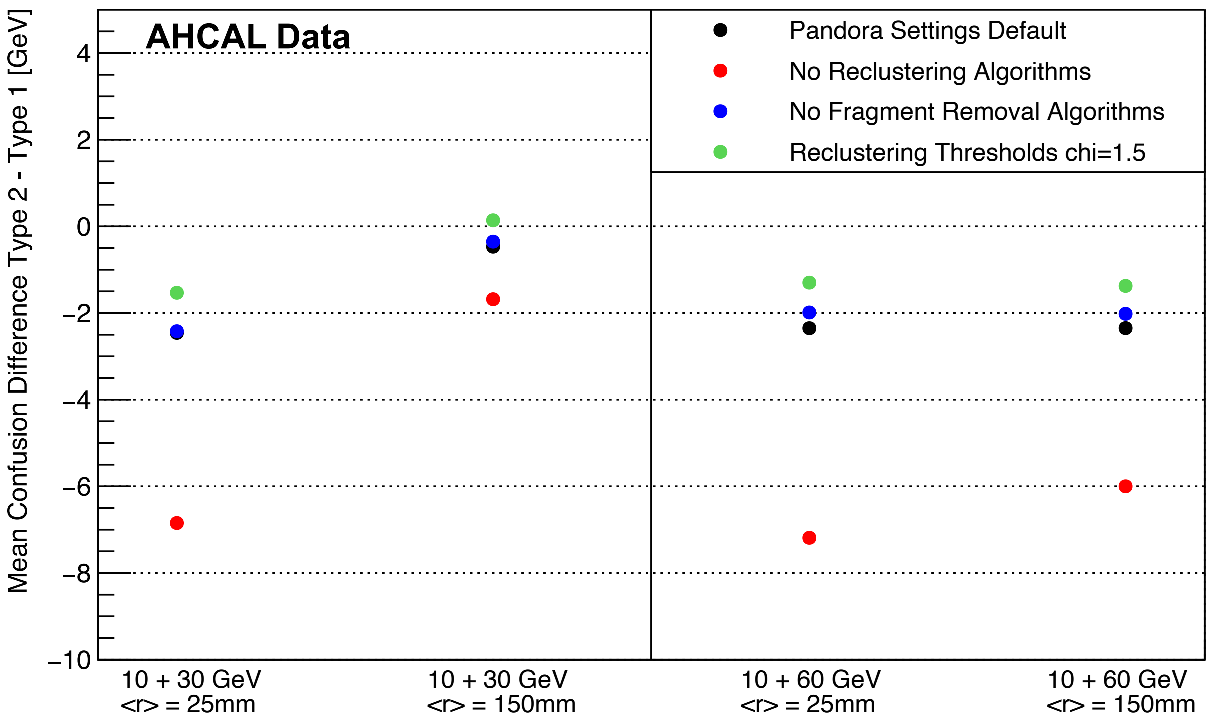
How well are Lost & Double Counted Energy Balanced?

Different PandoraPFA Settings - ILD Di-Jets Simulation & AHCAL 2018 Data

Mean Absolute Confusion Difference: Double Counted - Lost Energy vs. Di-Jet Energy



Mean Absolute Confusion Difference: Double Counted - Lost Energy vs. AHCAL Scenario



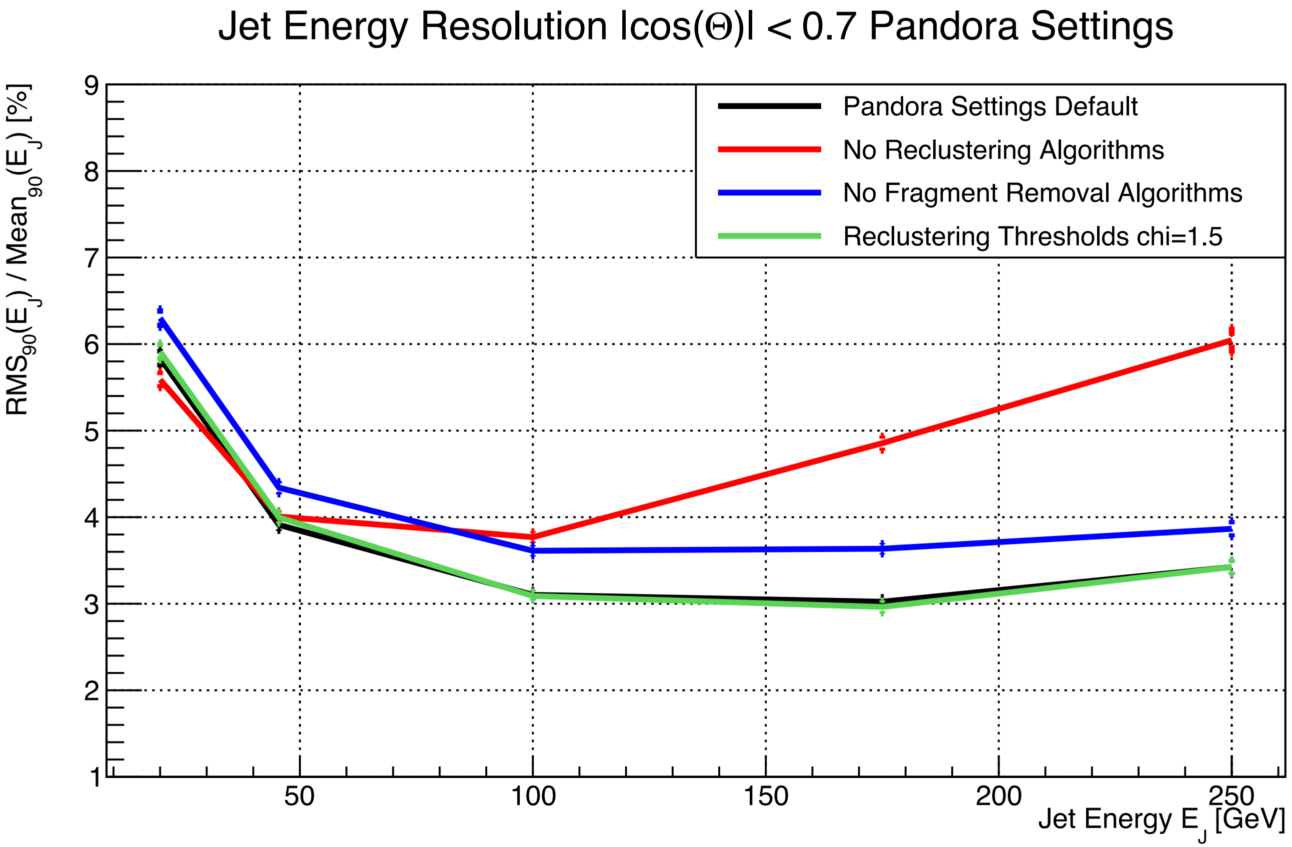
Yes, same trends observed for two particle AHCAL beam test events, but

➡ Fragment removal algorithms have less stronger impact due to smaller particle multiplicity/density

- Shower separation helps to balance confusion types, more difficult for higher energies

Total Reconstruction Performance for ILD Di-Jets?

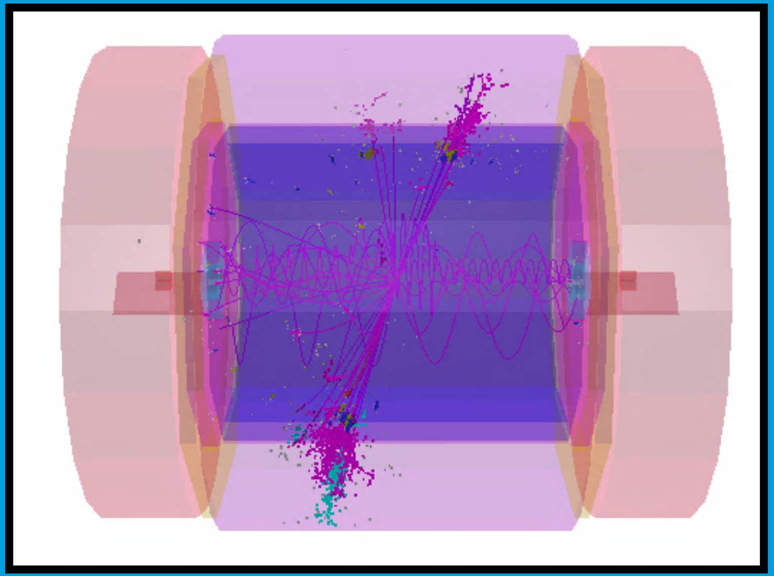
Different Pandora PFA Settings - Jet Energy Resolution



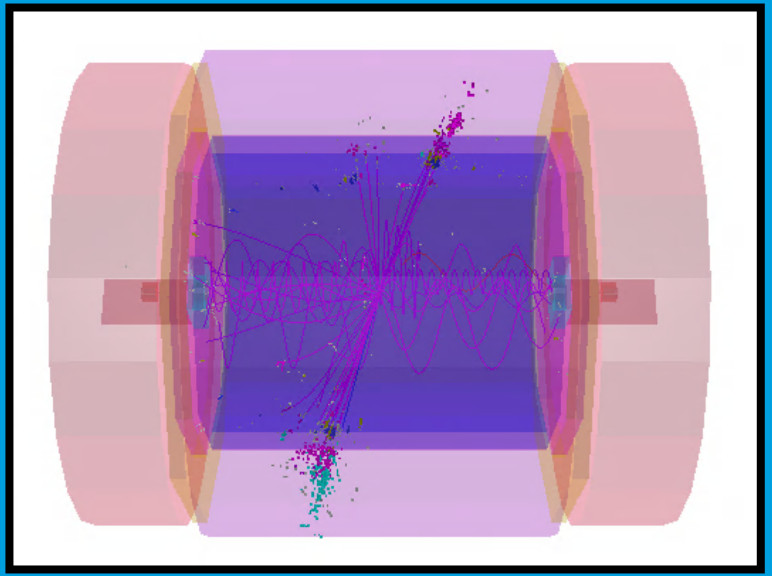
Agreeing with trends for total confused energy and energy loss/ double counted energy balance

- Validation: Default Pandora settings optimised, basically no influence for chi thresholds = 1.5
- No Fragment Removal Algorithms: Constant decrease of JER of ~0.6%
- No Re-clustering Algorithms: Decrease of JER at higher energies of up to ~2.5%

Performance Studies PandoraPFA Energy Thresholds AHCAL 2018 Data & ILD Jets



Threshold: 0.5 MIP

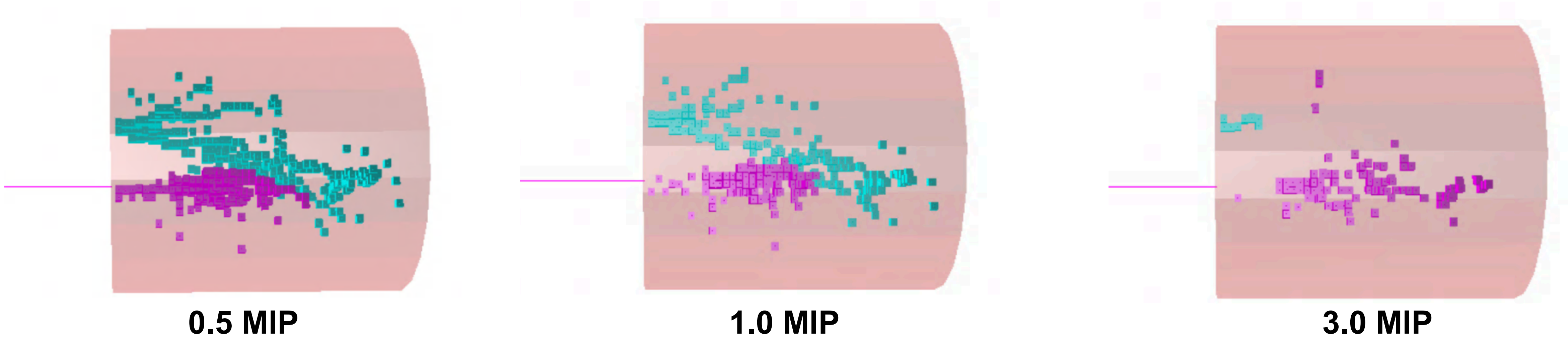


Threshold: 3.0 MIP

Variation of Internal Energy Thresholds

Introduction & Motivation

Is a highly granular calorimeter in a high radiation environment capable of achieving sufficiently high PFA performance over its full life time?

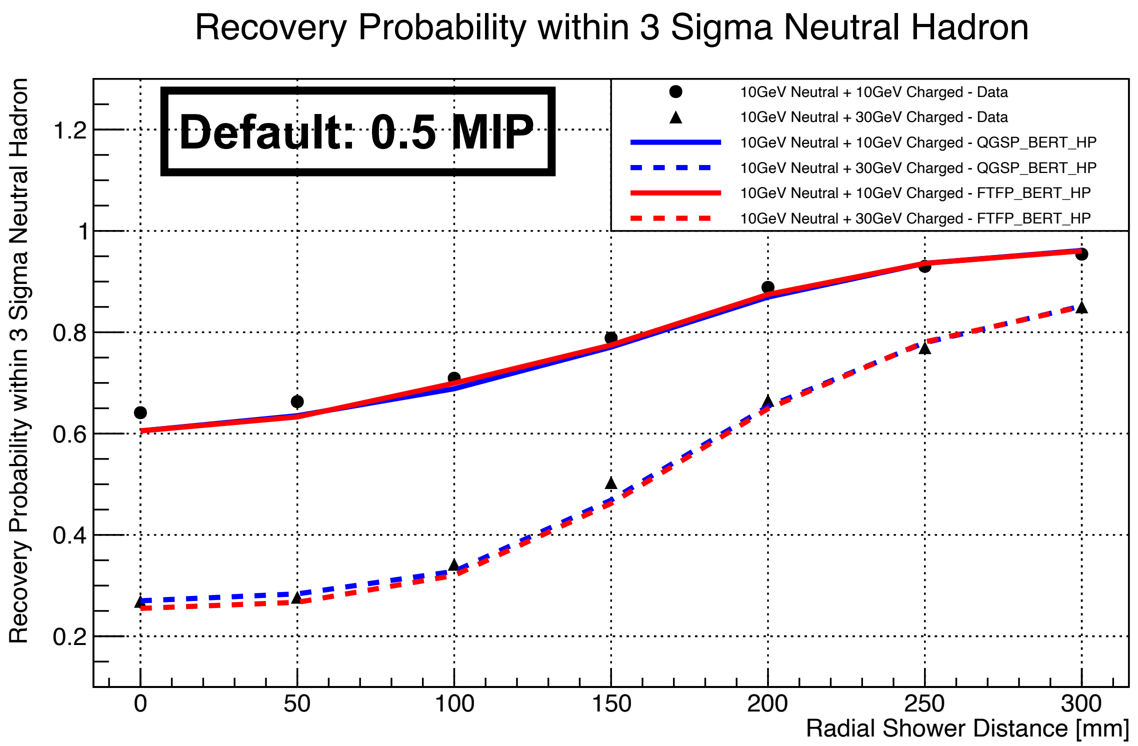


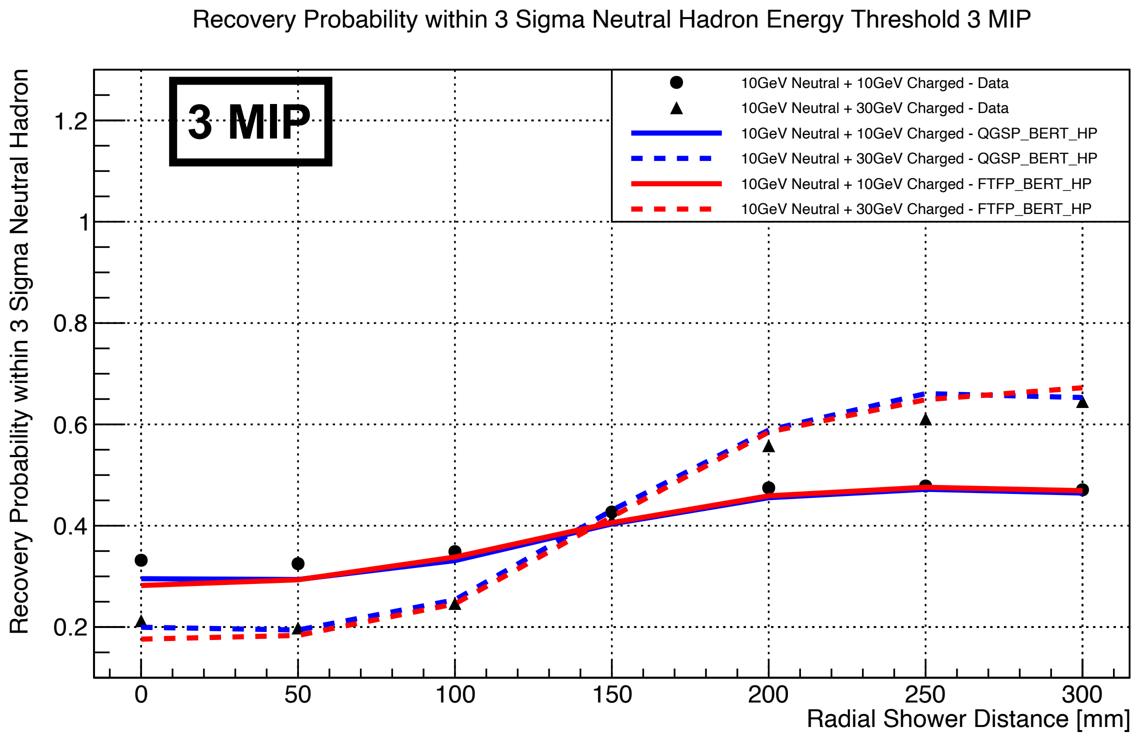
Same event, but different energy thresholds applied

- Study PandoraPFA performance with increasing internal energy thresholds (**ECAL + HCAL**)
  - ➡ **Motivation CMS HGCAL**: Increasing noise levels after exposure in high radiation environment
  - ➡ By increasing energy thresholds, shower energy as well as topology level heavily reduced (MIP tracks,…)
  - ➡ Recalibration of internal PandoraPFA calibration constants to allow fair comparison track - cluster energy

3 Sigma Recovery Probability Neutral Hadron - First Look

Different Energy Thresholds for AHCAL Two Particle Events

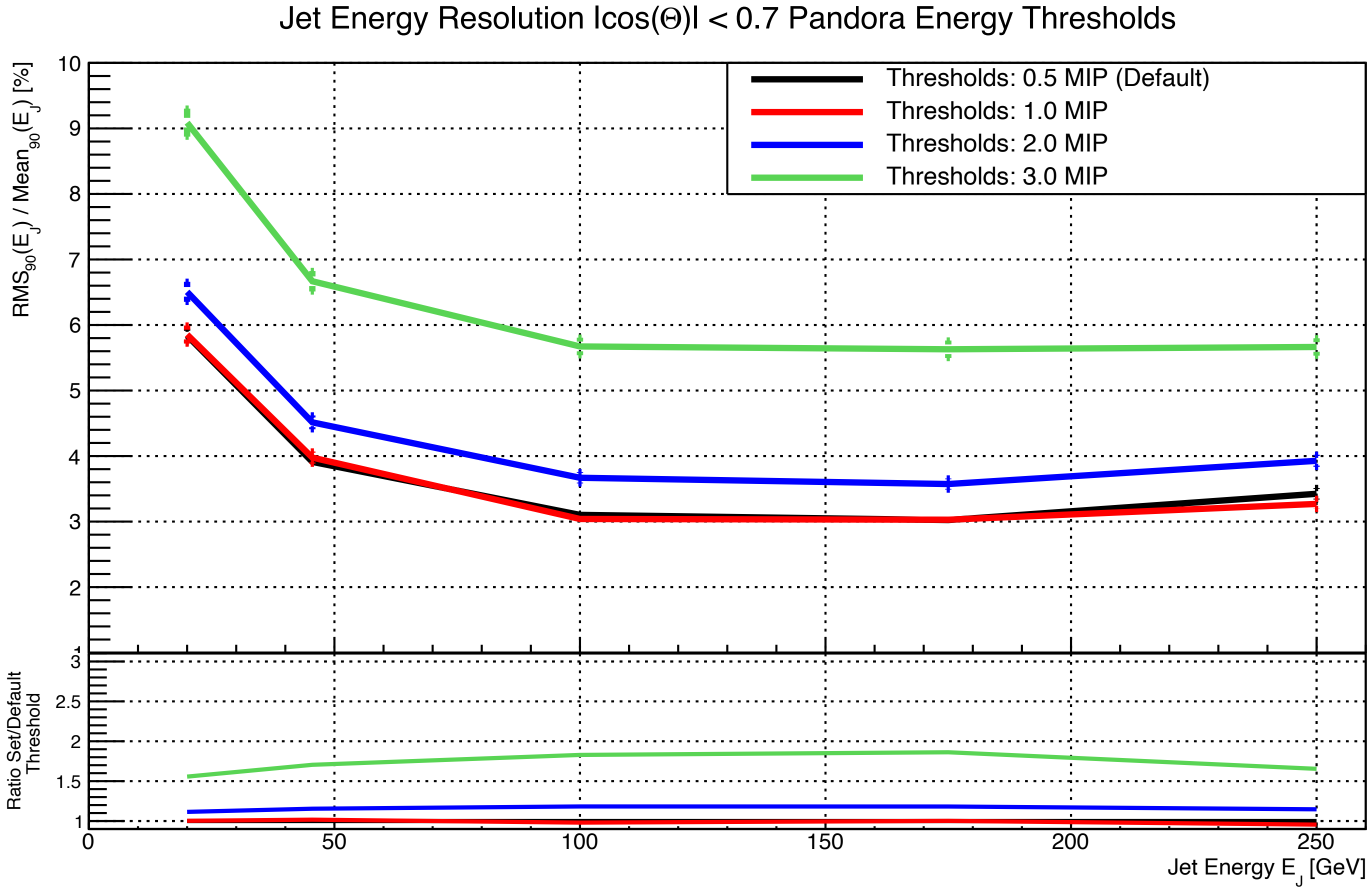




- Degradation of recovery probability by 20-30% (10+10 GeV) and by 5-20% (10+30 GeV)
  - ➡ Two particle separation more difficult with highly increased energy thresholds, especially at lower energy
    - ➡ Loss of topology information increases trend towards double counted charged energy?

Jet Energy Resolution

Different Energy Thresholds for ILD Di-Jets



- Basically no influence on JER for slightly increased thresholds (1 MIP)
- Even for highest threshold (3 MIP) degradation of JER "only" max. ~80% compared to default
  - ➡ Expected much worse performance, since huge loss of topology information in HCAL & ECAL
  - ➡ Partly compensated by PandoraPFA's emergency/force algorithms towards energy flow?
  - ➡ Is topology information used to full extent within PandoraPFA?
  - ➡ Do detector effects/granularity play a minor role as long as PFA is powerful enough?

Summary & Conclusion

PandoraPFA Studies with AHCAL Two Particle and ILD Di-Jet Events

- Application of PandoraPFA on AHCAL 2018 prototype & ILD jet events to study limiting effects of PFA and provide performance feedback on beam test data in comparison to simulations
  - ➡ Validated: Expected trends for confusion, total reconstruction and two particle separation performance
  - ➡ Across studies: Data to MC agreement 5-10% & same general trends for AHCAL and ILD di-jet events
  - ➡ Detailed insights into PandoraPFA by confirming expected changes for confusion types in relation to changes in specific internal algorithms
  - ➡ Performance studies for increased energy thresholds may indicate that detector effects play minor role in contrast to a powerful PFA like Pandora (compensating lost topology information to a high level)

- Outlook: Closer look into confusion types, PFO multiplicities & energies, etc. for increased energy thresholds

Summary & Conclusion

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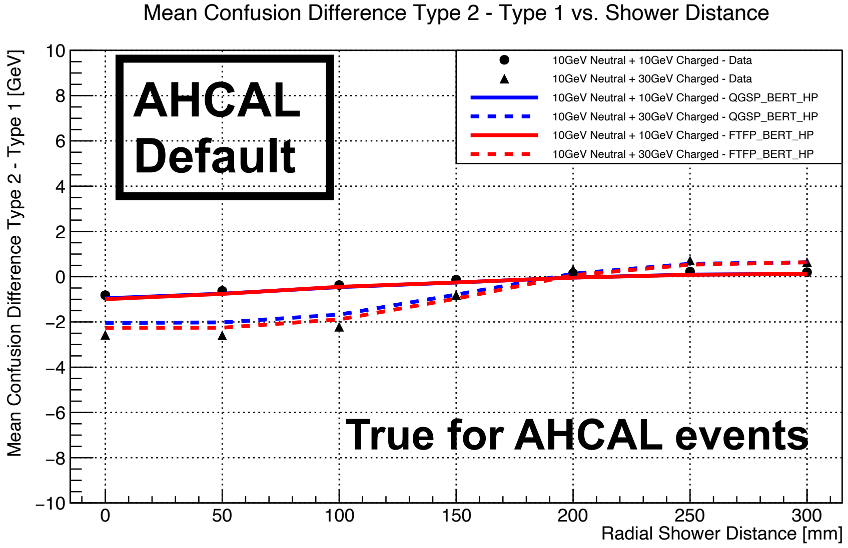
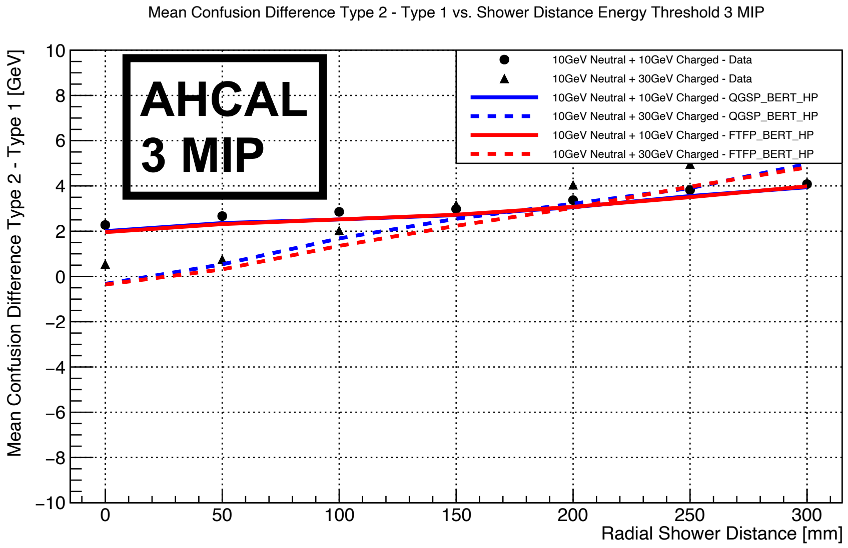
Thank you! (Special thanks to J. Marshall for his continuous support and advice to open Pandora's box!)

Backup

Outlook: Confusion Type Difference for Energy Thresholds

AHCAL 2018 Data & ILD Di-Jets

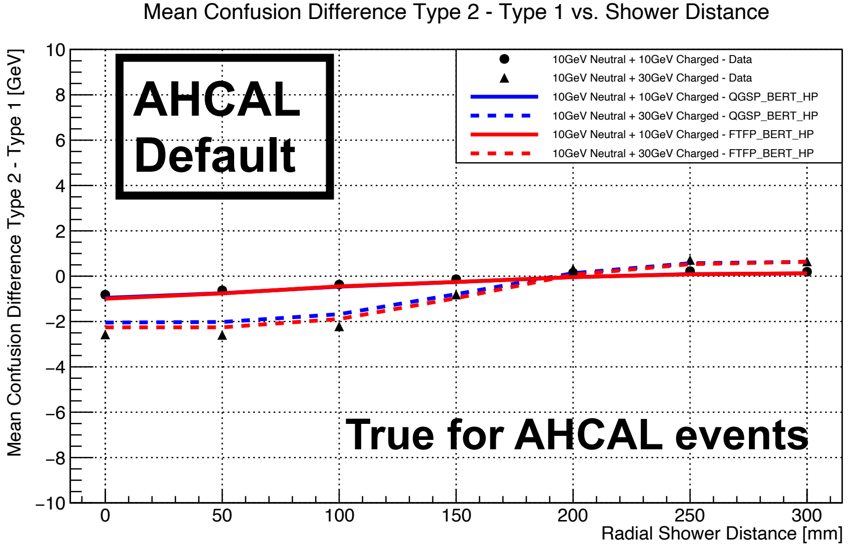


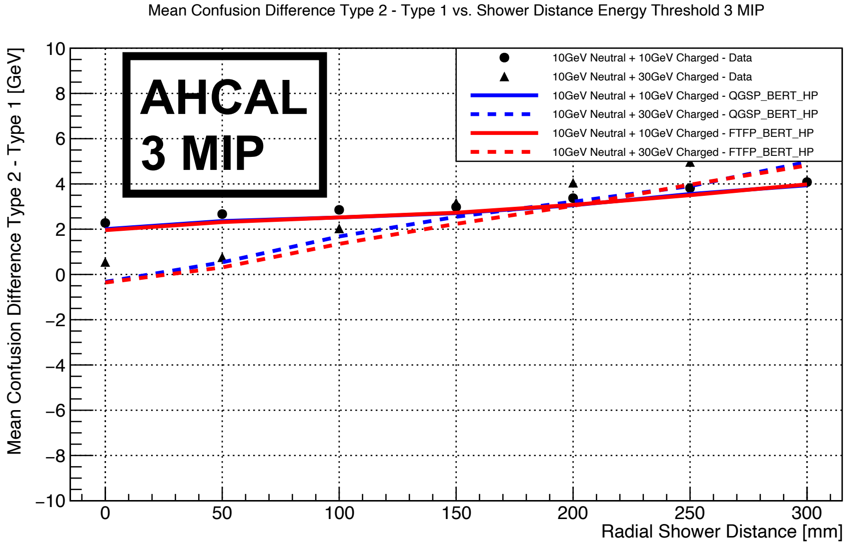


- Hypothesis for increasing energy thresholds: MIP tracks within shower sub-structure and before shower start are vanishing more and more
  - ➡ Trend towards double counted charged energy should increase (extra neutral fragments)

Outlook: Confusion Type Difference for Energy Thresholds

AHCAL 2018 Data & ILD Di-Jets





- Hypothesis for increasing energy thresholds: MIP tracks within shower sub-structure and before shower start are vanishing more and more
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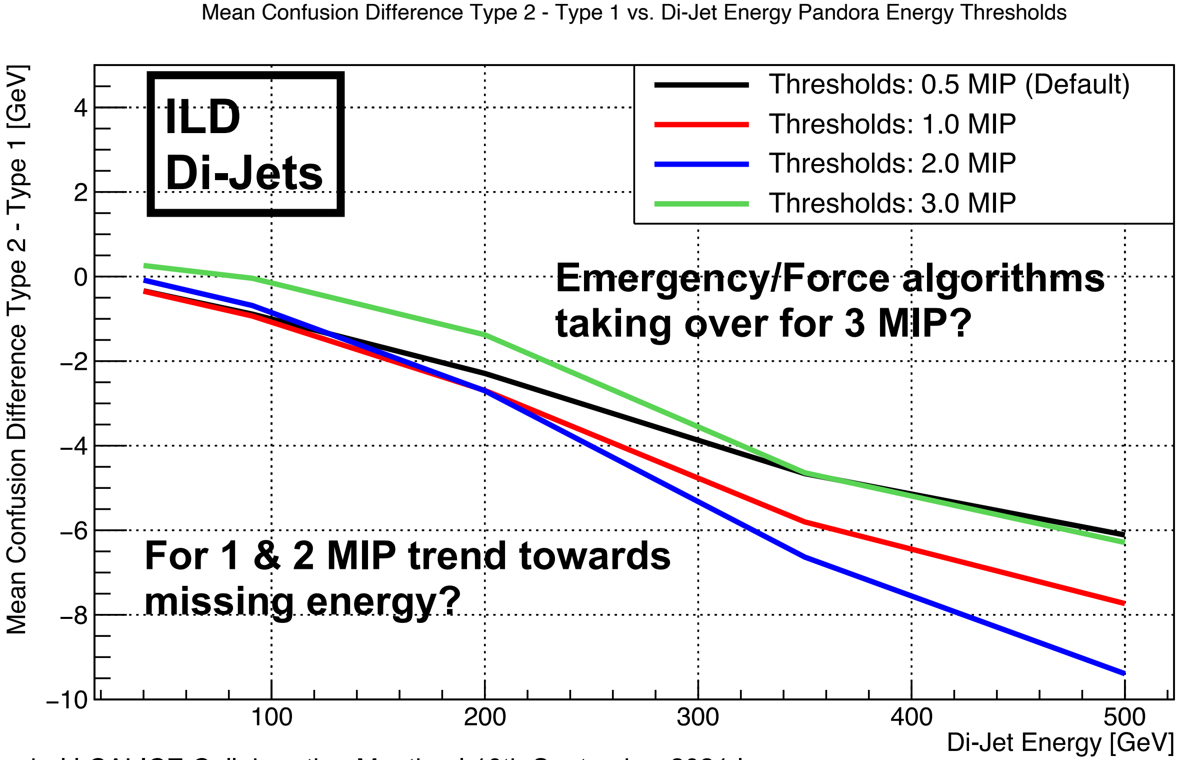
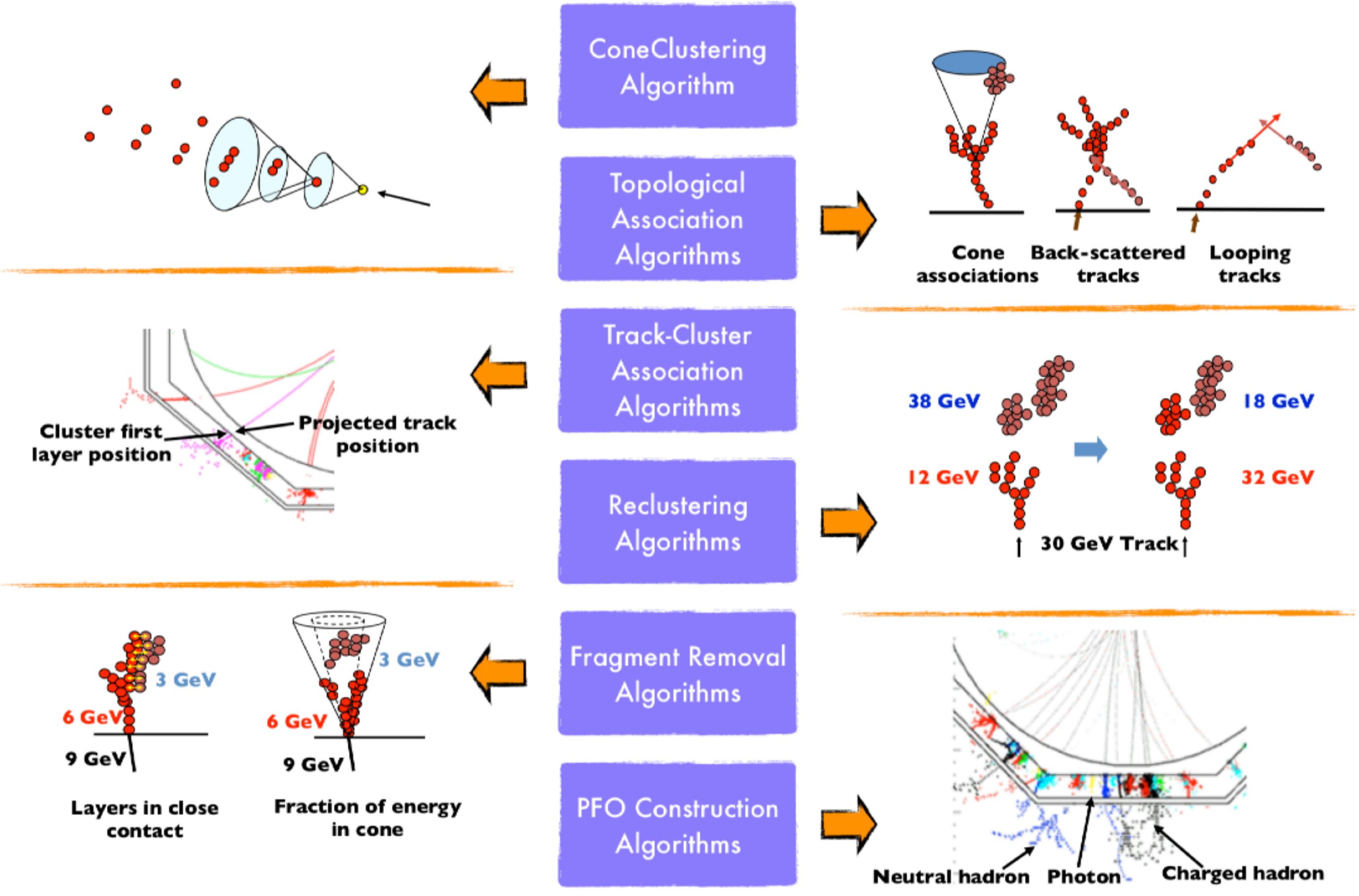


The Pandora Particle Flow Algorithm (PandoraPFA)

A Multi-Algorithm Pattern Recognition Tool

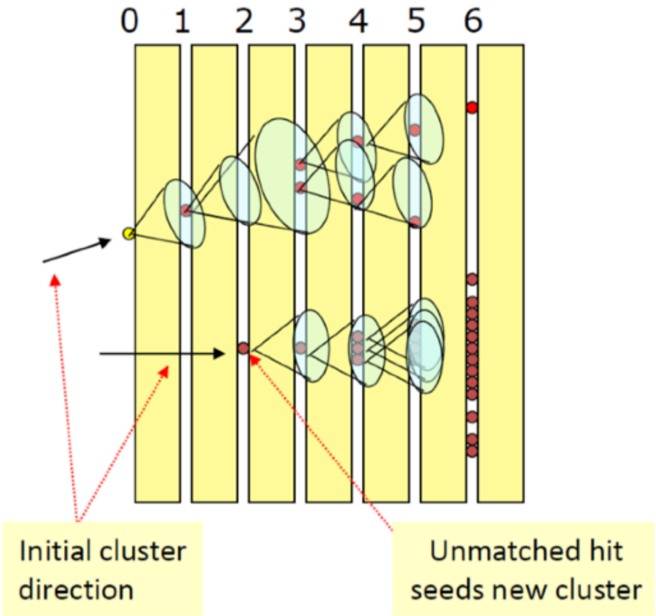
Illustration of Key Steps of PandoraPFA



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

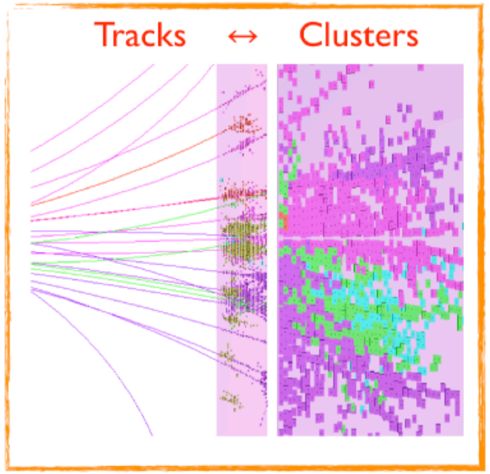
- **Challenge for PFA** to keep confusion level low:
  - ➡ **Separation** of energy deposits from different particles
  - ➡ Avoid double counting of energy from same particle
- State of the art: **PandoraPFA**
  - ➡ Highly recursive multi-algorithm chain using pattern recognition for event reconstruction
- Hardware requirements:
  - ➡ Compact calorimeters within magnetic coil to minimise dead space behind tracker
  - ➡ **Highly granular calorimeters** (e.g. AHCAL 2018 prototype) to exploit pattern recognition algorithms

Clustering



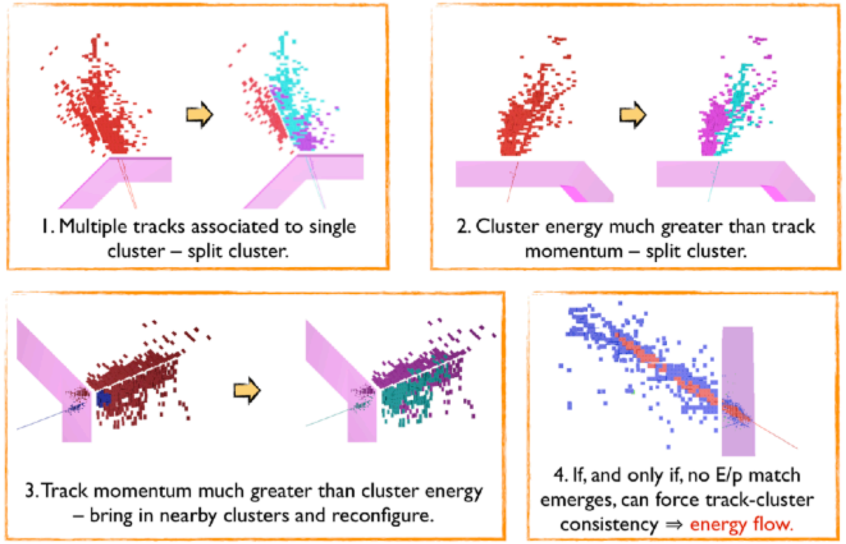
Track to Cluster Association

- 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.

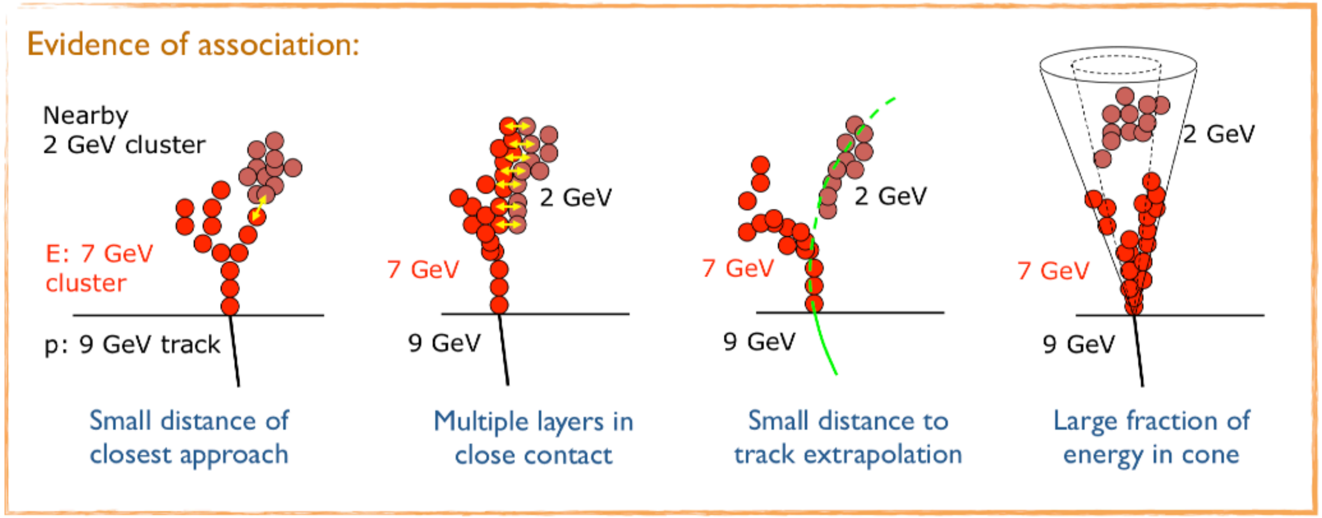


J. S. Marshall: https://indico.in2p3.fr/event/7691/contributions/42712/attachments/34375/42344/3_john_marshall_PFA_marshall_24.04.13.pdf

Re-Clustering



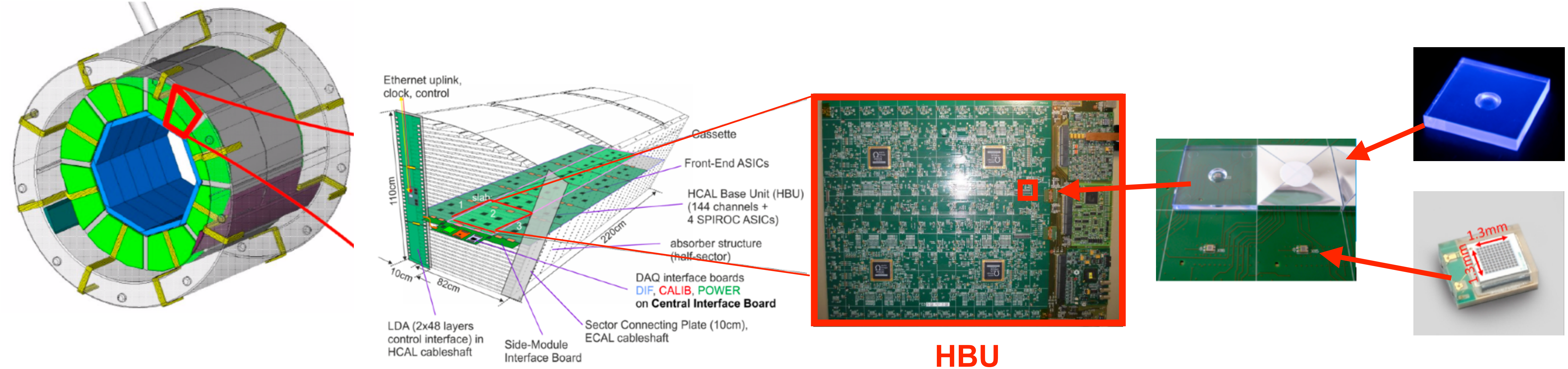
Fragment Removal



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

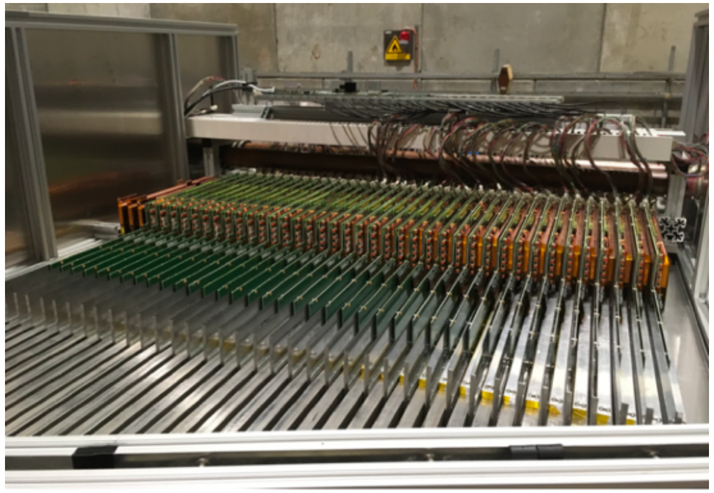


The Analog Hadron Calorimeter Prototype 2018

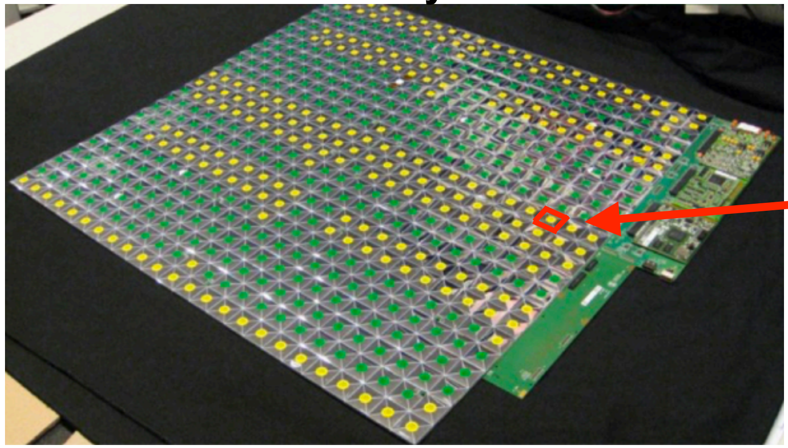
A Highly Granular SiPM-on-tile Sampling Calorimeter

- 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, passive cooling scheme
- Scalable detector concept developed for the 8-million-channel HCAL of International Large Detector (for ILC)
- In 2018: Three successful test beam campaigns at SPS CERN collecting electron/muon/**pion data**

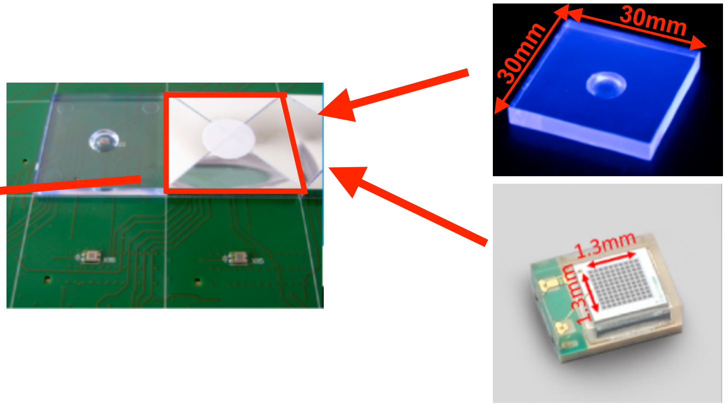
38 layers within steel absorber stack



One layer



One channel: Scintillating tile + SiPM



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

↓ **PandoraPFA**

Scenario 1: Single particle reconstruction studies

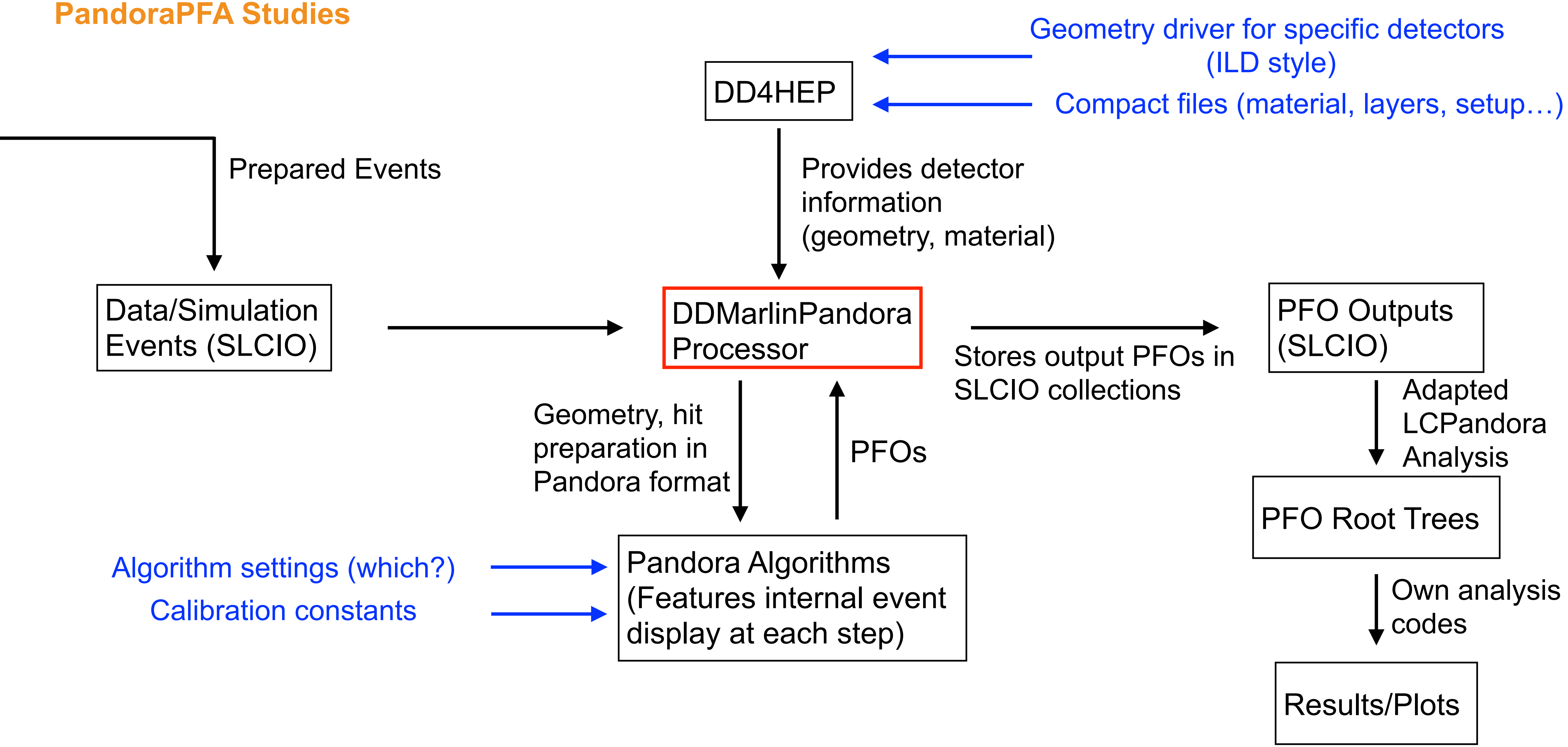
↓ **PandoraPFA**

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

Framework / Data Flow Diagram

PandoraPFA Studies

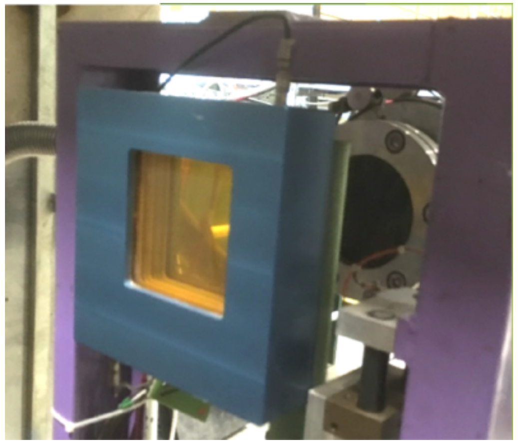


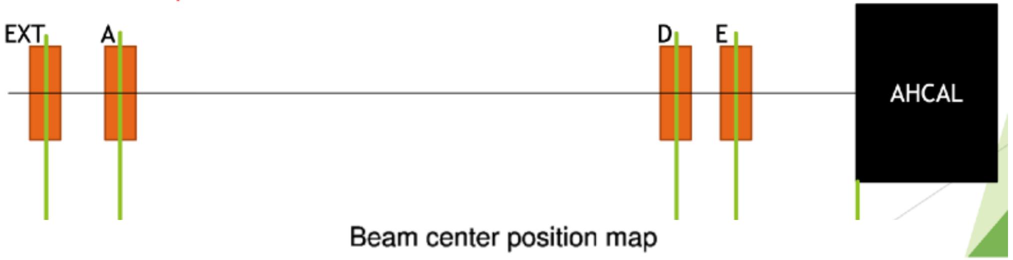
Delay Wire Chambers (DWC)

Providing Tracks for Beam Test Events

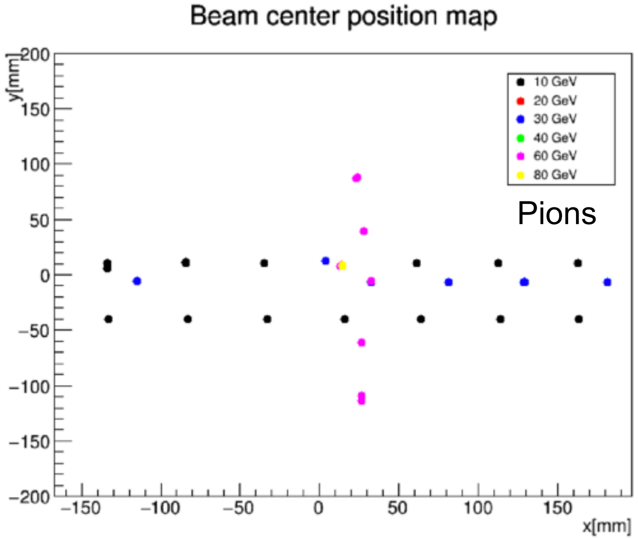
Work done by Linghui Liu (U. Tokyo)
(https://agenda.linearcollider.org/event/8368/contributions/44971/attachments/35214/54544/LL_AHCALmain_2019.pdf)

- 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

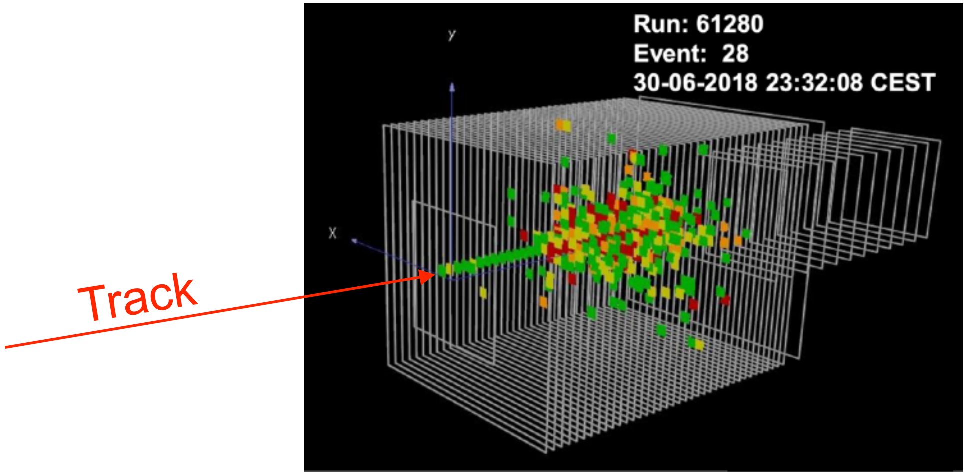
- Data tracks: Reconstructed from DWC of beam test
- MC tracks: MC primary particle endpoint position X/Y extrapolation

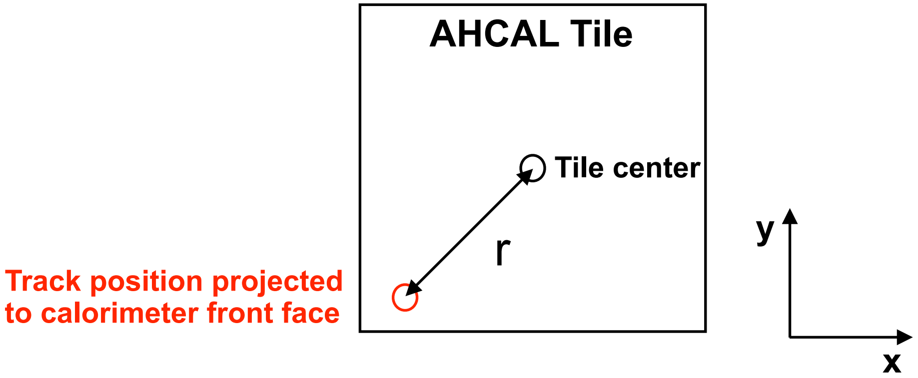
➡ **Track quality?**

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?

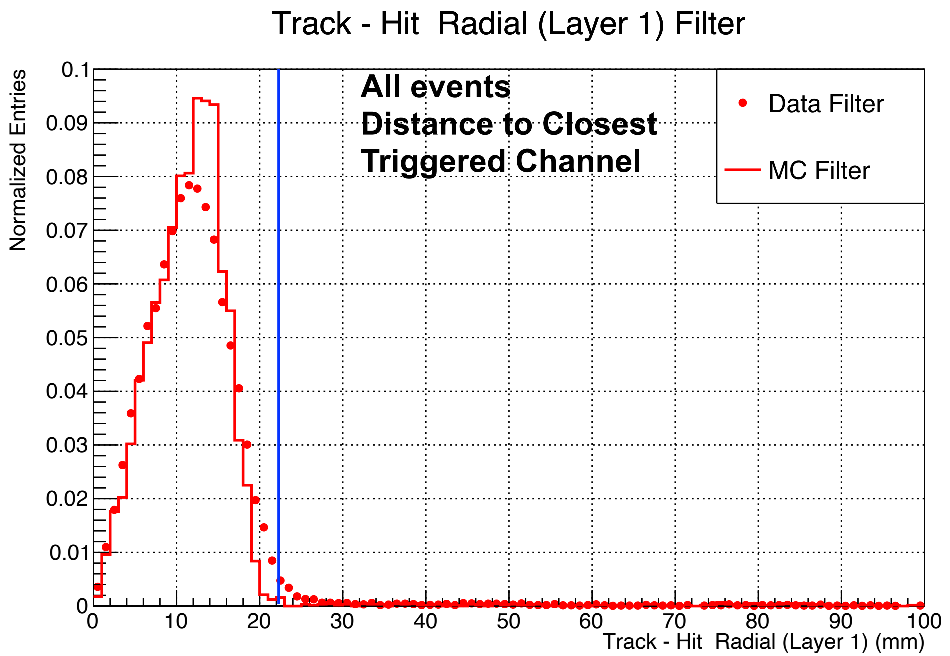




Track Quality Results 20 GeV π^-

Precise Tracks for PandoraPFA Reconstruction

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



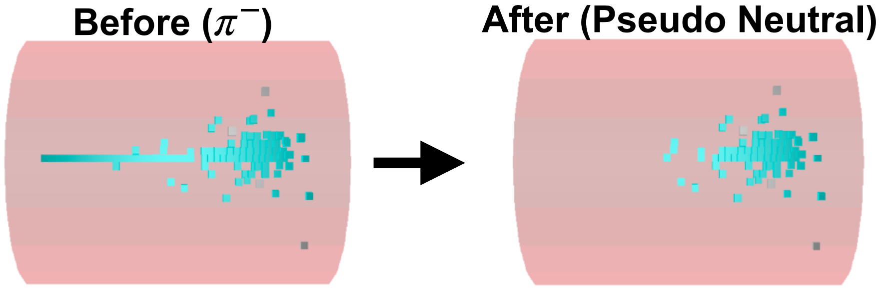
$$r = \sqrt{(x_{track} - x_{hit})^2 + (y_{track} - y_{hit})^2}$$

- 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^-

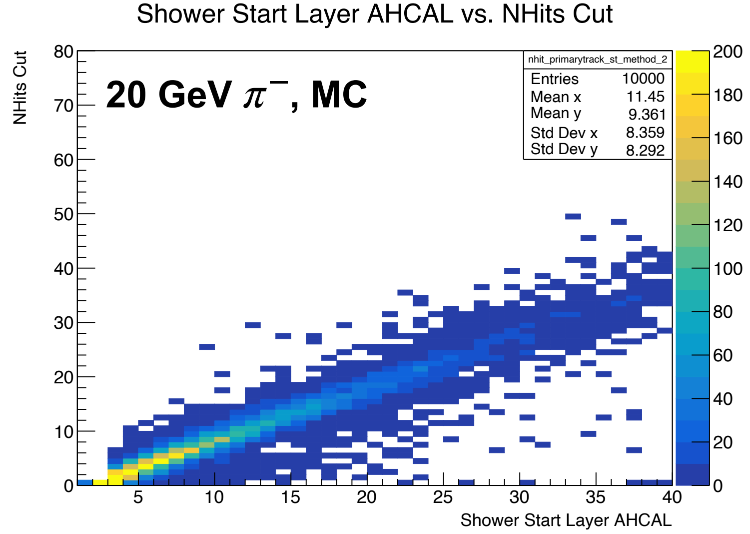
➡ **Excellent track quality validated for data and MC**

Finding and Removing Primary Track

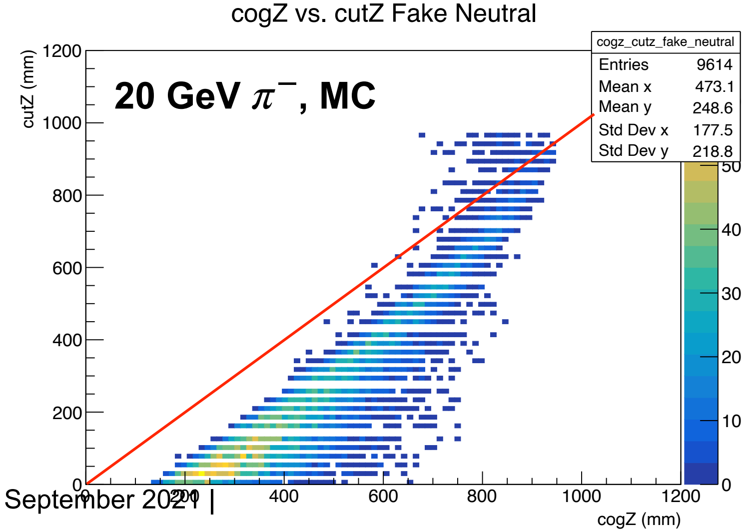
The Method for Creating Pseudo Neutral Hadrons



- 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

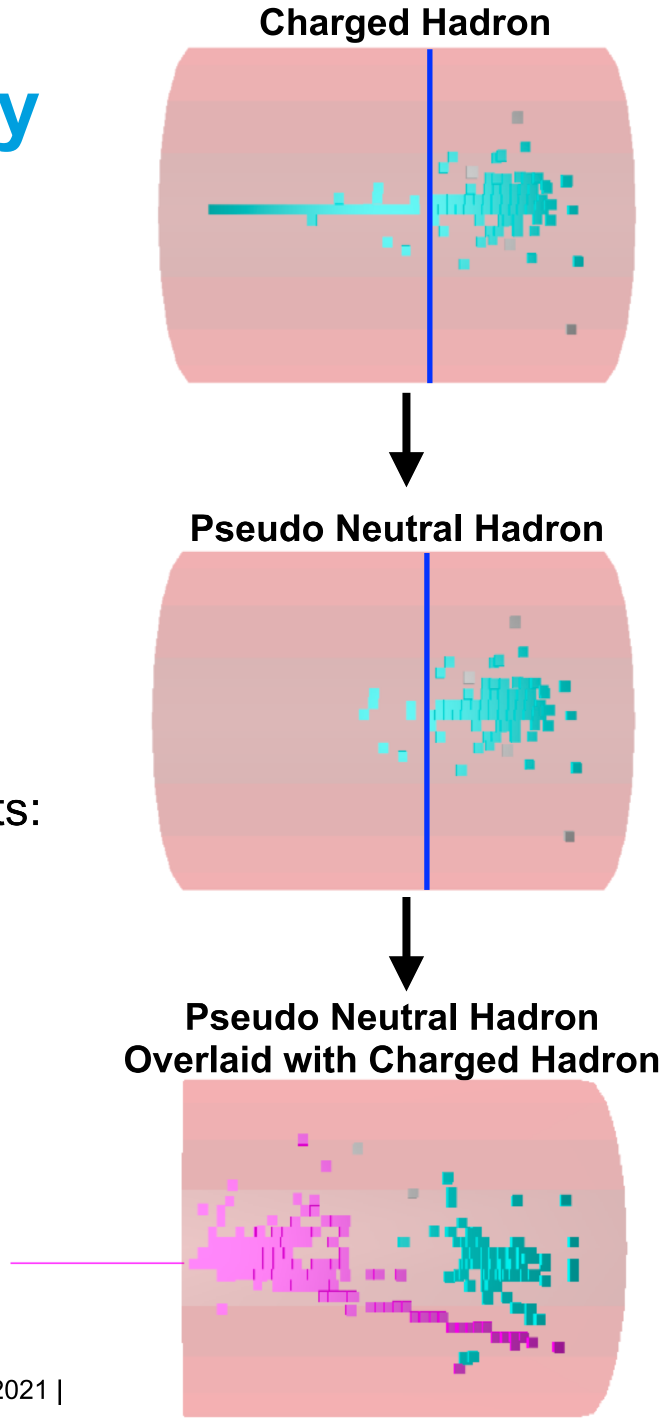


Intermezzo: Pseudo-Neutrals & Event Overlay

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

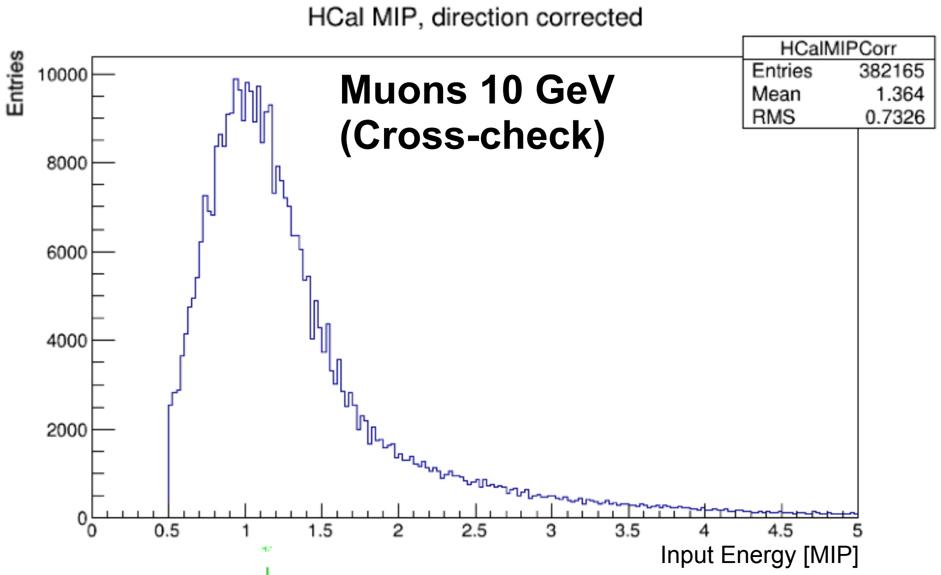
- Subsequent overlay with charged hadron to create desired two particle events:
  - ➡ Channel by channel overlay of hit information (+ origin flagging)
  - ➡ Energy threshold considerations
  - ➡ Control parameters: Energy of overlaid charged hadron, transversal shower distance, longitudinal shower separation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

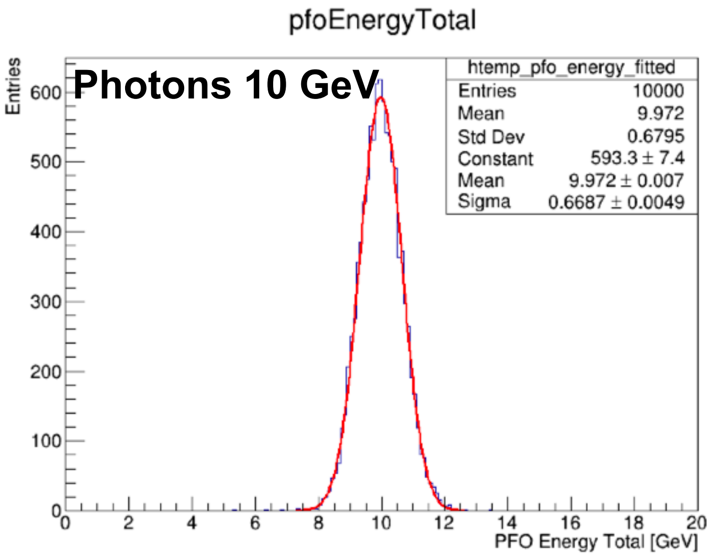


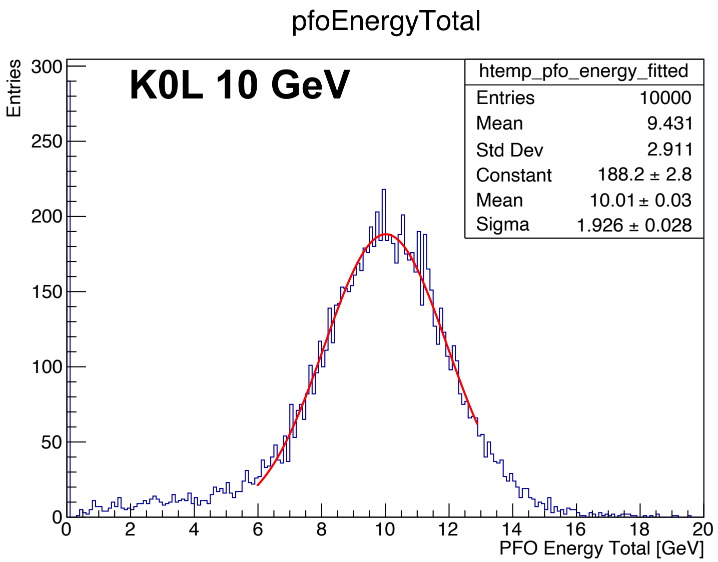
Pandora Energy Calibration

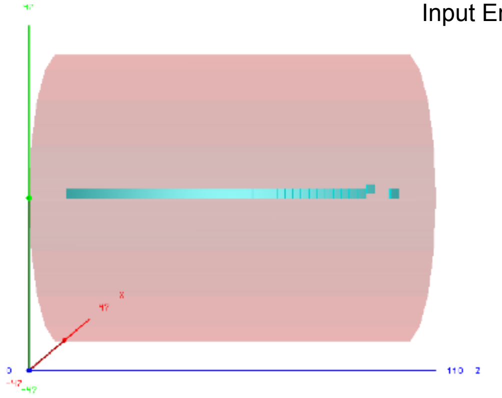
MC Muons, Photons, K0L

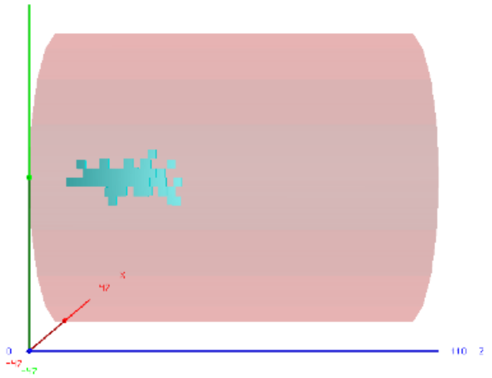
Note: Without tracks and ECAL everything classified as neutral hadrons at this step

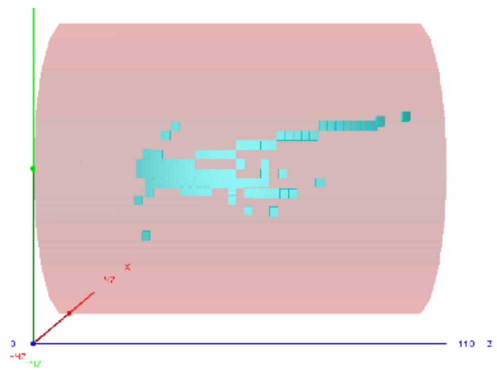










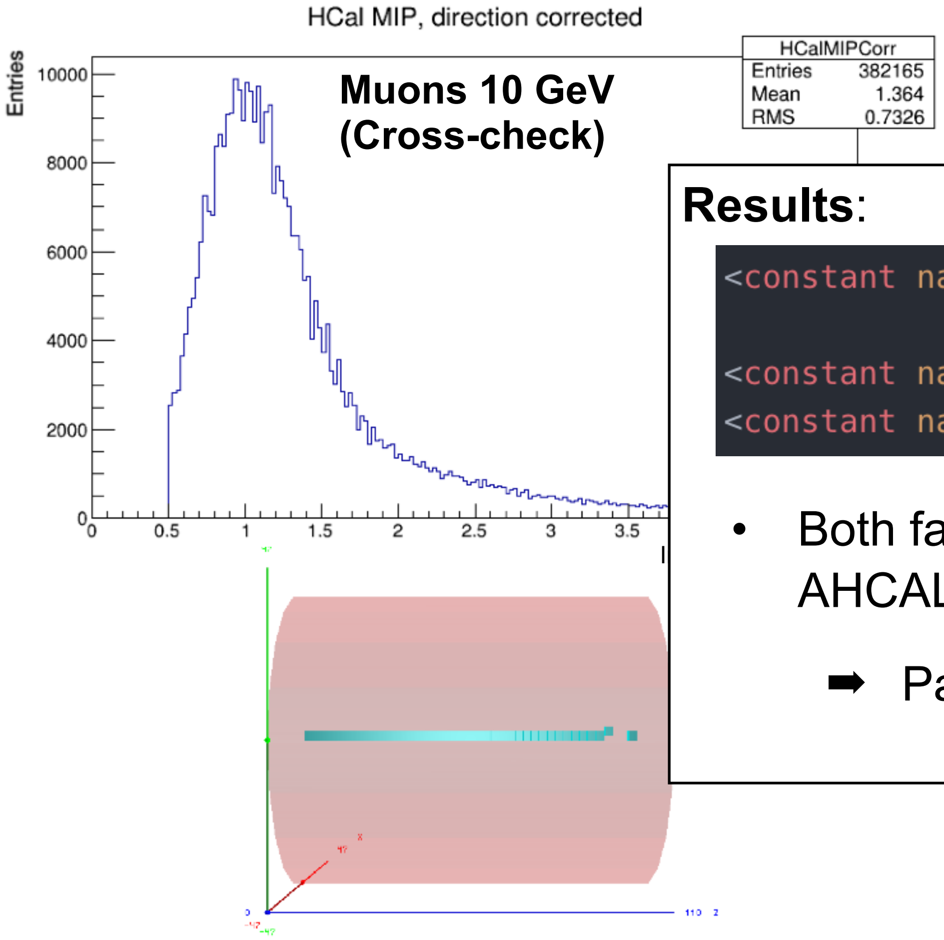


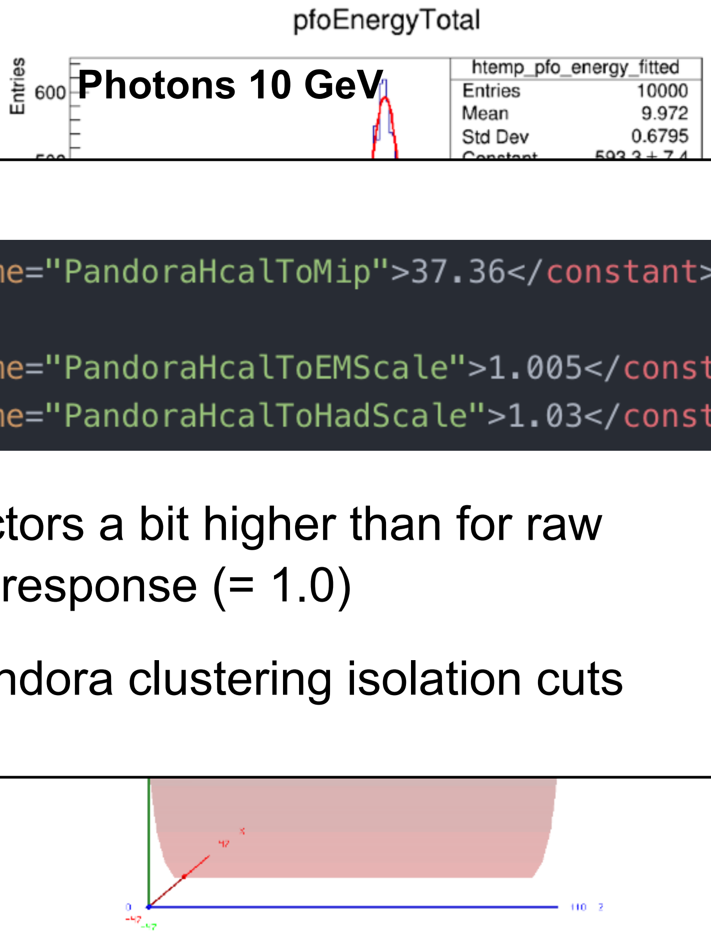
- **Muons**: AHCAL energy GeV -> MIP with negligible angle correction since straight TB tracks
- **Photons and K0L's**: Used to determine EM and HAD response, PFO energy tuned to peak at 10 GeV

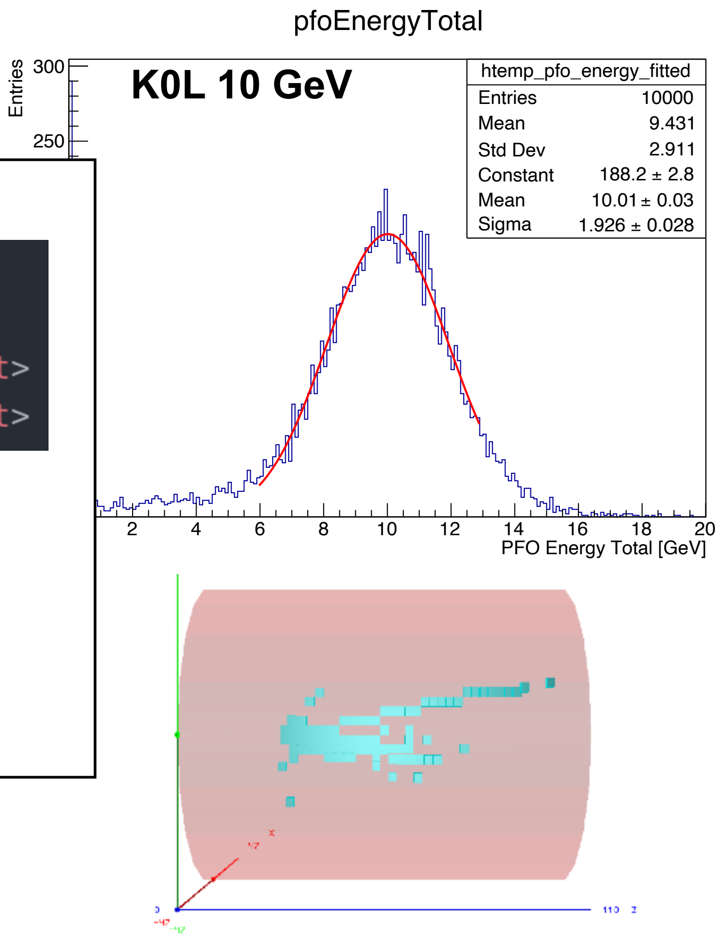
Pandora Energy Calibration

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>
```

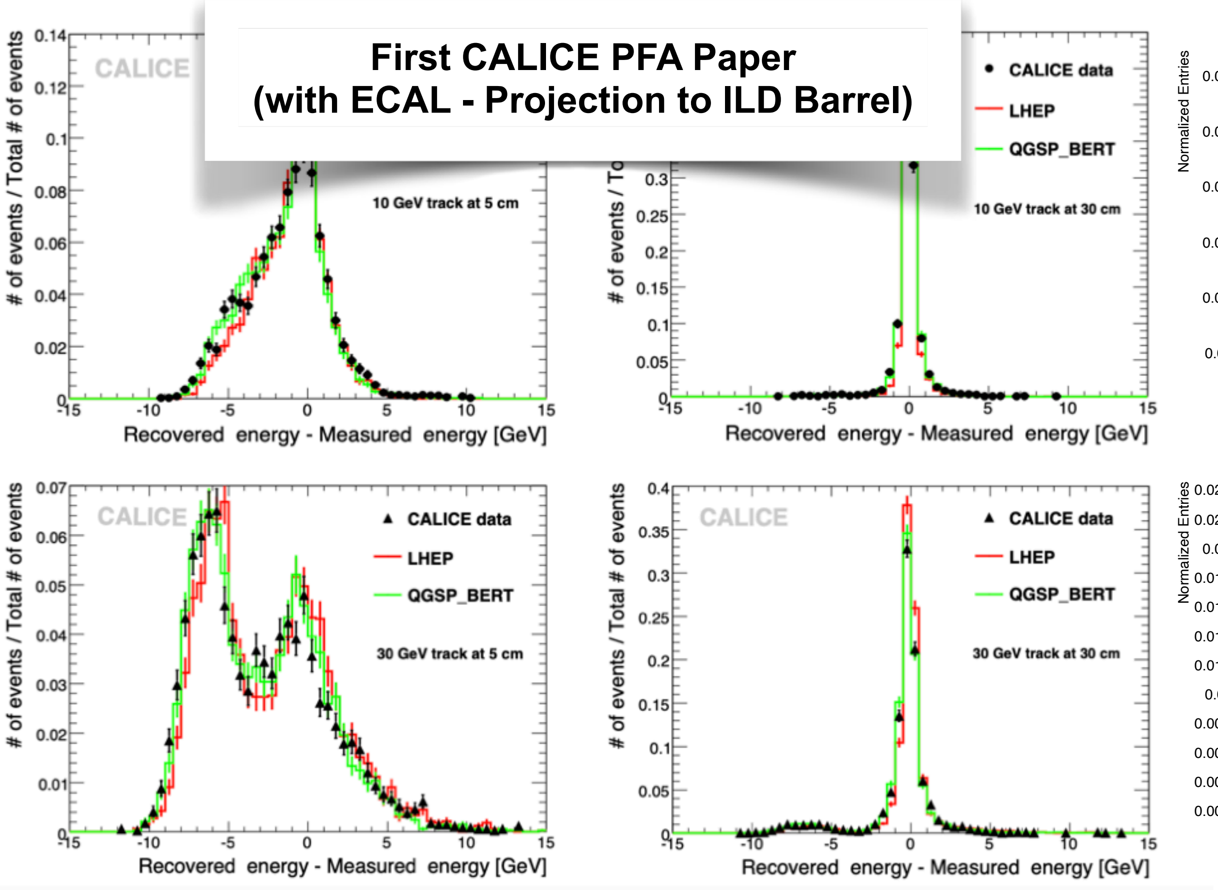
- Both factors a bit higher than for raw AHCAL response (= 1.0)
  - ➡ Pandora clustering isolation cuts

- **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

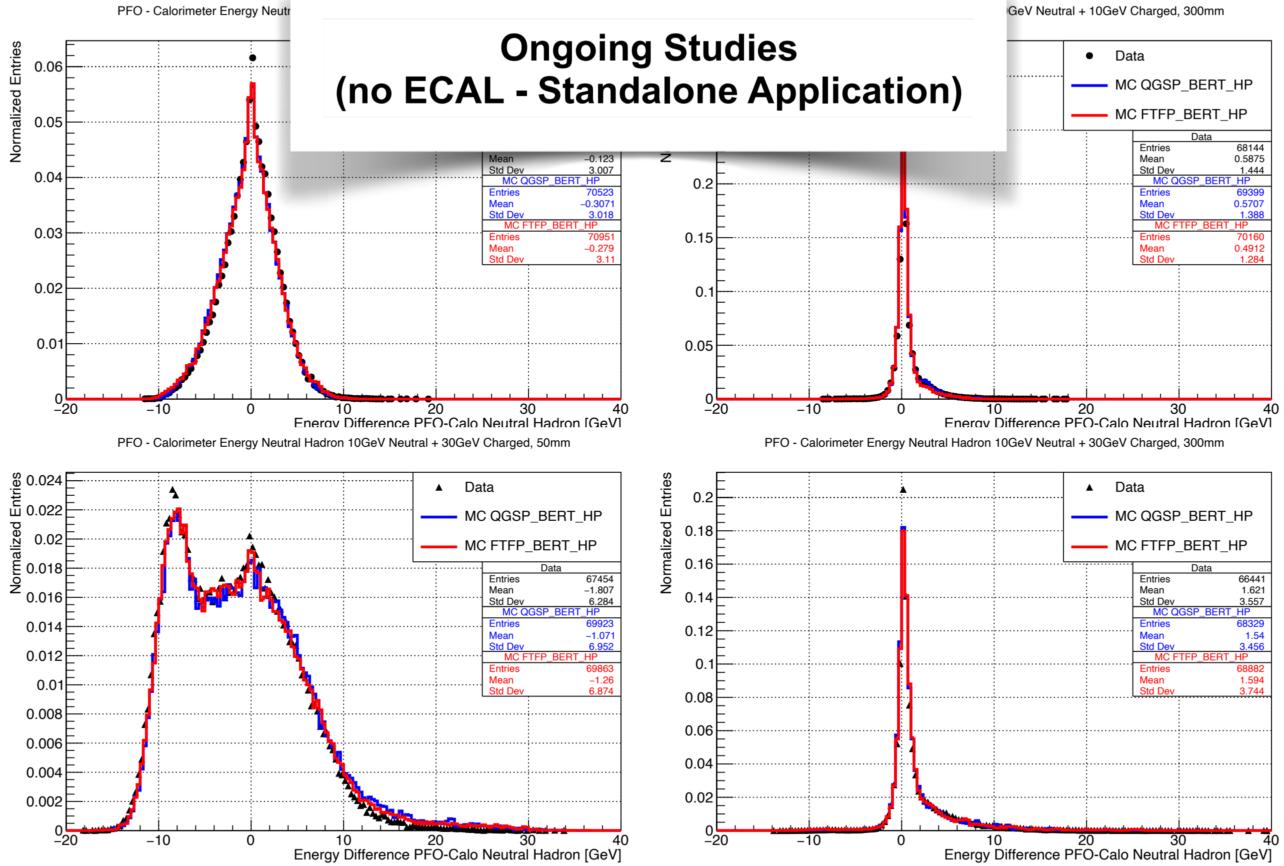
PFO Energy - Calorimeter Energy Neutral Hadron

Is the Energy of the Neutral Hadron Reconstructed Correctly by PandoraPFA?

First CALICE PFA Paper (with ECAL - Projection to ILD Barrel)



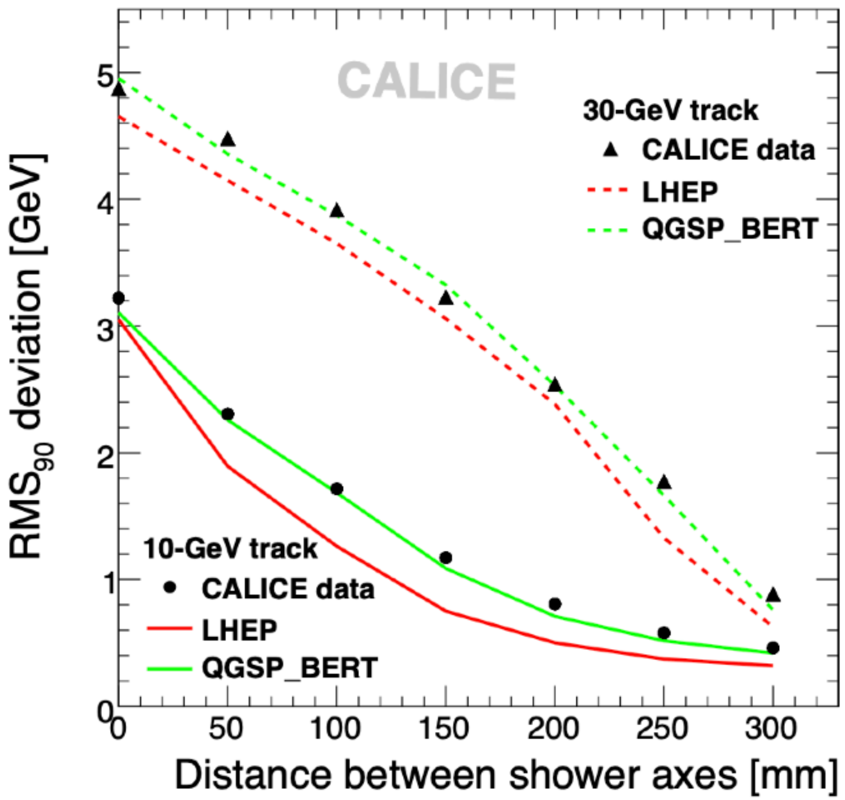
Ongoing Studies (no ECAL - Standalone Application)

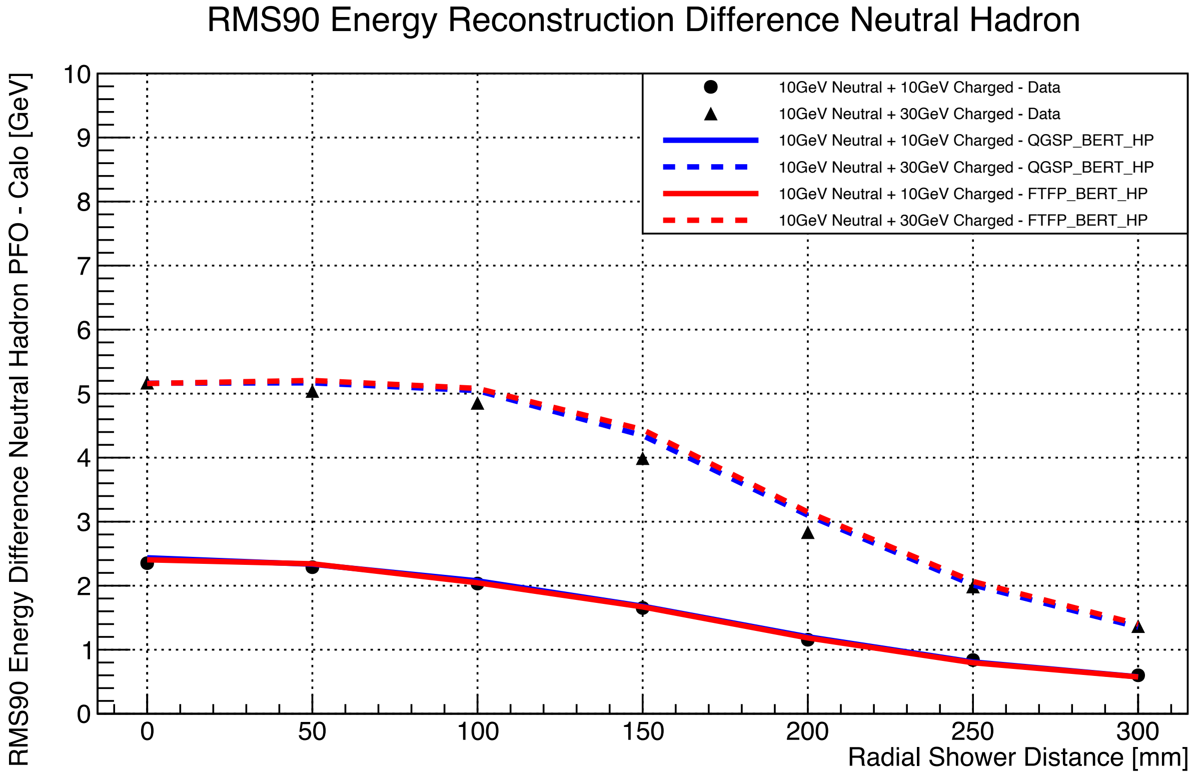


- Same features as for previous studies, but larger width and more pronounced tail to the right (high energy neutral PFO events)

PFO Energy - Calorimeter Energy Neutral Hadron: RMS90

First CALICE PFA Paper vs. Ongoing Studies

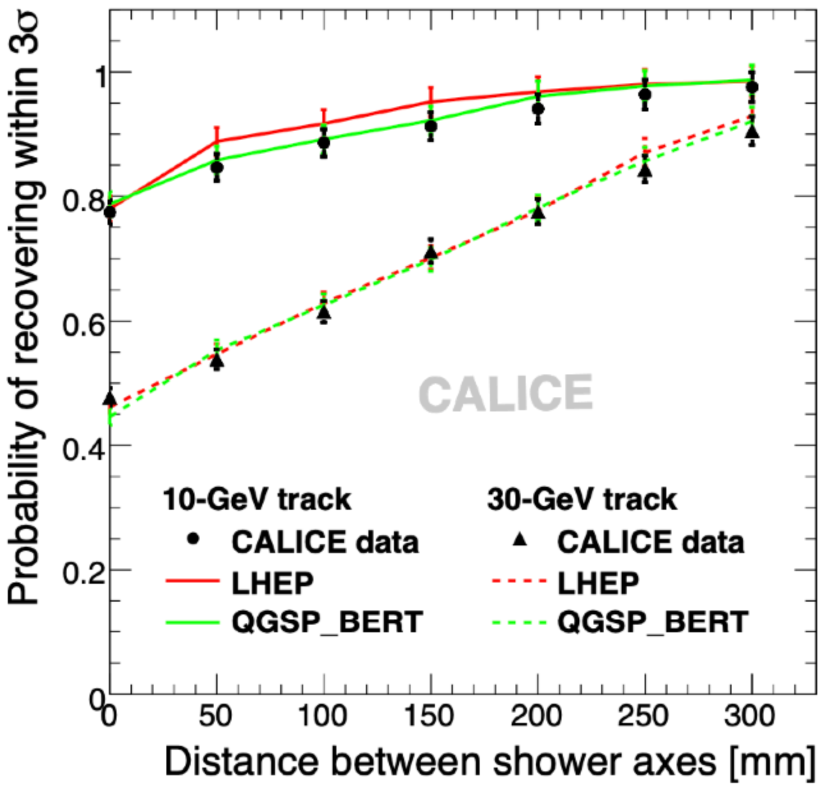


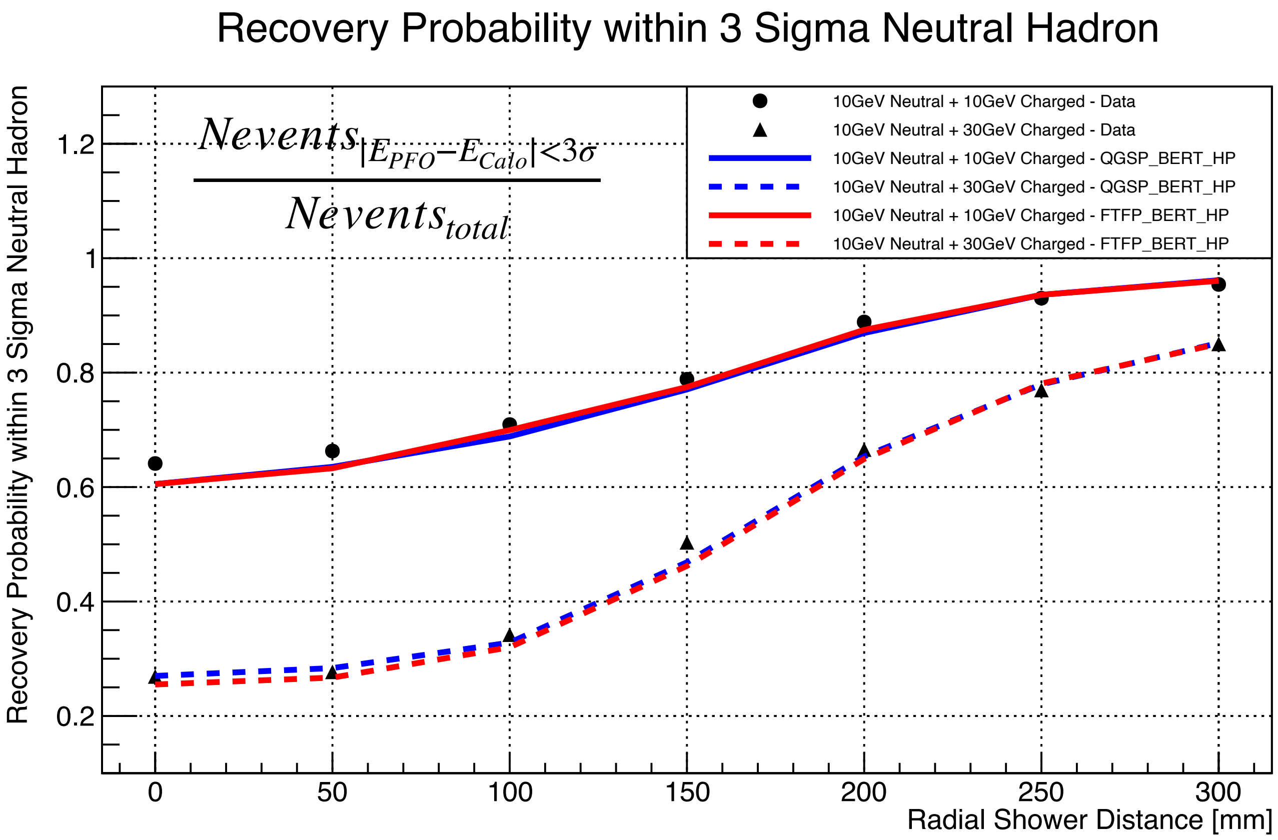


- Excellent data to MC agreement
- Slower falling trend for growing distance to 10GeV and 30GeV charged hadrons
  - ➡ Suspicion: Low distances very tricky without ECAL hits before AHCAL

Neutral Hadron Recovery Probability 3 Sigma

First CALICE PFA Paper vs. Latest Studies



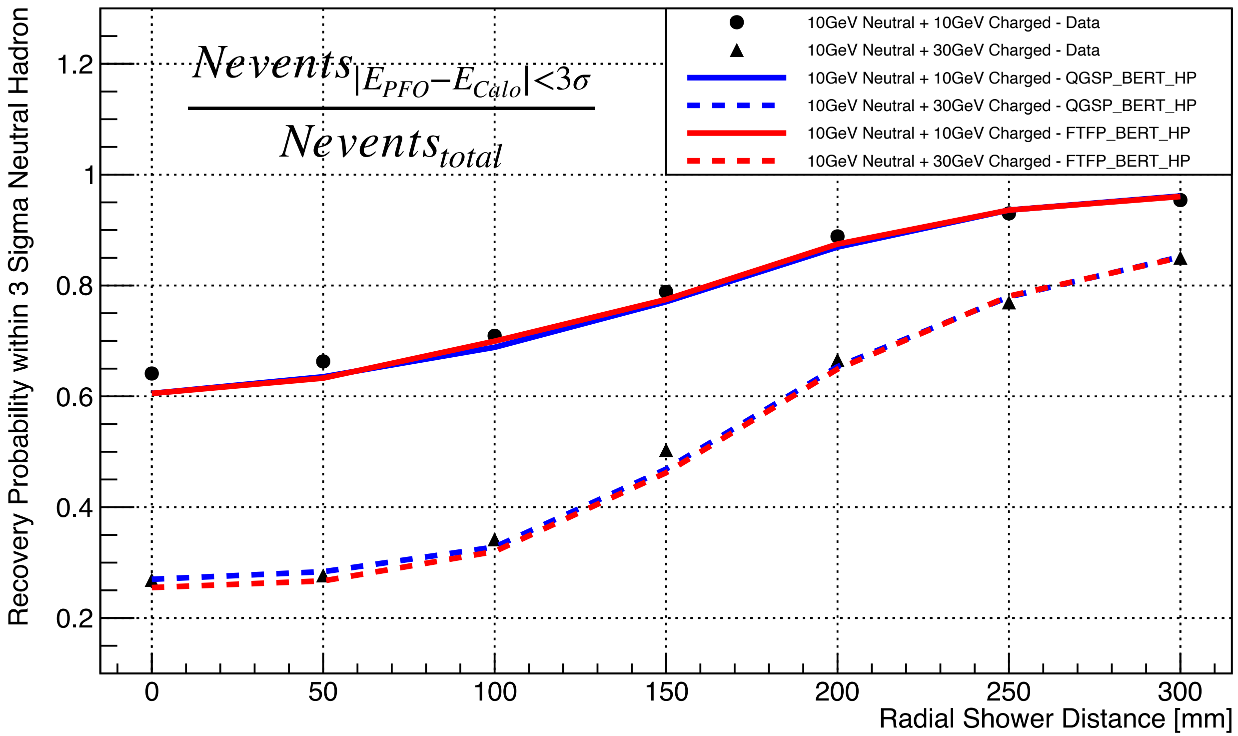


- Definition: Fraction of events for which PandoraPFA recovered neutral hadron energy within **3 sigma (sigma = width of neutral hadron energy sum of calorimeter measurement)**
- Same rising trend for larger separation, but slower growing especially for vicinity of 30 GeV charged hadron
  - ➡ Excellent data to MC agreement, slightly worse performance for current studies (no ECAL?)

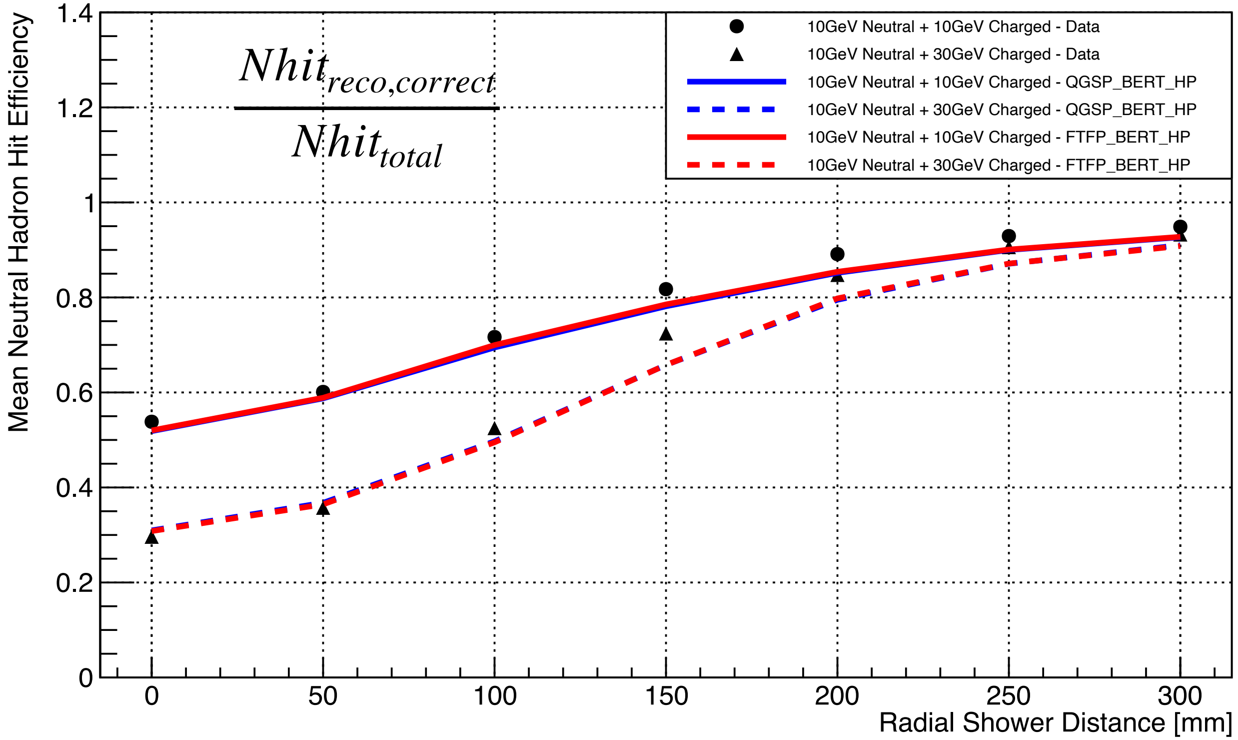
How well is the Neutral Hadron Energy/Hits Recovered?

3 Sigma Energy Recovery Probability & Mean Hit Efficiency

Recovery Probability within 3 Sigma Neutral Hadron



Mean Neutral Hadron Hit Efficiency

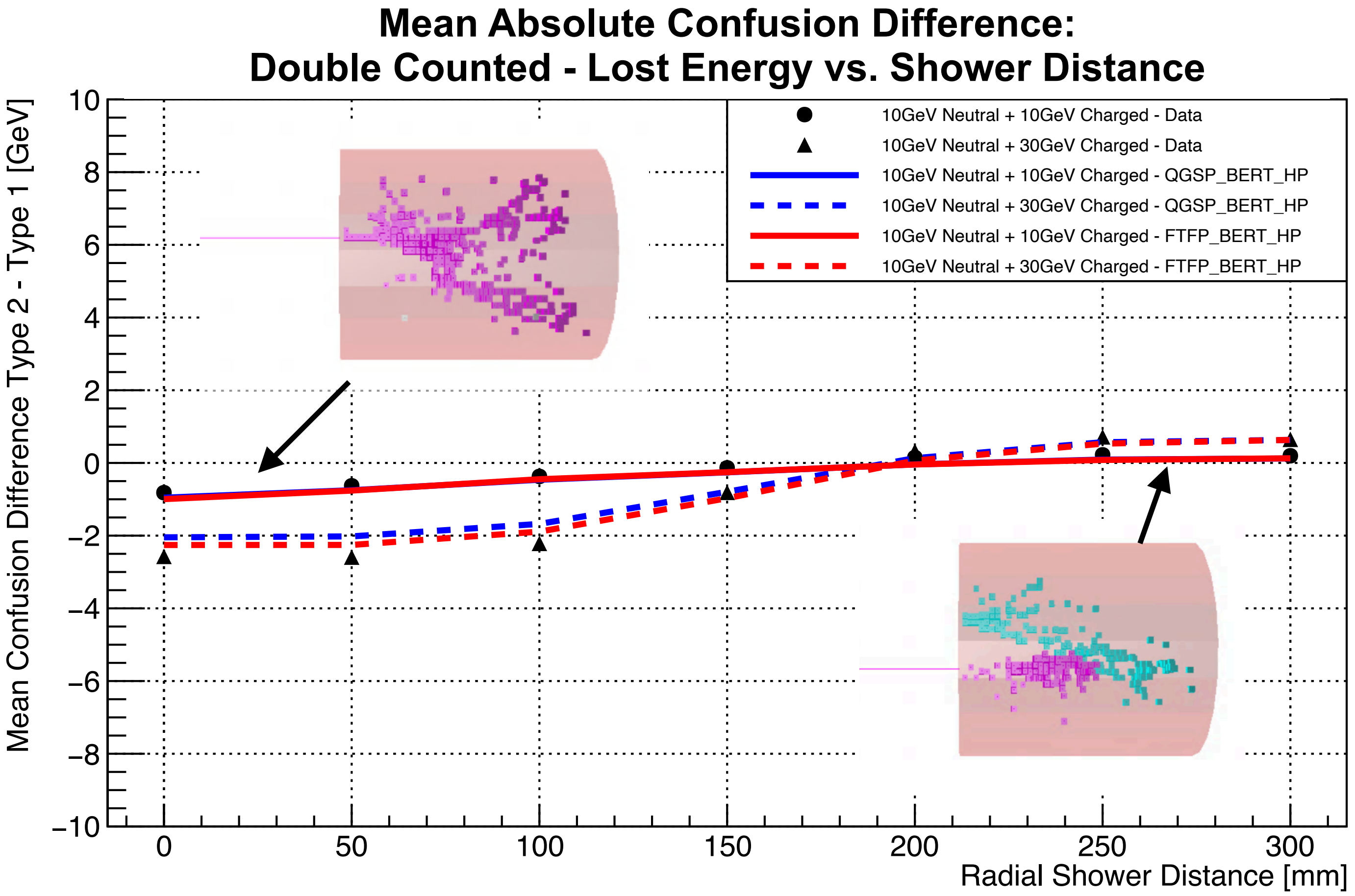


- For largest shower separation: Energy and hits of neutral hadron recovered well on average
- Falling trends for smaller separation; More pronounced for vicinity of 30 GeV charged hadron
- Good data to MC agreement within 5%

How well are Types of Confusion Balanced?

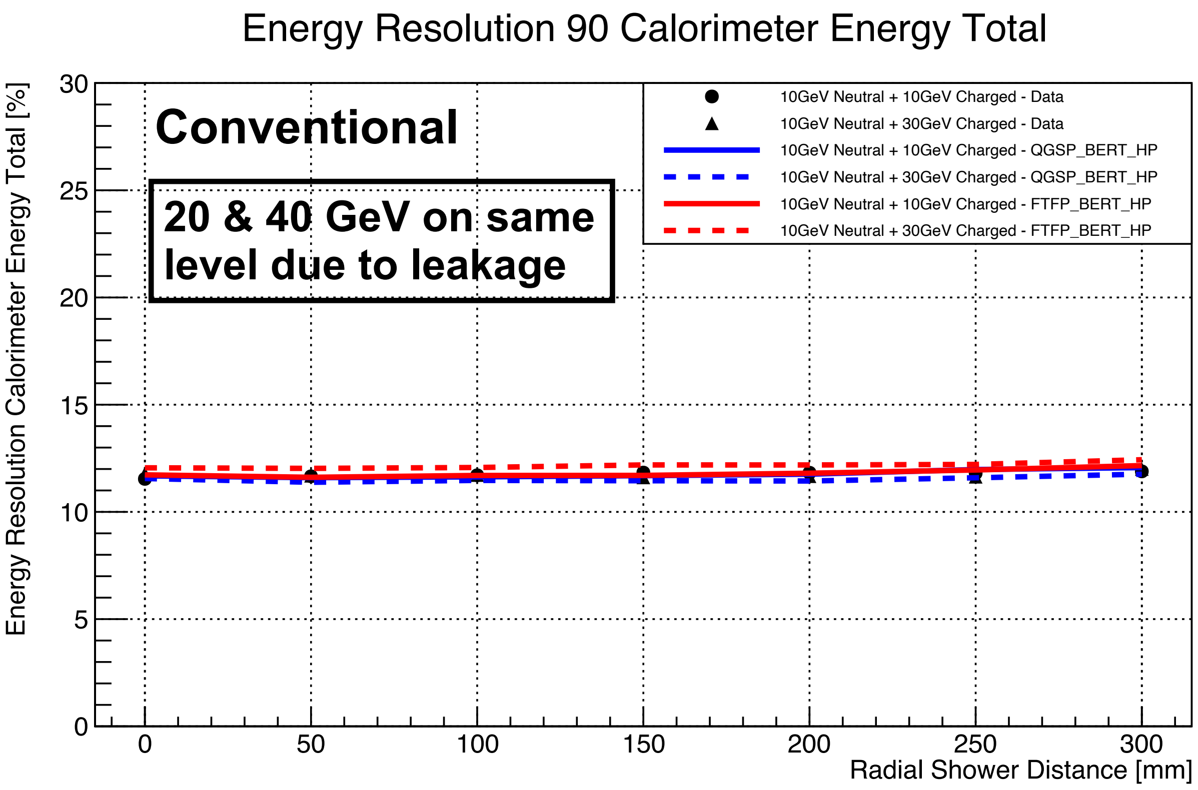
Double Counted Energy - Energy Loss Difference

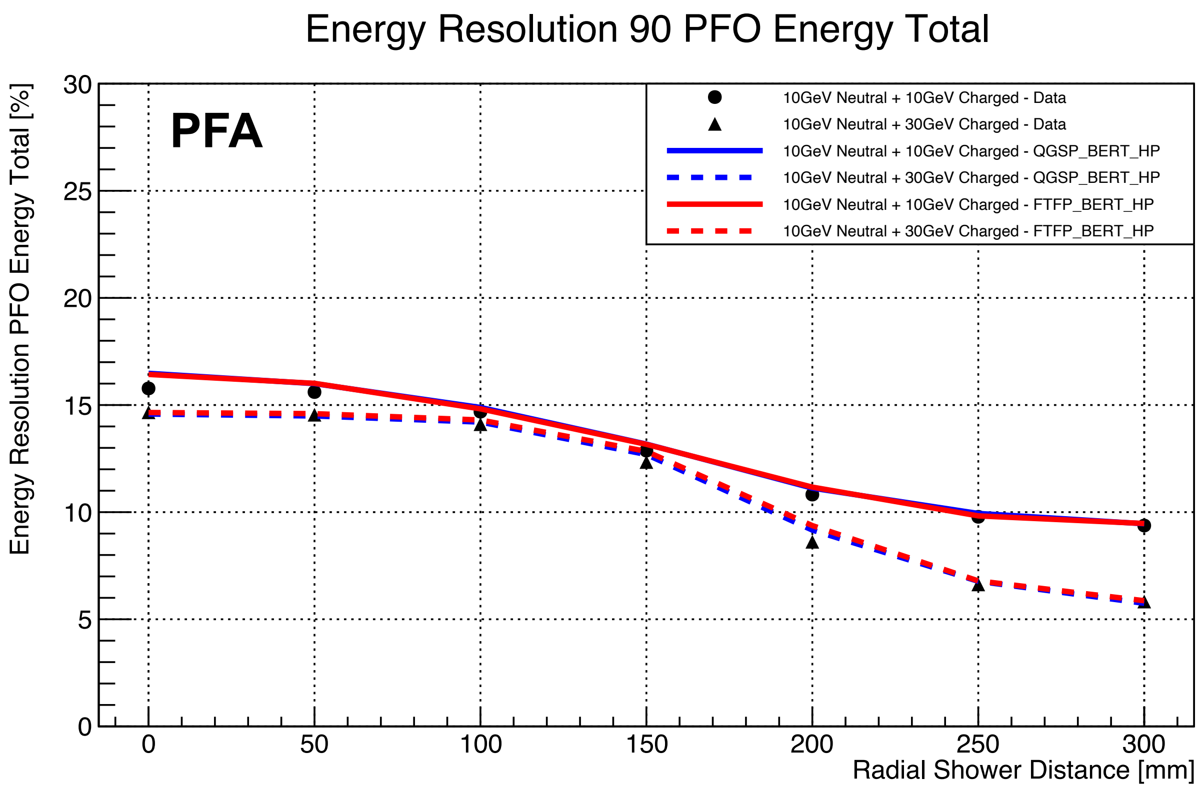
- Highest shower distances: Double counted energy (additional neutral fragments in shower sub-structure) dominant
- Lowest shower distances: Energy losses (neutral hit absorption into charged) dominant
  - ➡ In-balance more pronounced for vicinity of 30 GeV charged hadron
  - ➡ Turning point ~200mm shower distance
  - ➡ Good Data/MC agreement: Within ~10%



Total Energy Reconstruction Performance?

AHCAL Two Particle Events - Conventional vs. PFA Relative Resolution





- For simple two particle event scenario **PFA pays off for shower distances > 150mm**
  - ➡ Total confused energy gets on a smaller level & energy loss and double counting are more balanced

➡ For closest shower distances (dense event scenarios) still further potential within pattern recognition?

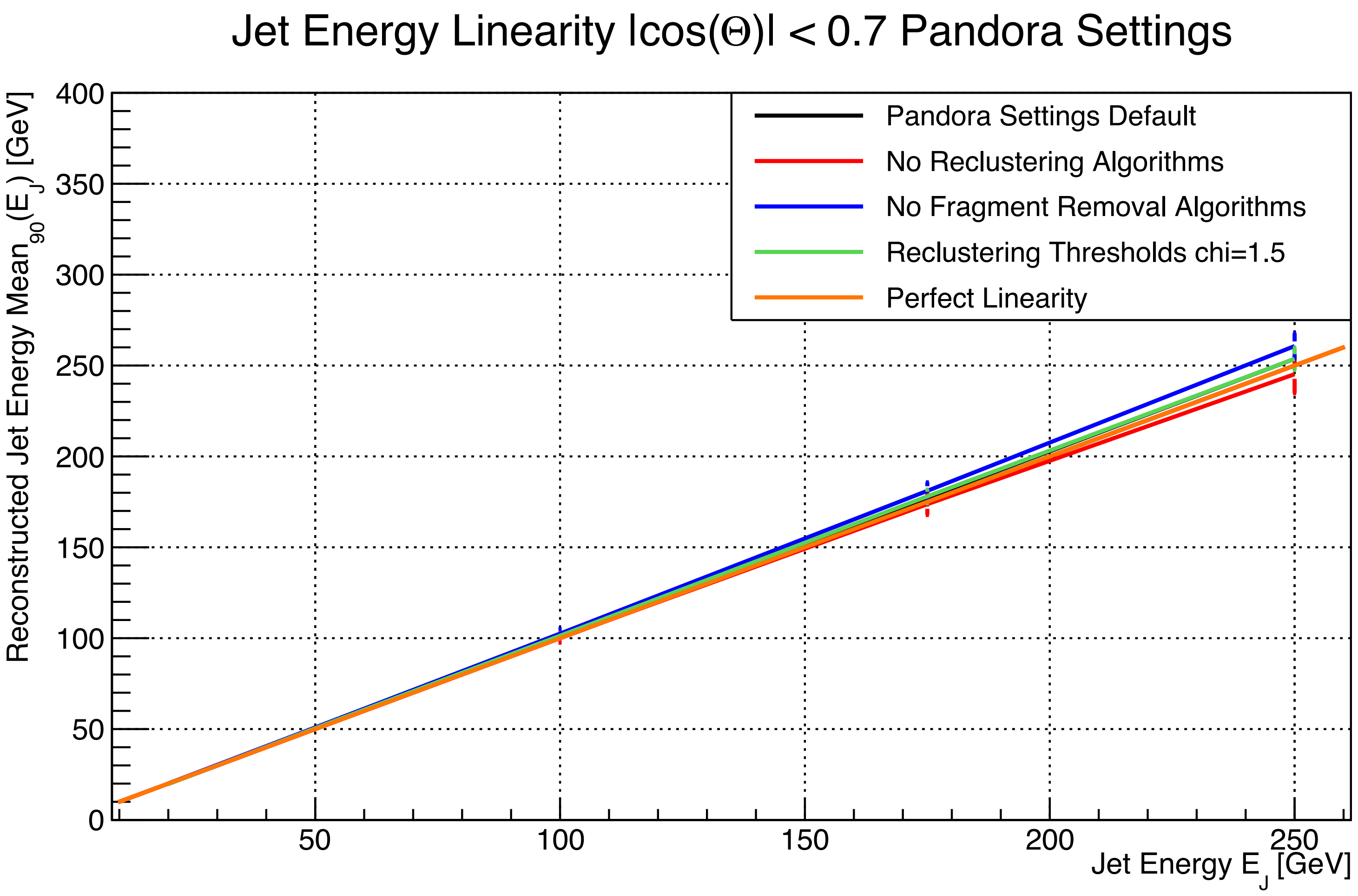
Jet Energy Linearity

Different PandoraPFA Settings

- For highest energies slight deviations of up to 5%
  - ➡ Default/Chi=1.5 still very close to perfect linearity

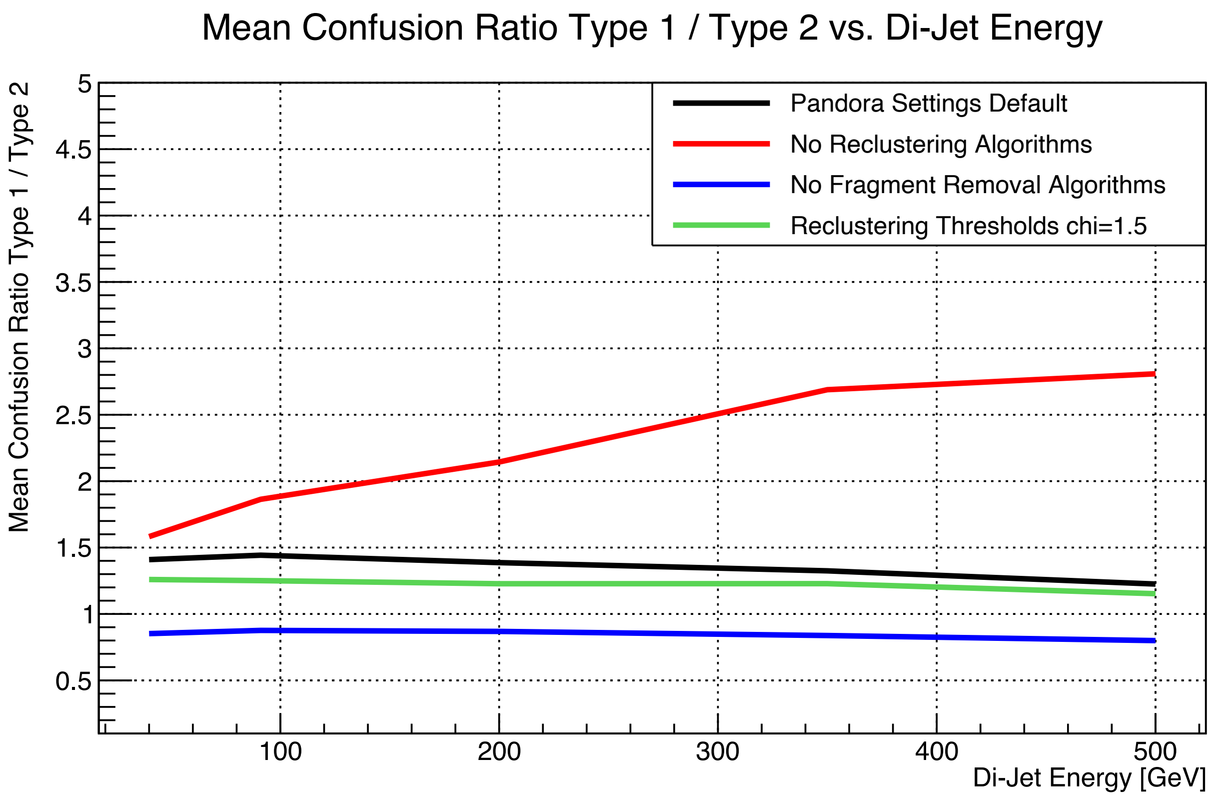
➡ Influence of confusion visible:

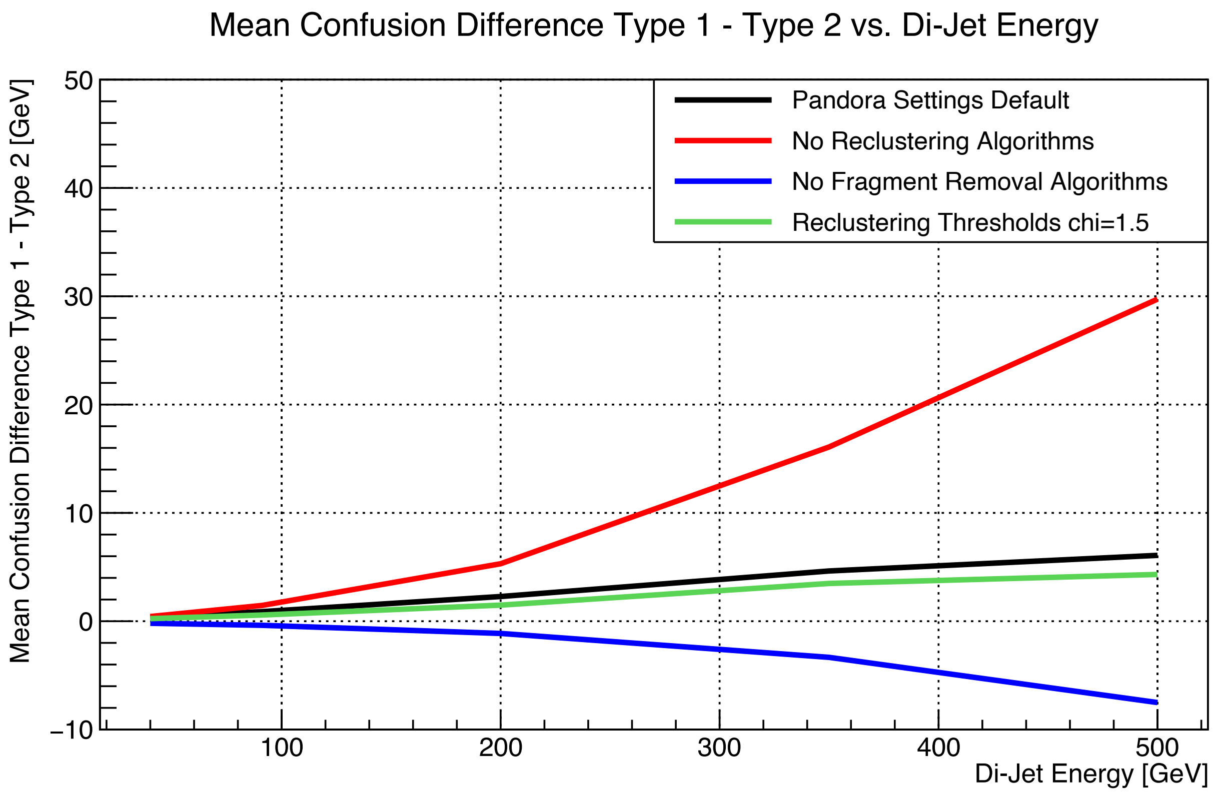
- ➡ No fragment removal: Overestimated energy / double counted energy (confusion type 2)
- ➡ No reclustering: Missing energy due to absorption of neutral hadrons into charged (confusion type 1)



Mean Confusion Type Ratio & Difference

Different PandoraPFA Settings

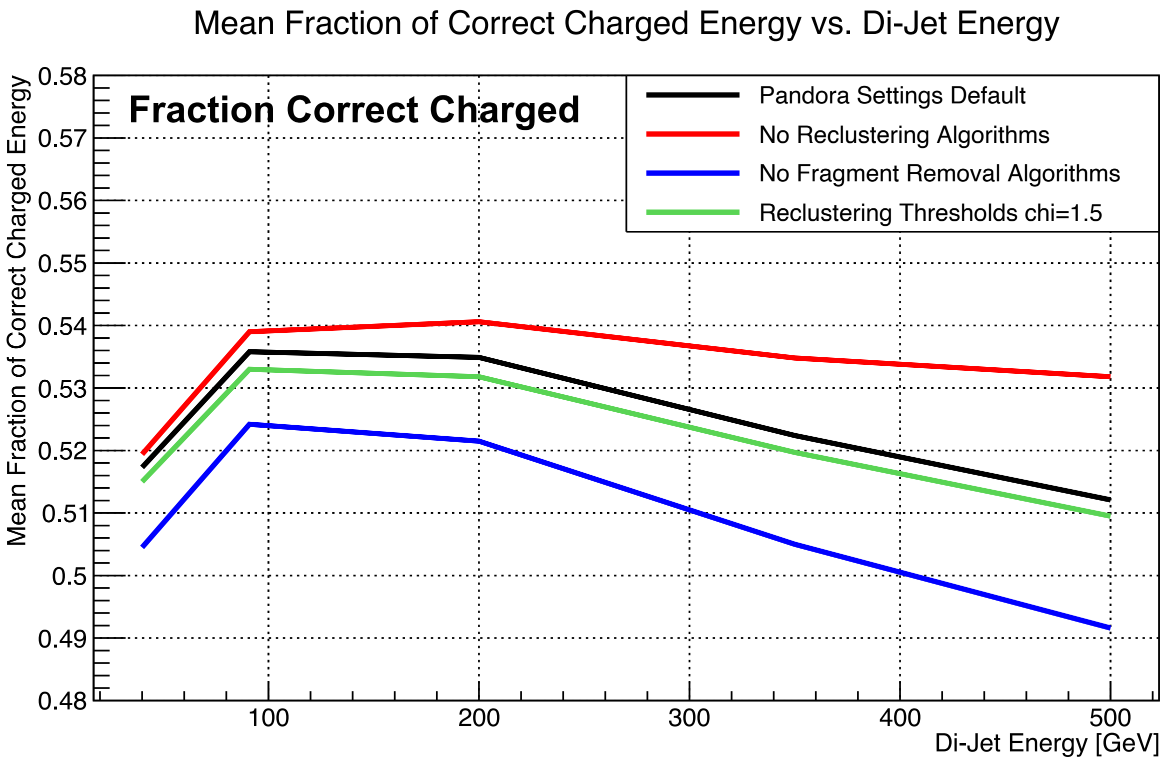


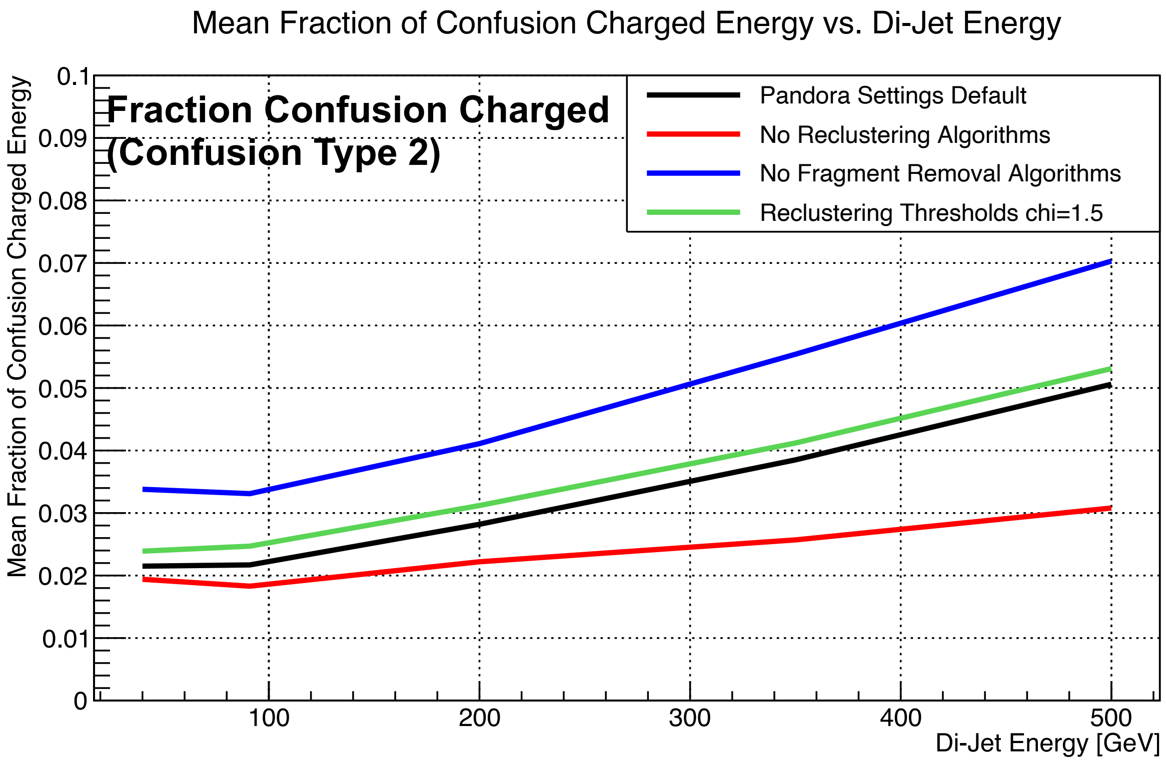


- Confusion type 1 dominant for no reclustering; confusion type 2 more dominant for no fragment removal
- Confusion types almost balanced for default/chi=1.5 settings

Mean Fraction of Correct and Confusion Charged Energy

Different PandoraPFA Settings

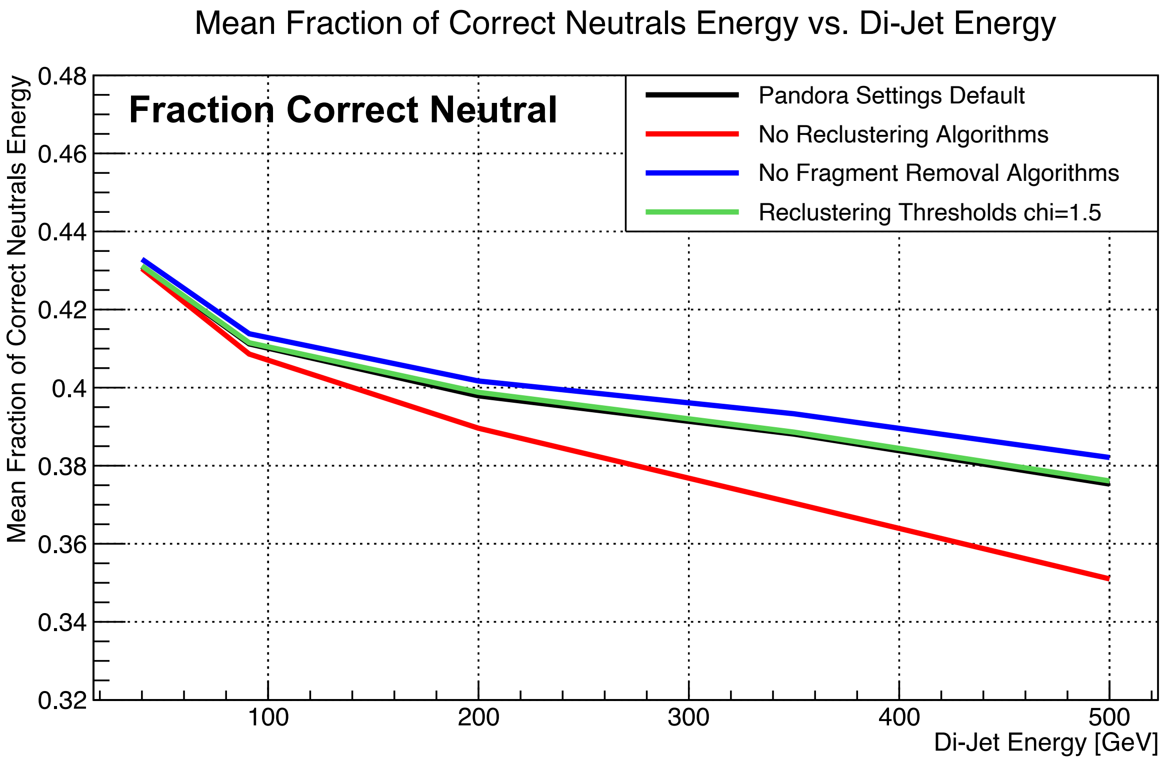


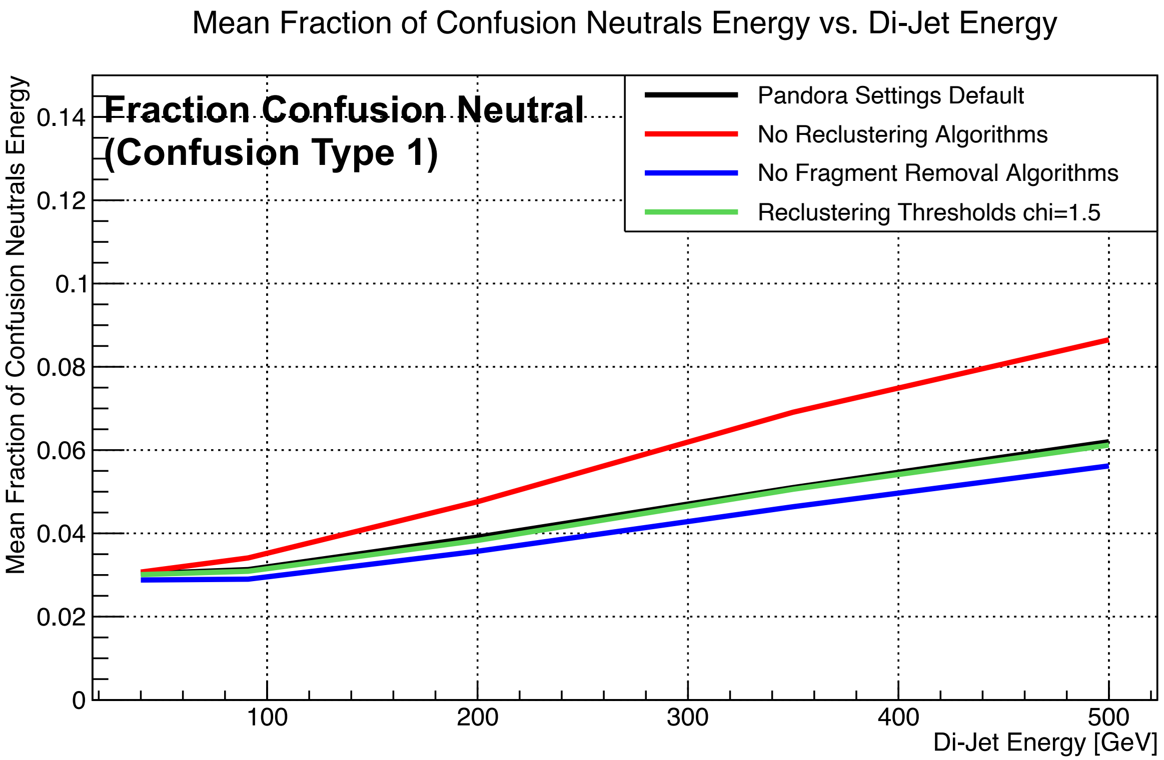


- Agreeing with trends for linearity and confusion ratio/difference
  - ➡ Best: No reclustering - Trend towards more charged energy assigned to tracks without reclustering
  - ➡ Worst: No fragment removal - Trend towards more neutral fragments not merged into charged particles
  - ➡ Chi = 1.5: Towards energy flow: More simply energy based re-clustering

Mean Fraction of Correct and Confusion Neutral Energy

Different PandoraPFA Settings



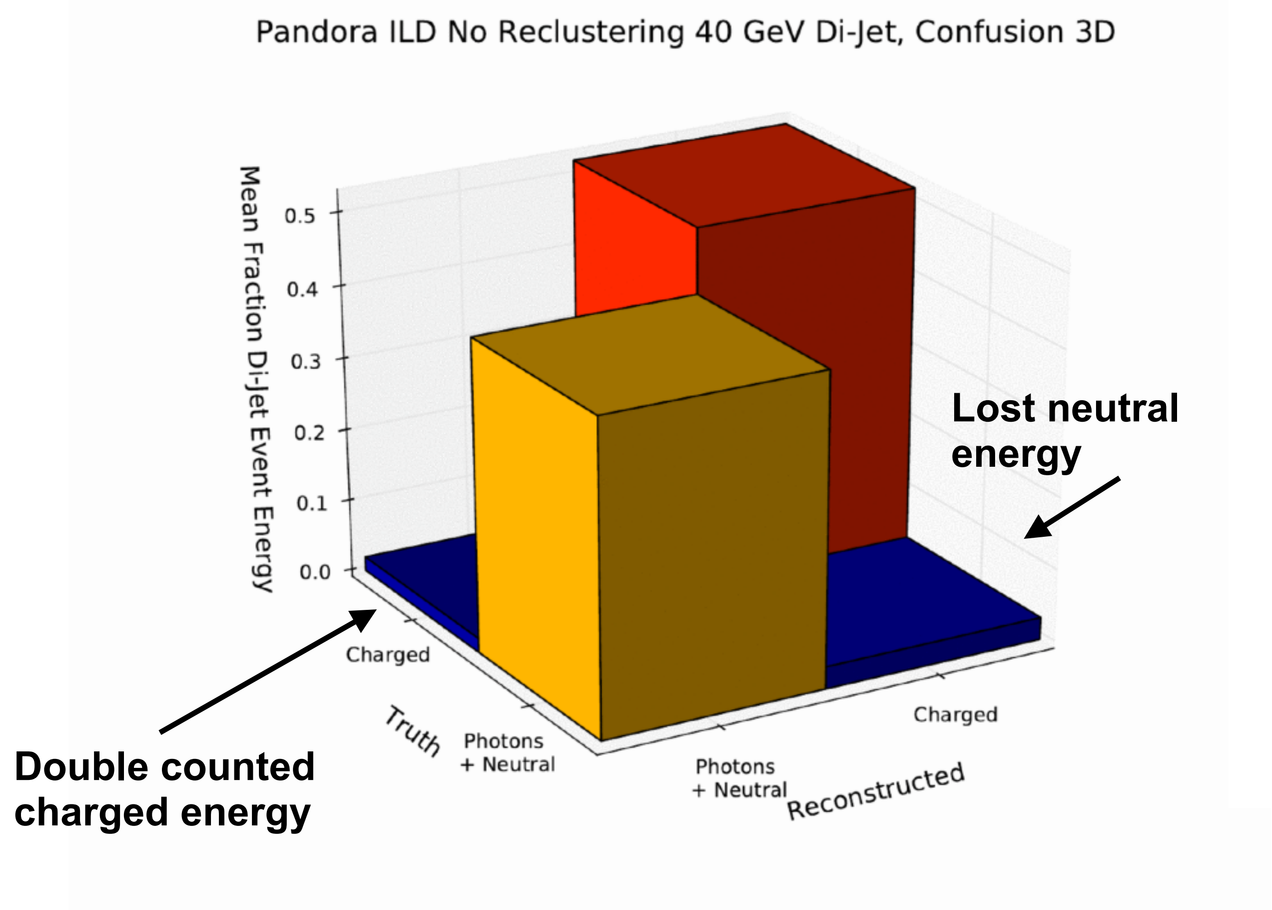


➡ Inverted picture/trends for neutral hadron energy verified

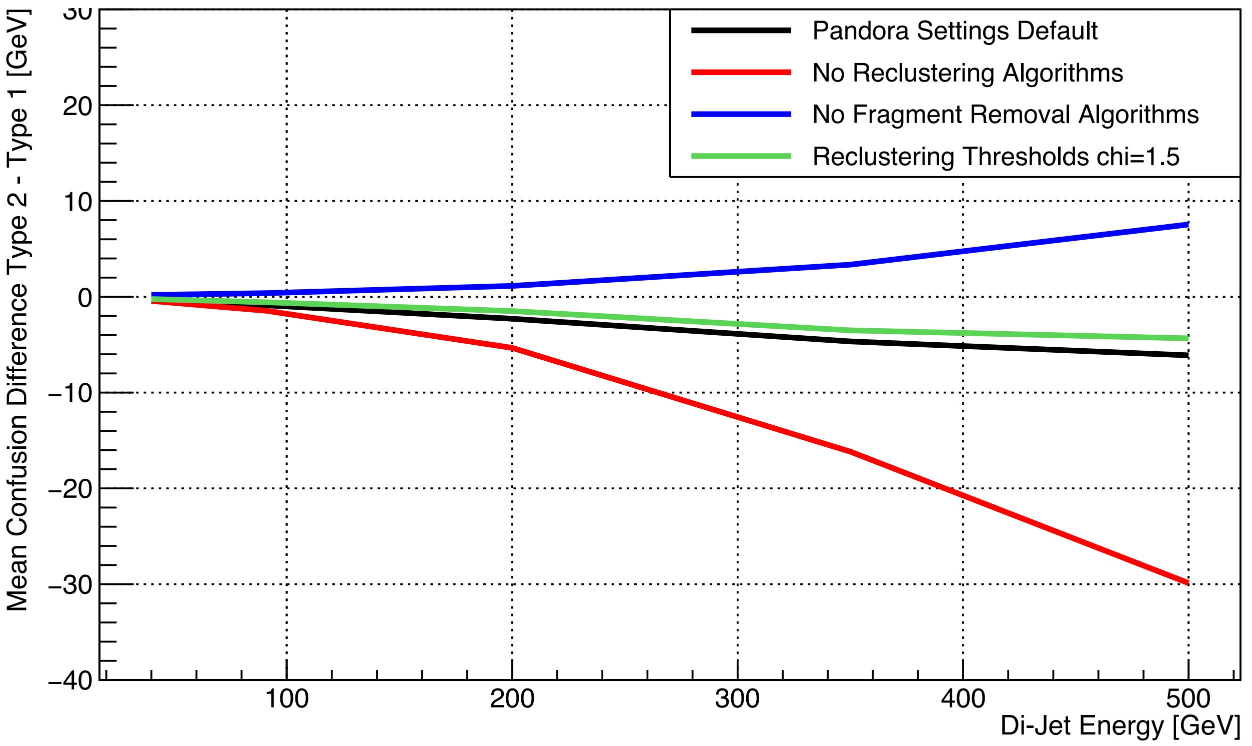
How well are Lost & Double Counted Energy Balanced?

Different PandoraPFA Settings - AHCAL 2018 Data vs. ILD Di-Jets

Example No Re-Clustering: Confusion Matrix



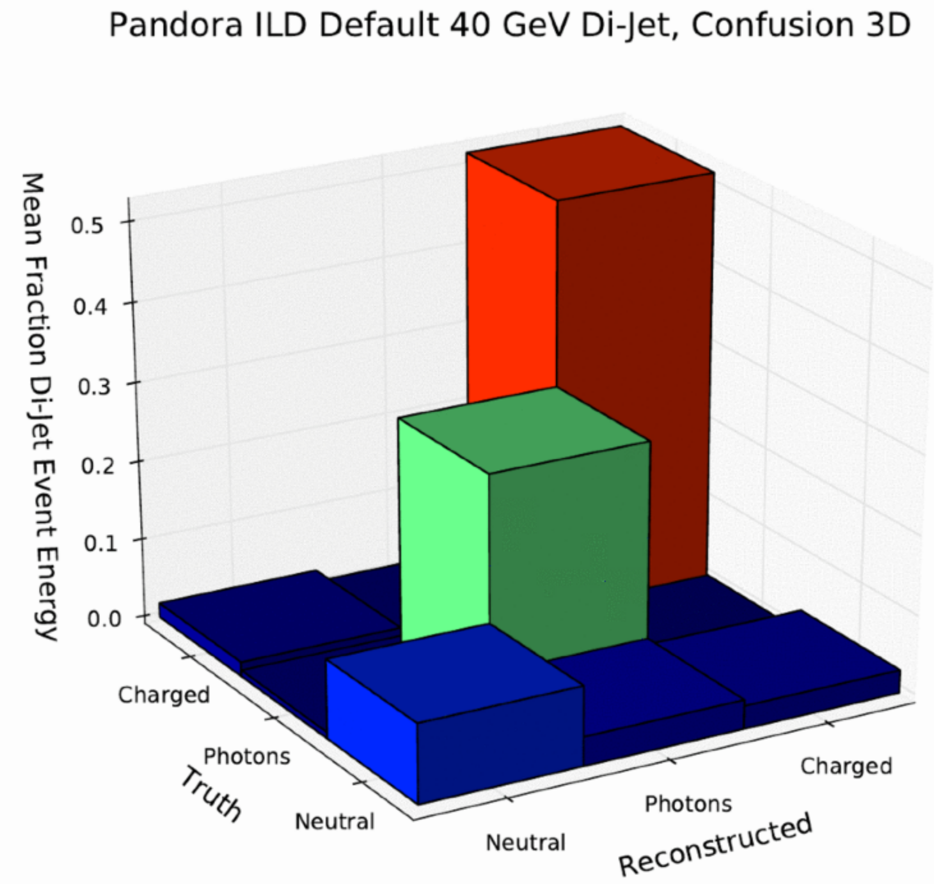
Mean Absolute Confusion Difference: Double Counted - Lost Energy vs. Di-Jet Energy

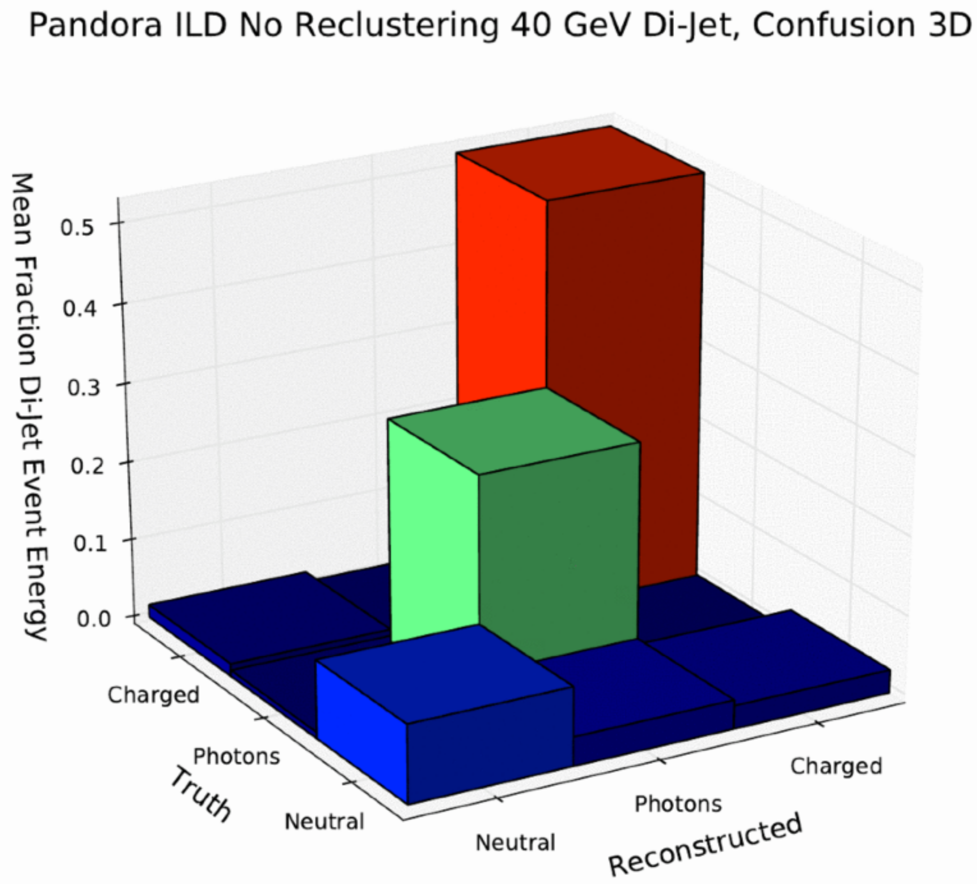


ILD Jets - Confusion Matrix - 3x3

Default Settings vs. No Reclustering Algorithms

Normalised to Mean Full Event Energy



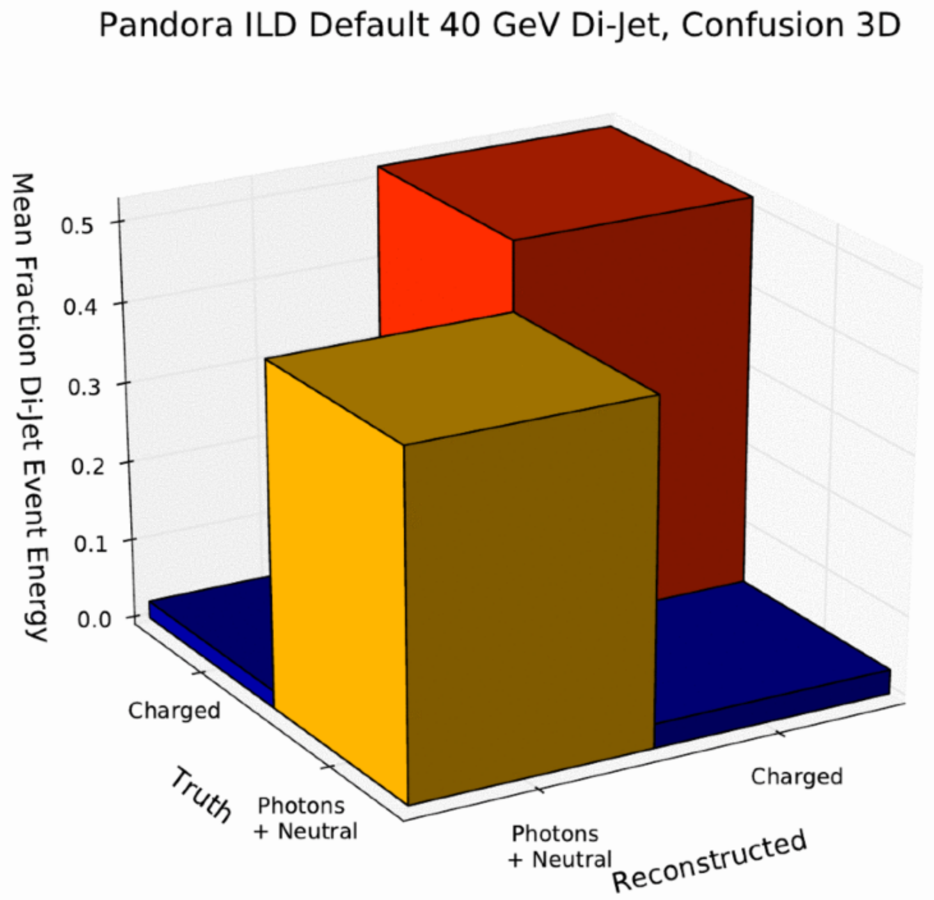


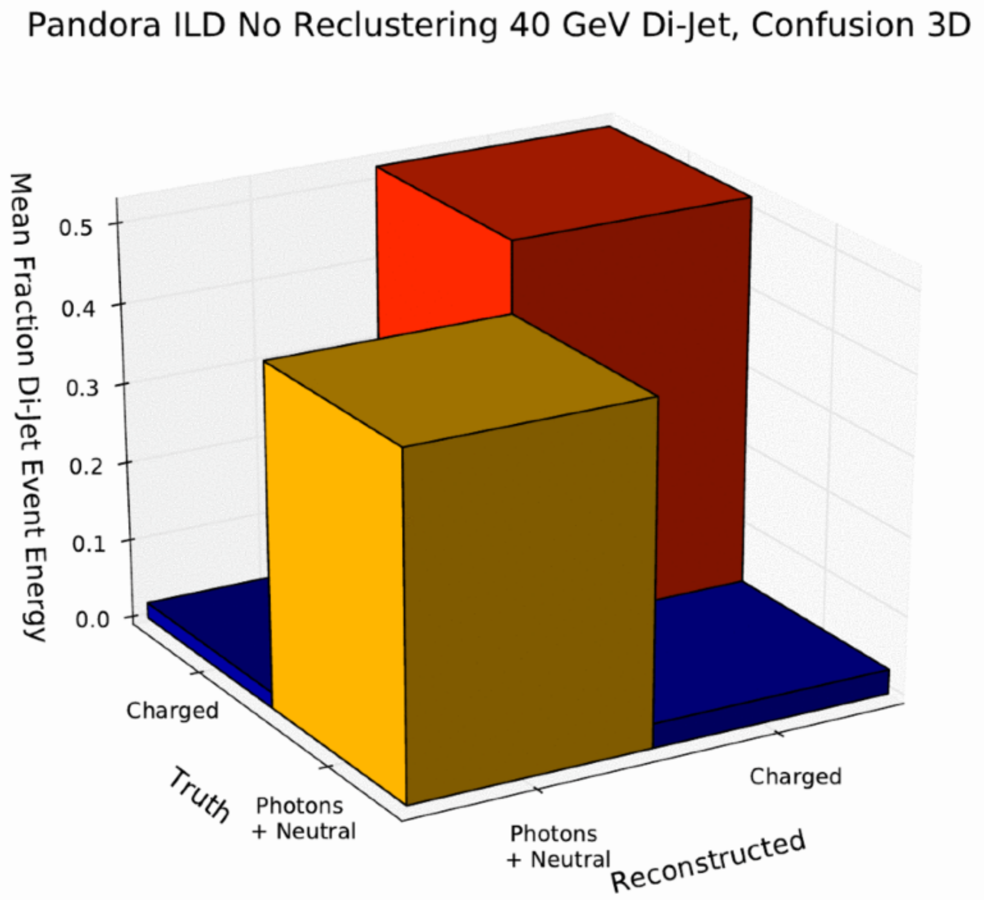
- With increasing jet energy, total confused energy and type in-balance is increasing
  - ➡ More dominant for reclustering algorithms turned off

ILD Jets - Confusion Matrix - 2x2

Default Settings vs. No Reclustering Algorithms

Normalised to Mean Full Event Energy





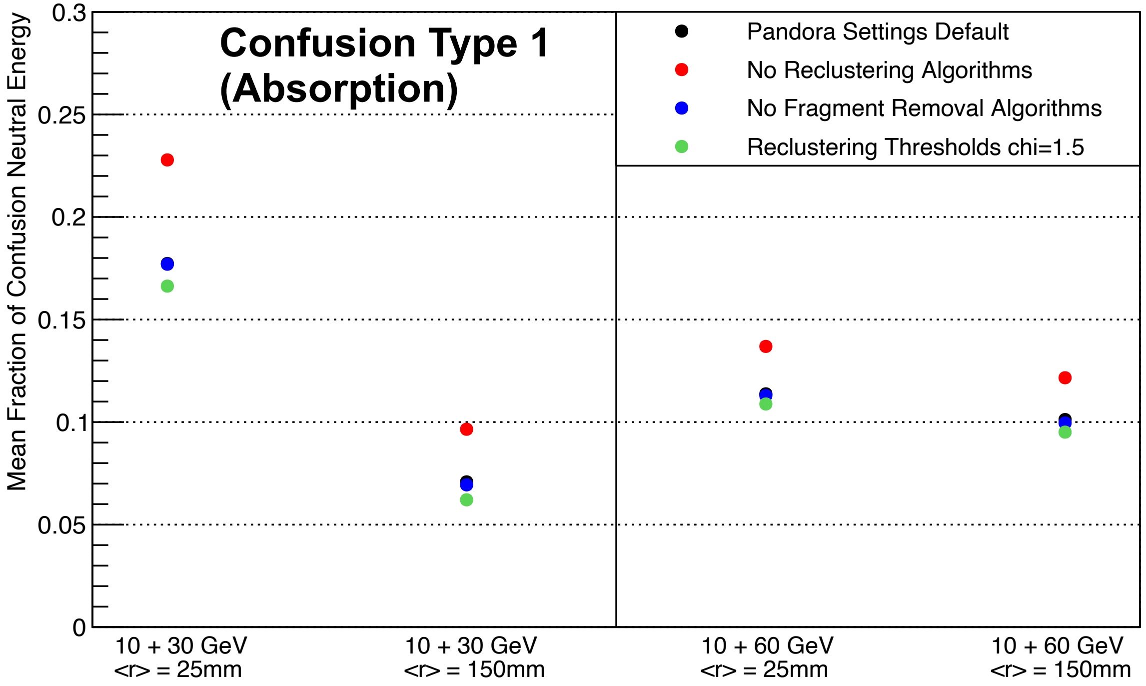
- With increasing jet energy, total confused energy and type in-balance is increasing
  - ➡ More dominant for reclustering algorithms turned off

Mean Confusion Fraction Type 1 & Type 2

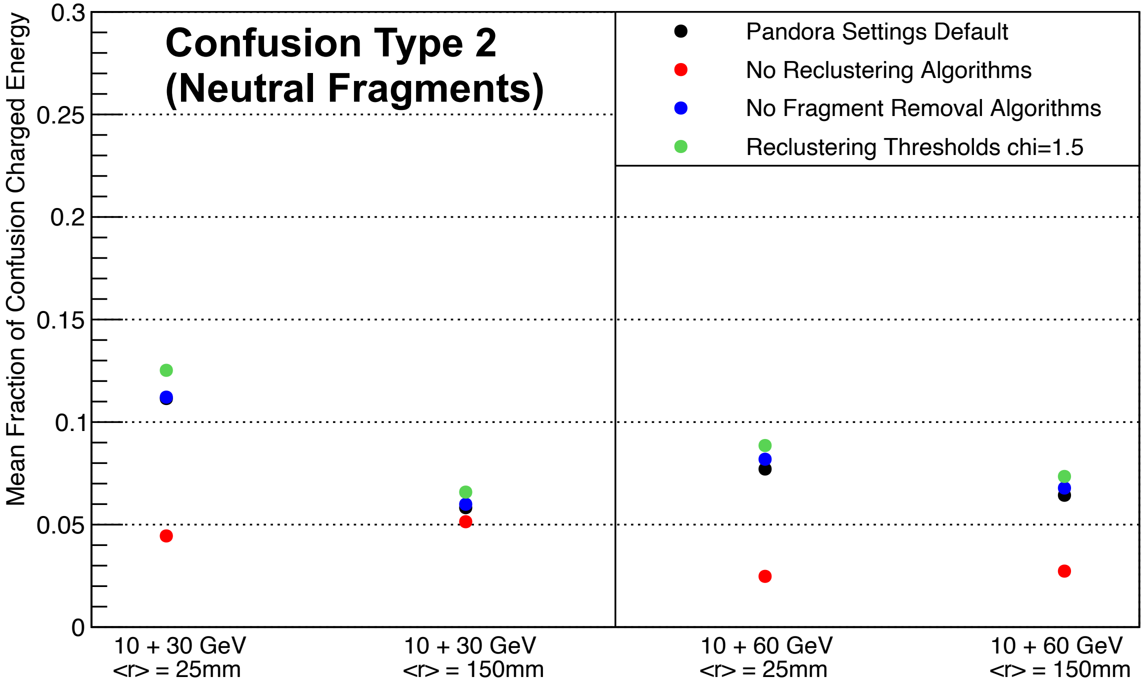
Different Pandora PFA Settings

Normalised to Mean Full Event Energy

Mean Fraction of Confusion Neutral Energy vs. AHCAL Data Scenario



Mean Fraction of Confusion Charged Energy vs. AHCAL Data Scenario

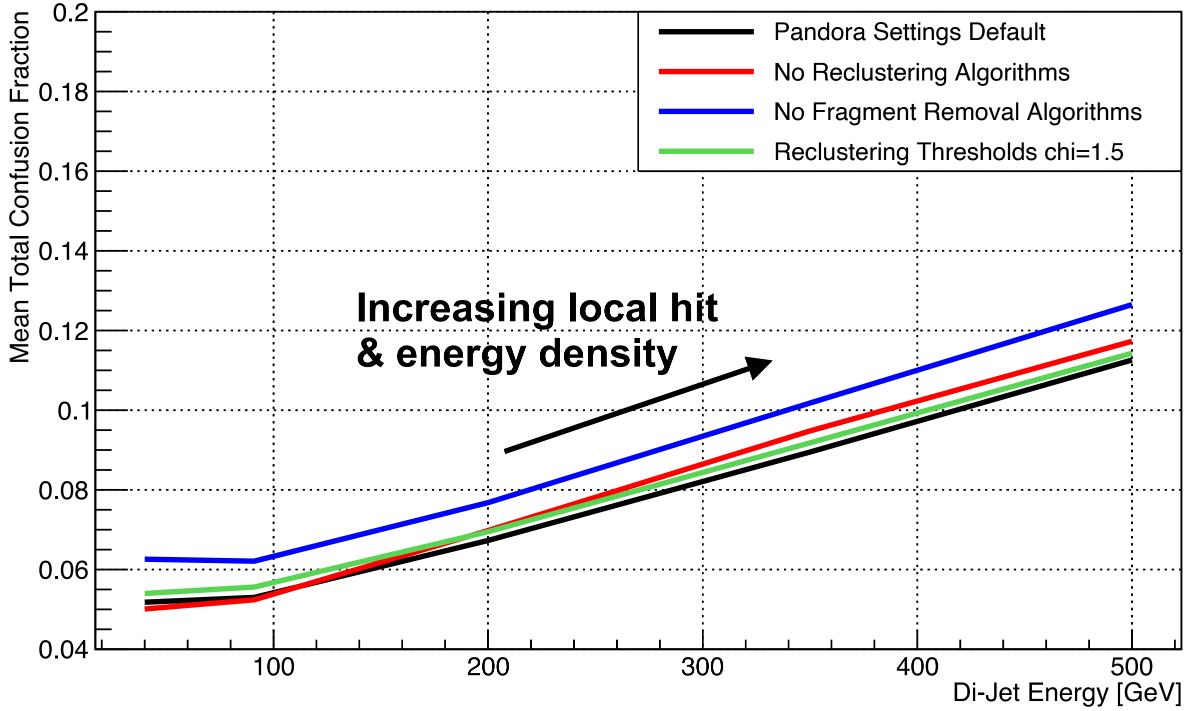


- With larger shower distance both types of confusion are decreasing
- As for ILD jets: No reclustering setting increases confusion type 1 and decreases confusion type 2
  - ➡ No fragment removal & chi = 1.5 setting show trend in the opposite direction

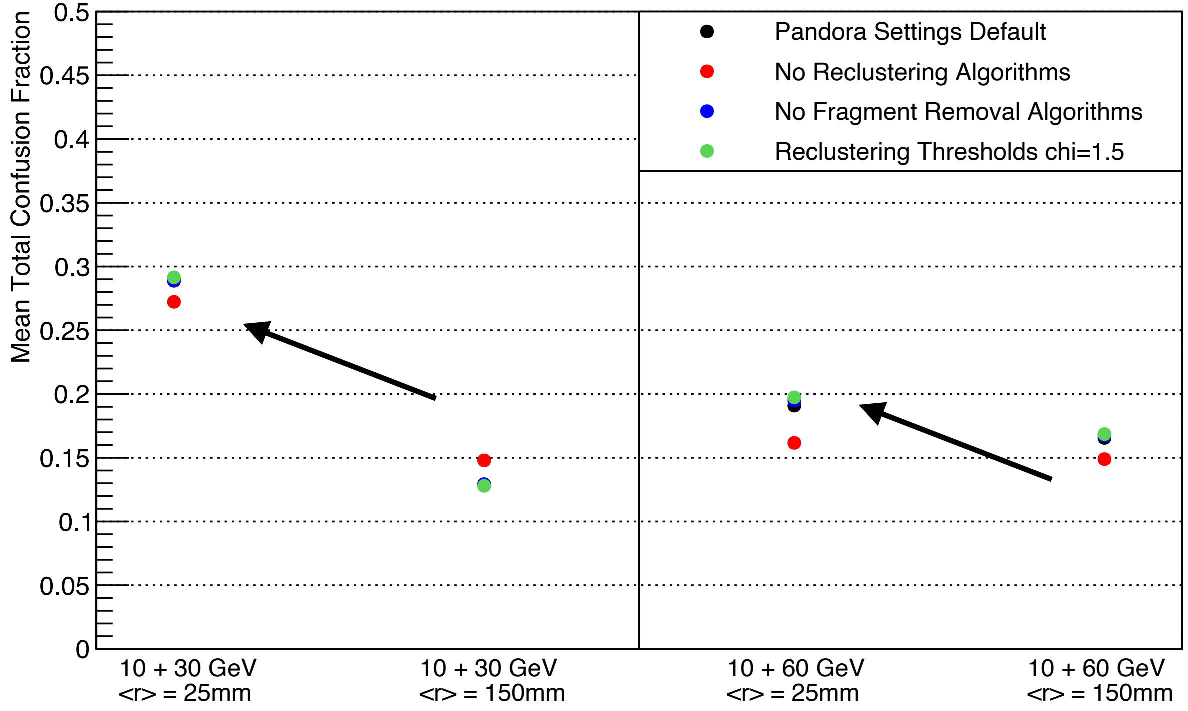
How is the Total Fraction of Confused Energy Scaling?

Different PandoraPFA Settings - ILD Di-Jets vs. AHCAL 2018 Data

Mean Total Confusion Fraction vs. Di-Jet Energy



Mean Total Confusion Fraction vs. AHCAL Data Scenario



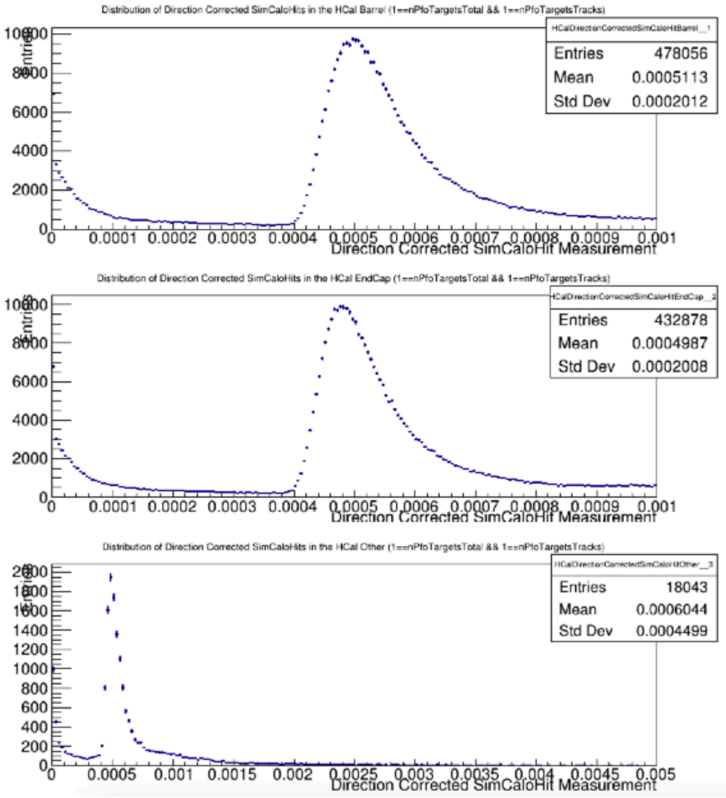
- Mean fraction of confused event energy is increasing with jet energy (local hit & energy density)
- Most fractional confusion energy for no fragment removal & no reclustering, best for default settings
  - ➡ Combination of good balance and low fractional confusion energy: Best JER for default settings

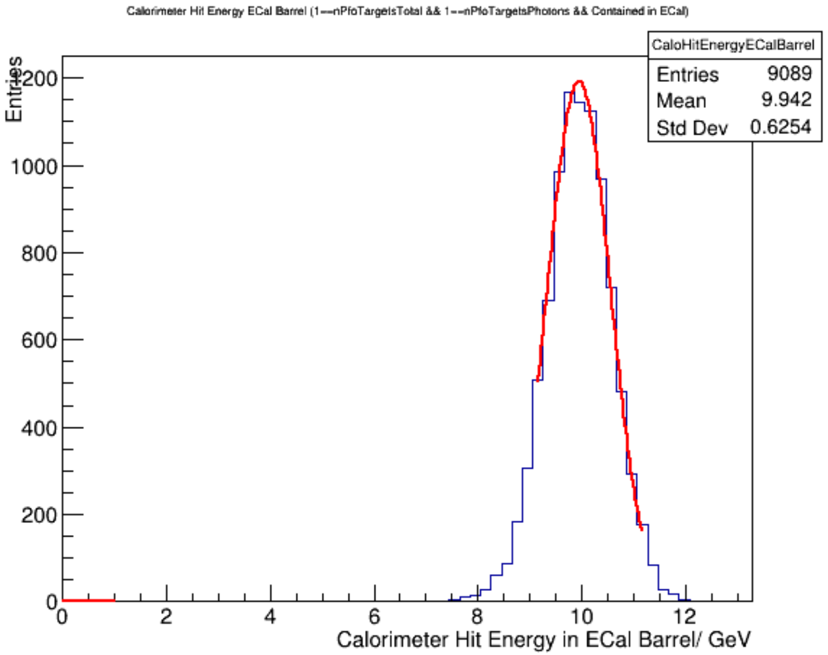
ILD Di-Jets

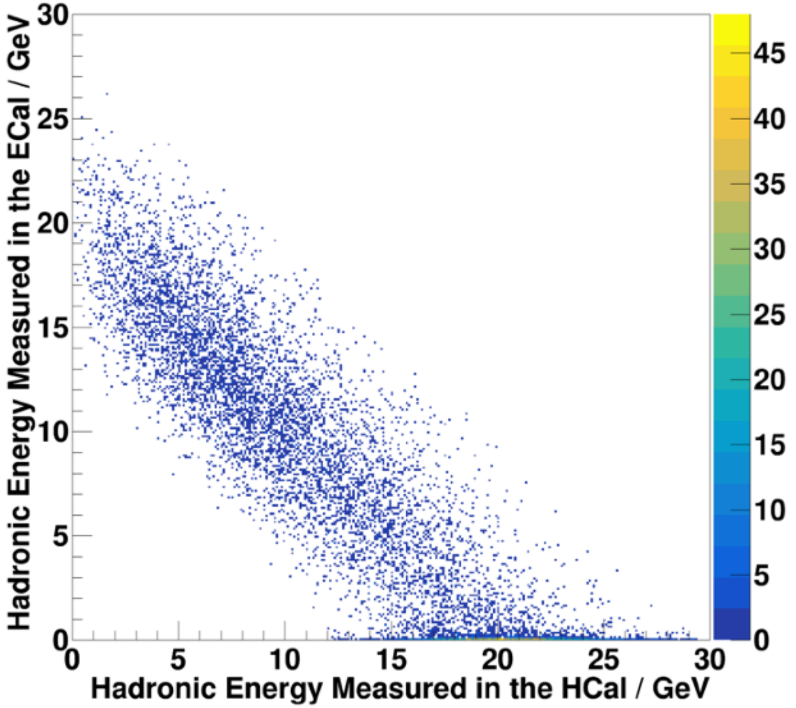
Recalibration PandoraPFA

https://github.com/iLCSoft/LCCalibration/tree/master/doc

- For each threshold scenario (1, 2, 3 MIP) **6 internal PandoraPFA calibration constants recalibrated** with 10 GeV muons/photons and 20 GeV K0L according to ILD calibration instructions
    - ➡ (Less) hits feature more energy after recalibration to allow fair track - cluster matching for charged hadrons
    - ➡ After initial problems successfully done!

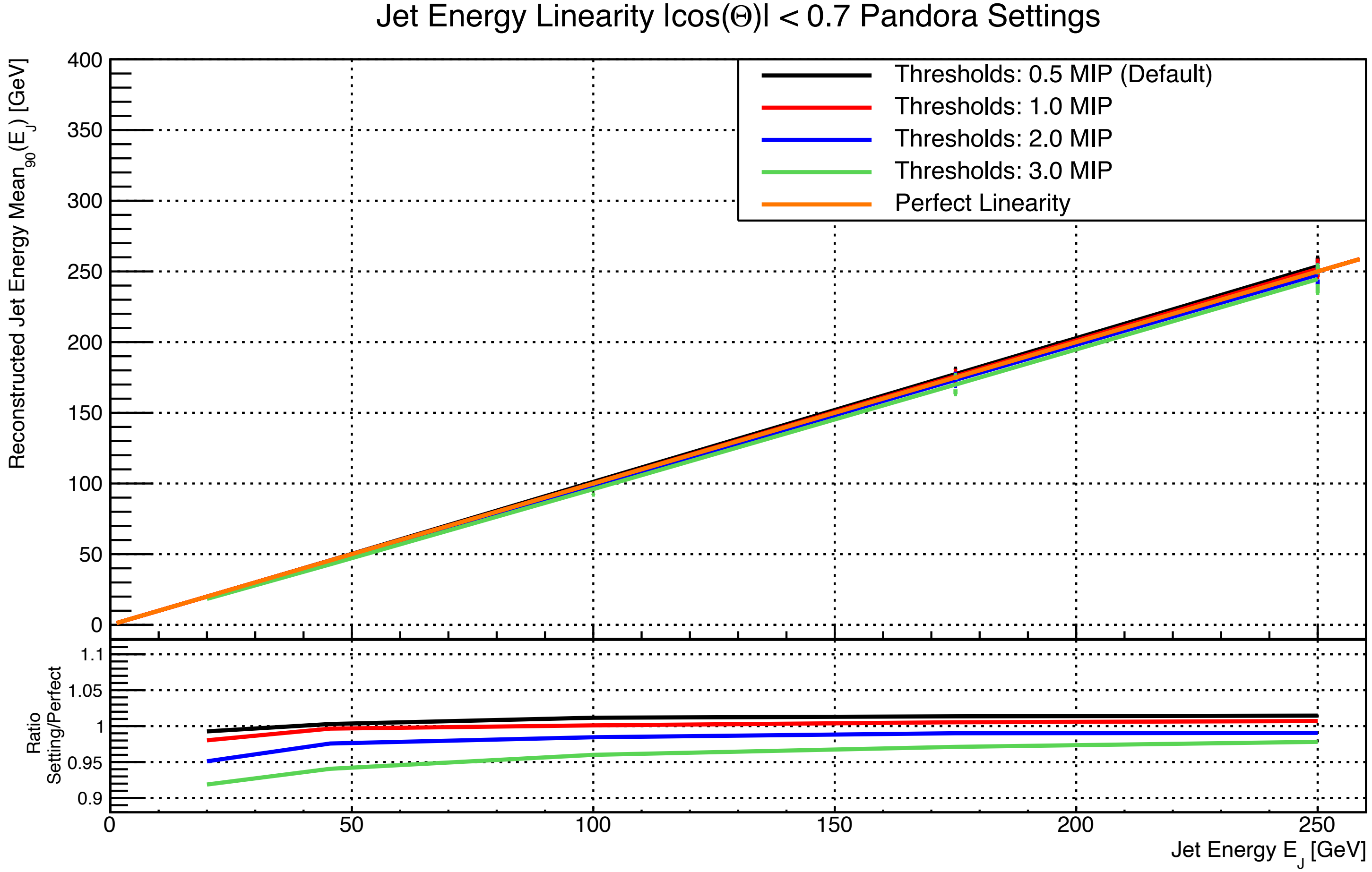






Jet Energy Linearity & Resolution

Different Energy Thresholds for ILD Di-Jets



- After recalibration: For almost all jet energies within 5% to perfect linearity despite confusion in PFA reco.

AHCAL Events

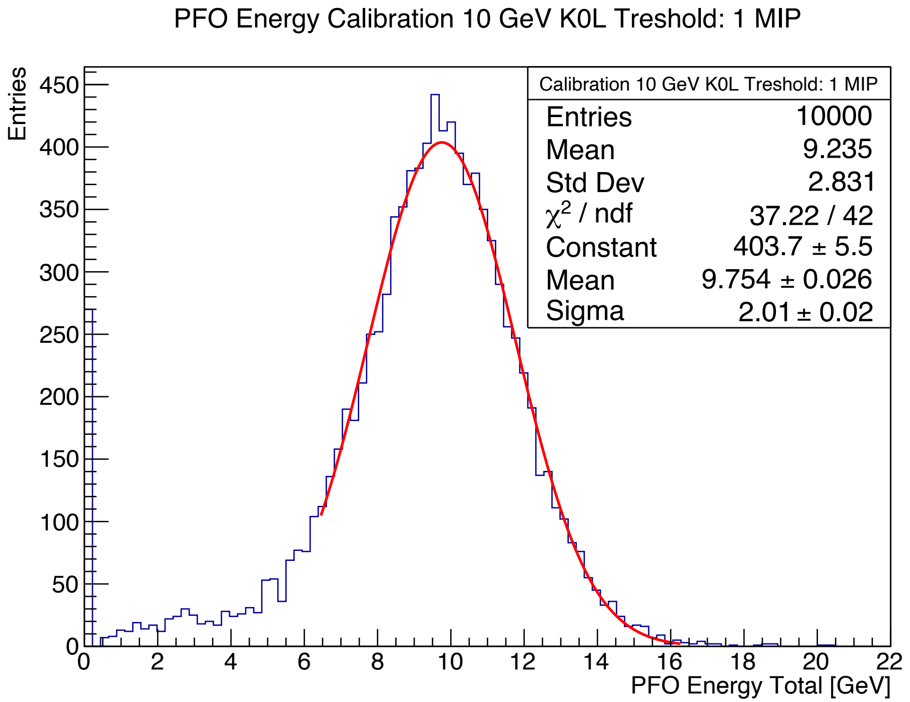
Recalibration PandoraPFA

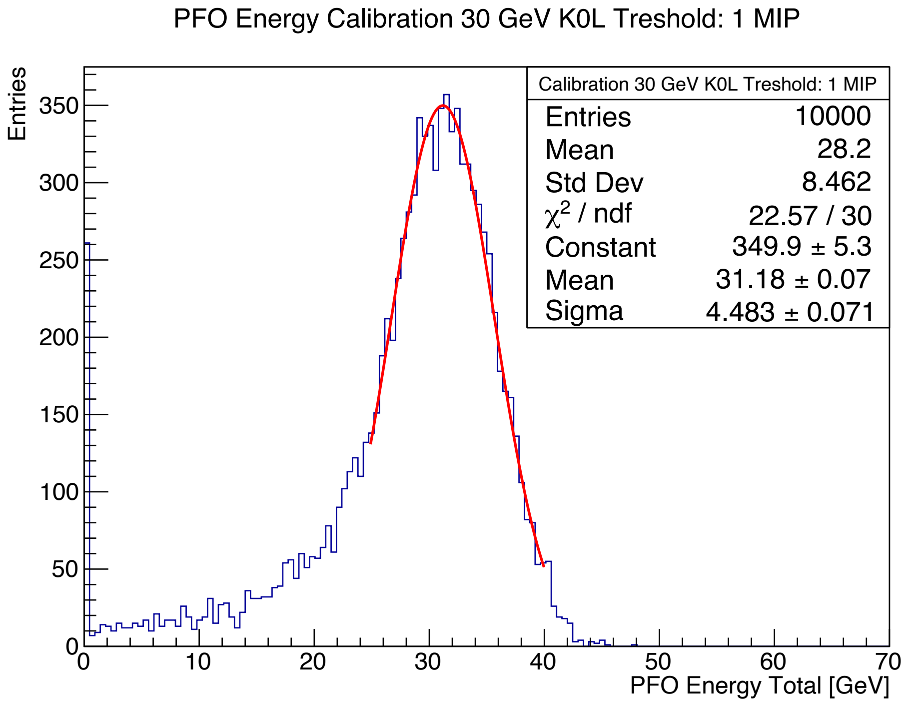
- For each threshold scenario (1, 2, 3 MIP) **1 internal PandoraPFA calibration constant** recalibrated with 10 & 30 GeV K0L for optimised PandoraPFA output

  ➡ Different energy thresholds for different shower energies introduces non-linearity in energy reconstruction

    ➡ Optimised to recover 10 & 30 GeV neutral hadrons simultaneously as accurate as possible (within 5%)

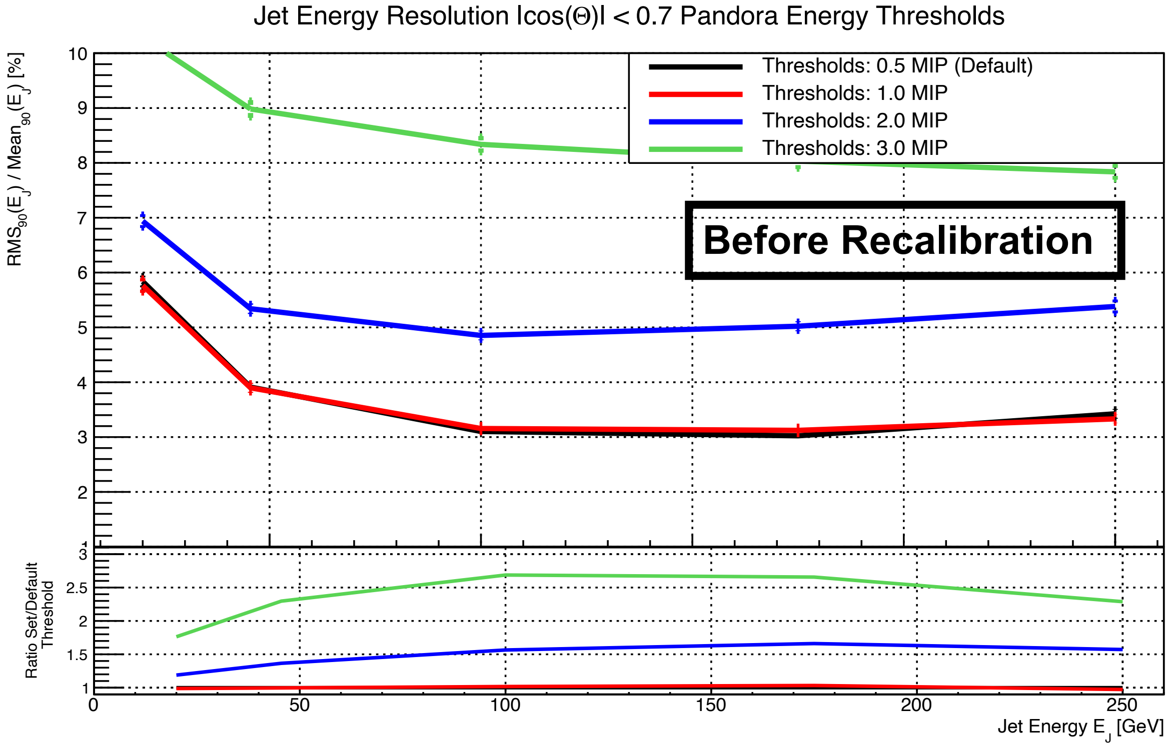
  ➡ Quite easy procedure due to less complexity compared to ILD - successfully done!

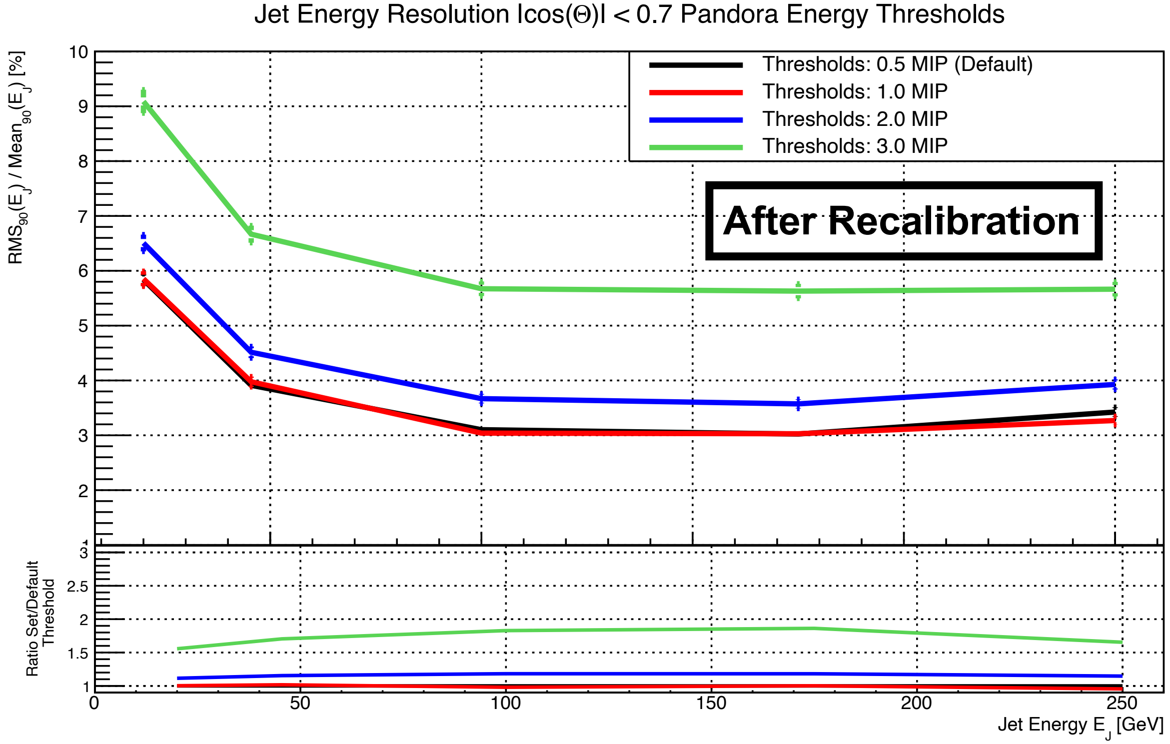




Jet Energy Resolution

Before and After Recalibration

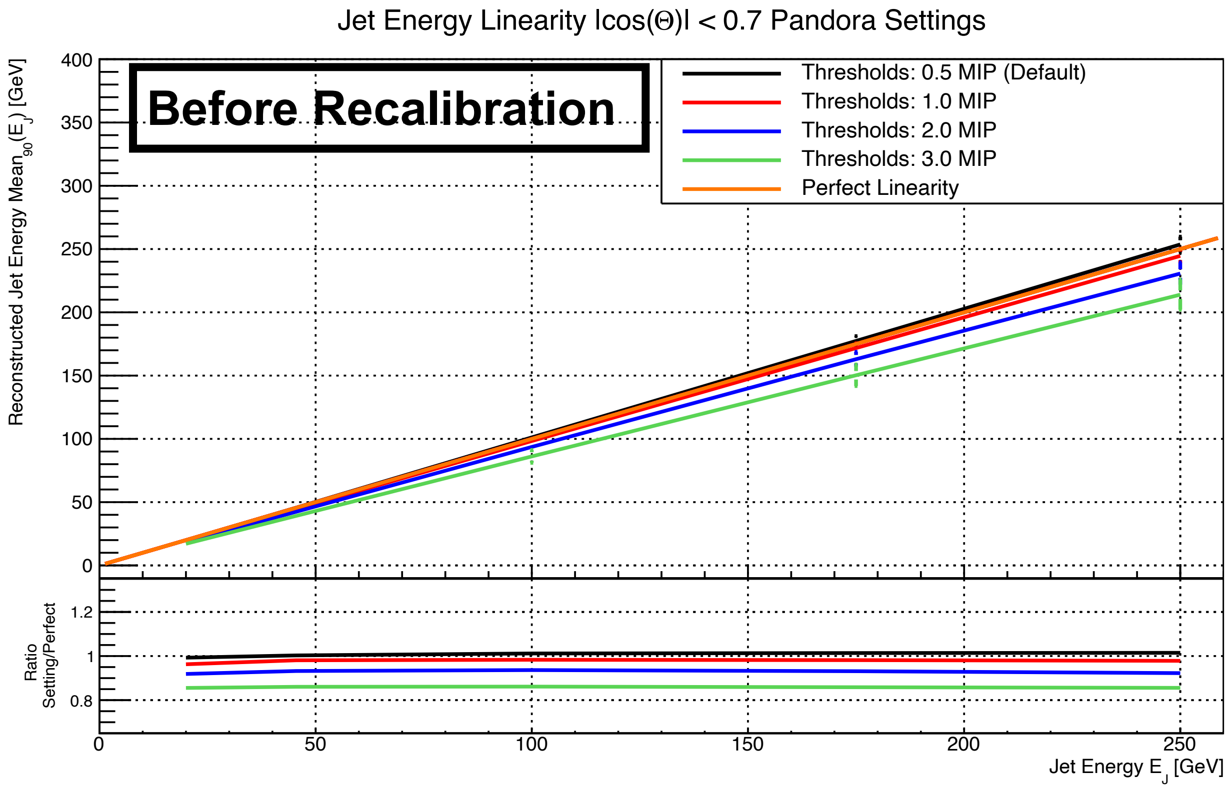


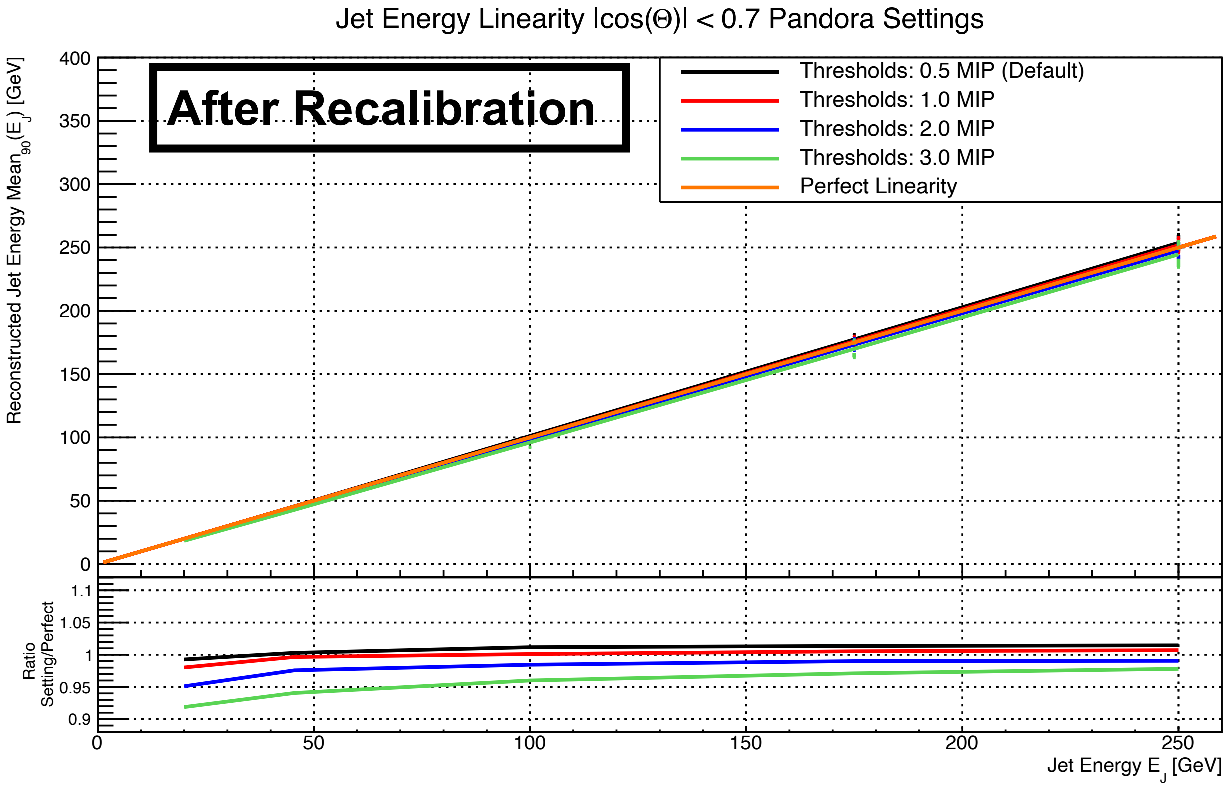


- Recalibration: Significant improvement in jet energy resolution, specifically for higher thresholds
  - ➡ Degradation of JER trend for highest energy threshold remain, but „only“ up to ~80% (before: ~160%)
  - ➡ For slightly increased thresholds 1 MIP - basically no effect, for 2 MIP only 20% worse JER
  - ➡ Expected worse performance: Pandora internal „emergency" algorithms seem to work properly

Jet Energy Linearity

Different Energy Thresholds (ECAL & HCAL)



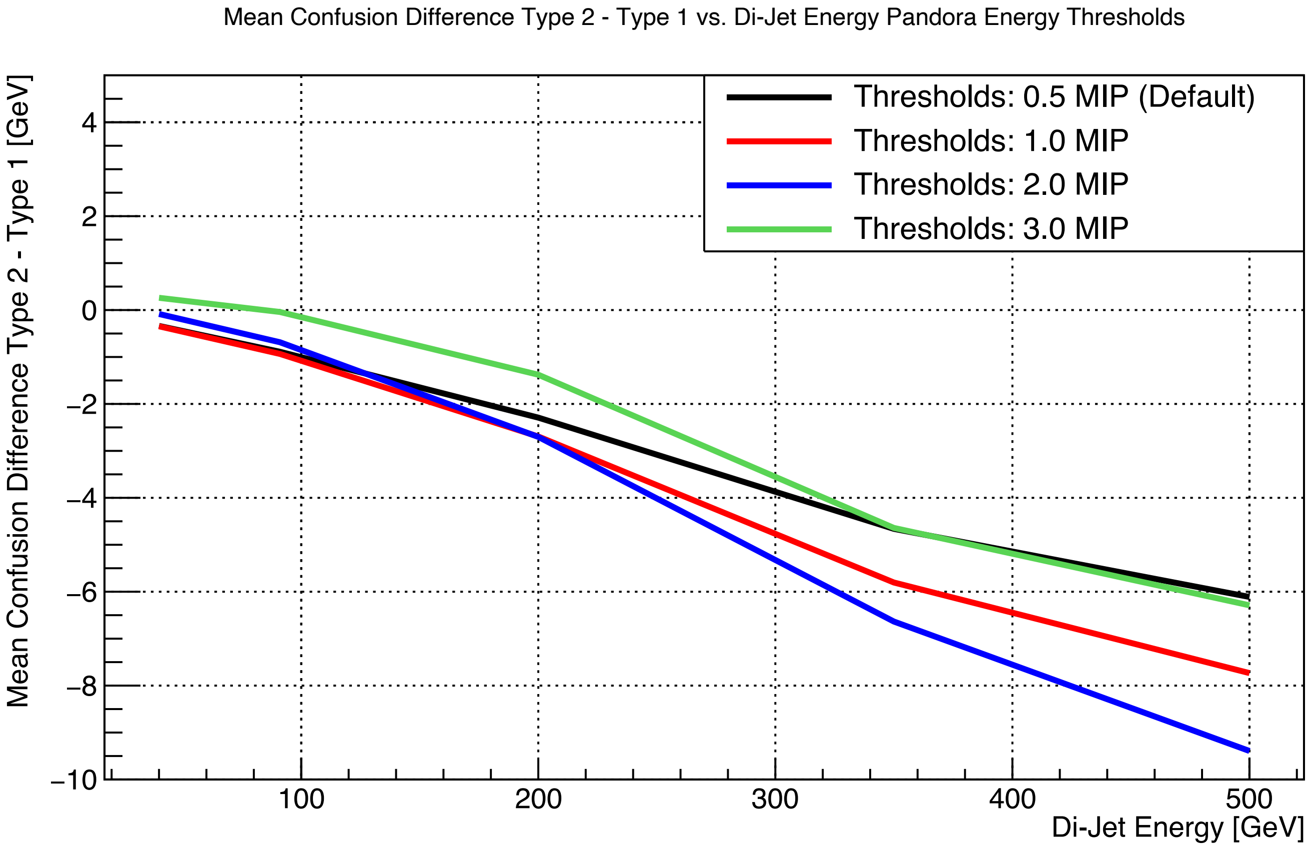


- Recalibration: Significant improvement in jet energy linearity, specifically for highest thresholds
  - ➡ For almost all jet energies within 5% to perfect linearity
  - ➡ Still slightly off due to difficult PFA reconstruction with increasing confusion term

Mean Confusion Type Difference

Different PandoraPFA Energy Thresholds

Normalised to Mean Full Event Energy



Comparison: For different Pandora settings observed type difference of up to 30 GeV

Confusion type balance changes only slightly with increasing energy thresholds

- ➡ Small trend towards confusion type 1 (neutral absorption) for 1 & 2 MIP
- ➡ **Balanced better for 3 MIP?**
  - ➡ **Emergency algorithms taking over?**

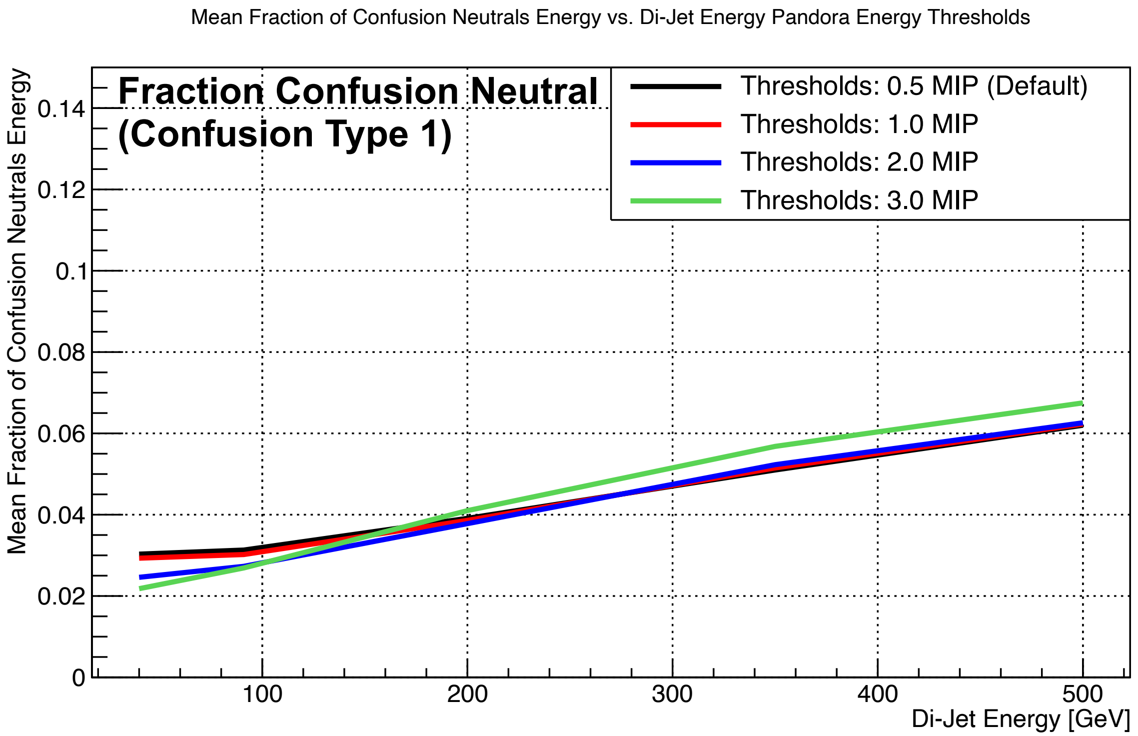
Hypothesis for 3 MIP thresholds: MIP tracks within shower sub-structure are mostly gone:

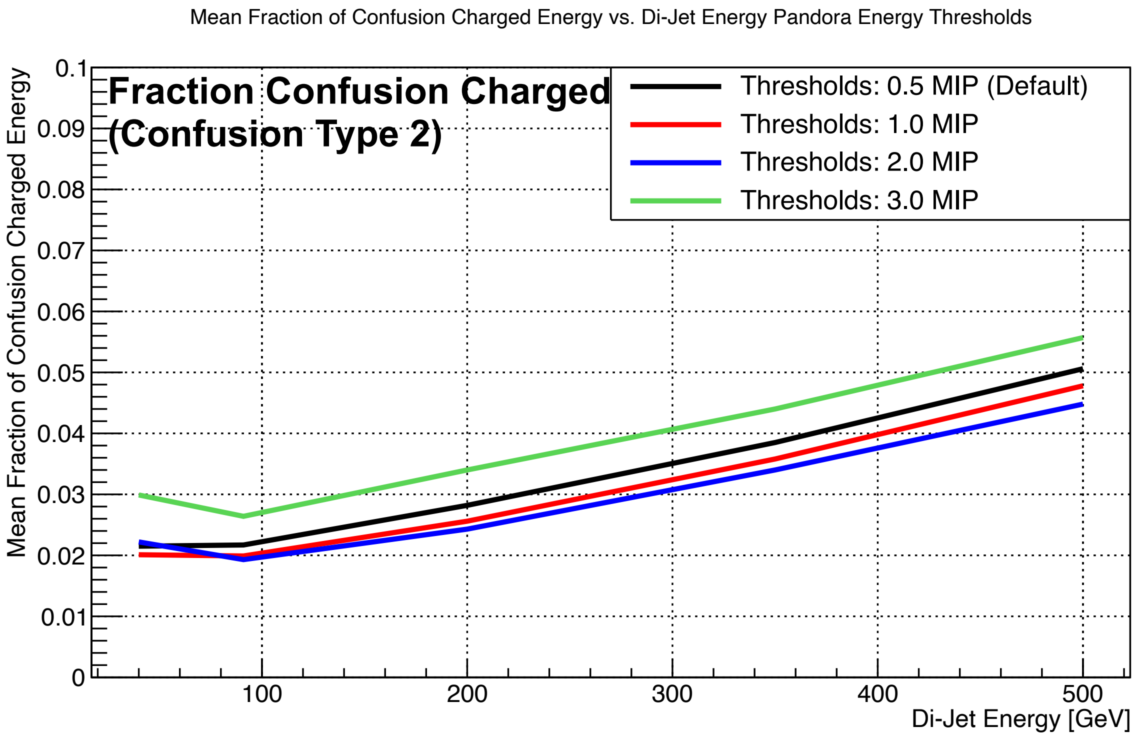
- ➡ Trend towards extra neutral fragments (confusion type 2) is increasing again
- ➡ Artificial topological separation between different particle showers

Mean Fraction Confused Energy Type 1 & 2

Different PandoraPFA Energy Thresholds

Normalised to Mean Full Event Energy



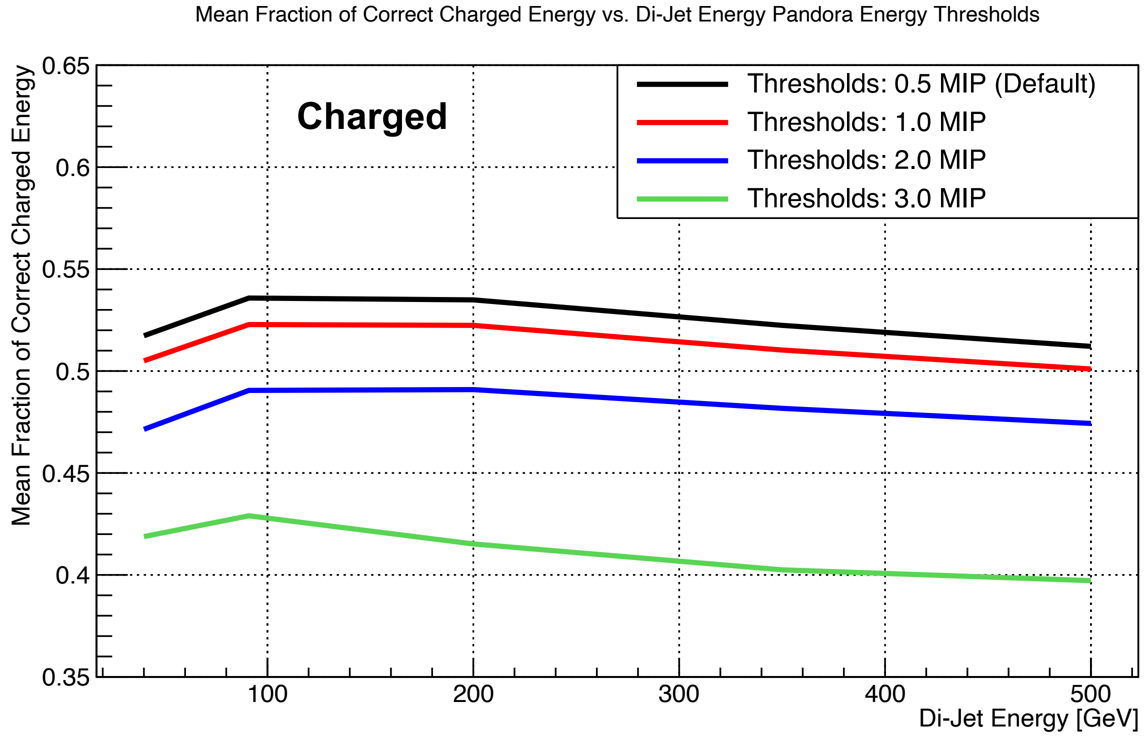


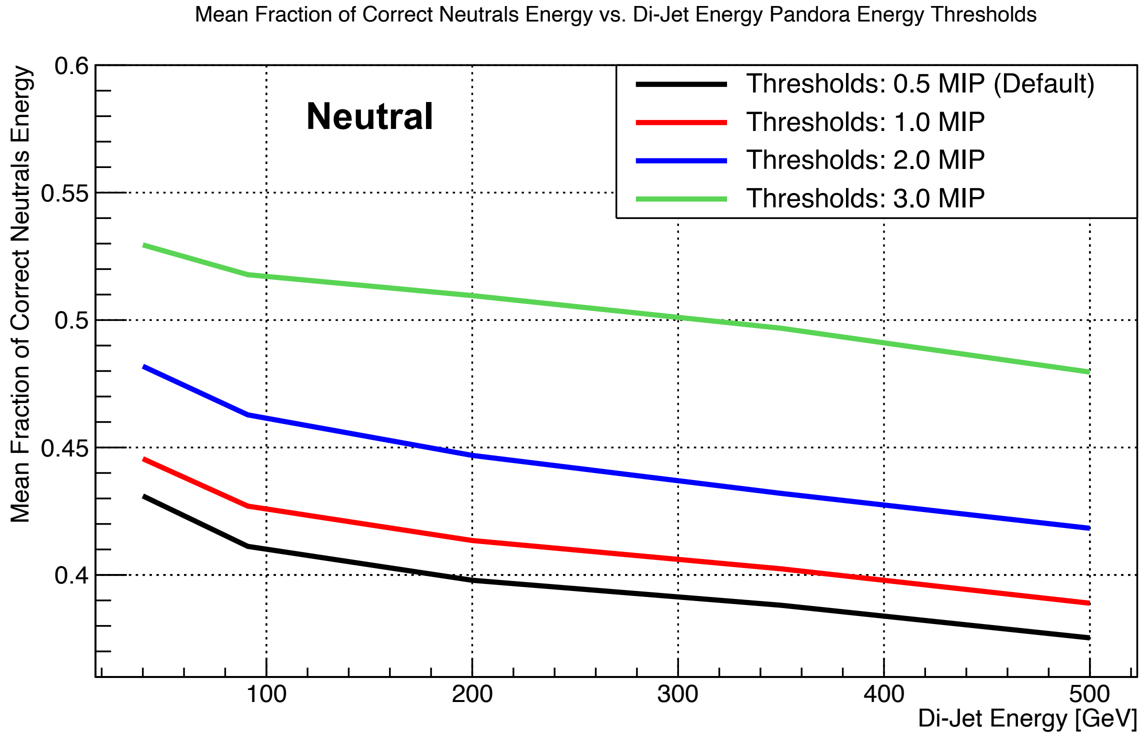
- Agreeing with hypothesis for 3 MIP: Confusion type 2 (extra neutral fragments) is fractionally increasing
  - ➡ 1 & 2 MIP showing less confusion type 2 than default threshold
- Confusion type 1 slightly more dominant only for 3 MIP threshold otherwise rather unaffected except for lowest energy

Mean Fraction Good Energy Charged & Neutral

Different PandoraPFA Energy Thresholds

Normalised to Mean Full Event Energy





- Agreeing with hypothesis for increasing energy thresholds: More separated/isolated neutral fragments within events and overlapping showers

  ➡ For highest threshold best correct neutral energy and worst charged energy reconstruction