PandoraPFA Studies with 2018 Prototype Beam Test Data & ILD Jet Simulations

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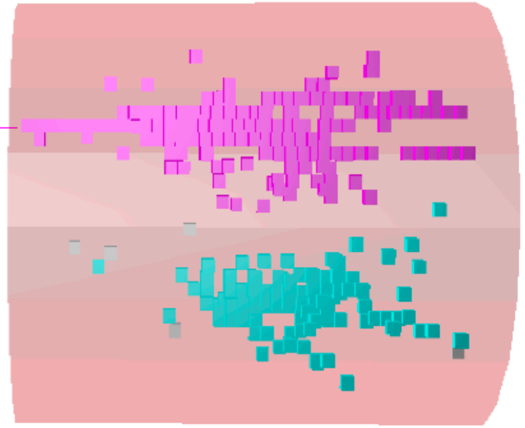
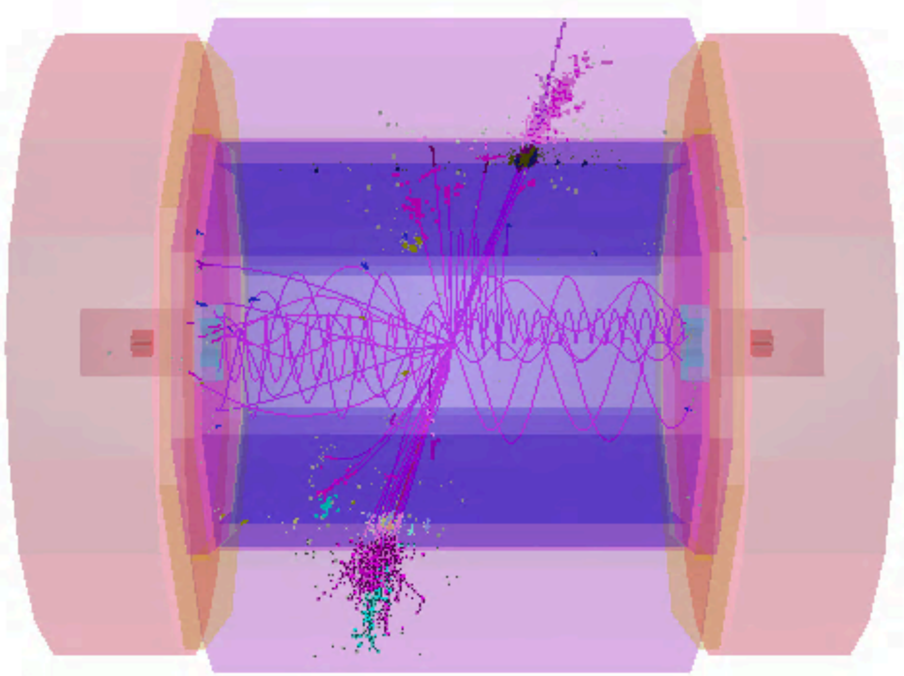
AHCAL Marzipan @ DESY
8th December 2021


AHCAL Beam Test Data


ILD Di-Jet Simulation

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Outline

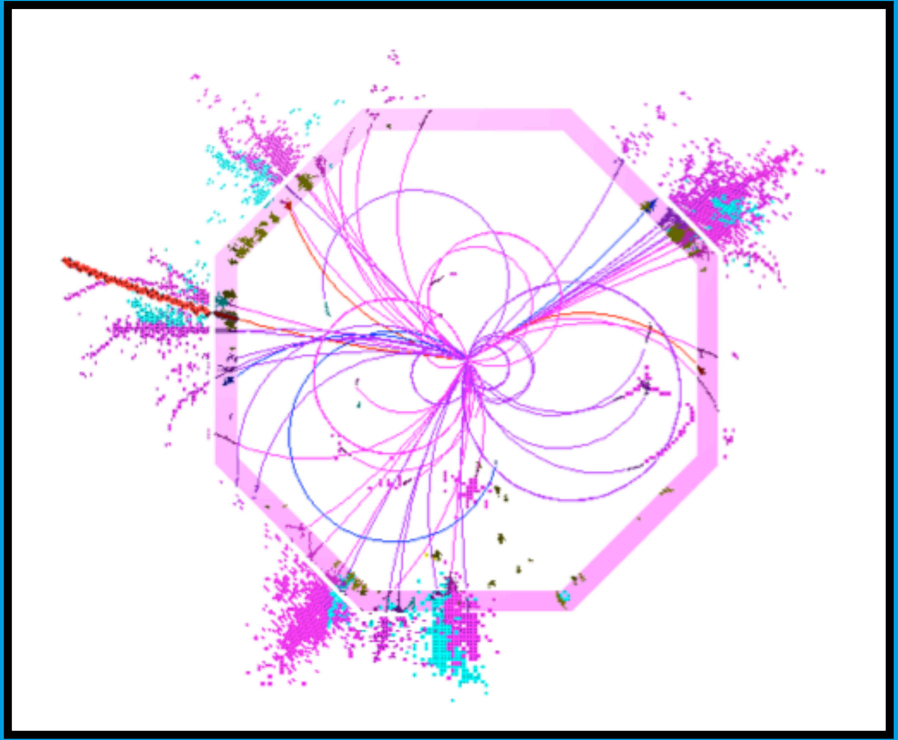
For this Talk

- Brief Reminder: Concept of Particle Flow and Confusion Types

- Two Particle Separation Studies
- Performance Studies with Different Particle Flow
  - ➡ Algorithm Settings
  - ➡ Energy Thresholds

- Summary & Conclusions

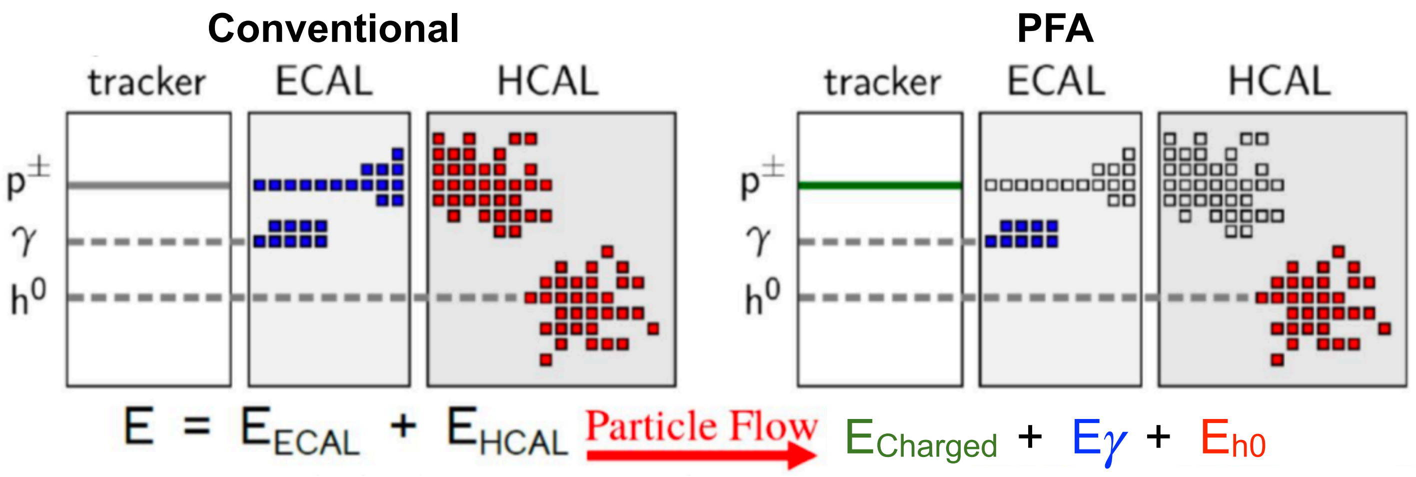
The Particle Flow Approach

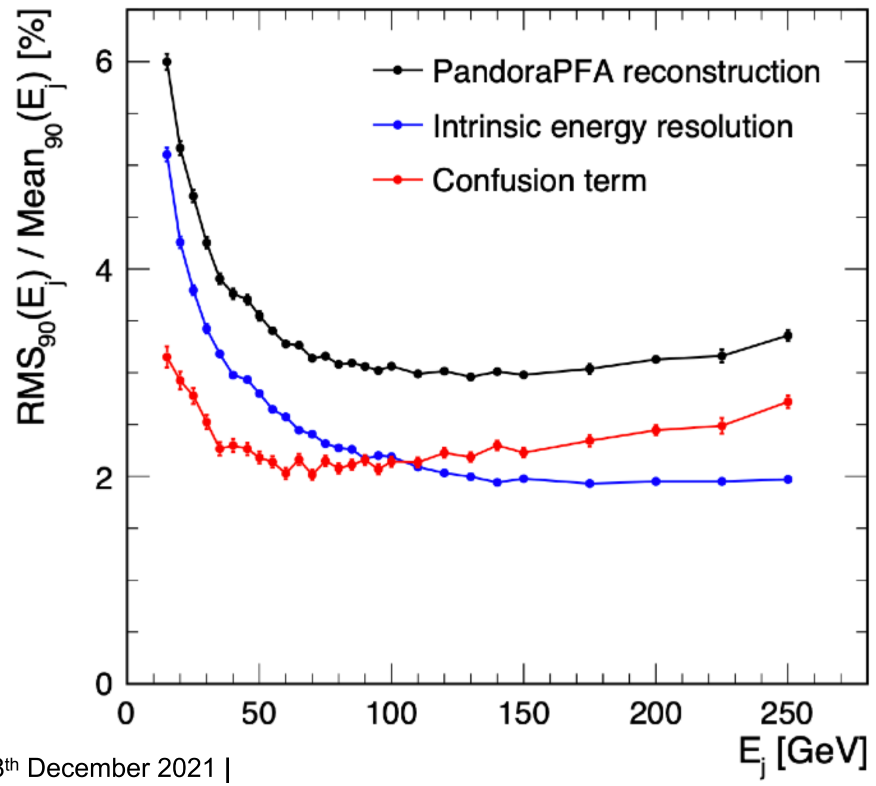


Particle Flow Approach

Key to Highest Precision

- Baseline goal: **Jet energy resolution** of **3-4%** for jet energies of **40-500 GeV**
  - Conventional calorimetry limited by intrinsic energy resolution of HCAL (~60%/√E)
  - ➡ 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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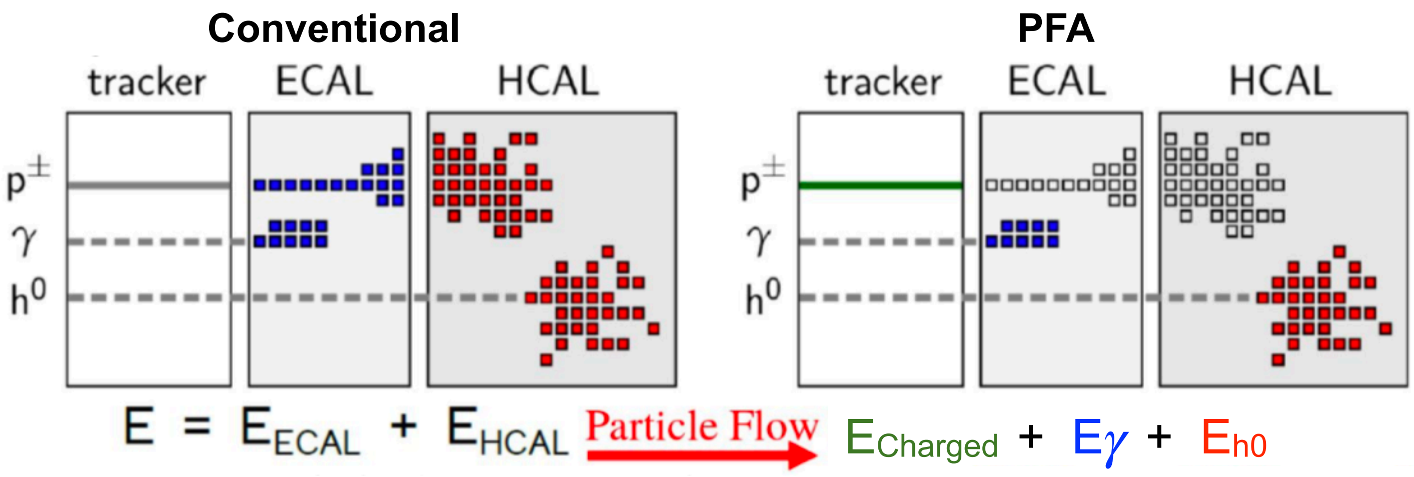

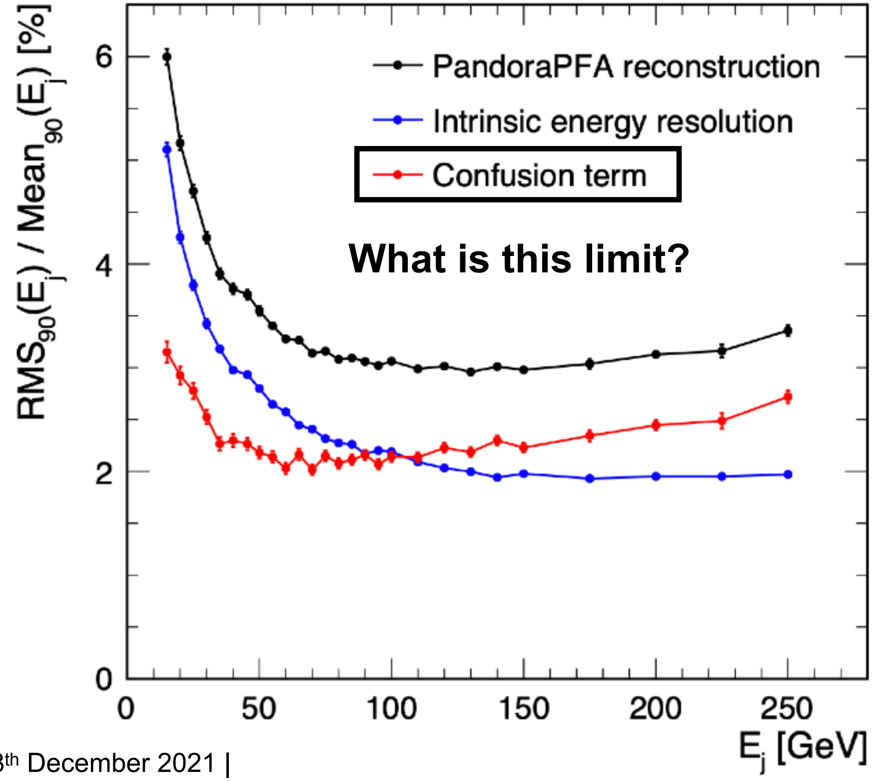

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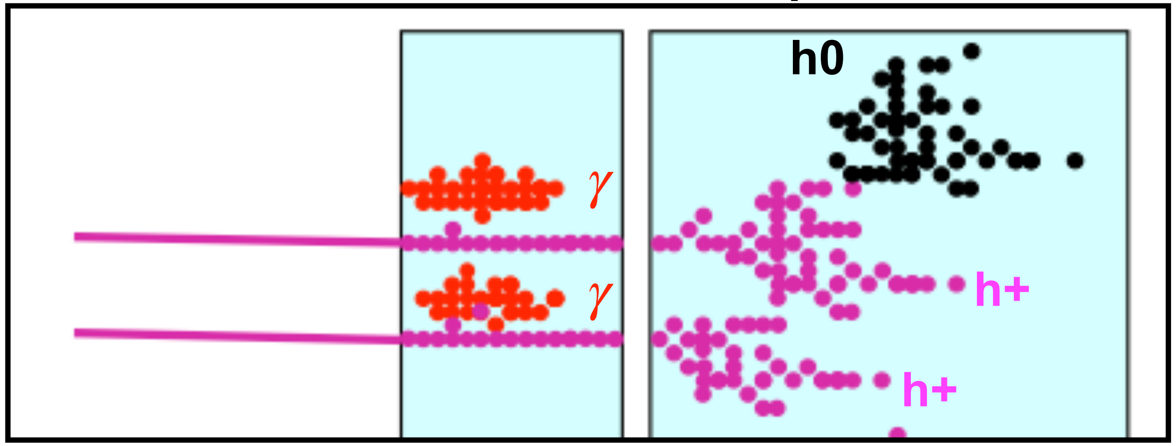
Confusion Types

Limits of Particle Flow Reconstruction

Well Reconstructed Example Event



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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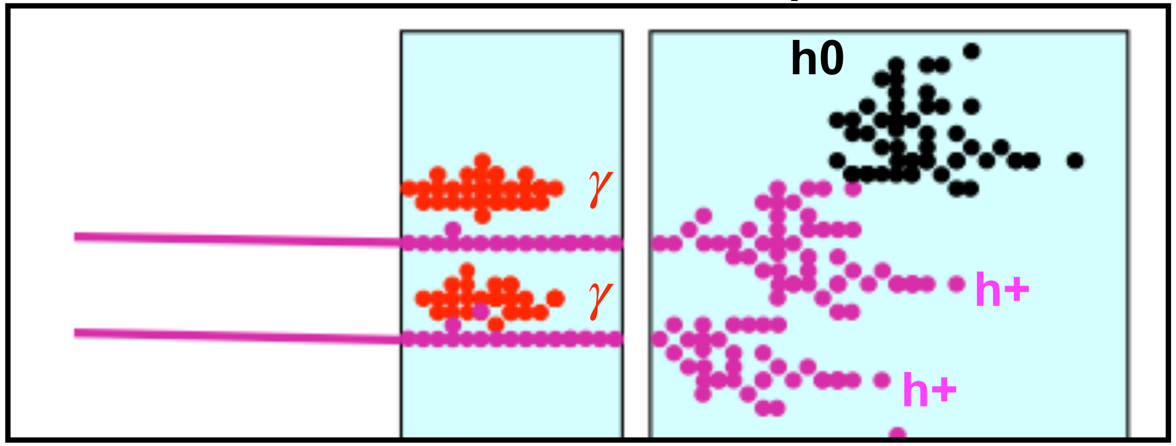

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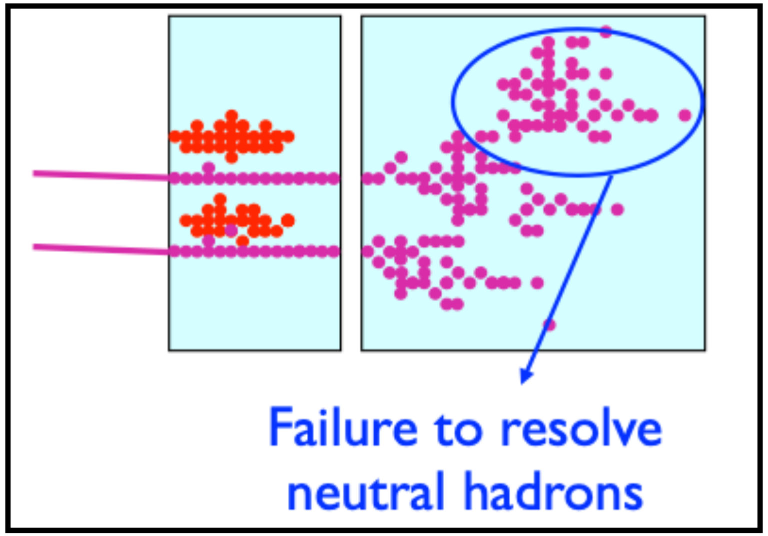
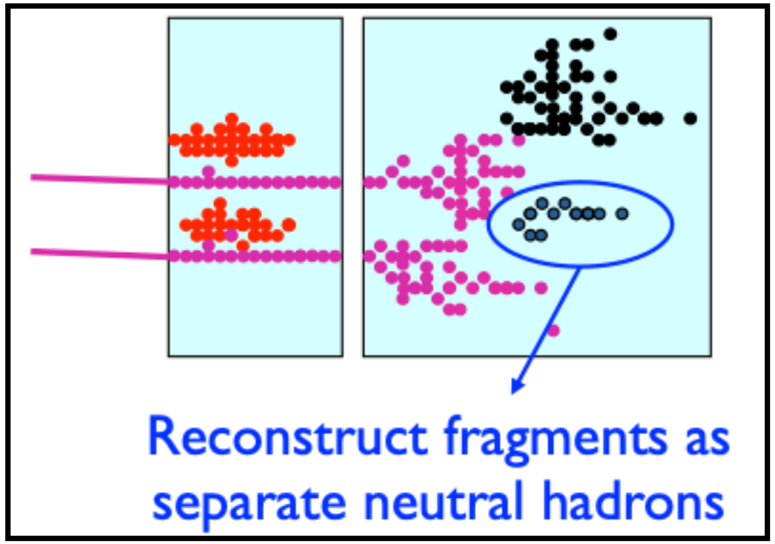
- Topologically/energetically confusing events potentially cause problems for PFA reconstruction:
  - ➡ **Two types of confusion**
  - ➡ Level and balance of this "mistakes" **limiting jet energy resolution at high energies**

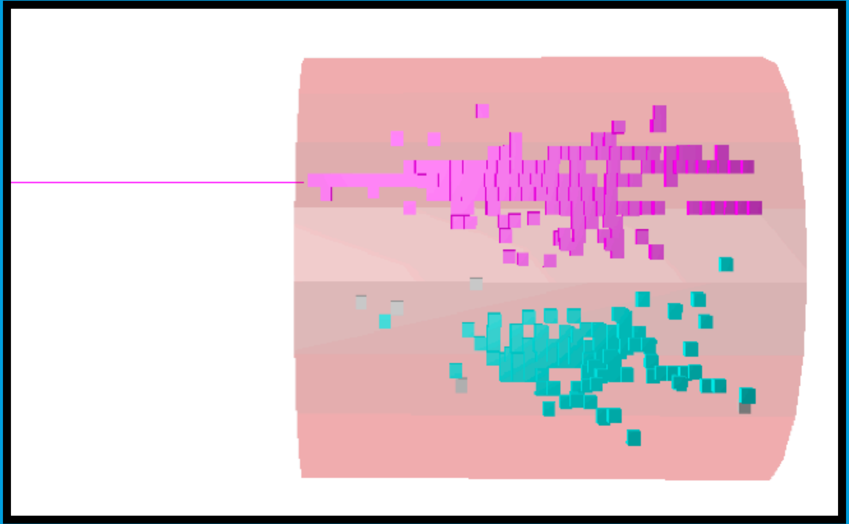


Loss of neutral energy



Double counting of charged energy

PandoraPFA Applied on AHCAL 2018 Beam Test Data & MC



Magenta: Charged Hadron Hits
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Motivation and Goals of Studies I

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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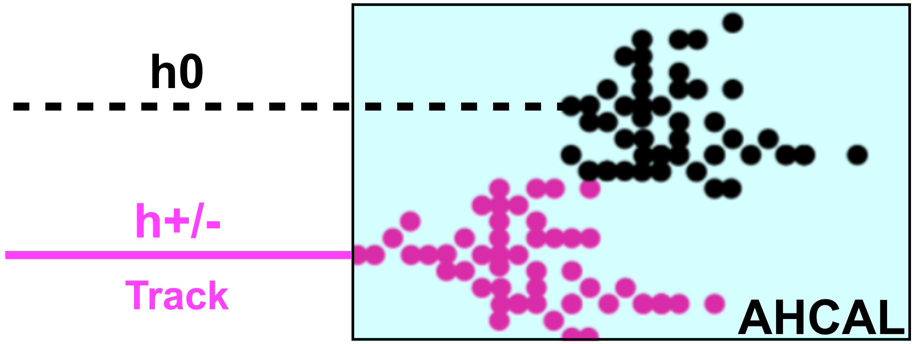
Baseline Scenario: Charged + Neutral Hadron Event



Questions to be Answered:

- How well can PandoraPFA separate and resolve the neutral and the charged hadron?
- How is confusion level scaling with energy & distance?
- How balanced are energy losses & double counting?
- Simulation agreeing well with beam test data?

Motivation and Goals of Studies II

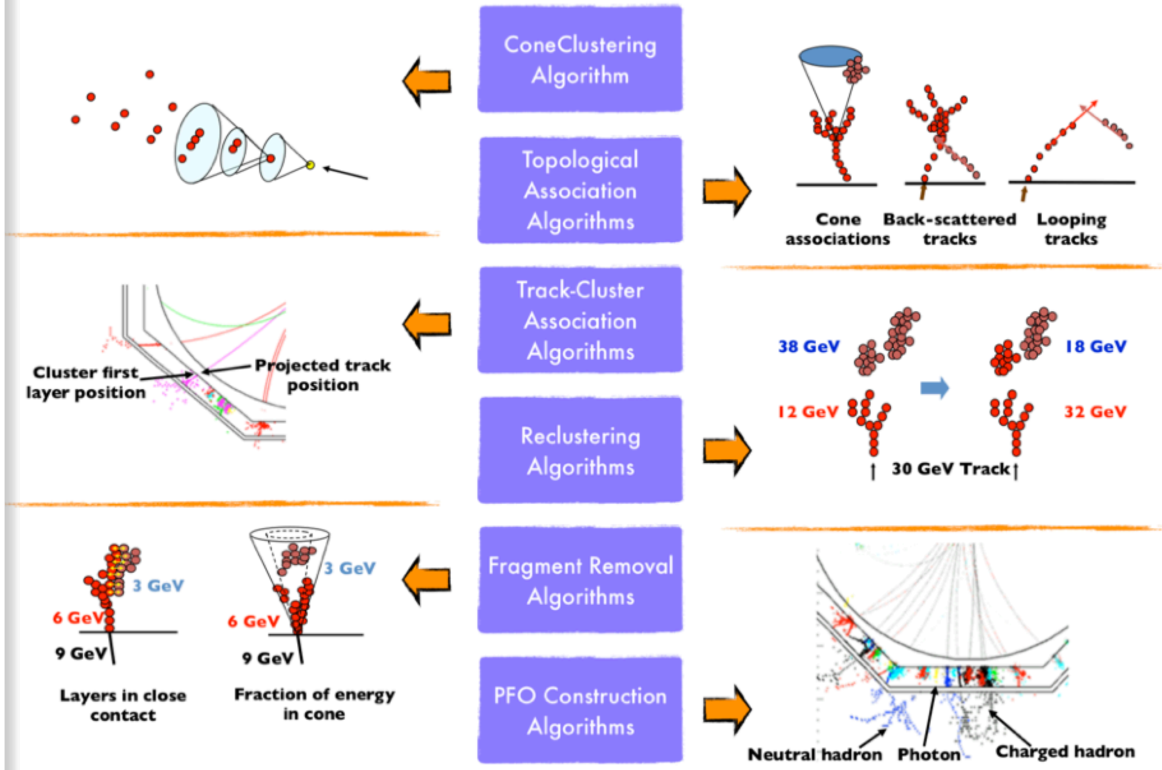
PandoraPFA on AHCAL 2018 Prototype Data

First comparable studies: Former AHCAL prototype (https://arxiv.org/abs/1105.3417) and SDHCAL with ArborPFA (http://cds.cern.ch/record/2669487/files/fulltext.pdf)

Why do it again on AHCAL 2018 prototype data?

- **Significant developments in PandoraPFA**
  - ➡ Modular drivers and applications (standalone AHCAL instead of projection of data to ILD)
  - ➡ Interface for changes/adaptions/plugins, 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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Still state of the art for PFA!

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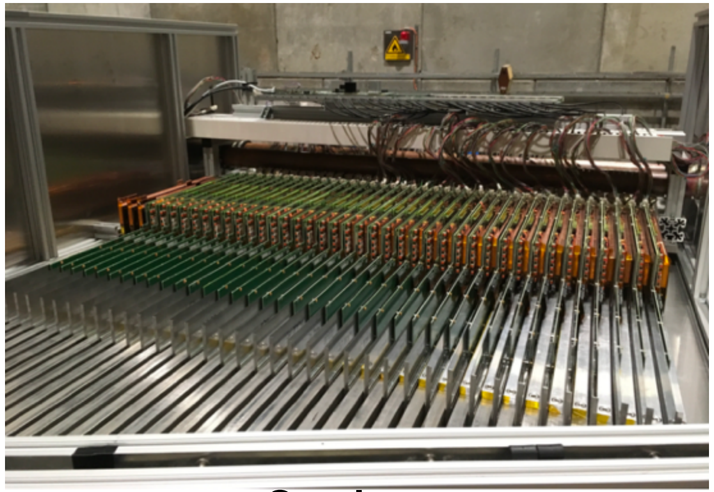
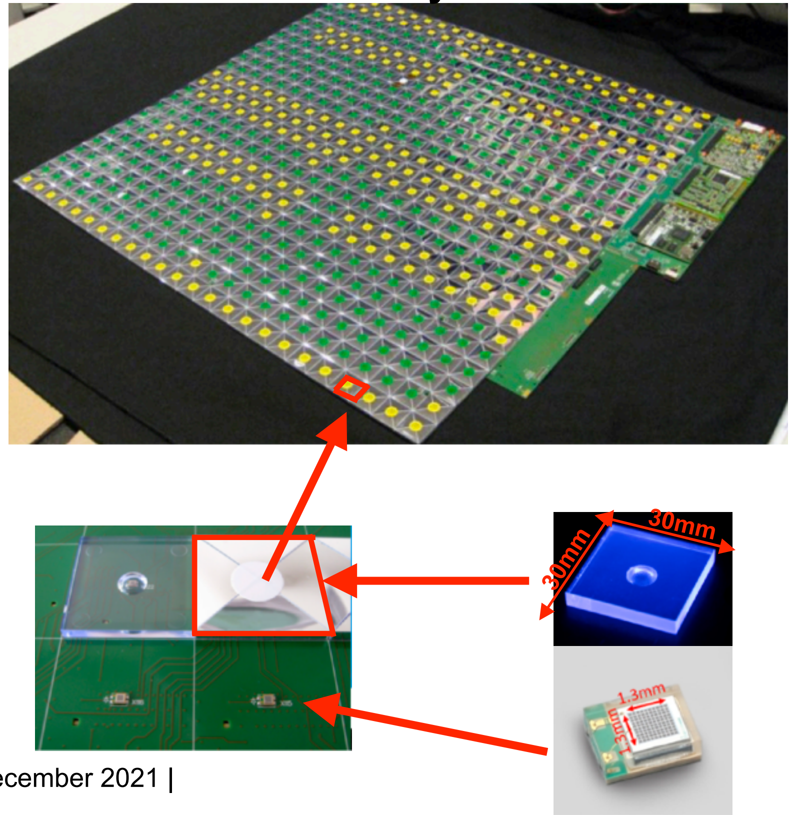
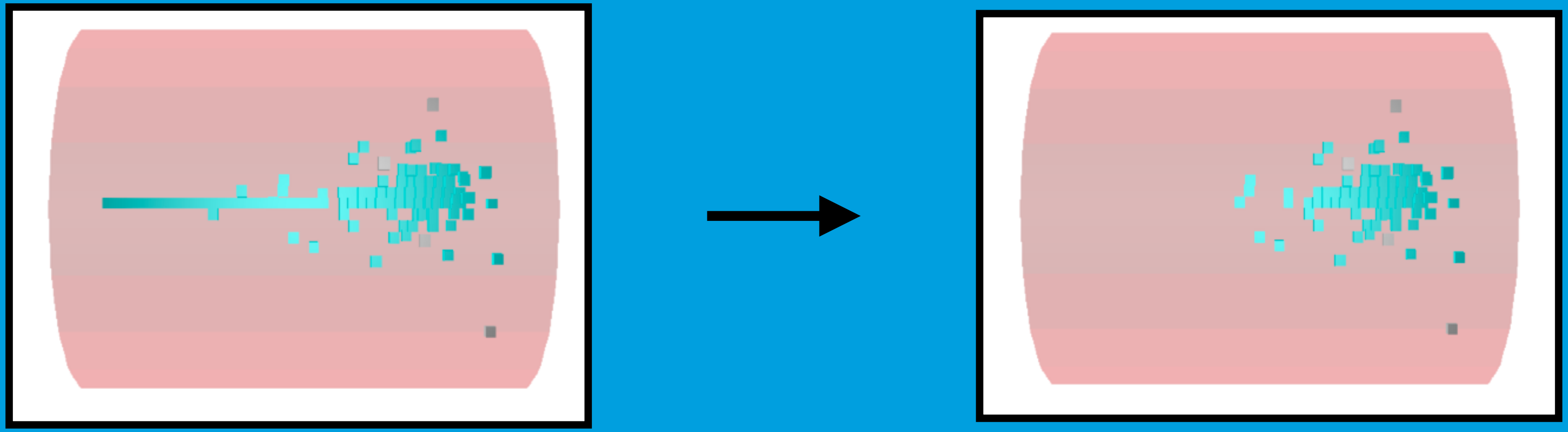
AHCAL 2018 Prototype: 38 layers within steel stack



One layer



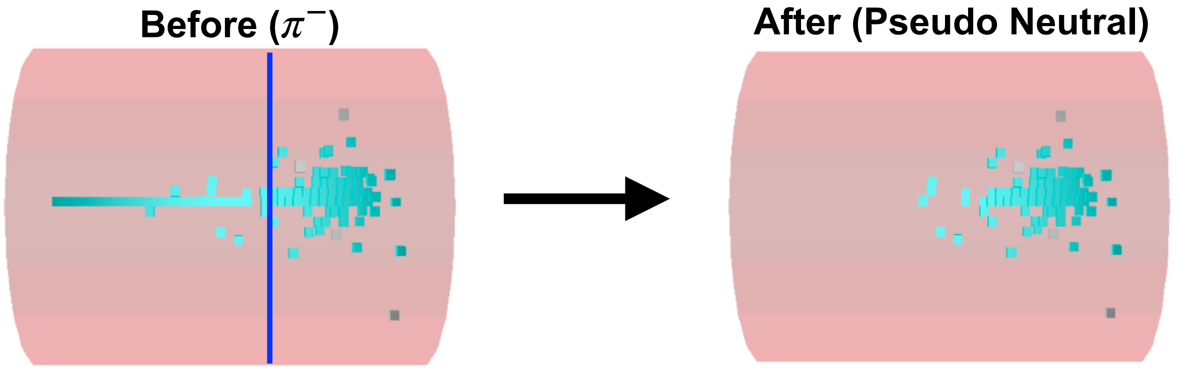
Intermezzo: Generation of Pseudo Neutral Hadrons & Event Overlay



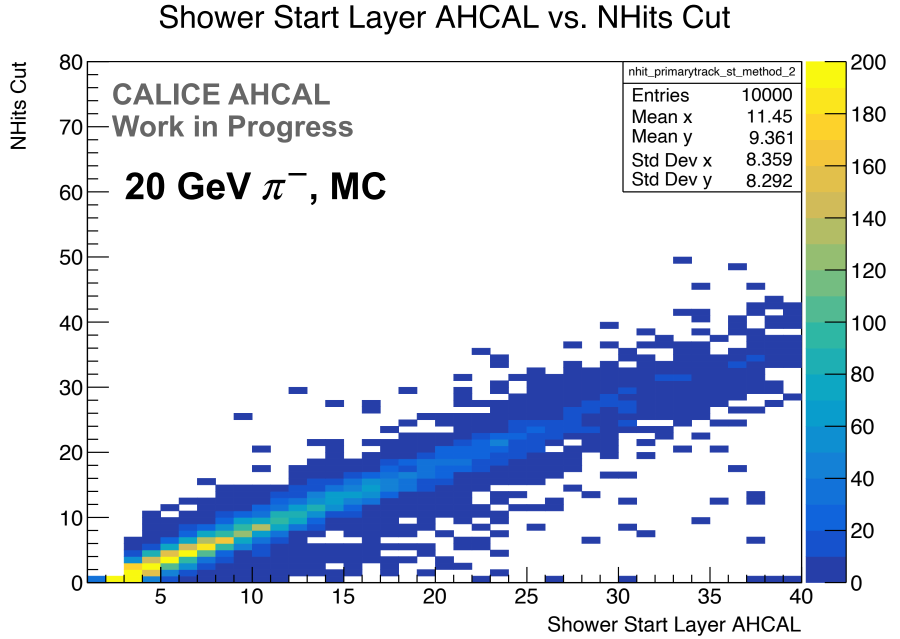
Finding and Removing Primary Ionising Track

Generation of Pseudo Neutral Hadrons

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



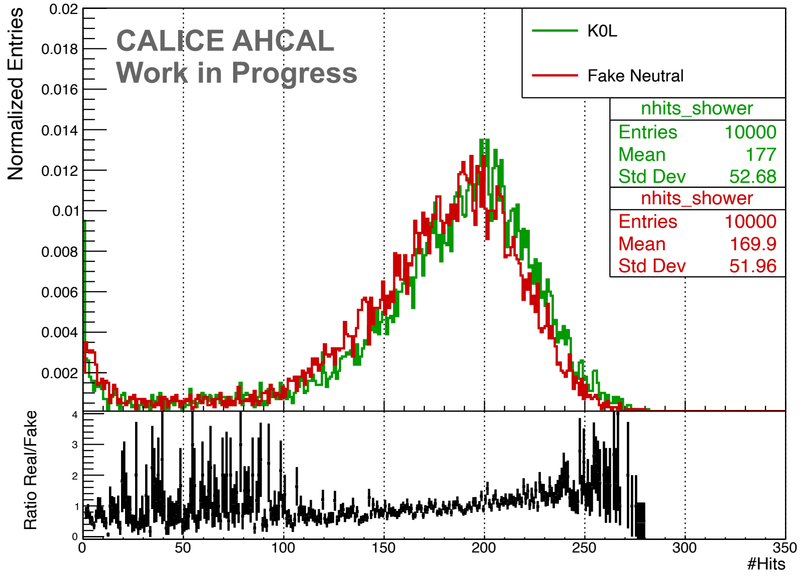
- Method robust and working well:
  - ➡ # cut hits (primary track) well correlated with shower start layer



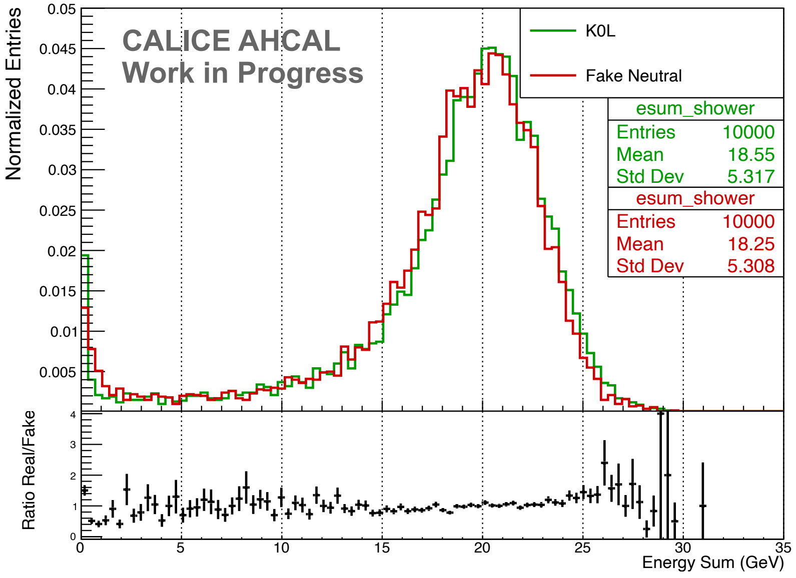
Validation of Pseudo Neutral Hadrons

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

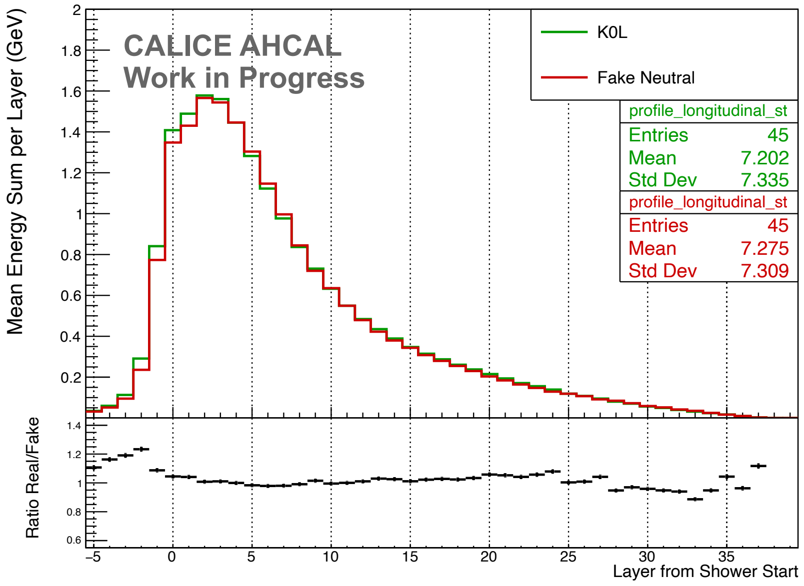
Number of Hits



Energy Sum



Longitudinal Energy Profile



- In general **good agreement** between real neutrals (K0L) and pseudo neutrals (cut π^-)

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

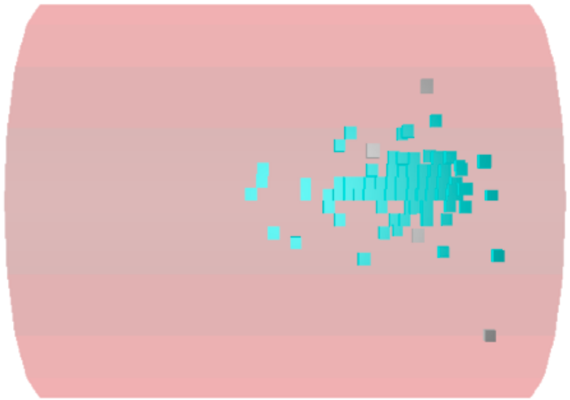
Note: "*Generation of Artificial Neutral Hadron Showers in A Highly Granular Calorimeter using Cycle-Consistent Neutral Networks*" proposed paper by J. Rolph, E. Garutti and G. Kasieczka

Event Overlay

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

- Channel by channel overlay of hit information to create desired two particle events:
  - ➡ Origin flagging of hits: Which hit was neutral/charged/mixed
  - ➡ Energy threshold considerations - Overlaid hits exceeding energy threshold?
  - ➡ Randomised
  - ➡ Control parameters: Energy of charged hadron, radial shower distance

Pseudo Neutral Hadron



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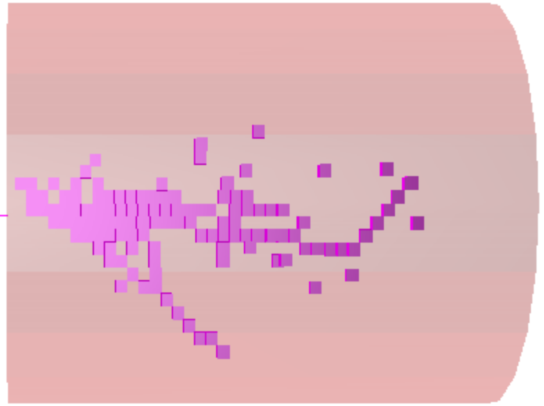
Charged Hadron



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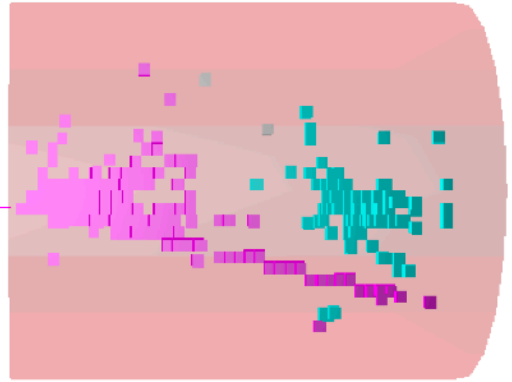
Pseudo Neutral Hadron
Overlaid with Charged Hadron



Sample Selection & PandoraPFA Framework

PandoraPFA Two Particle Separation - AHCAL 2018 Data & MC

Data: June 2018 + DWC
MC: GEANT4 v.10.03
QGSP_BERT_HP &
FTFP_BERT_HP
physics lists

- Boosted-Decision-Tree PID for hadrons (to remove beam contamination)
- **Event: 10 GeV pseudo-neutral + 10 GeV or 30 GeV charged hadron**
- Radial shower distance: **0-300 mm**
    - ➡ Track for charged hadron: Fixed sharp momentum of 10 GeV or 30 GeV
        - ➡ Data: Delay wire chambers at beam test; MC: MCTruth information

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    - ➡ Track-hit match layer 1||2||3, track-detector-gap rejection
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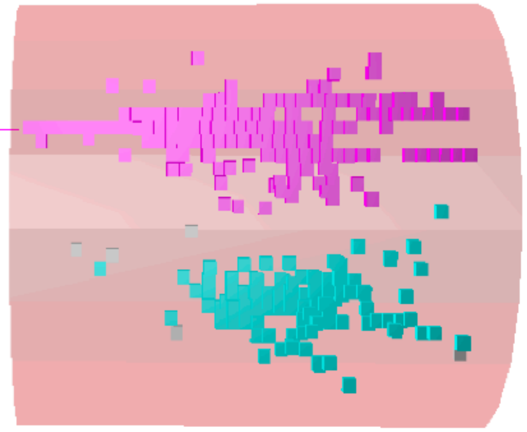
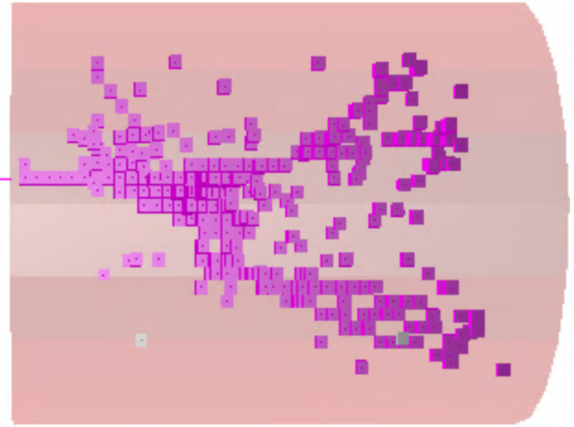
Good Reconstruction



10 GeV + 30 GeV

Confusion
(Lost neutral energy)

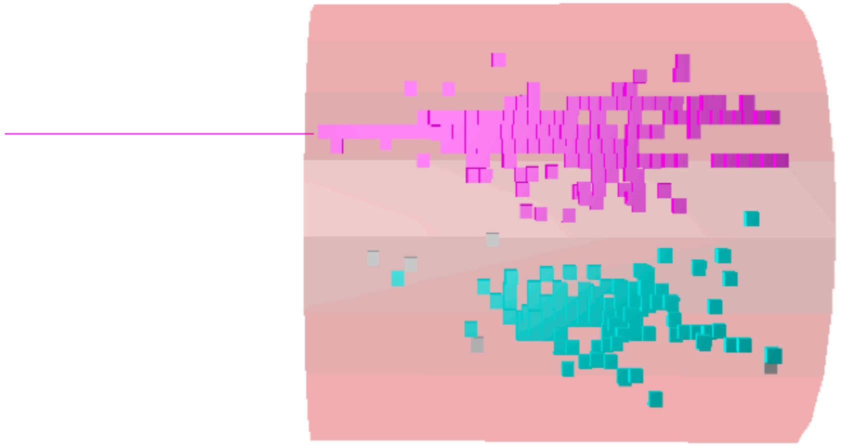


30 GeV

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

3 Sigma Neutral Hadron Energy Recovery Probability

Example Event: 300mm Separation



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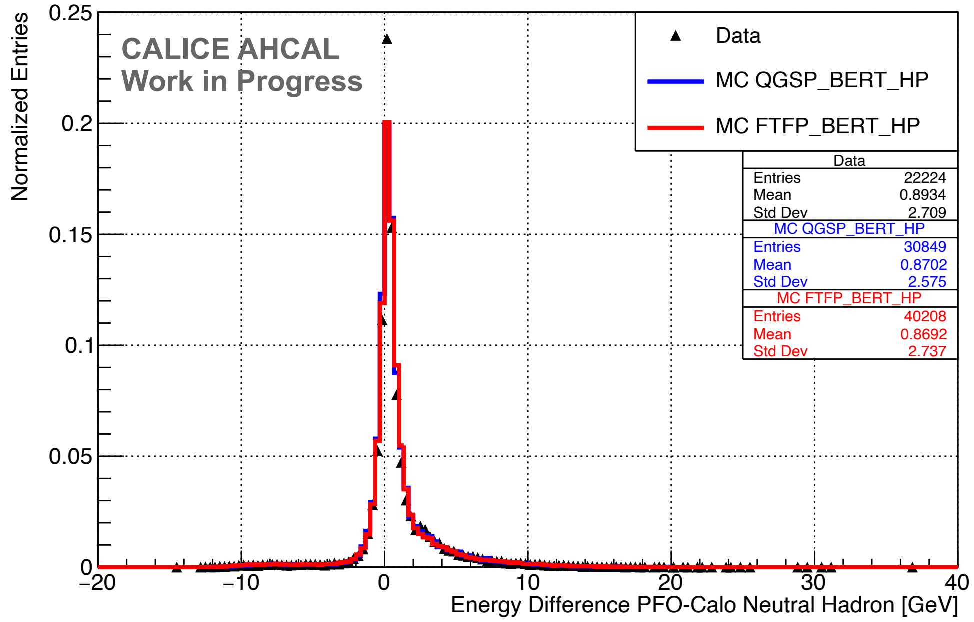
Example Spectrum: PFO - Calorimeter Energy
10 GeV Neutral Hadron, 300mm to Charged Hadron



Overall very good data to MC agreement

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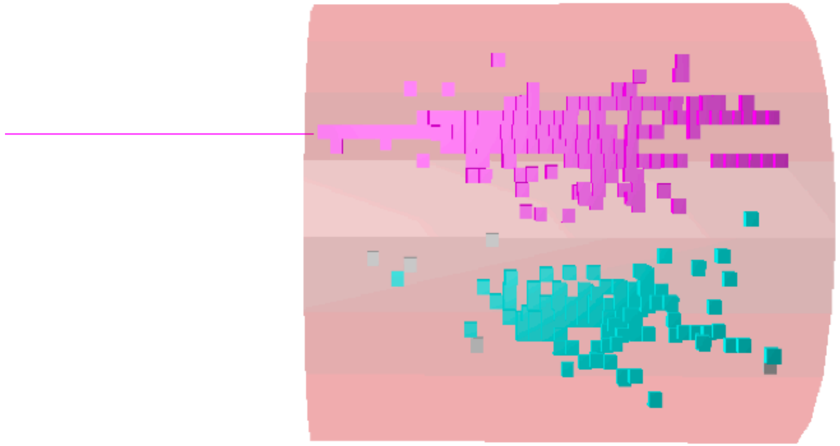

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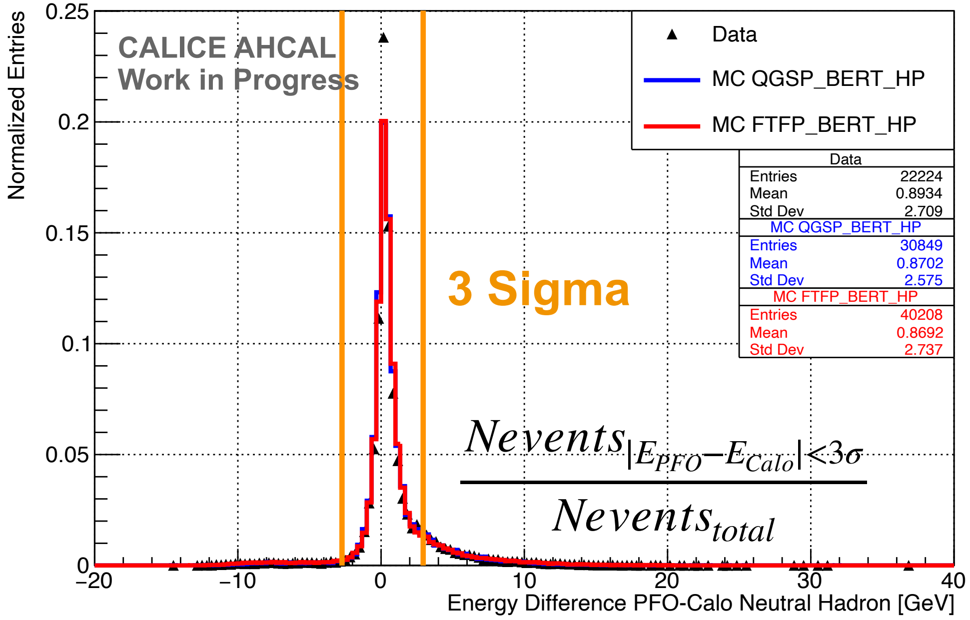

$$\frac{Nevents_{|E_{PFO}-E_{Calo}|<3\sigma}}{Nevents_{total}}$$

Overall very good data to MC agreement

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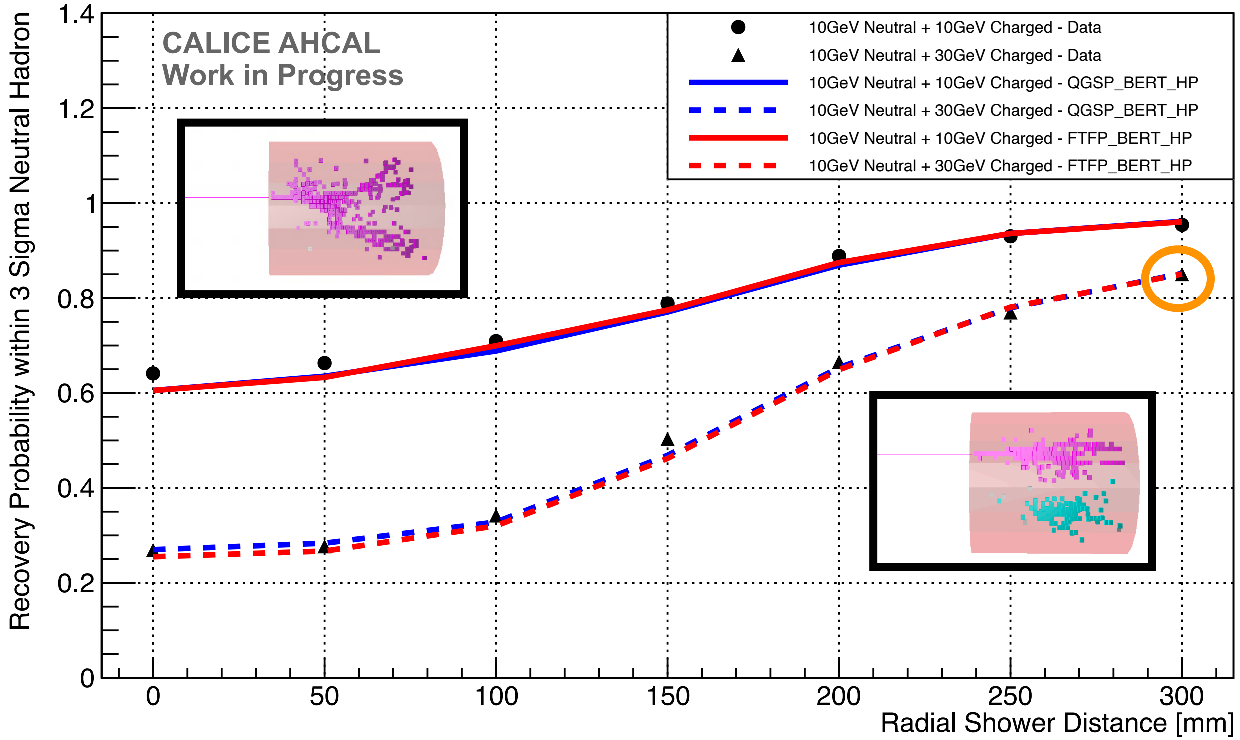

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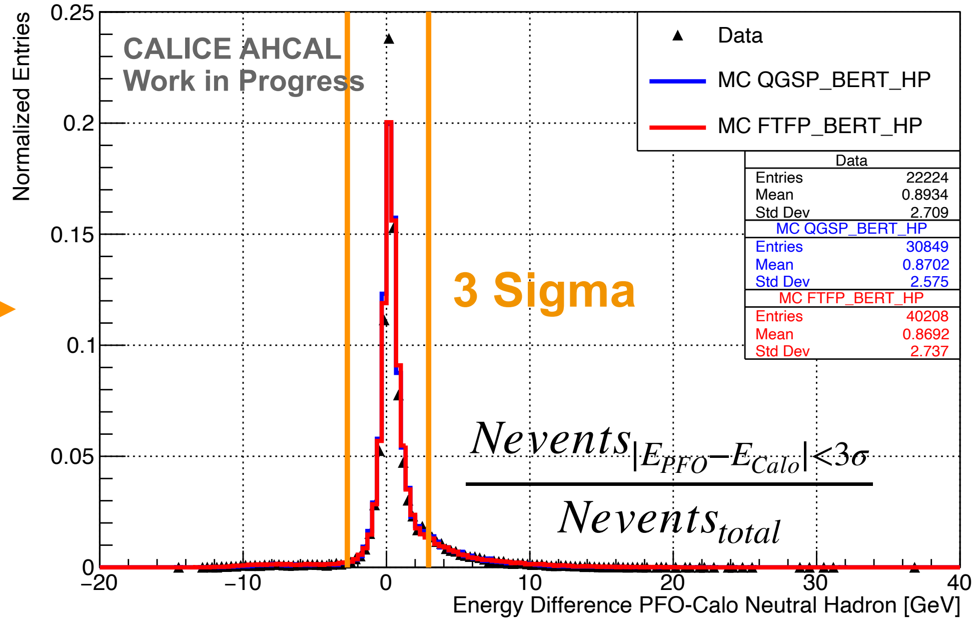
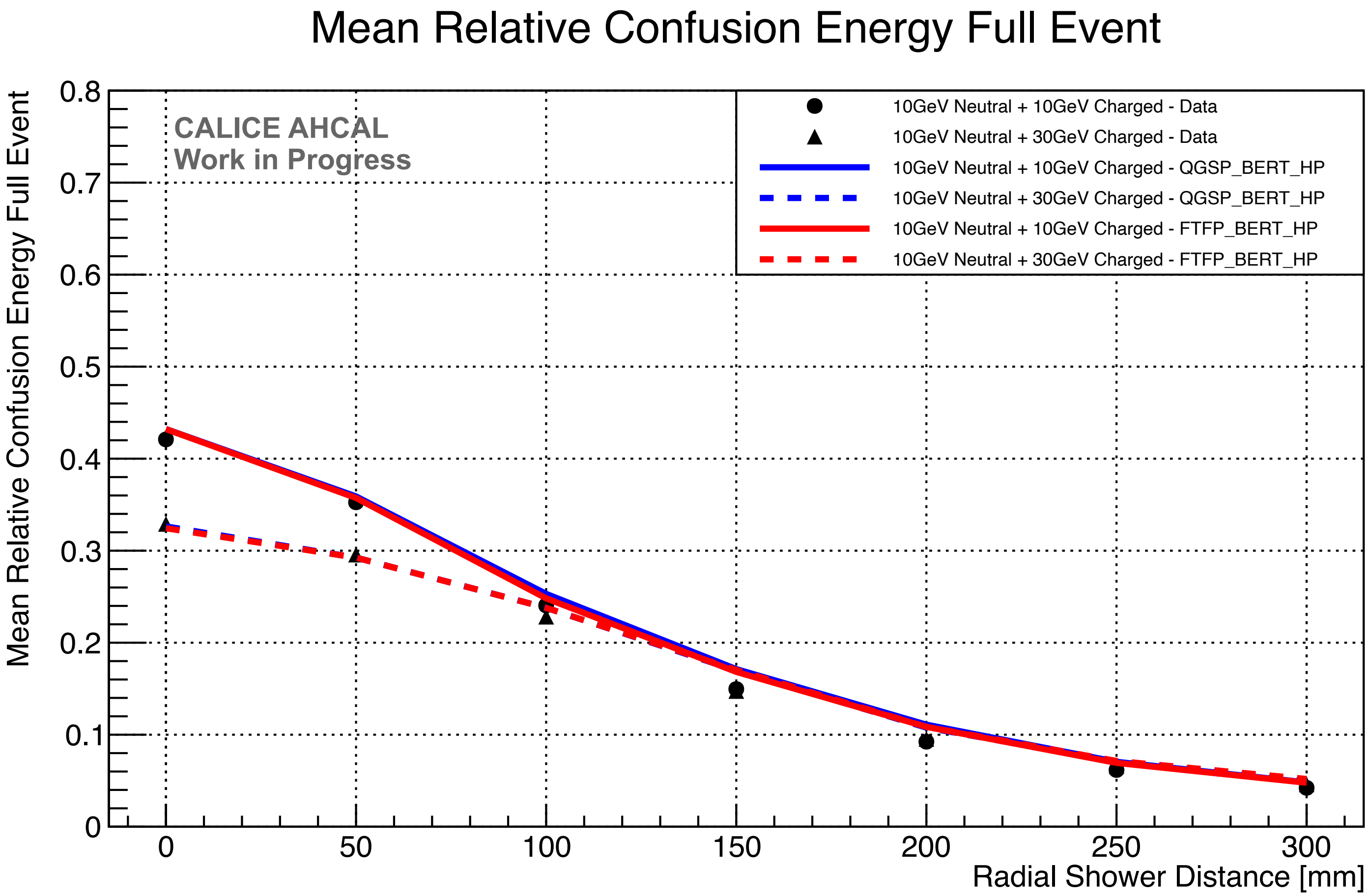


Overall very good data to MC agreement

- Large separation: Neutral hadron recovered well
- Smaller separation: Falling recovery probability
  - ➡ More pronounced for 30 GeV charged hadron ("more hungry for 10 GeV neutral hadron hits")

How is the Total Confusion Level Scaling with Shower Distance?

Mean Fraction of Confusion Energy in Events

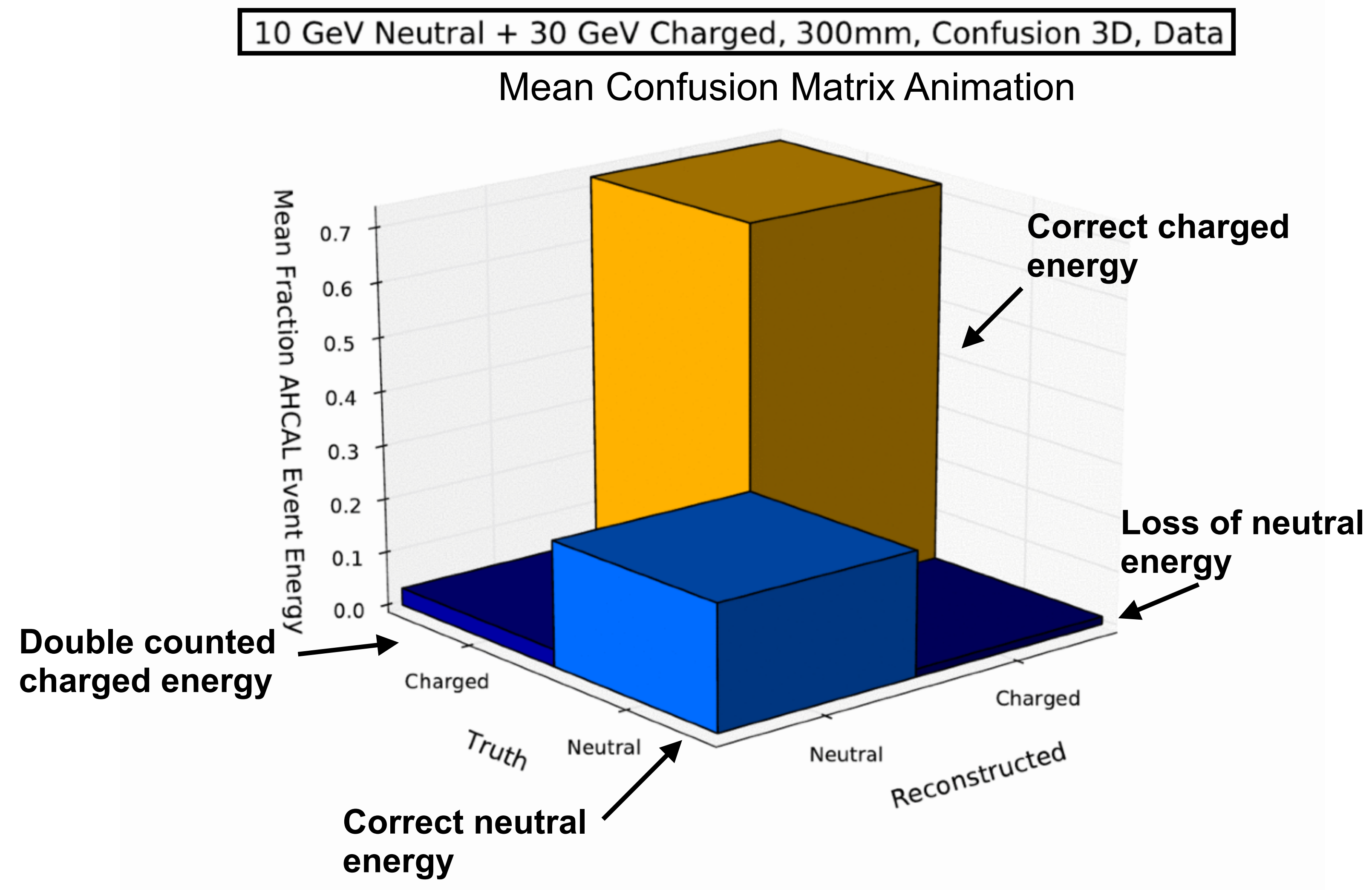


- For large shower distances: Mean fraction of confused energy < 10%
- With decreasing shower distance: Mean fraction of confused energy is increasing

➡ 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 and double counted charged energy
- Expected trends verified for decreasing shower distance:
  - ➡ Both confusion types increasing
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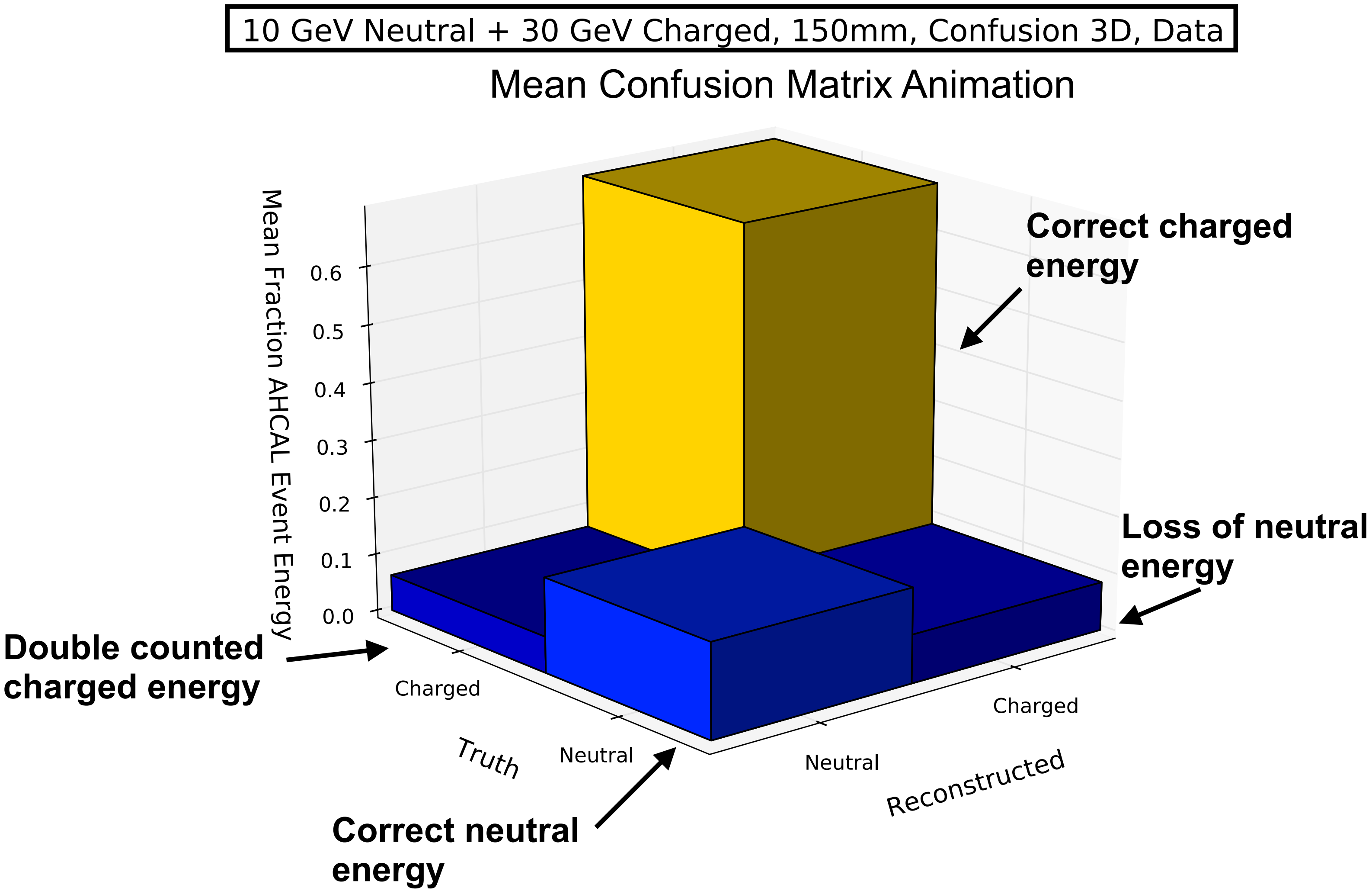

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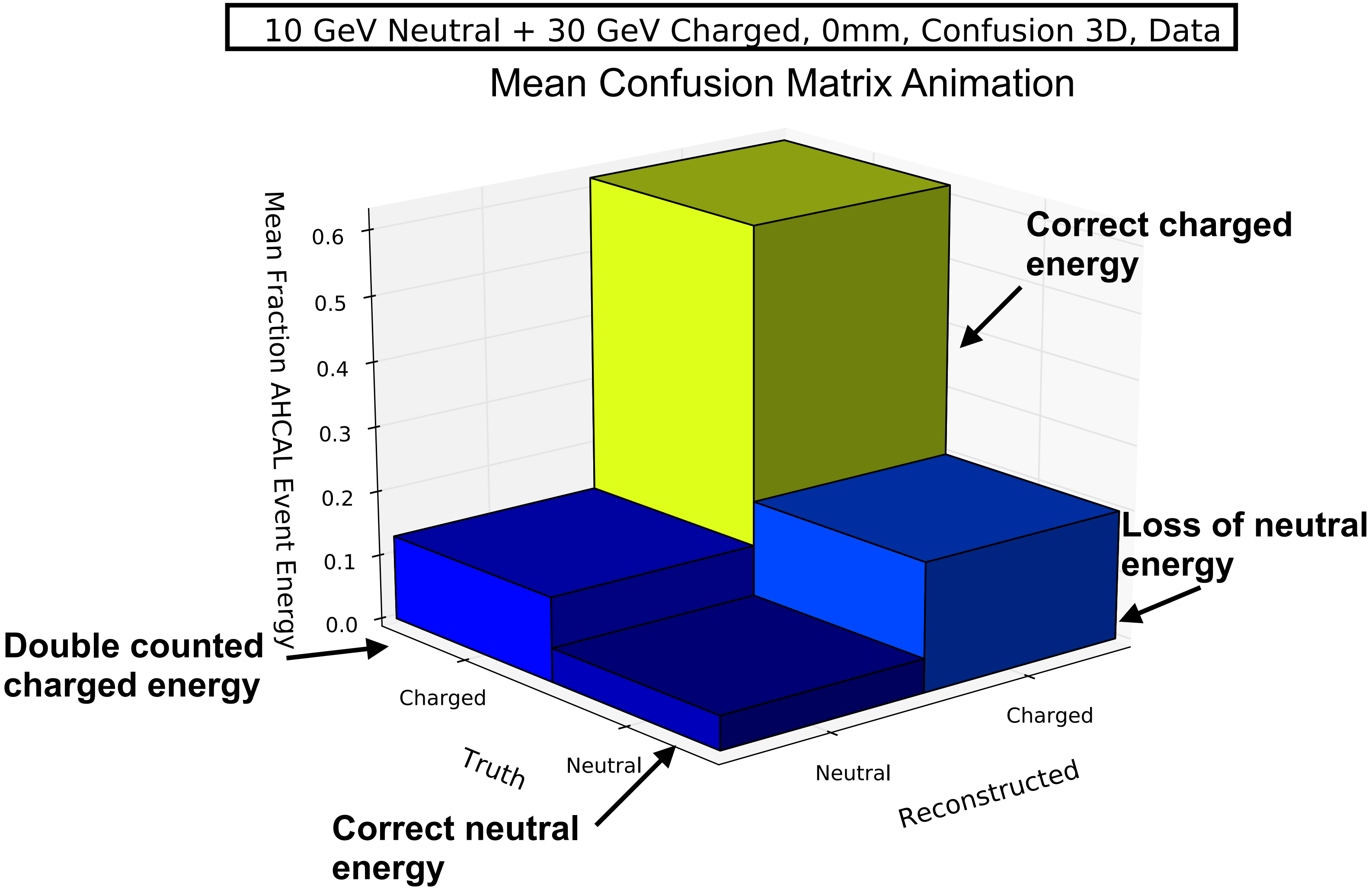

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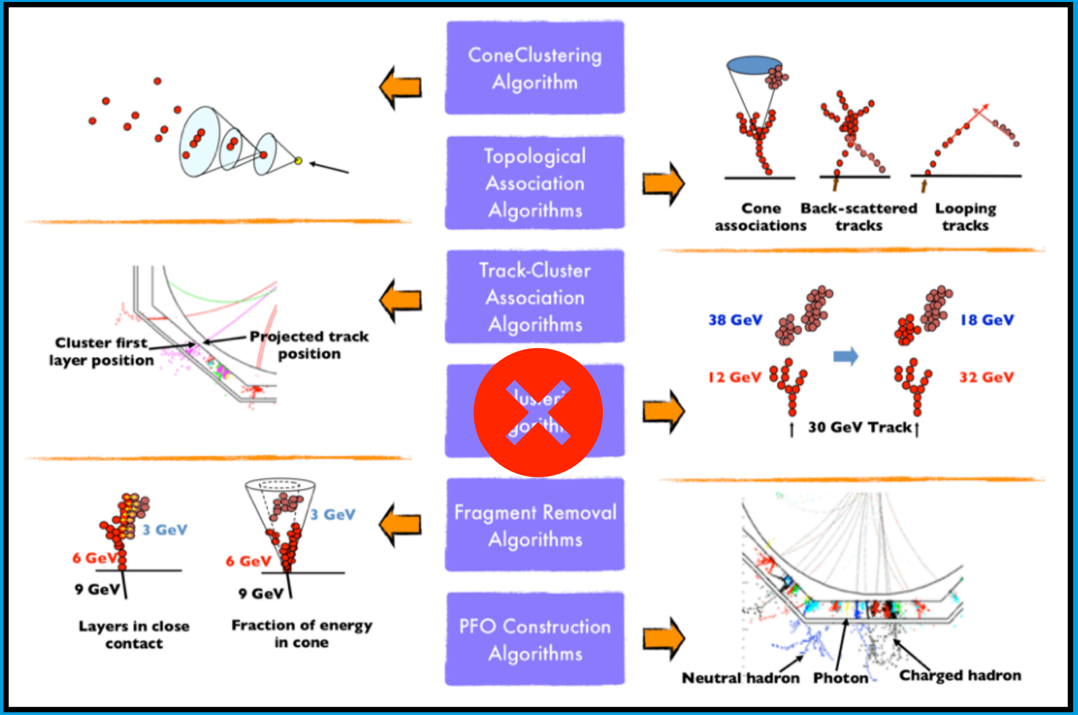
Performance Studies Different PandoraPFA Settings AHCAL 2018 Data & ILD Jets

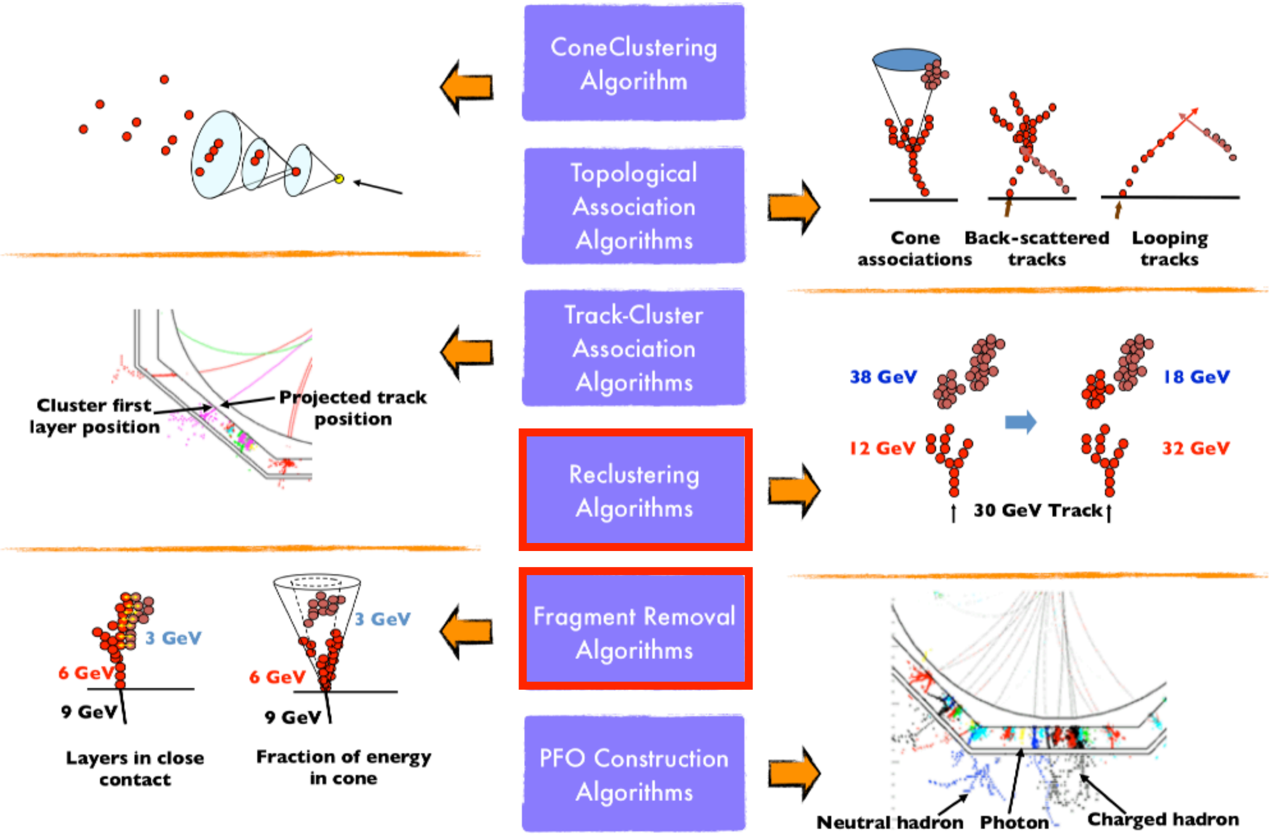


Studies of Different PandoraPFA Settings

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 AHCAL beam test data two particle 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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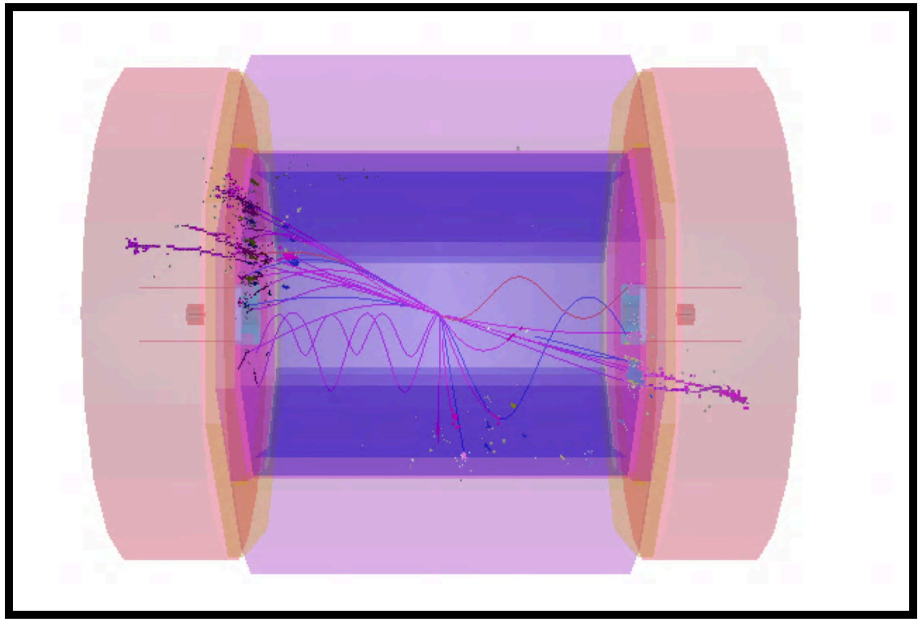
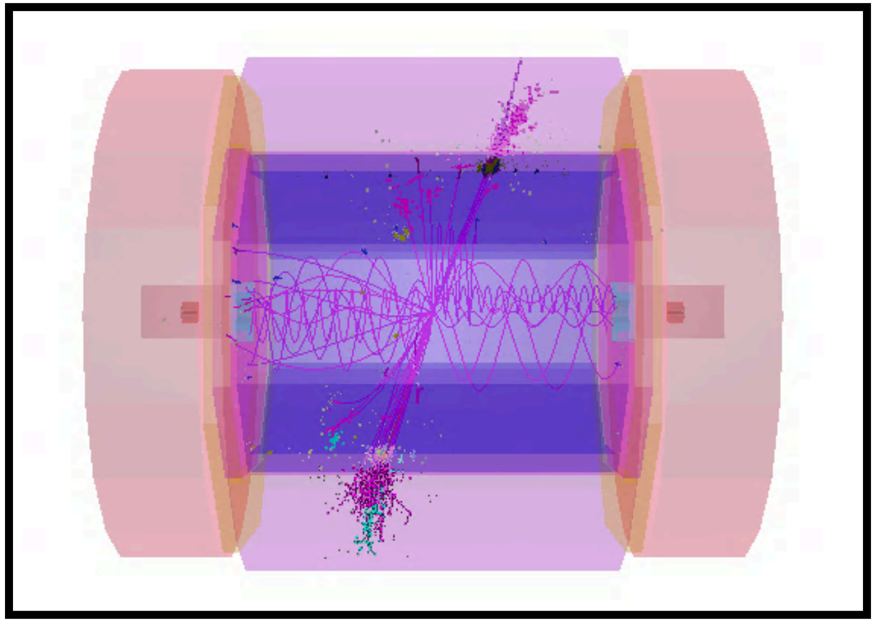
ILD Di-Jets

Used Input Samples

Big thanks to iLCsoft and ILD analysis experts @ FTX



Example: 200 GeV Di-jet

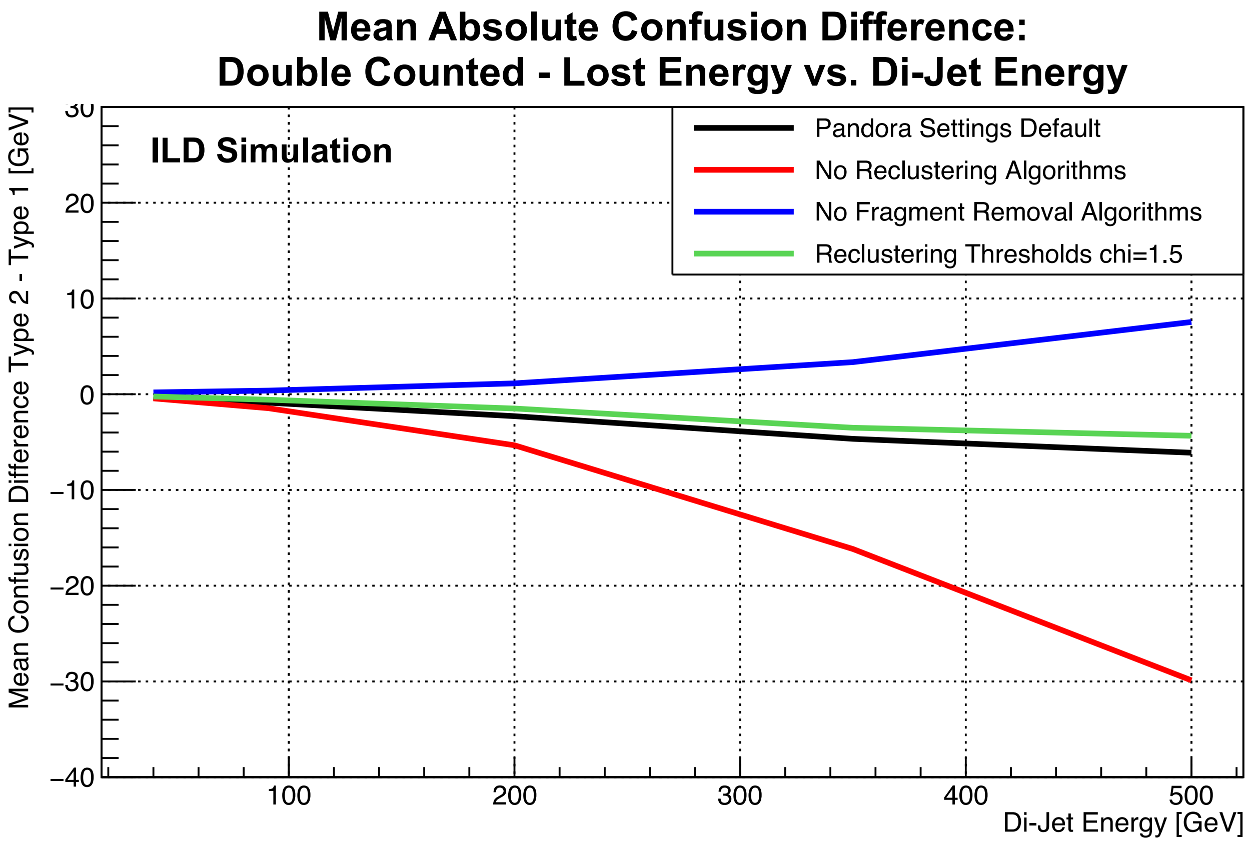


Example: 500 GeV Di-jet

- Jet energy resolution calibration samples for ILD (ILD_l5_o1_v02, GEANT4 v10.03.p02, QGSP_BERT)
  - ➡ Di-jet, back to back, light quarks: uds, energies: 40, 91, 200, 350, 500 GeV
- No backgrounds

How well are Lost & Double Counted Energy Balanced?

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



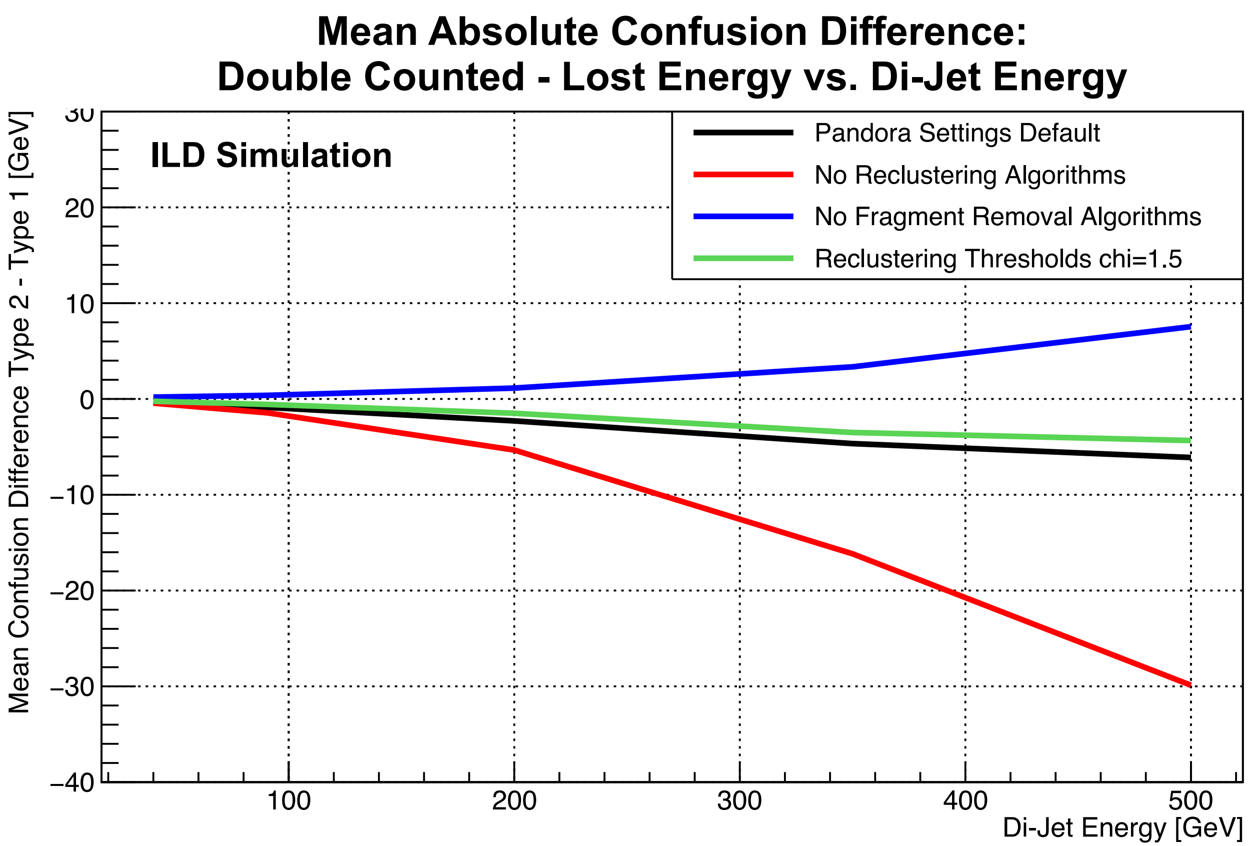
- Confusion types balanced well for default settings
- Excess of lost neutral energy for no re-clustering algorithms setting
- Excess of double counted charged energy for no fragment removal algorithms & chi=1.5 settings

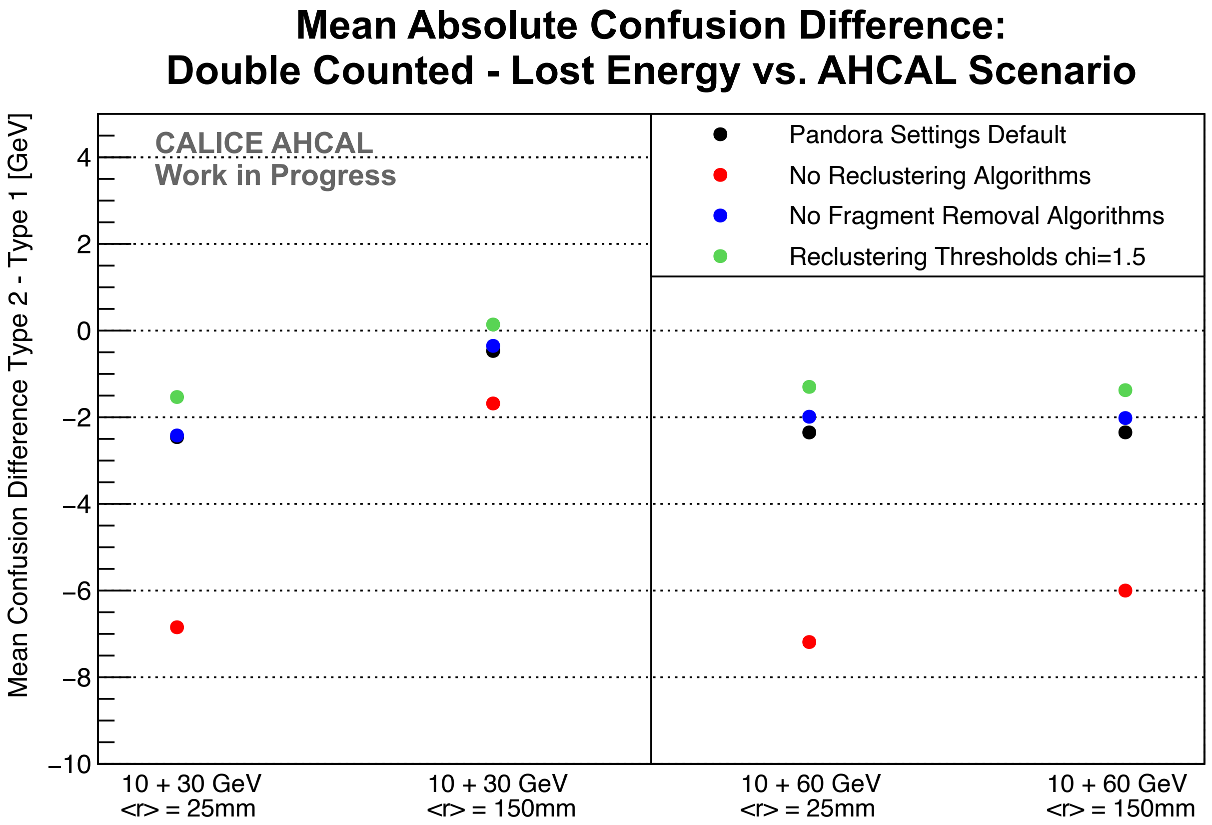
➡ **Verified expected trends for confusion types**

➡ **Same 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





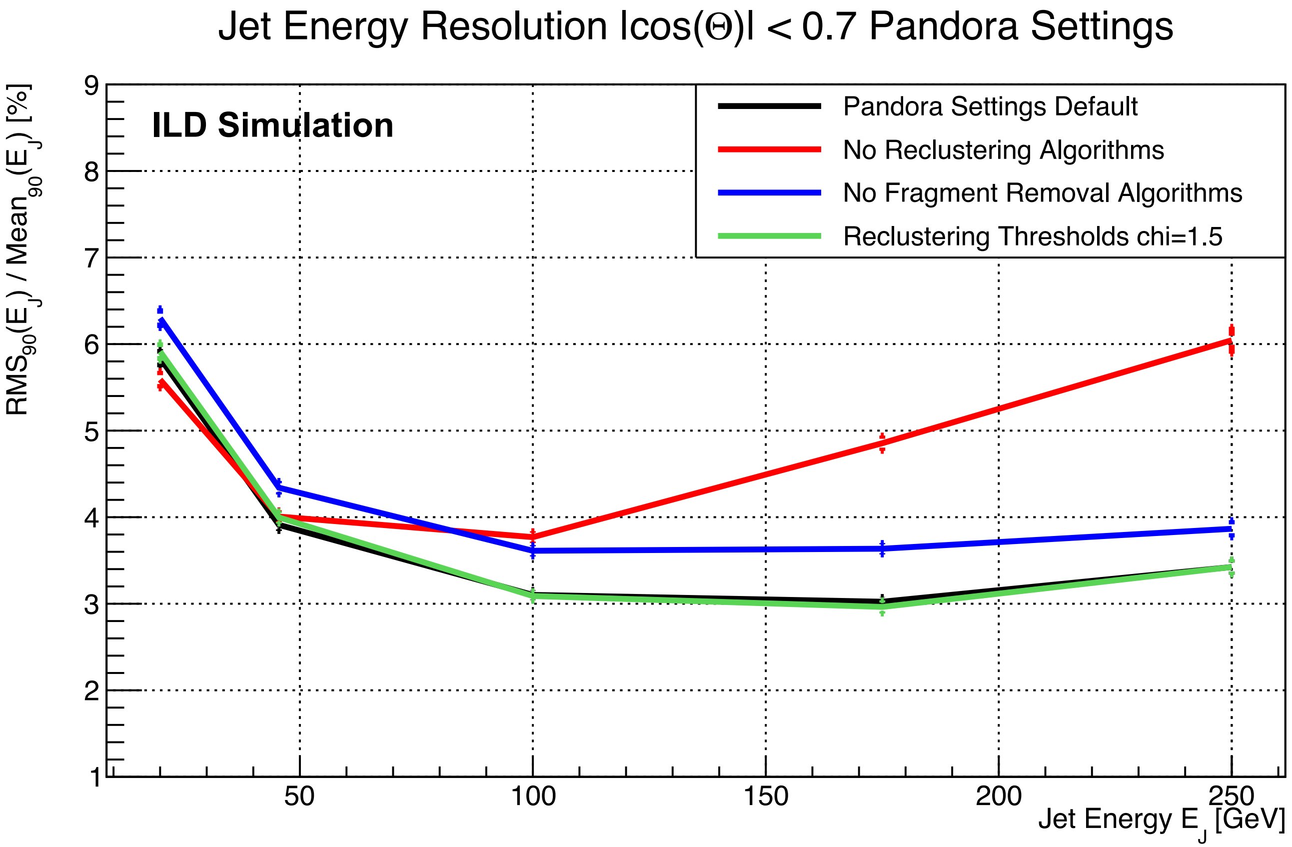
Yes, same trends

➡ but fragment removal algorithms have less impact due to smaller particle multiplicity/density

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

Total Reconstruction Performance for ILD Di-Jets?

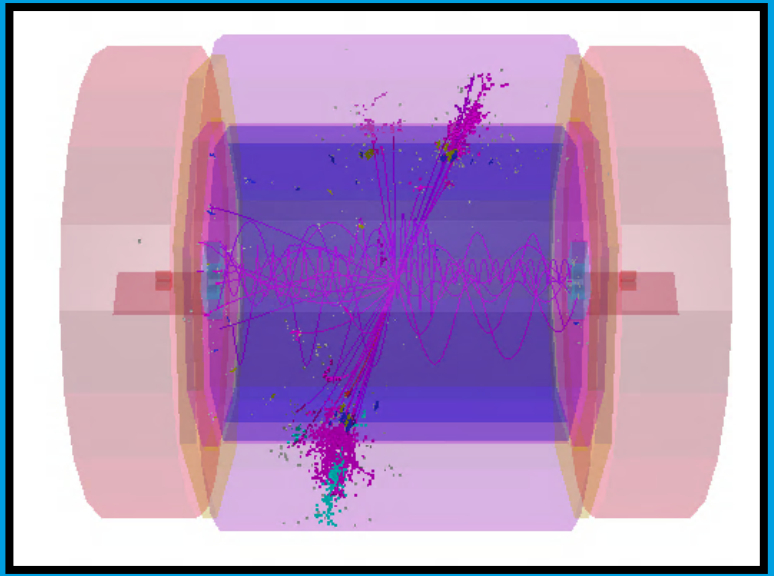
Different Pandora PFA Settings - Jet Energy Resolution - Closing the Circle



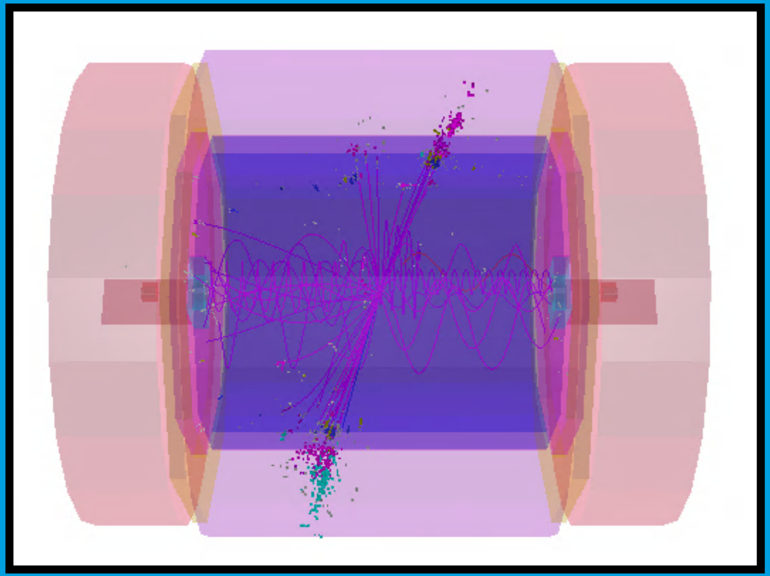
Agreeing with trends for total confusion level and lost/double counted energy balance

- Validation: **Default Pandora settings optimised to 3-4%**, no influence for chi thresholds = 1.5
- No Fragment Removal Algorithms: Constant decrease of ~0.6%
- No Re-clustering Algorithms: Decrease at higher energies of up to ~2.5%

Performance Studies PandoraPFA Energy Thresholds AHCAL 2018 Data & ILD Jets



Threshold: 0.5 MIP

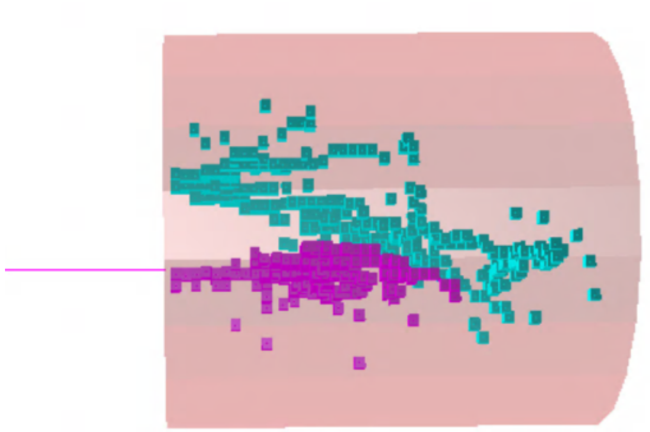


Threshold: 3.0 MIP

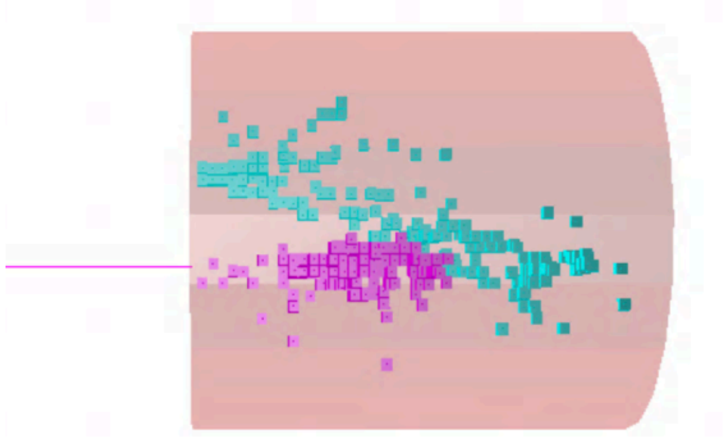
Variation of Internal Energy Thresholds

Introduction & Motivation

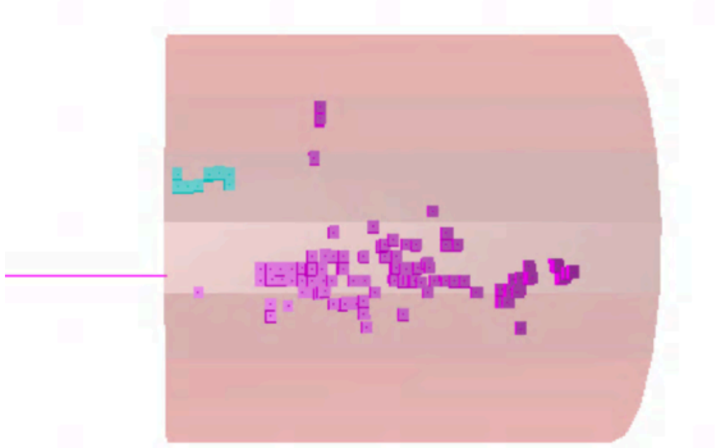
Is a highly granular calorimeter in a high radiation environment capable of achieving sufficiently high PFA performance over its full life time?



0.5 MIP



1.0 MIP

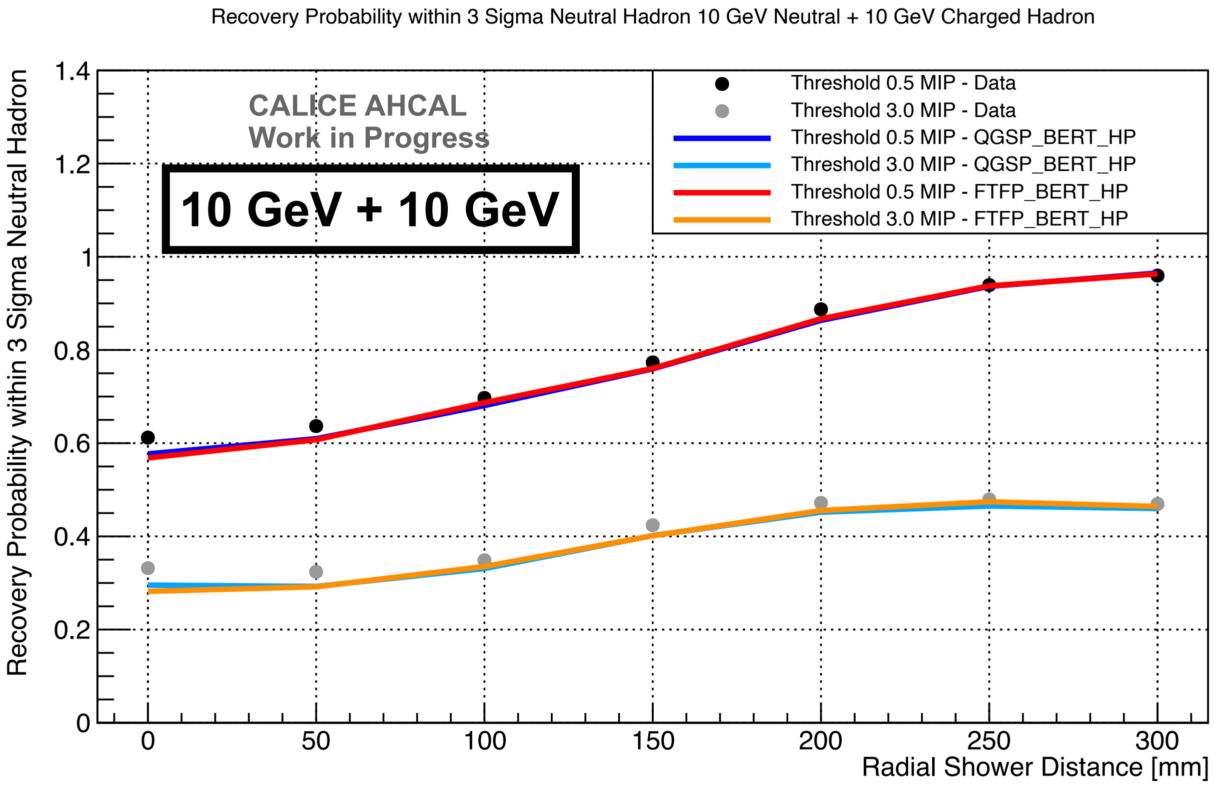


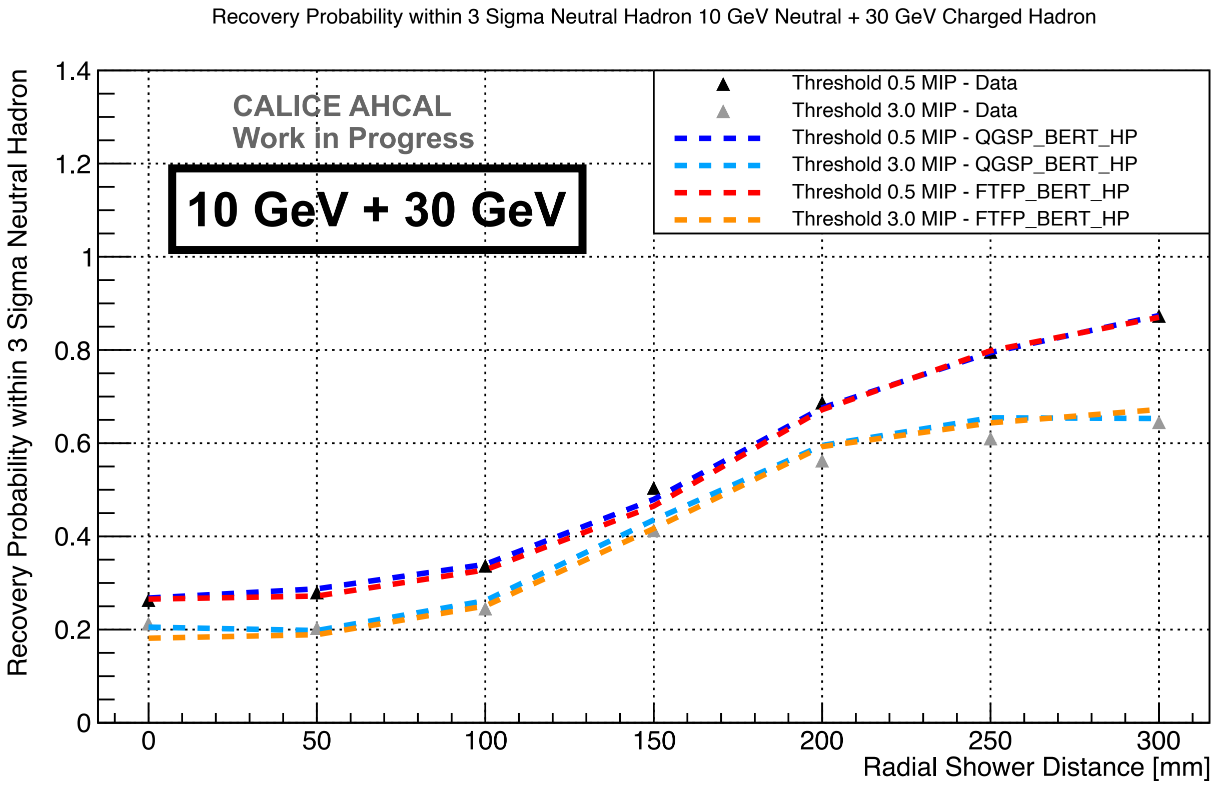
3.0 MIP

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

3 Sigma Recovery Probability Neutral Hadron

Different Energy Thresholds for AHCAL Two Particle Events

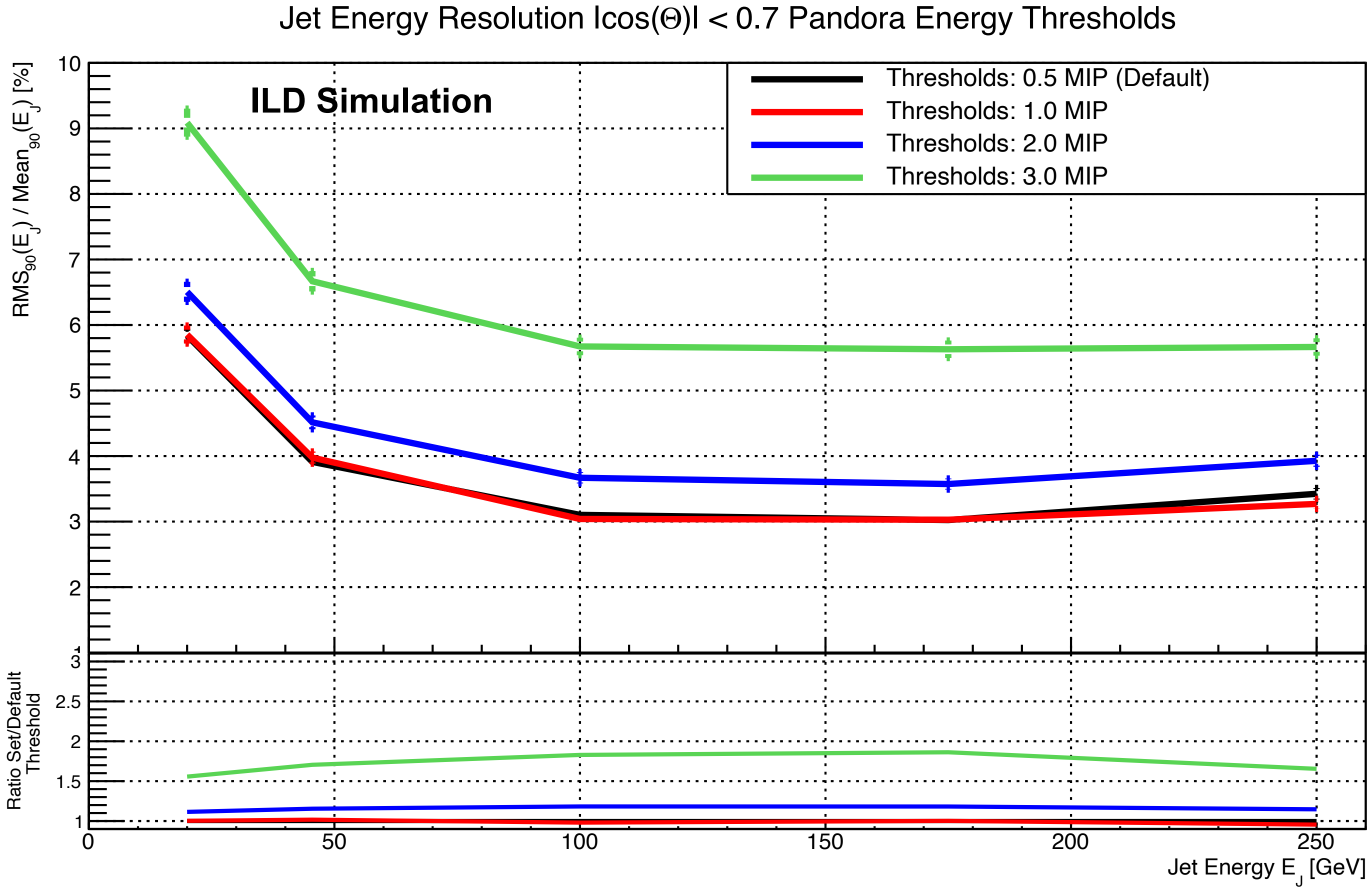




- Total degradation of recovery probability by 20-30% (10+10 GeV) and by 5-15% (10+30 GeV)
  - ➡ Two particle separation more challenging with increased energy thresholds, specifically at lower energy

Jet Energy Resolution

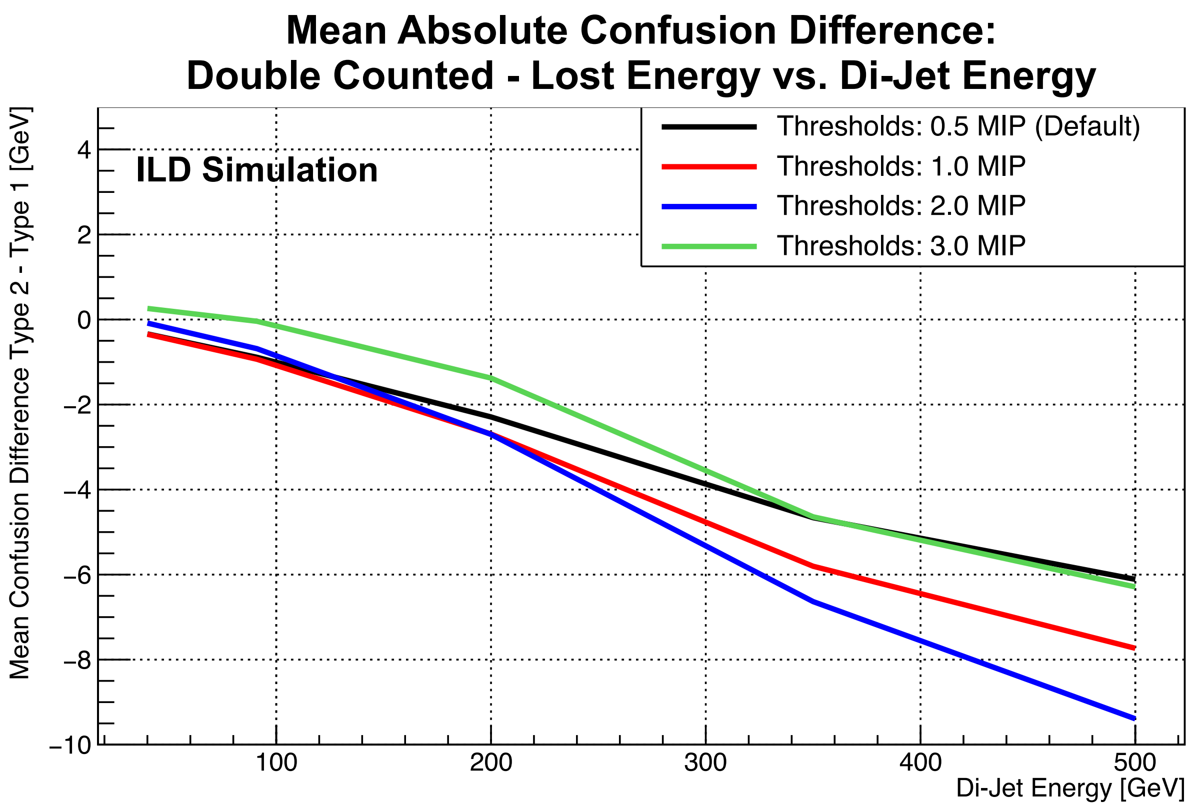
Different Energy Thresholds for ILD Di-Jets

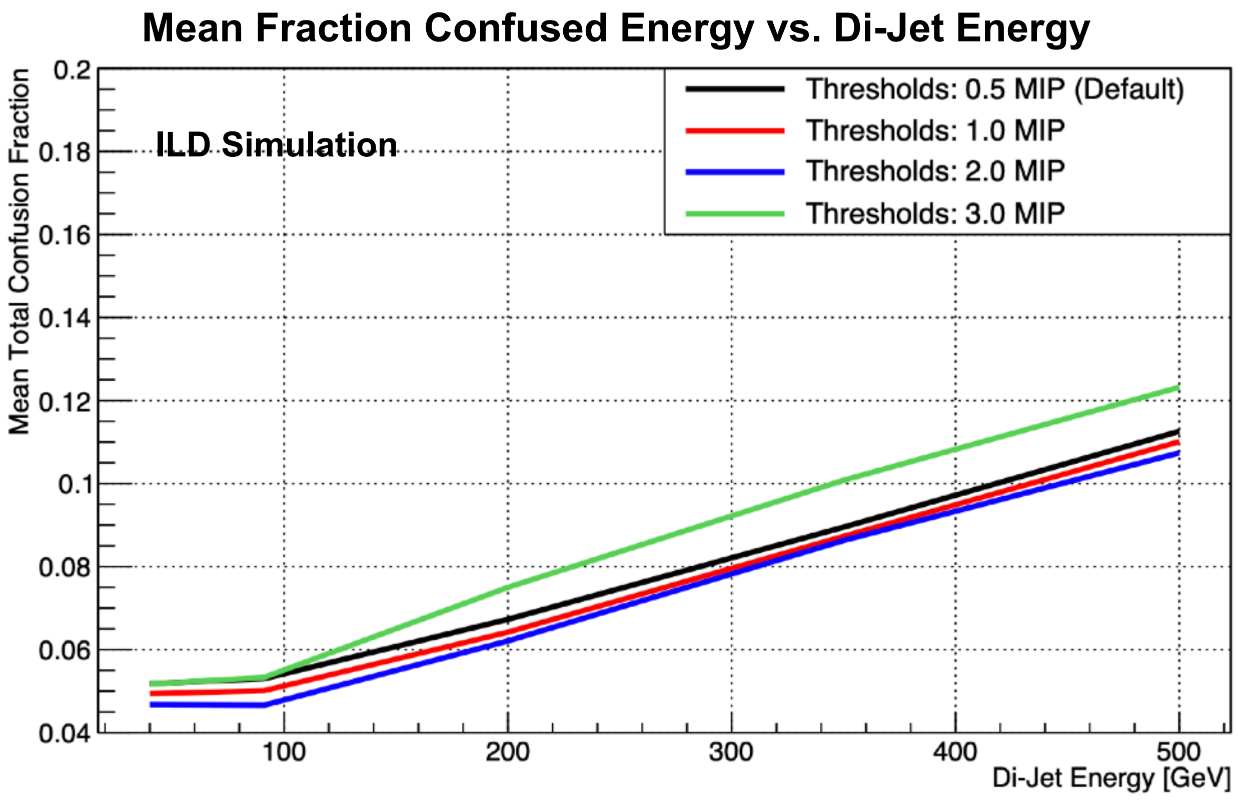


- Basically no influence on JER for slightly increased thresholds (1 MIP)
- Even for highest threshold (3 MIP) degradation of JER „only" ~80% compared to default
  - ➡ Partly compensated by PandoraPFA's emergency/force algorithms towards Energy Flow?
  - ➡ Do detector effects/granularity play a less important role than expected as long as a PFA is powerful enough?
  - ➡ Is topology information exploited to full extent within PandoraPFA?

Mean Confusion Type Difference & Confused Energy Fraction

Different Energy Thresholds for ILD Di-Jets





- Inversion with respect to default threshold settings going from 2 MIP to 3 MIP threshold
  - ➡ Indication for reaching internal point of changing reconstruction paradigm in PandoraPFA (emergency/force Energy Flow algorithms)?

Summary & Conclusions

PandoraPFA Studies with AHCAL Beam Test and ILD Di-Jet Events

- Applied **PandoraPFA** on **AHCAL 2018** & ILD events to study limiting effects for **beam test data** & simulations
  - ➡ Validated: Expected trends for confusion, two particle separation and total reconstruction performance
  - ➡ Across studies: Very good data to MC agreement 5-10% & same trends for AHCAL and ILD di-jet events
  - ➡ Gained detailed insights into PandoraPFA: Confirming expected changes of confusion types for changes in specific internal algorithms
  - ➡ Questions raised by energy threshold study: Optimised detector effects / ultra high granularity less important than expected in contrast to powerful PFA like PandoraPFA? Topology information fully exploited?

- Outlook: Closer look into energy threshold studies to draw explicit conclusions

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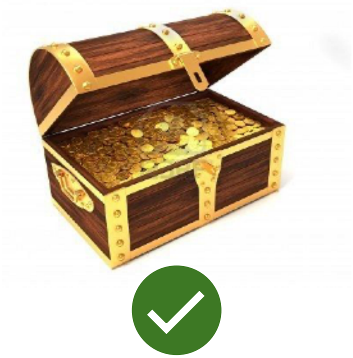
Thank you! (Special thanks to J. Marshall for his continuous support and advice to open Pandora's box!)



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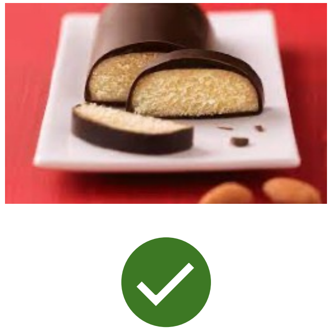
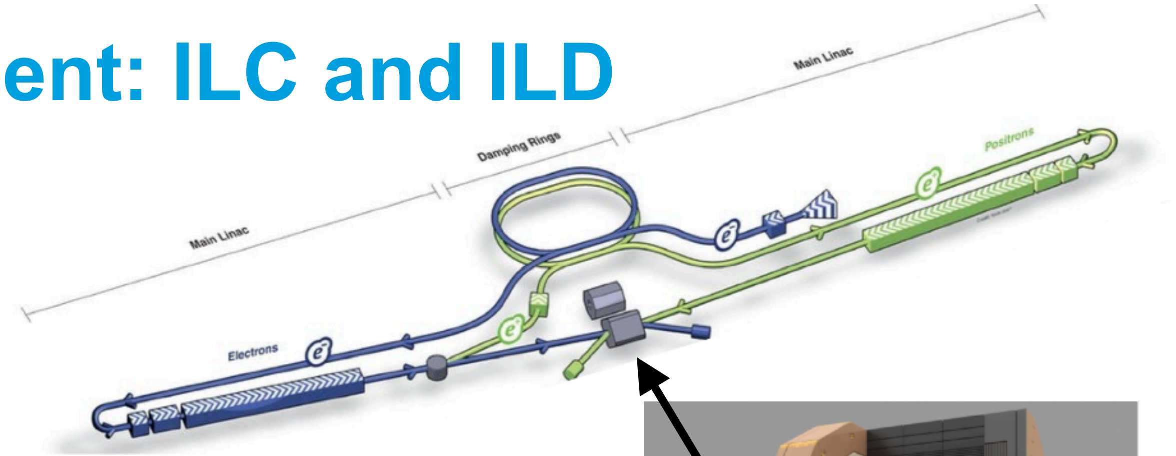


Thank you! (Special thanks to J. Marshall for his continuous support and advice to open Pandora's box!)

Backup

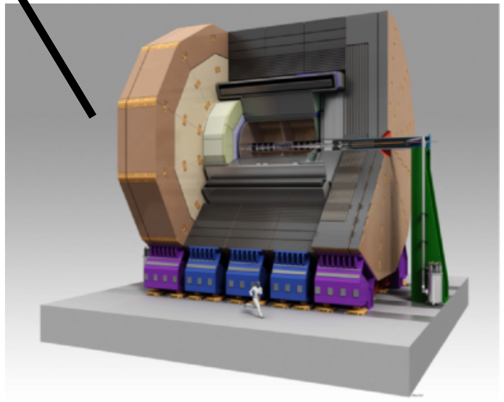
Example for a Future e^+e^- Experiment: ILC and ILD

The Precision Frontier



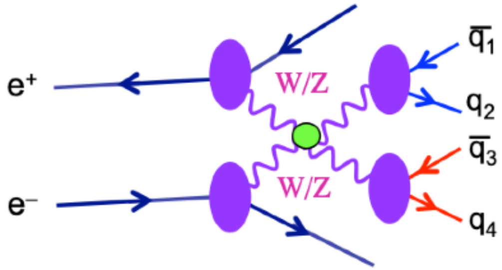
- International Linear Collider (ILC)
  - ➡ $\sqrt{s}$ = 250 GeV (upgradeable up to 1 TeV)
  - ➡ Polarised beams

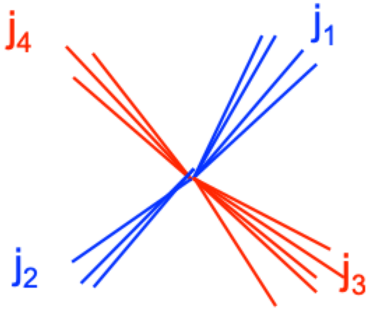
- International Large Detector (ILD)
  - ➡ Time projection chamber (TPC) and silicon tracker
  - ➡ Highly granular calorimeters within the solenoid magnet

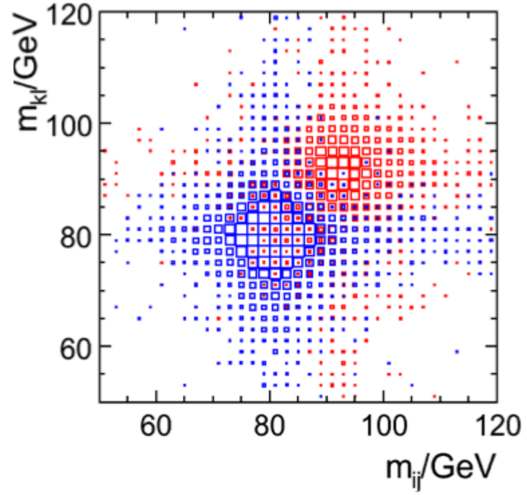


- Extensive physics program in clean and controlled environment: e.g. **precision measurements** of Higgs/E.W. sector, top quark,…

➡ One of many requirements: Sufficient separation of reconstructed di-jet masses of W and Z boson decaying hadronically





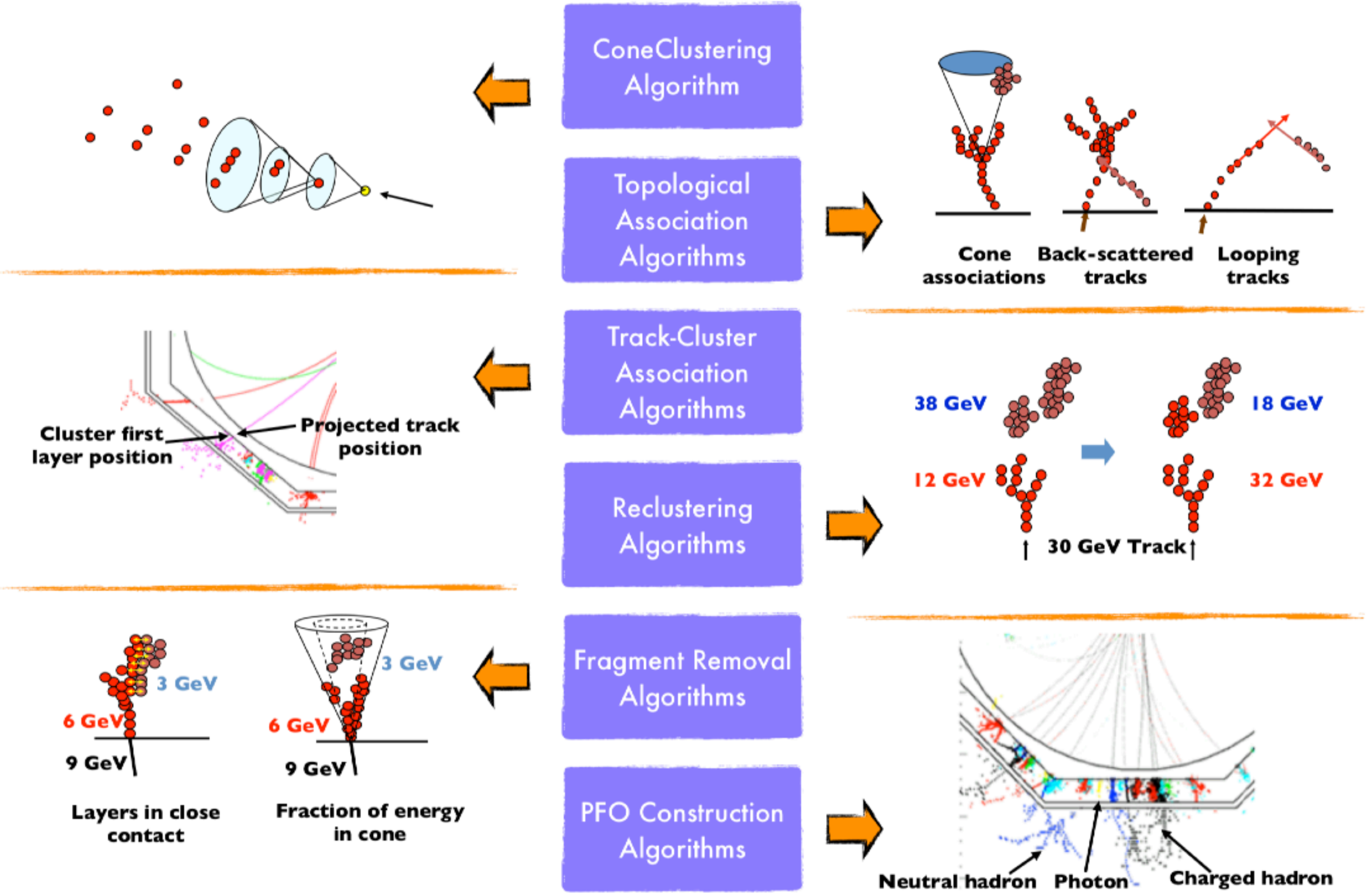


The Pandora Particle Flow Algorithm (PandoraPFA)

A Multi-Algorithm Pattern Recognition Tool

https://github.com/PandoraPFA

Illustration of Key Algorithms within PandoraPFA



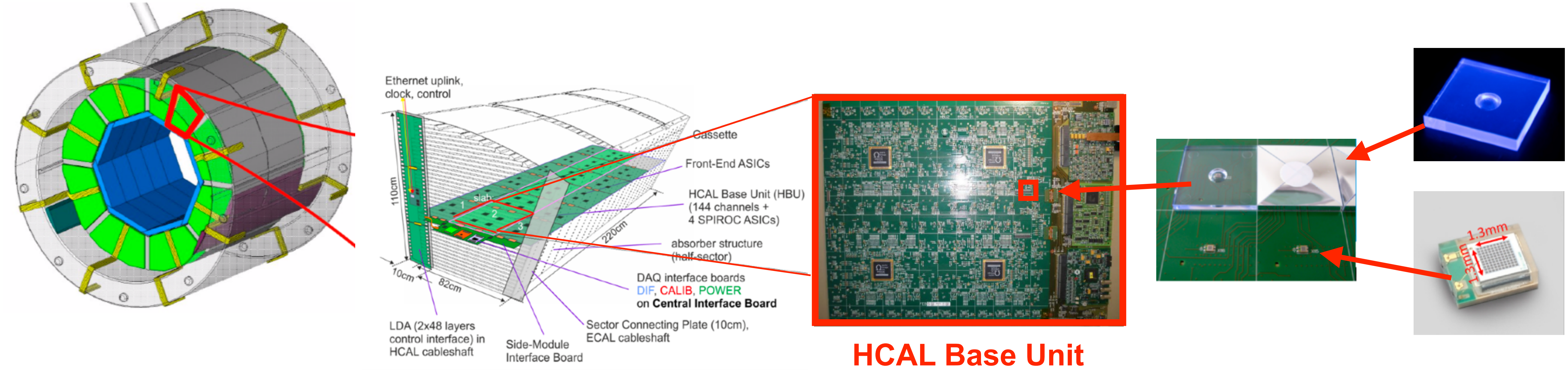
J. S. Marshall: https://indico.in2p3.fr/event/7691/contributions/42712/attachments/34375/42344/3_john_marshall_PFA_marshall_24.04.13.pdf

- Challenge for PFA to keep confusion level low:
  - ➡ Clean separation of particle showers
  - ➡ Avoid double counting of energy
- **State of the art: PandoraPFA**
  - ➡ Highly recursive multi-algorithm chain using pattern recognition
- **Hardware requirements:**
  - ➡ Compact calorimeters within magnetic coil to minimise dead space behind tracker and allow clean track-cluster association
  - ➡ **Highly granular calorimeters** to exploit pattern recognition algorithms

The Analog Hadron Calorimeter (AHCAL) for ILD

Designed for Particle Flow Reconstruction

- Highly granular sampling calorimeter for the International Large Detector
  - ➡ Total of **~8 million single channels**
  - ➡ One channel: Wrapped scintillator tile coupled to Silicon-Photomultiplier readout
- **Compact design in octagonal cylinder within solenoid magnet**:
  - ➡ Fully integrated front-end readout electronics
  - ➡ Internal LED calibration system, passive cooling scheme (power pulsing)

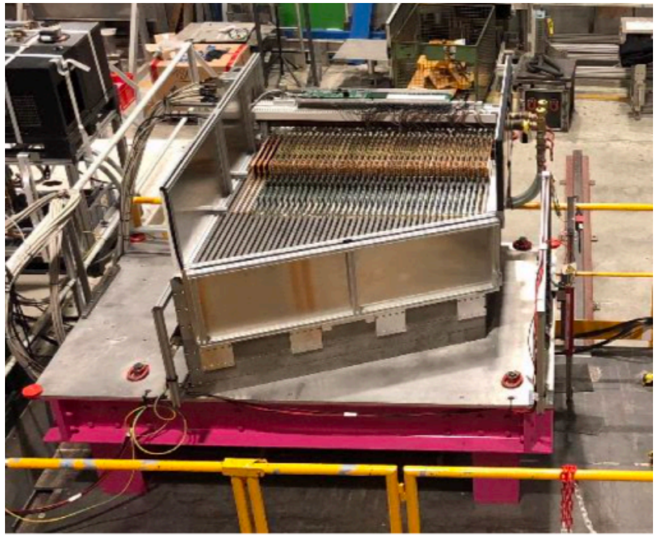


The CALICE AHCAL Prototype 2018

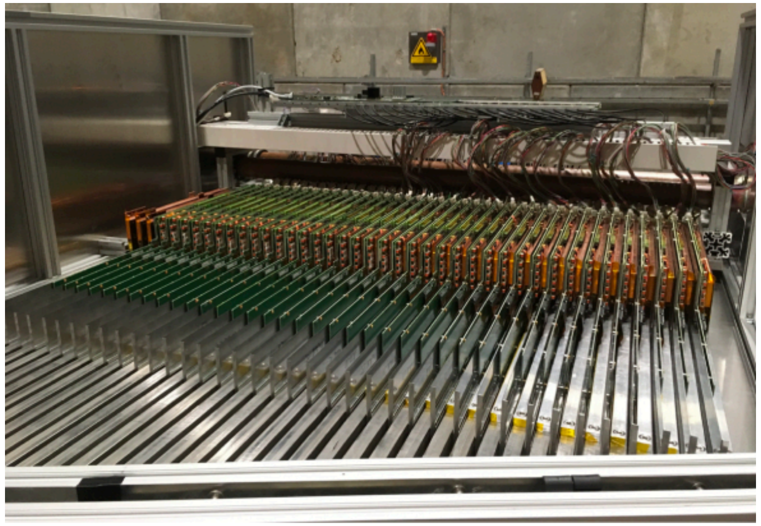
A Highly Granular SiPM-on-tile Sampling Calorimeter

- 38 layer steel sampling calorimeter (~4 λ_n) featuring a total of **~22000 channels**
- Active layers (72 x 72 cm^2) consisting of 576 channels
  - ➡ One channel: SiPM (Hamamatsu: MPPC S13360-5PE) coupled to wrapped scintillating tile (3 x 3 cm^2)
- Scalable detector concept developed for the 8-million-channel AHCAL of ILD

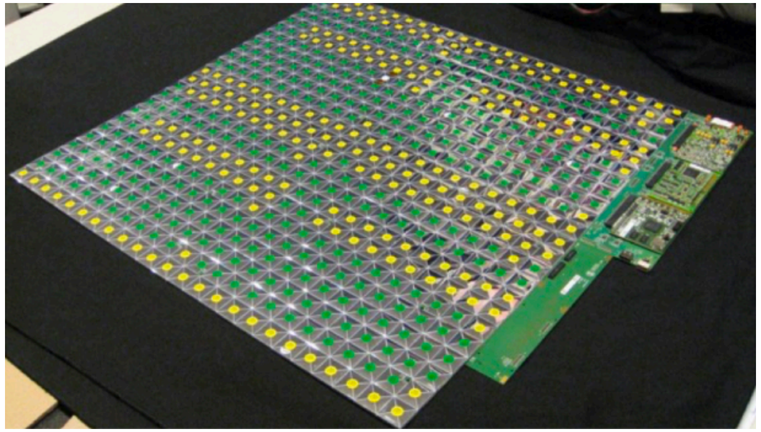
AHCAL Prototype on Moveable Stage



38 Layers within Steel Absorber Stack



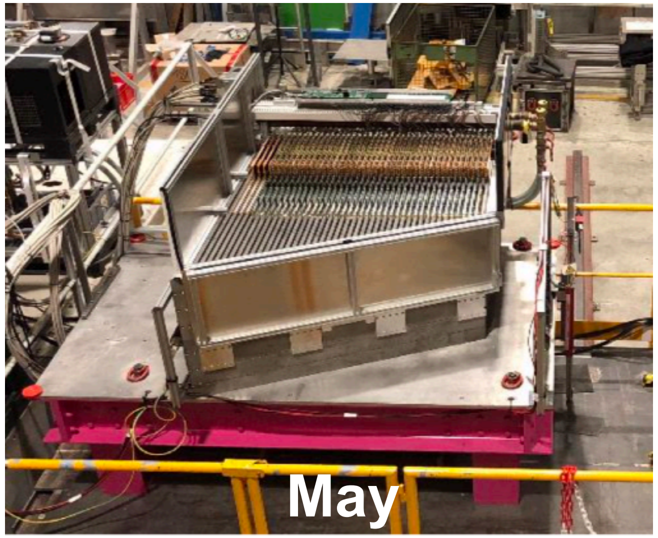
One AHCAL Layer

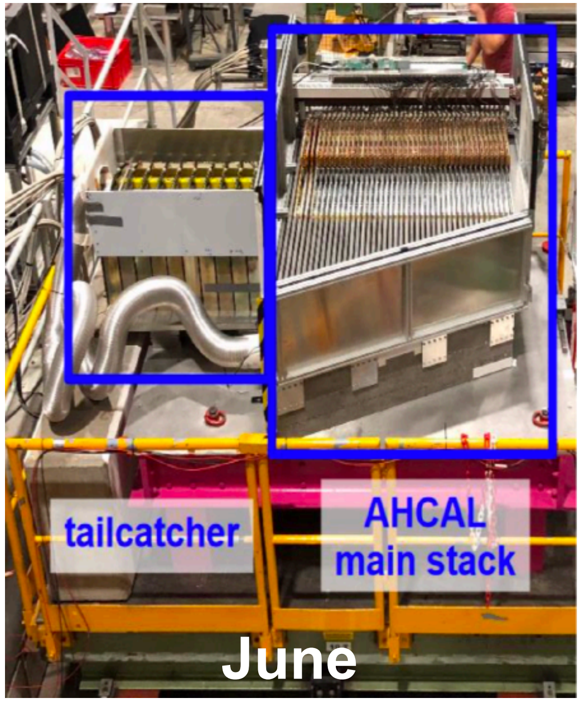


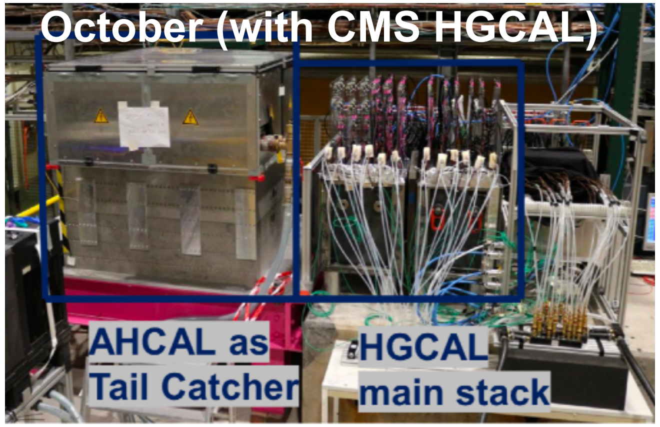
The CALICE AHCAL Beam Test Campaigns 2018

May, June and October @ SPS Cern

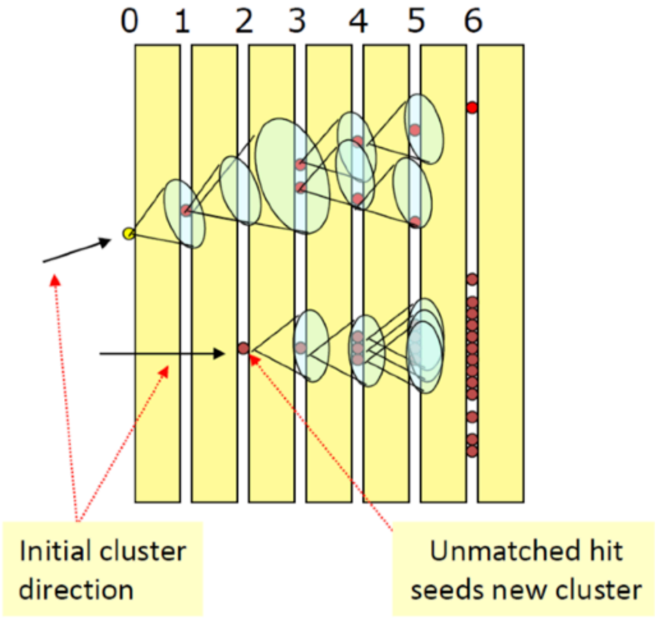
- Three successful beam test campaigns at SPS CERN in 2018
- Data sets:
  - ➡ Muons, electrons, **pions**
  - ➡ Energies: 10 - 200 GeV
  - ➡ Events: Multiple 10 million
  - ➡ **Movable stage for beam aiming at different detector positions**
- For this studies: June 2018 beam test data





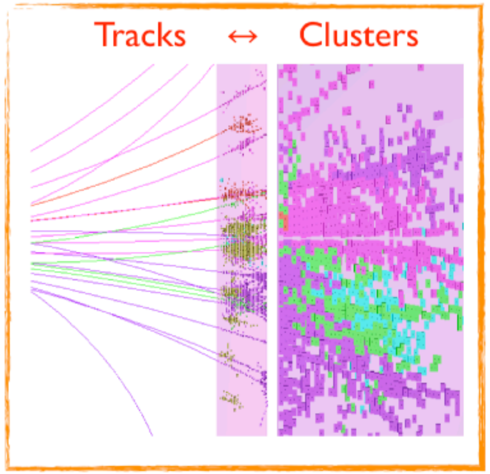


Clustering



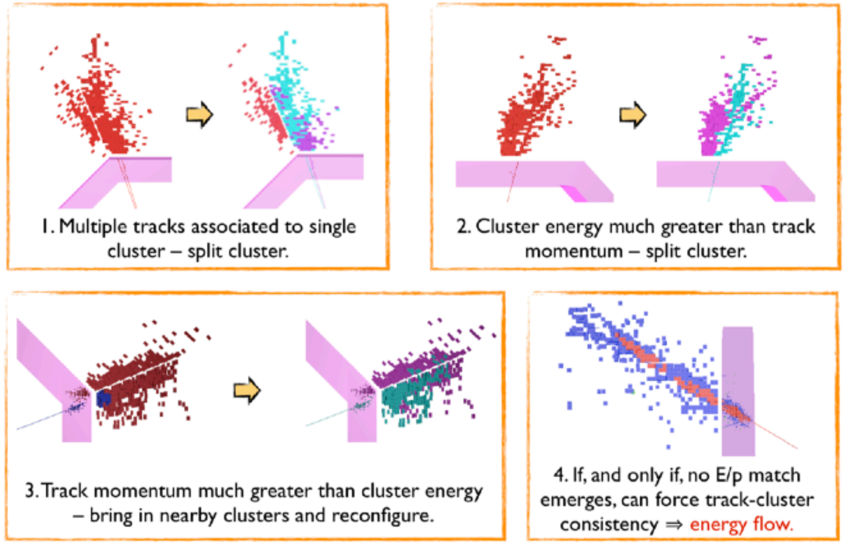
Track to Cluster Association

- 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.

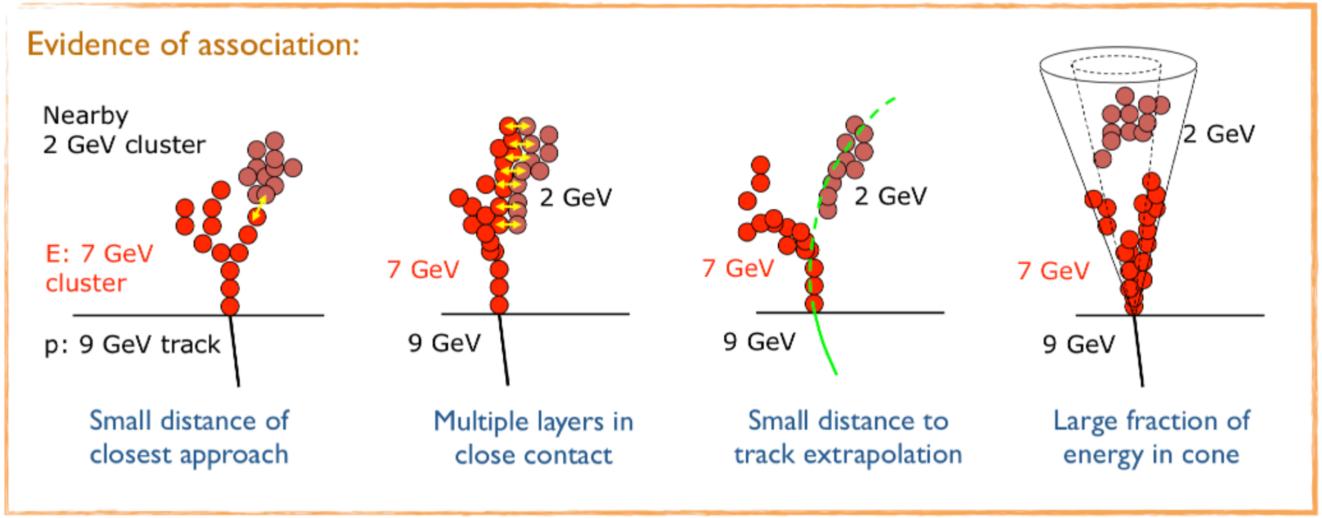


J. S. Marshall: https://indico.in2p3.fr/event/7691/contributions/42712/attachments/34375/42344/3_john_marshall_PFA_marshall_24.04.13.pdf

Re-Clustering



Fragment Removal

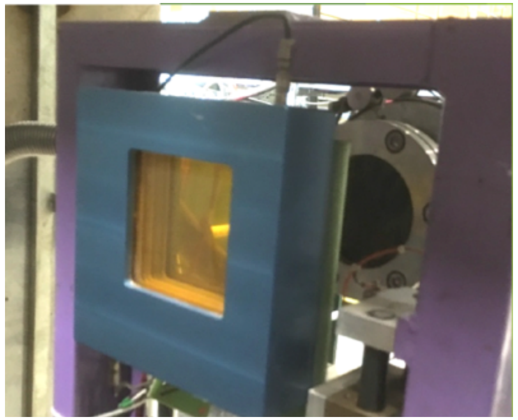


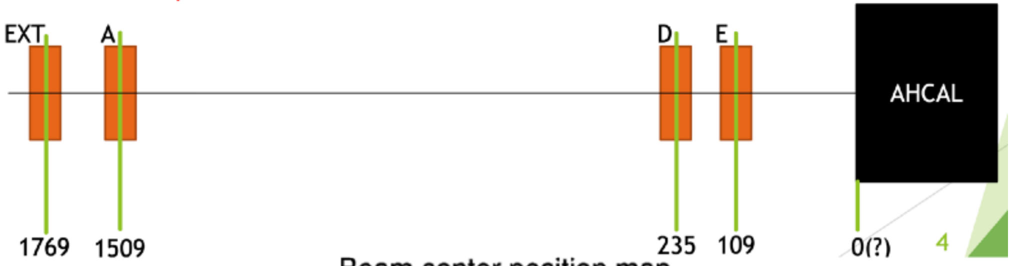
Delay Wire Chambers (DWC)

Providing Tracks for Beam Test Events

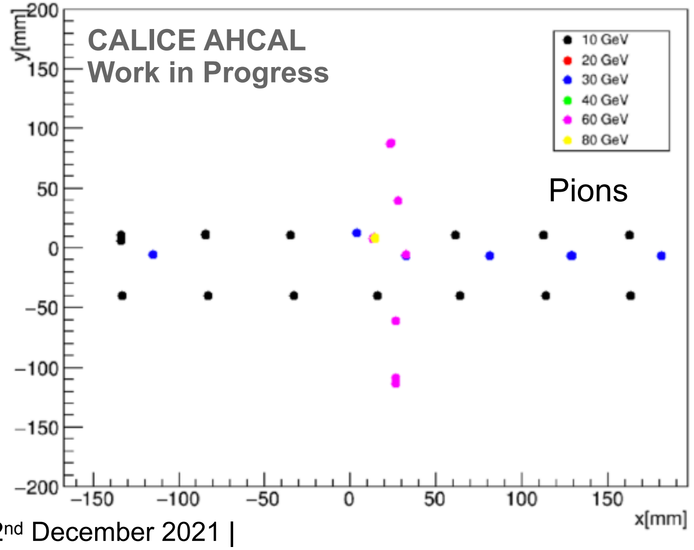
Work done by Linghui Liu (U. Tokyo)
(https://agenda.linearcollider.org/event/8368/contributions/44971/attachments/35214/54544/LL_AHCALmain_2019.pdf)

- Beam Test June 2018: Four 100 x 100 mm^2 delay wire chambers (MWPCs)
- Position resolution of each chamber: ~600 µm
  - ➡ **Sub-mm resolution at AHCAL front face**
- 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





Beam center position map



Brief Recap: AHCAL 2018 Calibration, Stability & Uniformity

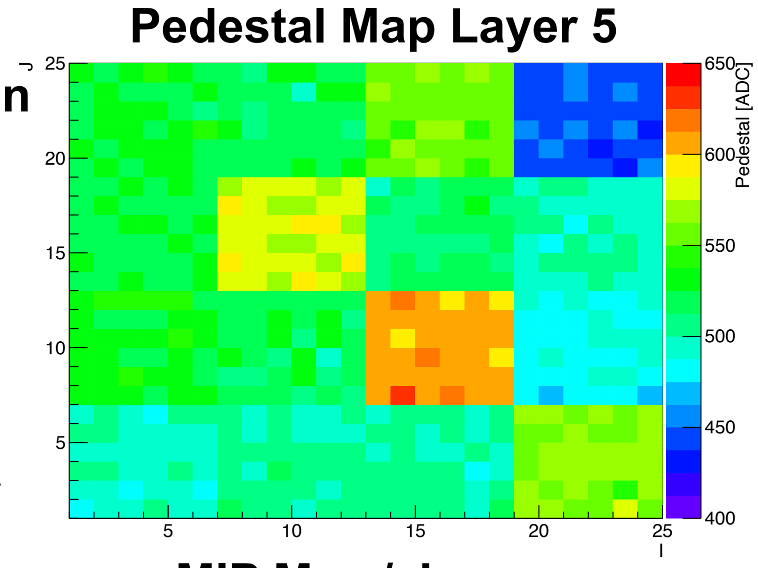
First Part of my PhD Studies: Calibration/Validation & Variation Studies

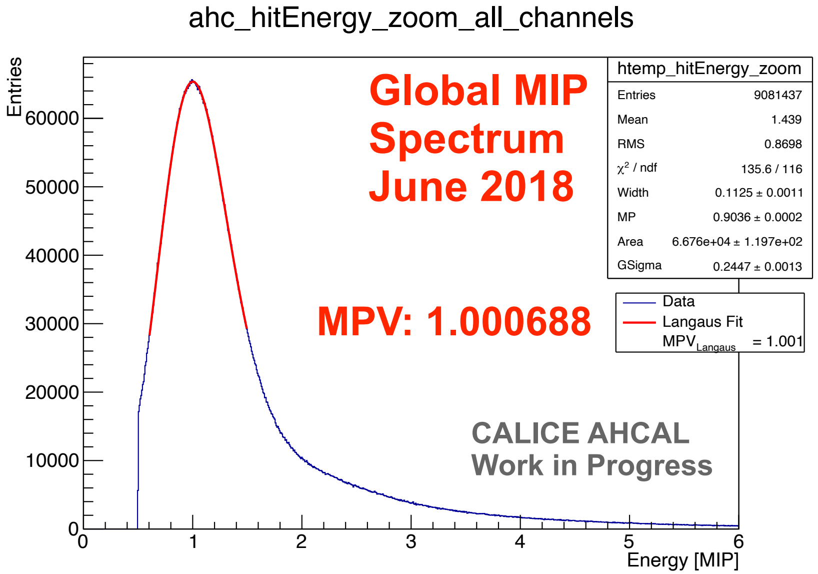
- Performed **pedestal extraction** and **MIP calibration, HG-LG inter-calibration**
  - ➡ Validation studies for determined calibration constants
  - ➡ Variation studies for constants (detector modes, beam test periods)

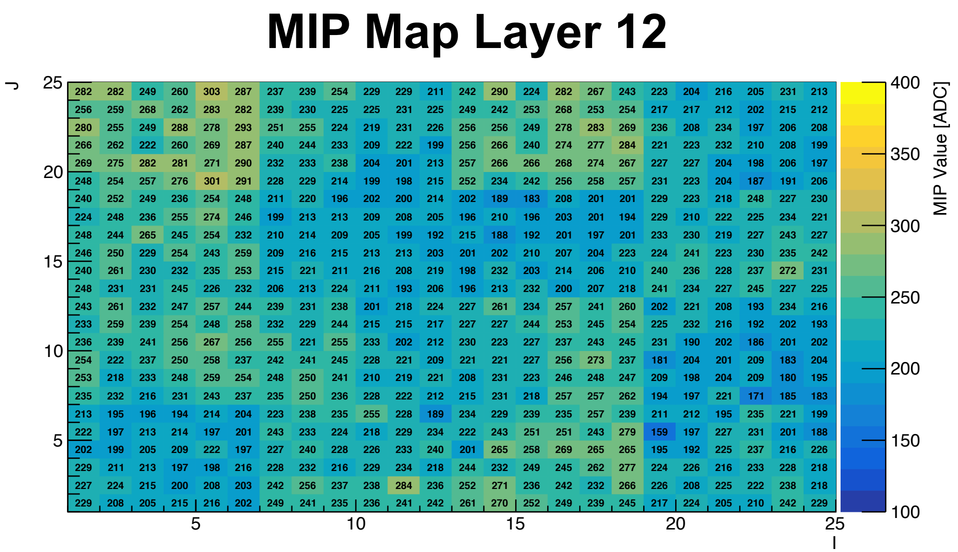
➡ Shown: Excellent detector uniformity, stability and signal to noise ratio

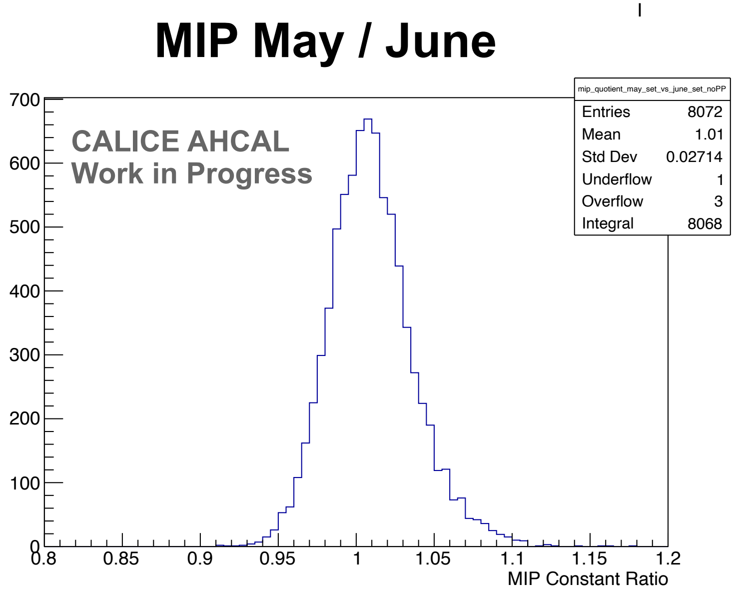
➡ Provided energy calibration of prototype - used in many analyses of 2018 data

https://agenda.linearcollider.org/event/8213/contributions/44354/attachments/34779/53694/DH_calice_9_19_ahcal_calibration_v2.pdf









Shower Start Finding Algorithm

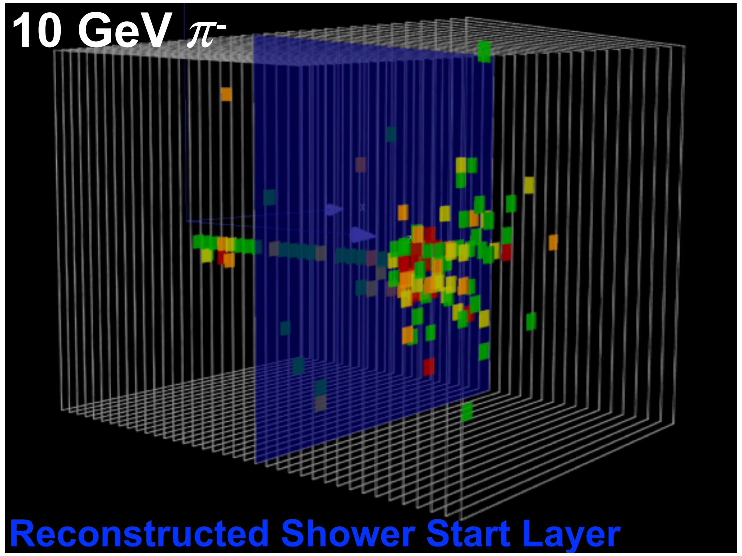
Finding the Layer of First Hard Hadronic Interaction

Implemented in cooperation with Jonas Mikhaeil (University of Heidelberg) during supervision of his Bachelor's Thesis.

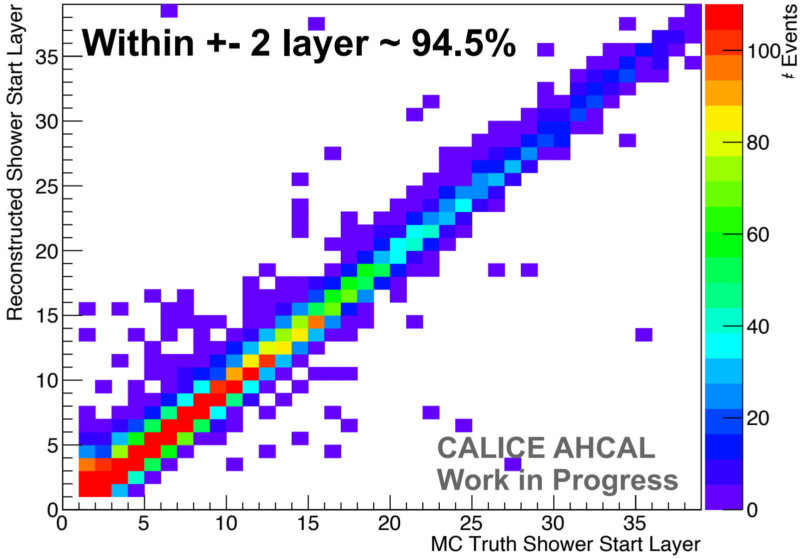
- Determines the layer of first hard interaction: **Shower start layer** based on number of hits and energy thresholds on layer level
- Optimised and tuned MC truth information of MC pion samples

➡ Achieved excellent results on same level as for study on last AHCAL prototype (https://arxiv.org/abs/1105.3417)

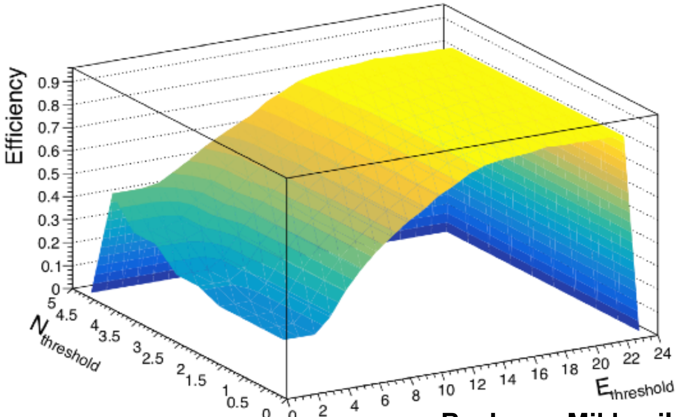
➡ **Central tool for many other developed algorithms**



30 GeV π^- (10k events)

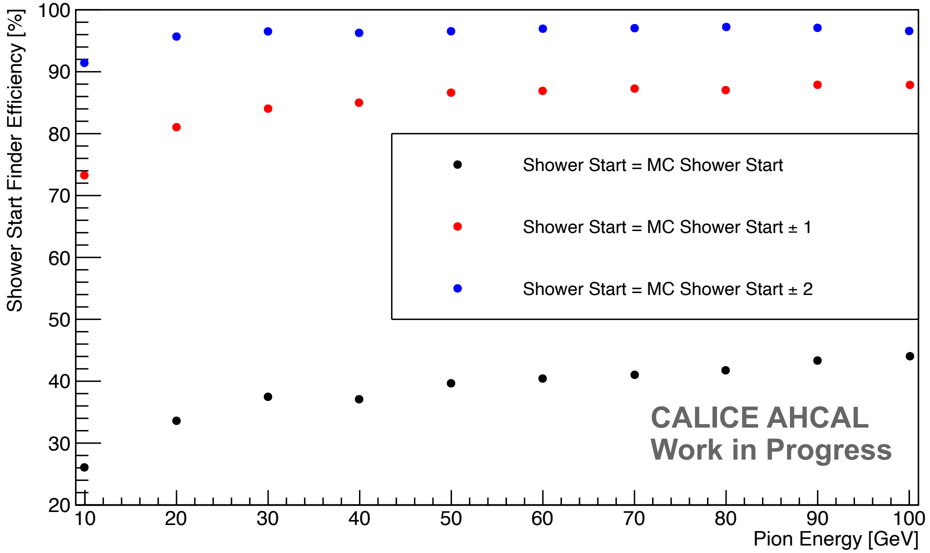


Thresholds vs. Efficiency Optimisation



By Jonas Mikhaeil (Bachelor Thesis)

Efficiency vs. Pion Energy



Track Quality Validation

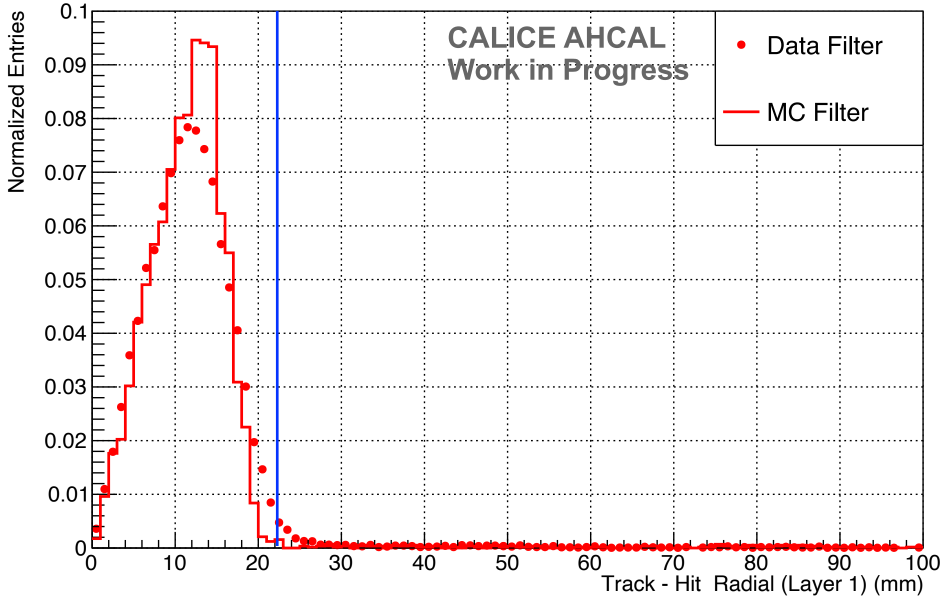
Implemented Data & MC Tracks for PandoraPFA Studies

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

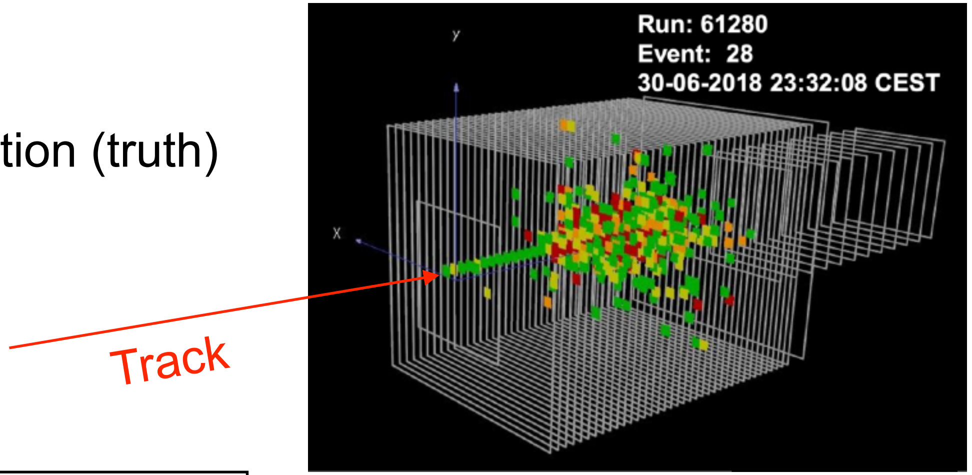
- Data tracks: Reconstructed from DWC of beam test
- MC tracks: Primary particle endpoint position extrapolation (truth)

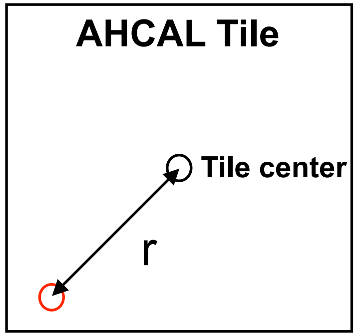
➡ **How is the track quality on average?**

Distance of Track to Center of Closest Triggered Channel in Layer 1



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





Track position projected to calorimeter front face

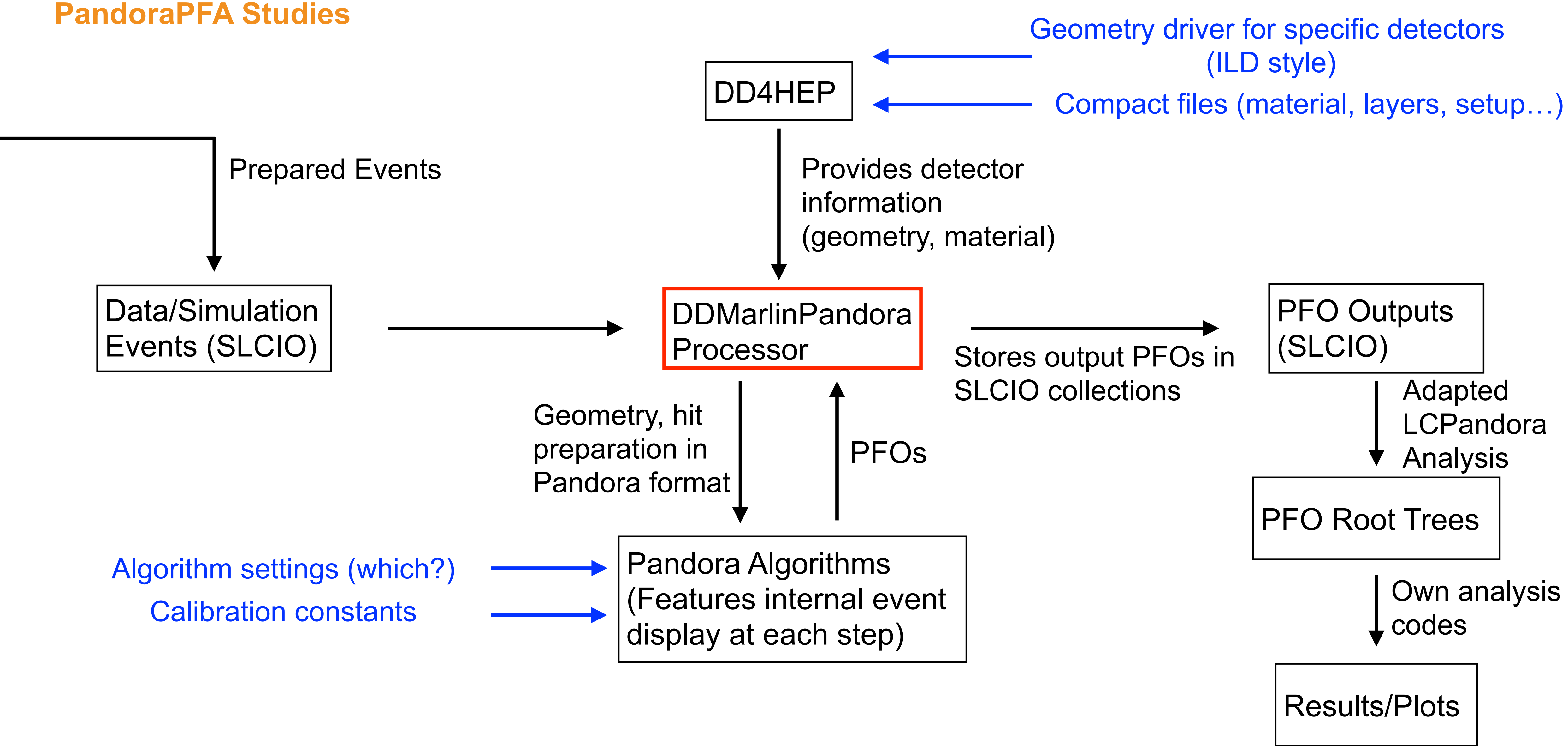
- 97.5% (data) and 98.5% (MC) of events within 22 mm radius (tile center - corner distance)

➡ Most of the tracks hit a triggered channel in layer 1

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

Framework / Data Flow Diagram

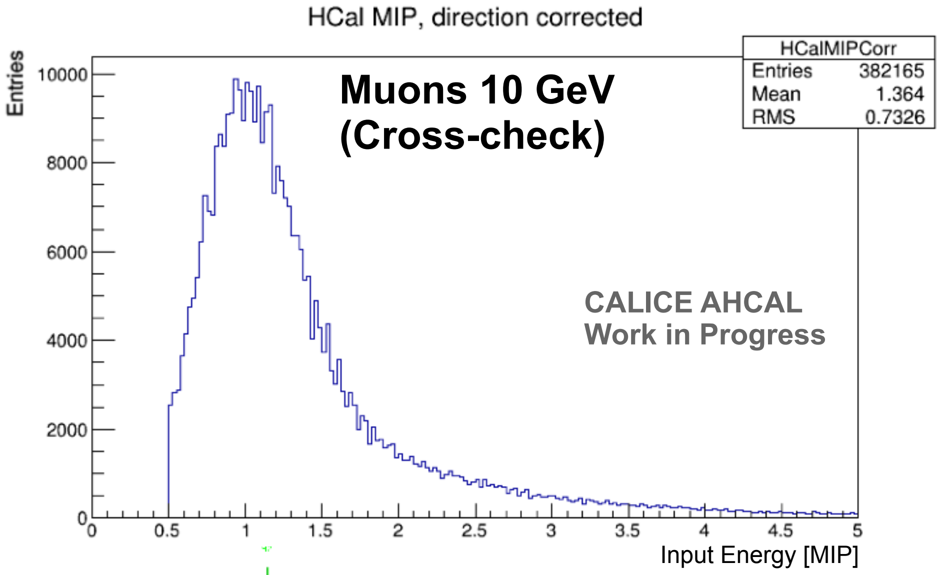
PandoraPFA Studies

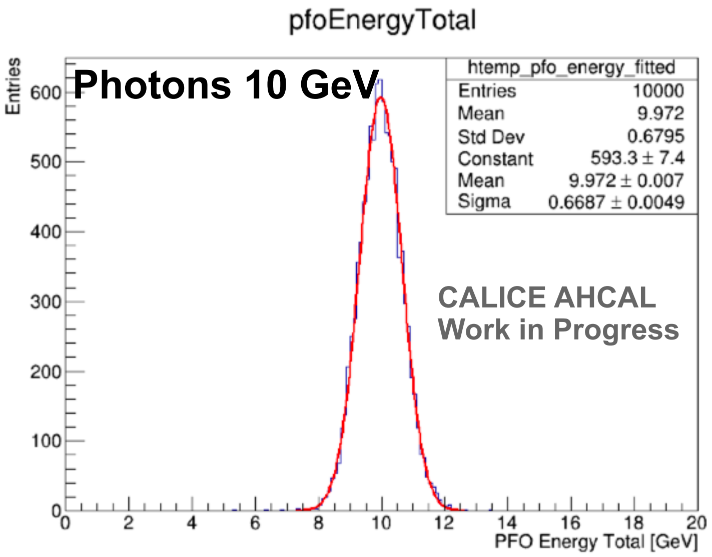


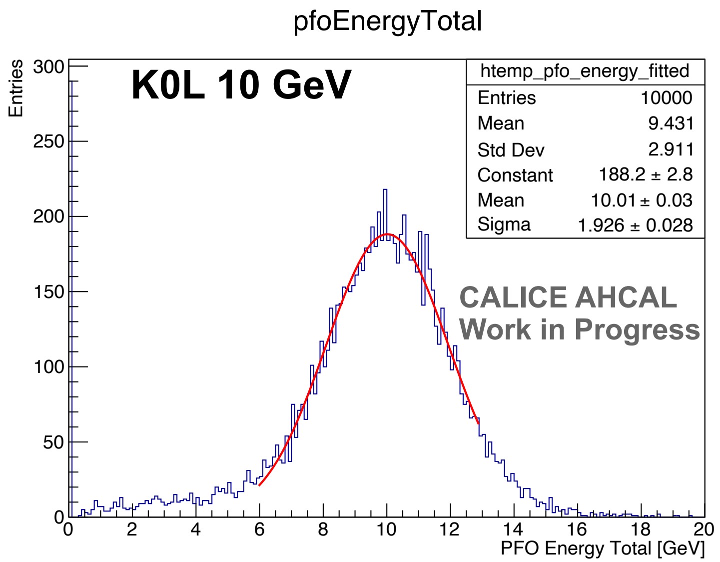
Pandora Energy Calibration

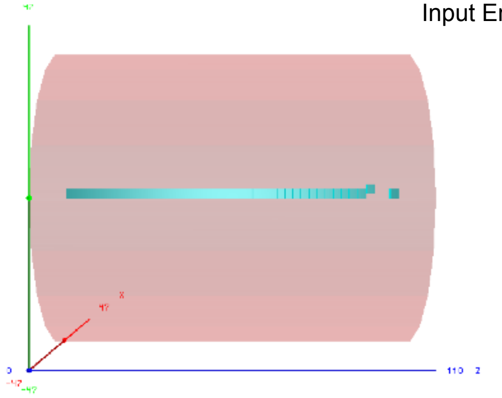
MC Muons, Photons, K0L

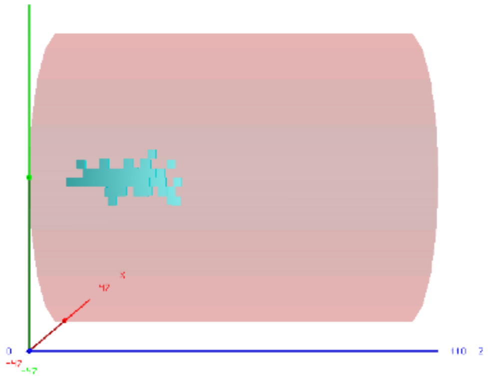
Note: Without tracks and ECAL everything classified as neutral hadrons at this step

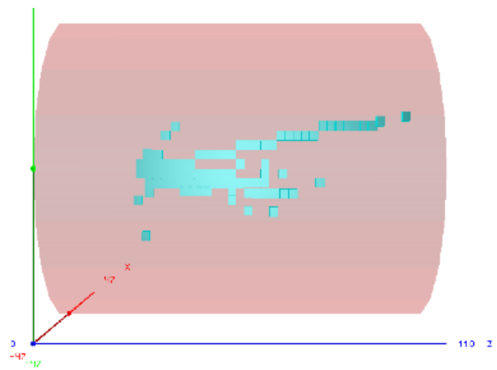










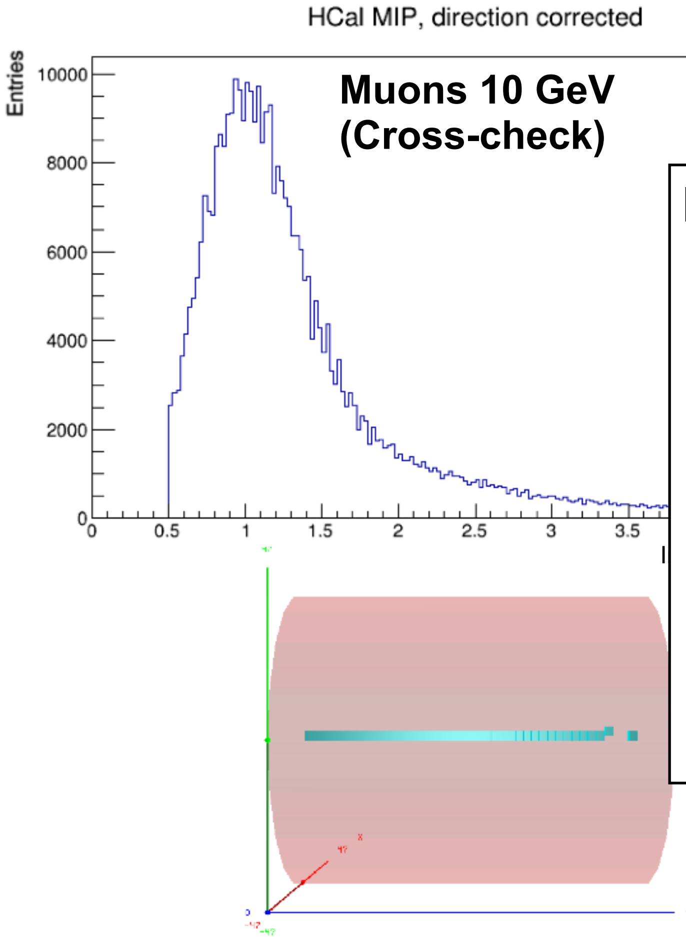


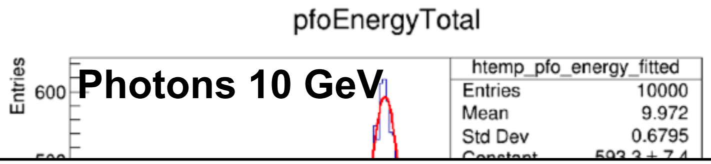
- **Muons**: AHCAL energy GeV -> MIP with negligible angle correction since straight TB tracks
- **Photons and K0L's**: Used to determine EM and HAD response, PFO energy tuned to peak at 10 GeV

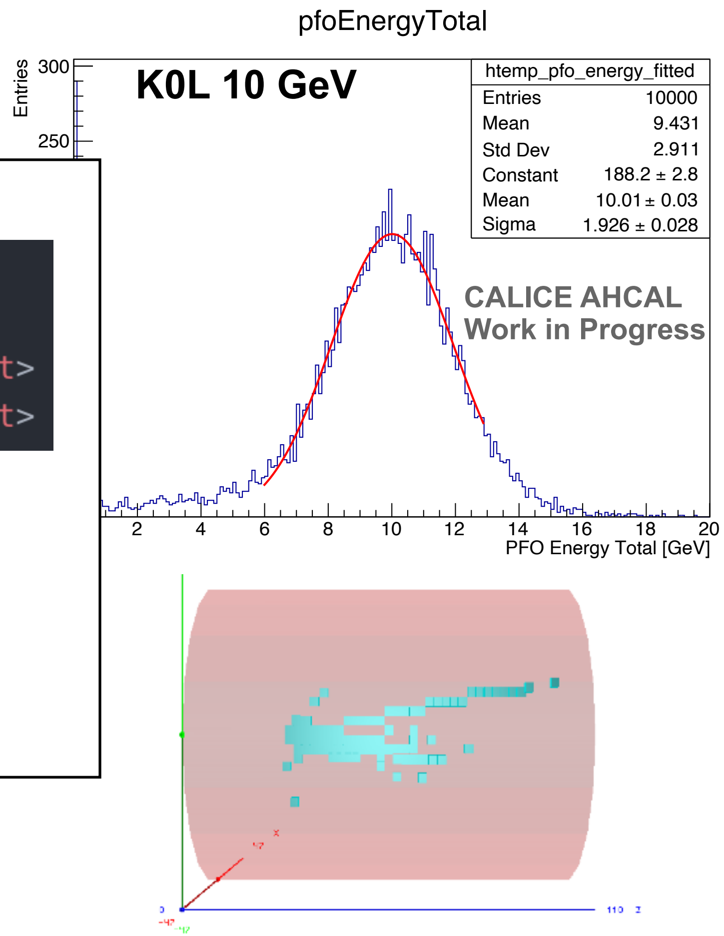
Pandora Energy Calibration

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>
```

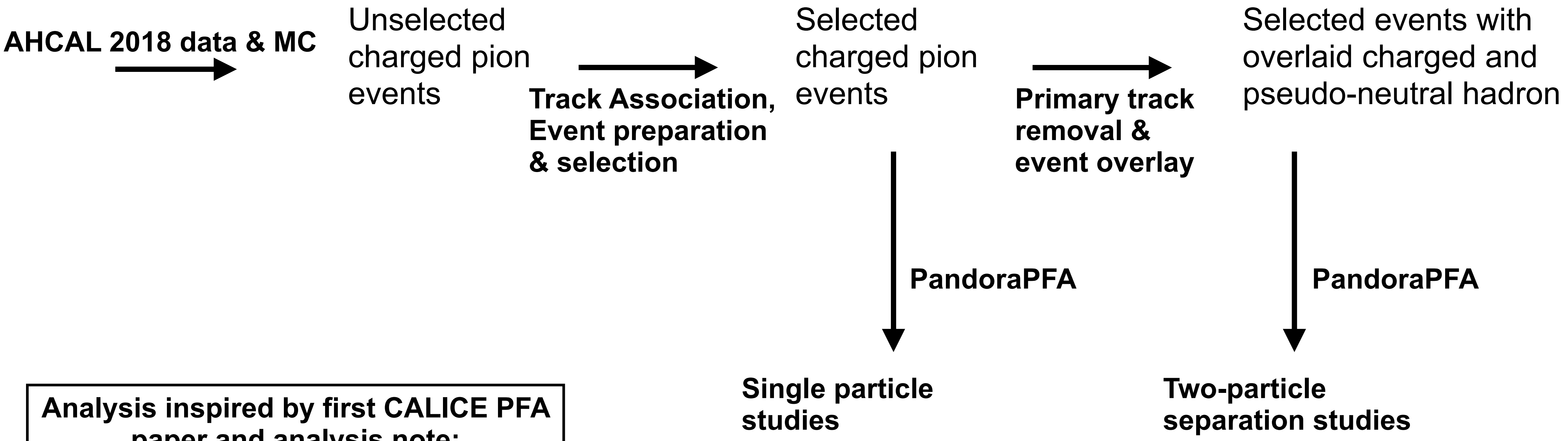
- Both factors a bit higher than for raw AHCAL response (= 1.0)
  - ➡ Pandora clustering isolation cuts

- **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

Analysis Strategy - Overview

Note: No neutral hadron beam during beam tests

Developed Algorithms for Event Preparation & Selection



Analysis inspired by first CALICE PFA paper and analysis note:
https://arxiv.org/abs/1105.3417
&
http://cds.cern.ch/record/2669487/files/fulltext.pdf

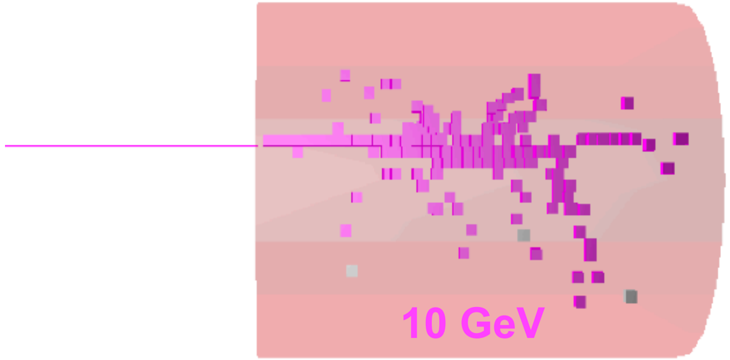
Sample Selection & PandoraPFA Framework

PandoraPFA Single Particles - AHCAL 2018 Data & MC

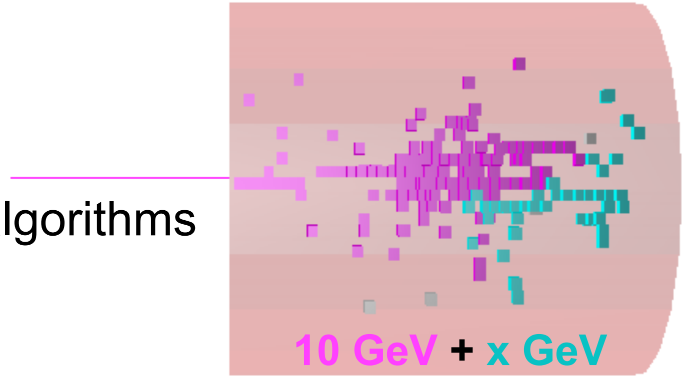
MC: GEANT4 v.10.03 QGSP_BERT_HP & FTFP_BERT_HP physics lists

- Applied Boosted-Decision-Tree PID for hadrons (to remove beam contamination)
- **Event: 10-80 GeV charged hadrons**
- Track for charged hadron: Fixed sharp momentum
  - ➡ Data: Delay wire chambers at beam test; MC: MCTruth information
- Additional event selection (since no ECAL in front of AHCAL):
  - ➡ Track-hit match layer 1||2||3, track-detector-gap rejection
  - ➡ At least 10% of charged hadron energy associated to track
- PandoraPFA: ILD default settings with PFA recalibration, specific adaptions on algorithms and interface processor due to AHCAL geometry & standalone application

Good Reconstruction

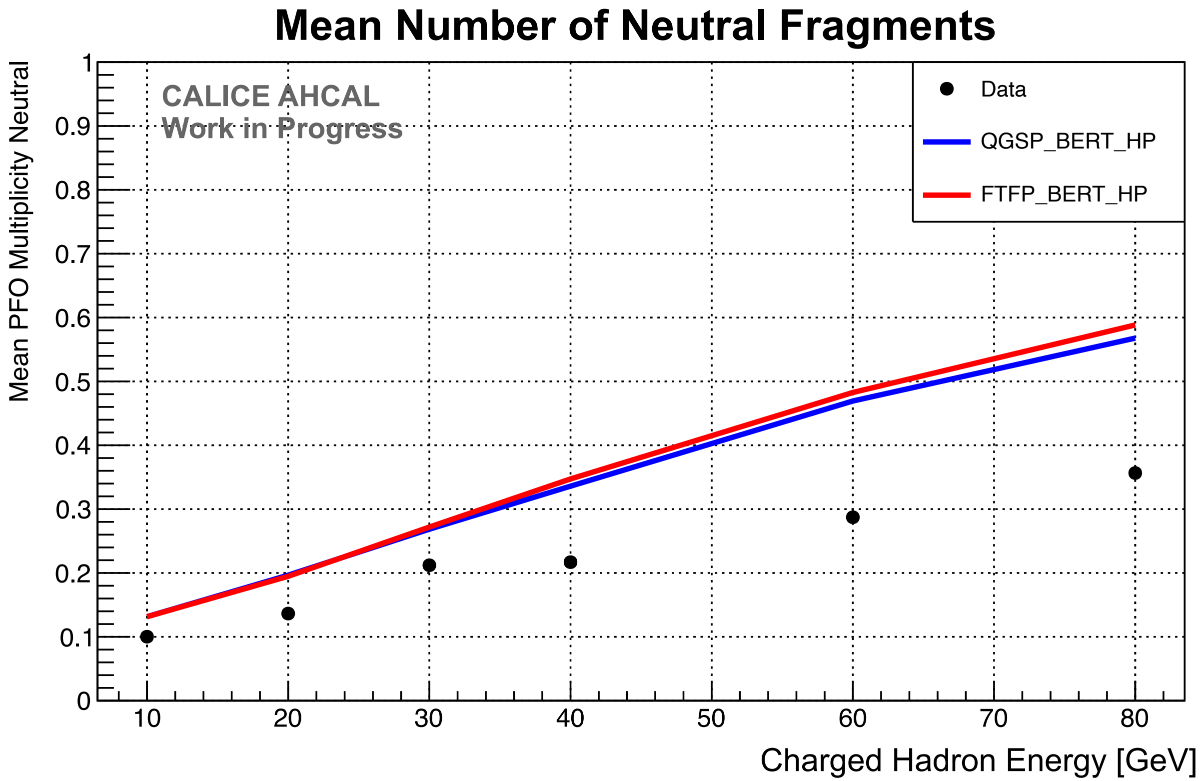


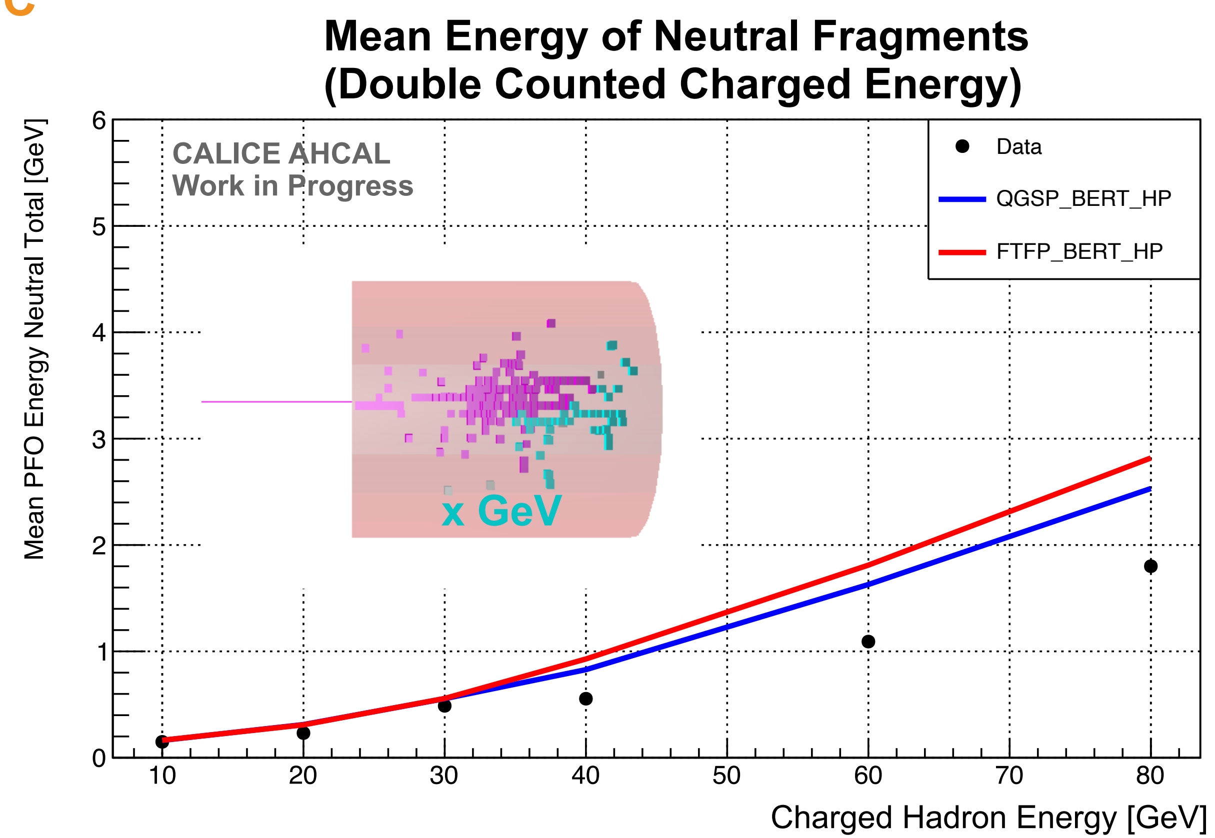
Confusion (Double Counted Charged Energy)



How many Neutral Fragments and Double Counted Energy?

PandoraPFA Single Particles - AHCAL 2018 Data & MC



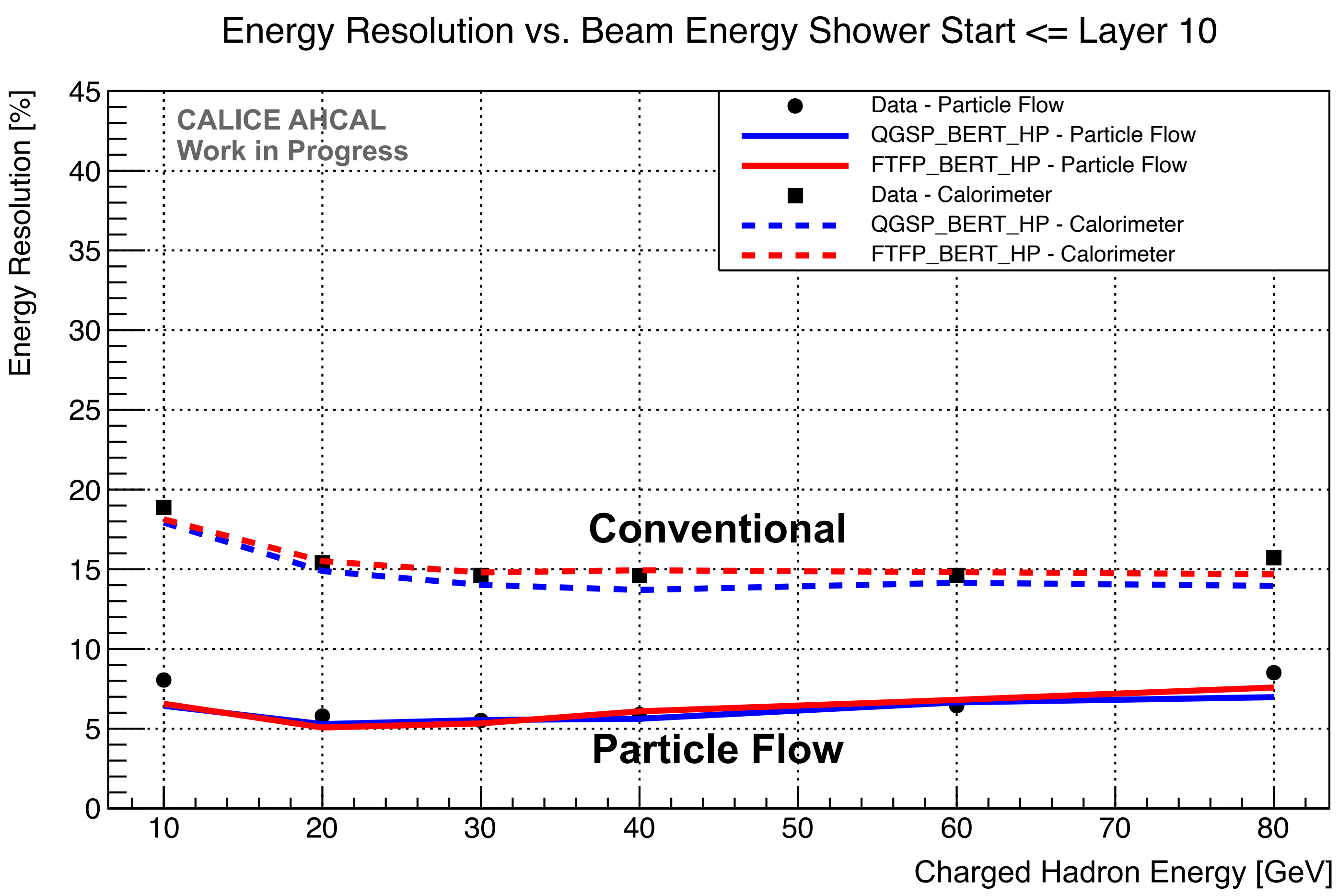


- Mean number of neutral fragments and double counted charged energy increasing with charged hadron energy
  - ➡ Richer topology within shower sub-structure for higher energies (more partially isolated sub-cluster)
- Slightly larger increase for simulations: Richer shower sub-structure topology compared to data?

Improvement in Single Particle Energy Resolution?

PandoraPFA Single Particles - AHCAL 2018 Data & MC

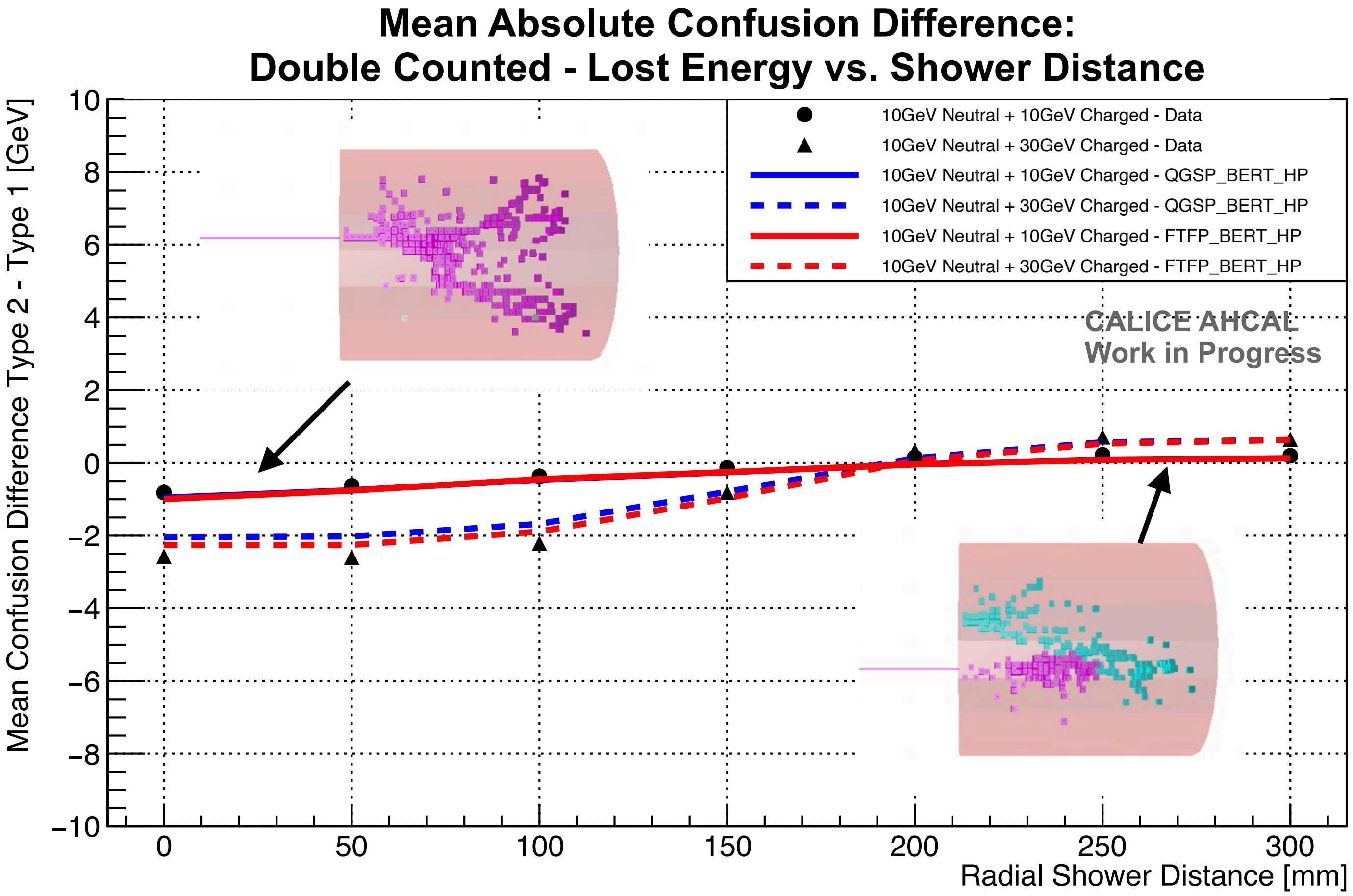
- Particle Flow: **Factor 2 better** single particle energy resolution compared to conventional calorimetry
  - ➡ Exploiting fixed track momentum
  - ➡ For higher energies: Resolution slightly decreasing due to increasing confusion level
- Good data to simulation agreement



How well are Types of Confusion Balanced?

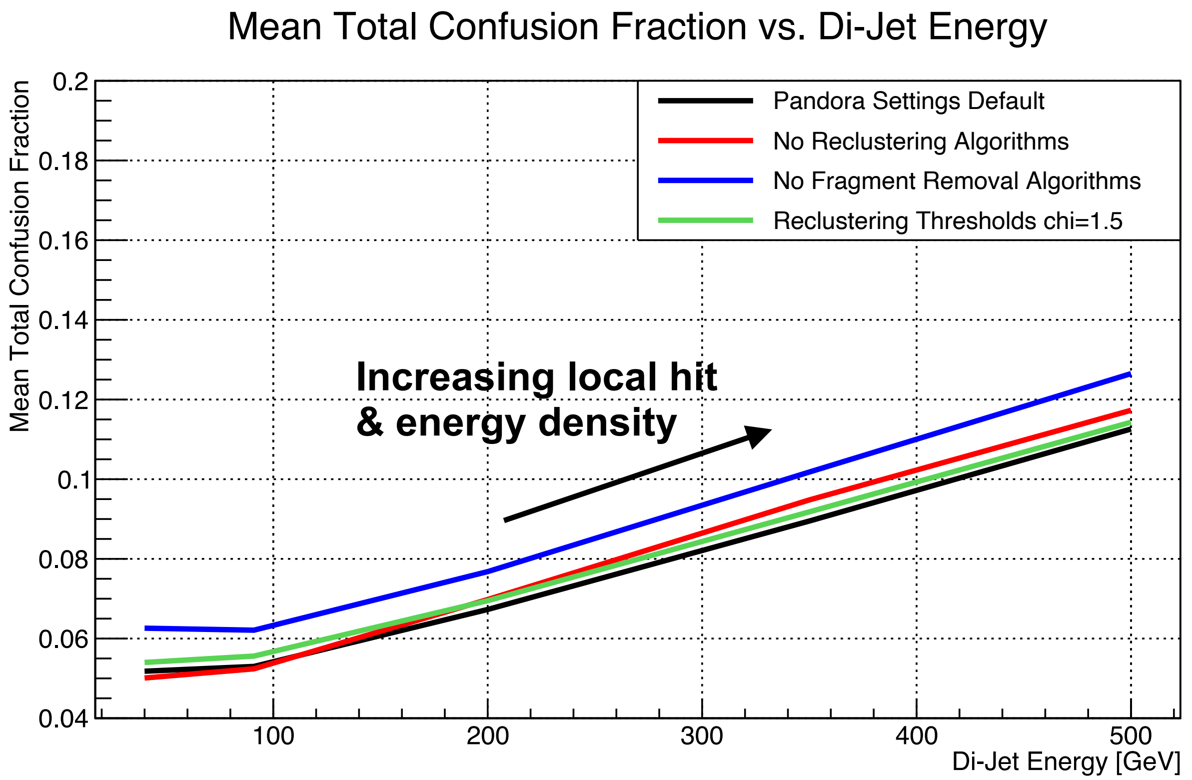
Double Counted Energy - Energy Loss Difference

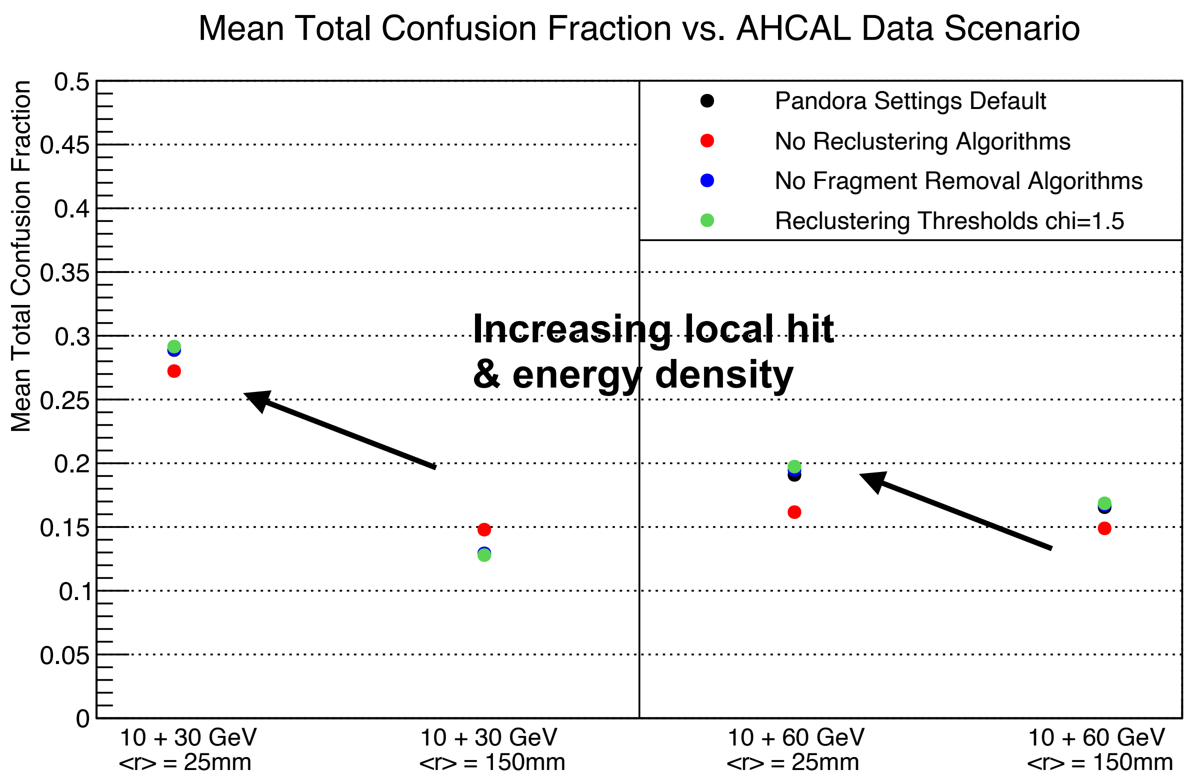
- Highest shower distances: Double counted energy (additional neutral fragments in shower sub-structure) dominant
- Lowest shower distances: Energy losses (neutral hit absorption into charged) dominant
  - ➡ In-balance more pronounced for vicinity of 30 GeV charged hadron
  - ➡ Turning point ~200mm shower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



How is the Total Fraction of Confused Energy Scaling?

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





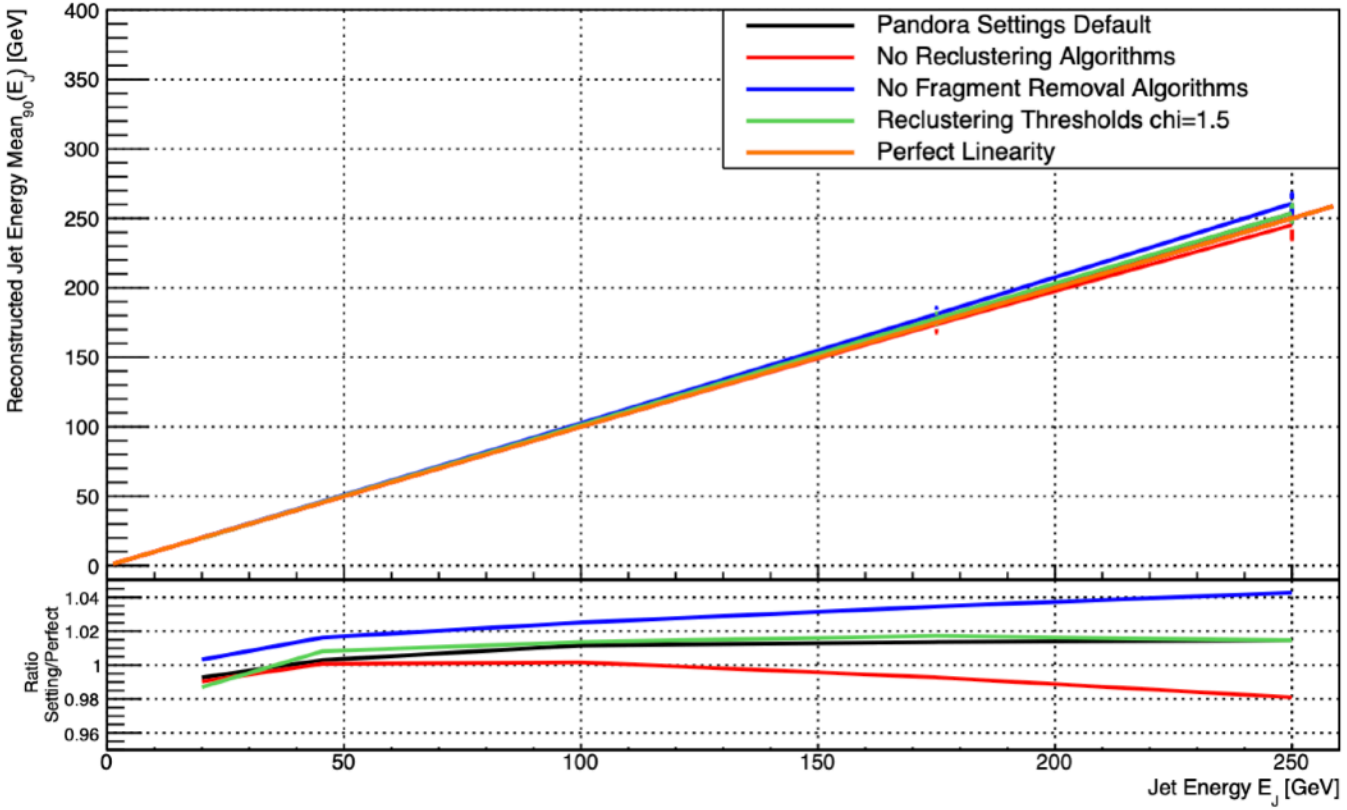
- Mean fraction of confused event energy is increasing with jet energy (local hit & energy density)
- Most fractional confusion energy for no fragment removal & no re-clustering, best for default settings

➡ Combination of balance and low level of confused energy contributing to best JER for default settings

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
  - ➡ No re-clustering: Missing energy due to absorption of neutral hadrons into charged

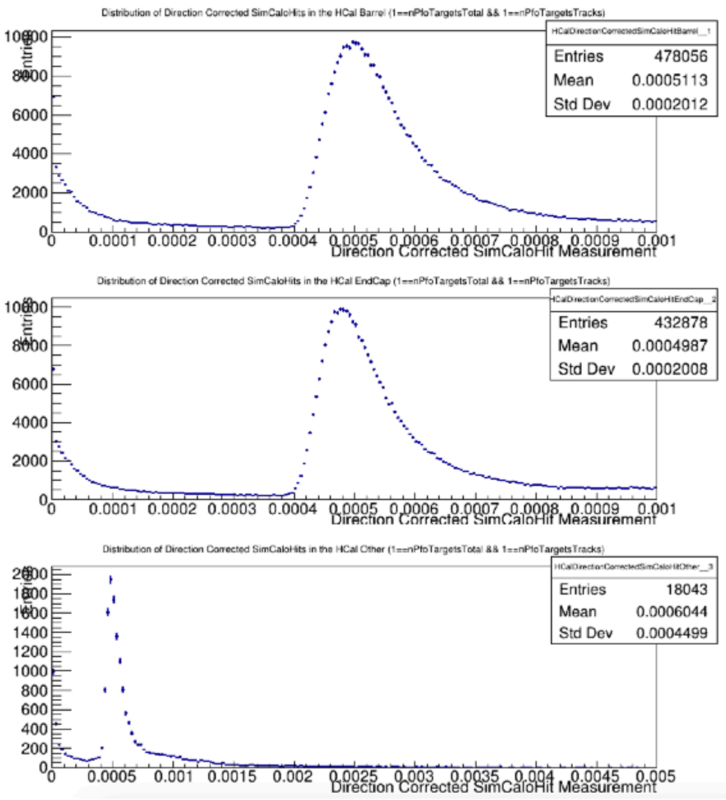


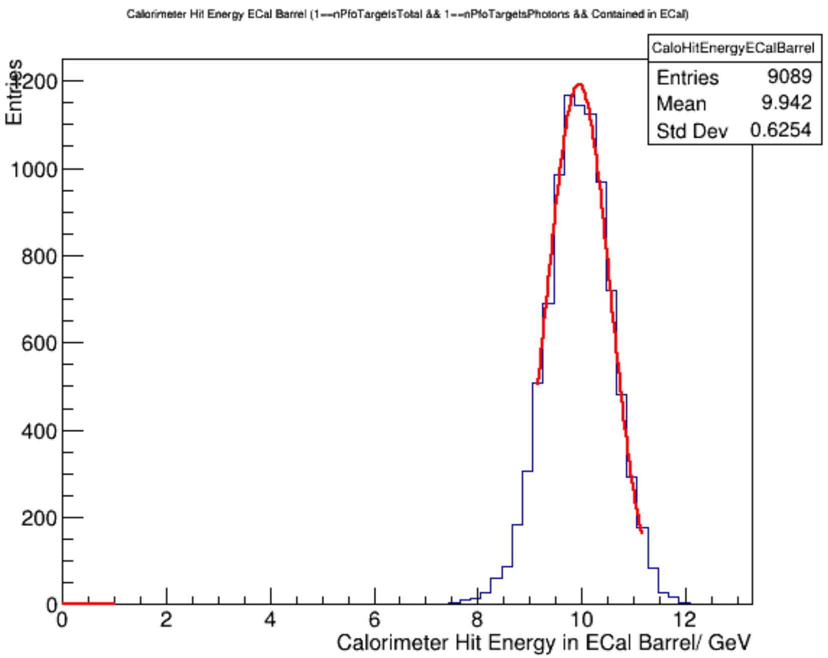
ILD Di-Jets

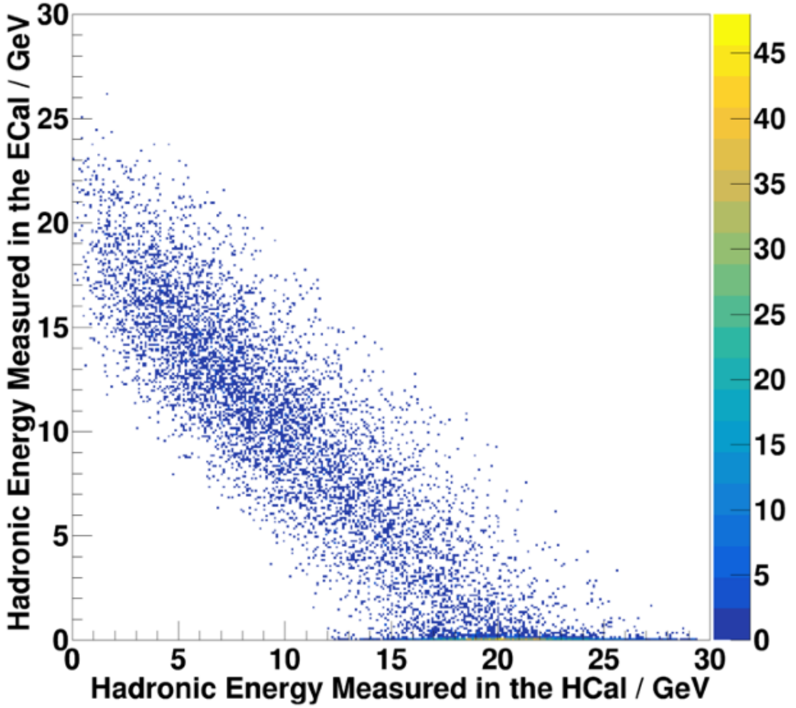
https://github.com/iLCSoft/LCCalibration/tree/master/doc

Recalibration PandoraPFA

- 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!







AHCAL Events

Recalibration PandoraPFA

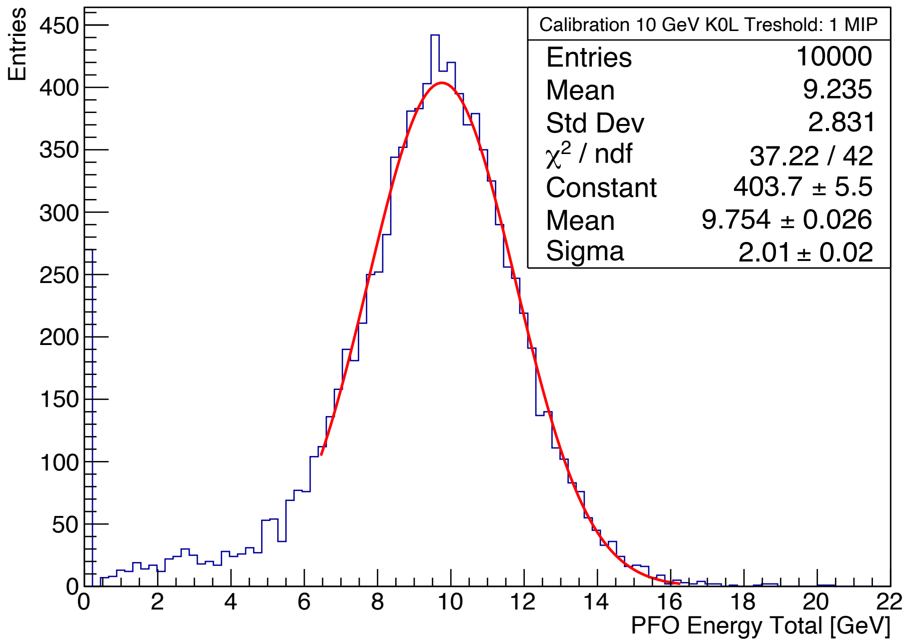
- For each threshold scenario (1, 2, 3 MIP) **1 internal PandoraPFA calibration constant** recalibrated with 10 & 30 GeV K0L for optimised PandoraPFA output

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

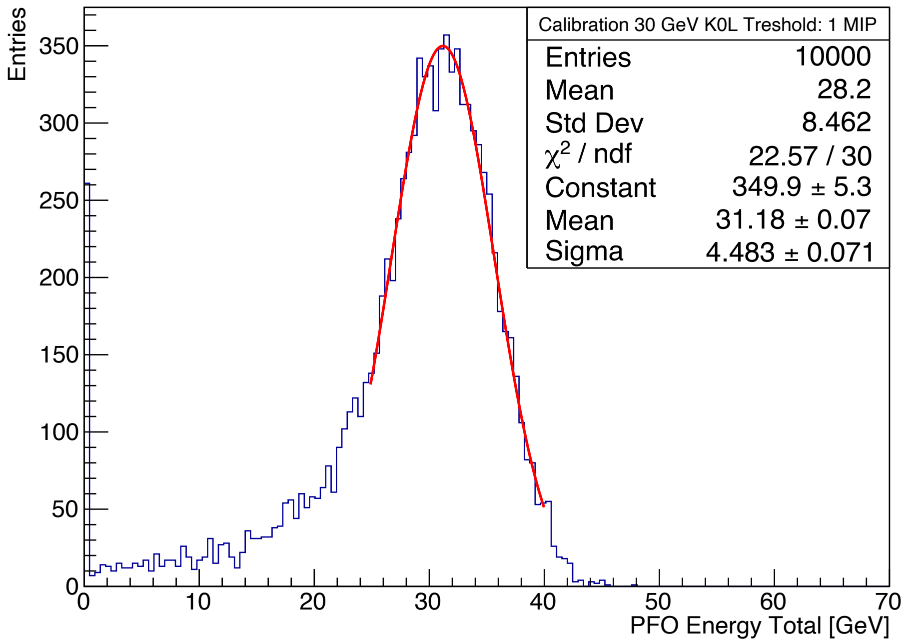
  ➡ Optimised to recover 10 & 30 GeV neutral hadrons simultaneously as accurate as possible (within 5%)

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

PFO Energy Calibration 10 GeV K0L Treshold: 1 MIP

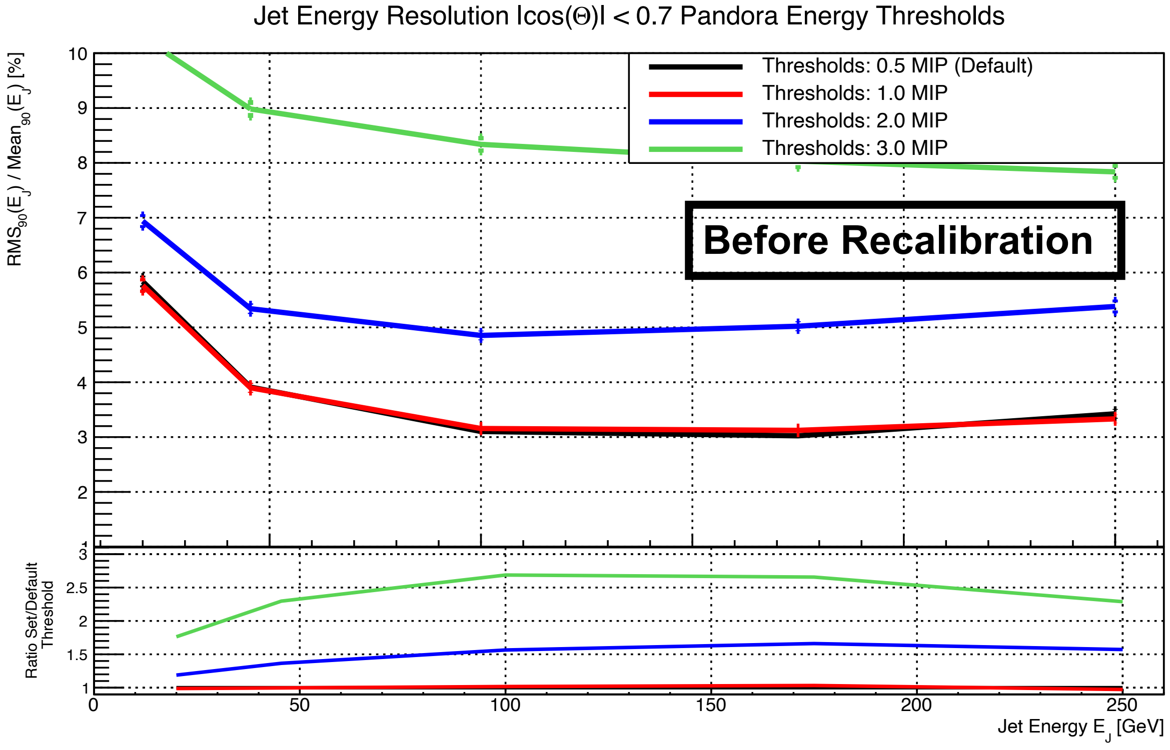


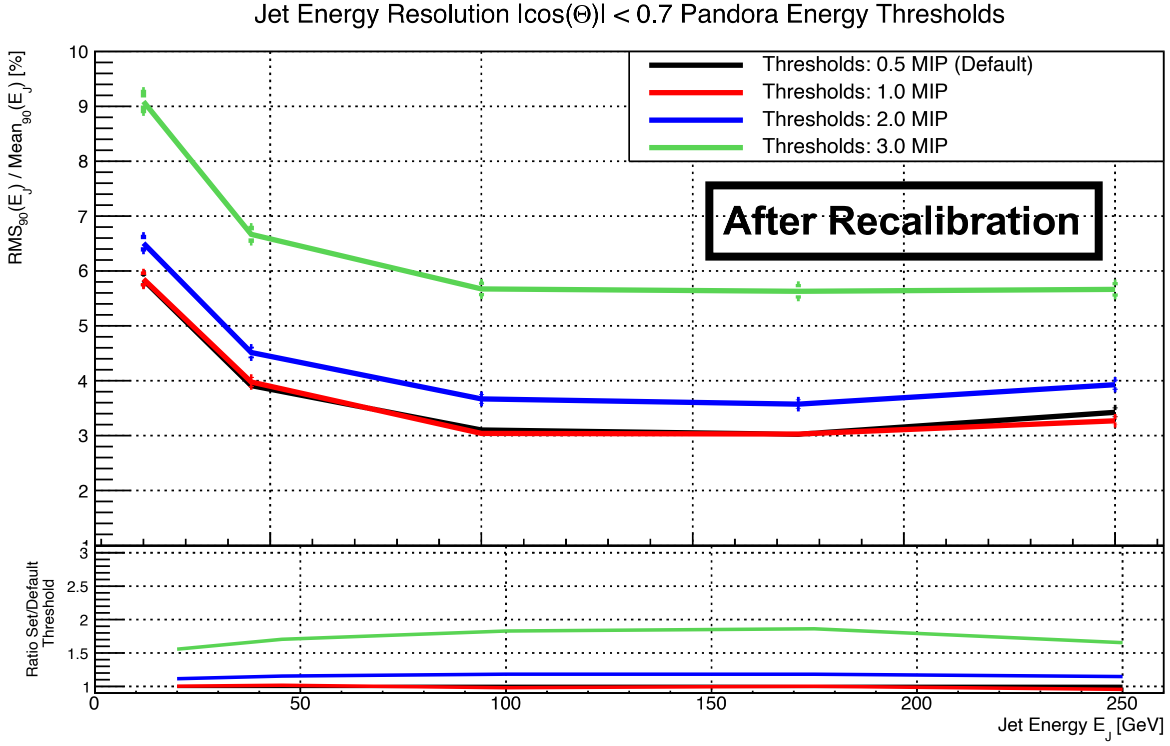
PFO Energy Calibration 30 GeV K0L Treshold: 1 MIP



Jet Energy Resolution

Before and After Recalibration

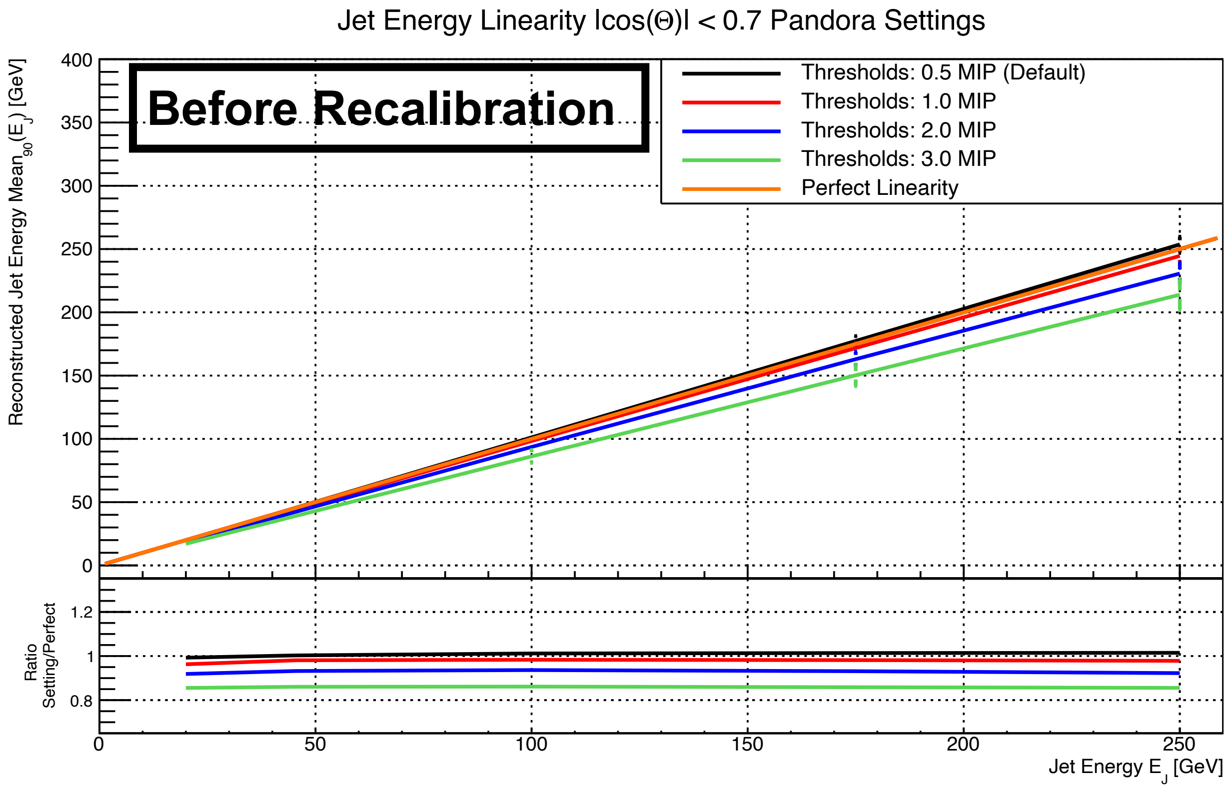


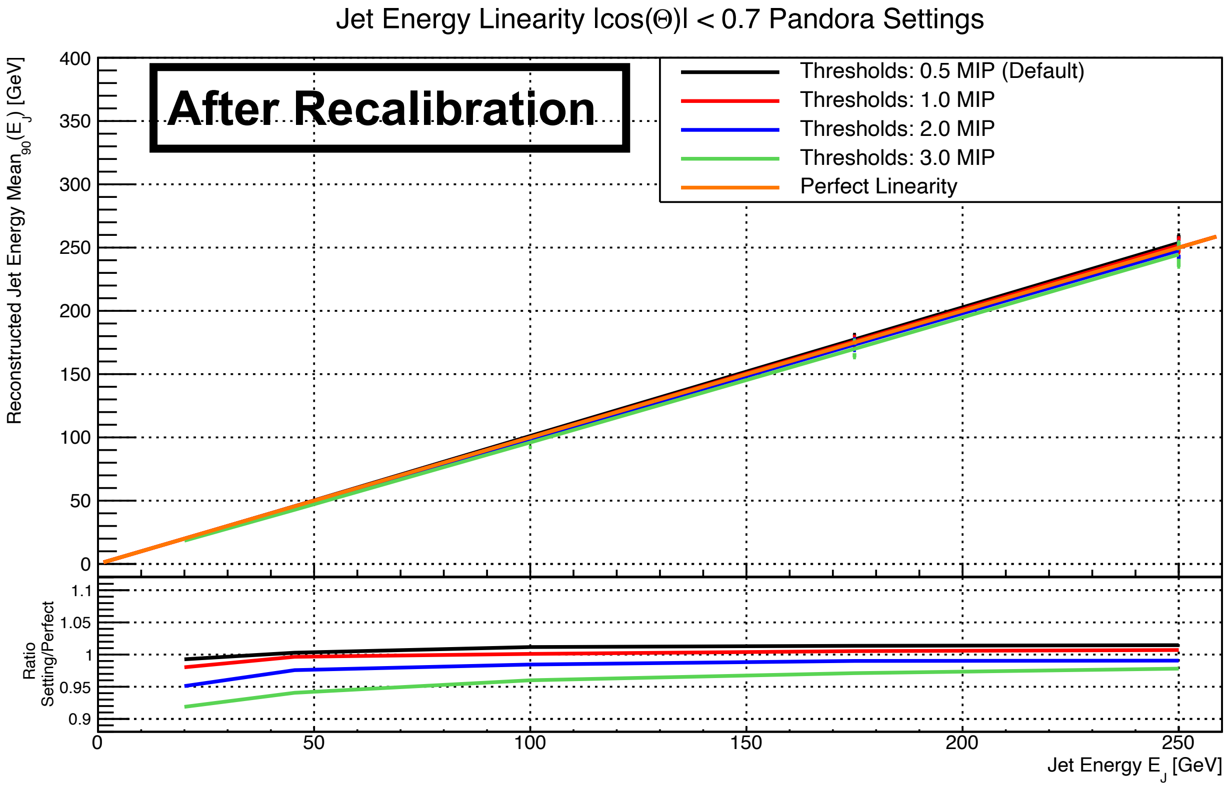


- Recalibration: Significant improvement in jet energy resolution, specifically for higher thresholds
  - ➡ Degradation of JER trend for highest energy threshold remain, but „only“ up to ~80% (before: ~160%)
  - ➡ For slightly increased thresholds 1 MIP - basically no effect, for 2 MIP only 20% worse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

Jet Energy Linearity

Different Energy Thresholds (ECAL & HCAL)



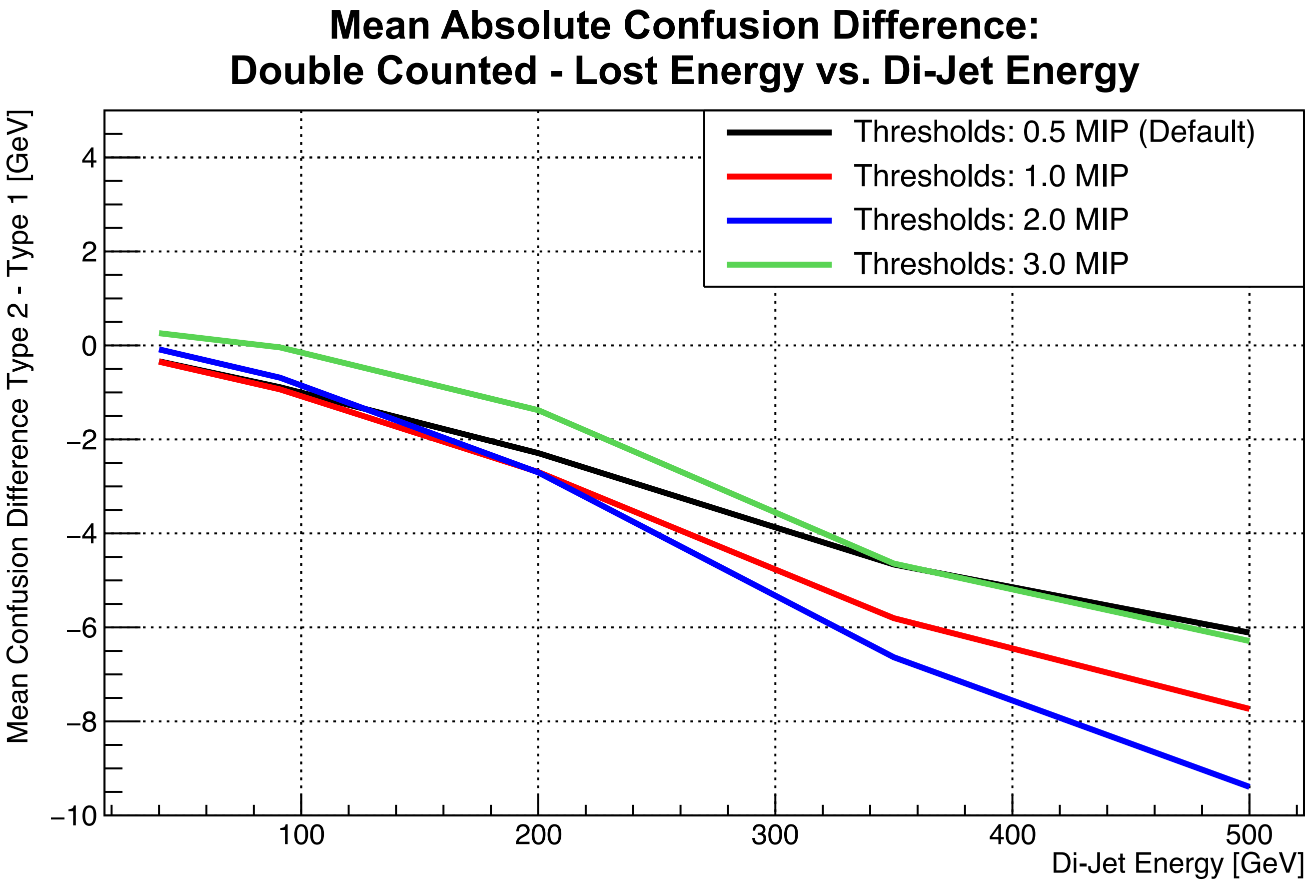


- Recalibration: Significant improvement in jet energy linearity, specifically for highest thresholds
  - ➡ For almost all jet energies within 5% to perfect linearity
  - ➡ Still slightly off due to difficult PFA reconstruction with increasing confusion term

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 neutral energy loss 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 double counted charged energy is increasing again
  - ➡ Artificial topological separation between different particle showers