AHCAL Analyses at DESY

CALICE Collaboration Meeting

McGill University, Montreal

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Outline

For this Talk

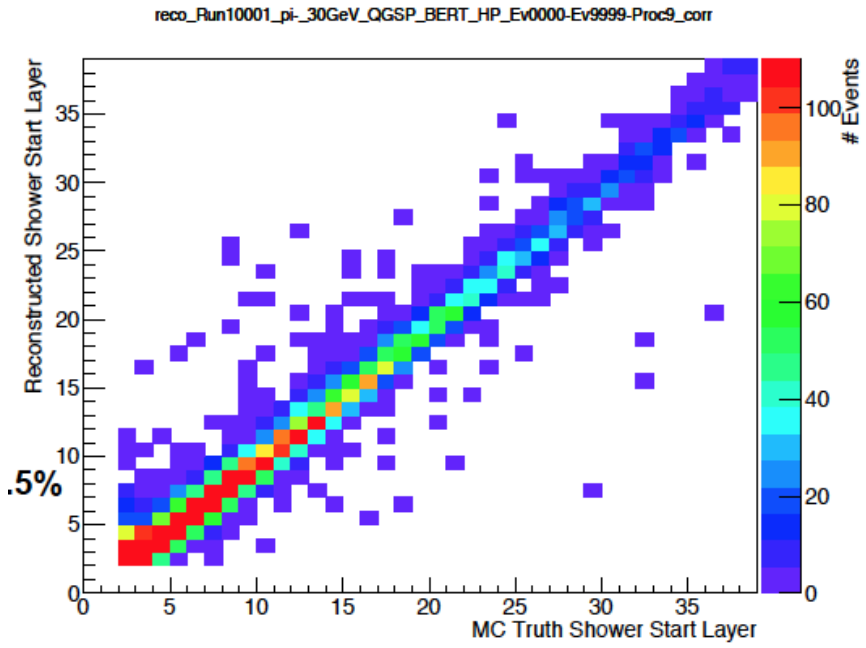
- Analysis tools
  - shower start finder beyond testbeam (Marina)
  - particle ID using Boosted Decision Trees (Vladimir)
  - Neutronness (Olin)
- Electron energy reconstruction
  - influence of gaps between tiles (Olin, Amine)
- Pandora (Daniel, Linghui)

Shower Start Finder

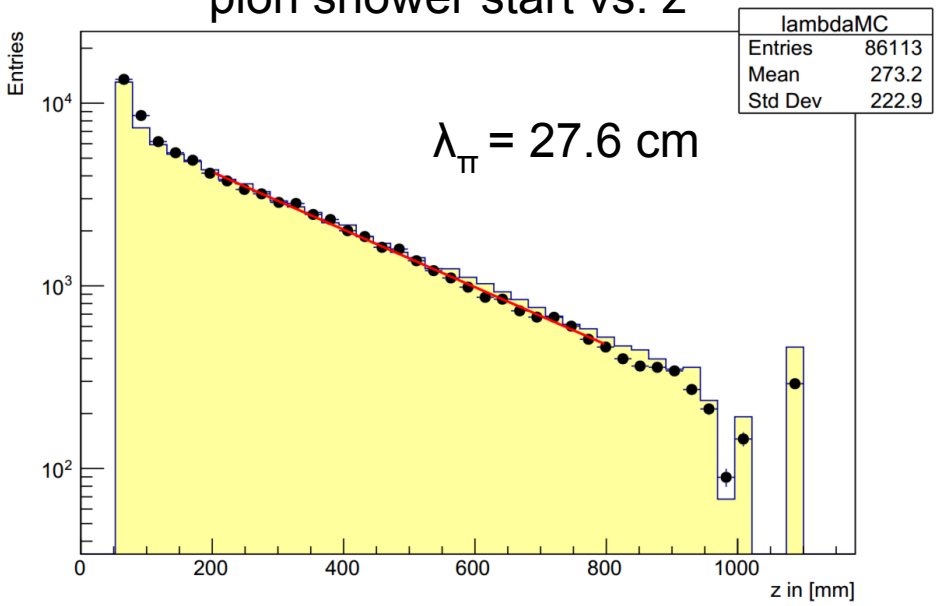
Analysis tools: Shower start finder

in testbeam data

- algorithm based on the shower start finder developed for the AHCAL physics prototype
- optimised shower start finder for technological prototype
  - based on number of hits and energy in sliding window of layers
  - reach >90% of events correctly reconstructed within +-2 layers
  - can be used to measure pion interaction length of AHCAL
  - important ingredient in particle identification



pion shower start vs. z

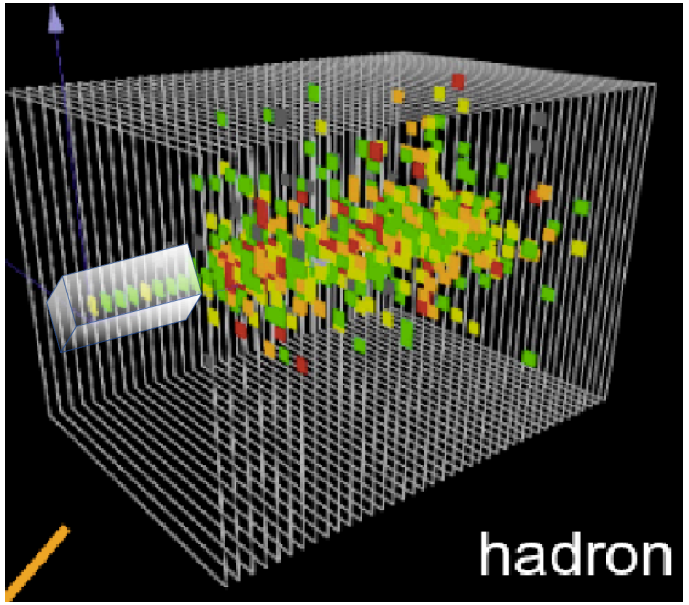


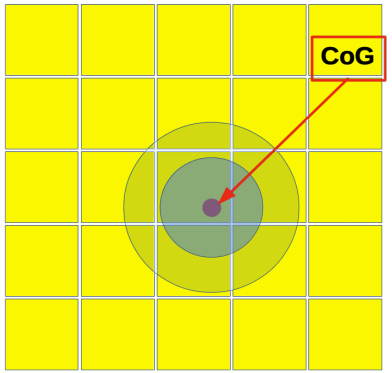
Shower start finder: beyond testbeam prototypes

From prototype to full scale detector

> Motivation

- Shower start finding might help with clustering, shower separation and leakage estimate
- Full-layer approach w/o transverse constraints is not applicable in a real detector (ILD)
- New condition is necessary: look for shower start inside the tower around track
- For charged particles: narrower tower around track, better for shower separation

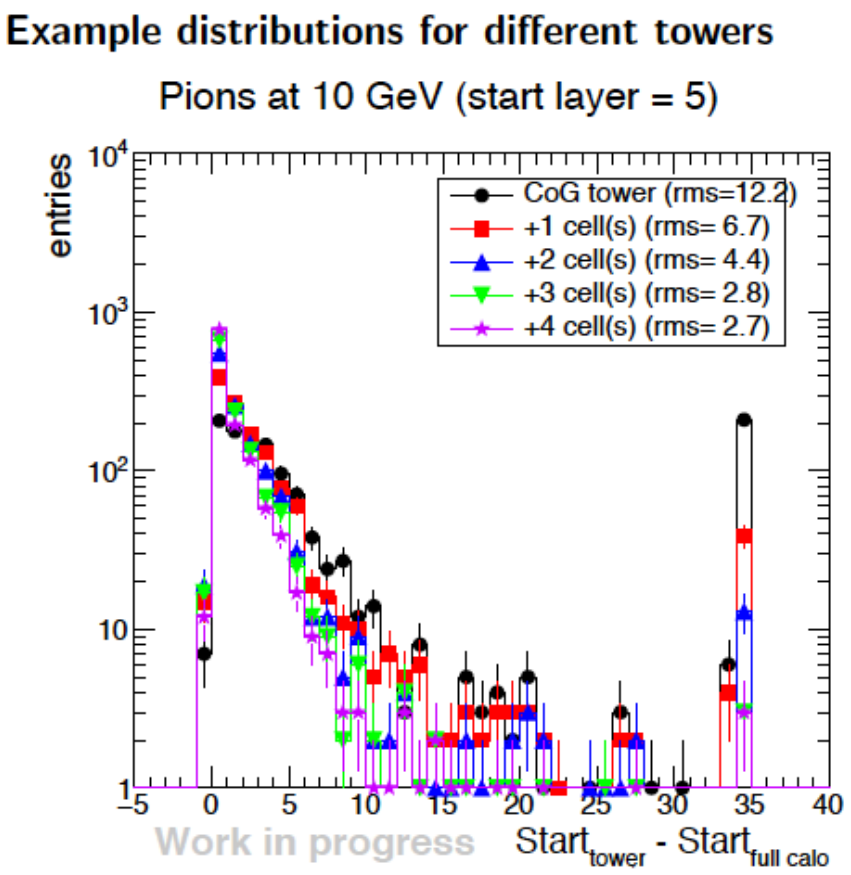


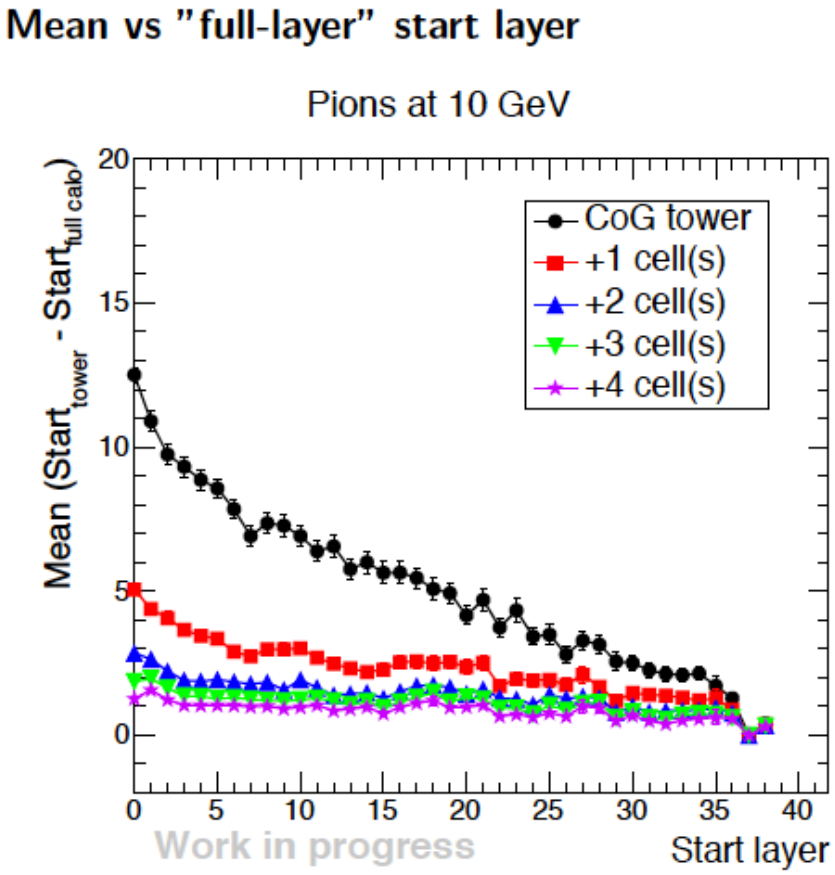


- construct towers around CoG
  step size = cell transverse size
  N.B.: for some events CoG tower might be biased w.r.t. track tower
- collect hits for start finder inside tower only
- find shower start for different towers around CoG (thresholds are the same)
- compare with the "full-layer" result

Shower start finder: Comparison constrained vs. full calo

10 GeV pions

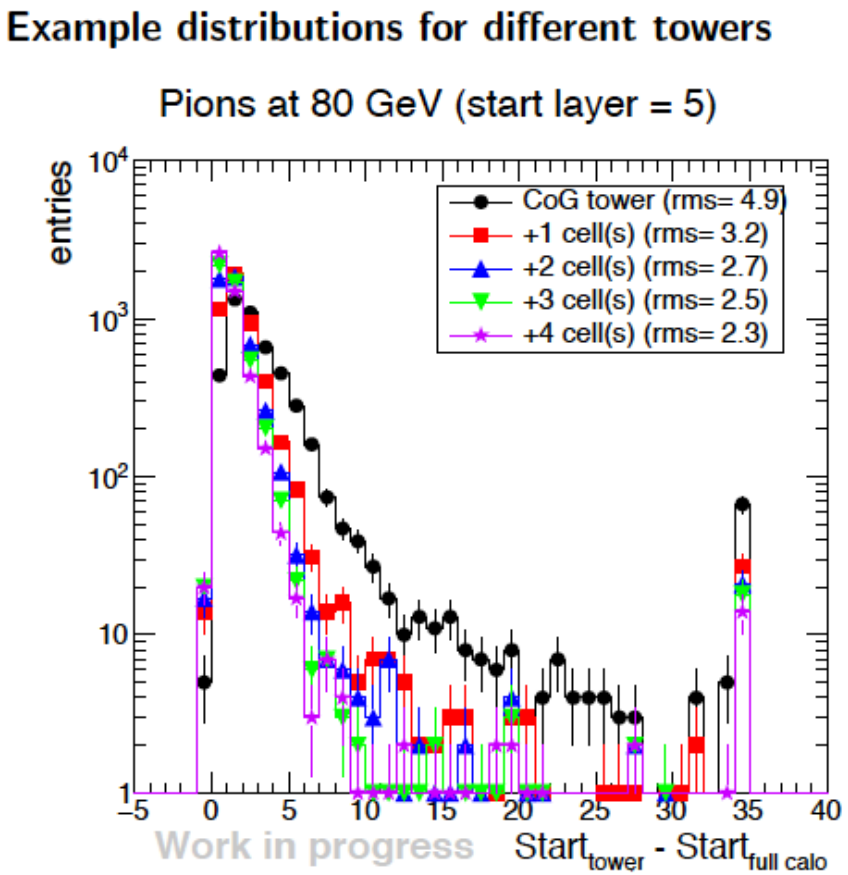


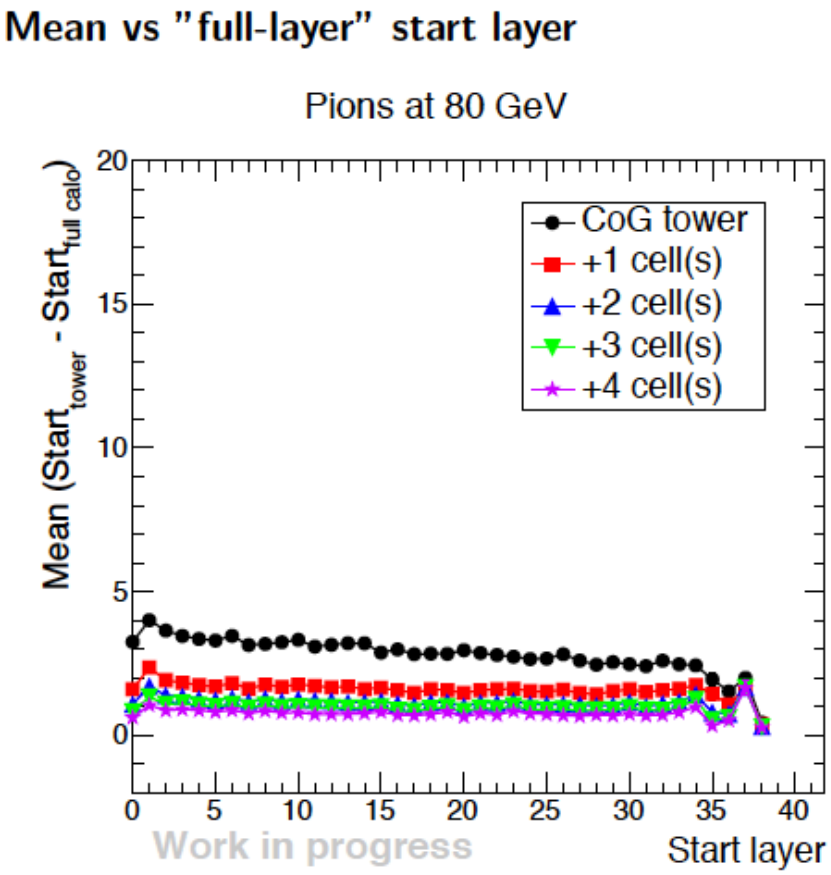


- Shower start is typically identified later with narrower towers — as expected
- fraction with the largest difference (not identified shower start) is 1% for the smallest tower

Shower start finder: Comparison constrained vs. full calo

80 GeV pions





> effects for higher particle energies smaller

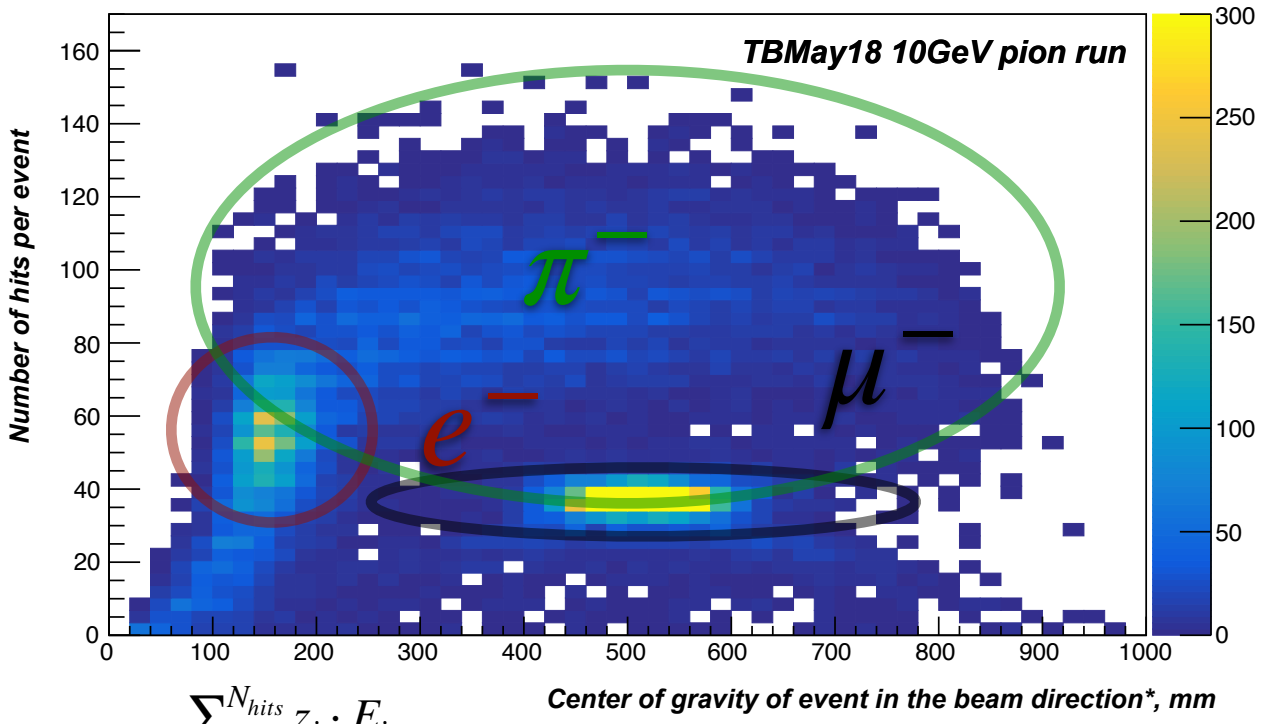
Shower start finder: Summary and Outlook

- Studies of the shower start finding algorithm
  - The algorithm was developed for test beam conditions. It is modified to fit the "real" reconstruction environment.
  - Modified (transverse constraint) versions are compared to the full-layer version.
  - The study was performed on test beam data (pions at 10-80 GeV).
- Preliminary conclusions
  - Modified algorithm with transverse constraints gives stable and consistent results.
  - Later identified showers by the modified version, as expected.
  - Bias and r.m.s. deviation from the full-layer result increase with decreasing particle energy.
  - For implementation of shower start finder in the analysis of full-scale detector, new tuning of the algorithm is necessary.
- TODO
  - Though CoG and track transverse positions are in good agreement, for some events track and CoG towers might not coincide. Hence, track finding/propagation/identification should be implemented for further studies.
  - Look at MC.

Particle ID using boosted decision trees

Motivation for particle ID

In test beam data



$$* \; z_{CoG} = \frac{\sum_{i=1}^{N_{hits}} z_i \cdot E_i}{E_{sum}}$$

We always deal with contamination by other particles.

⇒To investigate detector response to particles of given type we need to perform particle identification

Cut-based method

Observables and classification procedure

Observables:

- Number of hits
- Shower radius
- Center of gravity in z
- Energy fraction in first 22 layers
- Shower start
- Energy fraction in shower core
- Energy fraction in track hits

Event filtering (rejected events):

- **Number of hits**: nHits < nHits_min
- **multi-particle** and **early shower** events

Electron events:

- **Electron event cuts**

Muon (muon-like) events:

- **Not an electron event**
- **Muon-like event cuts**

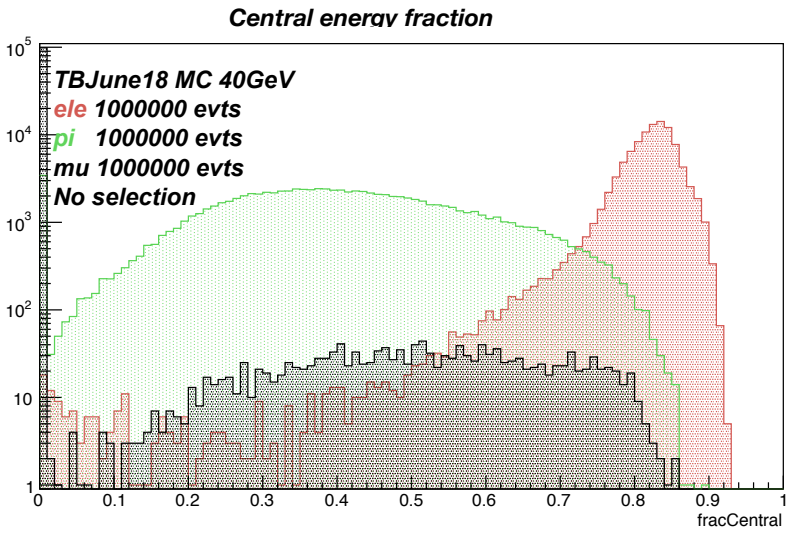
Remaining events are classified as **hadron events**.

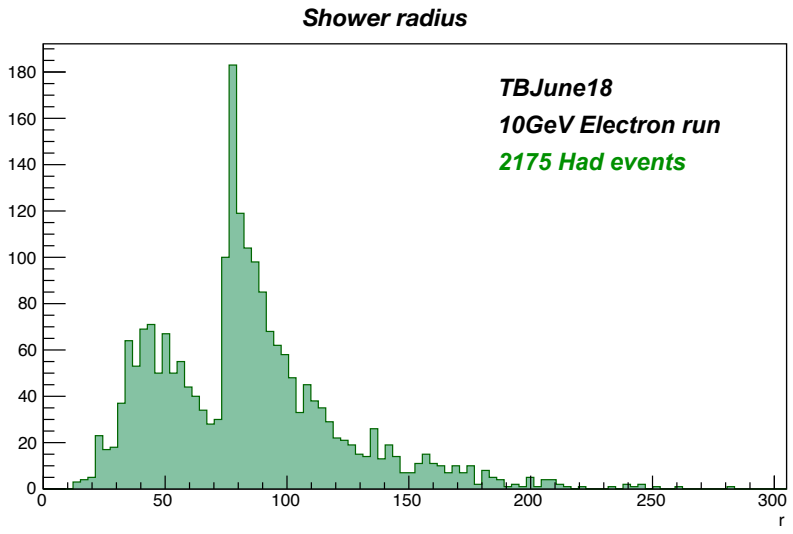
BDT for particle ID

Motivation

Cut-based method:

- > 10 steering parameters for each energy
- Asymmetric distributions/ long tails can be problematic
- Cut artefacts





BDT for particle ID

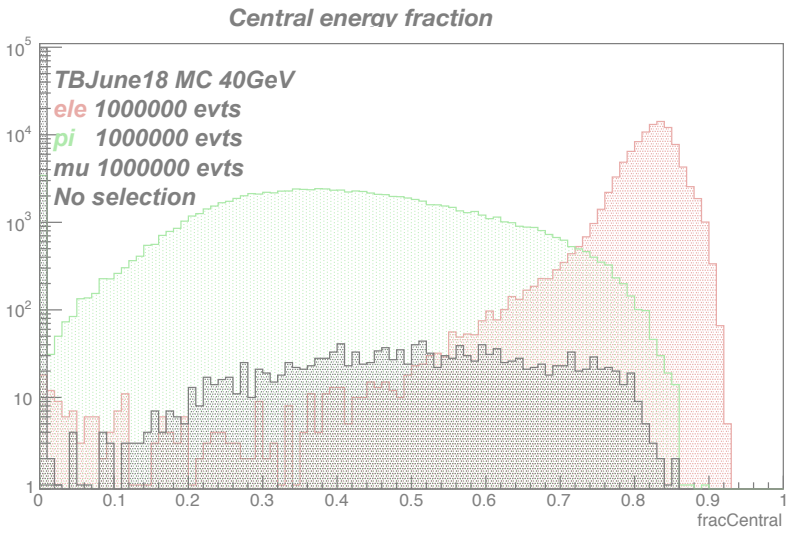
Motivation

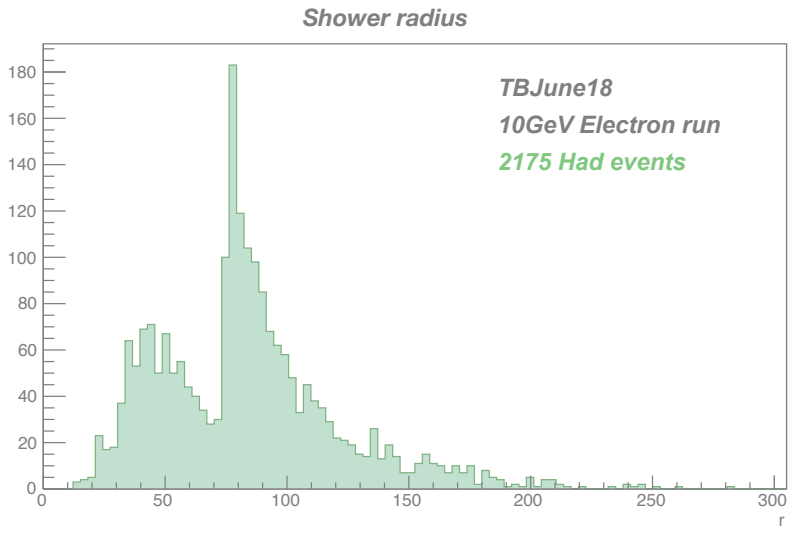
Cut-based method:

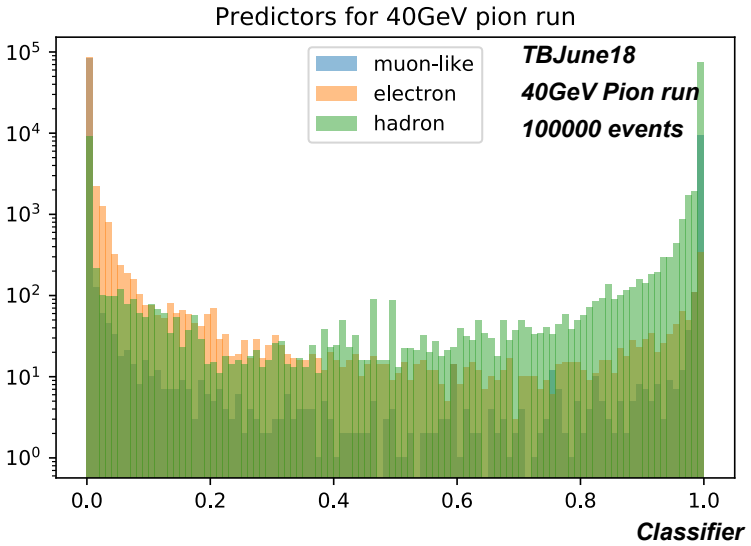
- > 10 steering parameters for each energy
- Asymmetric distributions/ long tails can be problematic
- Cut artefacts

Multivariate methods:

- Can provide probabilistic classifier trained on given distributions of observables
- One model can be used for whole dataset

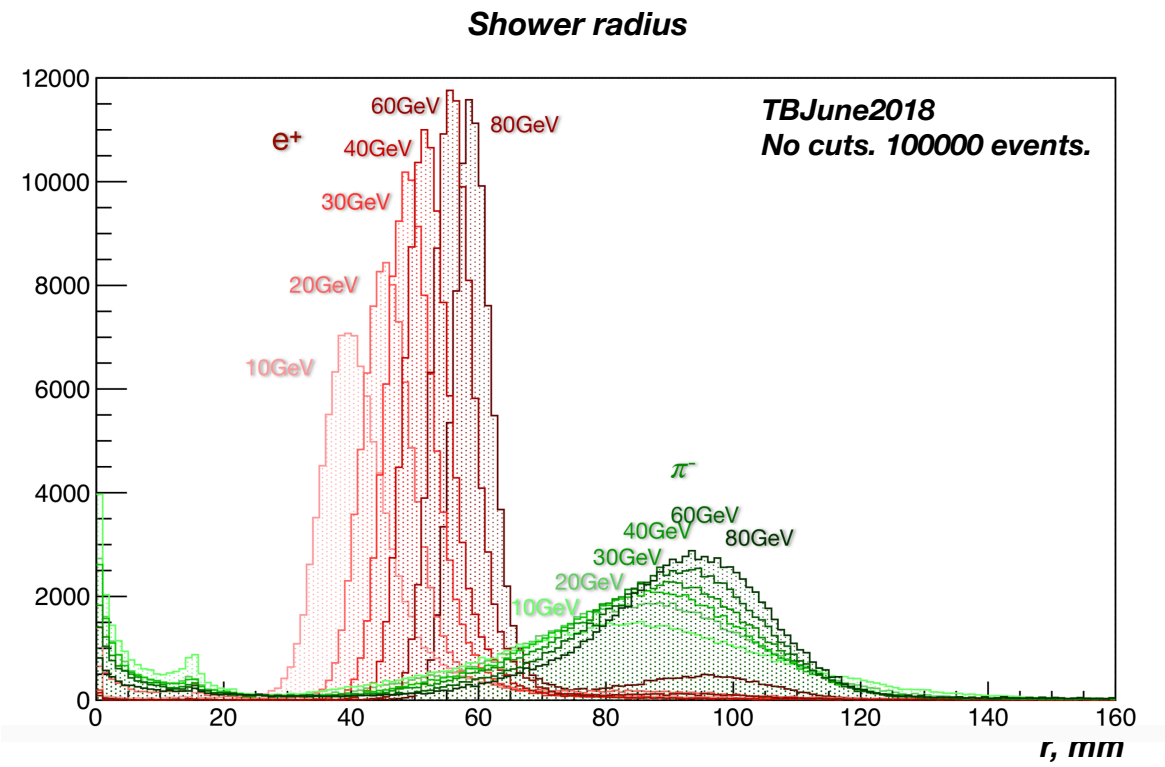






Radial variables

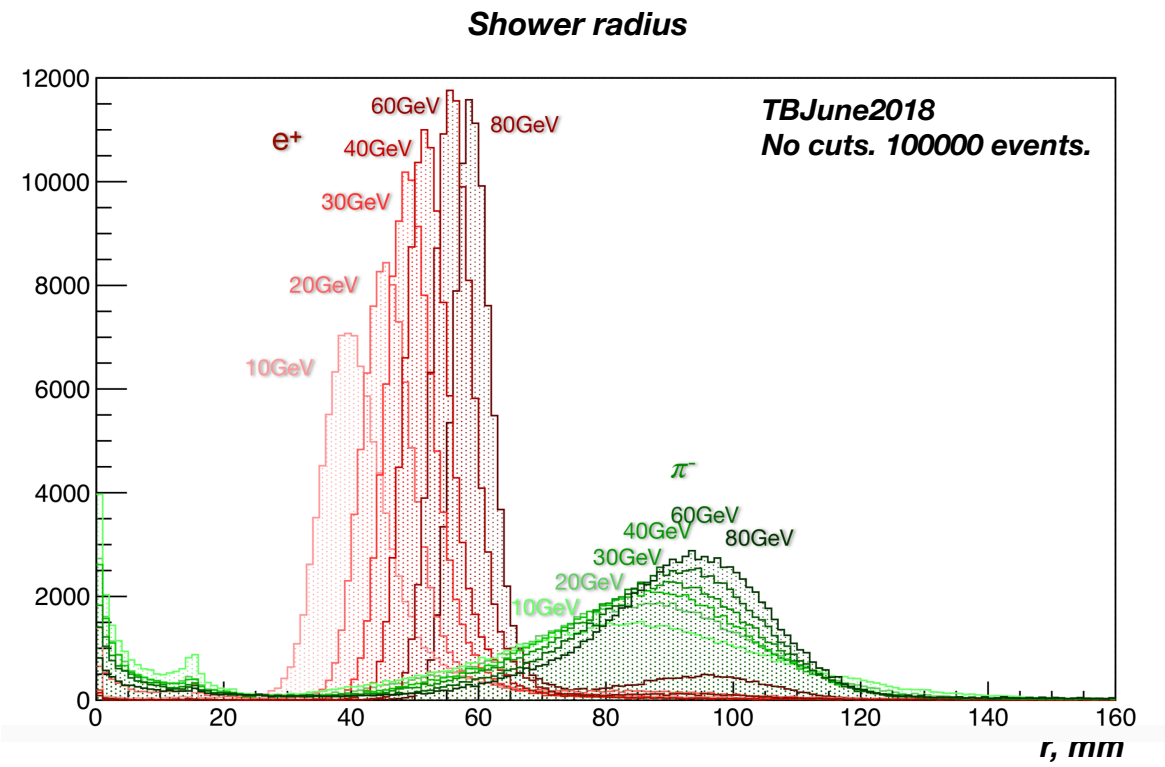
Shower radius.



High overlap of electron and pion shower radius distributions.

Radial variables

Shower radius.



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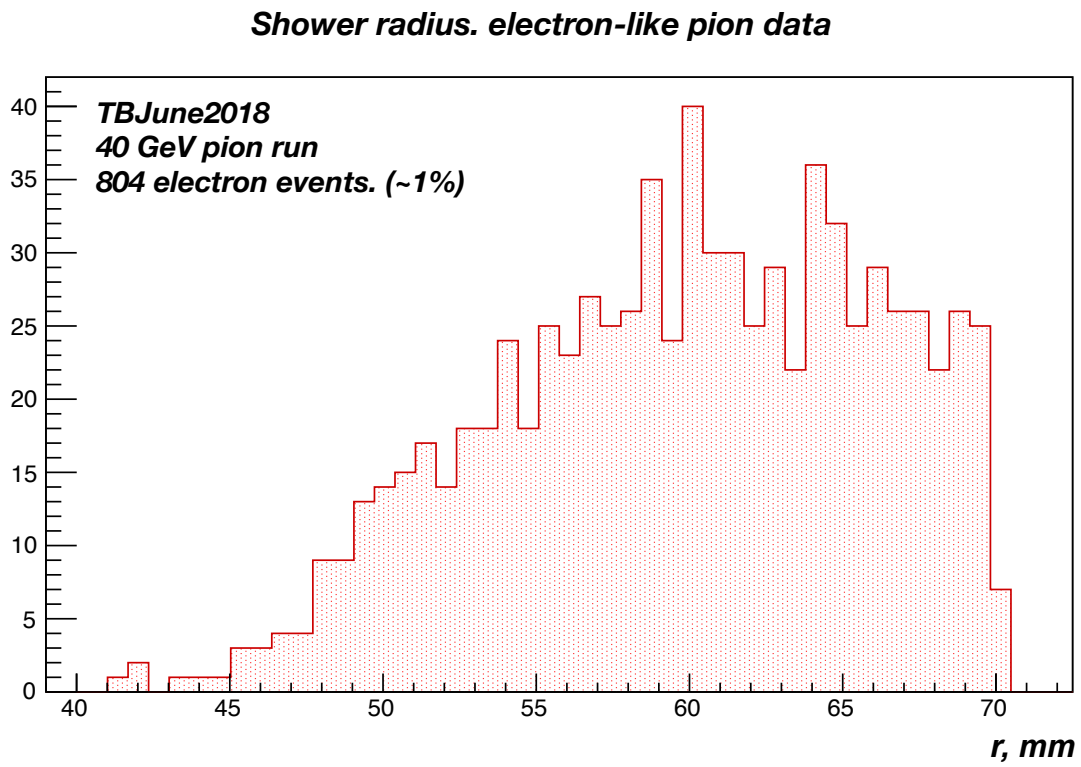
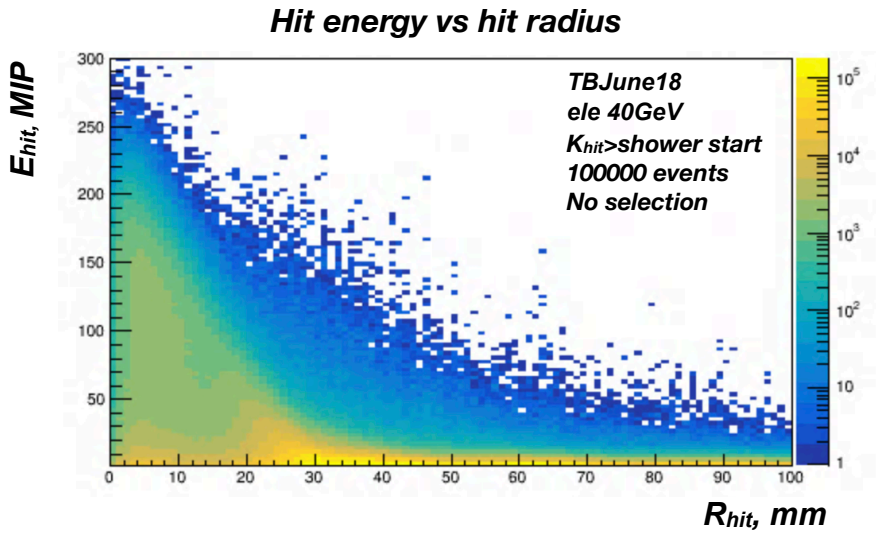


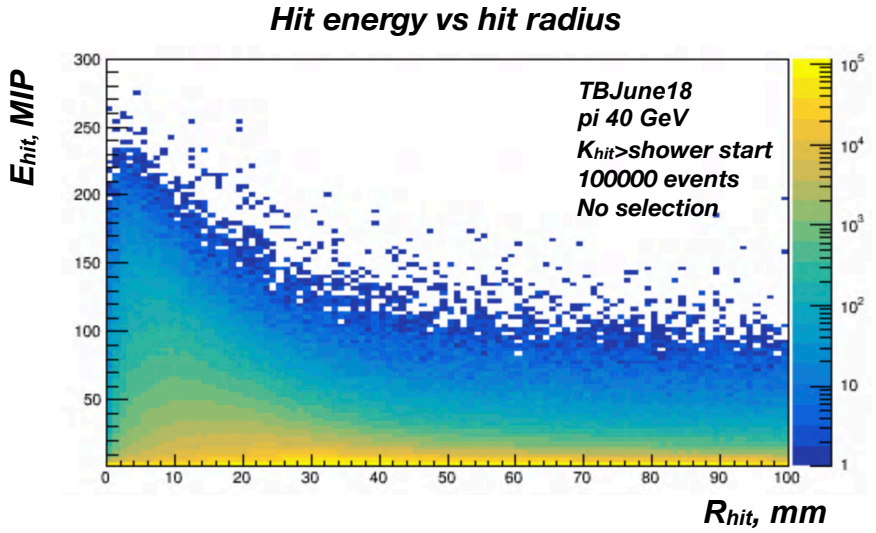
No peak at expected value for electrons (~*50mm*)

More radial information can improve identification of electron events

Radial variables

Central part of shower.





Most energetic hits with R_{hit} < *30mm,*

low energy hits with higher radii

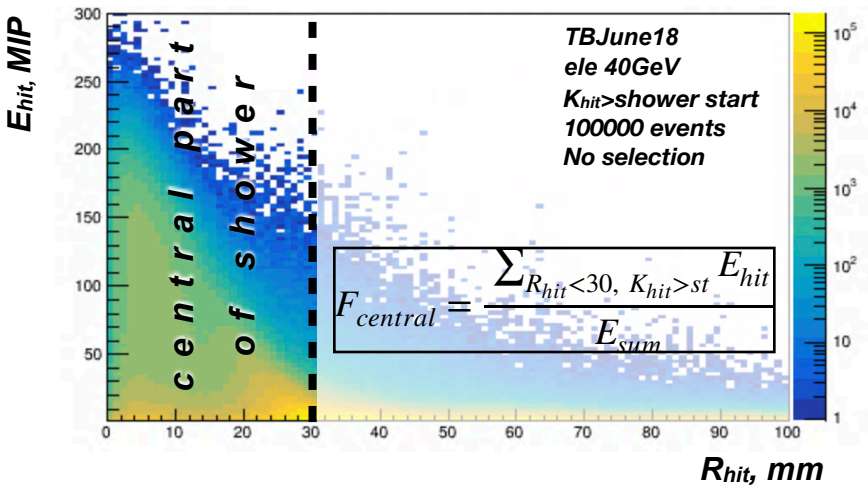
Lower E_{hit} expectation hits with R_{hit} < *30mm,*

higher E_{hit} expectation for hits with R_{hit} > *30mm*

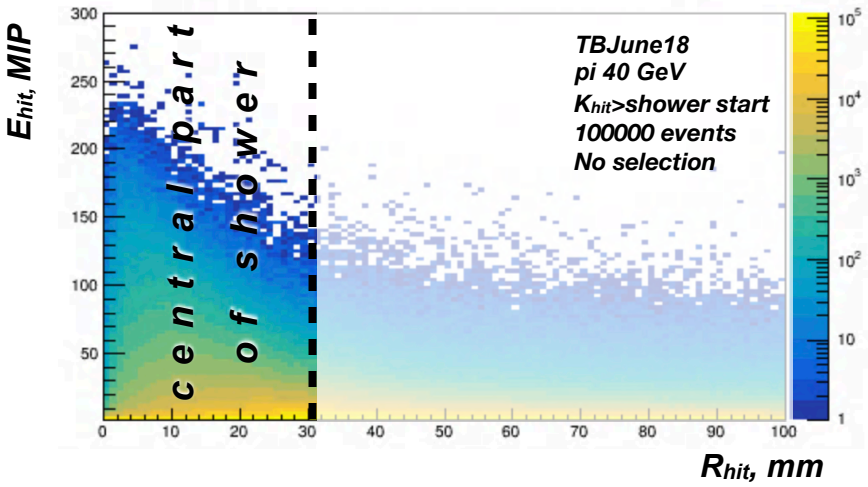
Radial variables

Central part of shower.

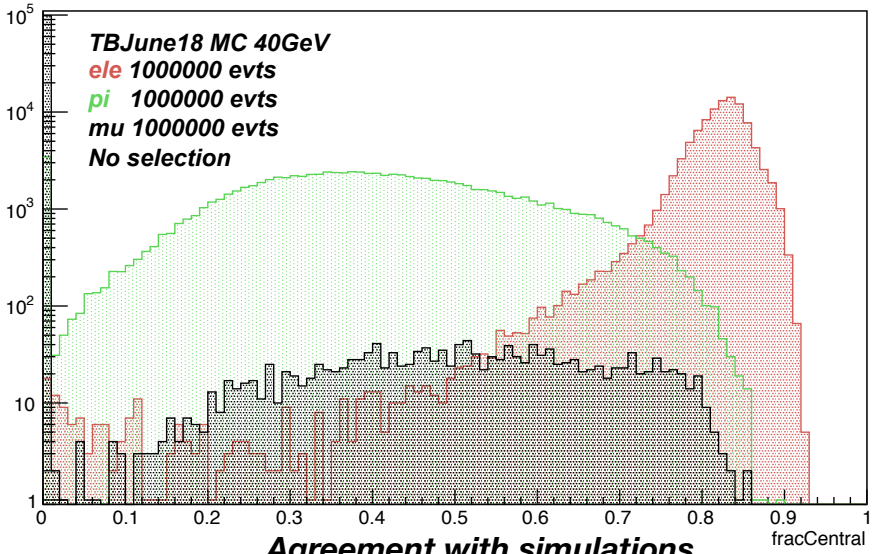
Hit energy vs hit radius



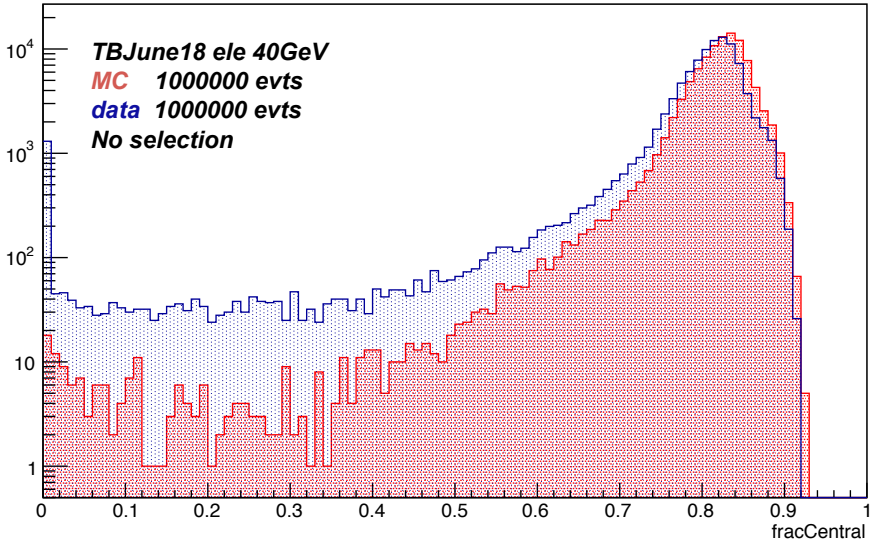
Hit energy vs hit radius



Central energy fraction



Agreement with simulations.

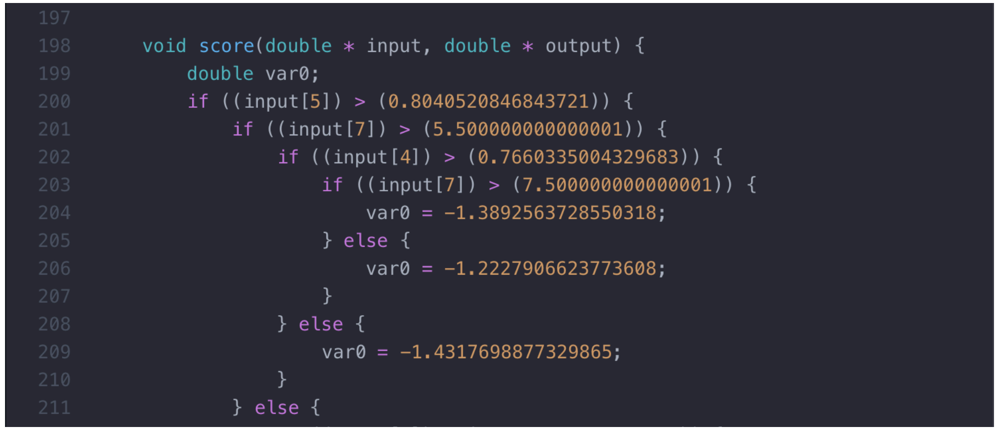


BDT classification

Model and input. TBJune18.

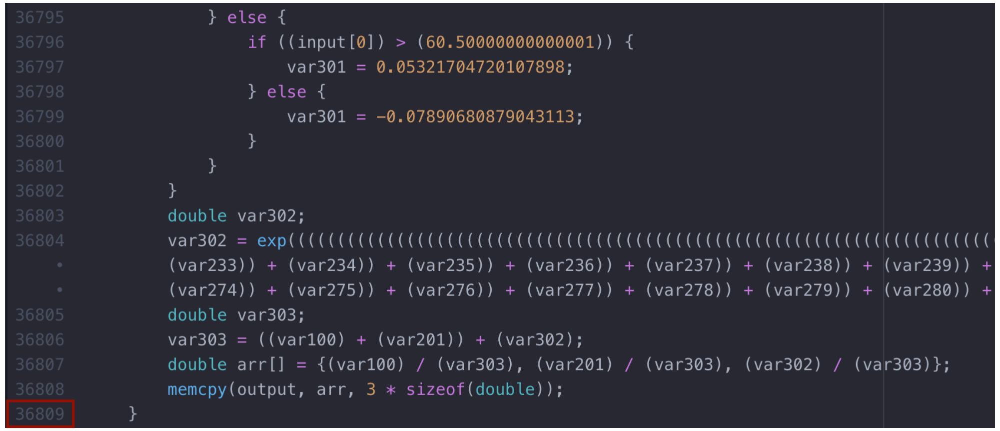
Software and model:

- **LightGBM**
- Multi-class **gbdt**
- **Multi log** loss function
- model to .C converter (**m2cgen**)
- implementation in **Marlin** processor was tested



```
197
198     void score(double * input, double * output) {
199         double var0;
200         if ((input[5]) > (0.8040520846843721)) {
201             if ((input[7]) > (5.500000000000001)) {
202                 if ((input[4]) > (0.7660335004329683)) {
203                     if ((input[7]) > (7.500000000000001)) {
204                         var0 = -1.3892563728550318;
205                     } else {
206                         var0 = -1.2227906623773608;
207                     }
208                 } else {
209                     var0 = -1.4317698877329865;
210                 }
211             } else {
```

(...)



```
36795               } else {
36796                   if ((input[0]) > (60.500000000000001)) {
36797                       var301 = 0.05321704720107898;
36798                   } else {
36799                       var301 = -0.07890680879043113;
36800                   }
36801               }
36802           }
36803           double var302;
36804           var302 = exp((((((((((((((((((((((((((((((((((((((((((((((((((((((((((((((((((((((((
    •           (var233)) + (var234)) + (var235)) + (var236)) + (var237)) + (var238)) + (var239)) +
    •           (var274)) + (var275)) + (var276)) + (var277)) + (var278)) + (var279)) + (var280)) +
36805           double var303;
36806           var303 = ((var100) + (var201)) + (var302);
36807           double arr[] = {(var100) / (var303), (var201) / (var303), (var302) / (var303)};
36808           memcpy(output, arr, 3 * sizeof(double));
36809       }
```

```
36807
36808
36809           }
```

Model gives same results as in python. Can be implemented in the next CaliceSoft release

BDT classification

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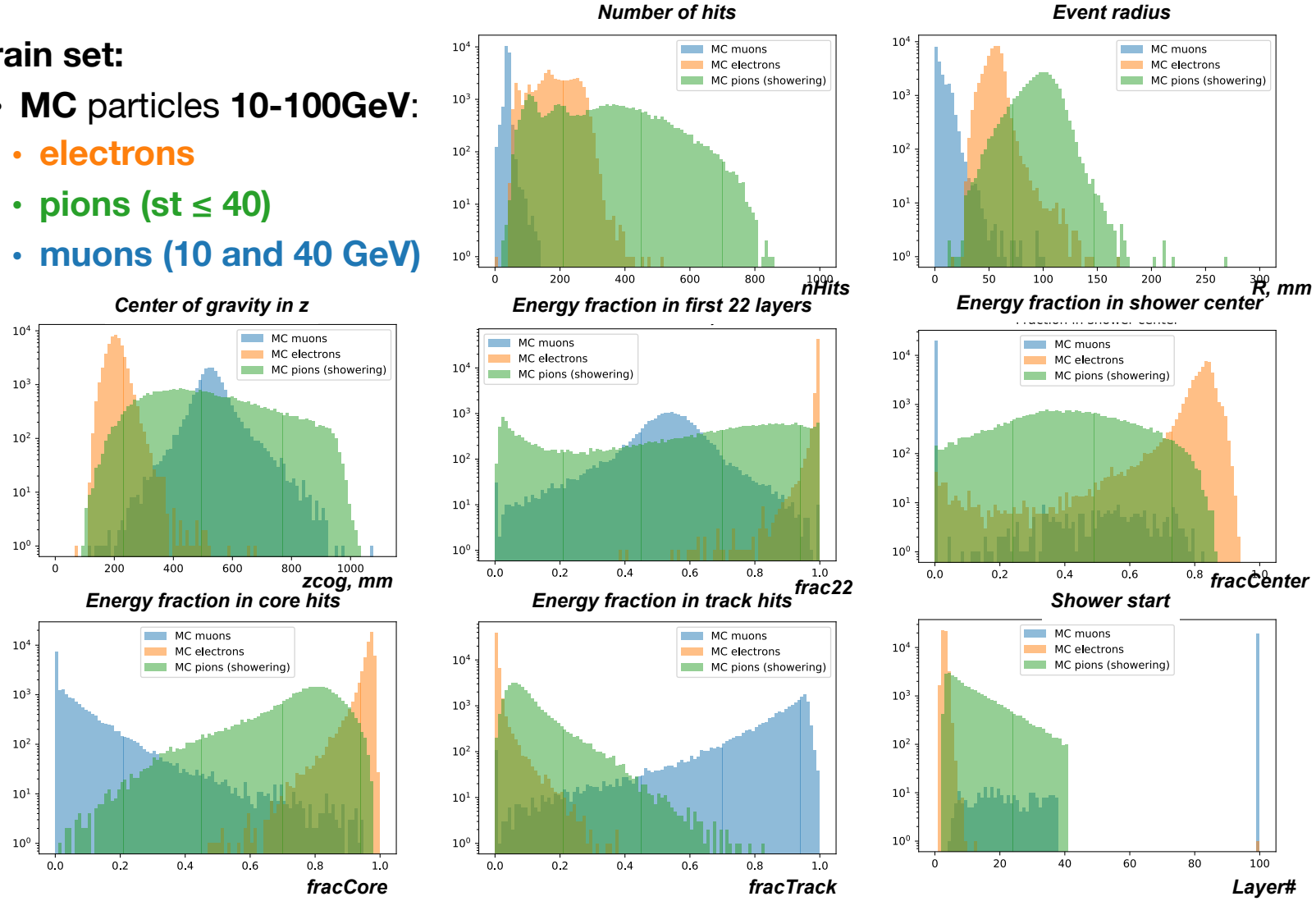
Observables:

- Number of hits
- Shower radius
- Center of gravity in z
- Energy fraction in first 22 layers
- Energy fraction in shower center
- Energy fraction in shower core
- Energy fraction in track hits
- Shower start

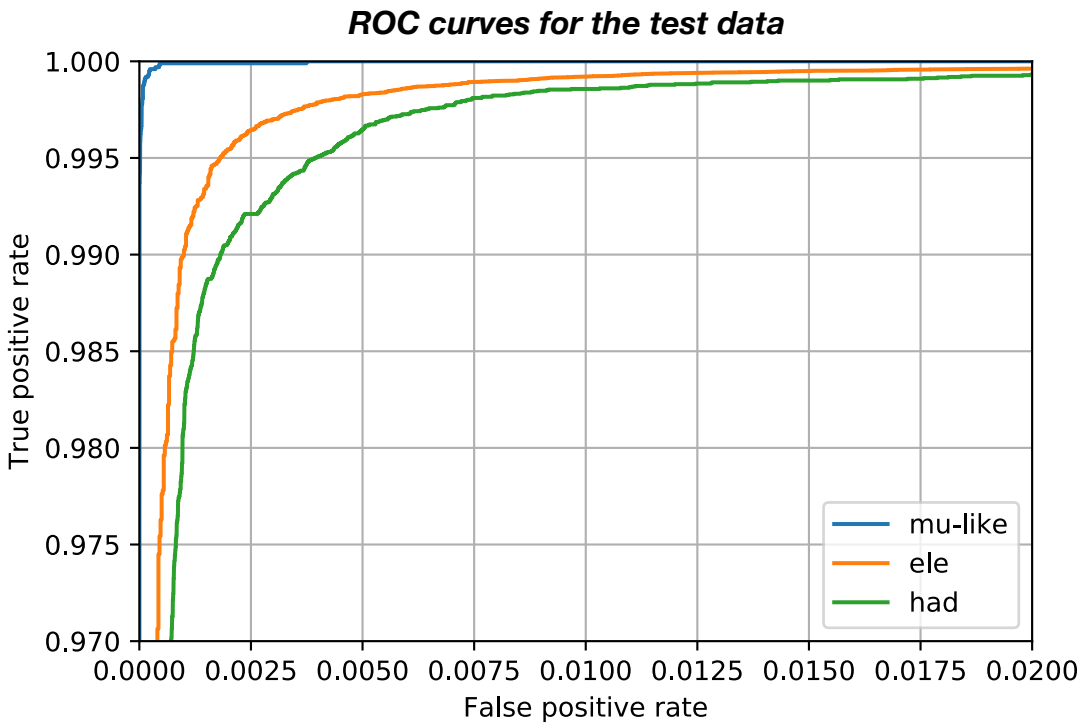
Train set:

- **MC** particles **10-100GeV**:
  - **electrons**
  - **pions (st ≤ 40)**
  - **muons (10 and 40 GeV)**



Resulting metrics

After training



Multi log loss:

$$L = -\frac{1}{N}\sum_{i}^{N}\sum_{j}^{3} Y_{ij} ln(p_{ij}) = 0.0086$$

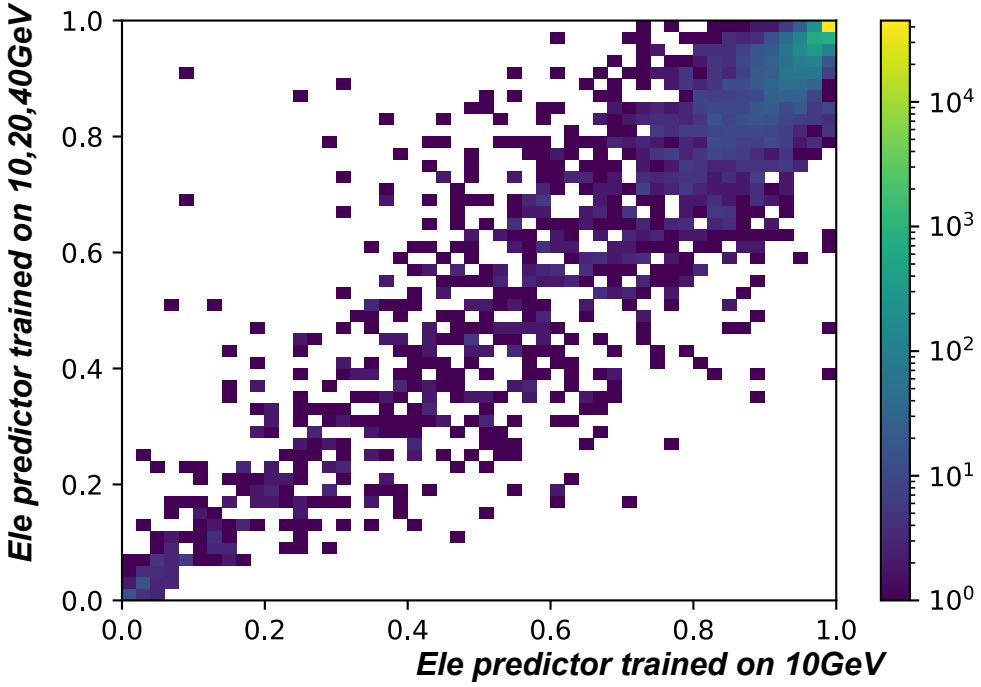
Where *N* - number of events in the test sample, *3* - number of classes, Y_{ij} is binary variable with the expected labels and p_{ij} is he classification probability output by the classifier for the i-instance and the j-label.

$e^{-L} \approx 0{,}92$ - the average probability of correct prediction

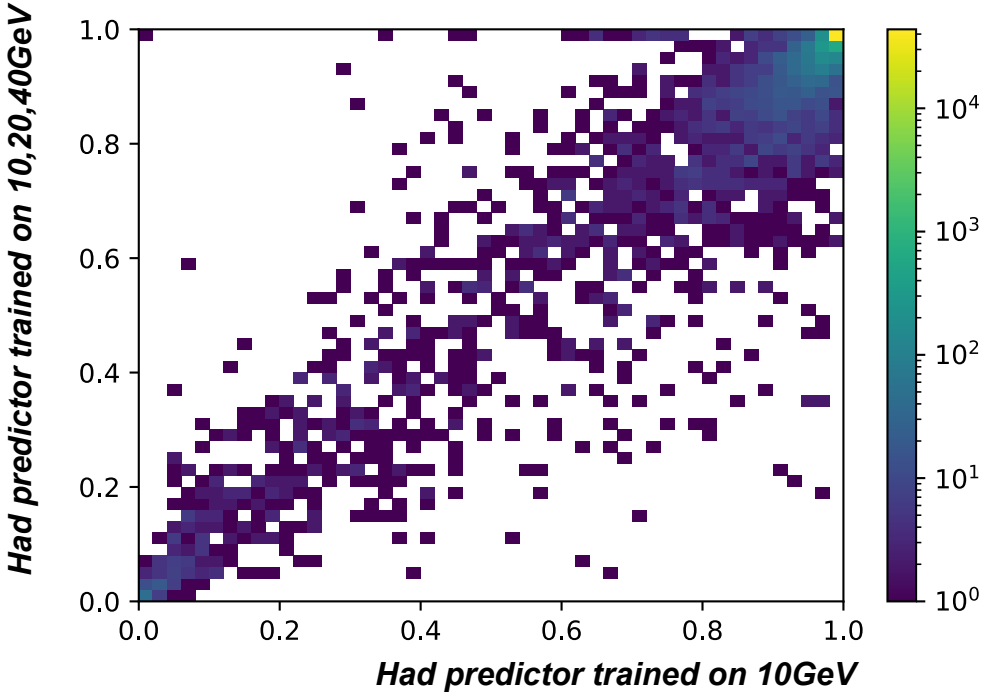
BDT output

Comparison with separate model trained only on 10GeV particles.

10GeV MC electron test sample
50000 events

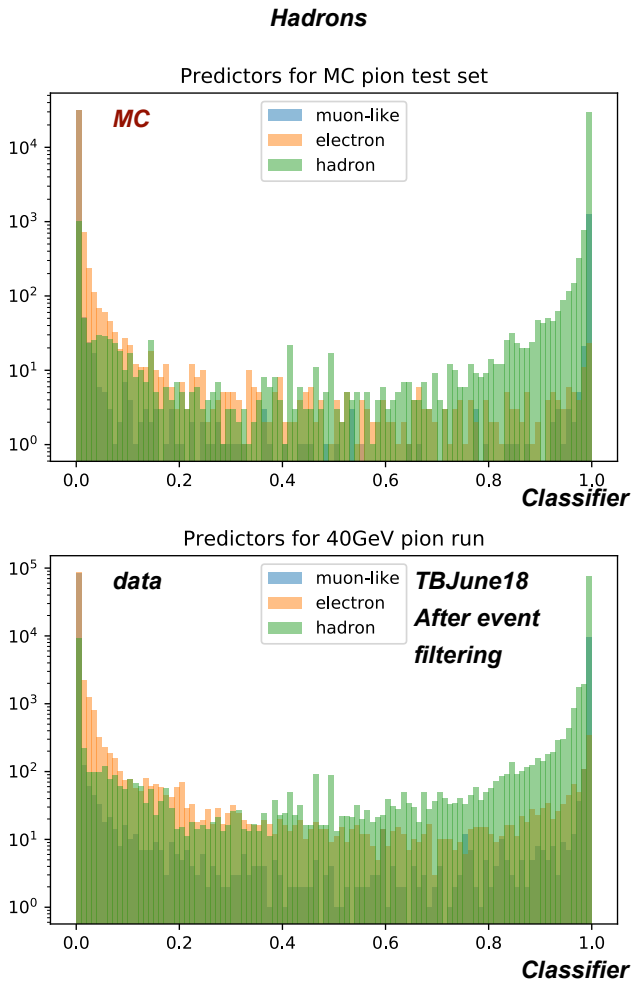


10GeV MC pion test sample
50000 events



BDT classification

Output. Comparison with data.



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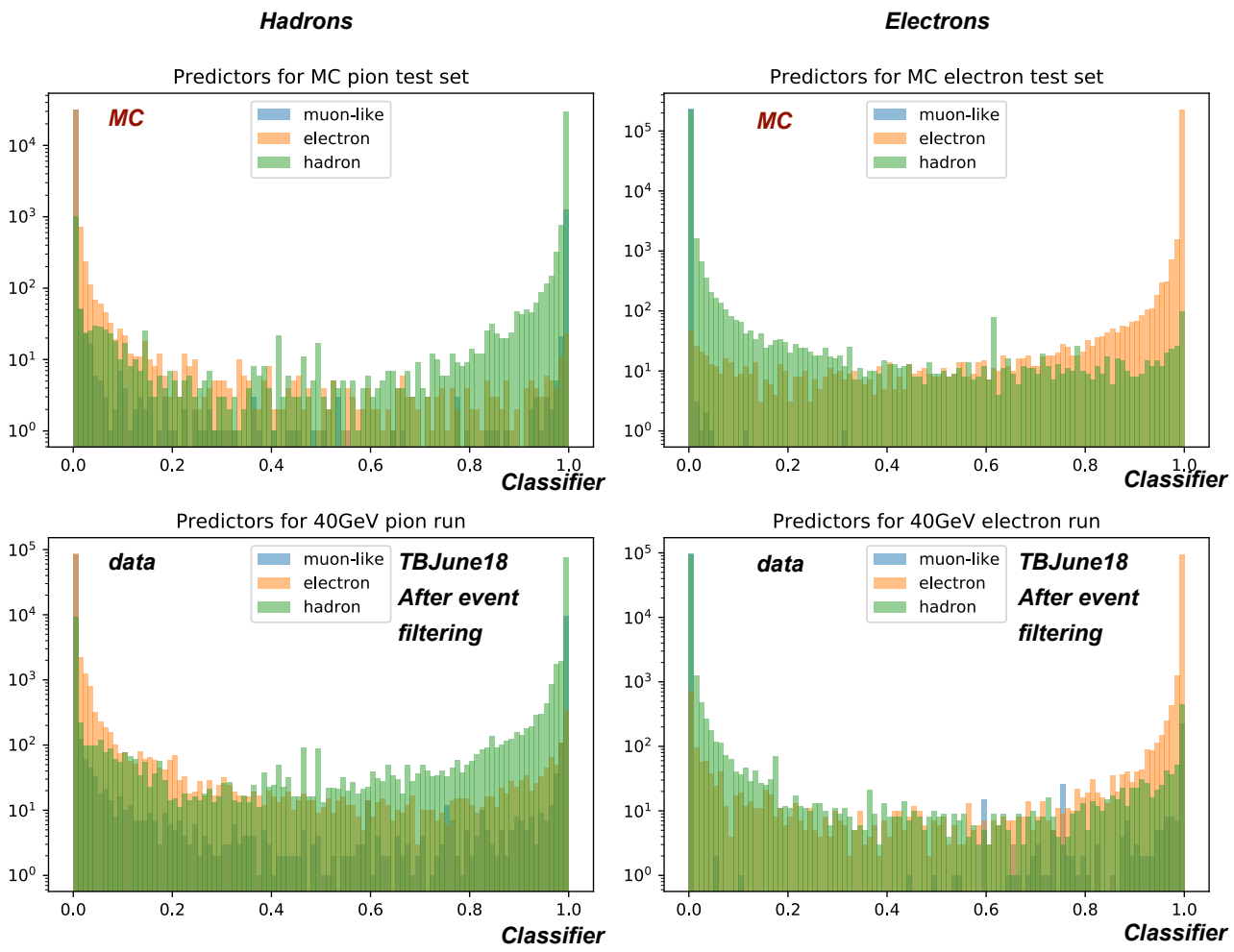

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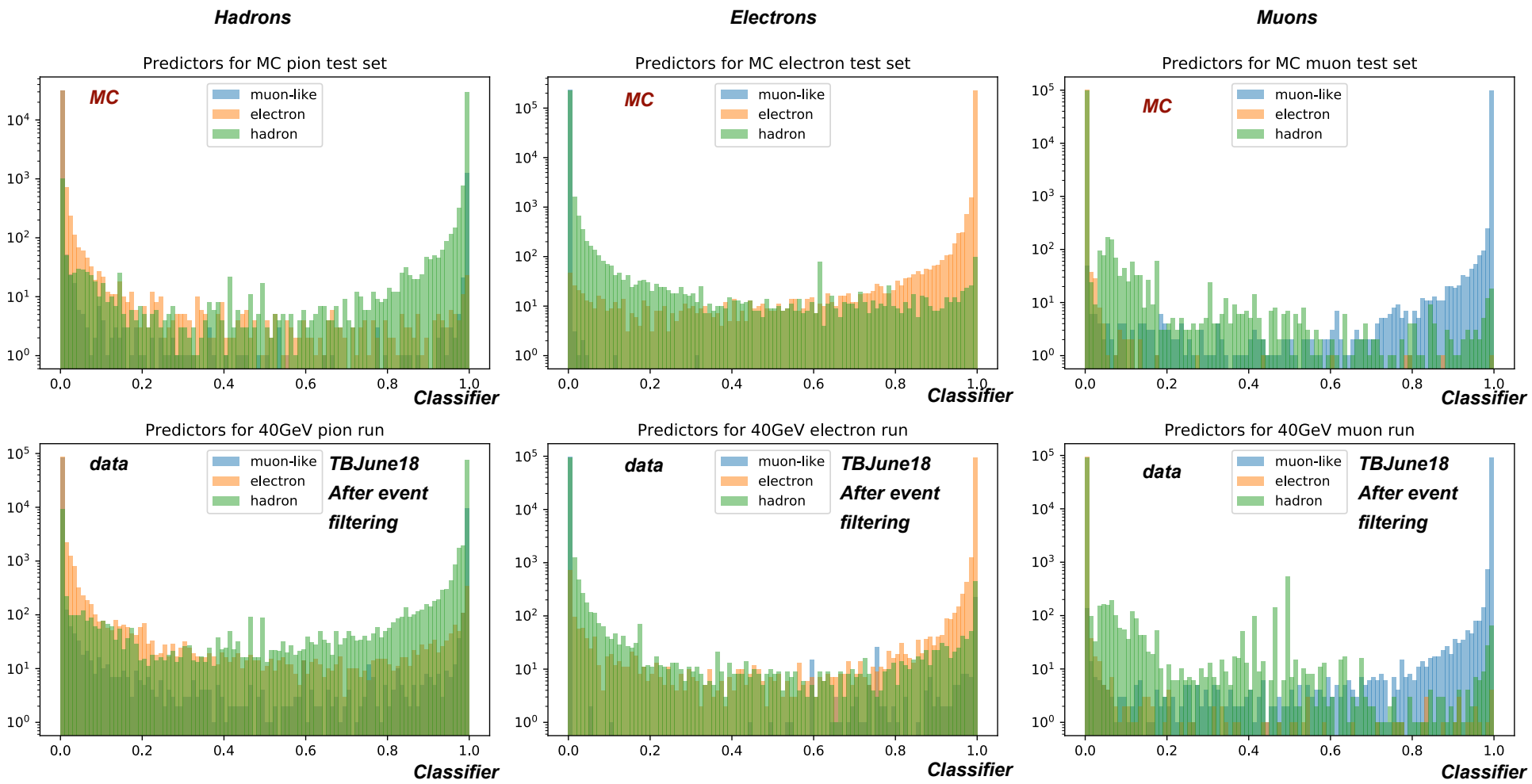


Particle ID using BDT: Summary & outlook

- ☑ **BDT** model for particle ID is trained and tested on energies up to 100GeV
  - ☑ One model can be used for whole set of energies
  - ☑ Provides good purification and agreement of data with simulations
  - ☐ Should be trained on remaining energies
- ☑ Marlin processor with implementation of BDT is tested
  - ☐ Will be released with next version of CaliceSoft

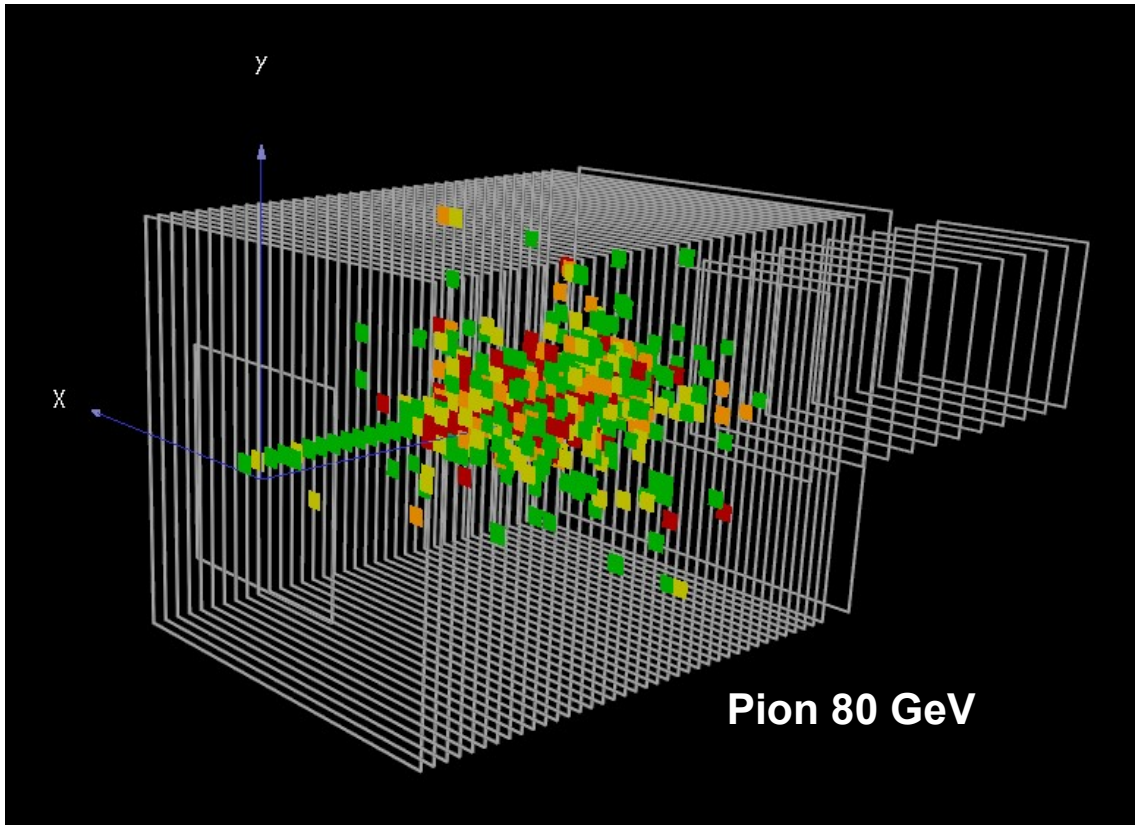
Neutronness

Motivation

Need for neutron study

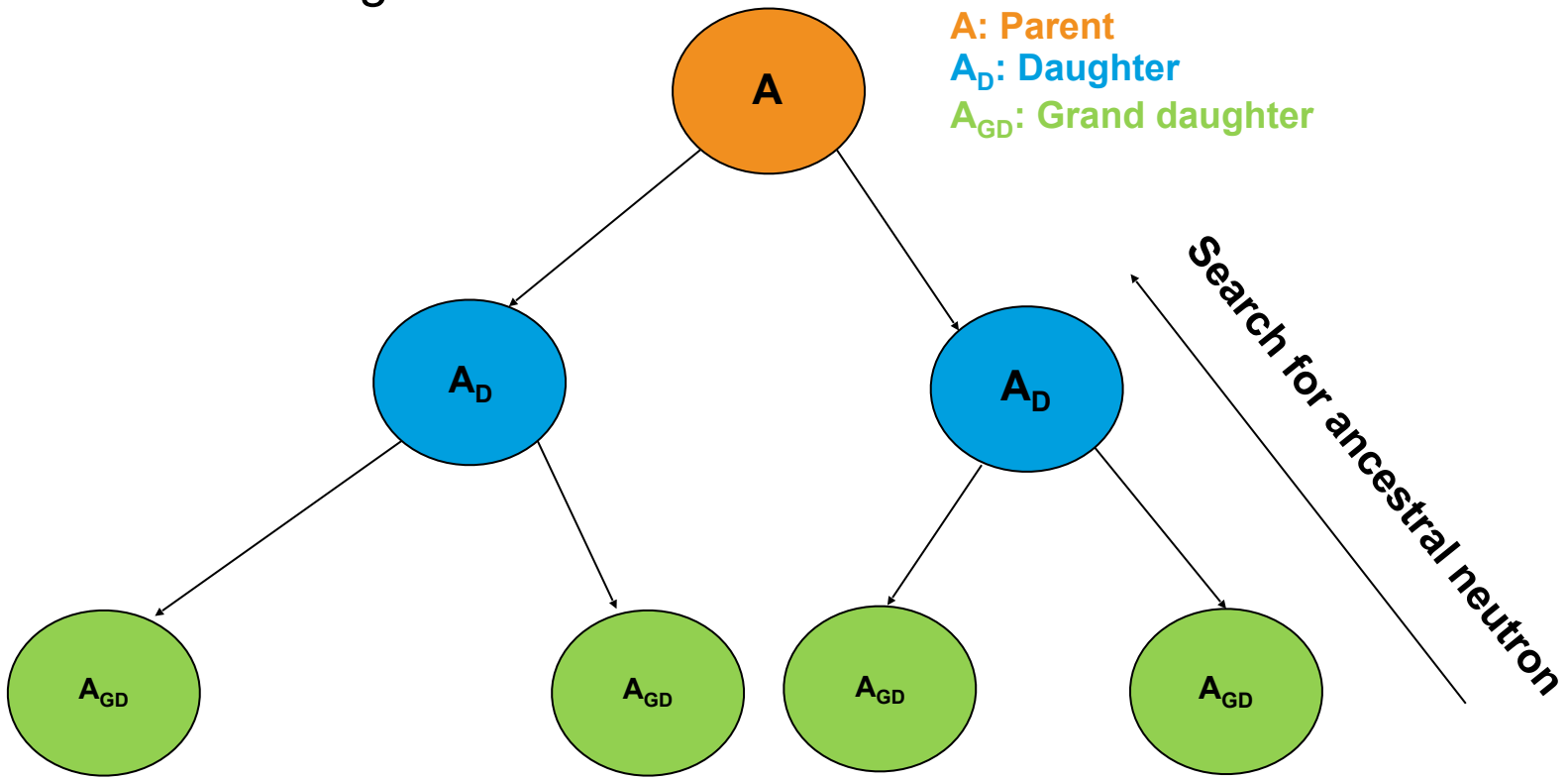
- In showers there are isolated hits – we assume they are neutrons. Is that true?
- What is the effect on energy and timing?

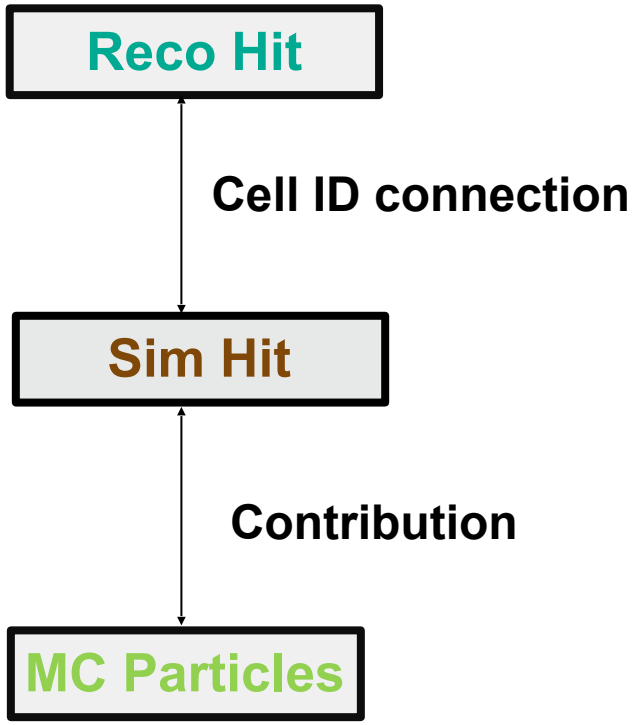
  → Investigate correlations!
- possible applications/studies:
  - Remove isolated neutrons in order to reduce confusion, in particular late neutrons.
  - What is the impact of after-glow contaminating later events?



Introduction

- Trace all the particles in the shower and extract the properties of the MC particles (energy, momentum, PDG and time stamps).
- A relation between the **Reco Hit** and the **Sim Hit** is built which gives all the **MC particles** contributing to that hit.



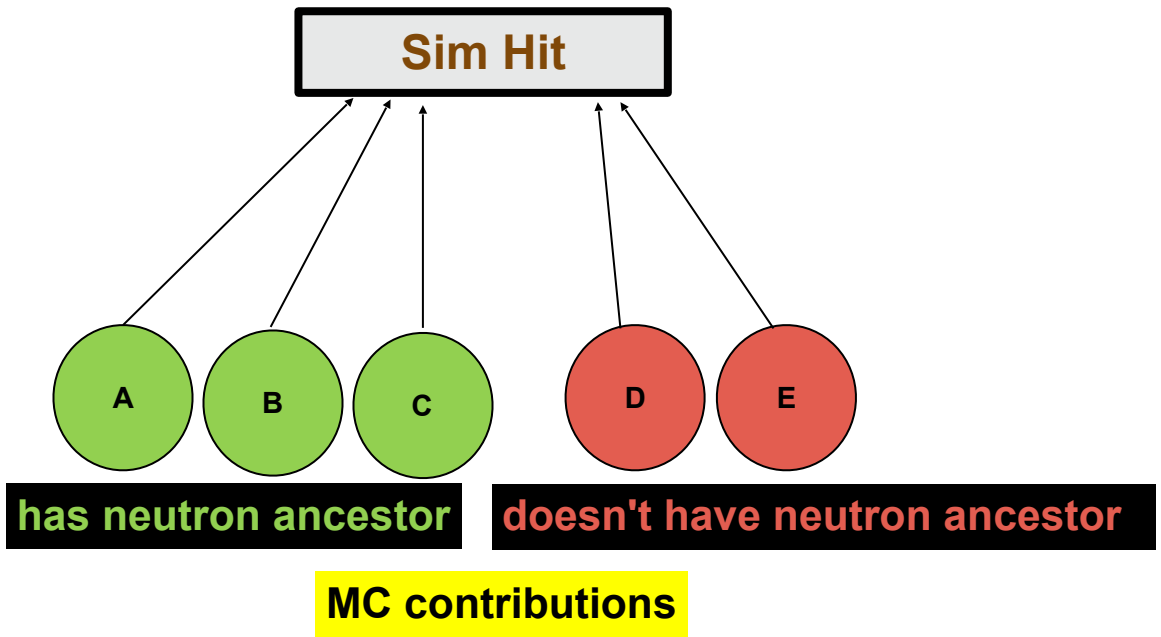


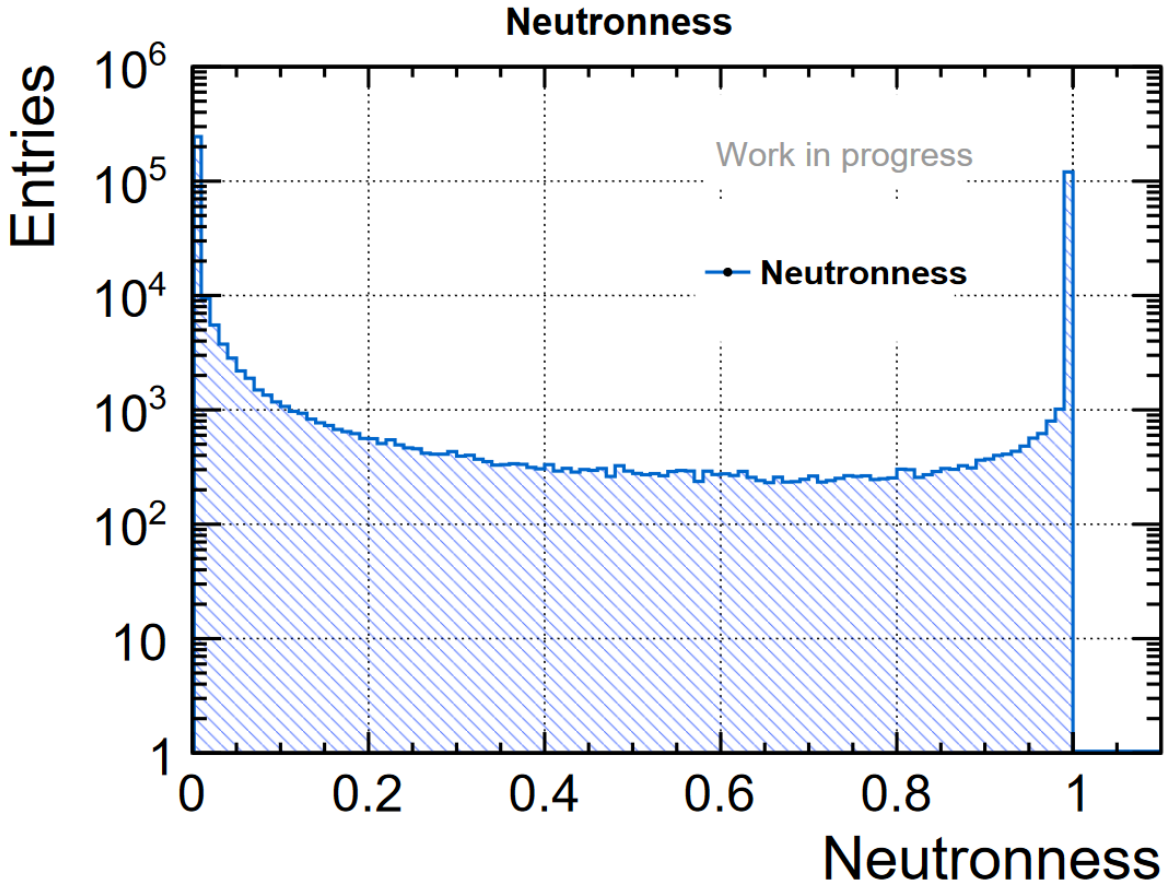
Neutronness

Neutronness is defined as the energy-weighted contributions of MC particles with a **neutron ancestor** compared to all contributions to the Sim hit.

$$\text{Neutronness(hit)} = \frac{\sum_{contribution:neutron\ ancestor} Energy(contribution)}{\sum_{contribution} Energy(contribution)}$$

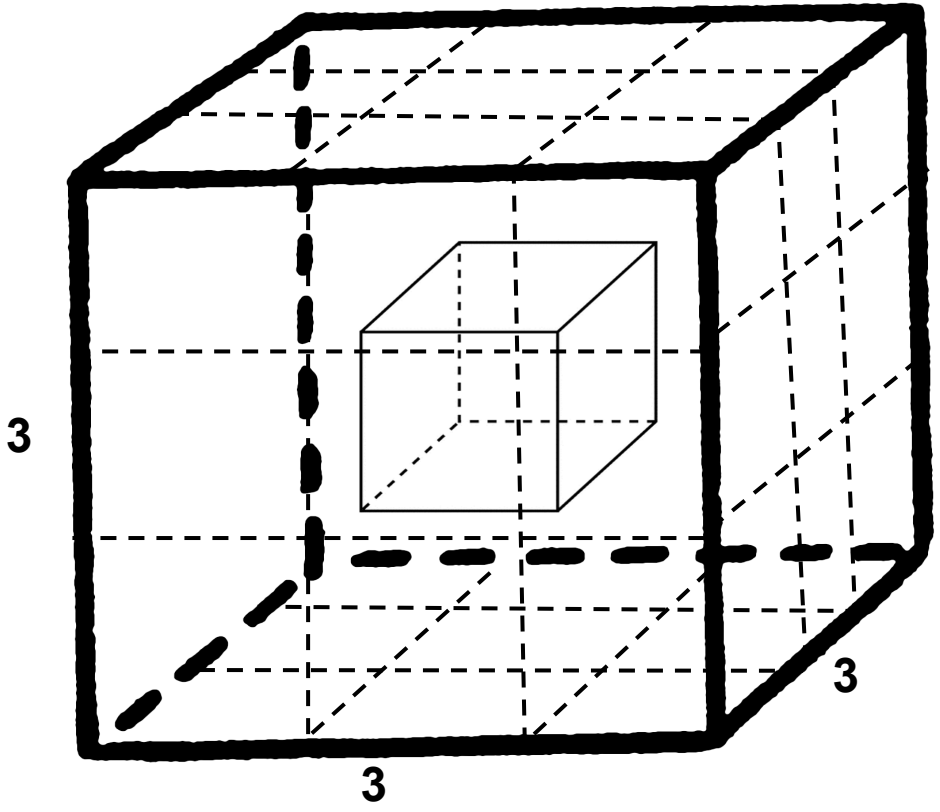
Define fraction cut, e. g. neutronness > 0.9 to call a hit “from a neutron”.





Definition of Isolation level

Compares the energy of a hit to the energy of its **neighbours.**

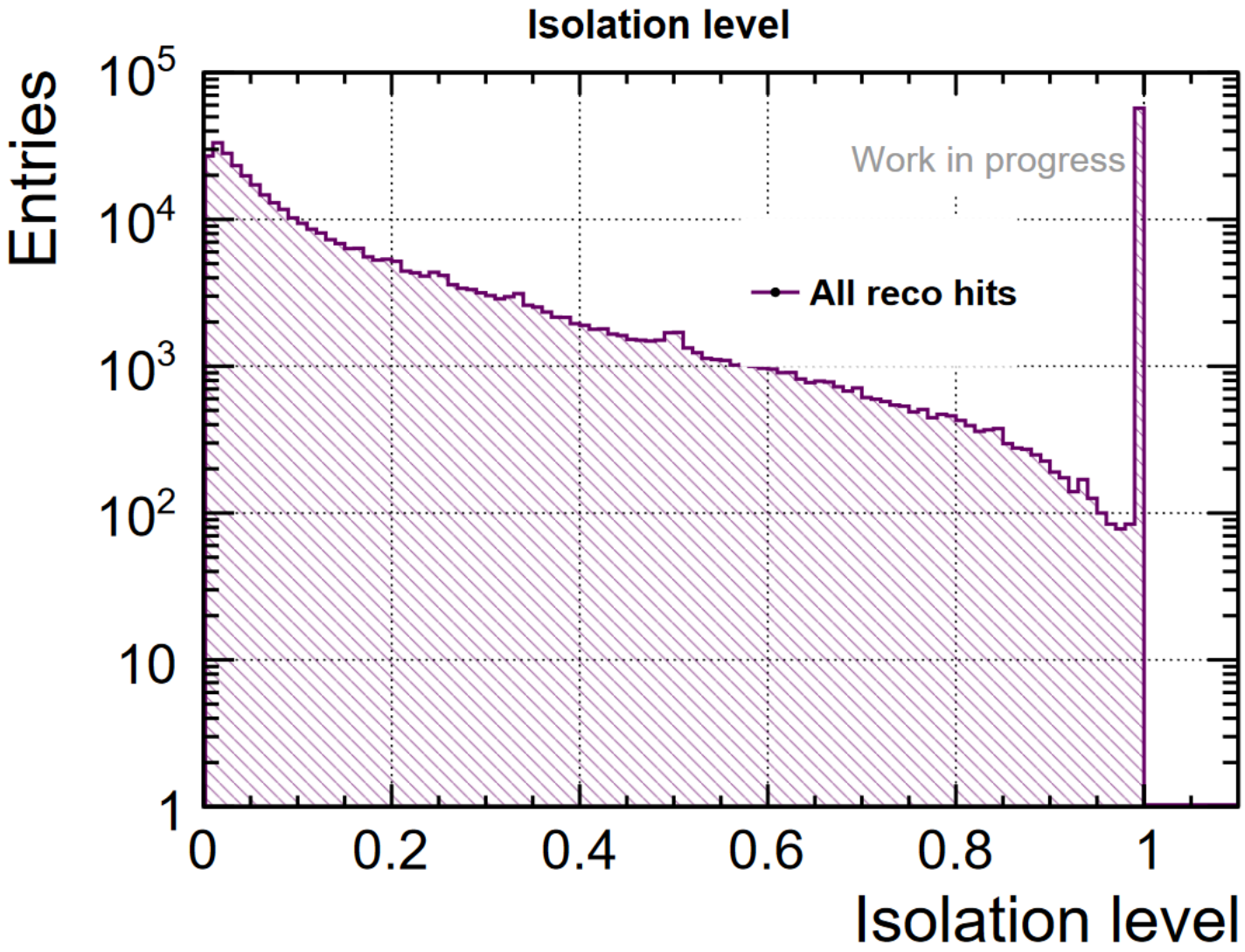


$$\text{Isolation level} = \frac{\text{Energy of hit}}{\text{Energy sum of all neighbours (all hits in 3 x 3 x 3 box)}}$$

Isolation level

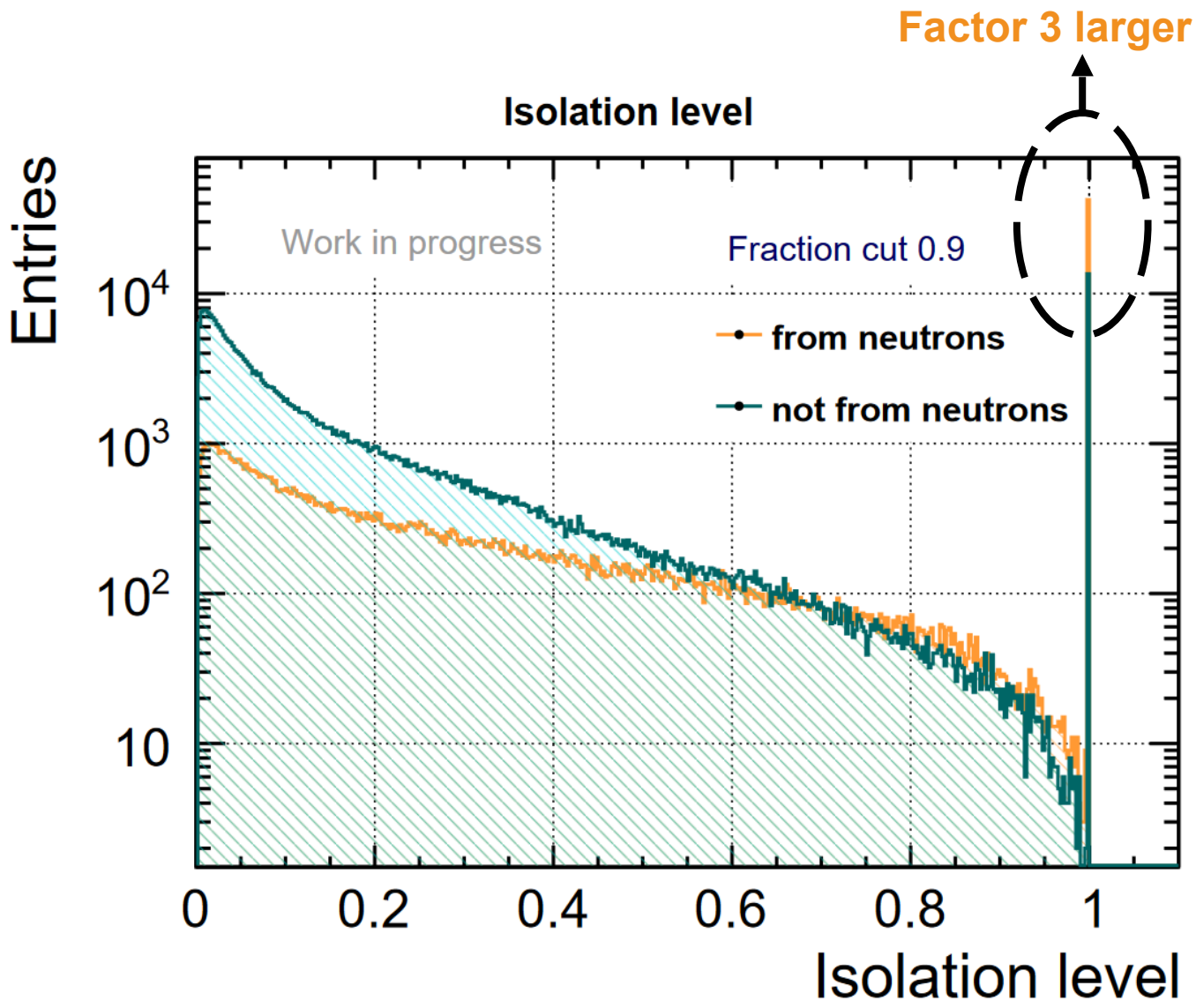
- Vast majority of Reco hits lie in the dense shower with low level of isolation.

- There is a peak at 1. These hits are **fully isolated**.



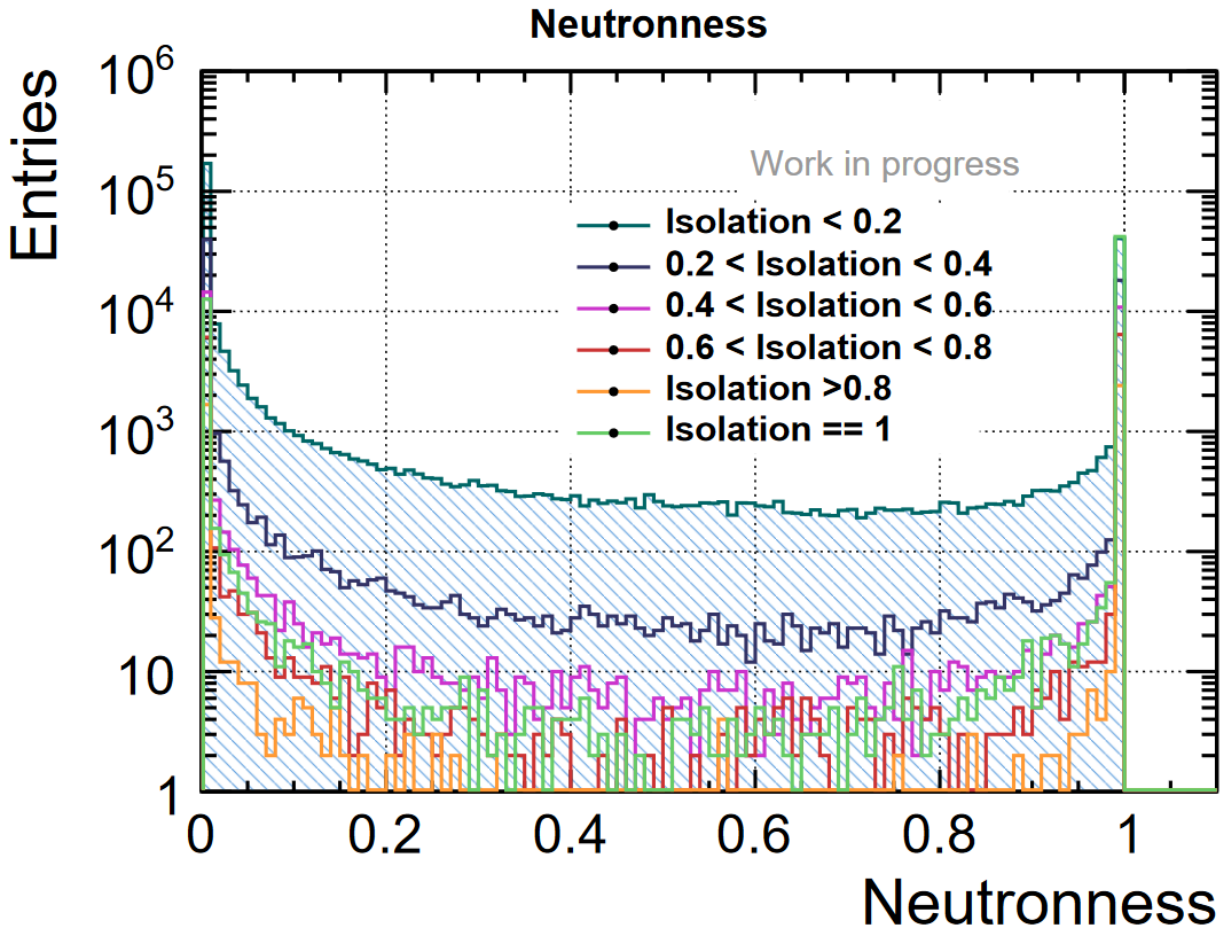
Isolation level

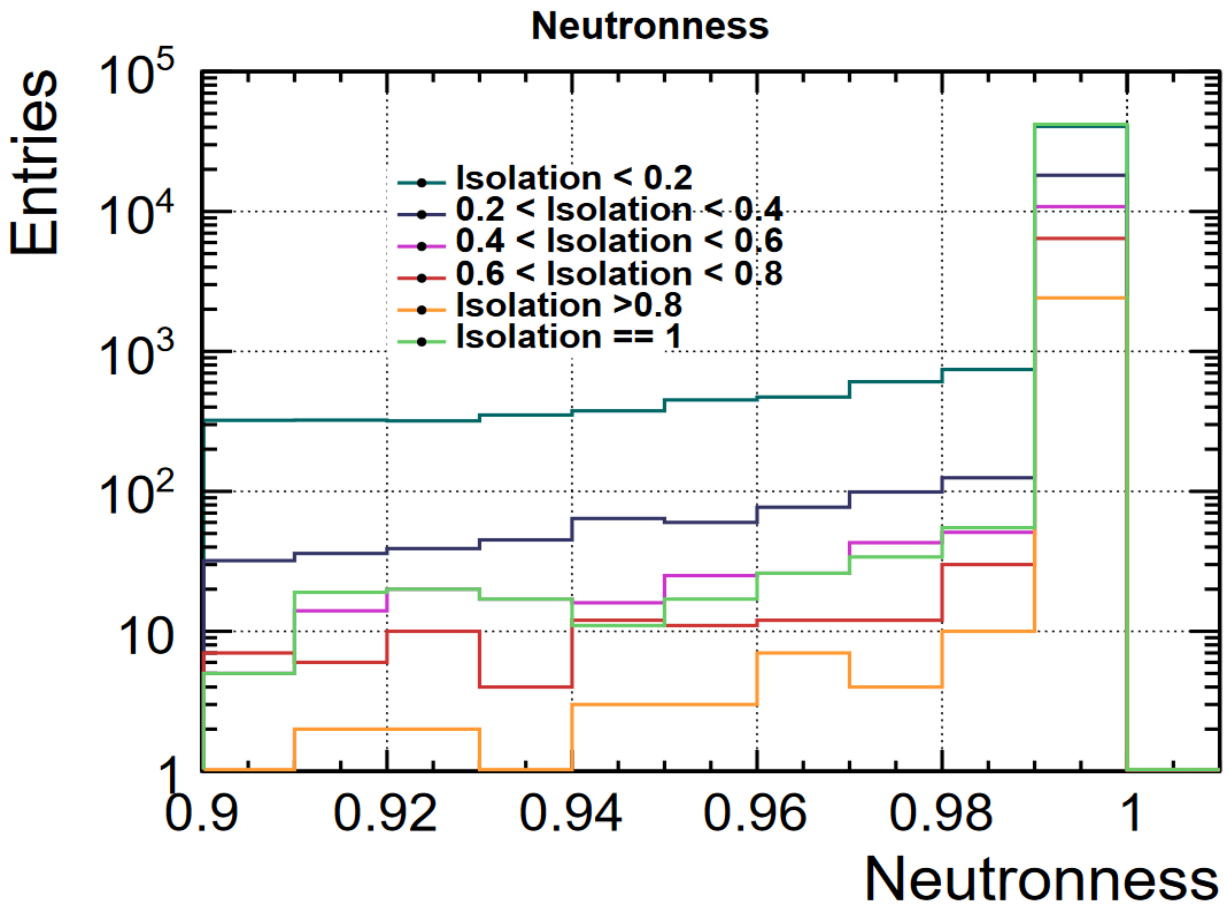
- Clear correlation with neutronness:
  - At isolation equal to 1,
    75 % of hits are from neutrons.
- Use isolation to identify neutrons!



Neutronness for different isolation levels

- For lower level of isolation the distribution is smooth but for isolation > 0.8 and 1 the distribution mainly peaks at two extremes





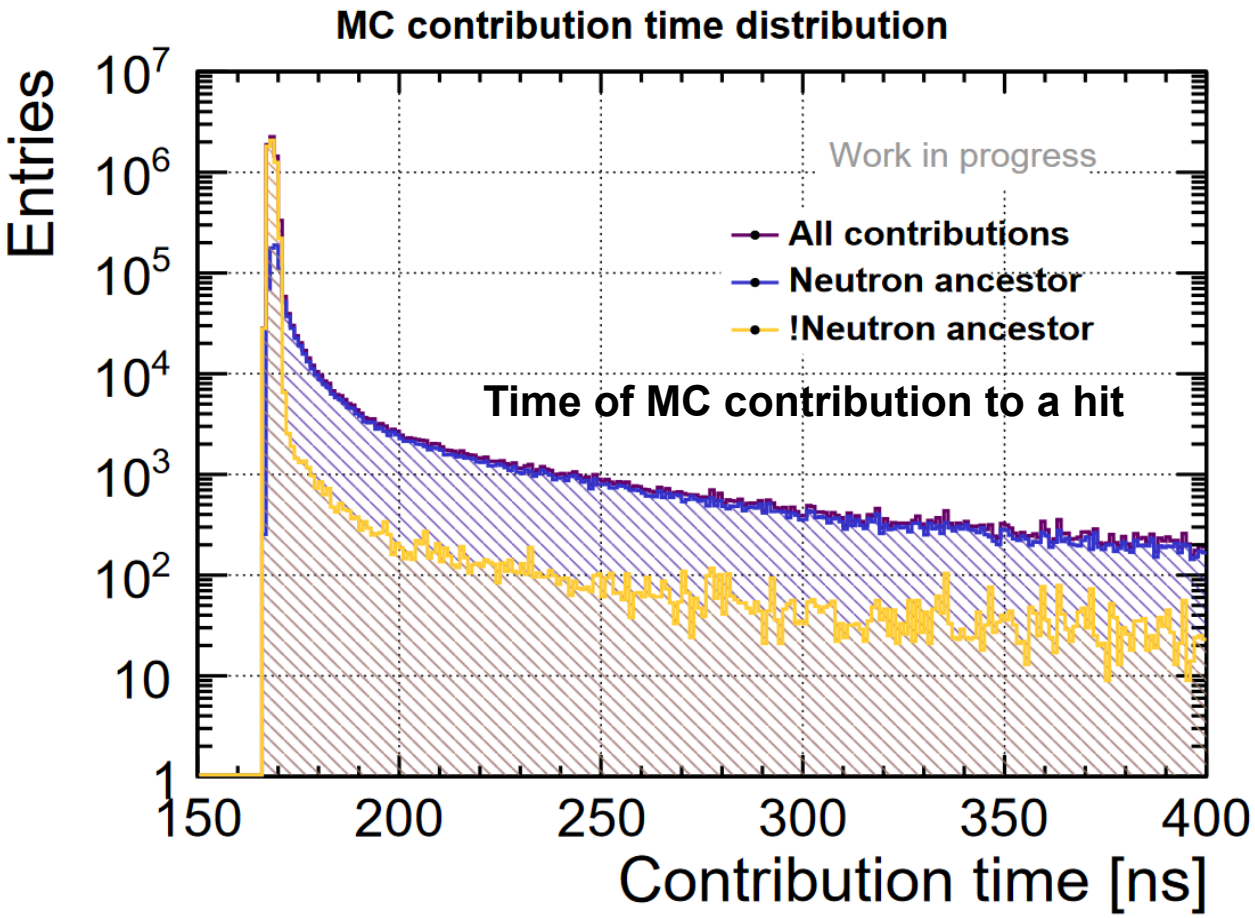
Time stamps

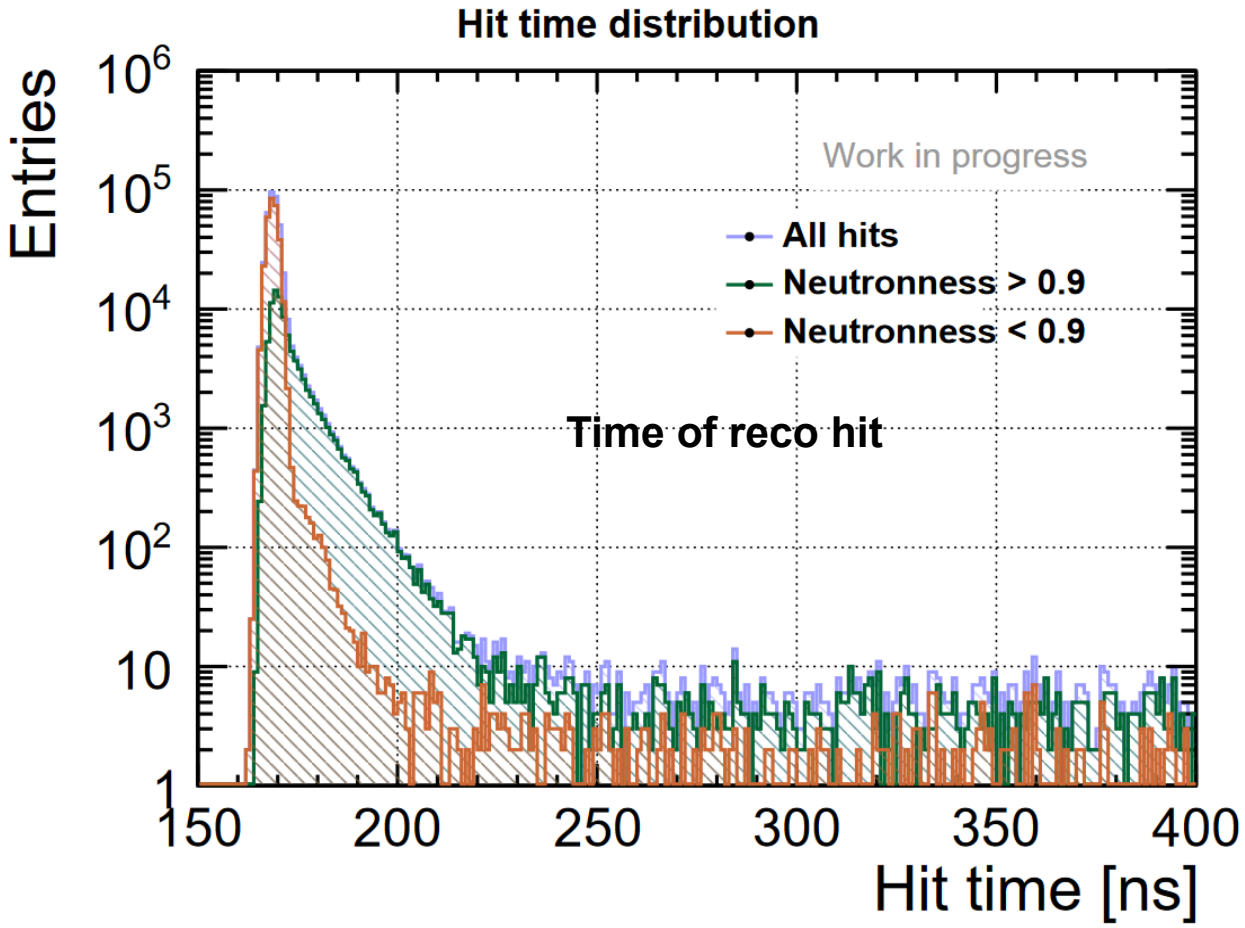
- Correlate neutronness with time stamp – we assume neutrons are late.
- In simulation, the time stamp is given relative to the simulation start, in our case when the pion started its way to the calorimeter.
- Look at **MC time**: exact time stamp of the MC contributions to a SIM hit.
- Look at **RECO time**: time stamp assigned by the standard reconstruction to a reconstructed hit.

Time distribution

ILC Mode: look at the first ~200 ns after shower start

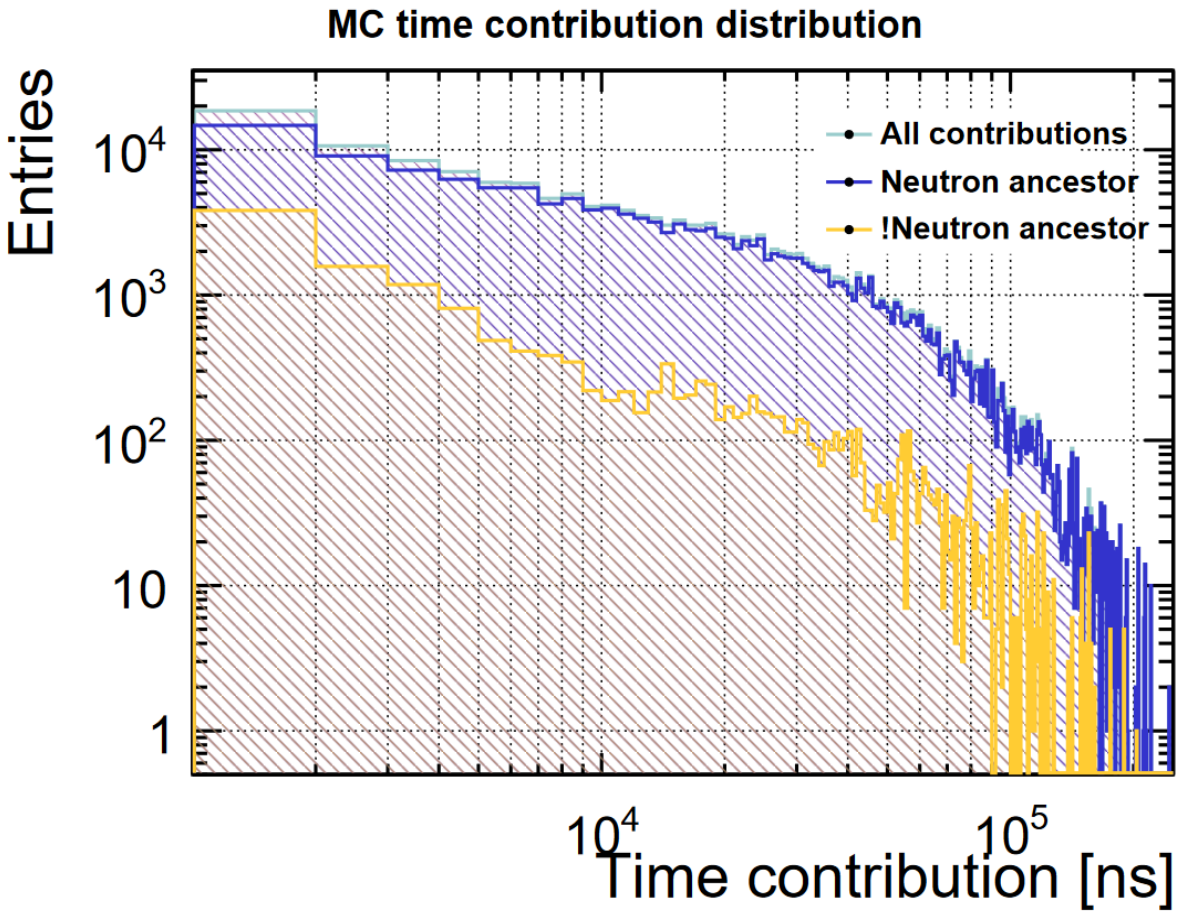
- Vast majority of hits with 15 ns < t < 50 ns after shower start are from neutrons
- Consistent between MC time stamp and hit time stamp

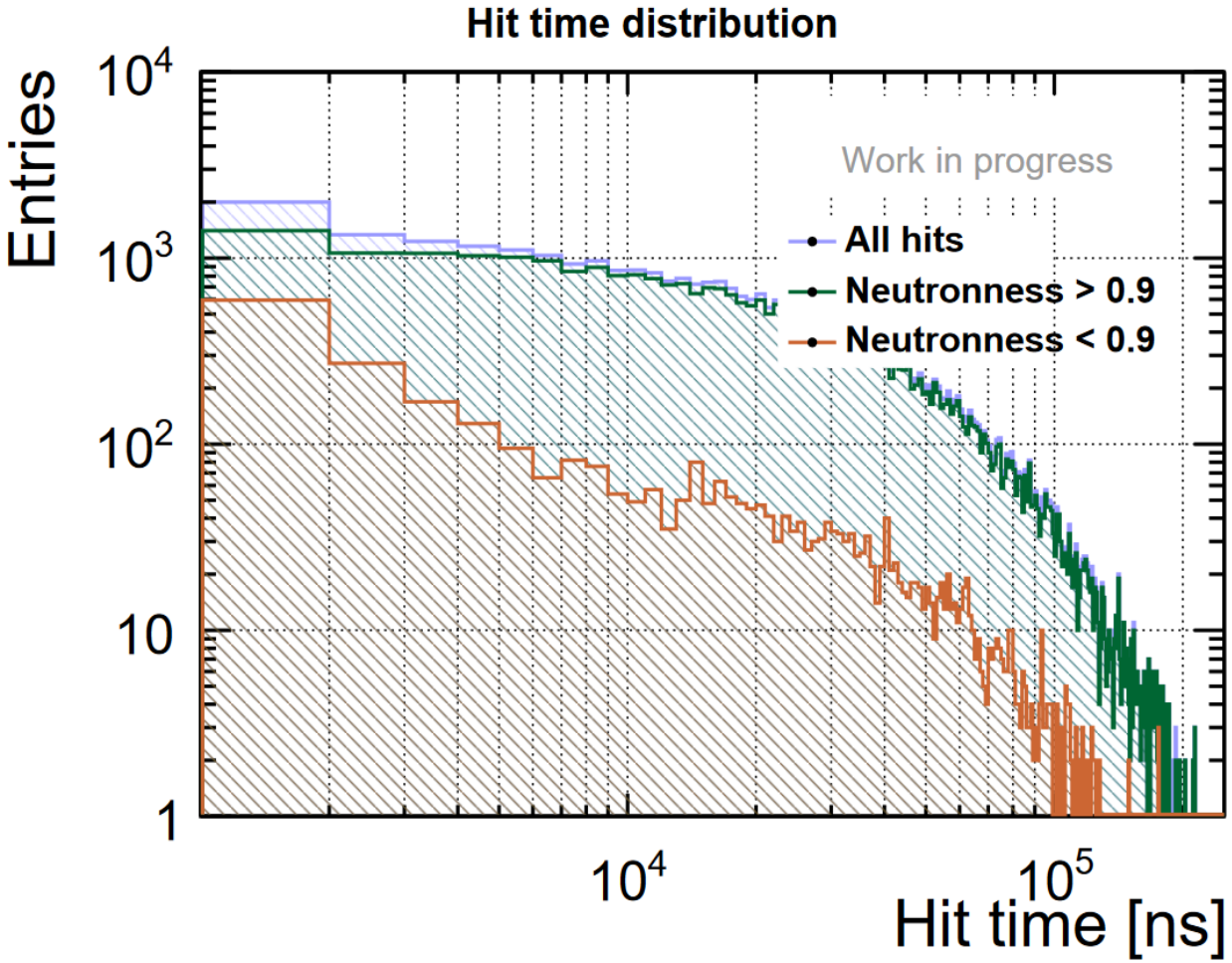




Time distribution

- The long term after-glow comes from neutrons.
- Neutrons are an order of magnitude more than non-neutrons for t > ~5 µs.

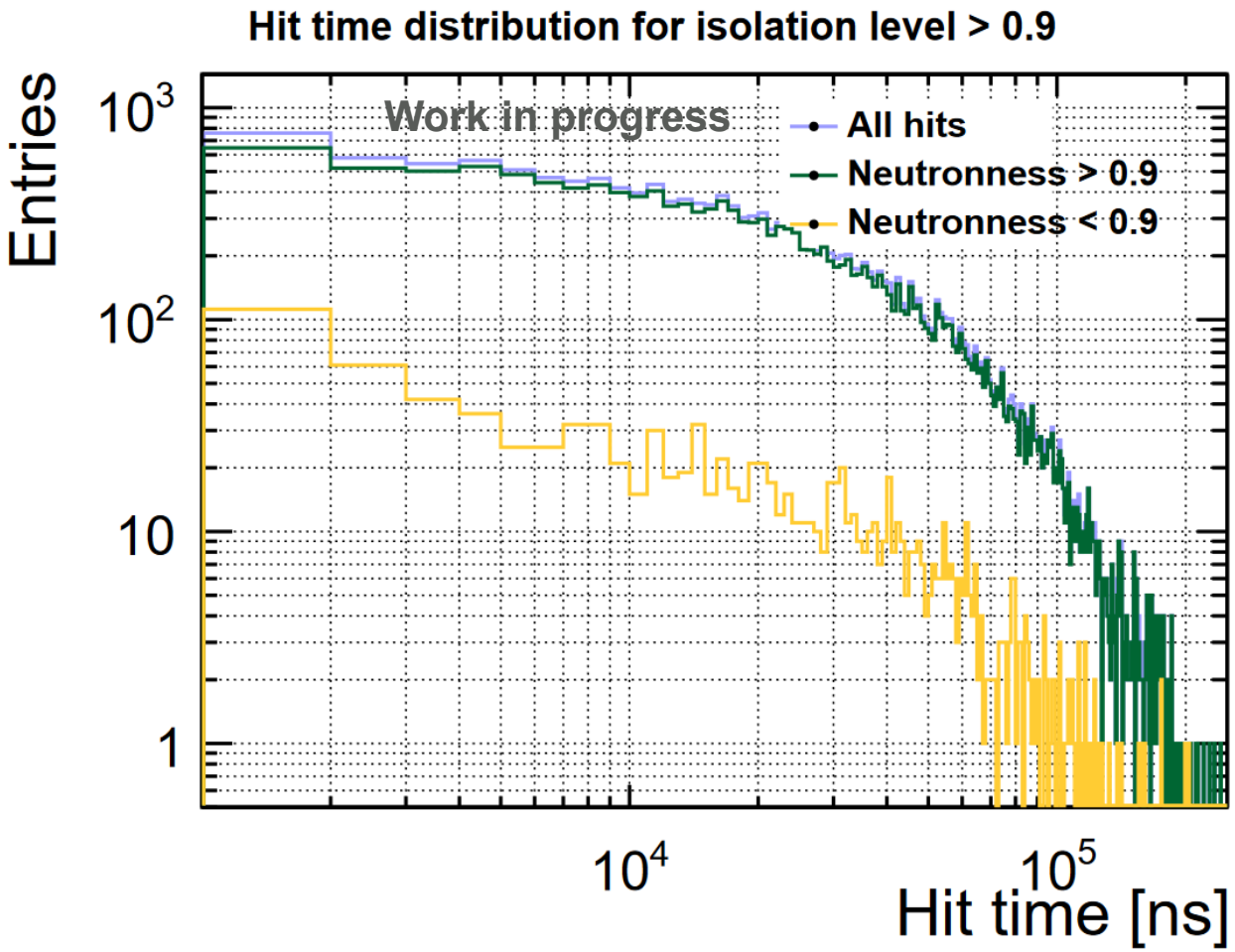


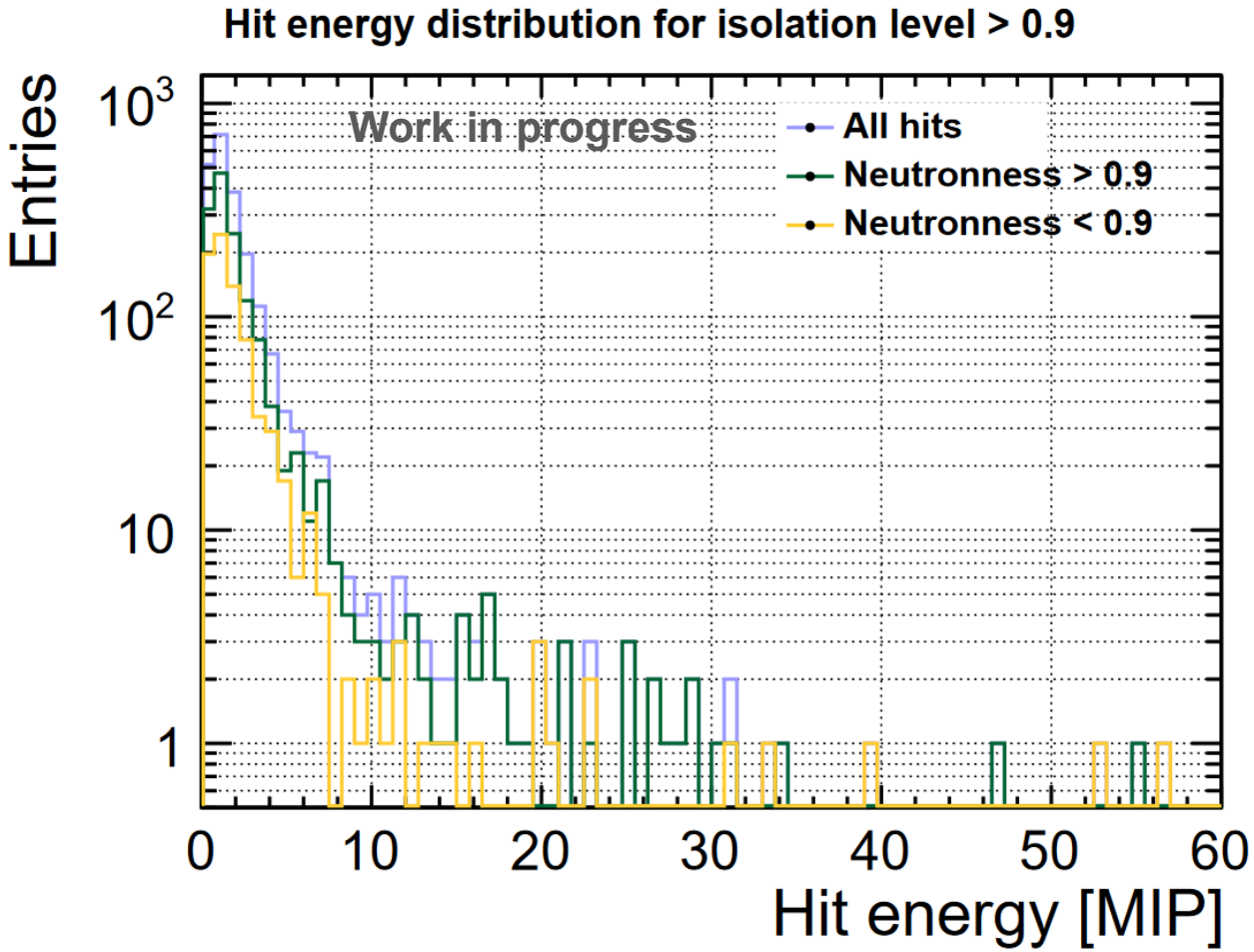


Hit distribution

Isolation level > 0.9

Most of the late hits which are isolated are from a neutron depositing energy of ~ 5 - 10 MIPs





Neutronness: Summary & Outlook

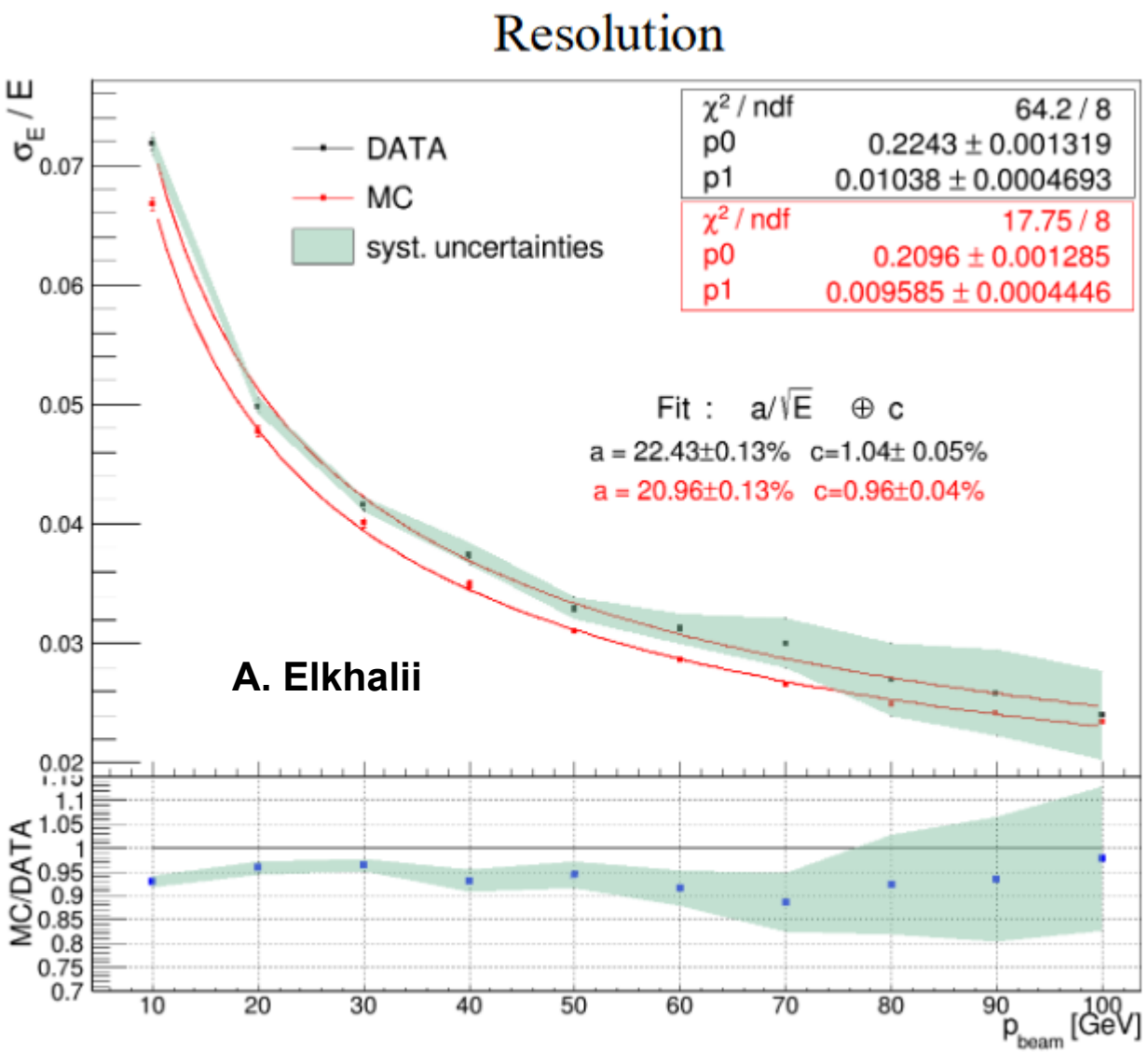
- Determination of Neutronness variable implemented as a MARLIN Processor.
- Most of the isolated late hits are from neutrons → can use isolation observable to separate neutrons.
- Outlook: Study correlation of neutronness with shower shape variables.

Electron Energy Reconstruction Influence of Gaps

Energy Resolution for electrons

Starting point

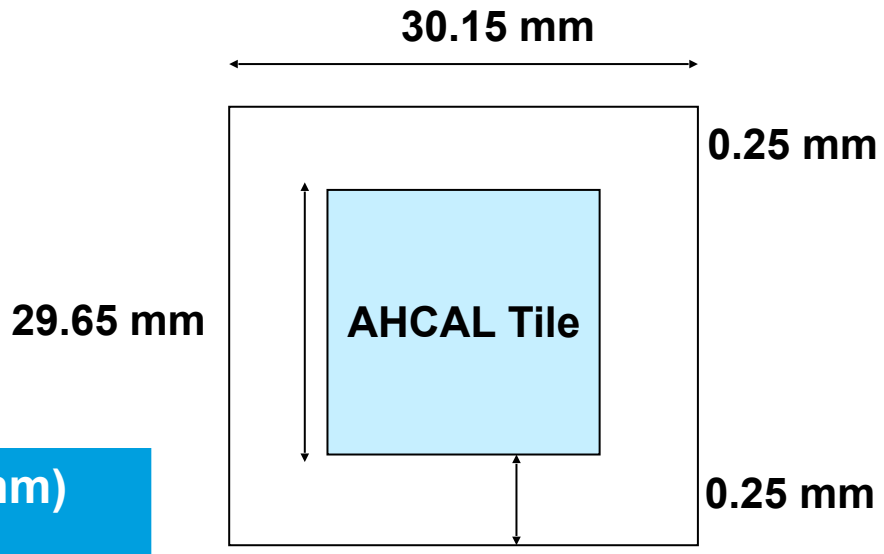
- for all comparisons between AHCAL 2018 testbeam data and simulation observe systematically better resolution in the simulation
  - of comparable size for all electron energies
  - not covered by the systematics we have studied, especially at low energies



AHCAL tile

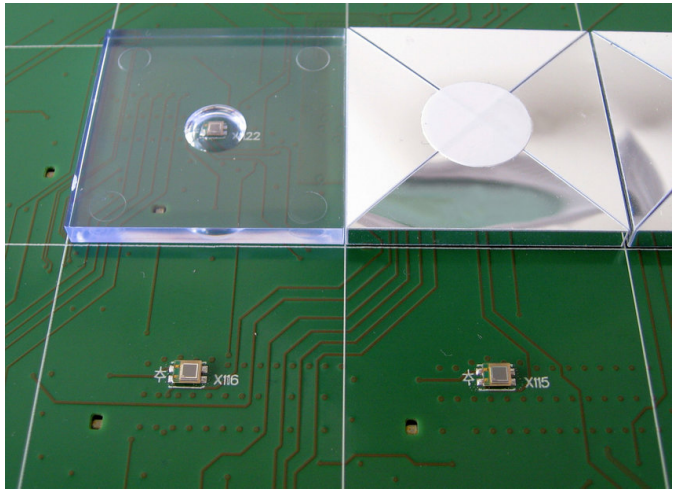
Nominal value

values according to production tolerances



Not to scale

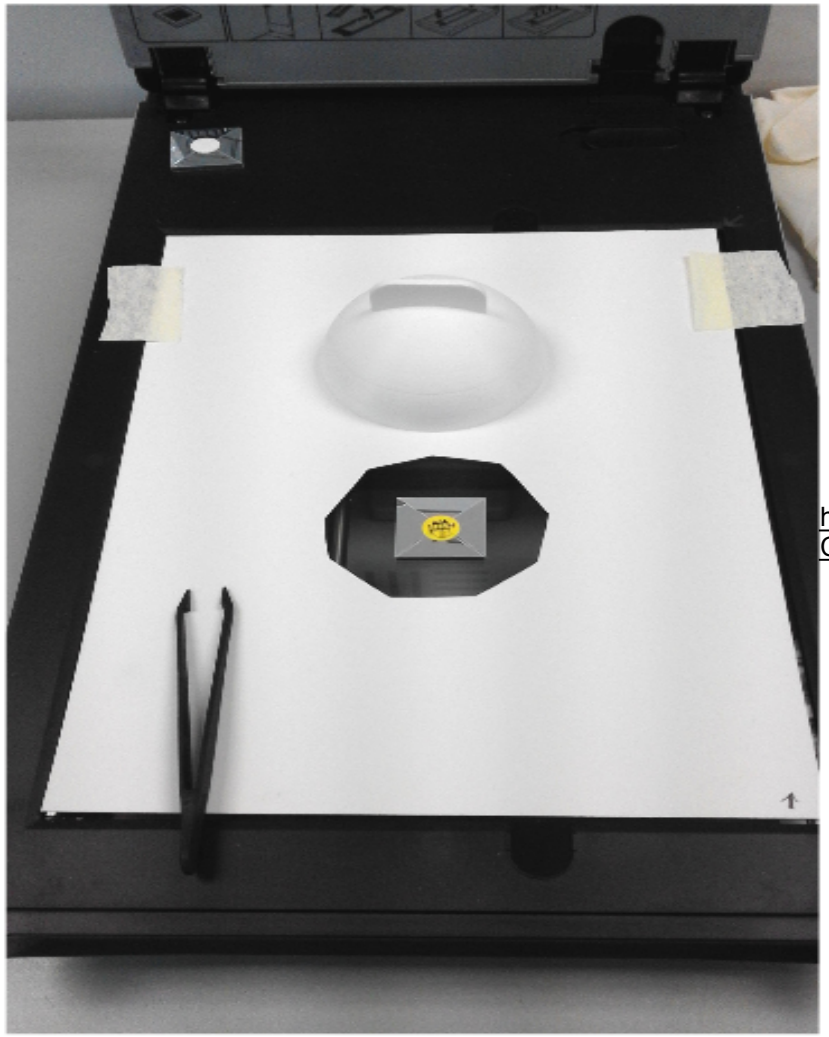
Tile pitch (mm)	Tile size (mm)	Dead space (mm)
Current	**Current**	**Current**
30.15	**29.65**	**0.5**



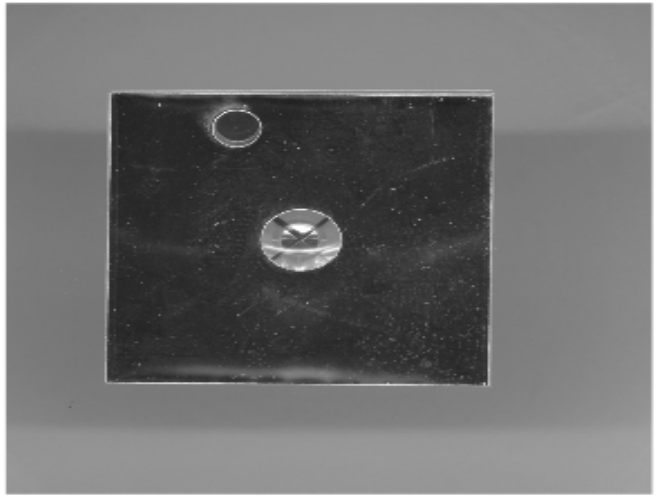
What are the actual tile sizes?
Does differences have an influence on the measurements?

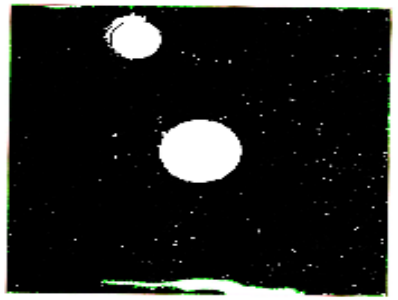
Quality Control – From each 50-tile-box: One Scan

- Squeezing with caliper is not allowed

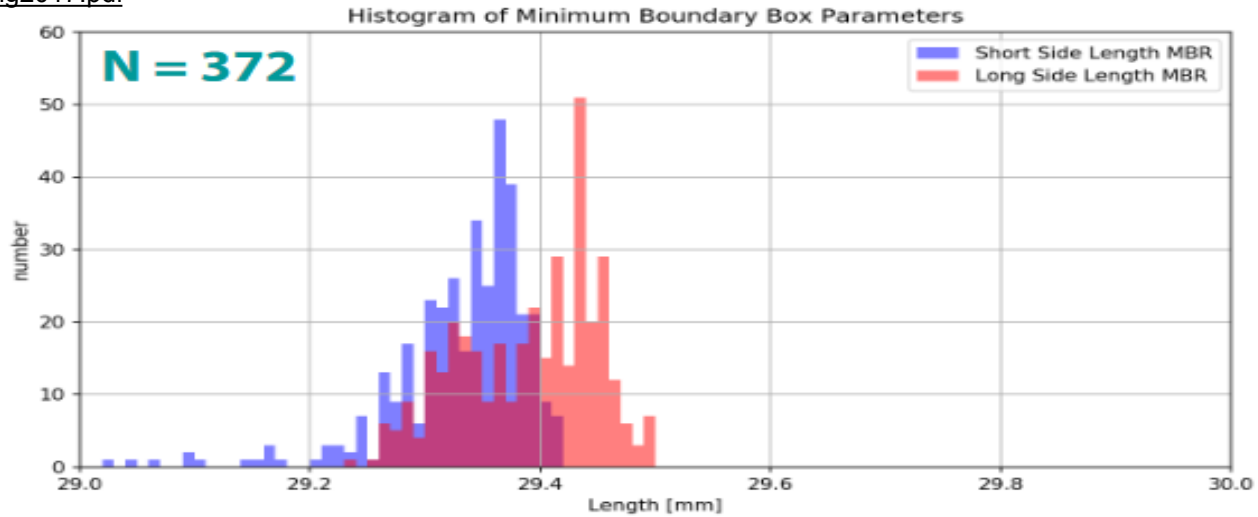


Half integrating sphere





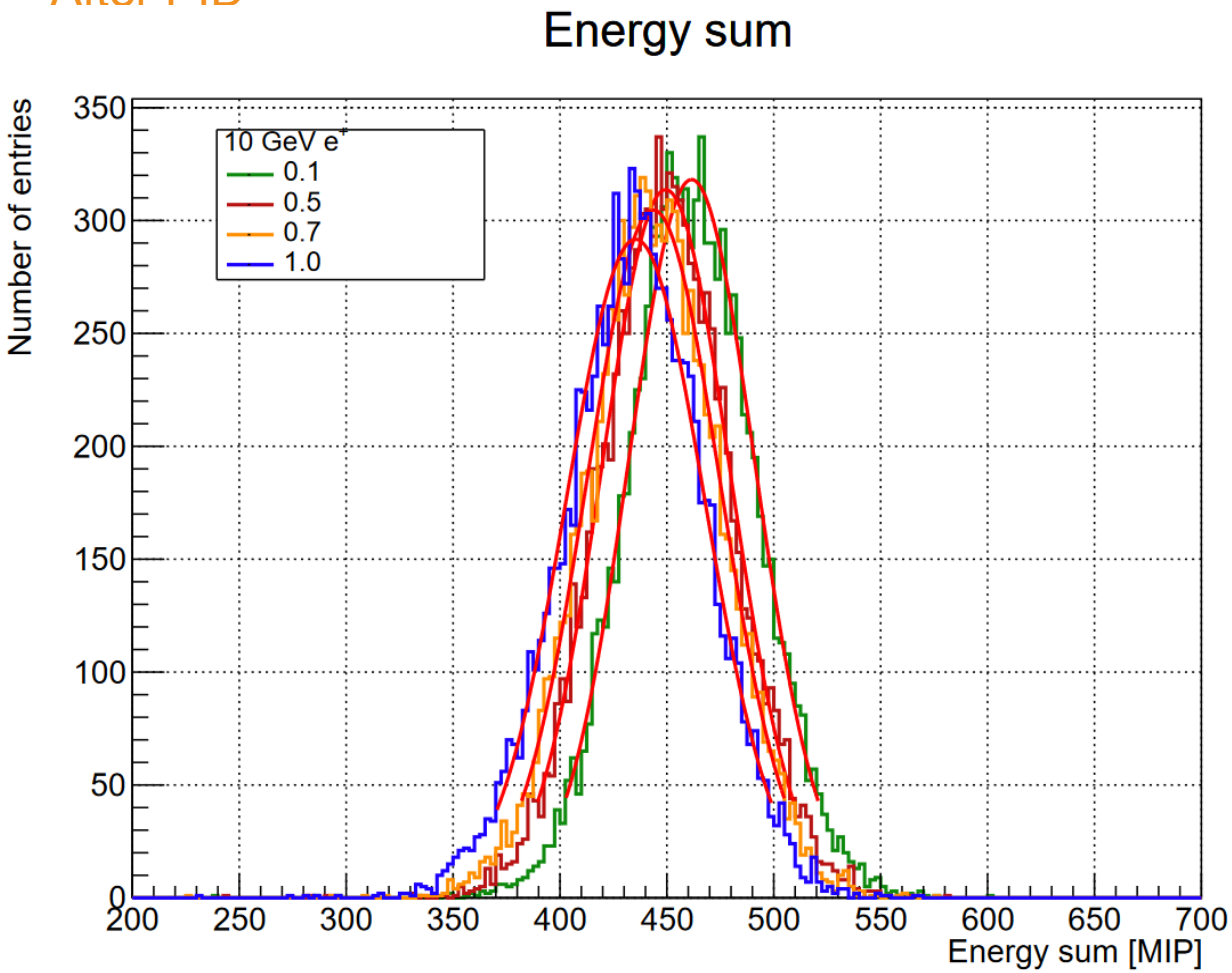
https://agenda.linearcollider.org/event/7807/contributions/40519/attachments/32551/49482/TileWrapping-CollMeeting2017.pdf

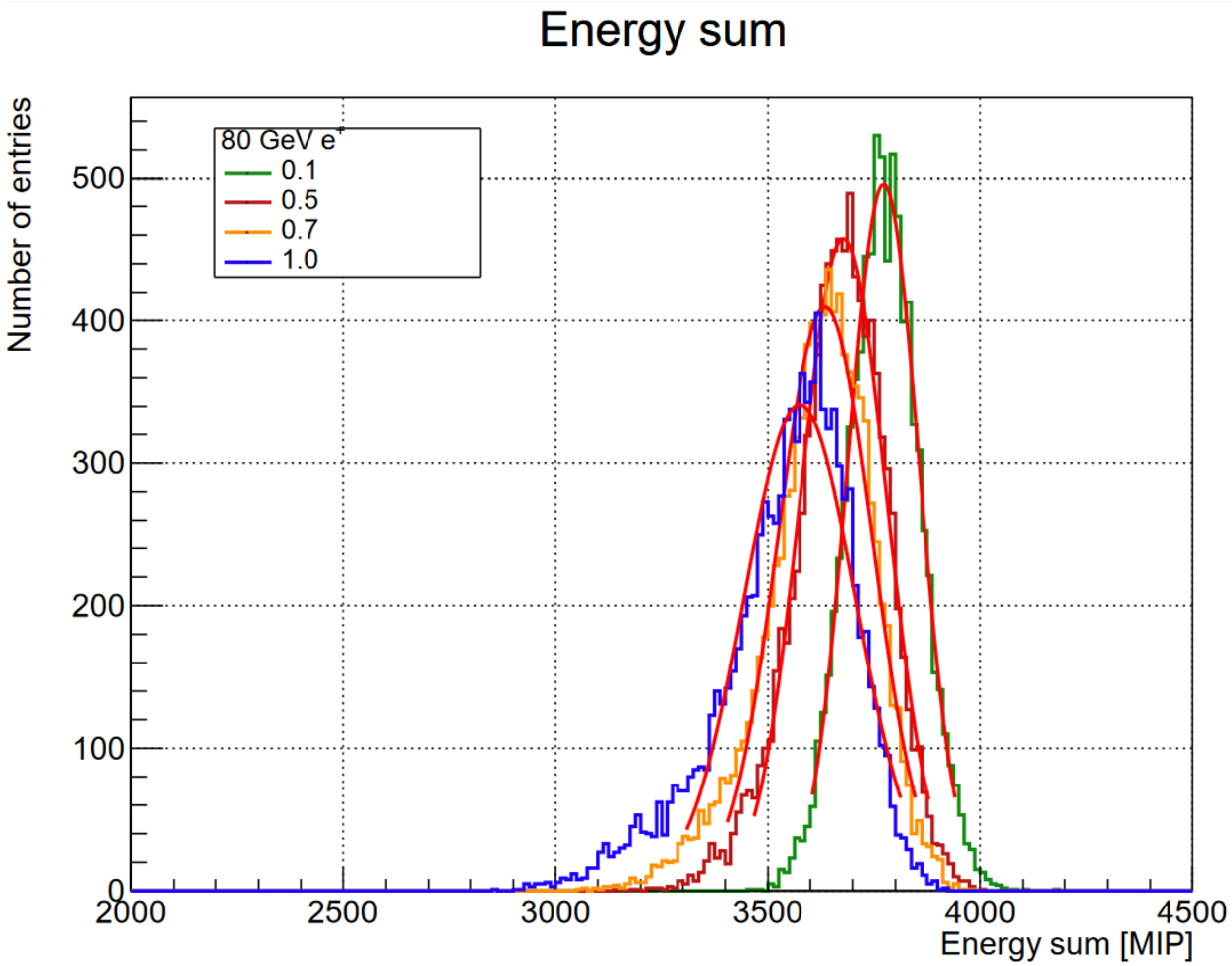


Energy sum distribution: influence of gap width

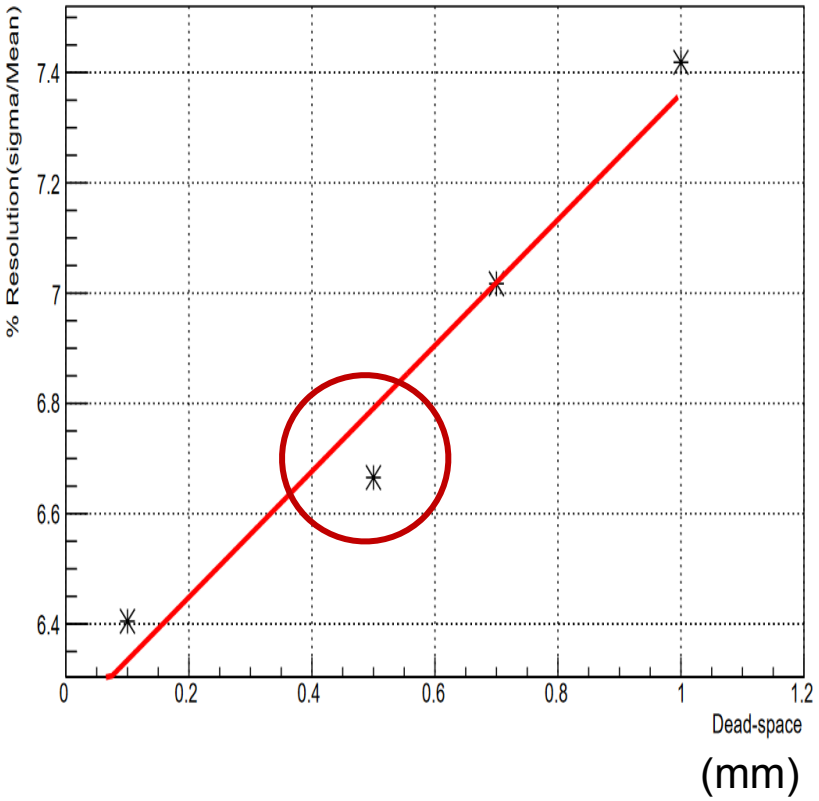
CaliceSoft: v04-13-02
No additional cuts on CoG_x & CoG_Y applied

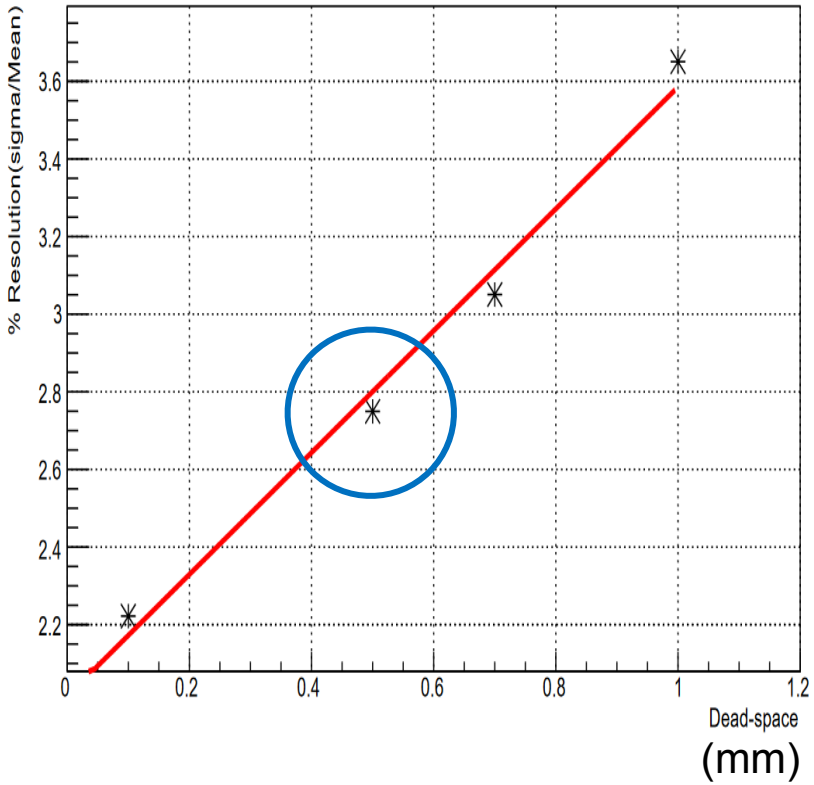
After PID

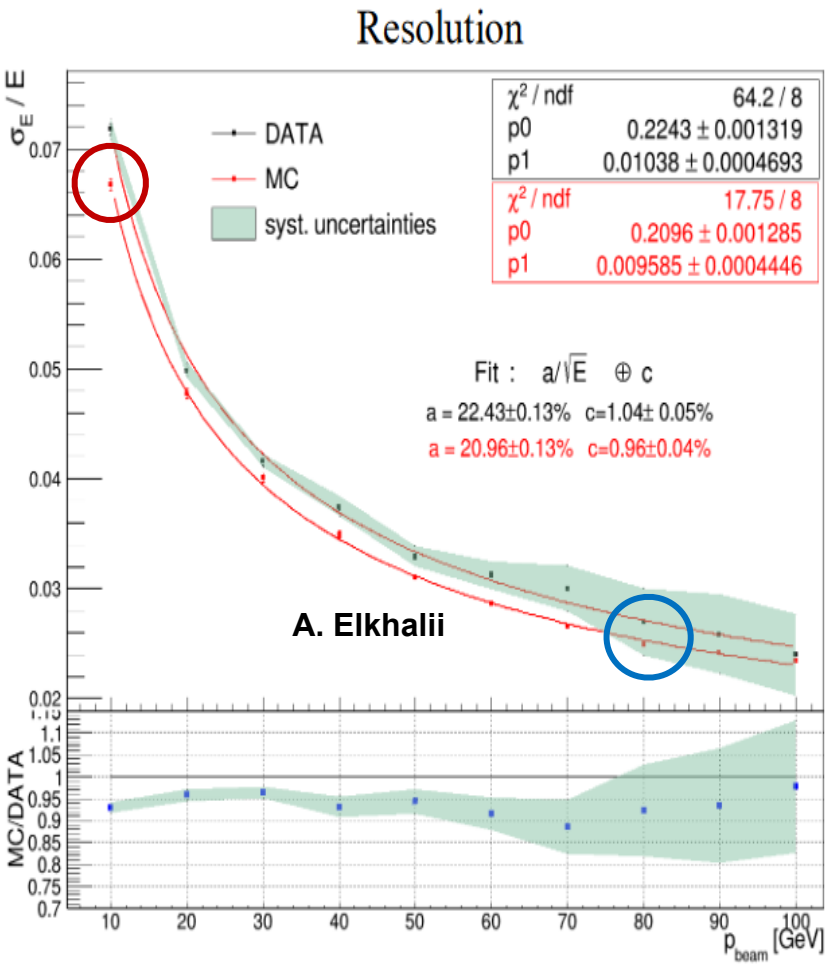




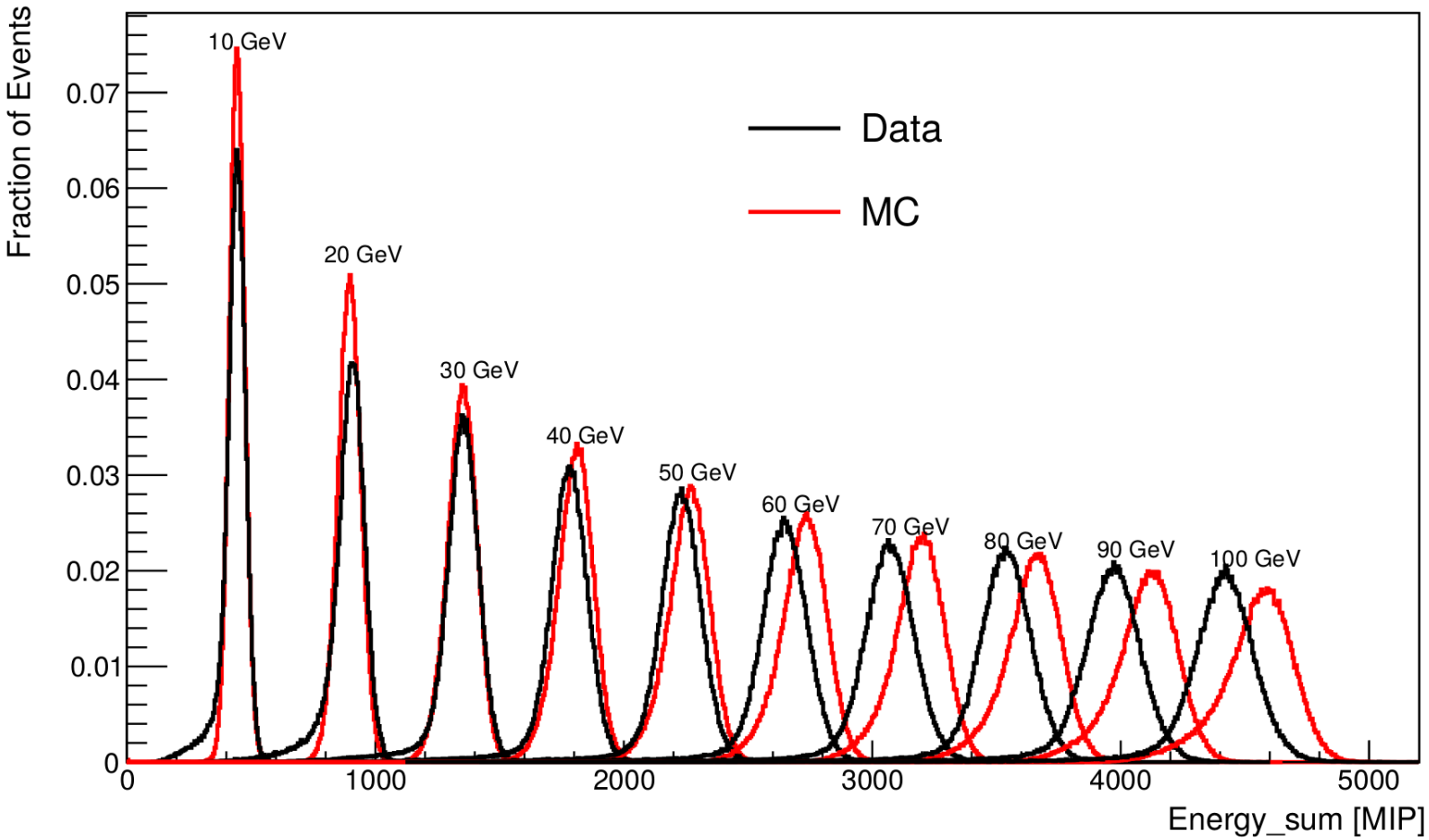
Dead-space influence







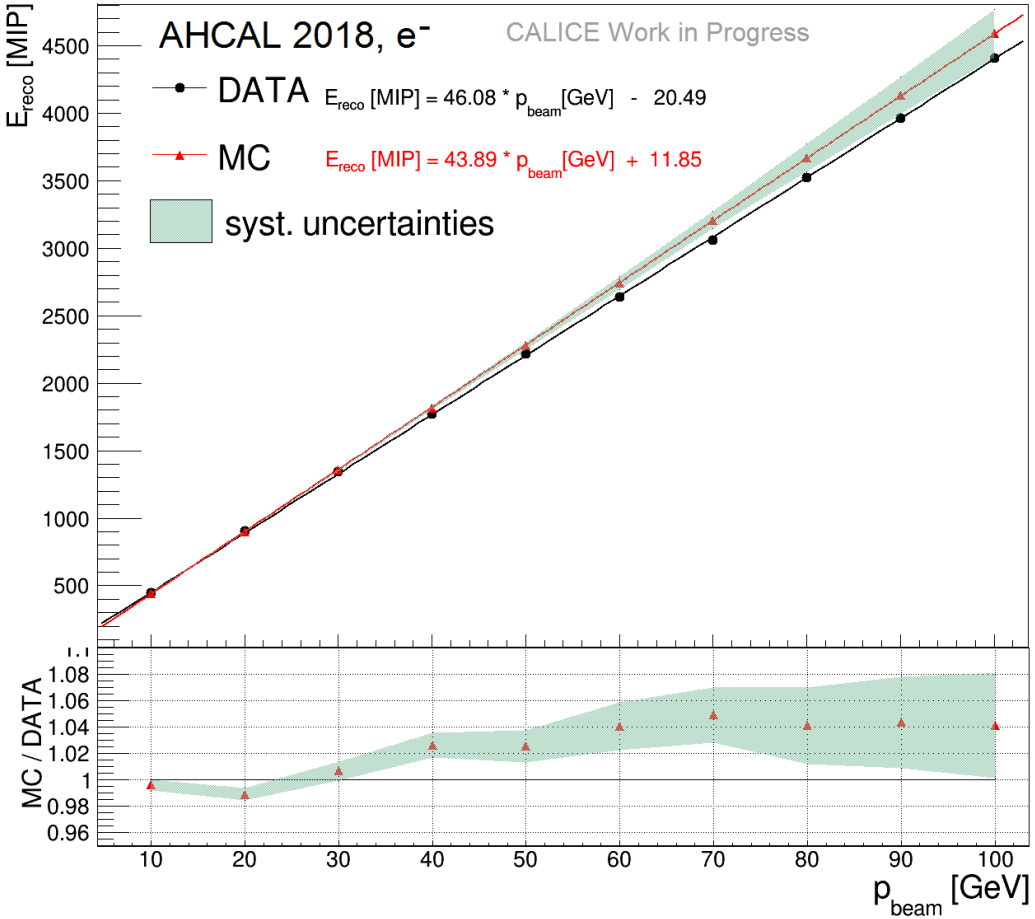
Data/MC Comparison with 0.7 mm gap size

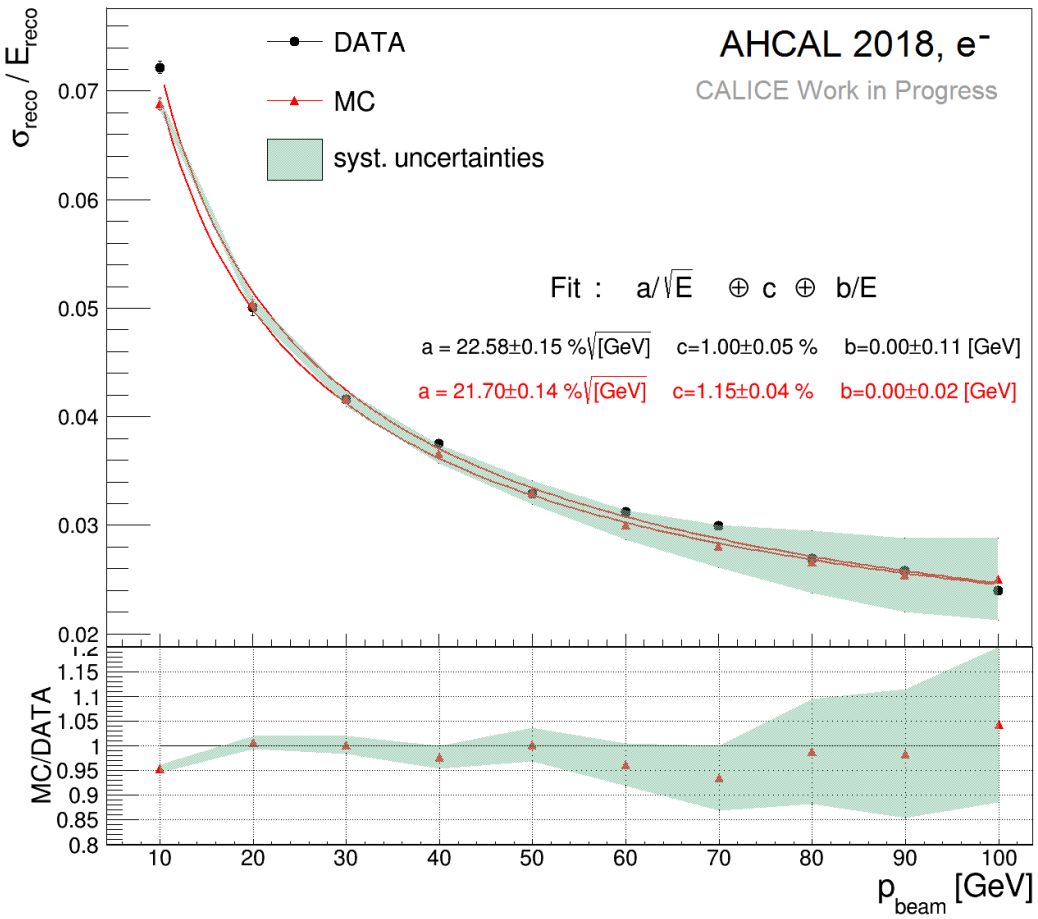


- still see a shift in energy scale
- at low energy, data has a larger tail towards small energies
- at large energy, MC has more tail towards lower energies

- Nevertheless, quantify mean and width by Gaussian fits in the range +- 1.2 sigma

Data/MC Comparison with 0.7 mm gap size





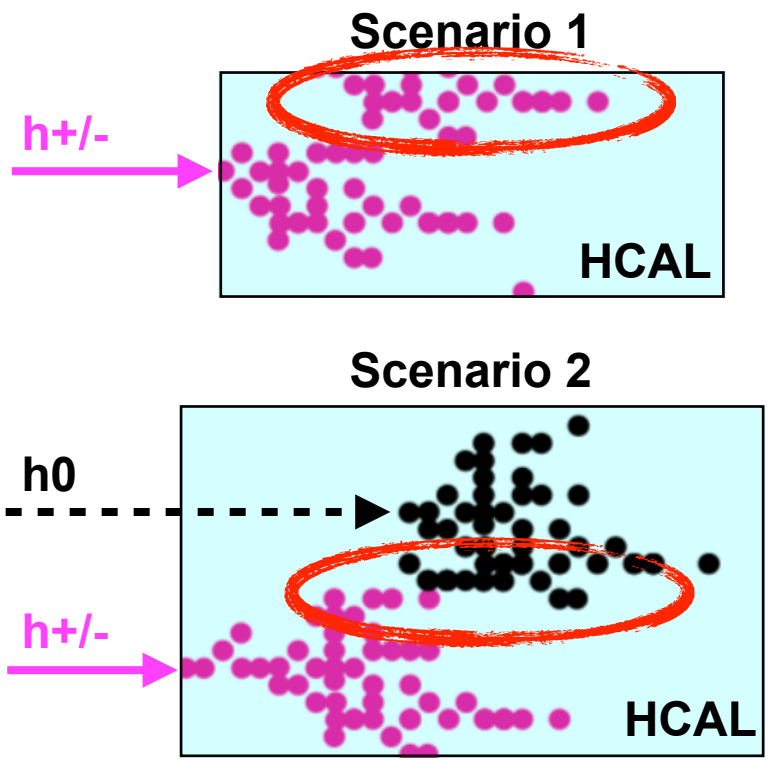
better overall agreement, differences mostly covered by systematic uncertainties
→ use 0.7 mm gap size in future simulations

PandoraPFA Studies with AHCAL 2018 Prototype Data

Idea and Goals of Analysis

- **Scenario 1**: One charged hadron in event
- **Scenario 2**: Overlaid charged and neutral hadron event

➡ **Perfect case**: PandoraPFA identifies the individual shower clusters and assigns the charged hadron track to its cluster
HCAL: Neutral hadron energy, Tracker: Charged hadron energy



- **Reality: Confusion**
  - Reconstruct fragments of charged cluster as separate neutral hadron
  - Failure to resolve neutral hadrons
    - ➡ Wrong assignment of energies, degrading energy resolution

- **Goal: Run PandoraPFA on AHCAL 2018 prototype standalone scenario (+ tracks for charged hadrons)**
  - ➡ **Study of single and two particle reconstruction performance**
    - ➡ **Different conditions (energies, particle types, distances, Pandora plugins, etc.)**

Overview

Pandora PFA Studies

AHCAL data & MC → Unselected charged pion events → Event selection (Shower start finding, PID,…) and using of track info (DWC) → Selected charged pion events → Primary track removal and dedicated event overlay → Events with overlaid charged and "neutral" hadron

Selected charged pion events → Pandora PFA → Scenario 1: Single particle reconstruction studies

Events with overlaid charged and "neutral" hadron → Pandora PFA → Scenario 2: Two particle reconstruction studies

Analysis based on first CALICE PFA Paper: https://arxiv.org/abs/1105.3417

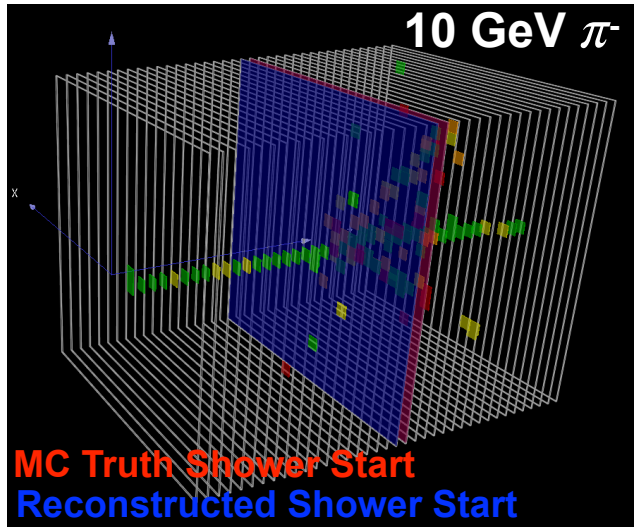
Sample Preparation Status

Pre/Post Pandora Processors

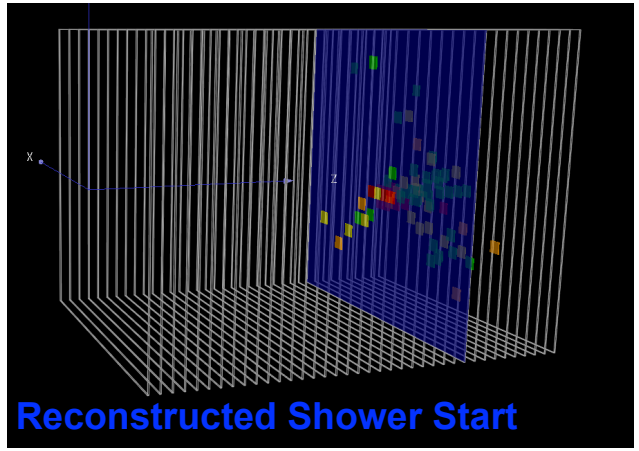
- **Unselected pion events:** Data from TB campaigns 2018 and MC simulation
- **Shower start finder:** Implemented and optimised for 10-100 GeV hadrons
- **Primary track removal:** Work in progress
- **PID:** Very advanced
- **MIP to GeV Calibration:** Done for EM and HAD scale

- **Event overlay and selection:** Advanced
- **Track info from Delayed Wire Chamber (DWC) of June test beam and tracks for MC from MC truth information:** Advanced

- **Output/Analysis processors for PFO objects:** Adapted LCPandoraAnalysis processor



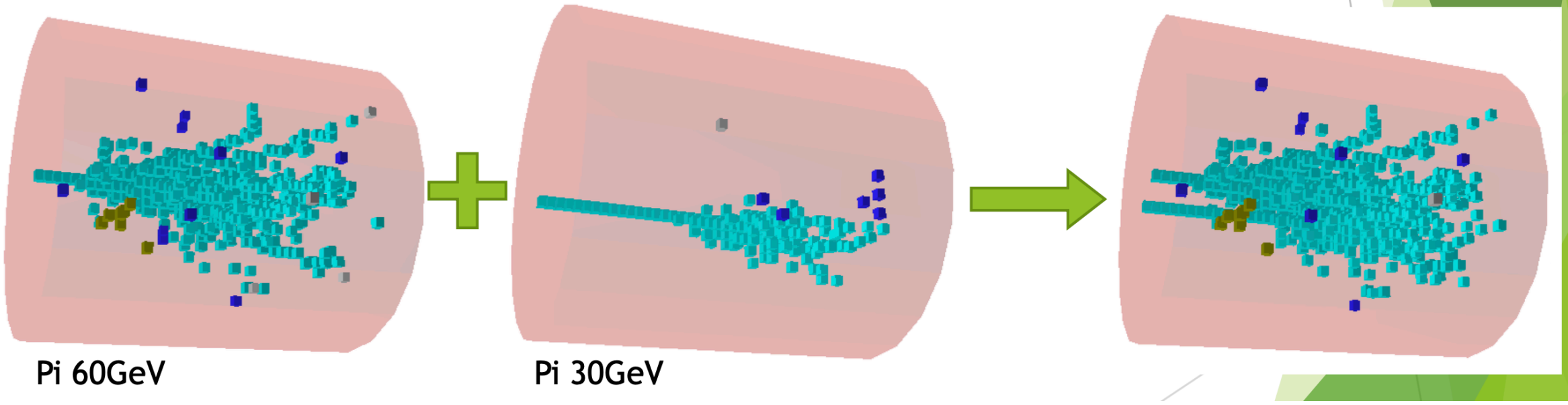
Charged Hadron



"Neutral Hadron“
(Removed primary track)

Event Overlay

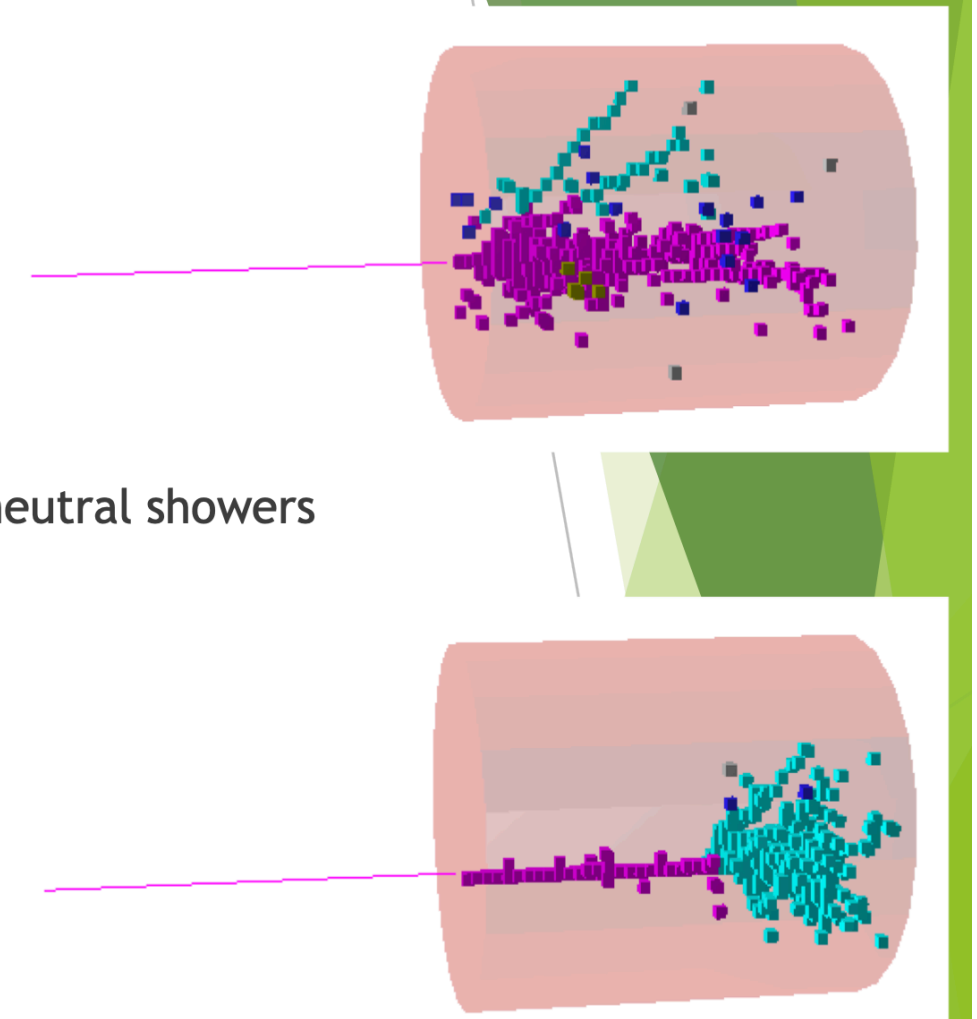
- Overlay two shower events to create “two-particle event”
- Merge the hits in AHCAL as well as track information from DWC
  - Required for track collection creation for Pandora (described later)
  - (Technically this was the hardest part as other functions were already existing)

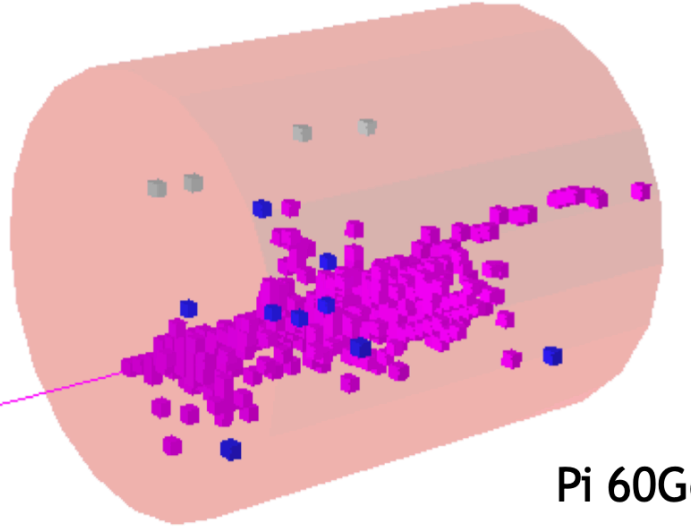


Linghui Lu, AHCAL Main Meeting 2019, DESY

Track Collection Creating

- Track collection created for pandora
  - Particle type and energy is yet manually input
- Clusters associated with track became “charged”
- Yet there are sometimes neutral fragments or completely neutral showers
  - Further calibration, studies on Pandora plugins, …





Pi 60GeV

Linghui Lu, AHCAL Main Meeting 2019, DESY

7

Overview

Pandora PFA Studies

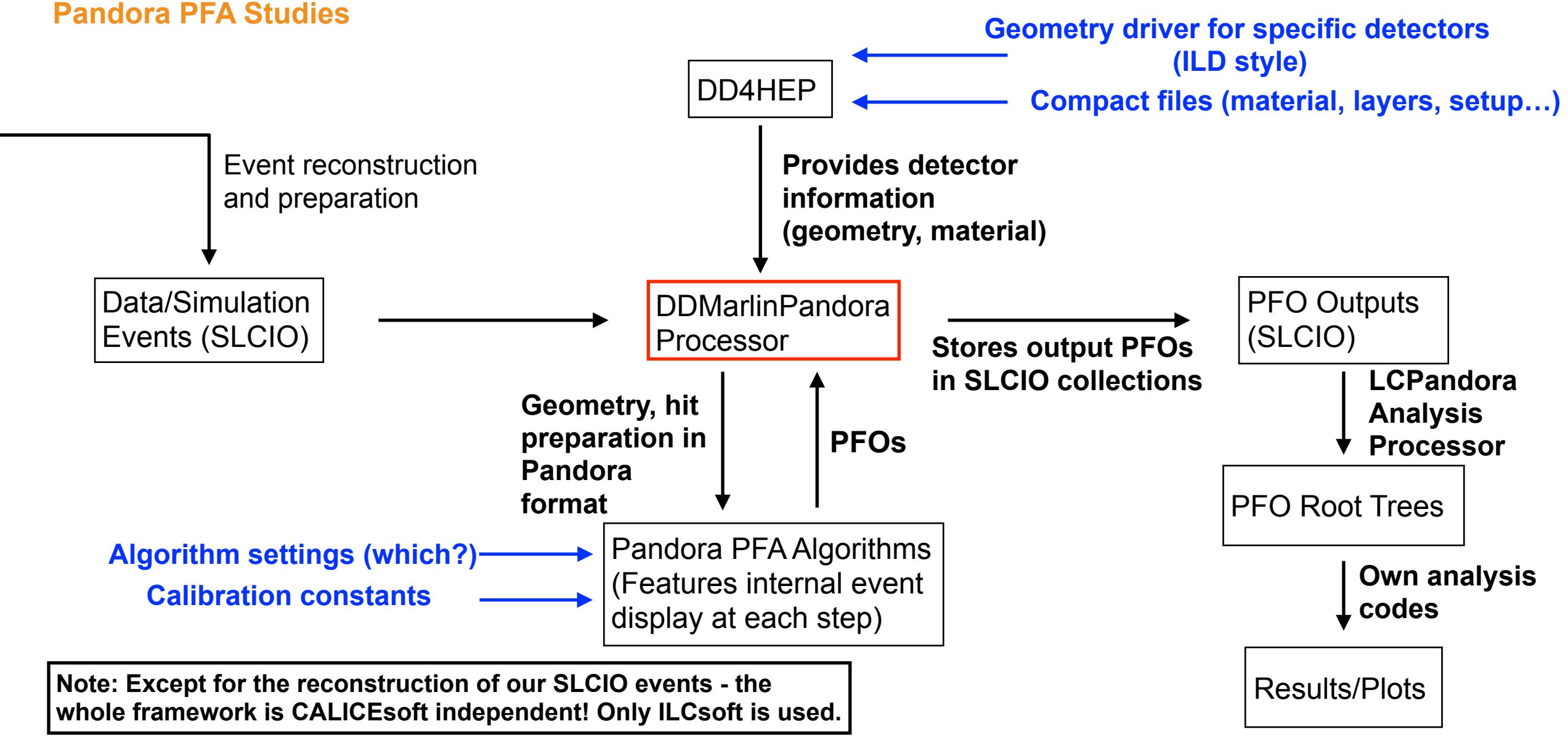
AHCAL data & MC → Unselected charged pion events → Event selection (Shower start finding, PID,…) and using of track info (DWC) → Selected charged pion events → Pandora PFA → Scenario 1: Single particle reconstruction studies

Selected charged pion events → Primary track removal and dedicated event overlay → Events with overlaid charged and "neutral" hadron → Pandora PFA → Scenario 2: Two-particle separation studies

Analysis based on first CALICE PFA Paper: https://arxiv.org/abs/1105.3417

Framework / Data Flow Diagram

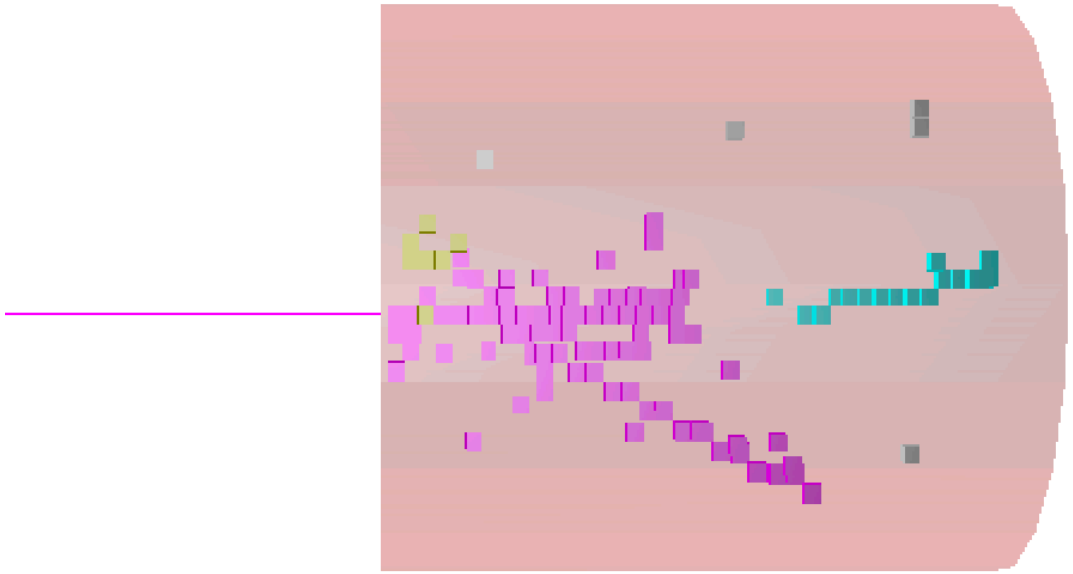
Pandora PFA Studies



Note: Except for the reconstruction of our SLCIO events - the whole framework is CALICEsoft independent! Only ILCsoft is used.

Pandora Visual Monitoring

Hits, Clusters & PFOs

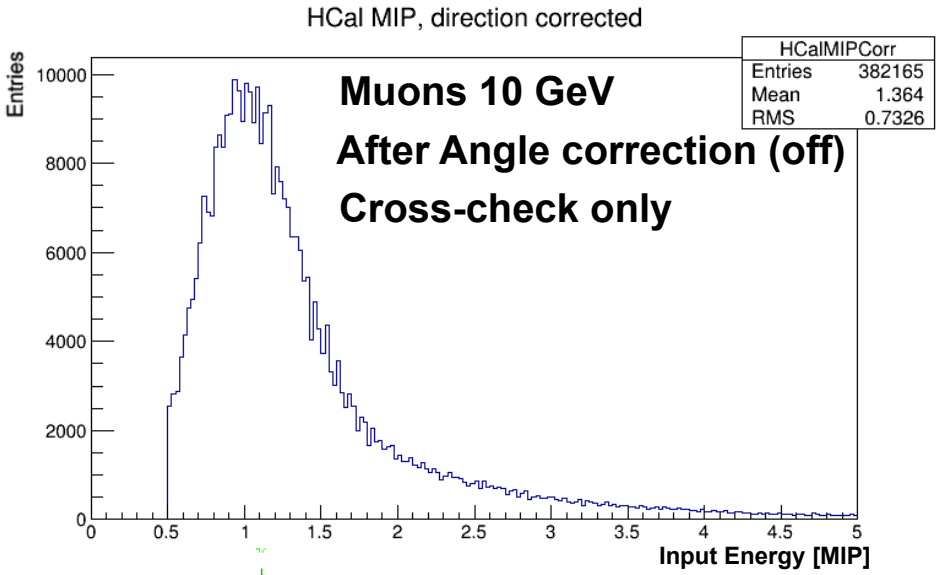


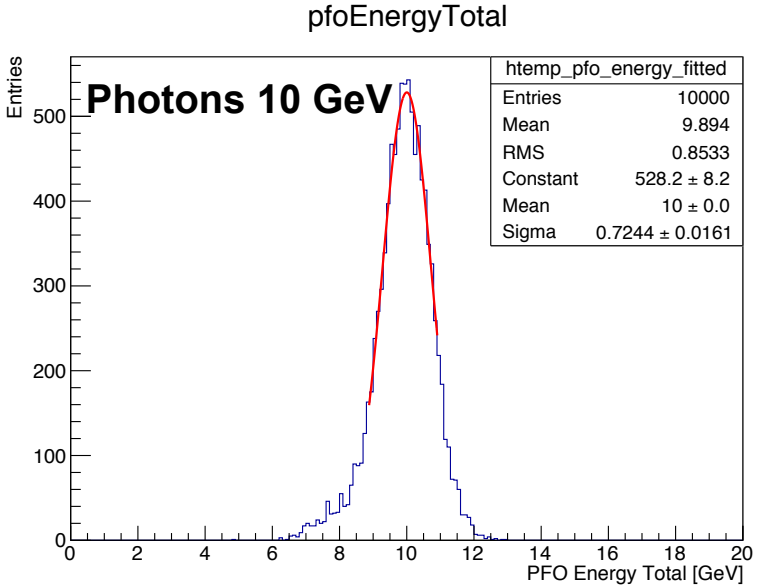
- Existing HCAL-Endcap class used for our setup
- Pandora visual monitoring working fine displaying hits, clusters, tracks and PFOs

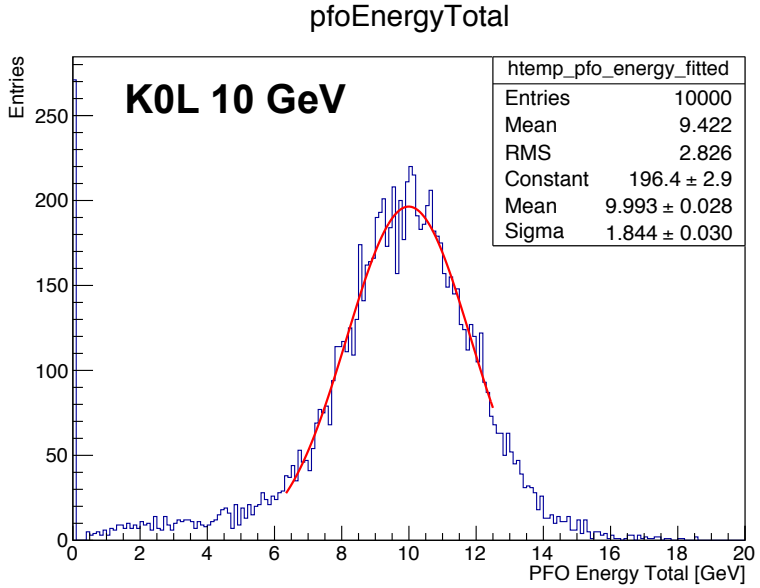
Pink: Charged Hadron
Cyan: Neutral Hadron
Yellow: Photon
Grey: Unclustered Hits

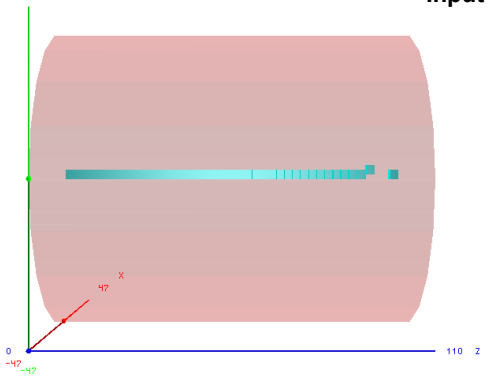
Pandora Energy Calibration

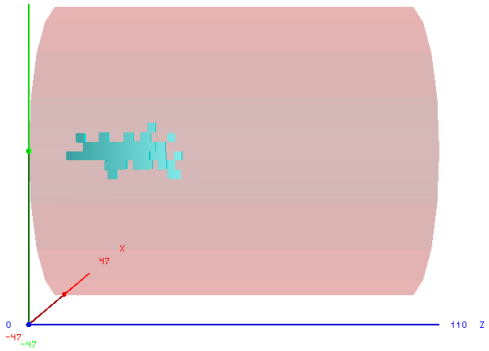
MC Muons, Photons, K0L

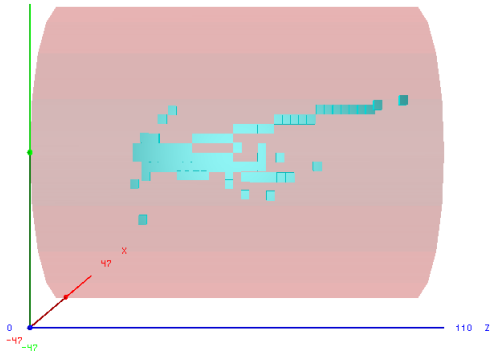












- **Muons**: Used to determine GeV to MIP factor (currently 1.0), AHCAL energy in MIP and angle correction off
- **Photons and K0L's**: Used to determine EM and HAD response, PFO energy tuned to peak at 10 GeV

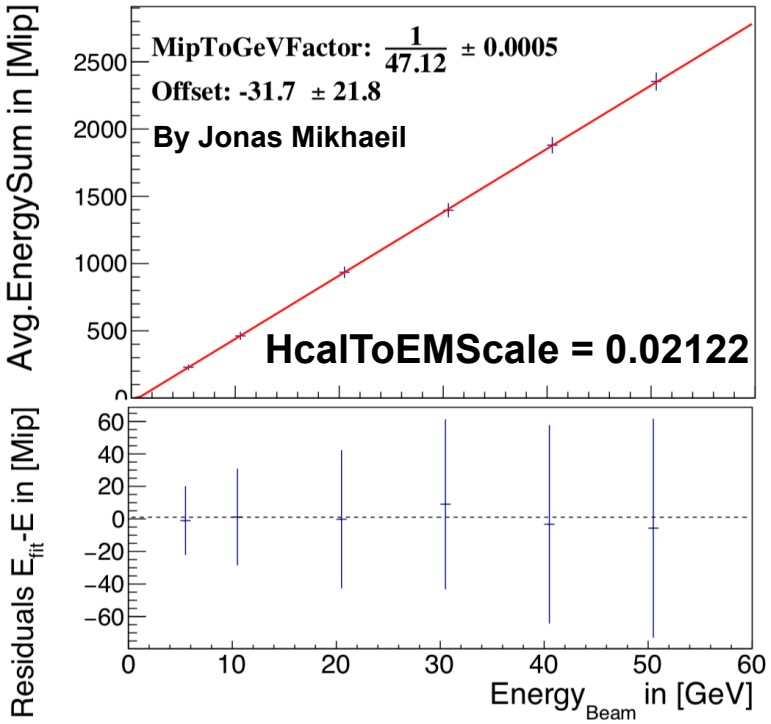
Pandora Basic Energy Calibration Results

EM and HAD Responses (MC)

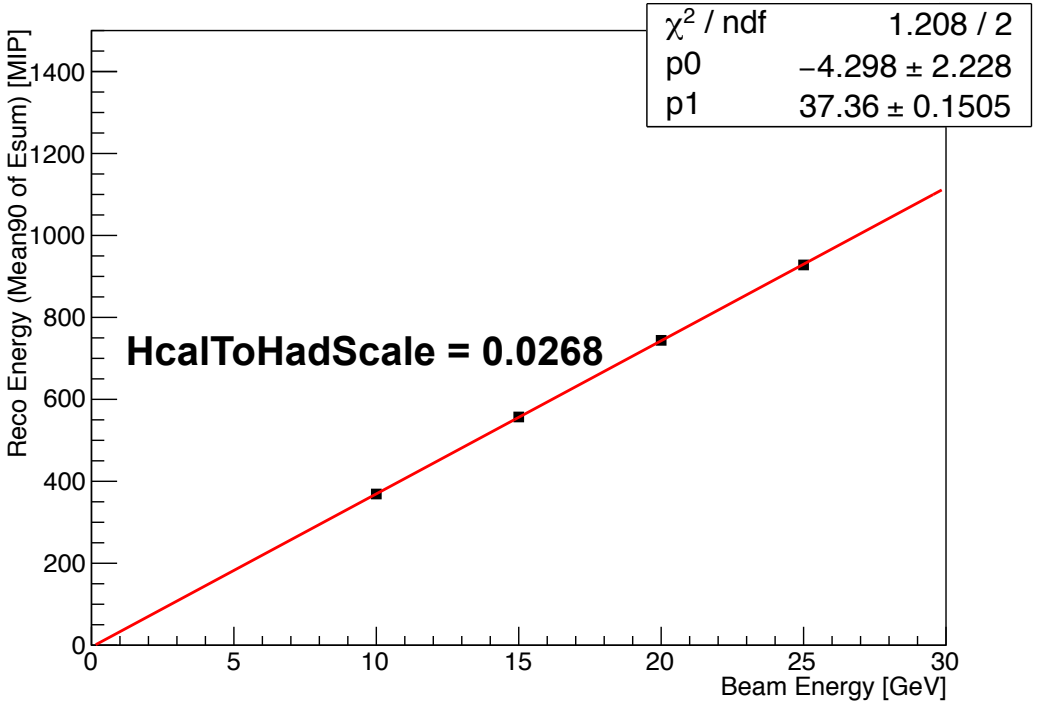
```
<constant name="PandoraHcalToMip">1.</constant>

<constant name="PandoraHcalToEMScale">0.02252</constant>
<constant name="PandoraHcalToHadScale">0.0275</constant>
```

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

EM Response Determination (e-)



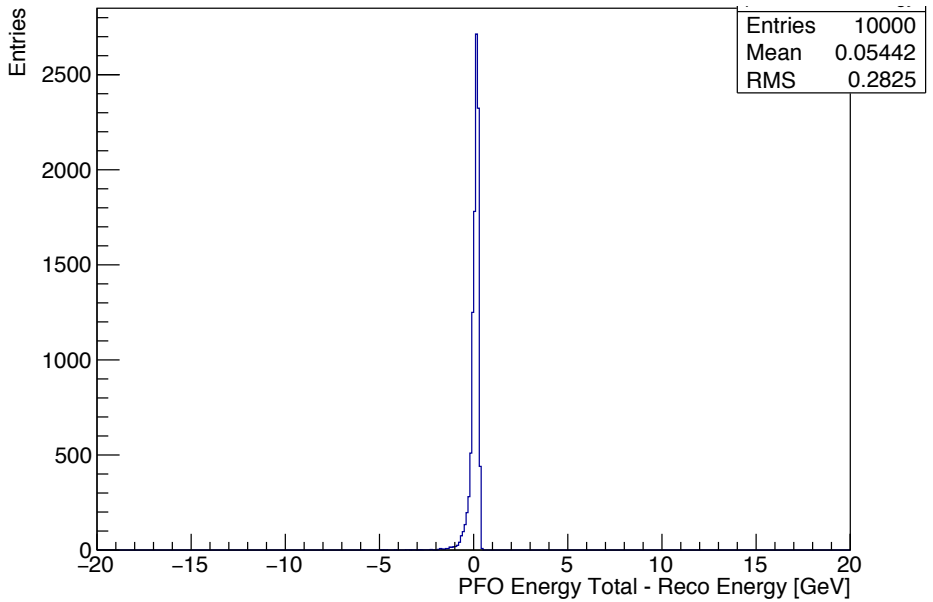
HAD Response Determination (K0L)



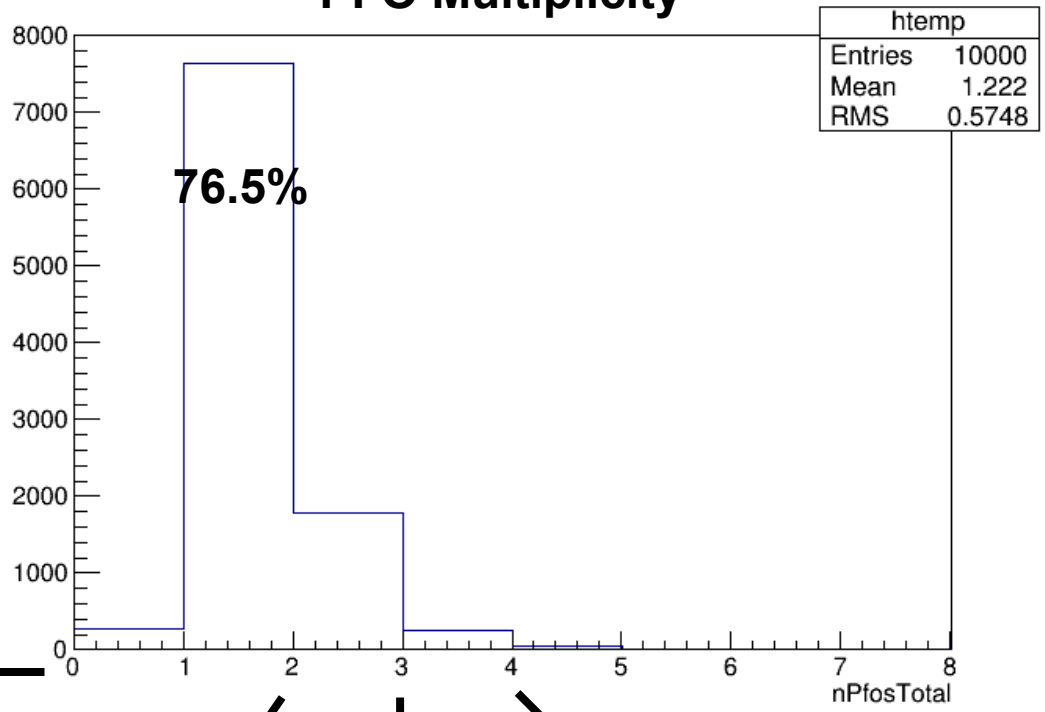
First Look: K0L 10 GeV (MC)

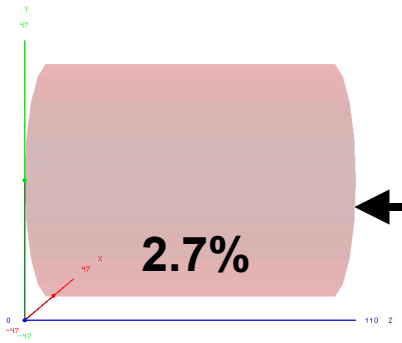
Applied Calibrated Pandora

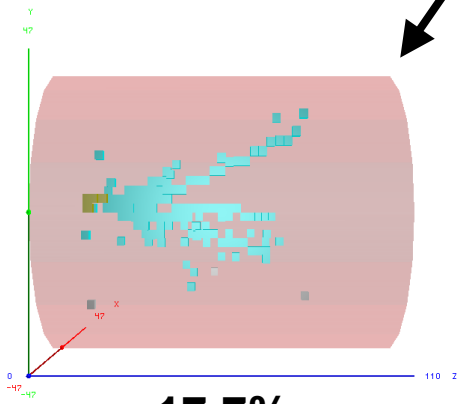
PFO Esum - AHCAL Esum (HAD)

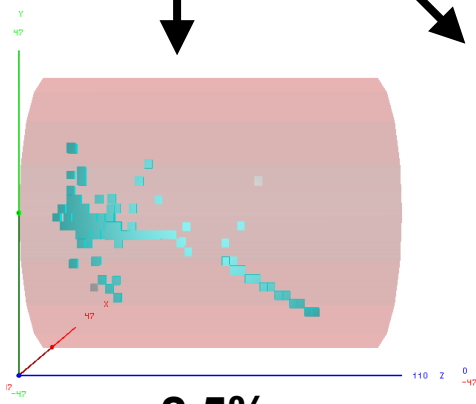


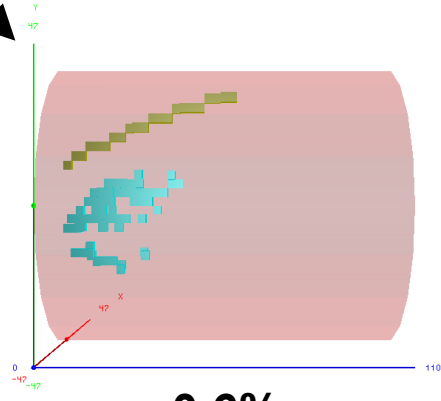
PFO Multiplicity









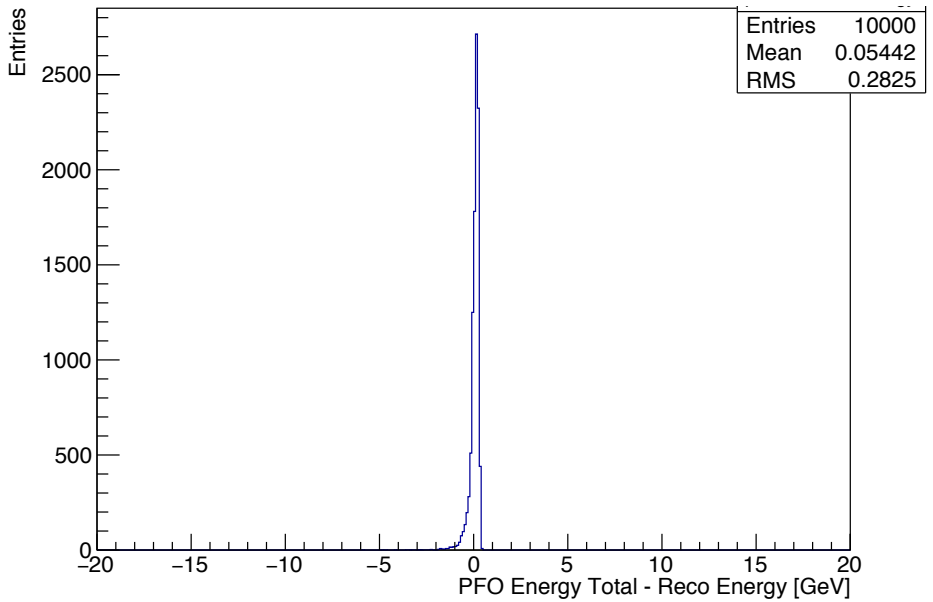


- Fairly good agreement between AHCAL and Pandora reconstruction (small left tail due to PFO multiplicity?)
- The earlier the particle showers the higher its PFO multiplicity?

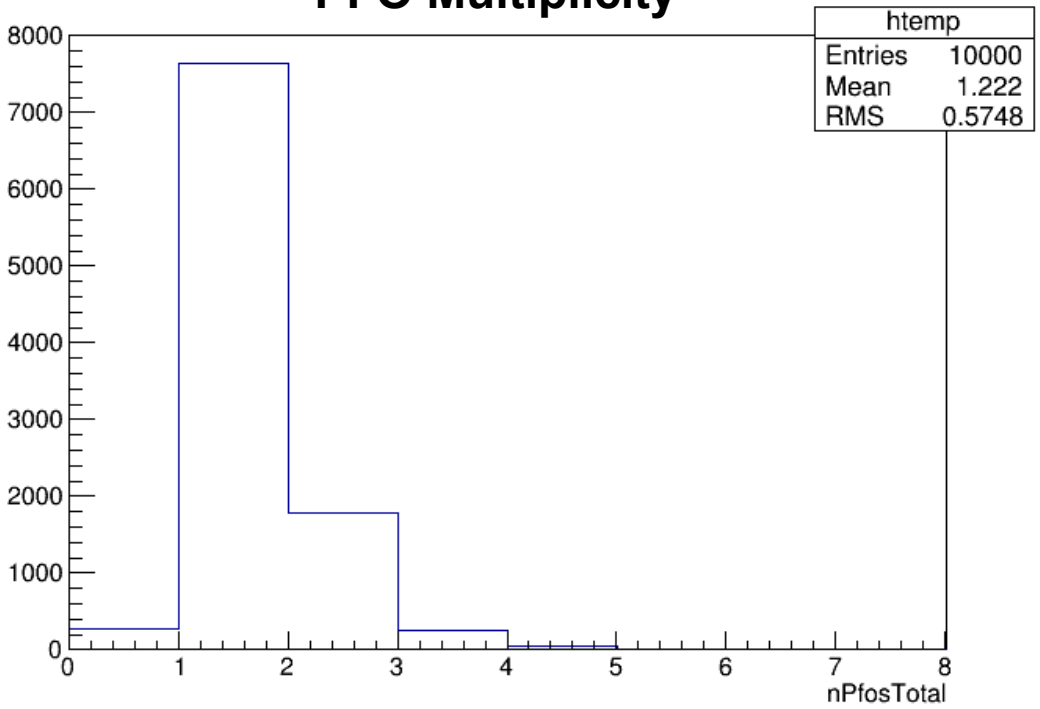
First Look: K0L 10 GeV (MC)

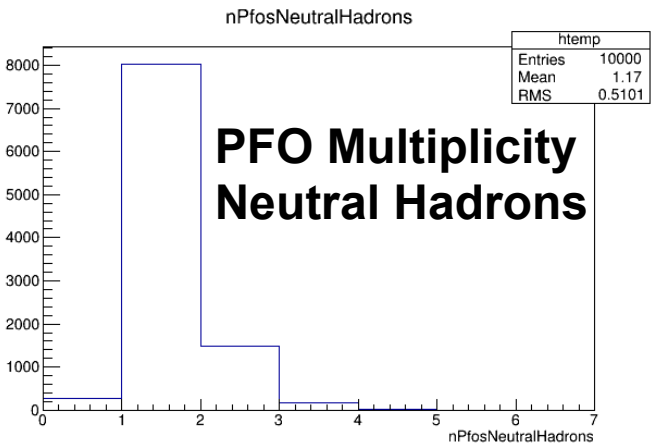
Applied Calibrated Pandora

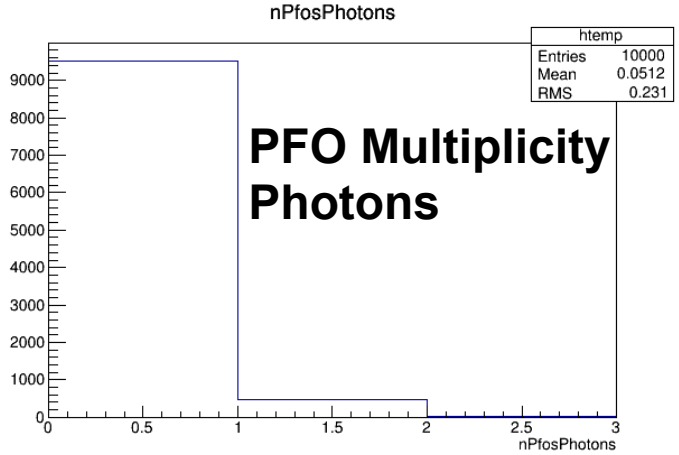
PFO Esum - AHCAL Esum (HAD)



PFO Multiplicity







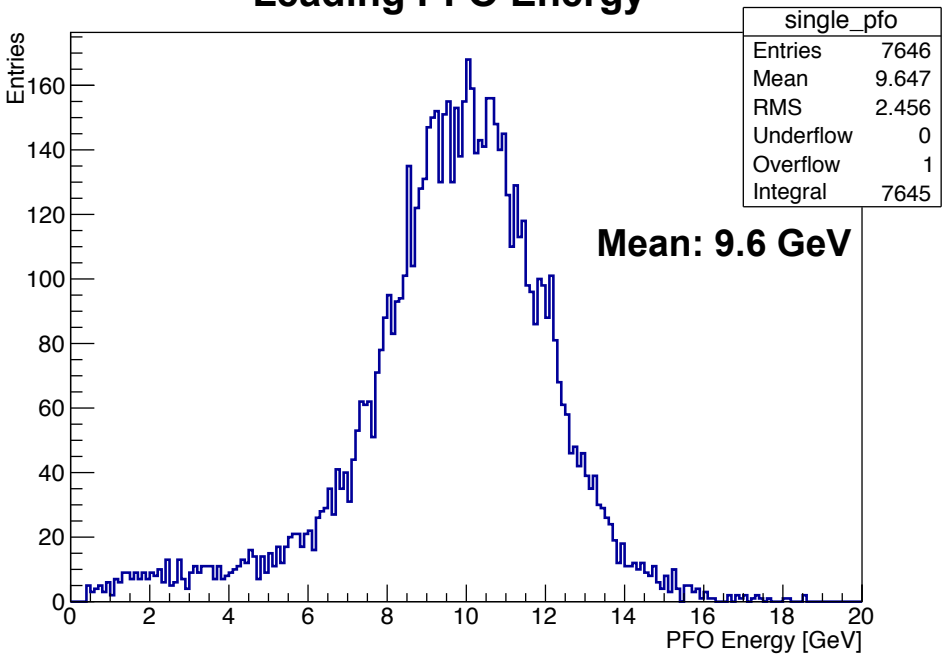
- Fairly good agreement between AHCAL and Pandora reconstruction (small left tail due to PFO multiplicity?)
- The earlier the particle showers the higher its PFO multiplicity?

➡ **Few photons as additional PFO, but mostly neutral hadrons**

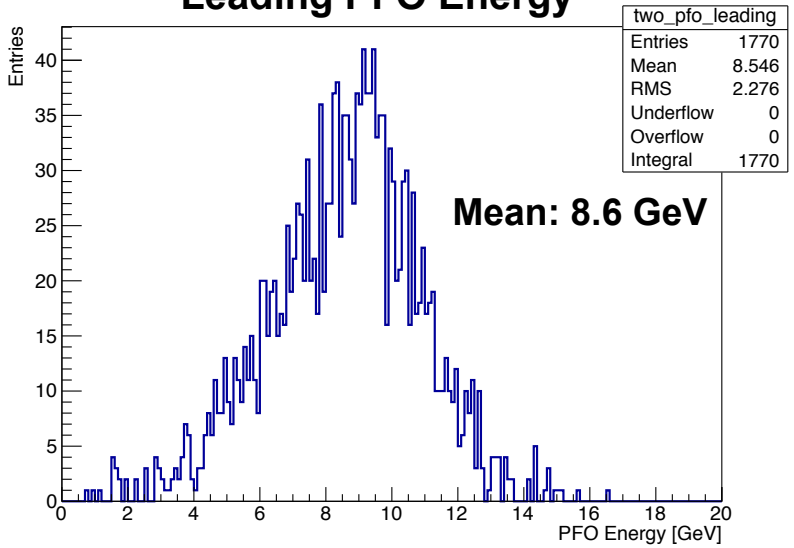
First Look: K0L 10 GeV (MC)

Applied Calibrated Pandora

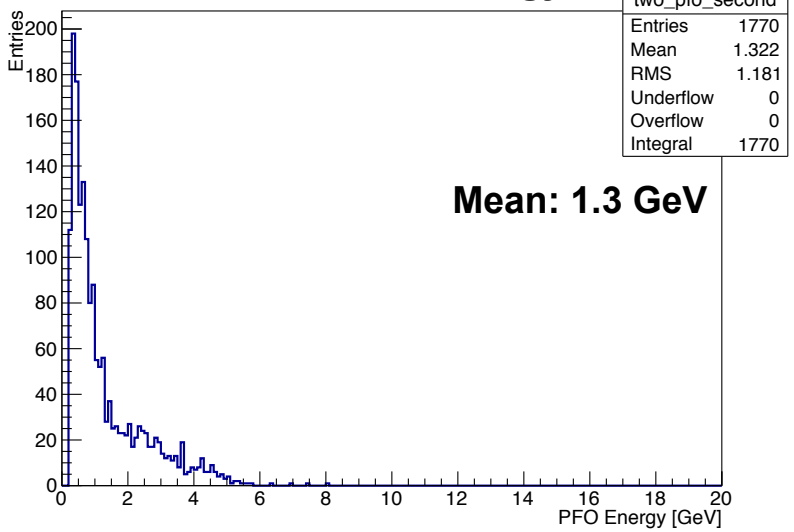
Single PFO
Leading PFO Energy



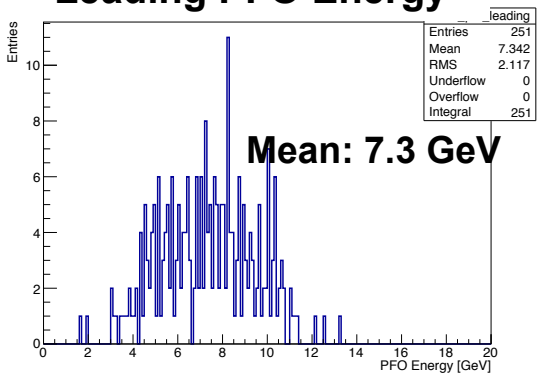
Two PFOs
Leading PFO Energy



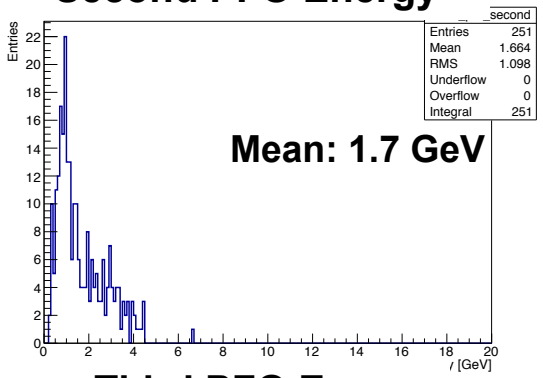
Second PFO Energy



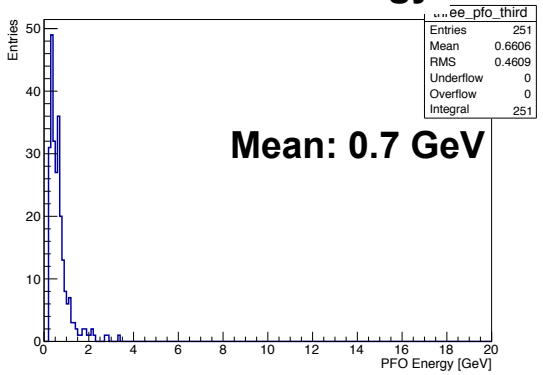
Three PFOs
Leading PFO Energy



Second PFO Energy



Third PFO Energy

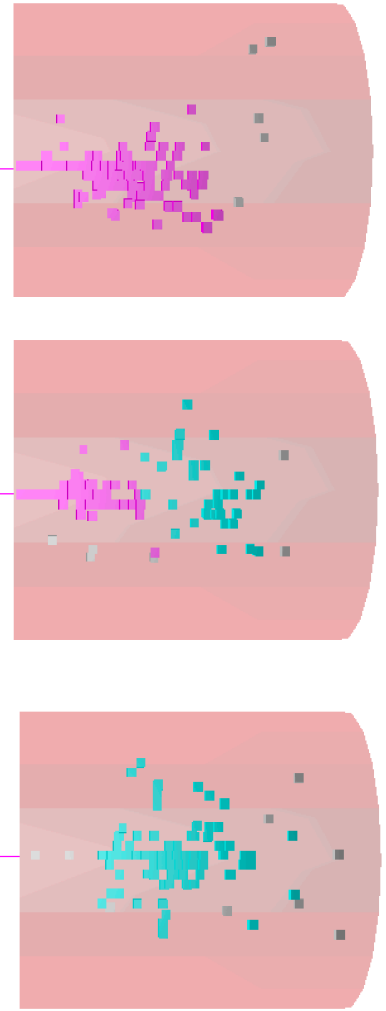


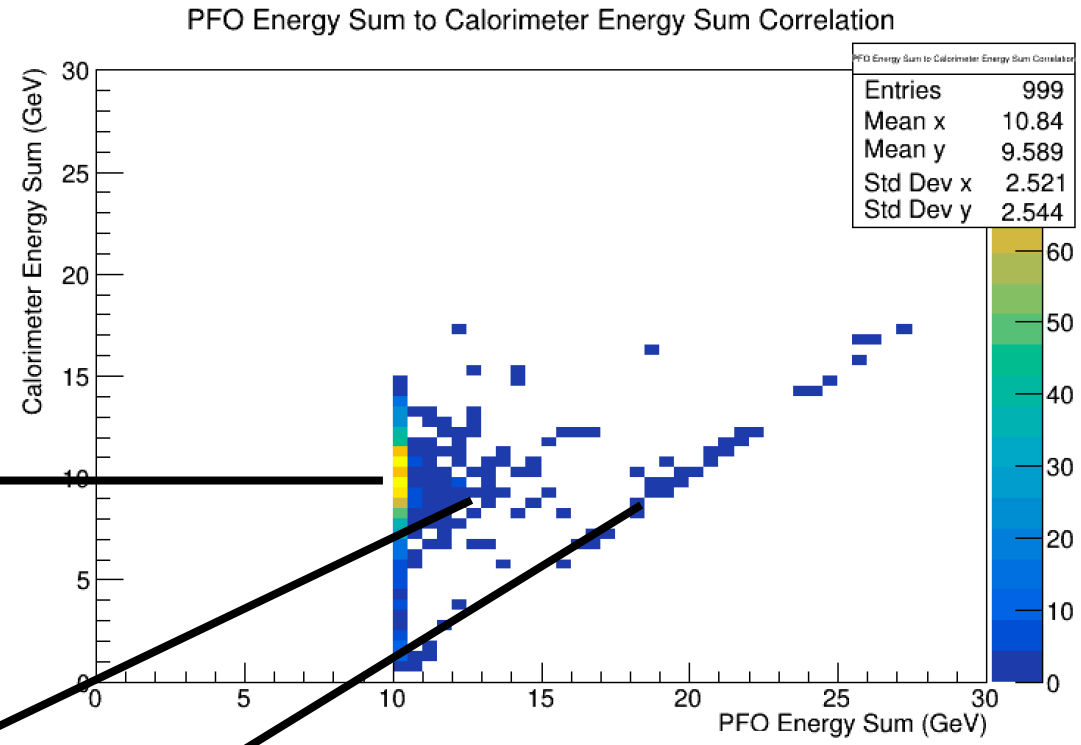
- If multiple PFOs: Leading PFO with most energy of event and lower energy PFOs with on average ~10-20% energy of event

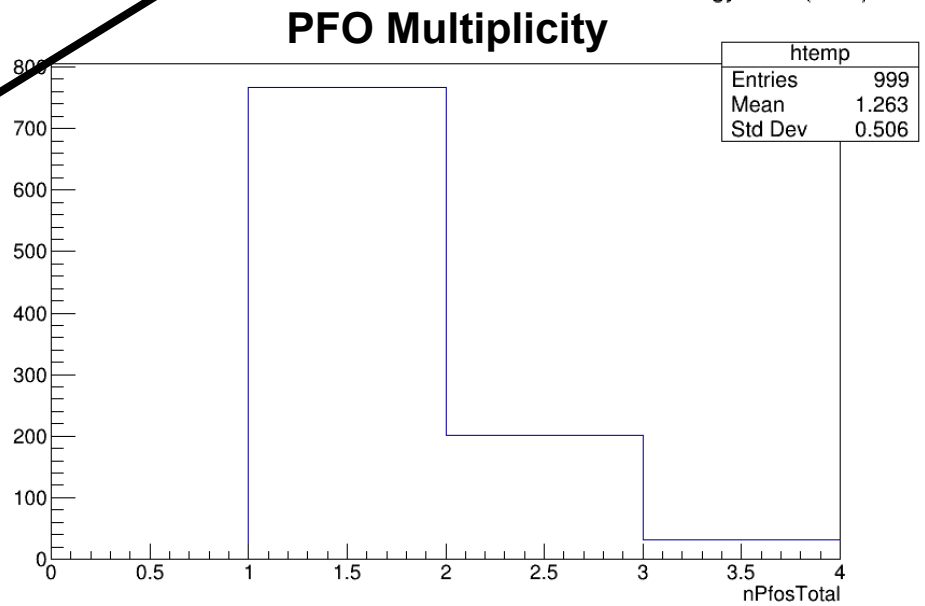
First Look: Pions 10 GeV (MC)

Single Particle Reconstruction

- Most events: Charged cluster reconstructed correctly with correct track association
- Few events: Charged cluster partly reconstructed correctly with additional neutral cluster
- Few events: No track to cluster association at all!?
  - ➡ Investigate



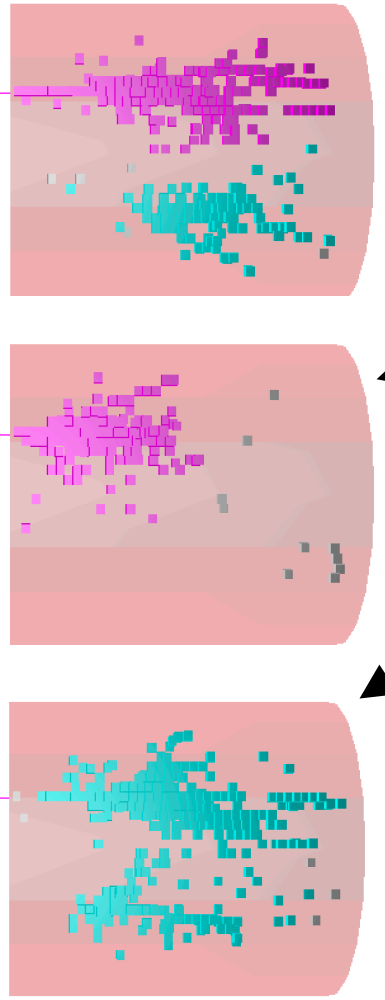


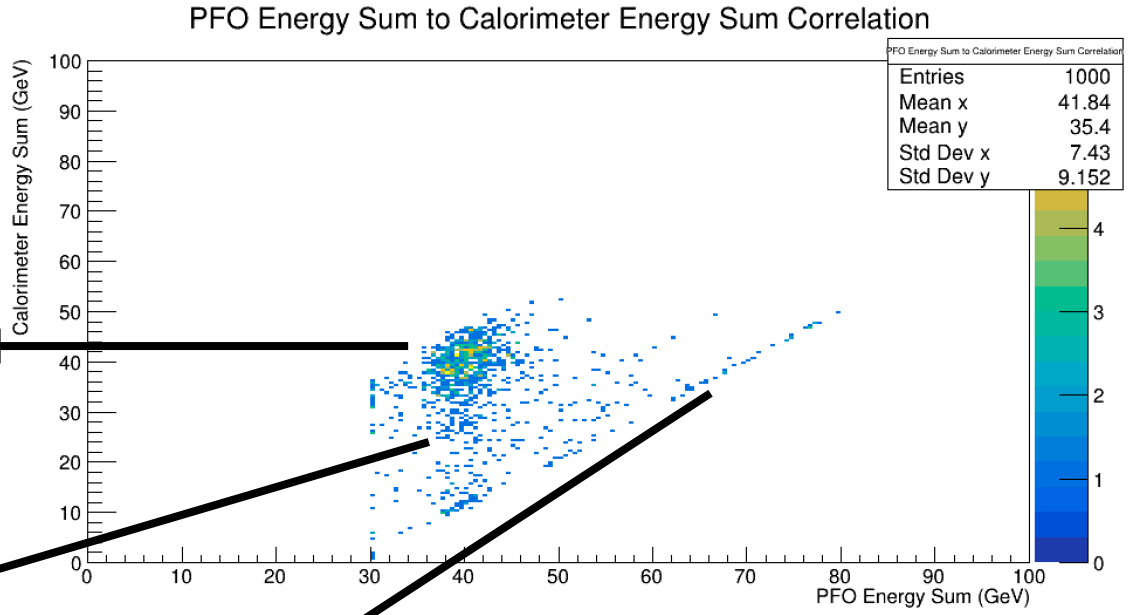


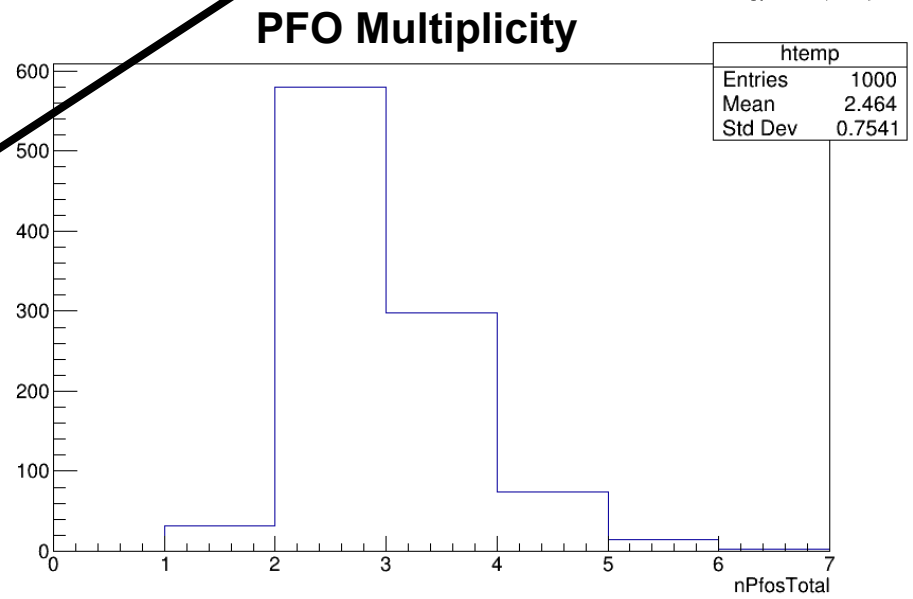
First Look: Pions 30 GeV overlaid with K0L 10 GeV (MC)

Separation Performance

- Scenario: Overlaid events of pion 30 GeV entering detector at Y = 180mm and K0L 10 GeV at Y = -180mm
  - Most events: Both particles reconstructed correctly
  - Few events: Leakage, track assignment to a cluster of all hits or additional neutral clusters
  - Few events: No track to cluster association at all!?
    - ➡ Investigate







Pandora studies: Summary & Outlook

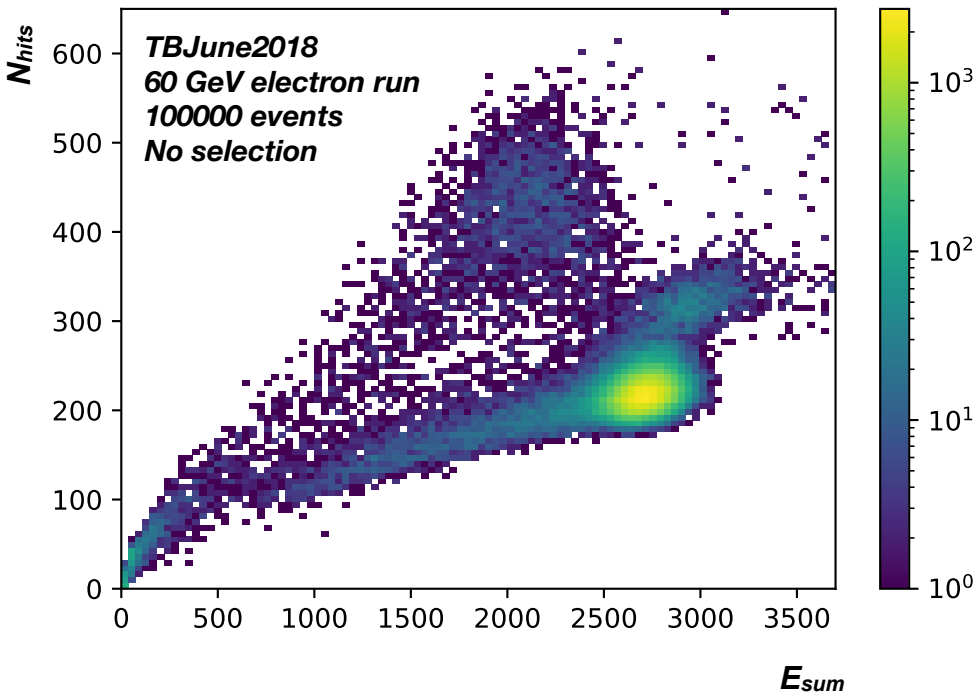
- **First time: PandoraPFA framework running on AHCAL 2018 prototype data standalone!**
  - ➡ Geometry implemented, DDMarlinPandora adapted, basic algorithms enabled, basic calibration done
  - ➡ First look into single particle and simple two particle reconstruction (MC) looks **promising!**
- Sample preparation for extended study well advanced

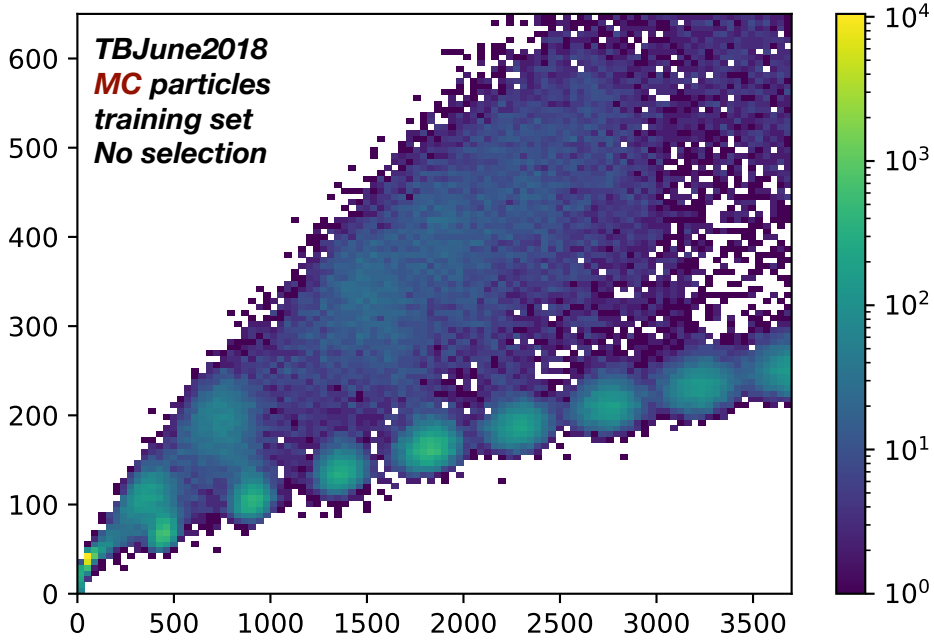
- Next: Check applied algorithms in more detail & enable plugins step by step
  - ➡ Re-check calibration & cross-check single particle reconstruction
  - ➡ After verification: Systematic studies of single particle reconstruction with PandoraPFA (Data vs MC)
- Not so far future: Move on to two particle scenario studies

Backup

Application on electron data

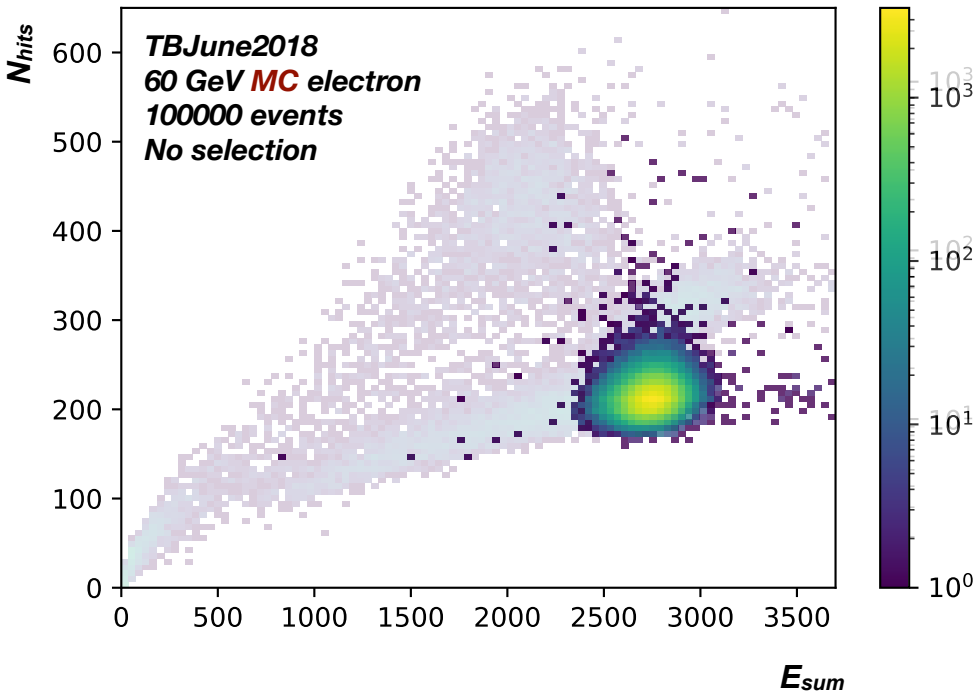
Of trained BDT model





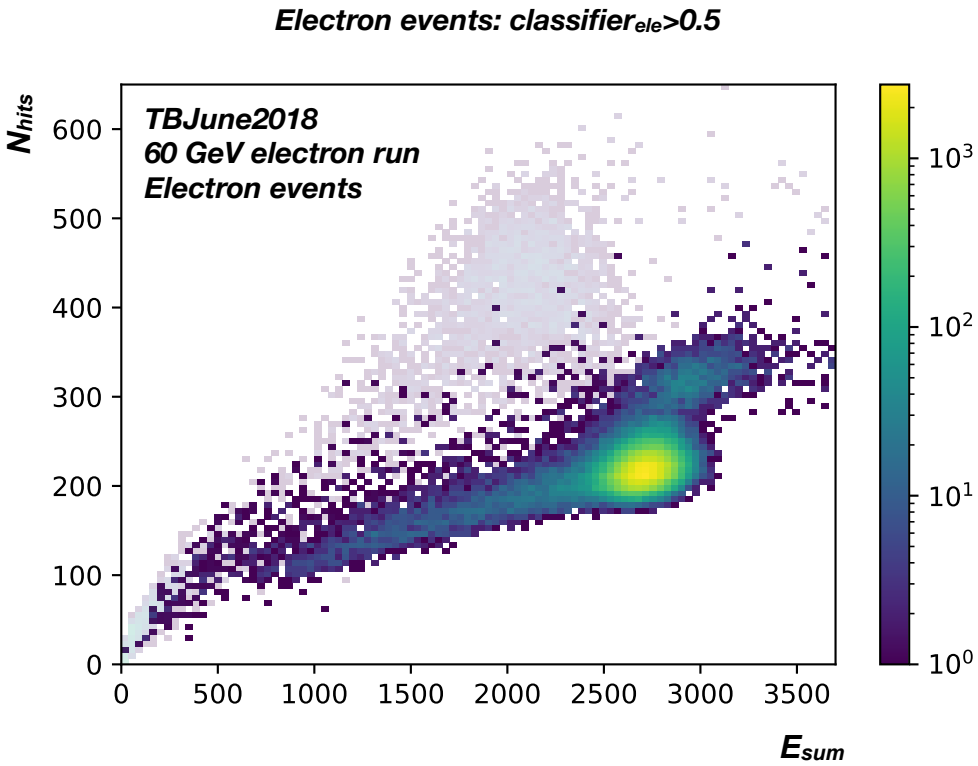
Application on electron data

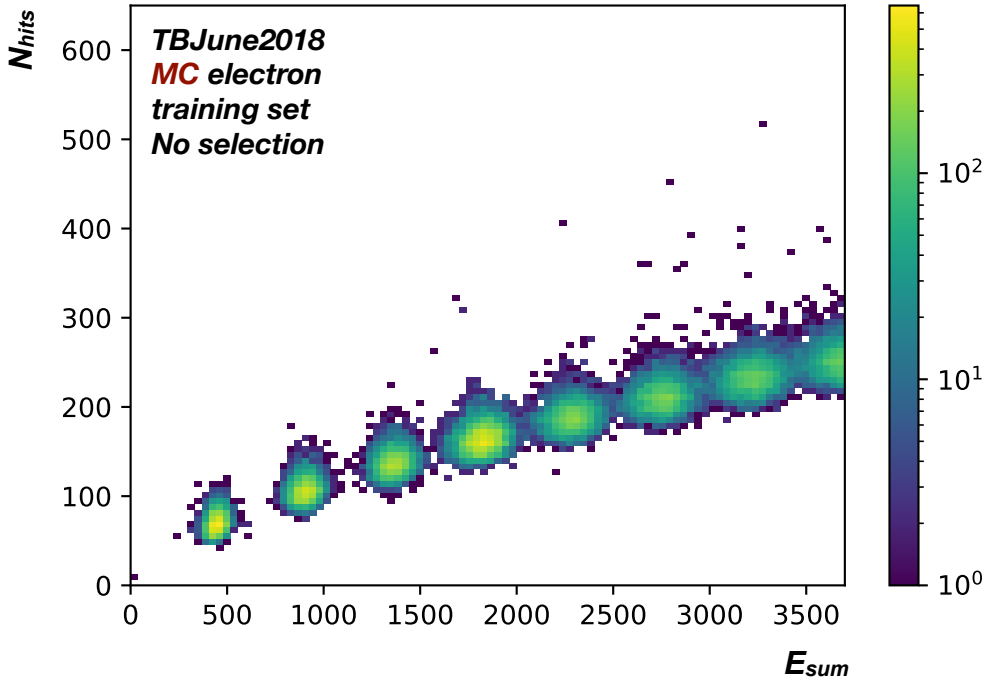
Of trained BDT model



Application on electron data

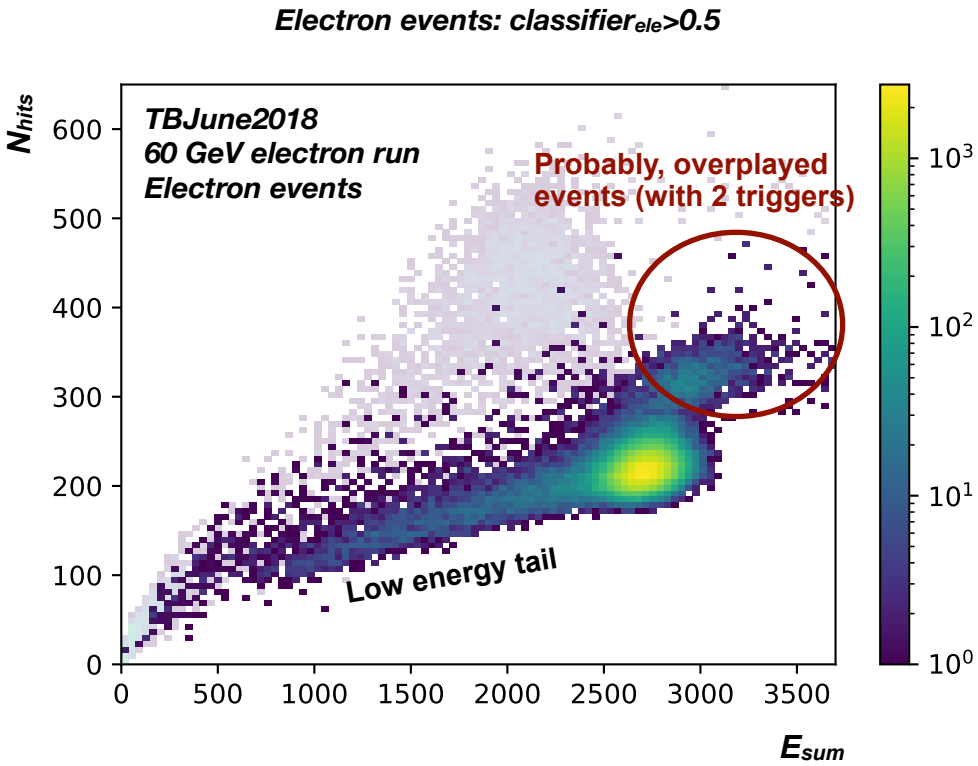
Of trained BDT model

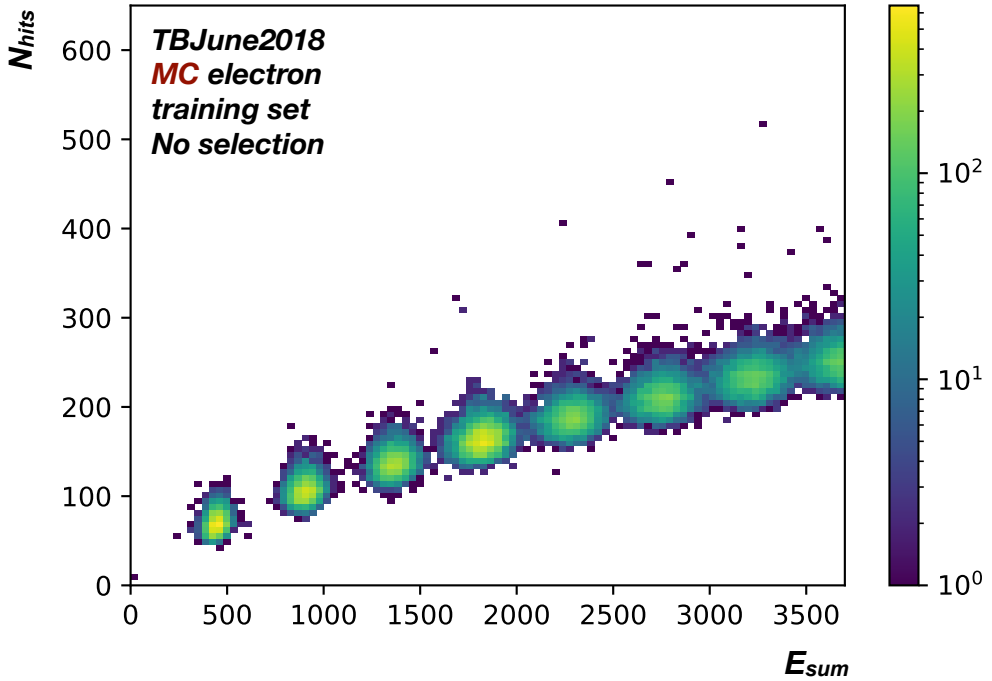




Application on electron data

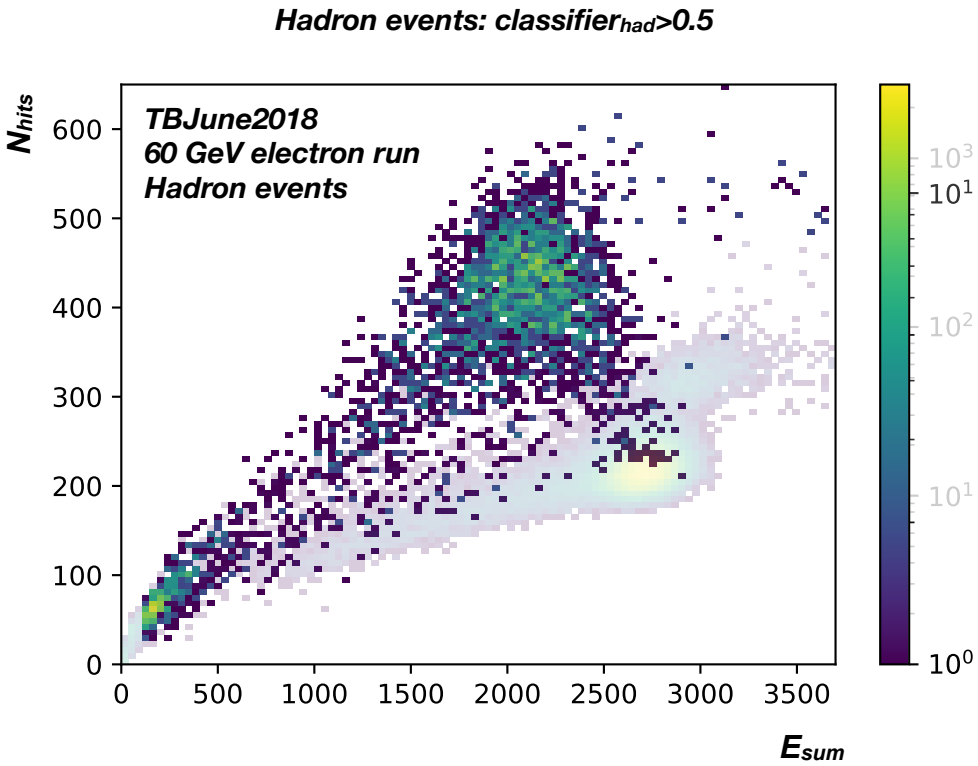
Of trained BDT model

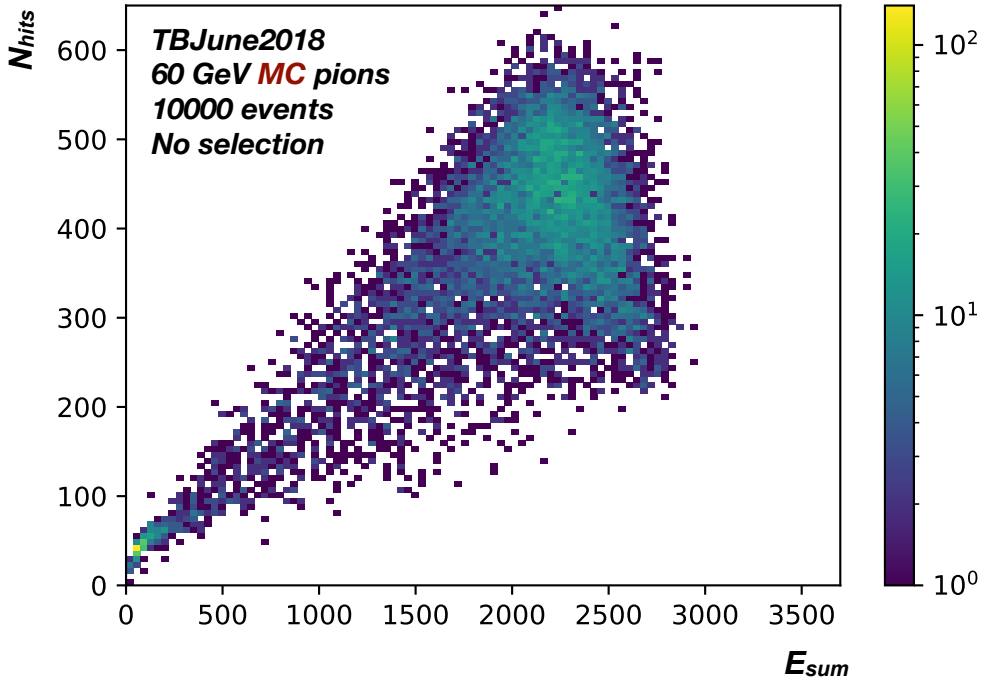




Application on electron data

Of trained BDT model





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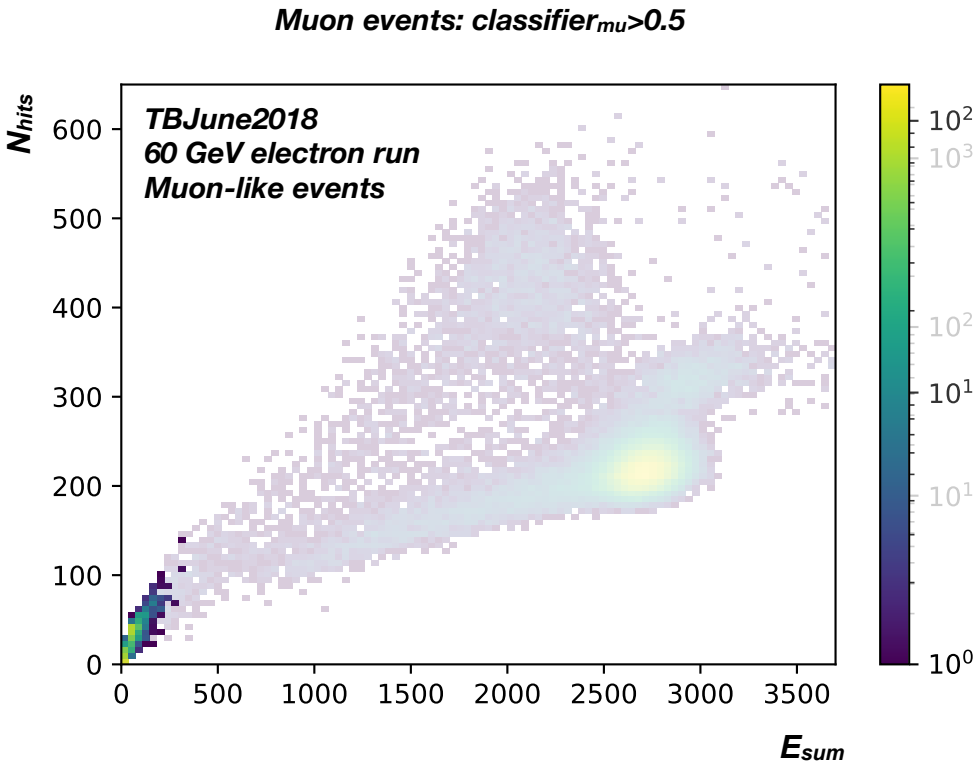
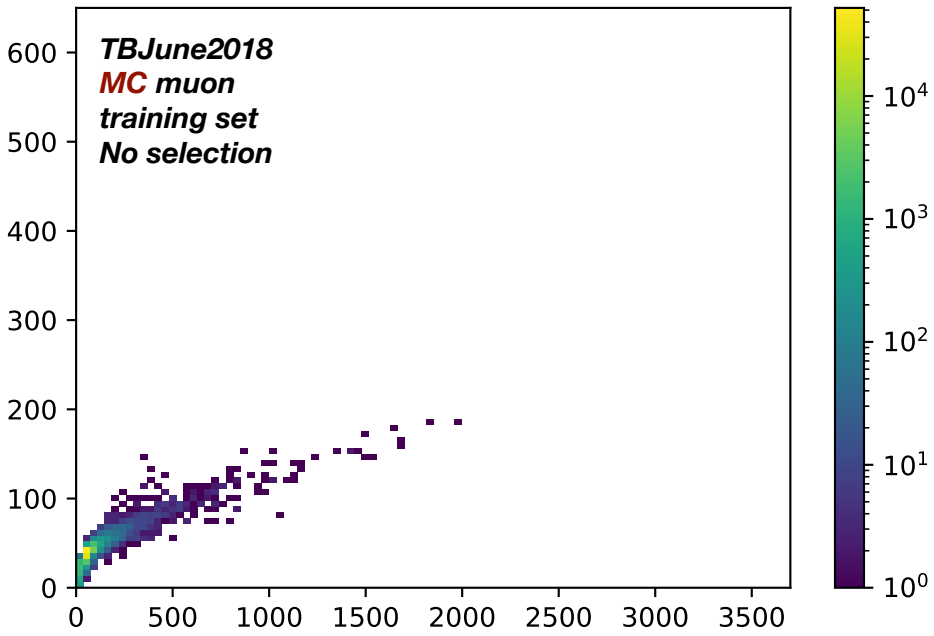
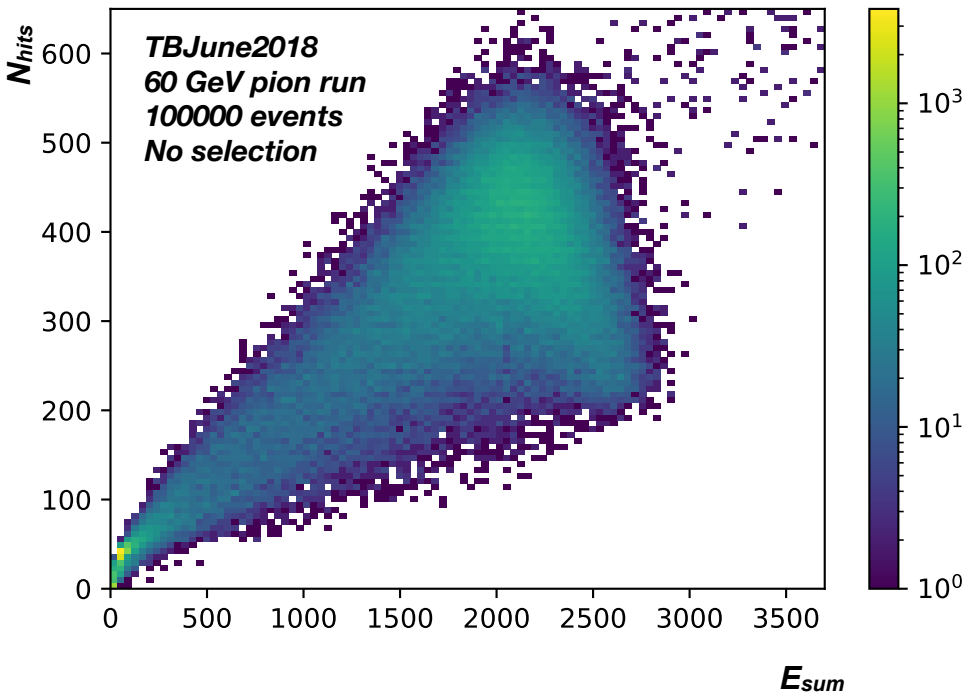
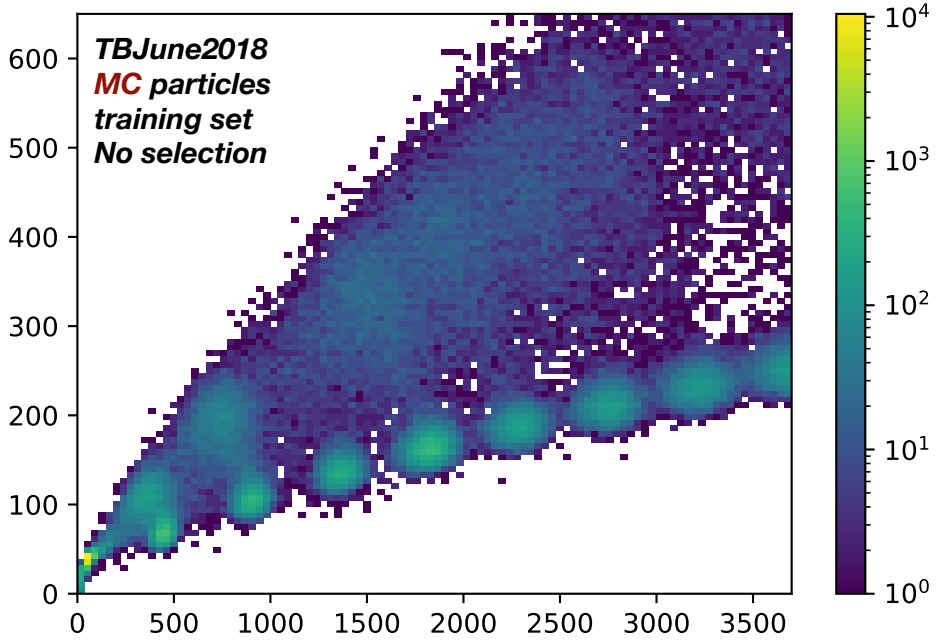




Application on pion data

Of trained BDT model





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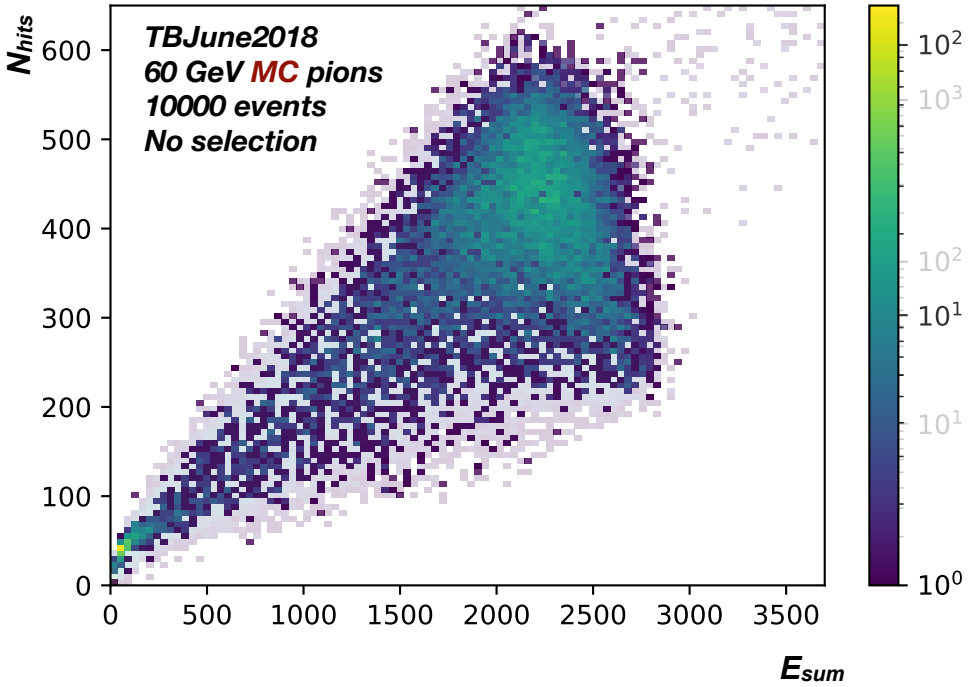

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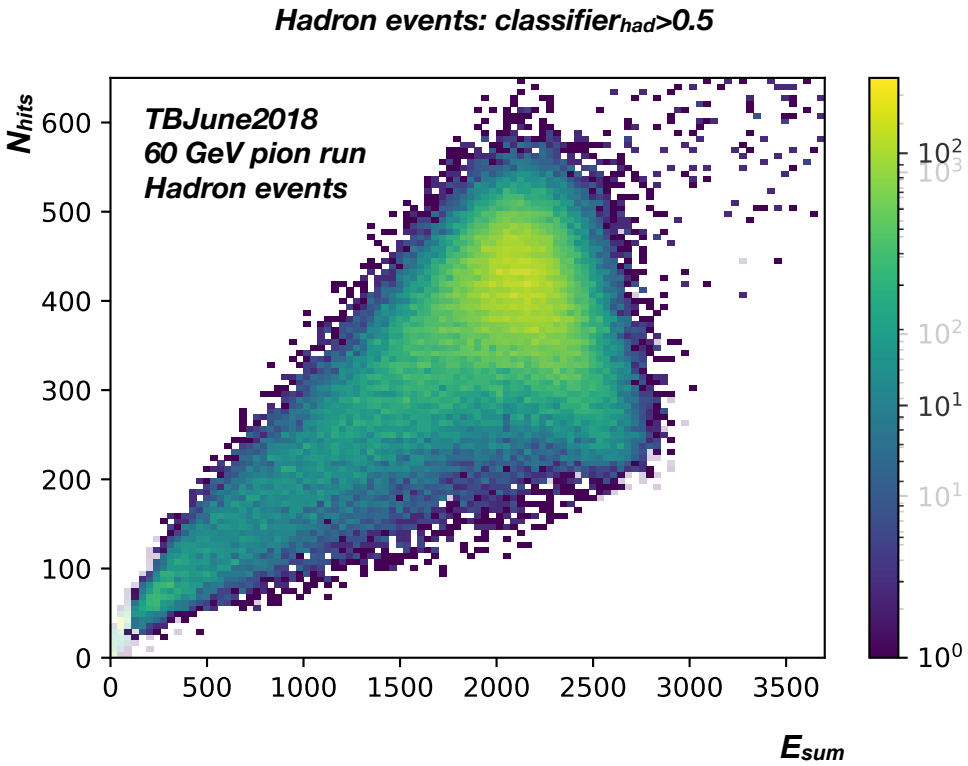
Of trained BDT model



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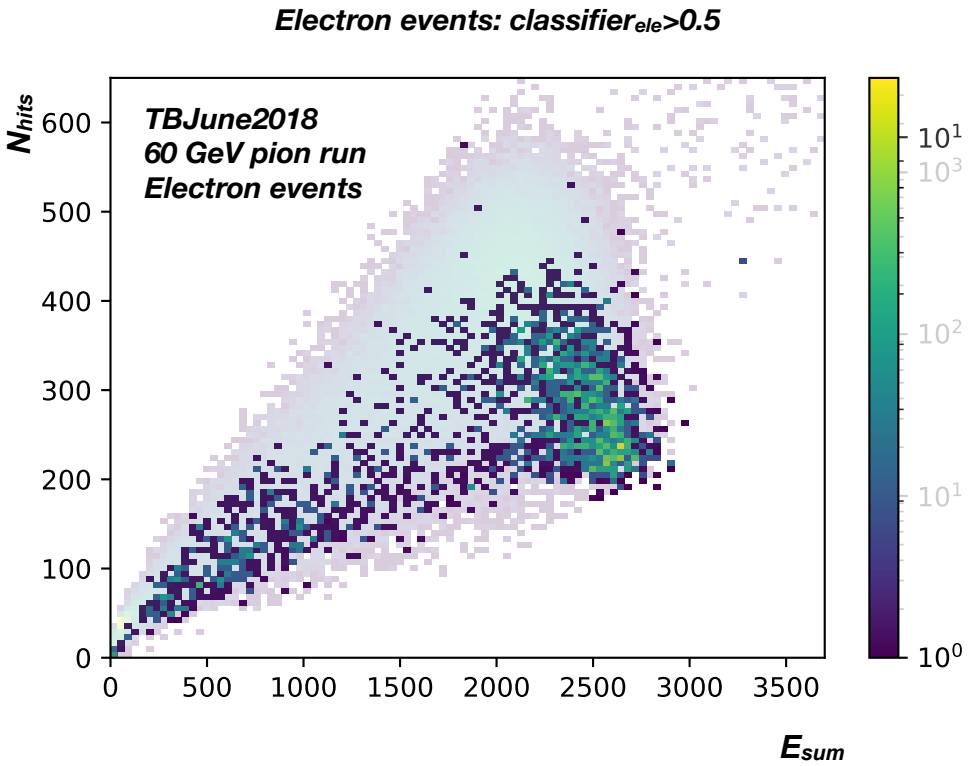

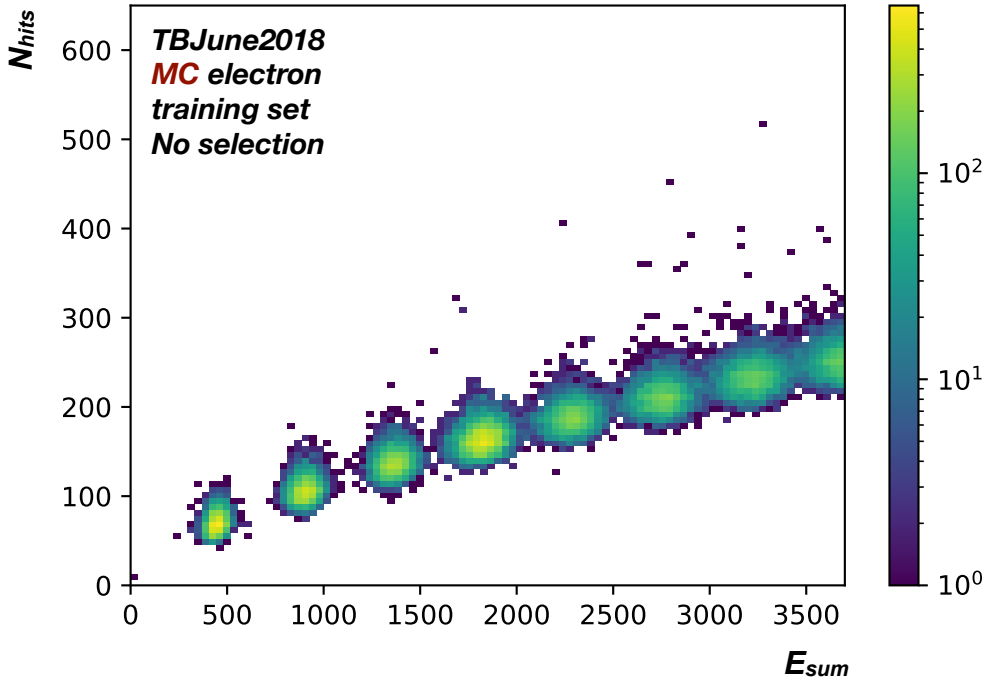

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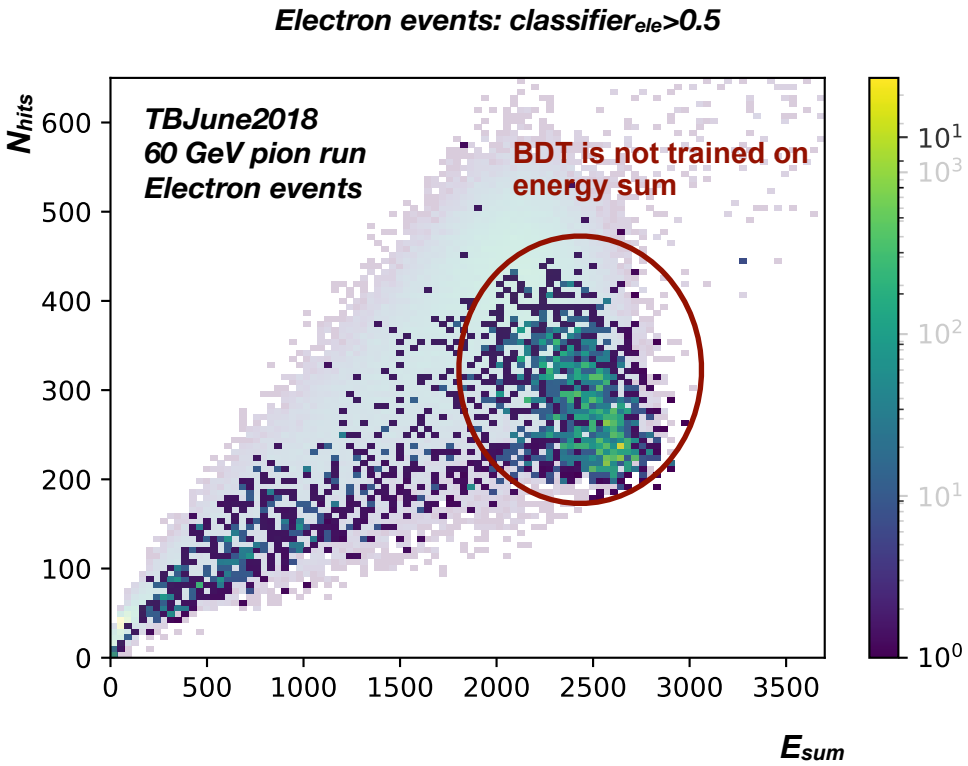

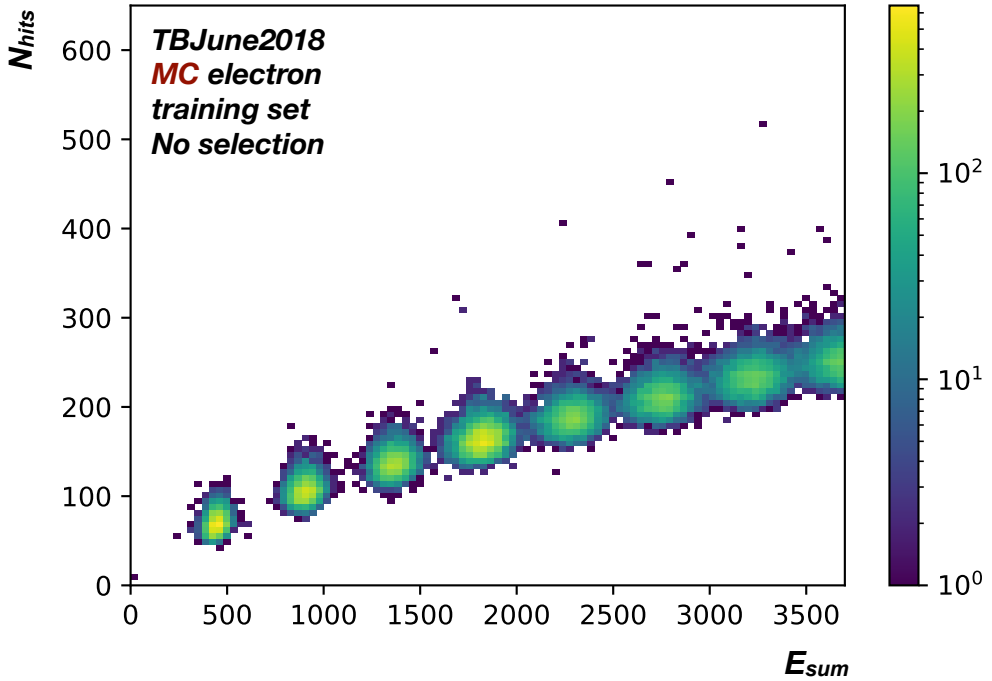

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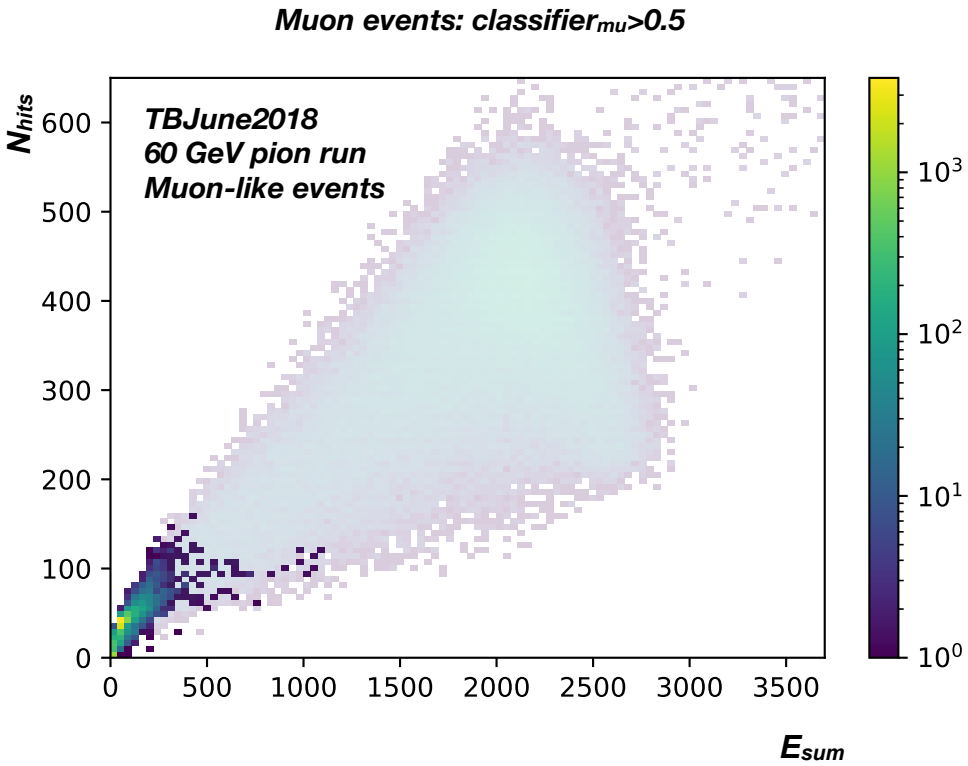
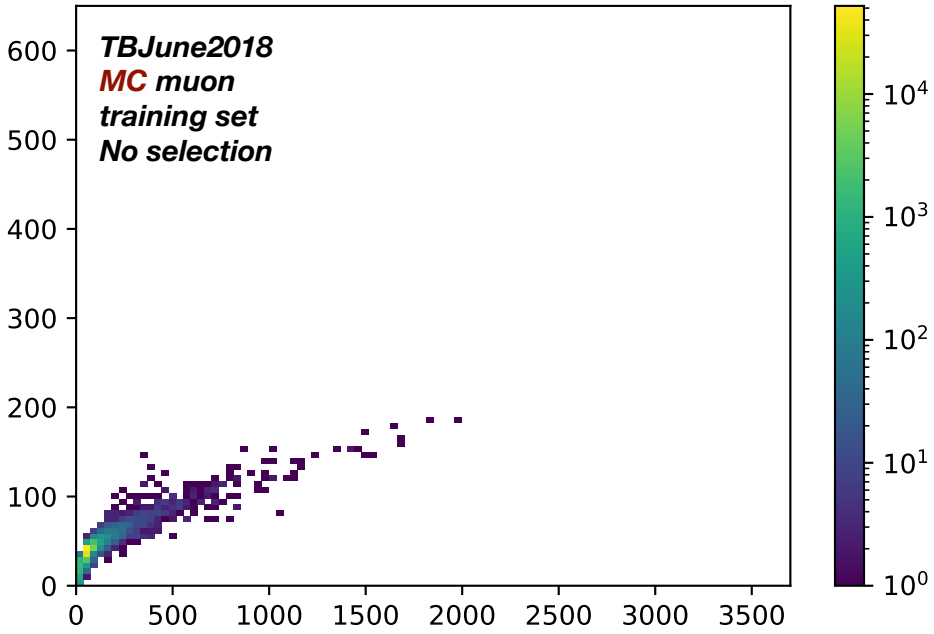
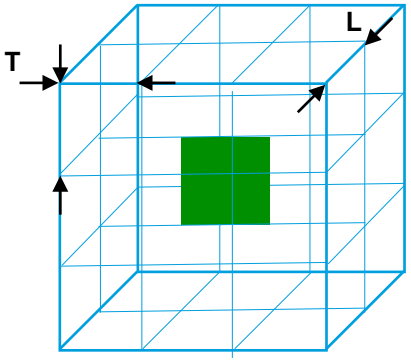




Clustering

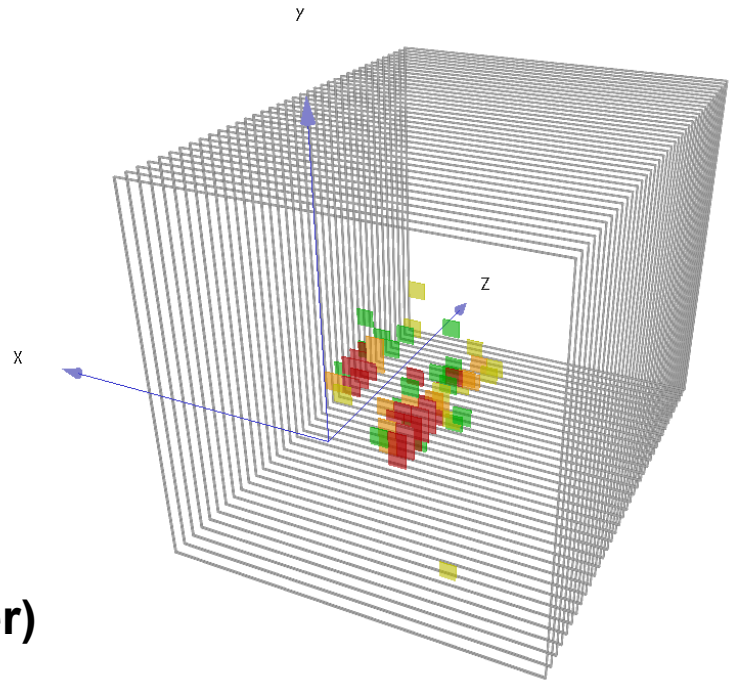


Algorithm: Hits are grouped in clusters if if they are neighbours in volume, {I,J,K}-space is used.

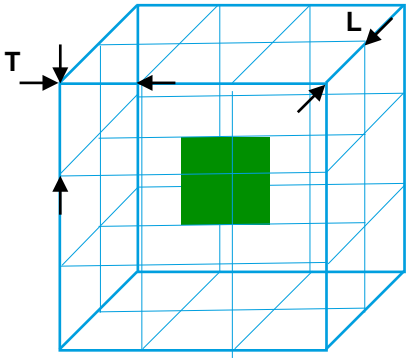
Parameters:

- **Size of volume (*T = 1, L = 2*),**
- **minimum nHits in cluster (*nHits_min = 5*)**
- **Number of first layers for clustering (*5 first layers*)**

If nClusters > 1 => multi-particle event (or early shower)



Clustering



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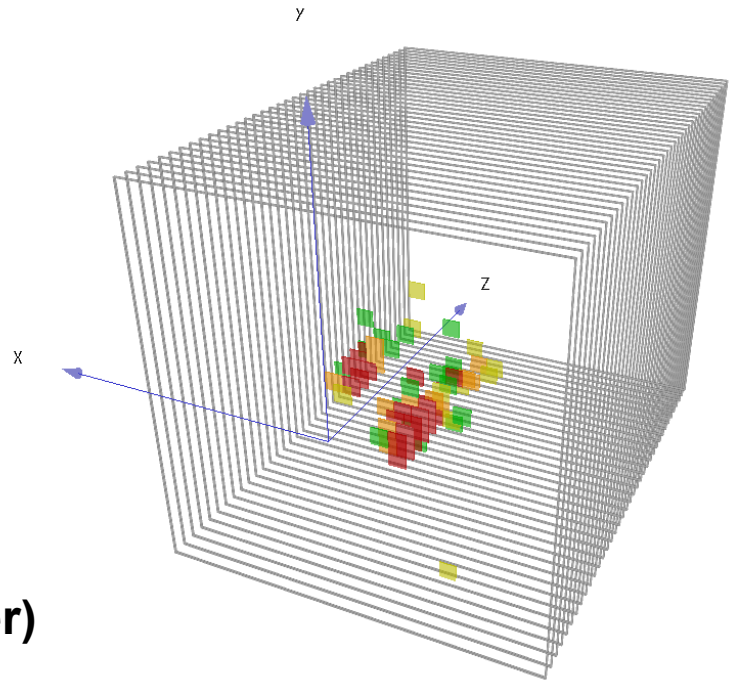


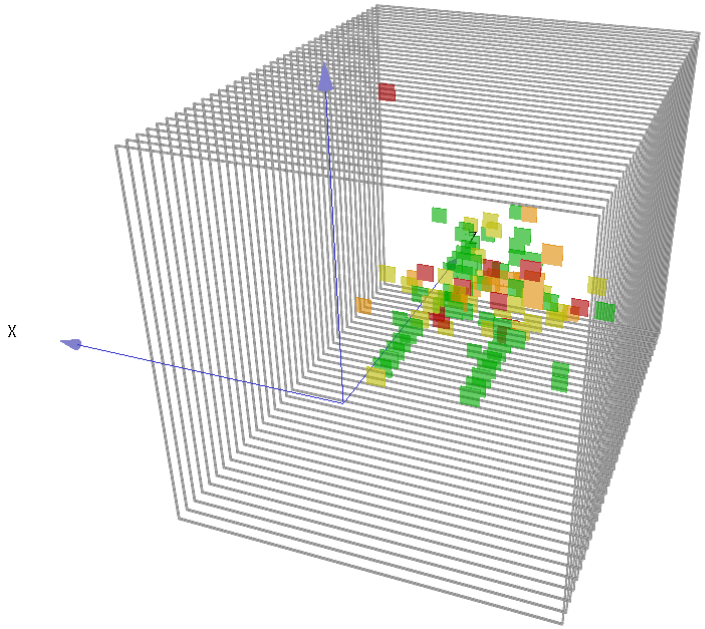
Incoming MIP tracks

Construct towers with same I and J in first layers.

Parameters:

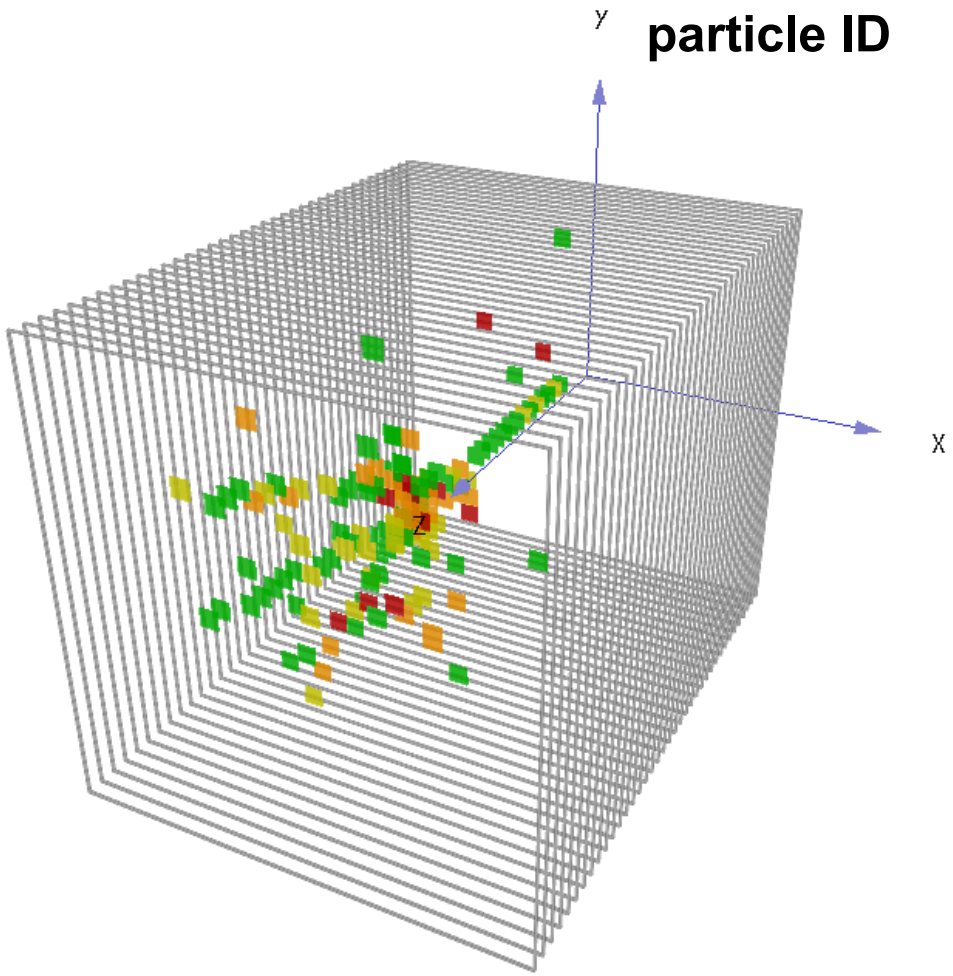
- **Number of first layers (*nPrimaryTrackLayers = 4*)**
- **Minimum number of hits in track (*MinHitsInPrimaryTrack = 3*)**

If nMIPTracks > 1 => multi-particle event



Track finding

Important tool for shower characterisation, Can be used for particle ID



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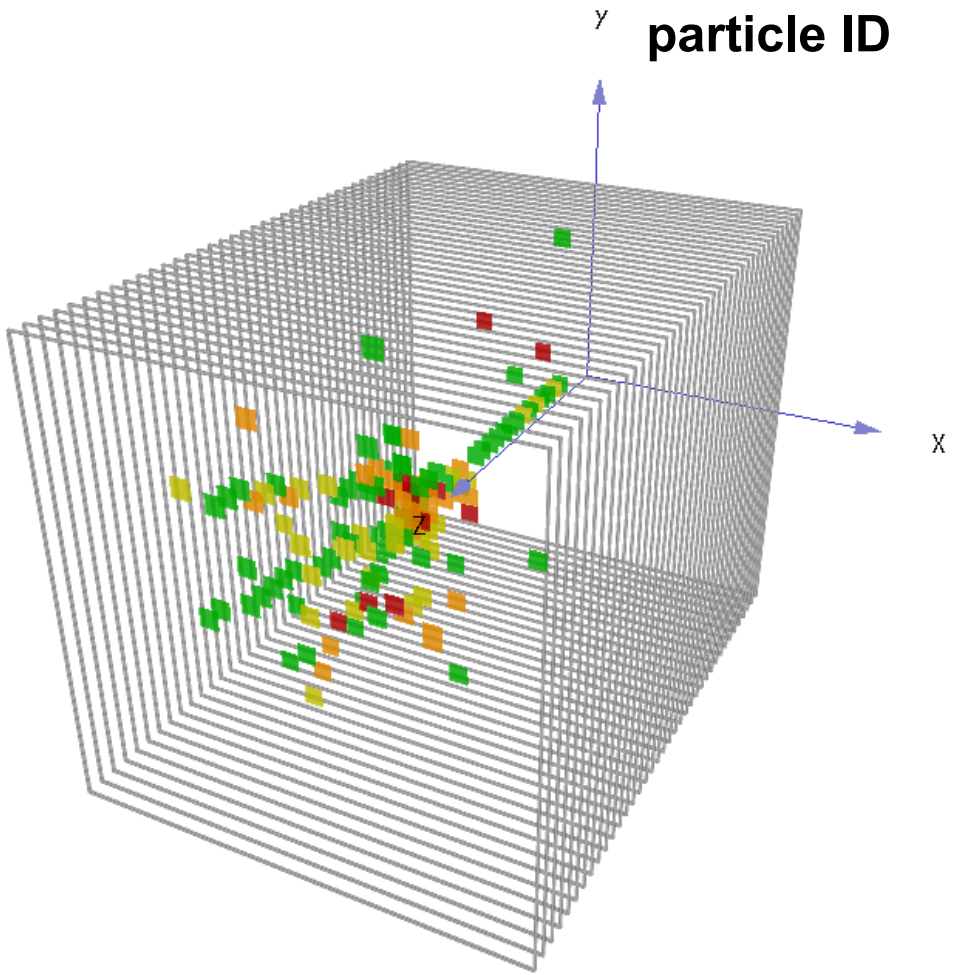
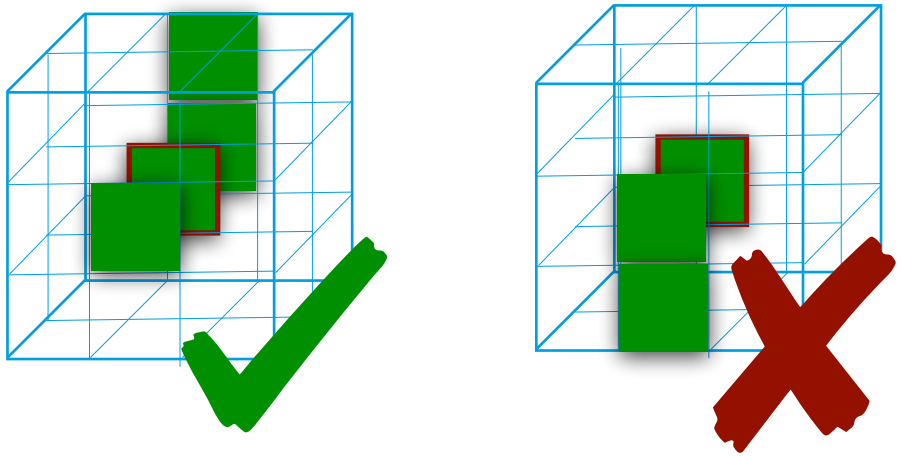
Important tool for shower characterisation, Can be used for particle ID



Track candidates:
2/3 neighbours in surrounding volume. 2 of them on different sides



Candidates ordered:

- **z-coordinate**
- **Distance to (0,0,z) in same layer**

Track finding

Grouping candidates into tracks

Hit#1
A
Seed
(first from candidates)

Nearest neighbour of hit#1

Distance check

Hit#2
B

Nearest neighbour of hit#1

Distance check

Angle check with **AB**

Hit#3
C

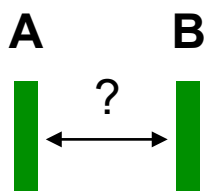
Nearest neighbour of hit#1

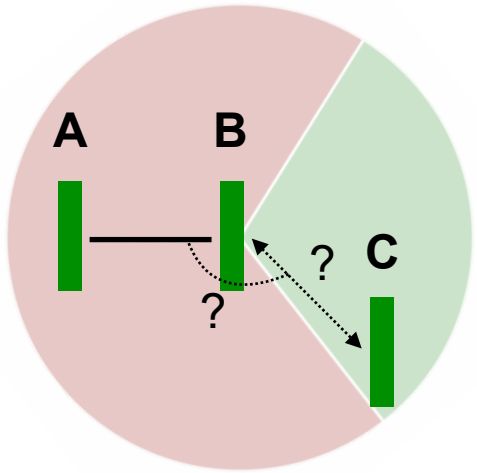
Distance check

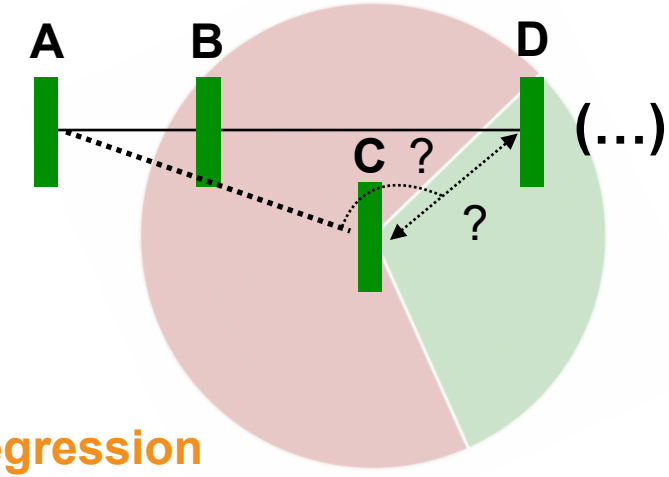
Angle check with **AC**

Angle check with **AB**

(…)





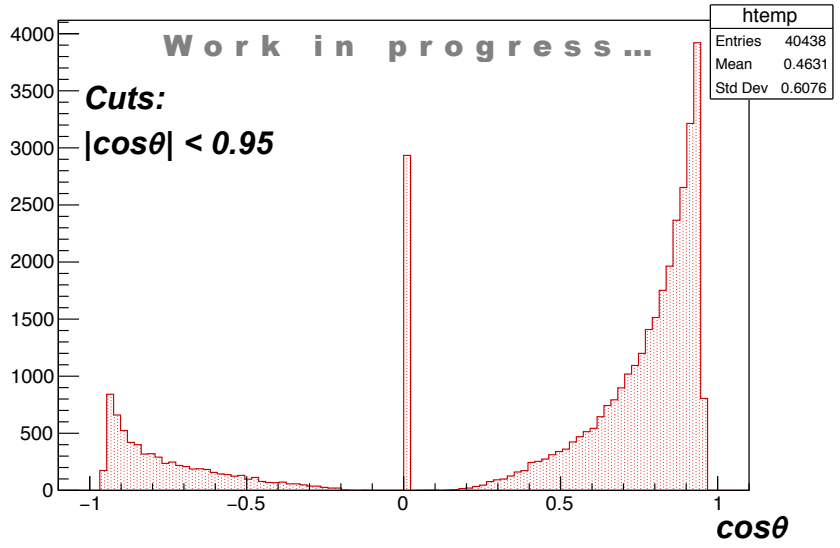


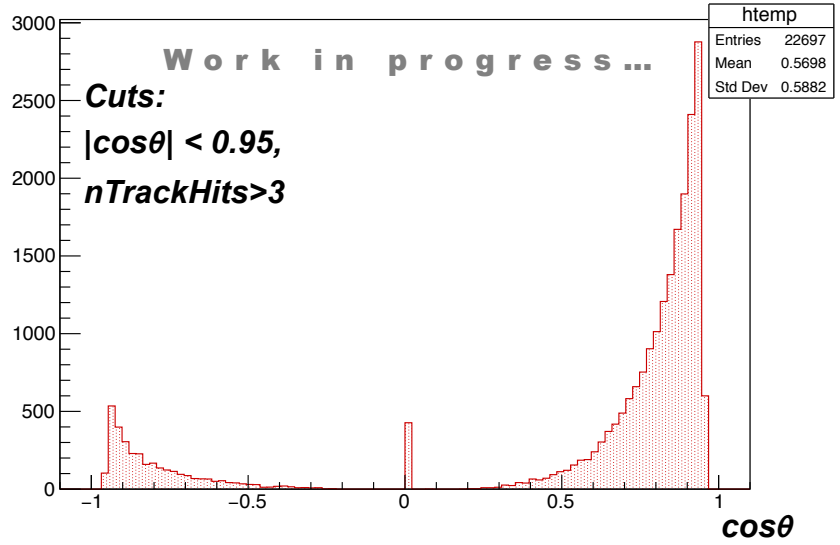
After grouping, track angle is obtained using MSE linear regression

**** Procedure repeated iteratively ****

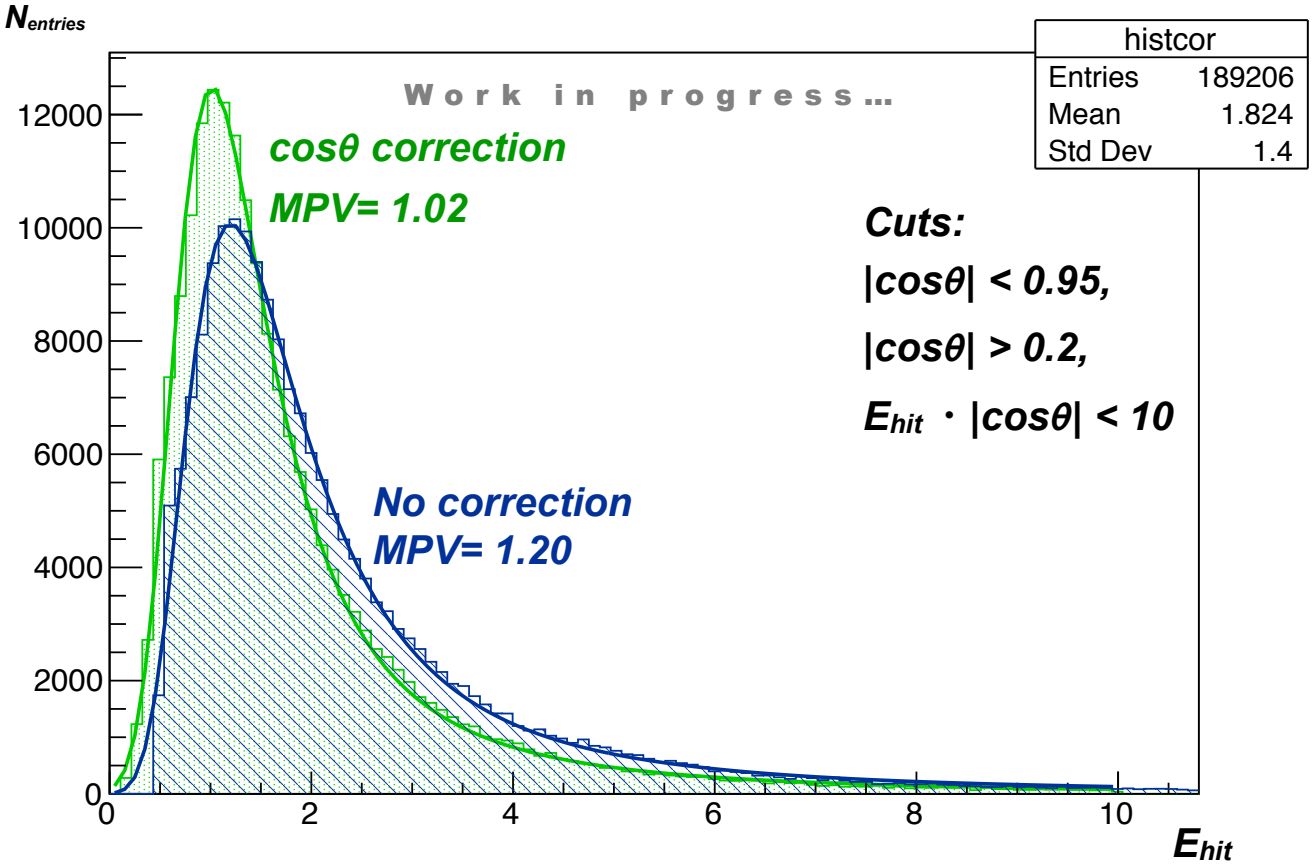
Tracking quality check

TBMay18 10GeV pion run. 50039 events.



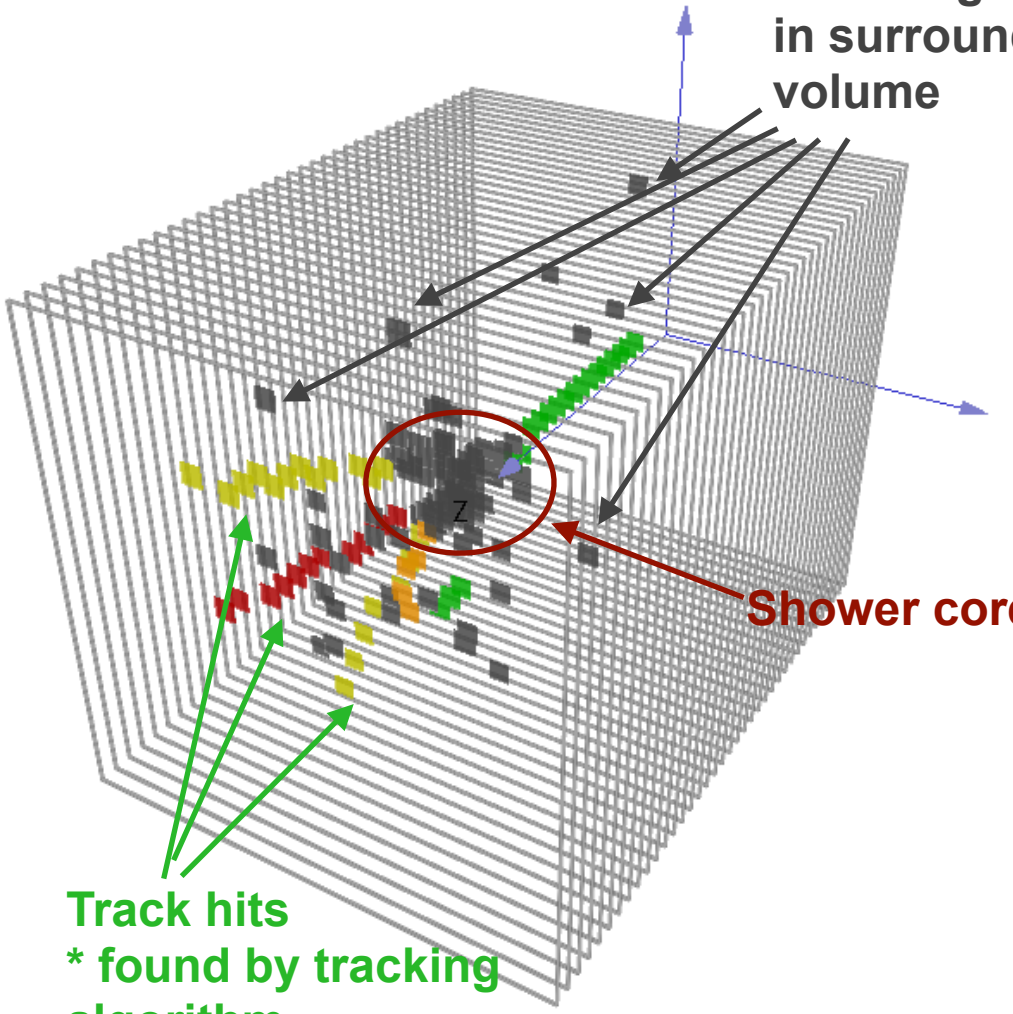


Scintillator path length correction for track hits



Resulting ID variables

After performing tracking



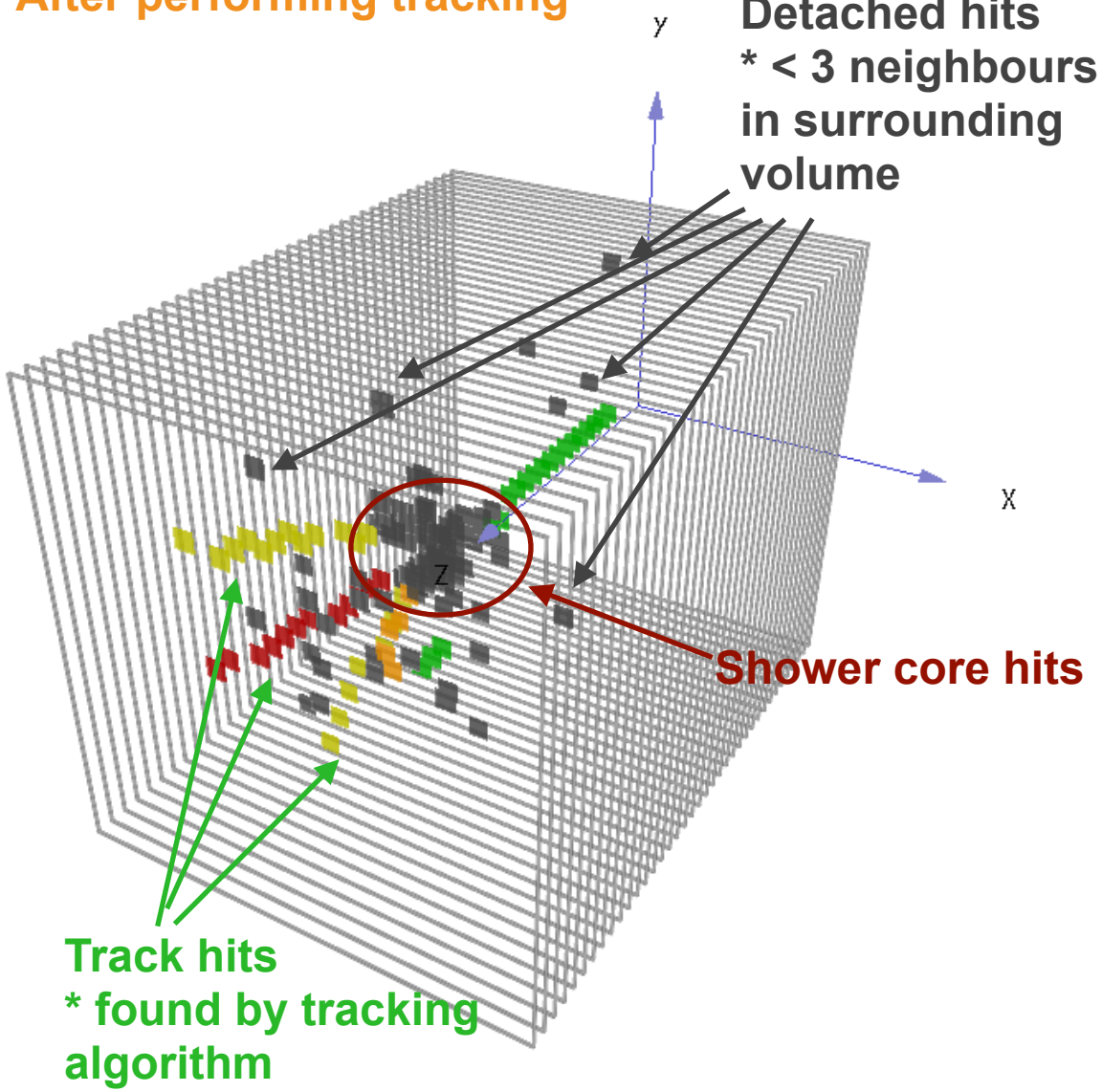
Detached hits
* < 3 neighbours in surrounding volume

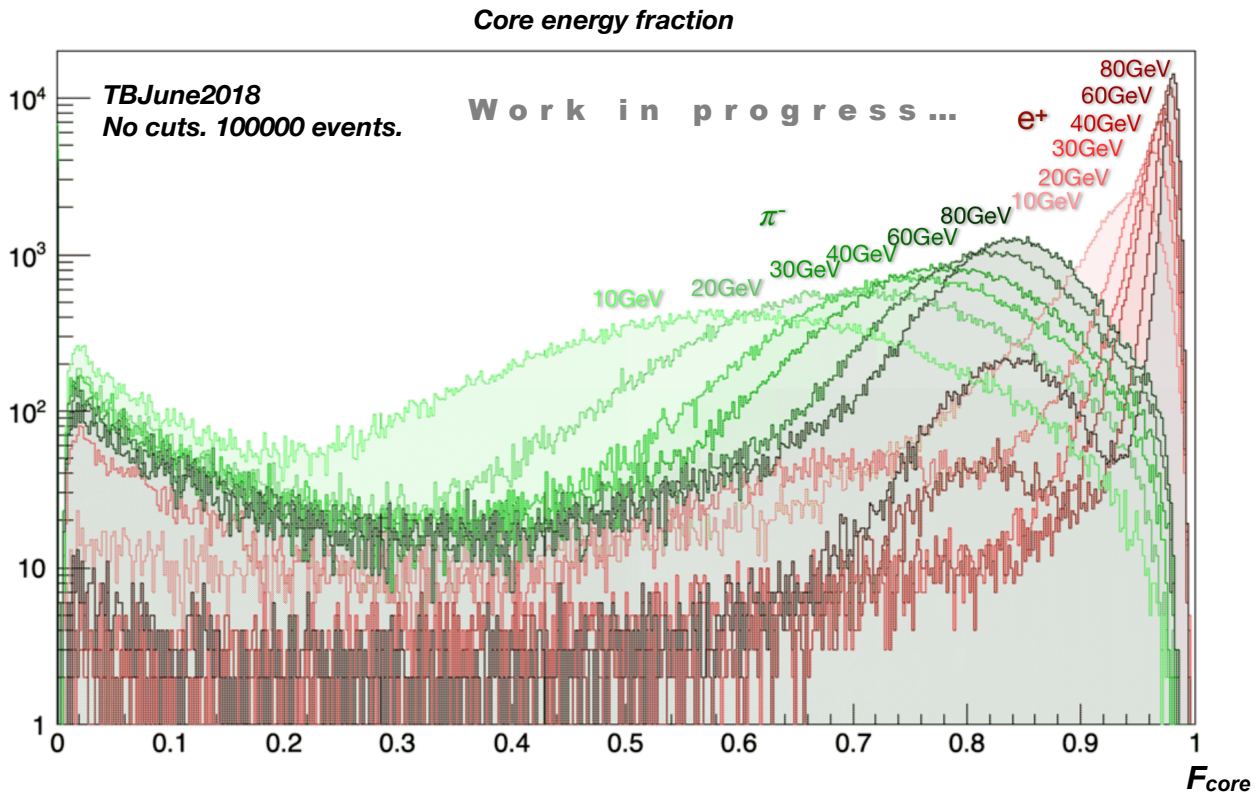
Shower core hits

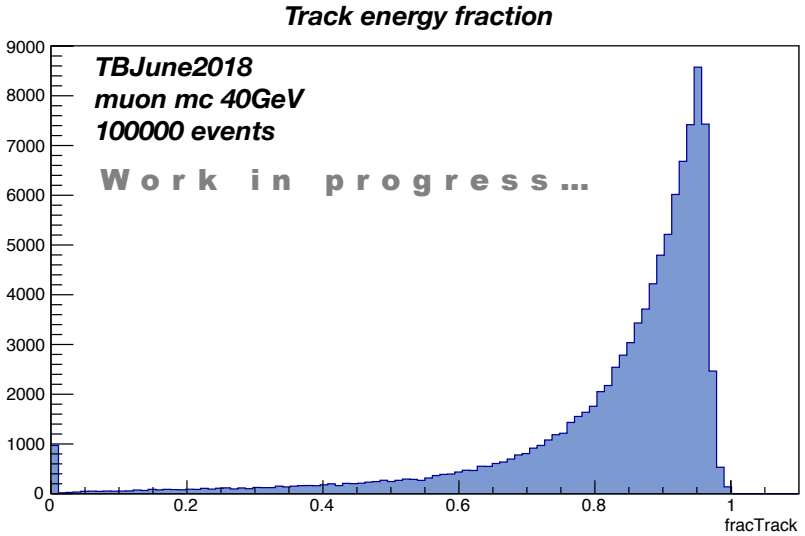
Track hits
* found by tracking algorithm

Resulting ID variables

After performing tracking

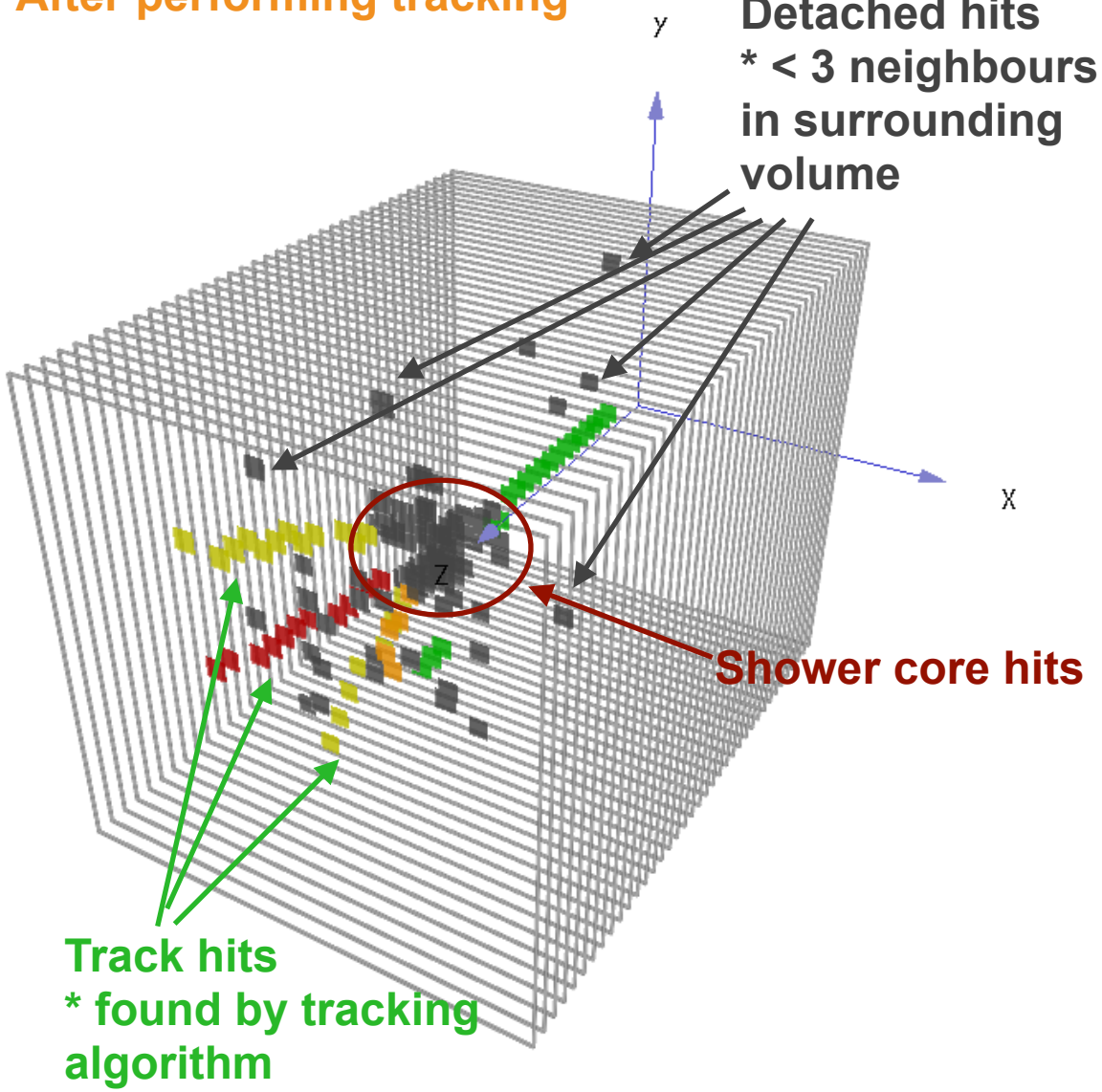


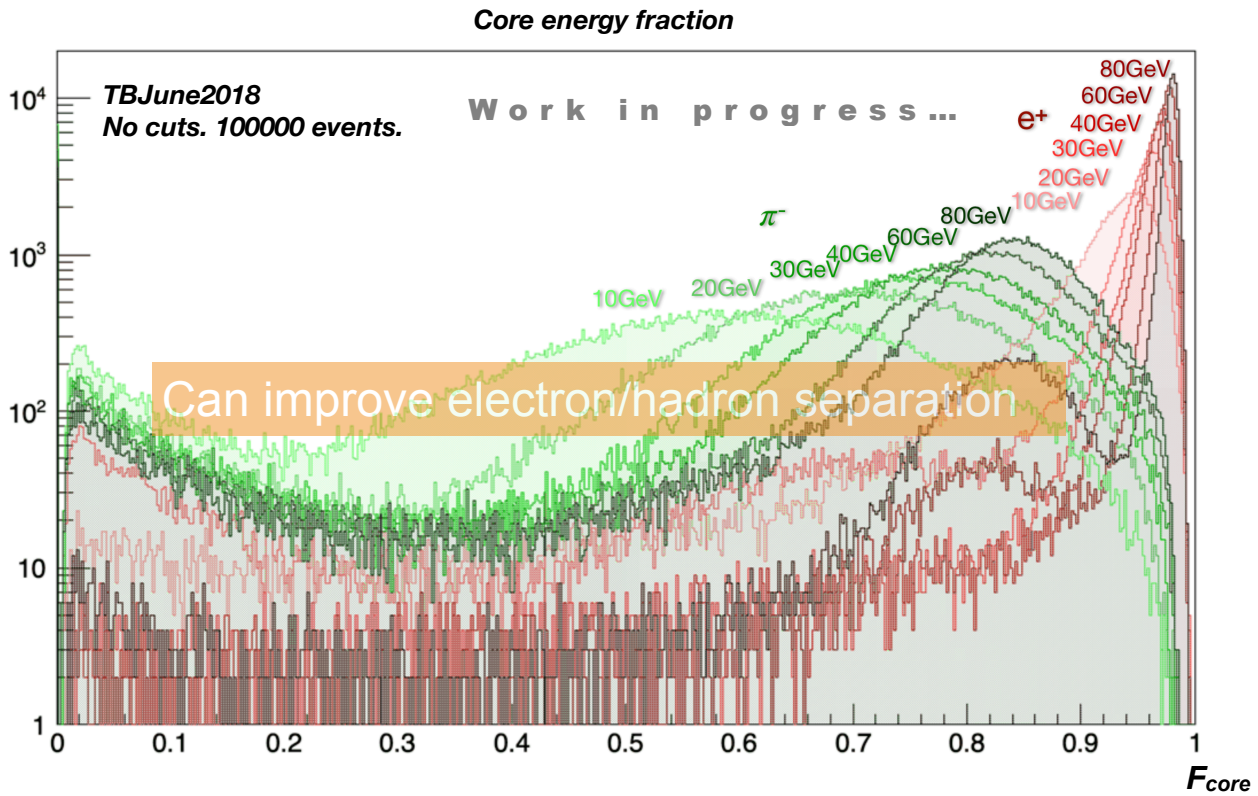


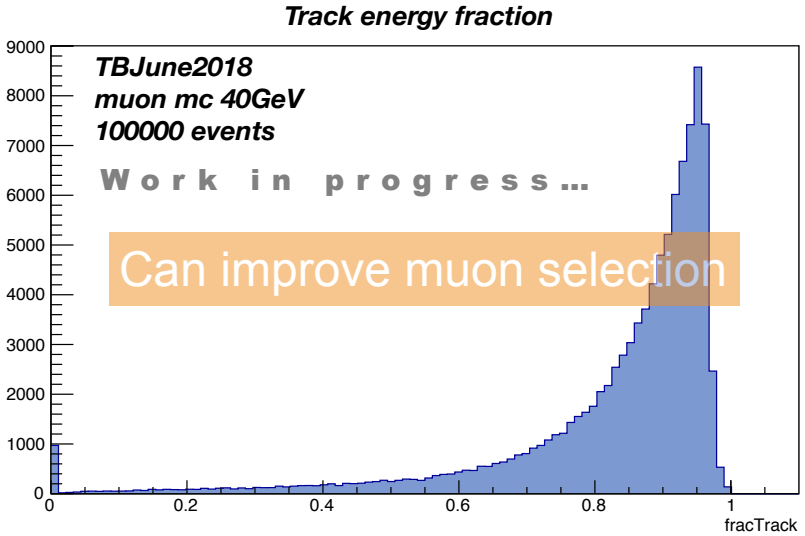


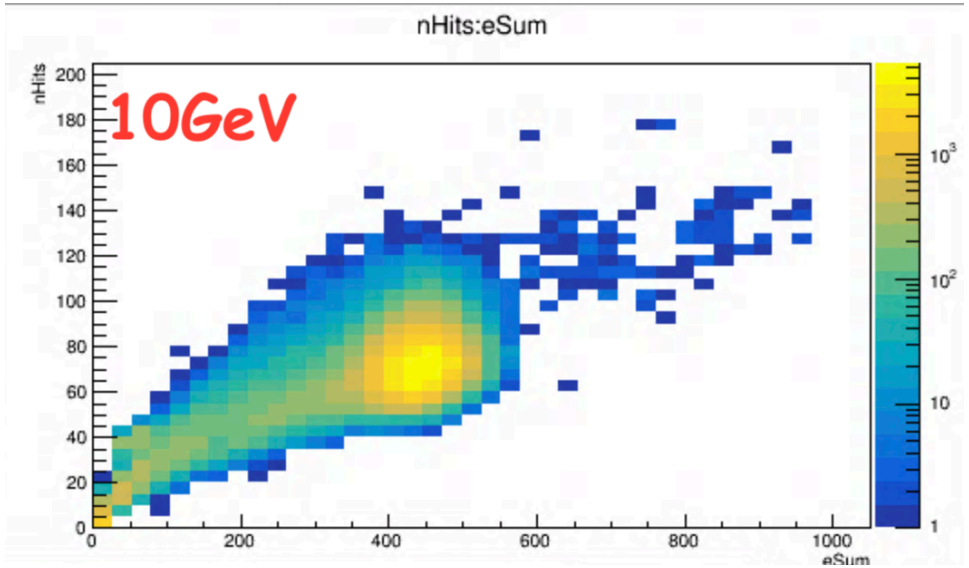
Resulting ID variables

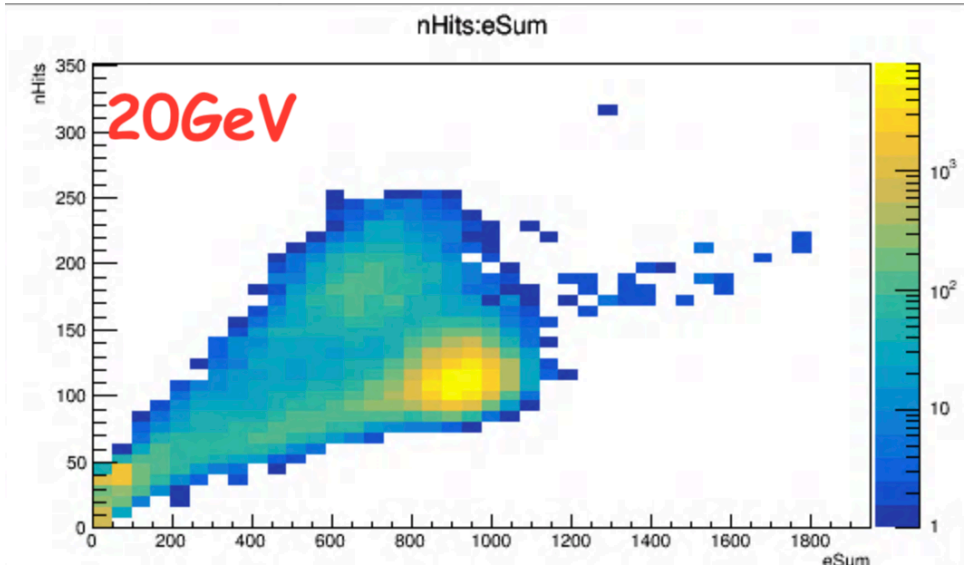
After performing tracking

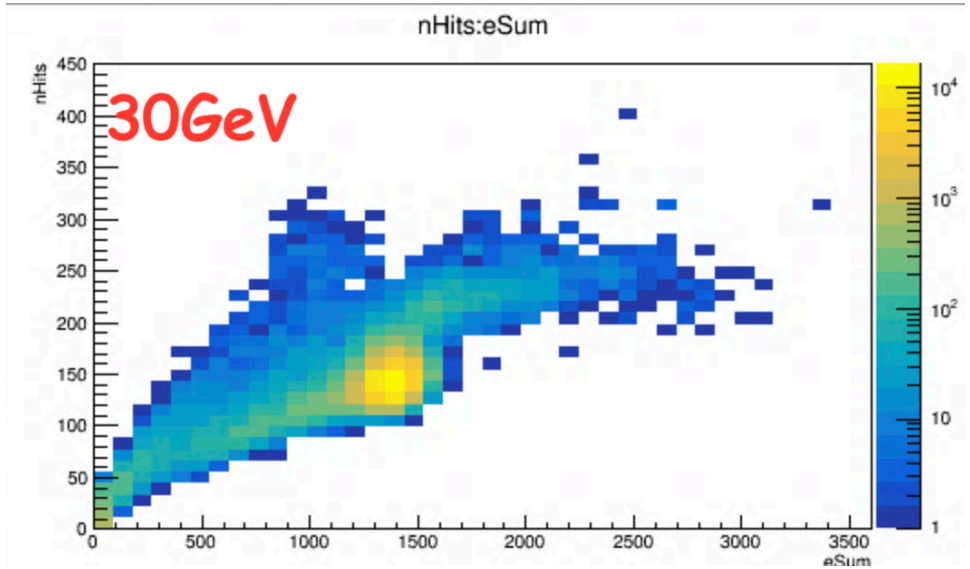


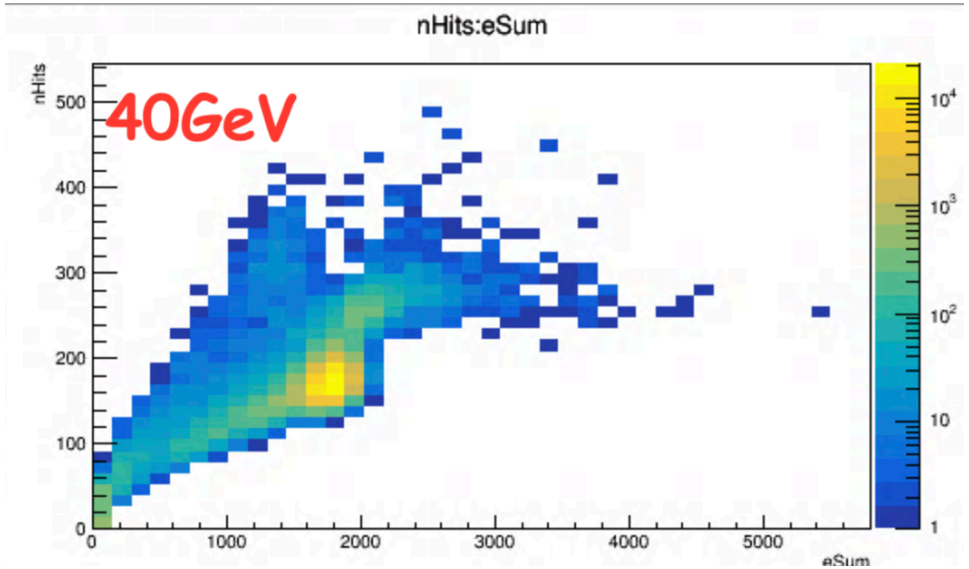





nHits:eSum
10GeV
nHits
eSum


nHits:eSum
20GeV
nHits
eSum

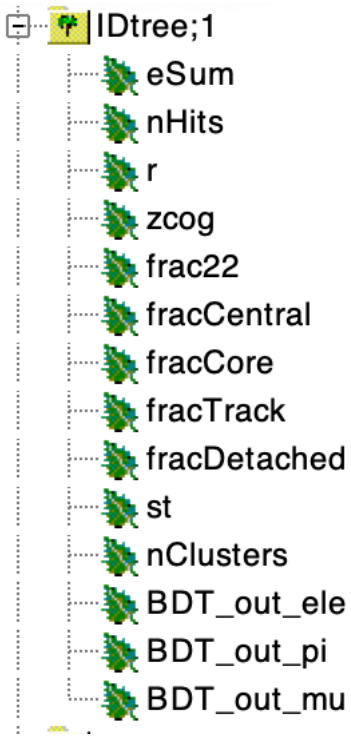

nHits:eSum
30GeV
nHits
eSum

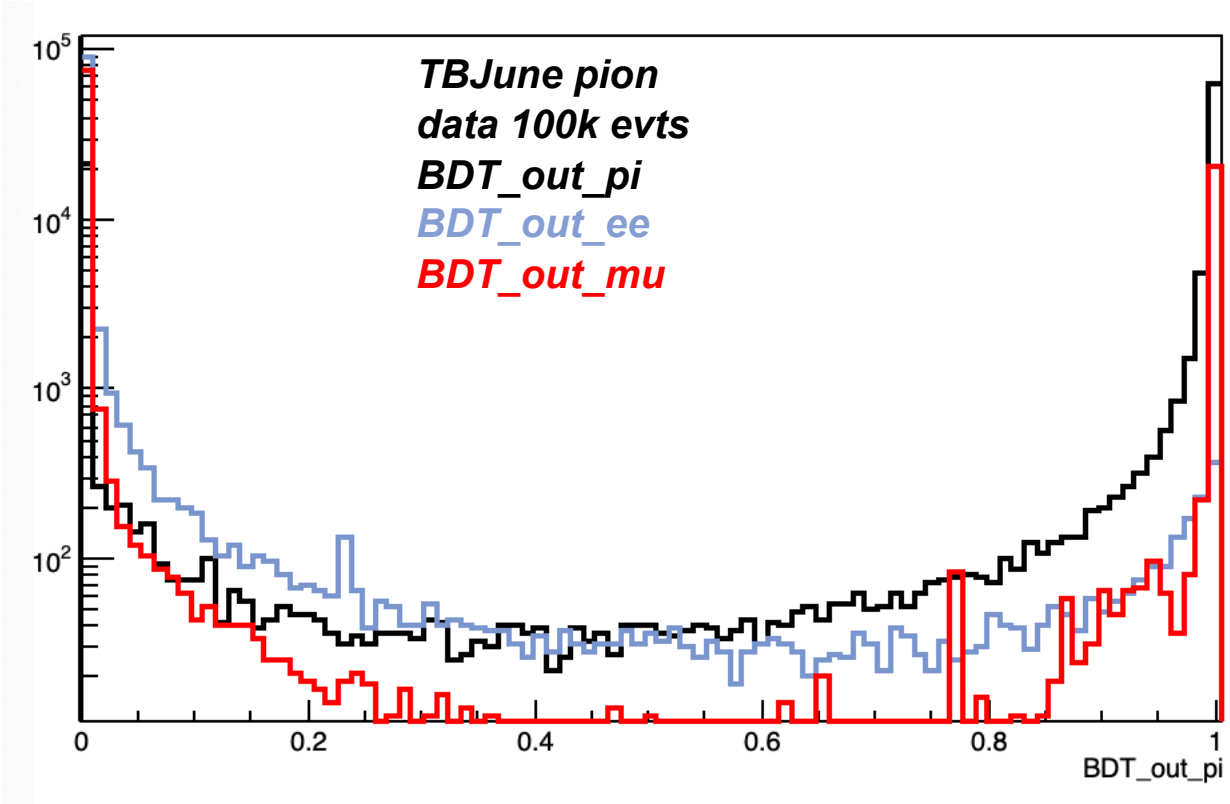

nHits:eSum
40GeV
nHits
eSum

BDT update

Output. Implemented in feature PID processor

- ~36000 line C function (converted from python model)

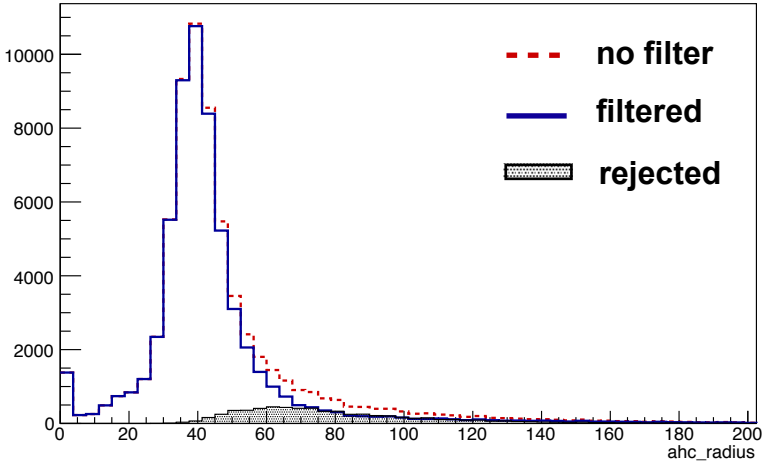


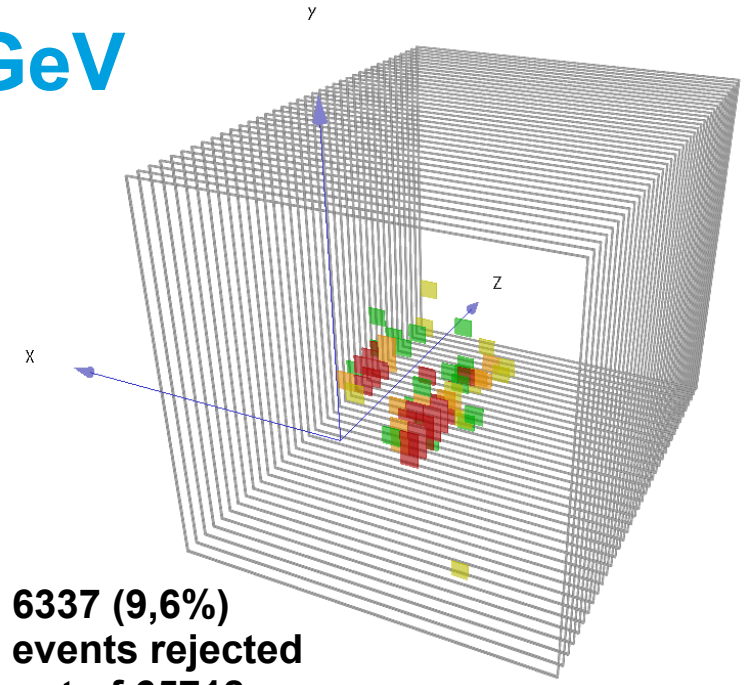


TBMay18 electron 10GeV

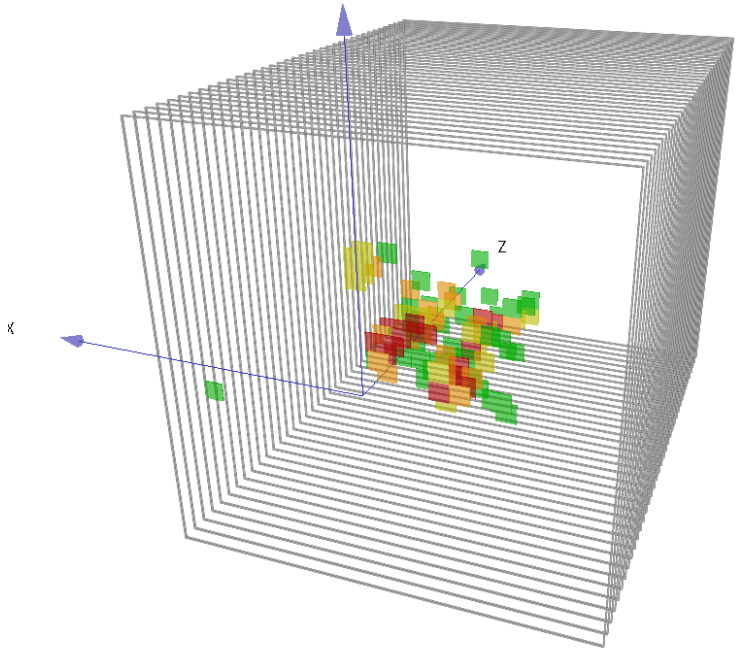
Applying filtering to data.

Shower radius, [mm]

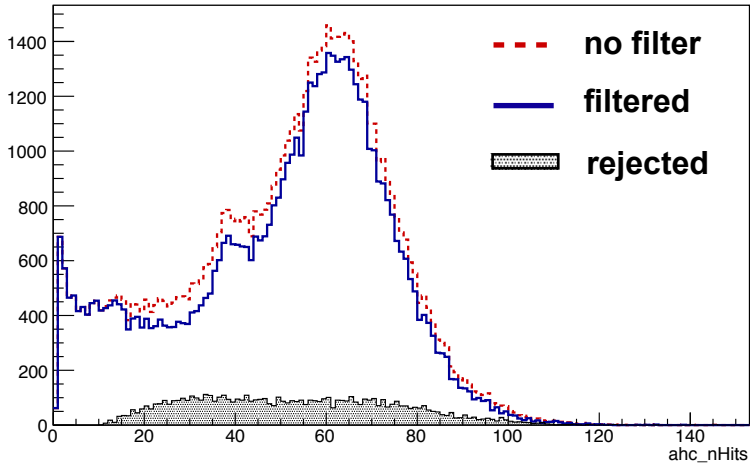




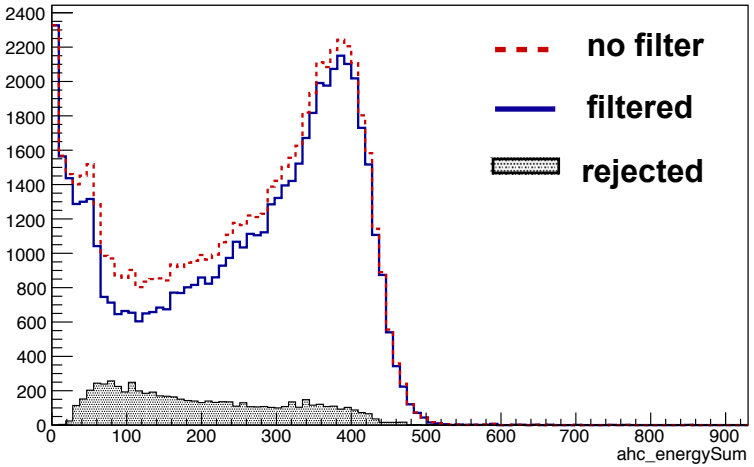
6337 (9,6%) events rejected out of 65718



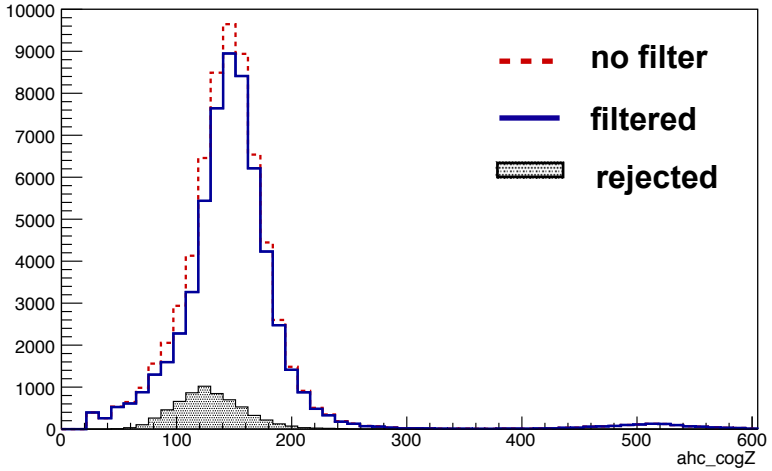
Number of hits



Energy sum, [MIP]

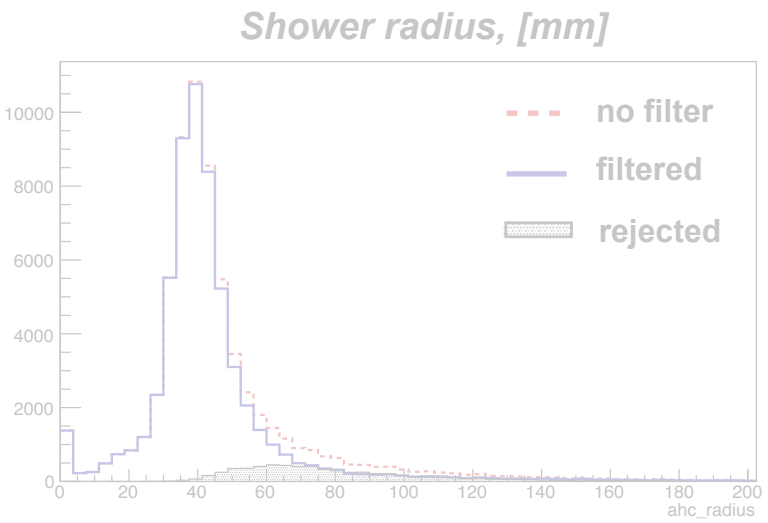


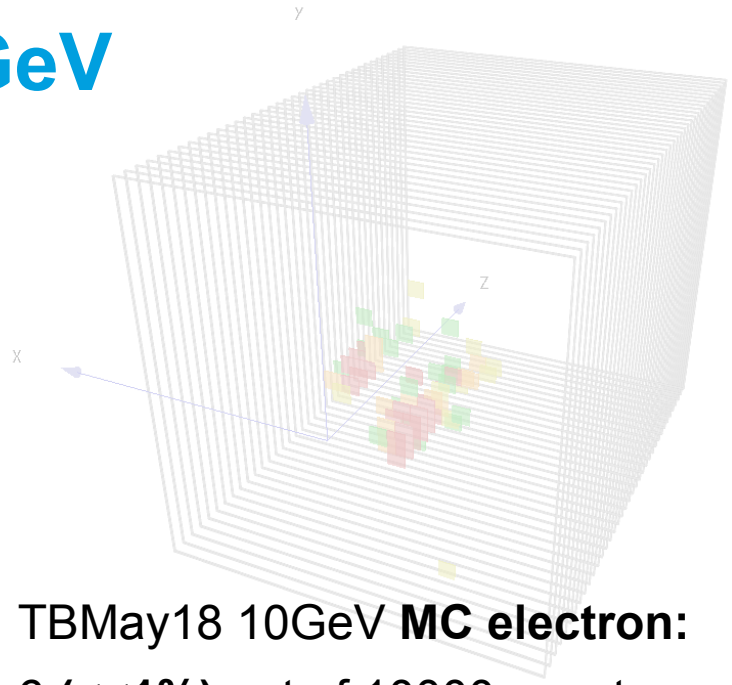
Center of gravity in z, [mm]

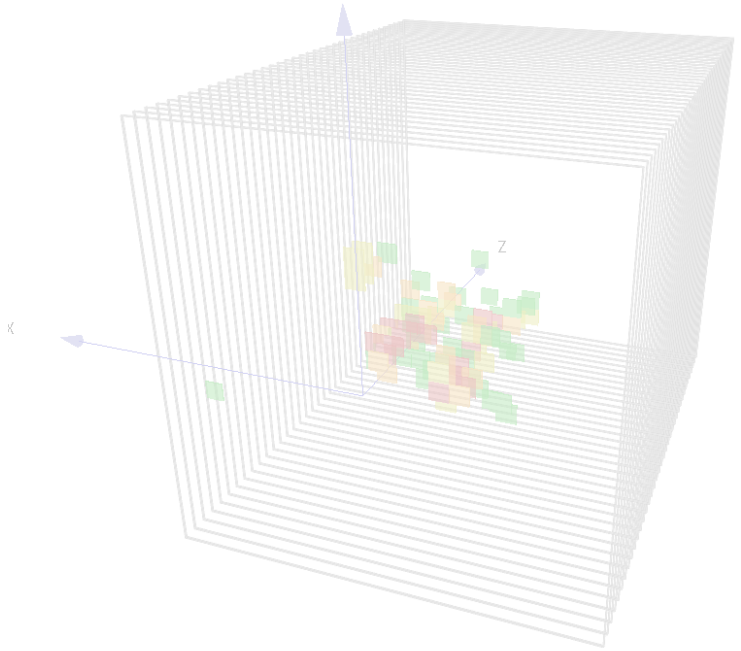


TBMay18 electron 10GeV

MC vs data

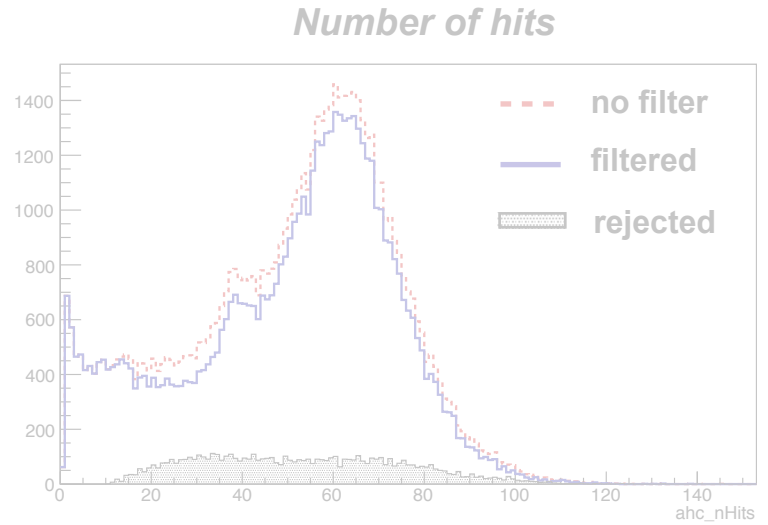


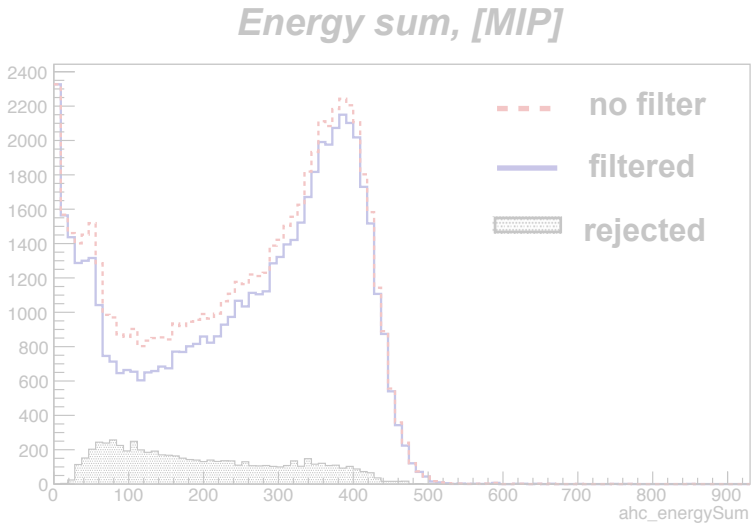


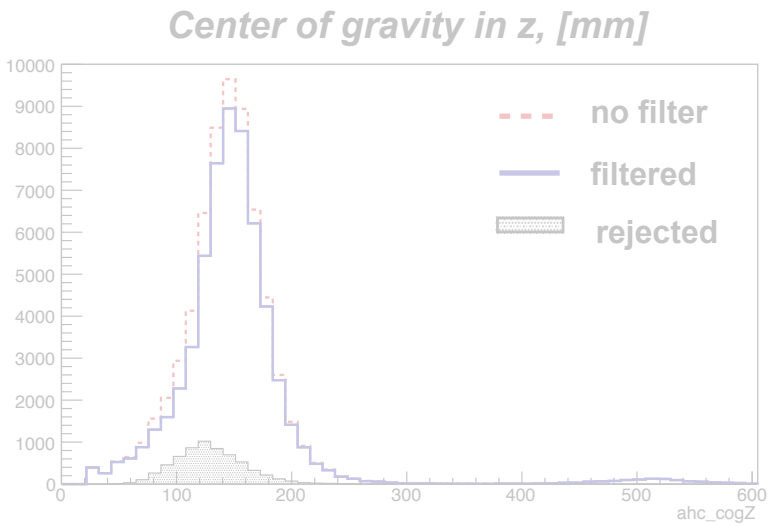


TBMay18 10GeV **MC electron:**

6 **(<<1%)** out of 10000 events



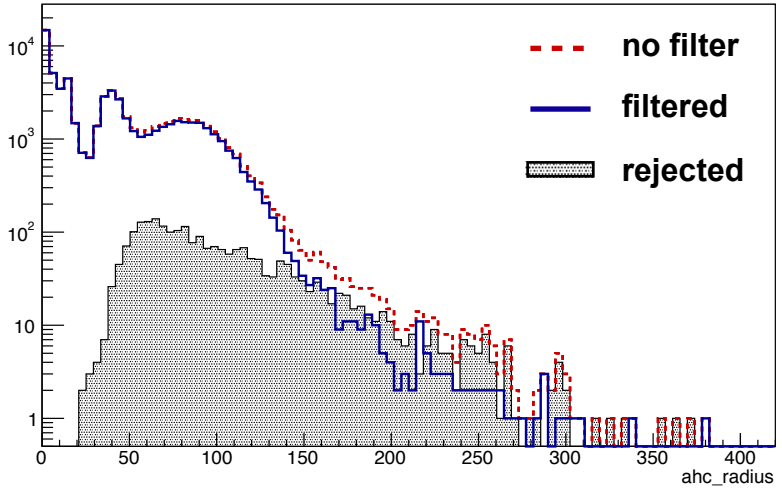


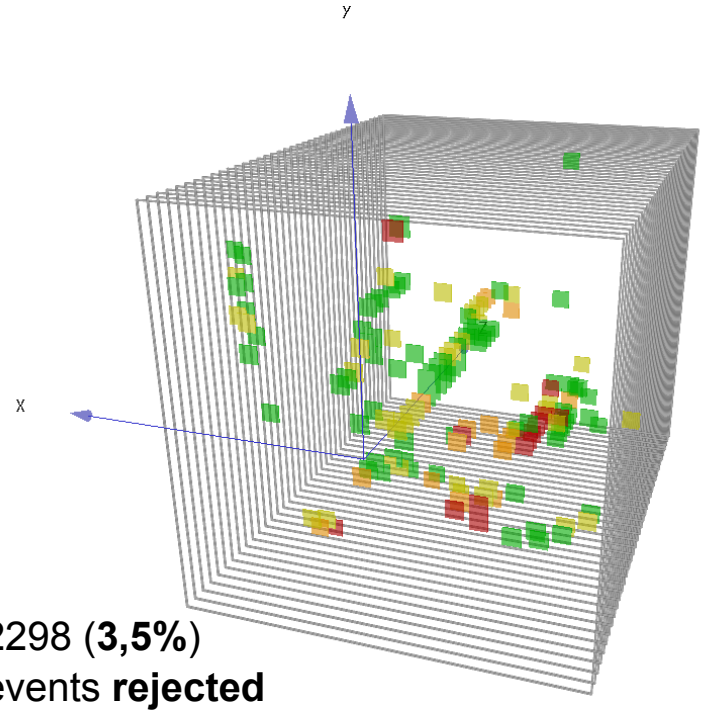


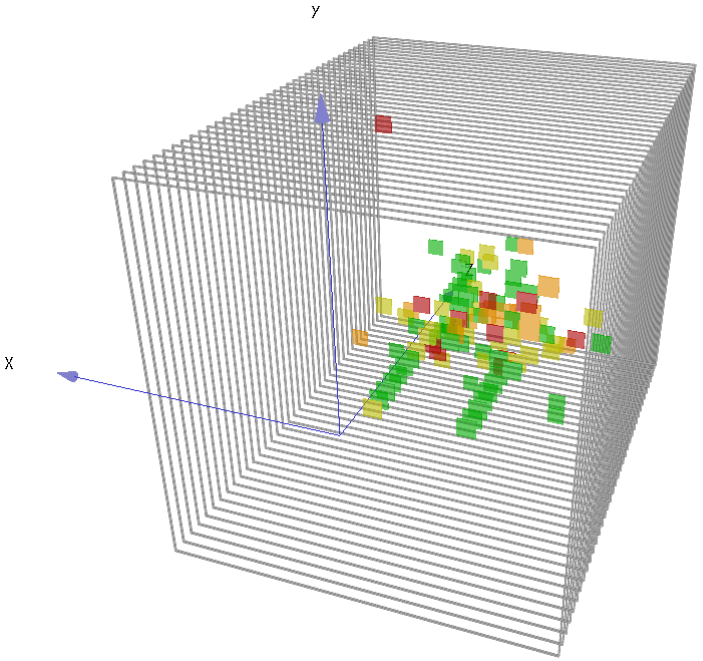
TBMay18 pion 10GeV

Applying filtering to data.

Shower radius, [mm]

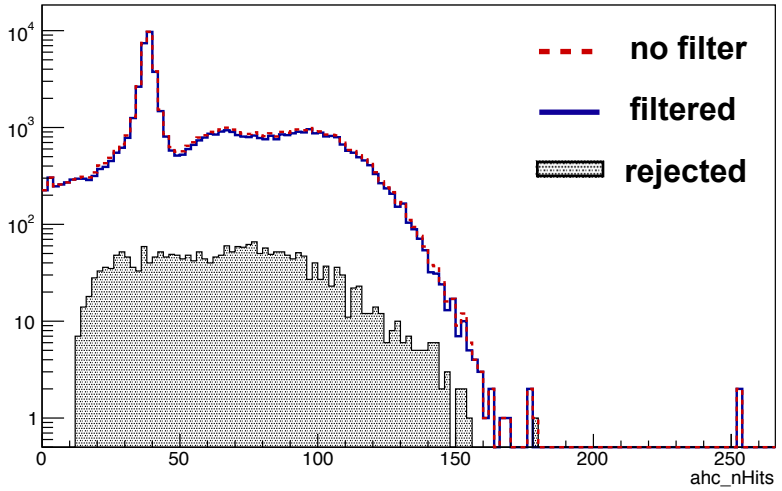




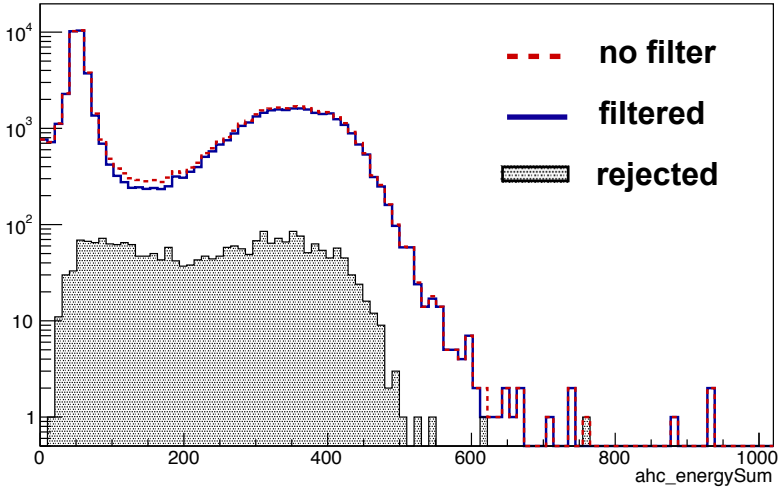


2298 (**3,5%**)
events **rejected**
out of 64884

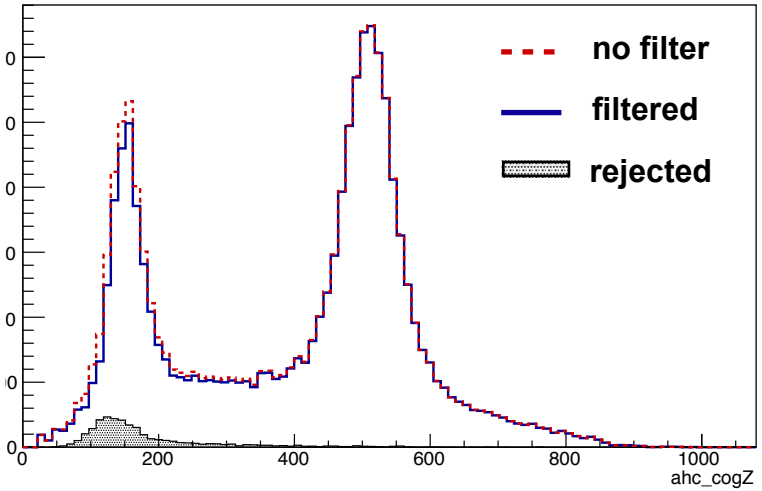
Number of hits



Energy sum, [MIP]



Center of gravity in z, [mm]



Rejected events. Simulations vs. data

10GeV pion.

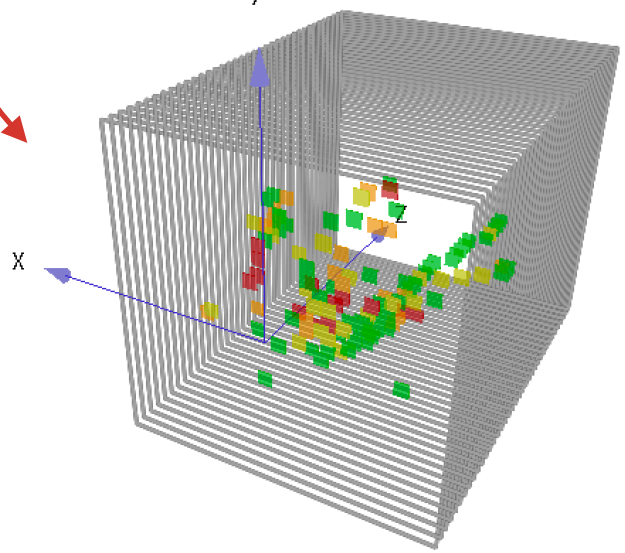
TBMay18 10GeV pion run:

2298 (**3,5%**) out of 64884 events

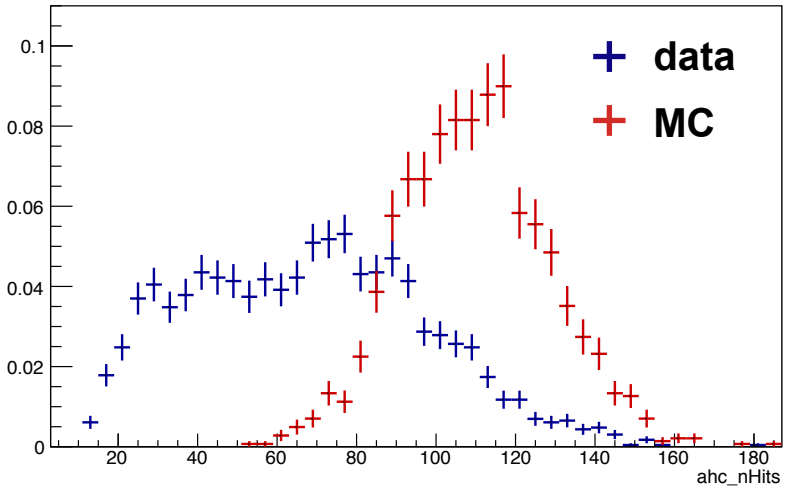
TBMay18 10GeV MC pion:

QGSP_BERT_HP physics list

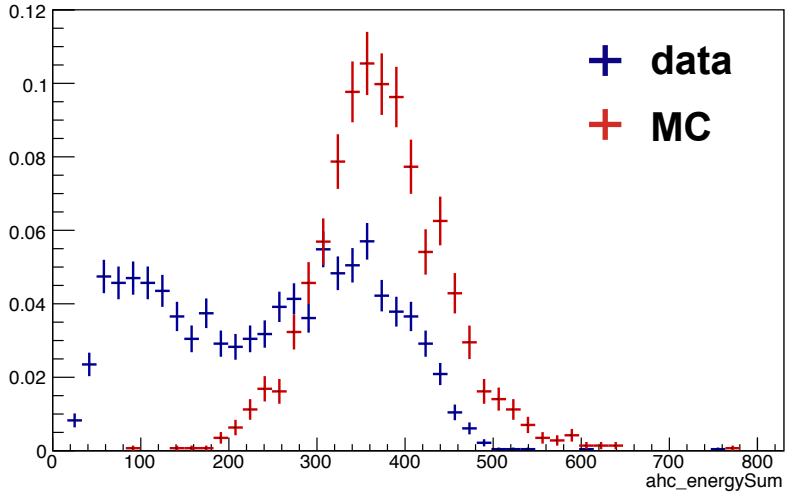
1423 (**3,3%**) out of 41000 events



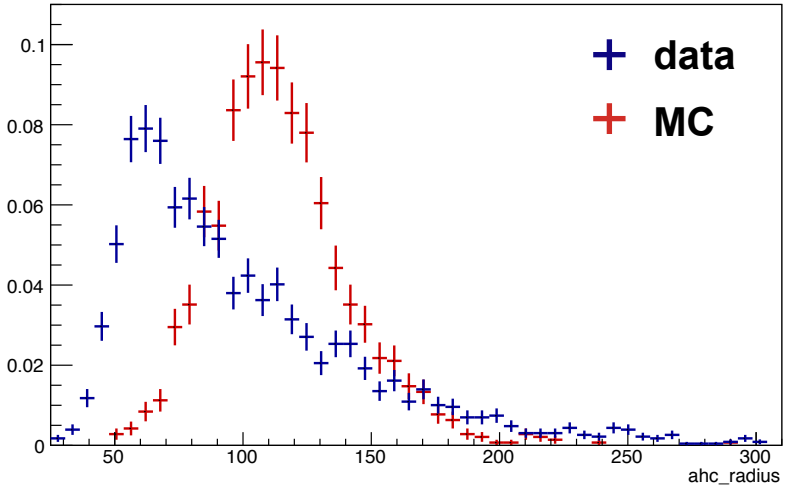
Number of hits



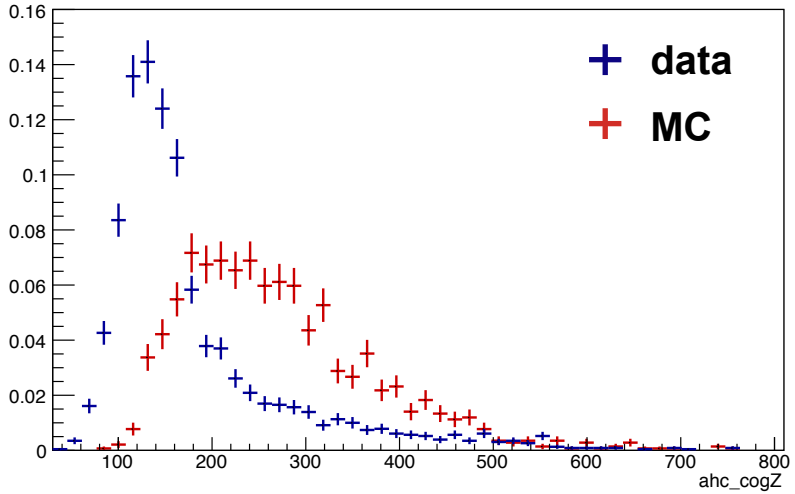
Energy sum, [MIP]



Shower radius, [mm]



Center of gravity in z, [mm]



Rejected events. Simulations vs. data

10GeV pion.

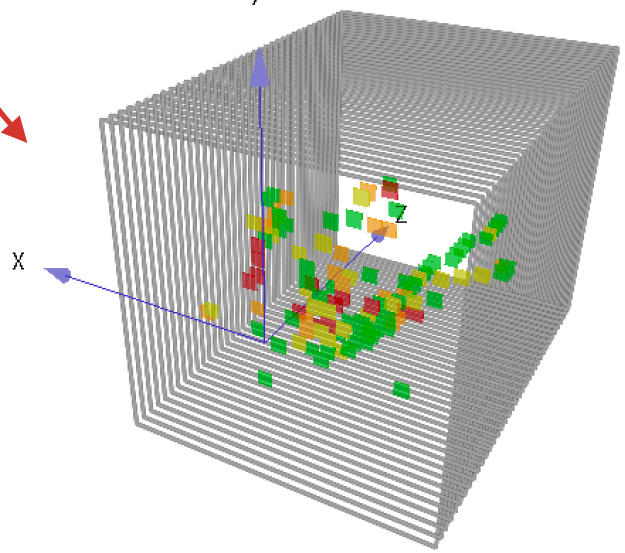
TBMay18 10GeV pion run:

2298 (**3,5%**) out of 64884 events

TBMay18 10GeV MC pion:

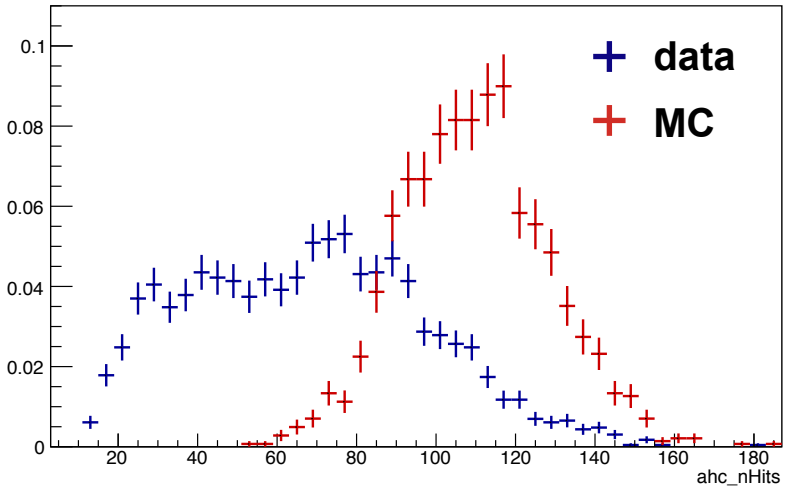
QGSP_BERT_HP physics list

1423 (**3,3%**) out of 41000 events

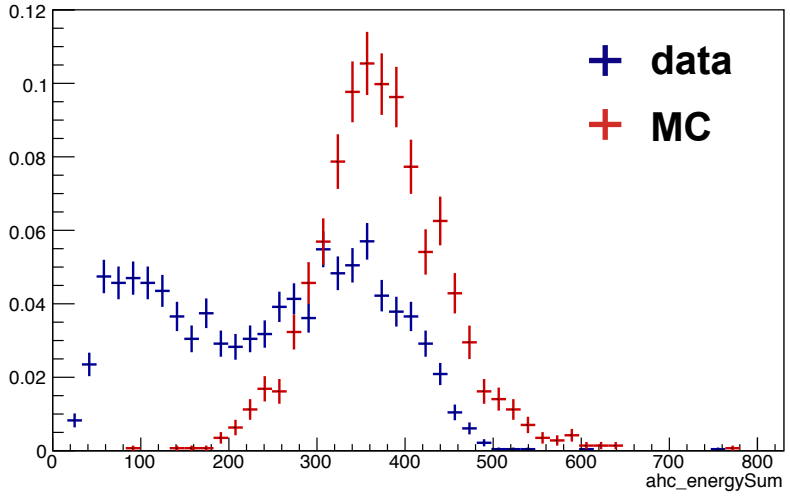


Same fraction of events for MC and data, **different distributions => too much early showering events simulated.**

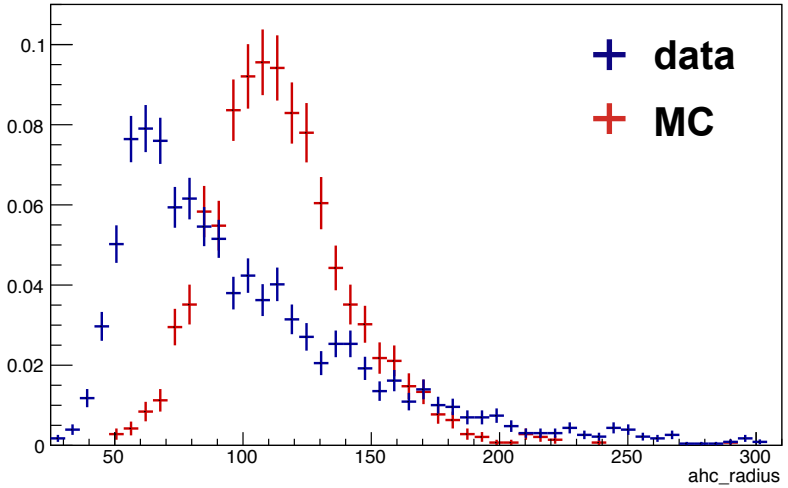
Number of hits



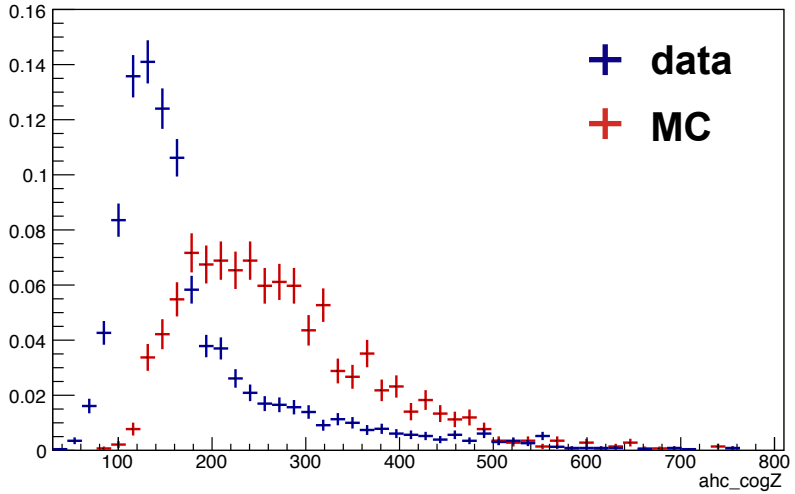
Energy sum, [MIP]



Shower radius, [mm]

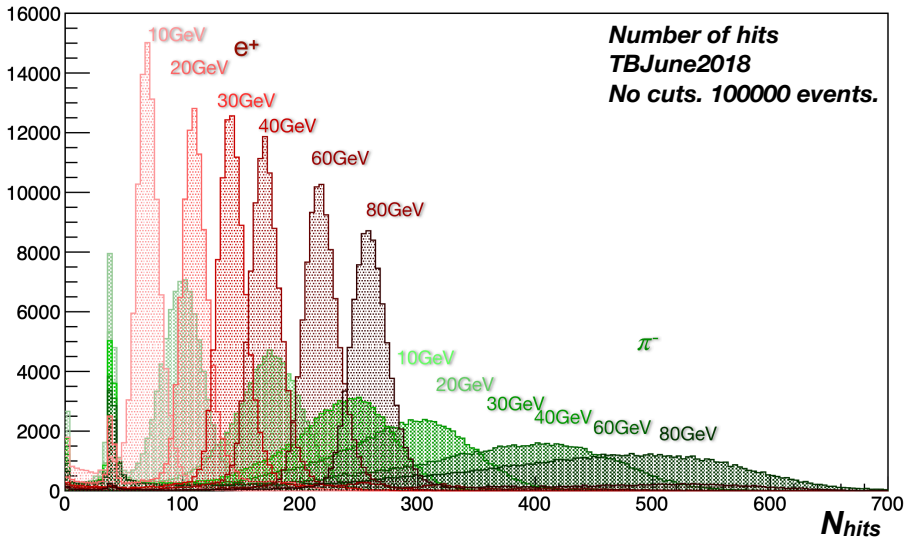


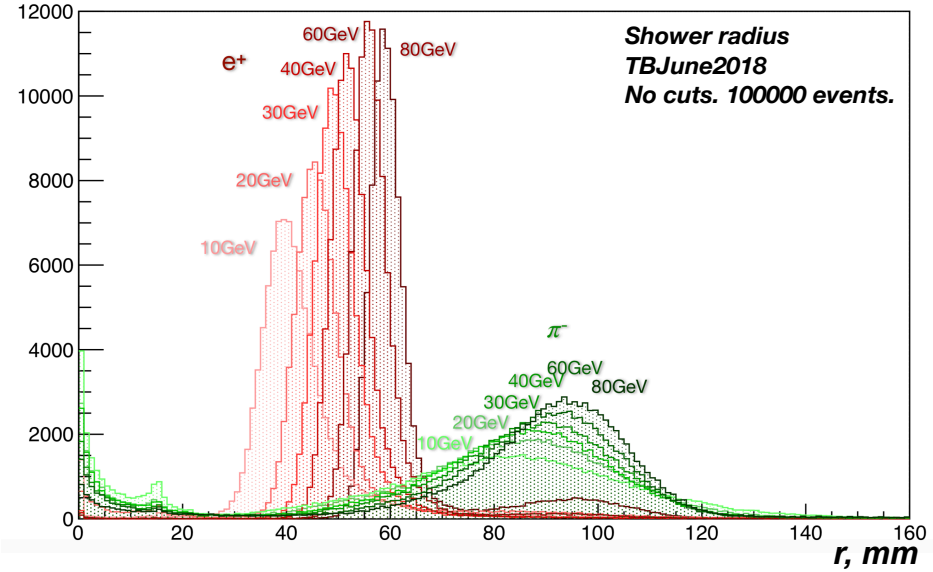
Center of gravity in z, [mm]

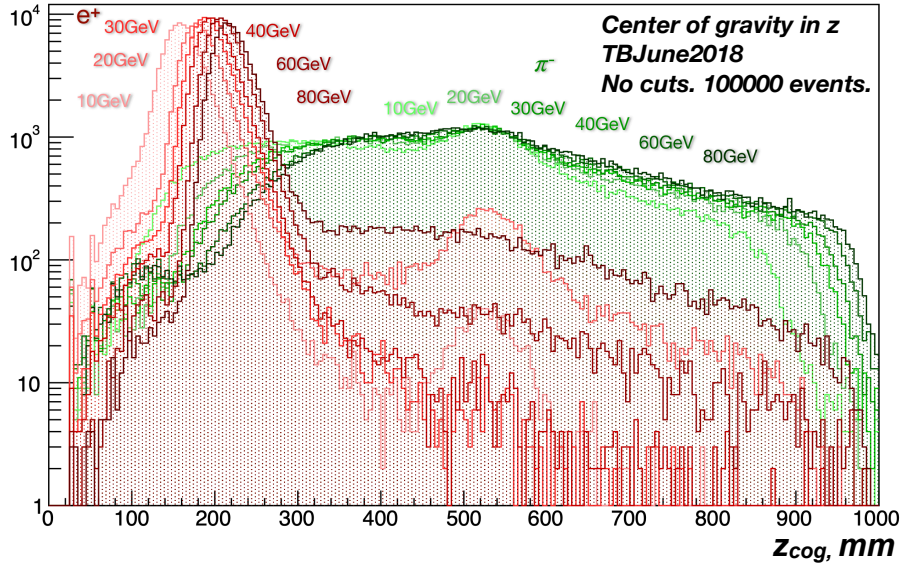


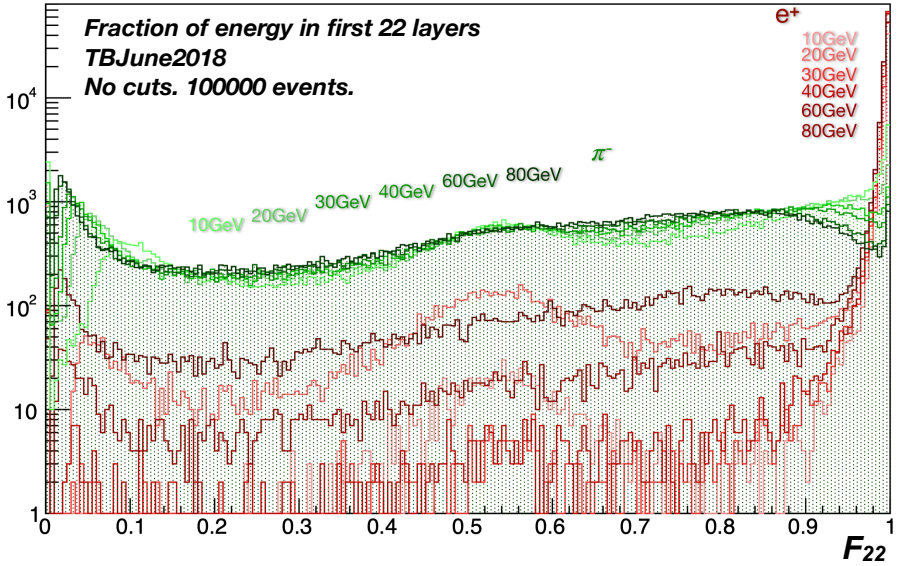
ID variables

TBJune2018. Electron and pion runs









Classification table

TBJune2018. Electron and pion runs

Work in progress…

Input. Output	Hadron events	Muon-like events	Electron events	Rejected
10GeV electrons	2.2 %	0.7 %	88.1 %	9 %
20GeV electrons	6.5 %	4.3 %	84.3 %	5.6 %
30GeV electrons	1.3 %	0.1 %	94.7 %	3.7 %
40GeV electrons	1.8 %	0.1 %	95.4 %	2.7 %
60GeV electrons	3.9 %	0.2 %	93.2 %	2.7 %
80GeV electrons	13.4 %	0.4 %	83.1 %	3 %
10GeV pions	74 %	14.8 %	4.4 %	6.8 %
20GeV pions	81 %	10.2 %	2.2 %	6.6 %
30GeV pions	82.2 %	9.8 %	1.9 %	6 %
40GeV pions	85 %	7.8 %	1.3 %	5.9 %
60GeV pions	85.8 %	7 %	1.3%	5.9 %
80GeV pions	85.6 %	4.9 %	1.3 %	8.2 %

Results are used in other analyses