Particle Flow in a $\mu\mu$ Environment: The Pandora Algorithm

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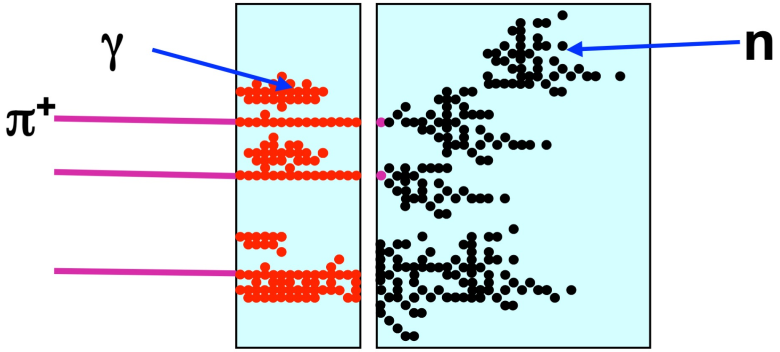
What is Particle Flow?

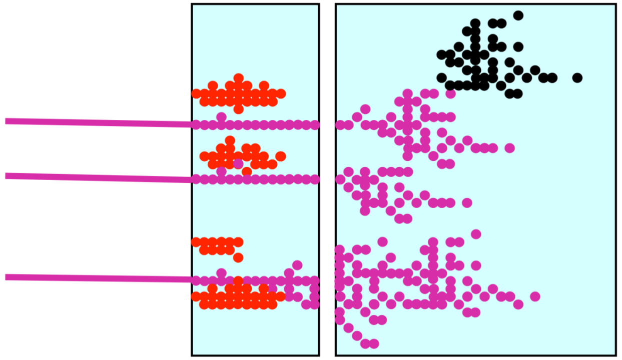
- **Traditional Calorimetry:**
  - Not all stable particles are identified
  - Jets: measure energy entirely in calorimeter
    - High reliance on poor HCal resolution
- **Particle Flow:** Coherently combine information from all detector components
  - Identify all stable particles in an event
  - Jets are formed from list of particles
- Advantages of Particle Flow:
  - Use tracker measurement to measure charged particles
  - More natural for substructure measurements
- Disadvantages of Particle Flow:
  - Requires high granularity detectors
  - The reconstruction software becomes complicated

Traditional Calorimetry



$$E_{JET} = E_{ECAL} + E_{HCAL}$$

Particle Flow



$$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$$

Images from [1]

The Pandora Particle Flow Algorithm

- Designed for detectors (ILD) at a linear e^+e^- collider (ILC, $\sqrt{s}$ ~ 500 GeV)
  - Extended to detectors at CLIC ($\sqrt{s} = 3$ TeV)
- It reads and accounts for calorimeter parameters → *flexible*!

Event Preparation

- Track selection
- Calorimeter hit selection

Clustering

1. Photon Clustering
2. Fast photon ID
3. Main clustering
4. Topological merging
5. Reclustering
6. Photon recovery + ID
7. Fragment removal

Particle Flow Object Creation

Set of basic ID algorithms

links to code in backup

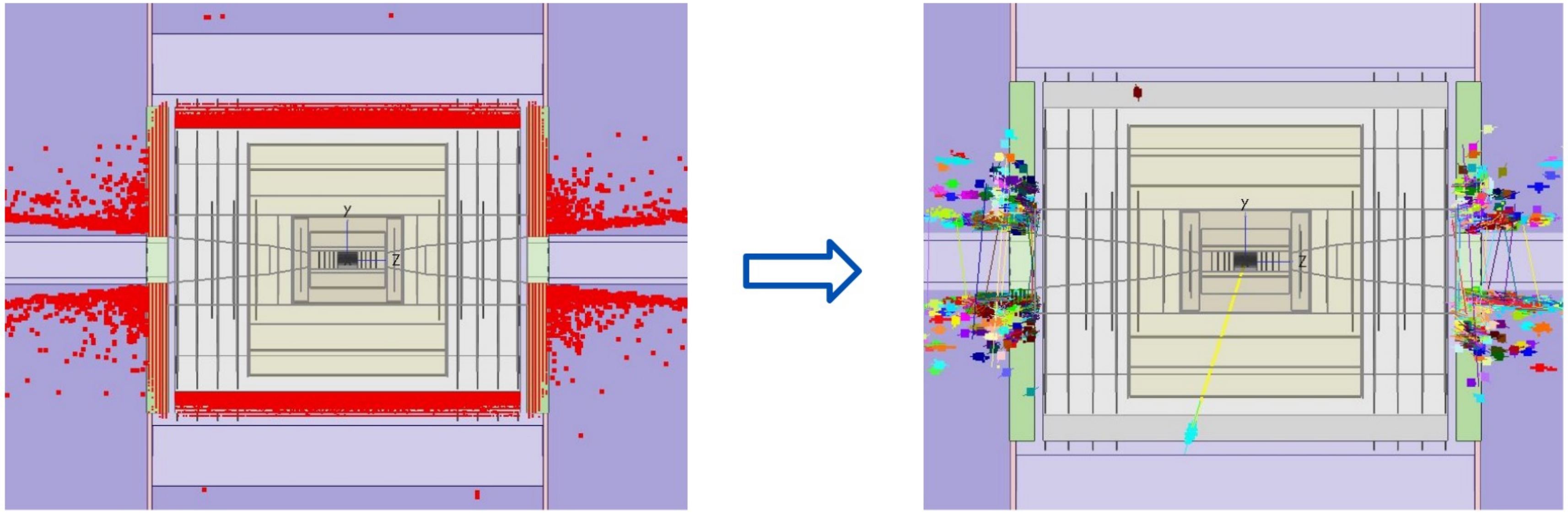
I

Pandora requires tweaking and / or reworking to perform optimally in a 10 TeV muon collider

*: Denotes potential projects

Pandora: Event Preparation

- Track selection
  - $\frac{\sigma(p_T)}{p_T}$ requirement to match to clusters
- Calorimeter hit selection
  - Categorization for isolated hits to be excluded from clustering
  - MUSIC: Reject hits with < 3 other hits in the neighboring 3x3 detector cell matrix * Potential MAIA study



Reconstruction of single photon, Leonardo Palombini, MUSIC detector [2]

Pandora: Cone Clustering Algorithm

- First seeds clusters with tracks projected to ECal face
- Then seeds clusters with remaining hits, beginning at innermost layers
- Work from inner layer of ECal, iteratively adding hits outward through calorimeter
- Errs on the side of forming smaller clusters. *Easier to put things together than to split them up.*

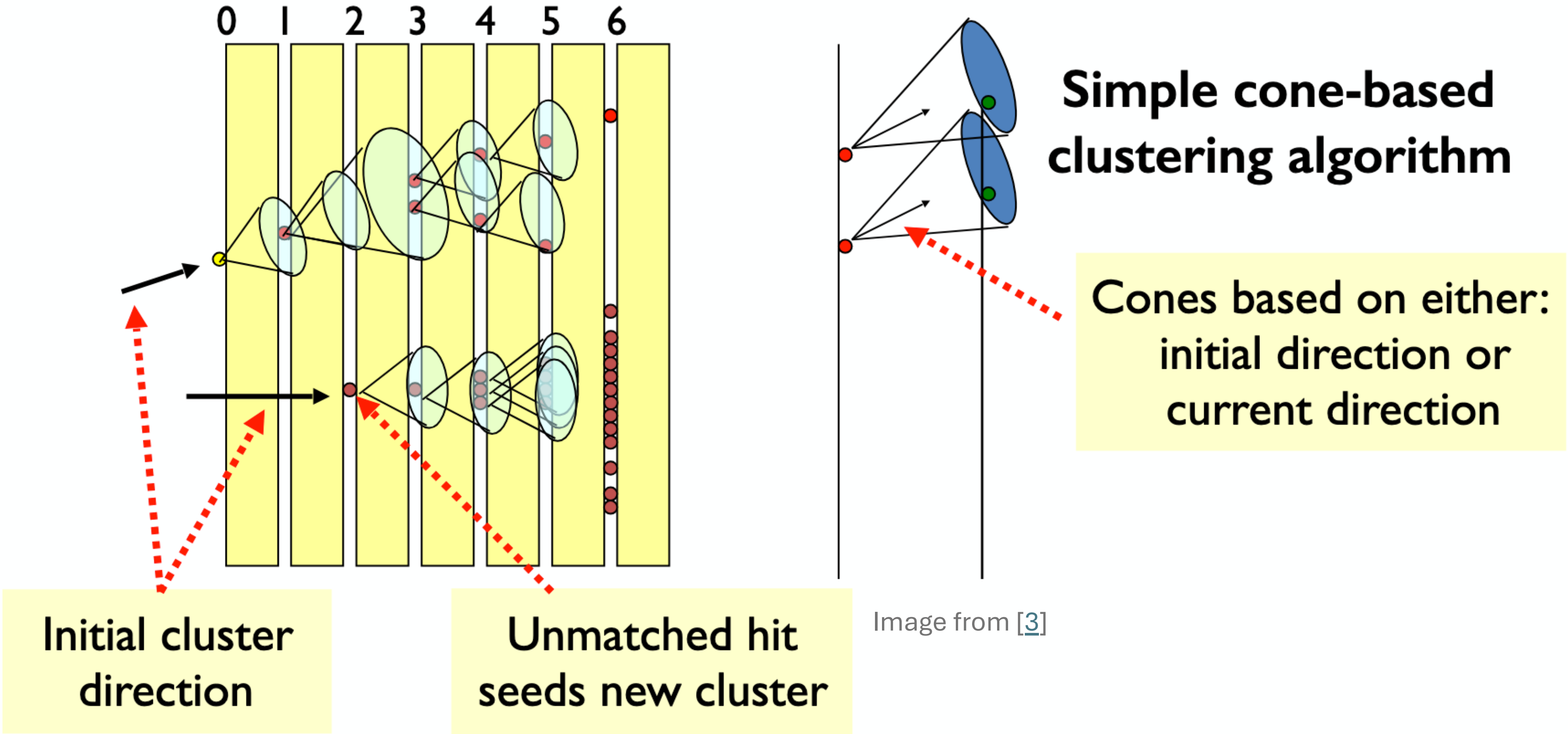
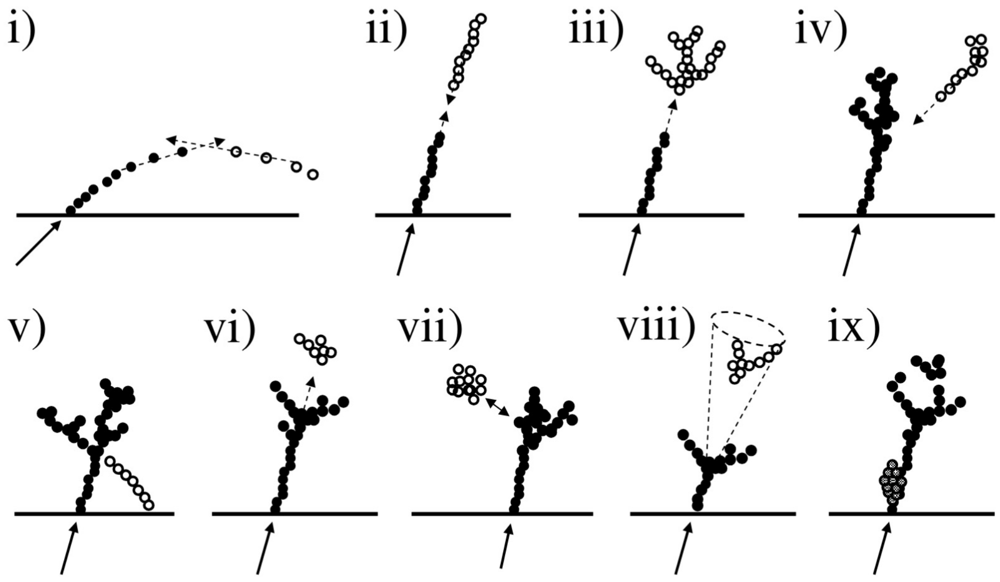


Image from [3]

Pandora: Clustering

- Fast photon ID
- Cone clustering
- Topological cluster merging algorithms
- Recluster to achieve better track – cluster consistency
- Photon recovery and fragment removal
- **50 GeV jets:** Frag. Rem. and Topo. Merging are important
- **250 GeV jets:** Reclustering is the most important

Topology-based cluster merging



arXiv:0907.3577. Details in backup.

ILD

* Potential μC study

Algorithm	Jet Energy Resolution $\text{rms}_{90}(E_j)/E_j$ [%]			
	E_j=45 GeV	E_j=100 GeV	E_j=180 GeV	E_j=250 GeV
Full PandoraPFA	3.74 ± 0.05	2.92 ± 0.04	3.00 ± 0.04	3.11 ± 0.05
a) No Topological Clustering	4.02 ± 0.05	3.25 ± 0.04	3.52 ± 0.05	3.67 ± 0.06
b) No Reclustering	3.83 ± 0.05	3.30 ± 0.04	3.91 ± 0.05	4.19 ± 0.07
c) No Photon Clustering Stage	3.66 ± 0.05	2.99 ± 0.04	3.13 ± 0.04	3.31 ± 0.05
d) No Fragment Removal	4.05 ± 0.05	3.21 ± 0.04	3.25 ± 0.04	3.40 ± 0.06
e) No V^0/Kink Tracks	3.78 ± 0.05	2.96 ± 0.04	3.02 ± 0.04	3.13 ± 0.05

arXiv:0907.3577

Pandora: Clustering

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- Topological cluster merging algorithms *
- Recluster * to achieve better track – cluster consistency
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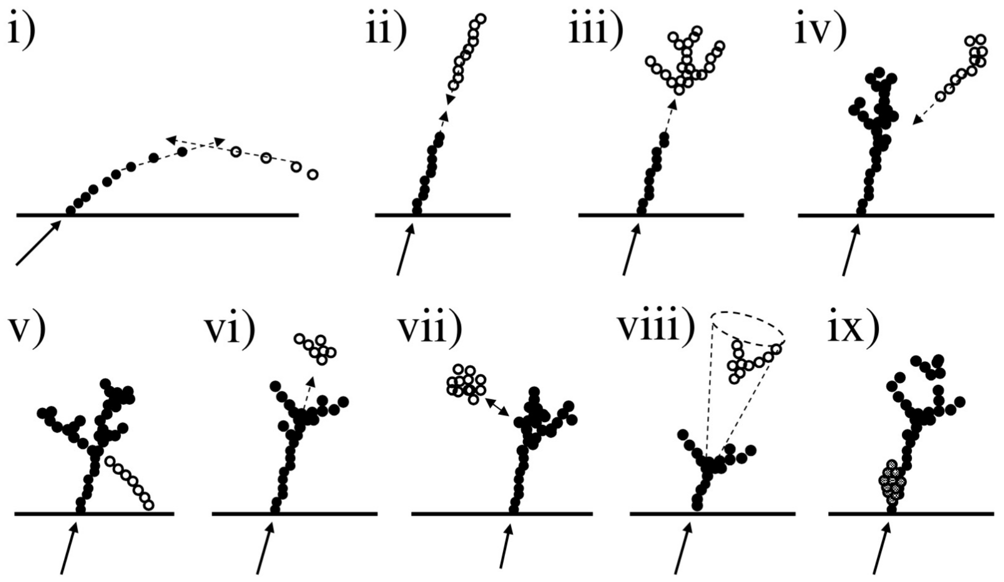

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* : computationally expensive!

ILD

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* Potential μC study

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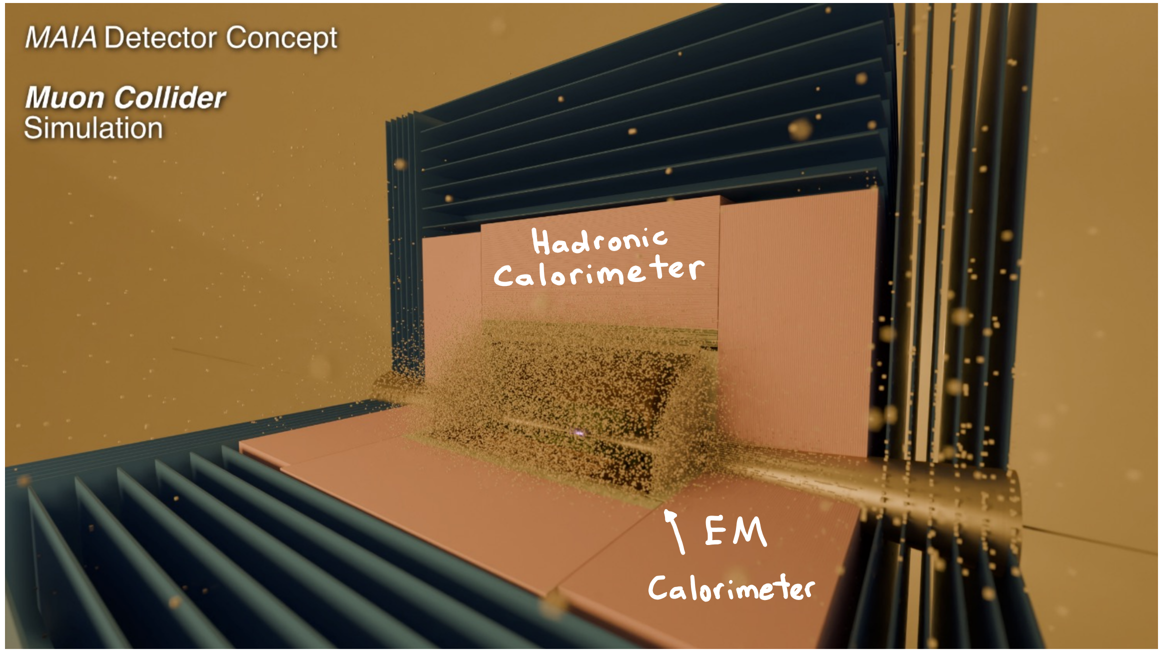
$\mu\mu$: Other Clustering Algorithms

- BIB creates a high detector occupancy, particularly in the first few layers in the Ecal
- Forward-projective clustering algorithm starts in the busiest environment
- Is it better to seed clustering elsewhere?
    - From the back of the HCal, cluster outwards → inwards (Larry Lee, Federico Meloni) ✱ Potential μC study



arXiv:2502.00181

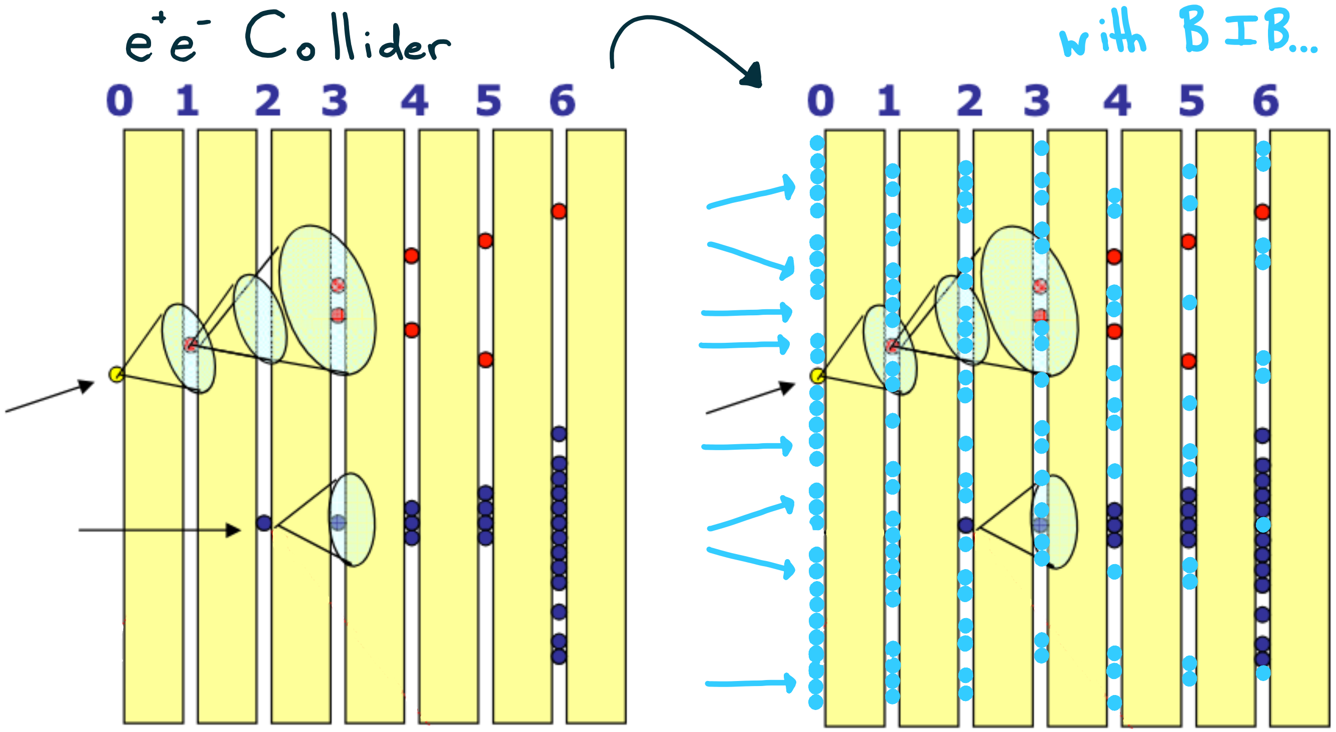
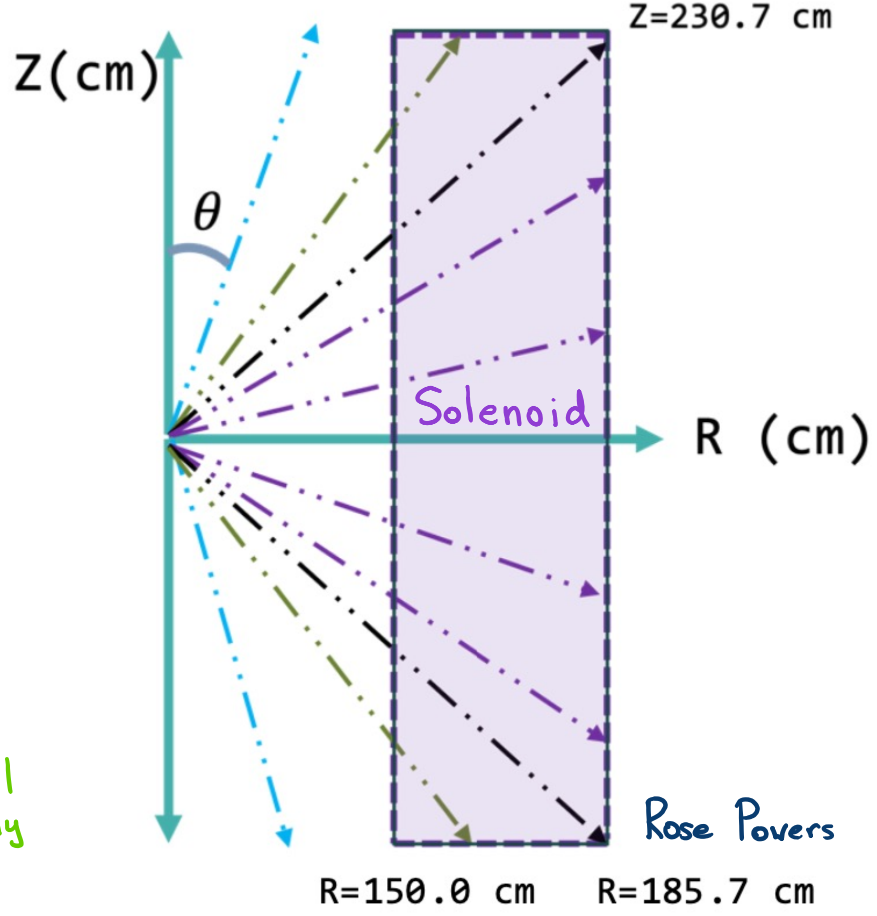


Image from [3]

Pandora: Particle Flow Object Creation

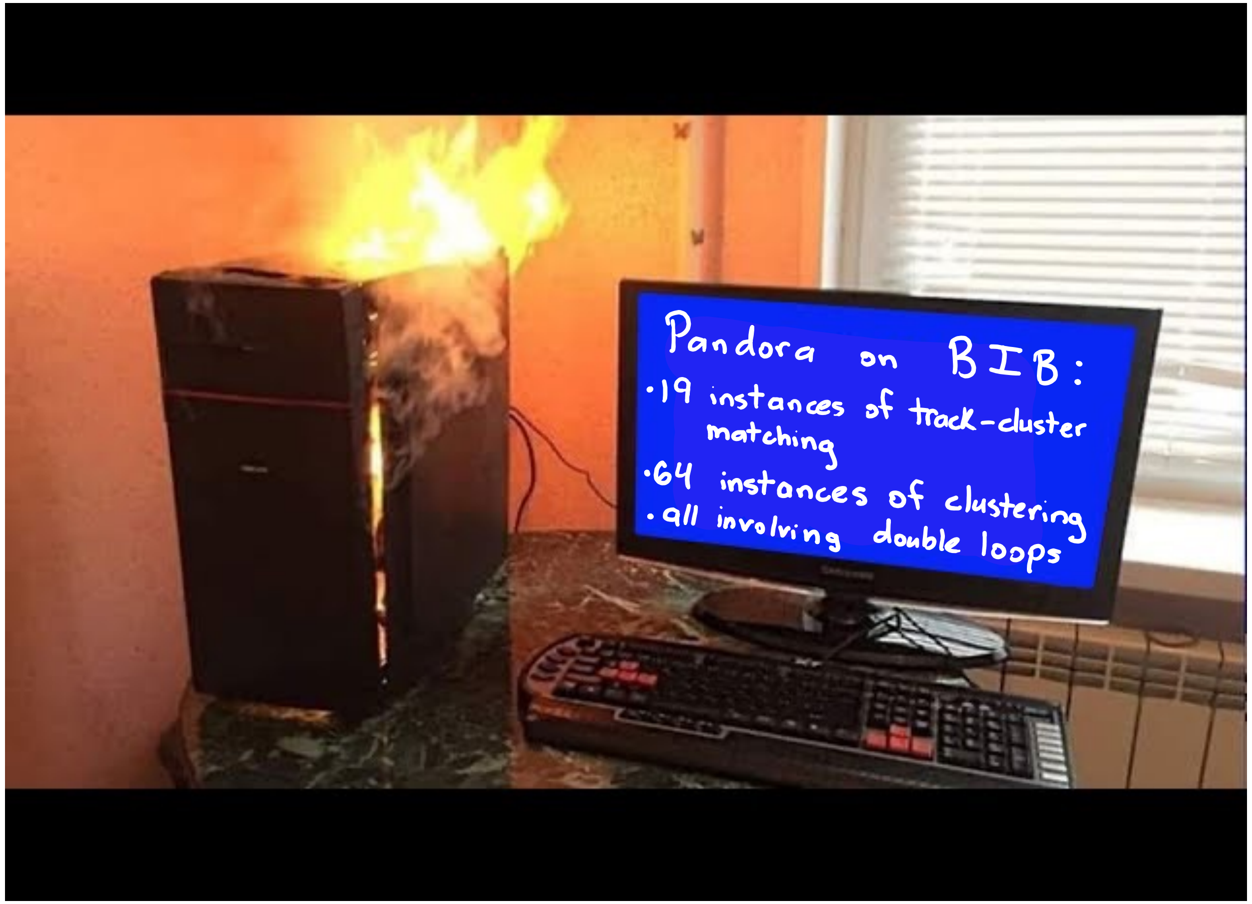
- Final track-cluster matching
- Three basic ID algorithms:
  - Muons
  - Photons
    - Neutral hadrons are neutral PFOs that are not photons
  - Electrons
    - $\pi^{\pm}$ are charged PFOs that are not electrons
- Algorithms aren't necessarily suitable for our environment * Potential μC study
  - Expected electron profile independent of θ
    - *Not the case for MAIA!*



θ determines how many X_0 of solenoid (Al) particle traverses through (MAIA)

$\mu\mu$: Simplified Versions of Pandora

- It can take **1 day** to reconstruct a single event with BIB using Pandora
- Increasing effort to run with a subset of Pandora algorithms
- Main benefit: can lead to *~10x speed-up* with BIB



Simplified Pandora: Charged Pions (MAIA)

Track Selection + Hit Preparation + Cone Clustering + Resolve Track Associations + PFO Identification

Track Selection
- consistency requirements
- $\frac{\sigma(p)}{p}$ cut

Hit Preparation

define isolated hits

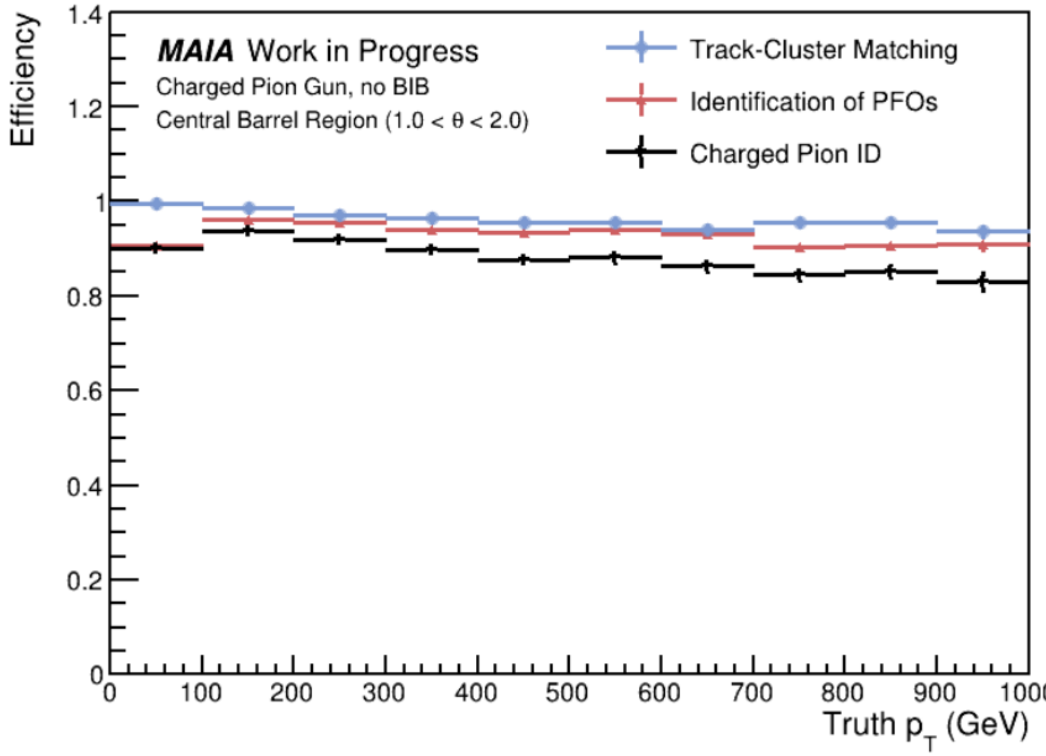
Cone Clustering

main clustering algorithm

Resolve Track Associations

χ^2-based consistency between track, cluster

PFO Identification
- track-cluster matching
- basic ID algorithms



Simplified Pandora: Electrons (MUSIC)

Track Selection + **Hit Preparation** + **Cone Clustering** + **PFO Creation** + **Custom ID**

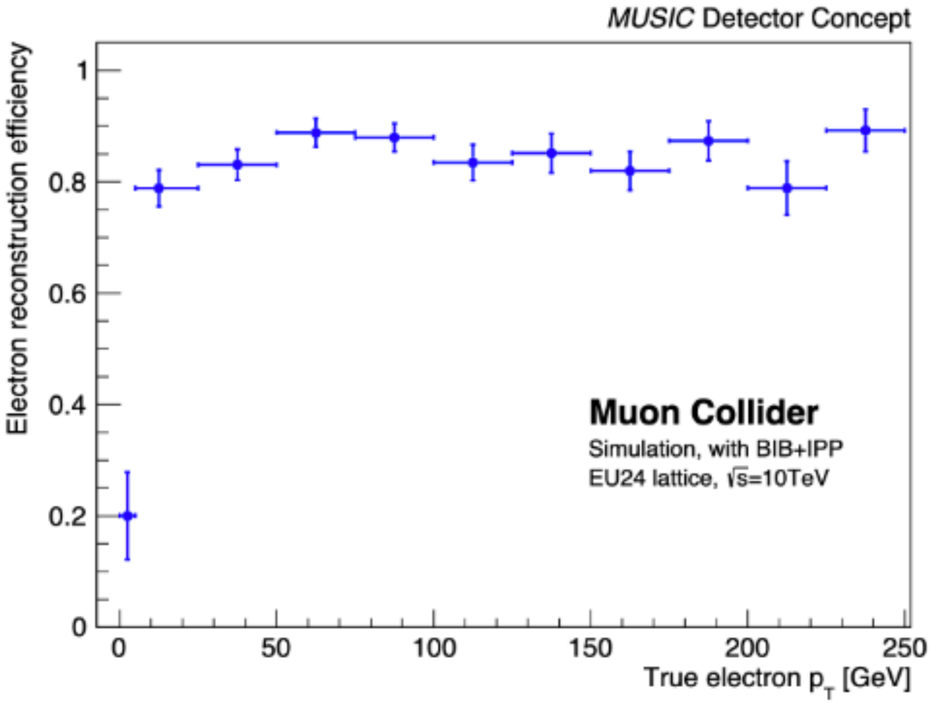
Track Selection
- consistency requirements
- $\frac{\sigma(p)}{p}$ cut

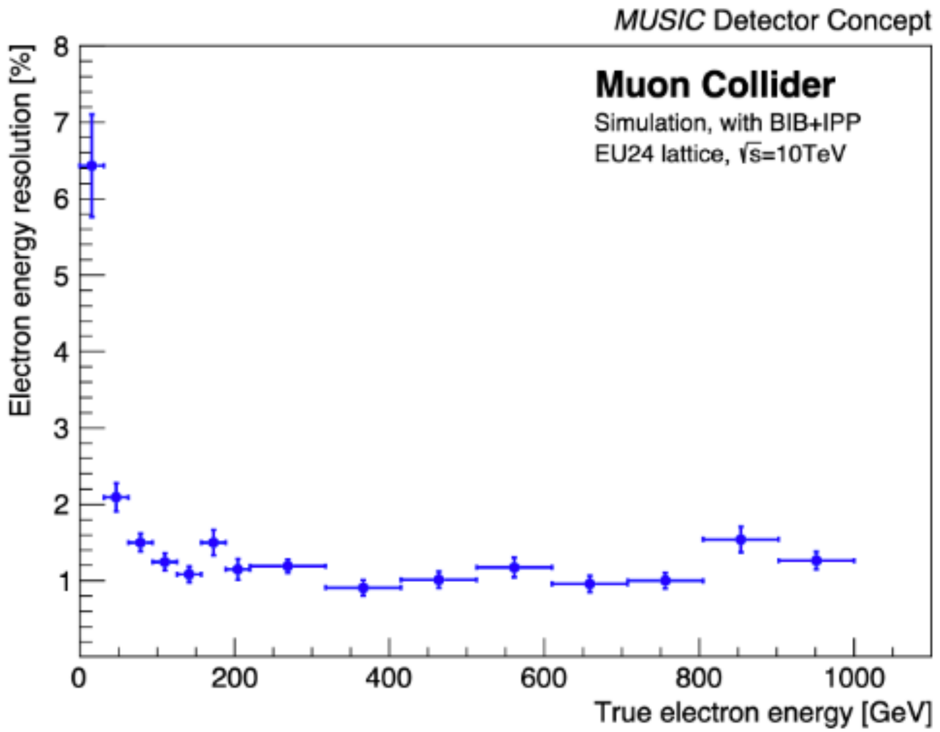
Hit Preparation
define isolated hits (slide 5)

Cone Clustering
- main clustering algorithm
- optimized parameters

PFO Creation
track-cluster matching

Custom ID
based on location of cluster centroid



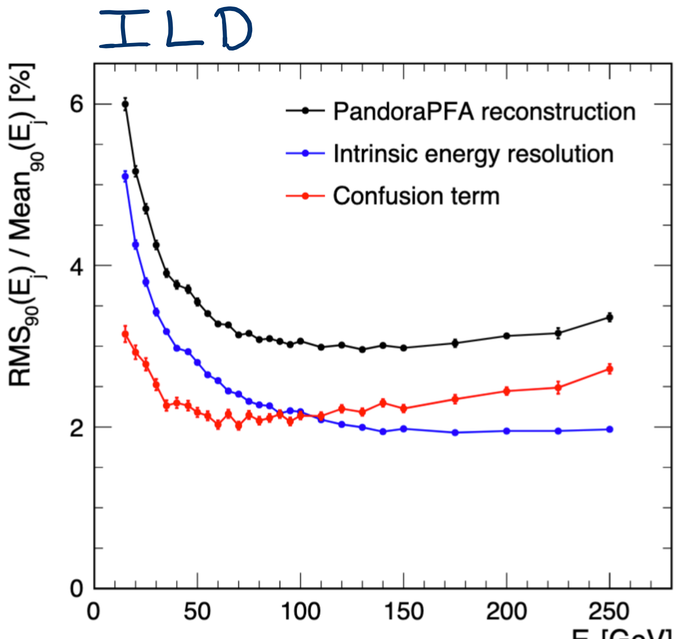


II

There are also challenges for <u>any</u> Particle Flow algorithm at a 10 TeV $\mu^+\mu^-$ Collider.

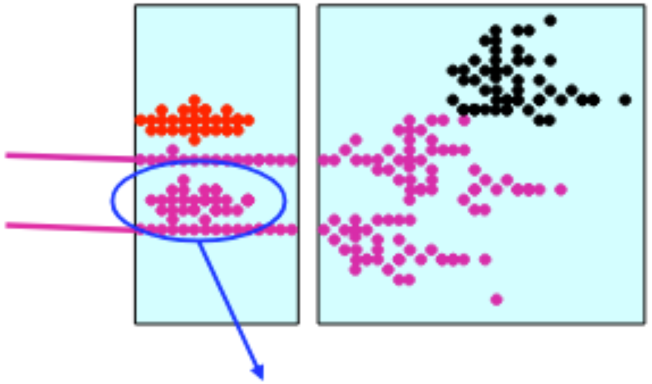
Interpretation of PFlow Performance

- Particle flow performance parameterized into two components:
  - Intrinsic energy resolution
  - Confusion term
- Confusion dominates particle flow performance at high jet energies
  - Separation of particles within jet decreases
- *Poses challenge for* $\sqrt{s} = 10\ TeV\ \mu\mu$ *collider!*

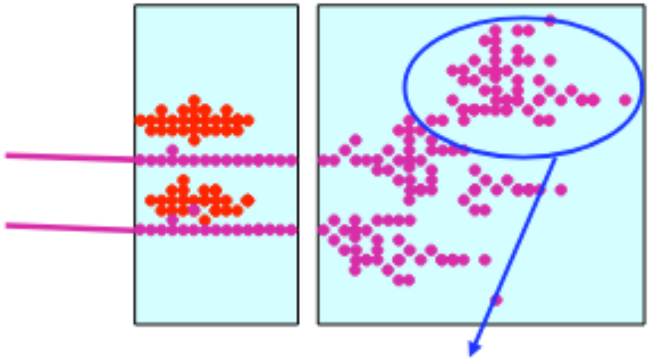


arXiv:1705.10363

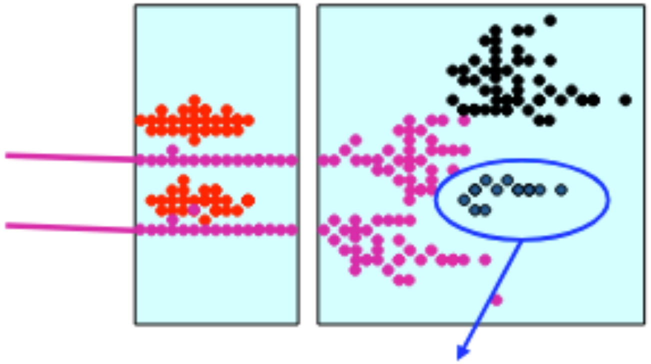
Types of confusion



Failure to resolve photons



Failure to resolve neutral hadrons



Reconstruct fragments as separate neutral hadrons

Images from [1]

Confusion term: CLIC

MAIA example in backup

- Confusion term has been studied at CLIC ($\sqrt{s} = 3\ TeV$)
- *Solution:* Transition from particle flow to ***energy flow***
  - Neutral hadrons identified as excesses of energy, *not directly reconstructed*
- *At what E_{jet} scale do we become dominated by the confusion term?* * Potential μC study
- *Will a transition to energy flow help?* * Potential μC study
- *Do we have to rely on high-momentum tracking?* * Potential μC study

Energy Flow

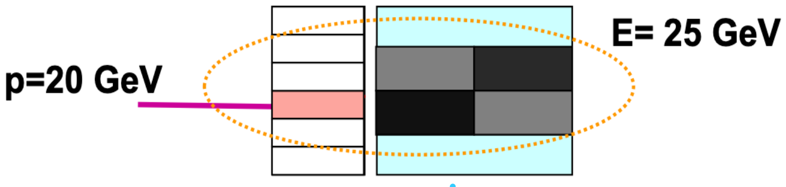
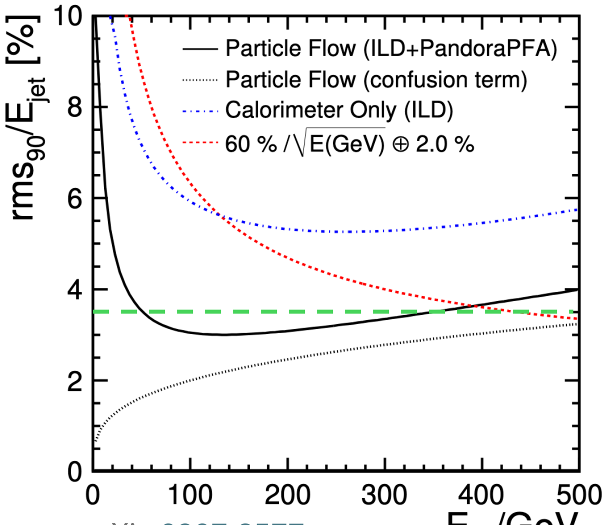


Image from [4]

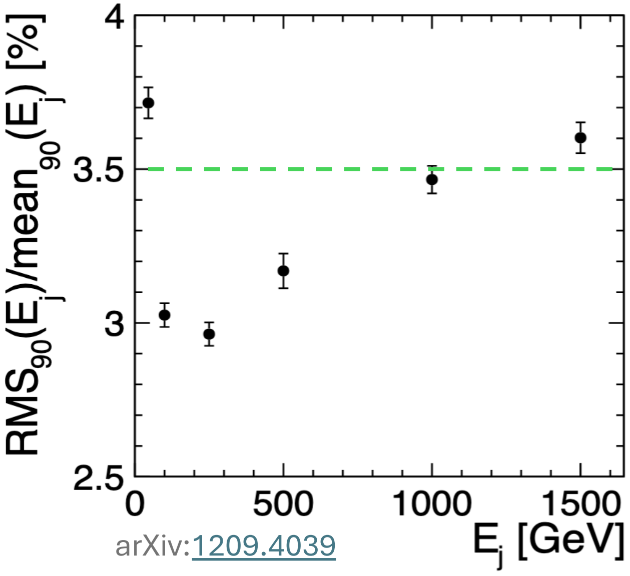
E_n = 5 GeV

Particle Flow
ILD



arXiv:0907.3577

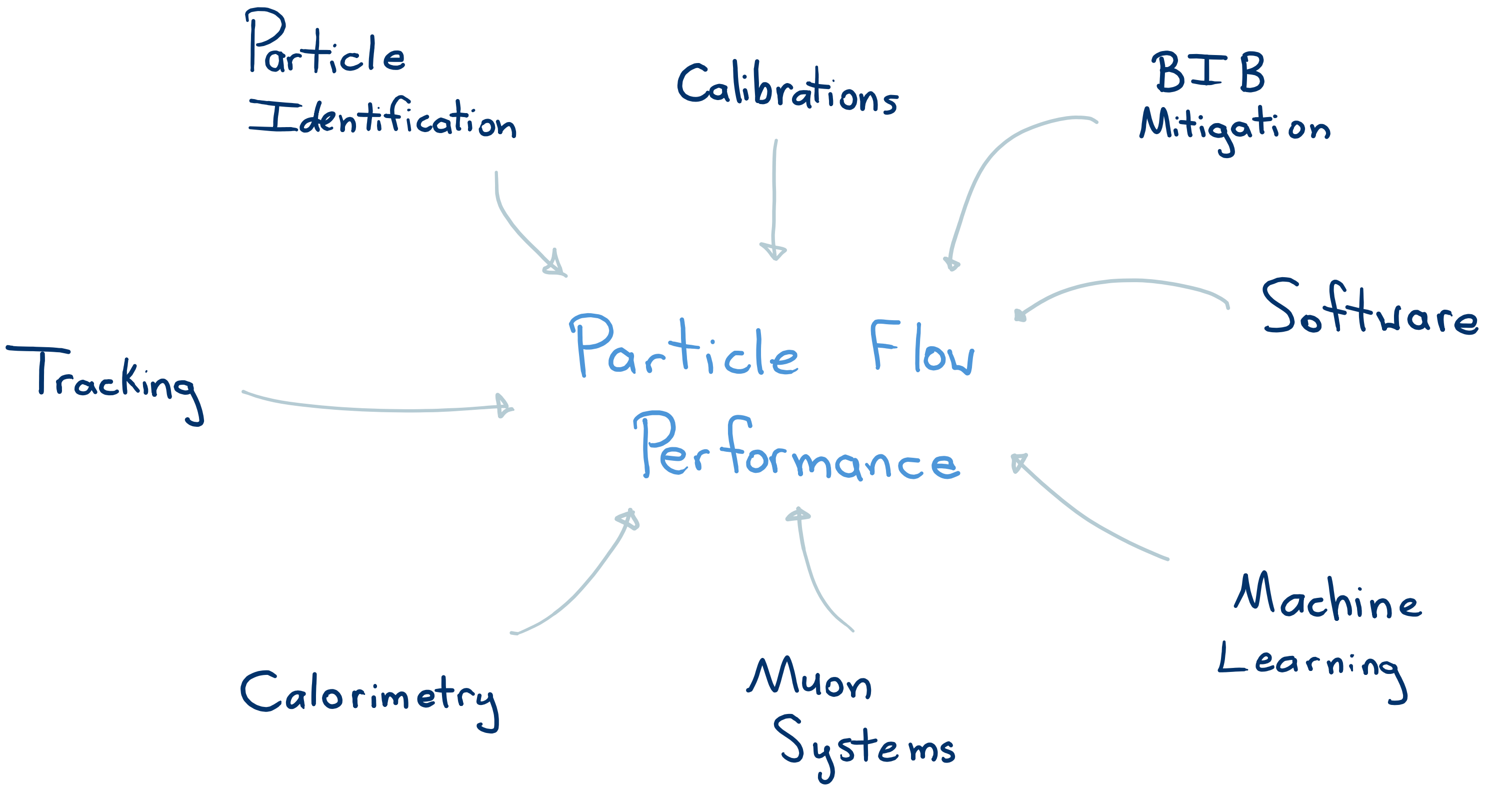
Particle + Energy Flow
CLIC



arXiv:1209.4039

Outlook

- Pandora is an excellent starting tool, but needs significant re-thinking to operate under BIB environment
- Physics goal for in $\sqrt{s} = 10\ TeV\ \mu\mu$ collider: Study of 4-5 TeV W / Z / H
  - *Boosted topology → narrow, overlapping jets → challenging environment for any particle flow algorithm*
- Optimal performance comes from combining efforts across many fronts



Backup

Pandora: Links to Code

- Event preparation:
    - Track selection (code)
    - Calorimeter hit selection (code)
- Clustering:
    - Fast photon clustering and ID (code)
    - Cone clustering (code)
    - Topological cluster merging (code)
    - Reclustering (code)
    - Photon recovery (code)
    - Fragment Removal (code)
- PFO Identification:
    - Electrons (code)
    - Photons (code)
    - Muons (code)
- Rough instructions for local installation of Pandora (link)

Disclaimer: I don’t claim to have carefully read all of this code.

Topological Cluster Merging Algorithms

i) Looping track segments (code)

ii) Track segments with gaps (code)

iii, iv) Track segments pointing to hadronic showers

- (code1, code2, code3, code4)

v) Back-scattered tracks from hadronic showers (code1, code2)

vi, vii) Neutral clusters nearby a charged shower (code)

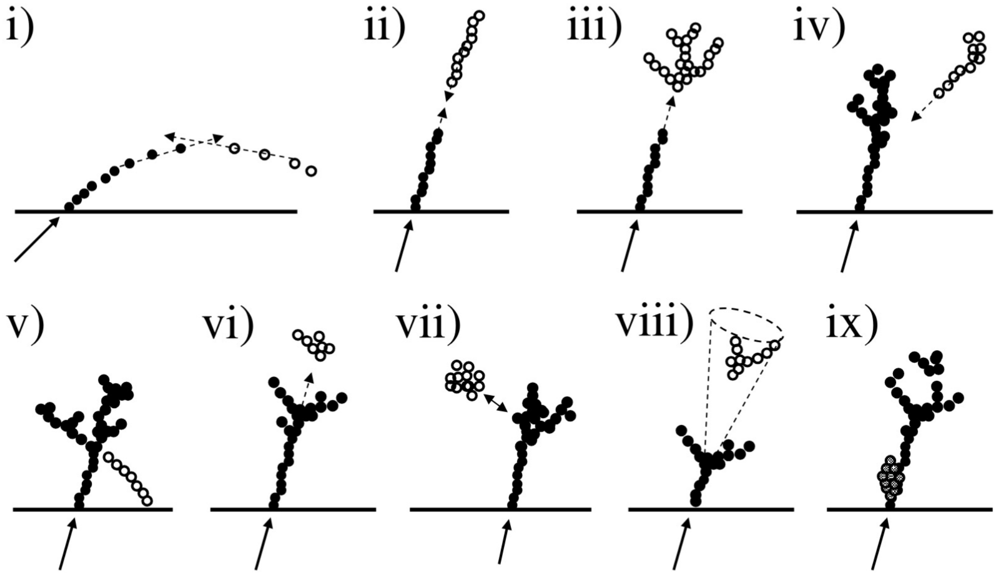
viii) Cone association (code)

ix) Recovery of photons which overlap with track segment (code)

Not all should occur in MAIA or MUSIC!

- E.g., no looping tracks in MAIA

Topology-based cluster merging



arXiv:0907.3577

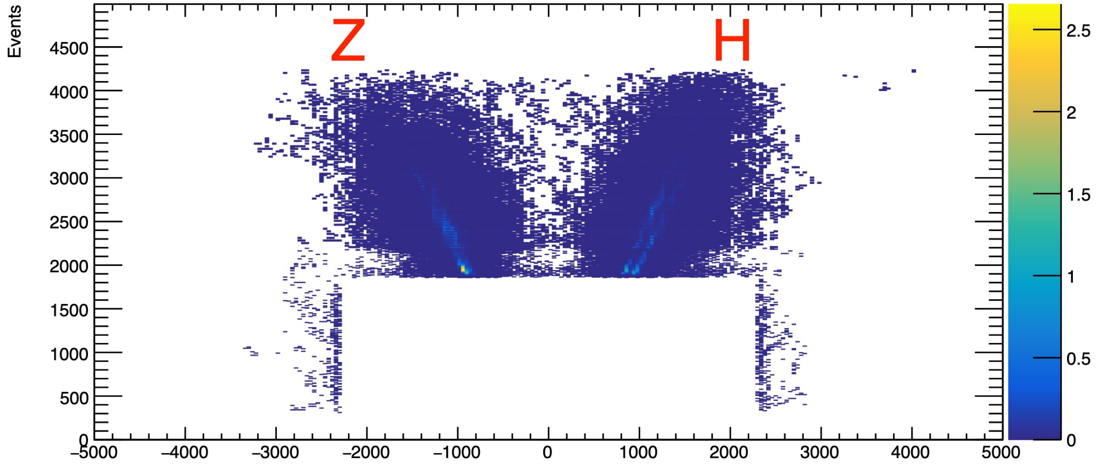
Arrows: Tracks
Filled dots: Hits in charged cluster
Open dots: Hits in neutral cluster

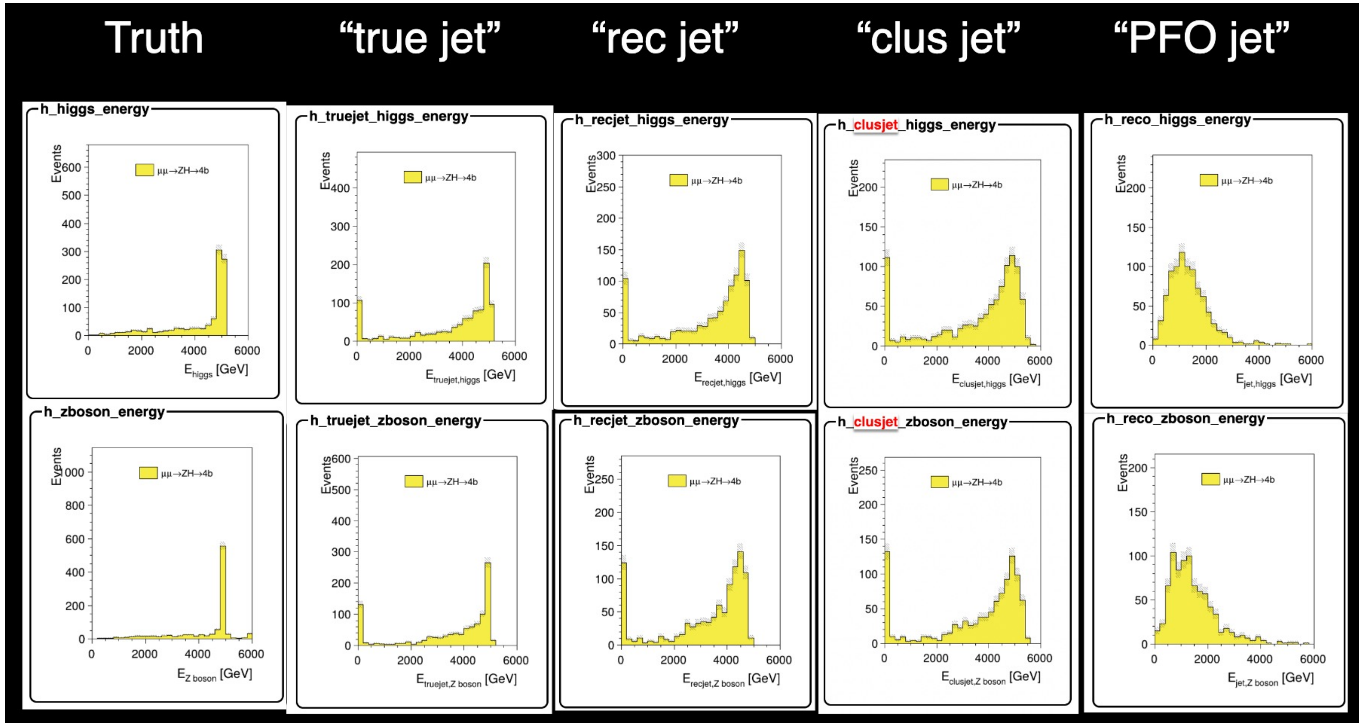
Disclaimer: I don't claim to have carefully read all of this code.

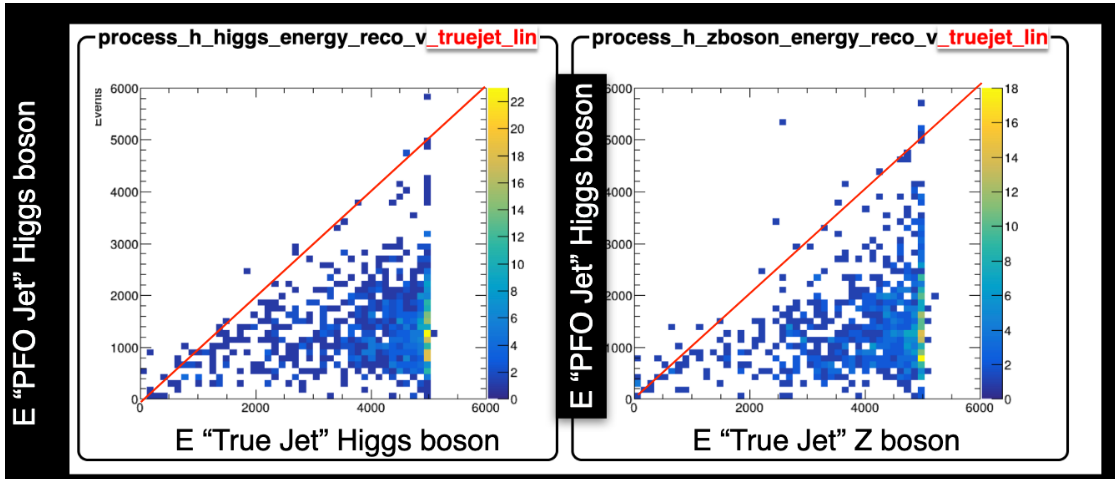
Philip Chang

Example of Confusion: MAIA

- $\sqrt{s}$ = 10 TeV $\mu^-\mu^+ \rightarrow ZH \rightarrow 4b$
- "True Jet": Sum status = 1 particles within ΔR < 0.8 of H / Z
- "Rec Jet": Sum of calorimeter hits within ΔR < 0.8 of H / Z
- "Clus jet": Sum of Pandora clusters within ΔR < 0.8 of H / Z
- "PFO jet": Sum of Pandora PFOs within ΔR < 0.8 of H / Z
- ***Clear demonstration of Particle Flow confusion in our environment***







High Momentum Tracking

- Particle flow relies on precise tracking measurement
- But tracking resolution decreases as a function of energy
- MAIA: With BIB, ECal (HCal) precision surpasses tracking at ~ 400 GeV (3.4 TeV)
- *Does it make sense to always use the track as the measurement for charged PFOs? Other options?*

* Potential μC study