# Particle Flow Reconstruction – Status and Challenges

Gregory Penn
Yale University

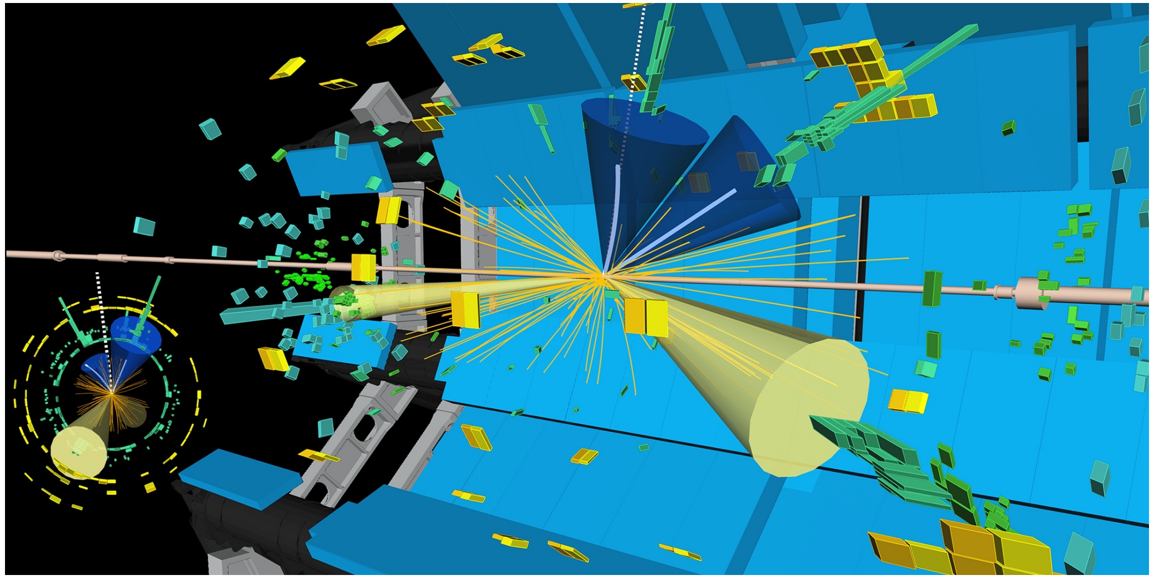
# What is Particle Flow?

- Particle flow is a strategy for event reconstruction where all stable particles are individually identified and measured

# What is Particle Flow?

- Particle flow is a strategy for event reconstruction where all stable particles are individually identified and measured

think less like...

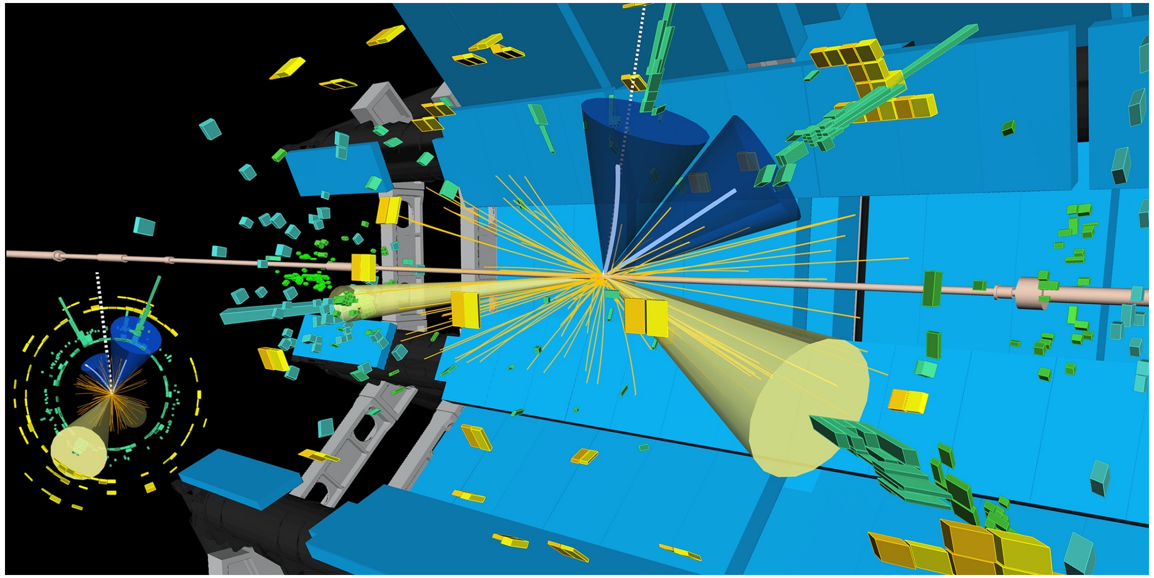


objects : detector - level information

# What is Particle Flow?

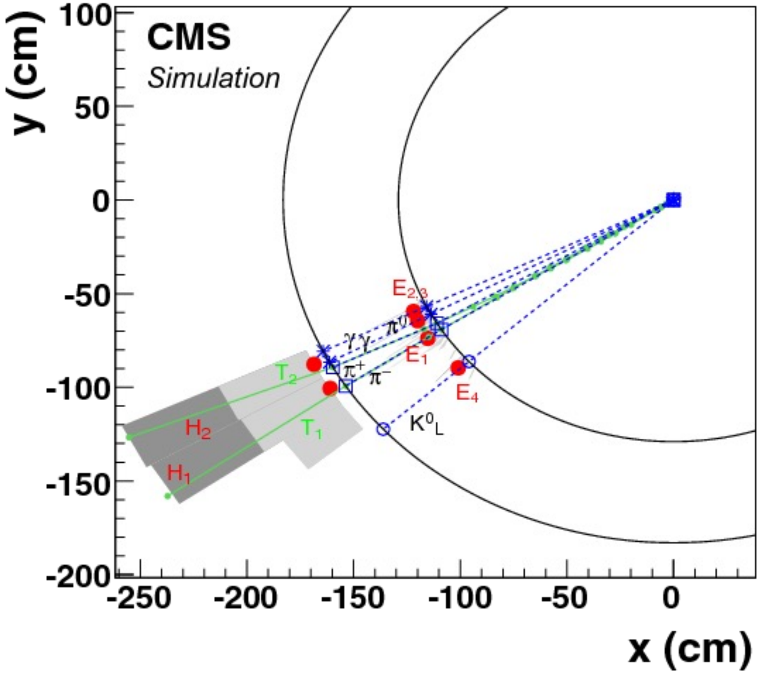
- Particle flow is a strategy for event reconstruction where all stable particles are individually identified and measured

think less like...



objects : detector-level information

more like...




objects : list of reconstructed stable particles and their properties

# Why do Particle Flow?

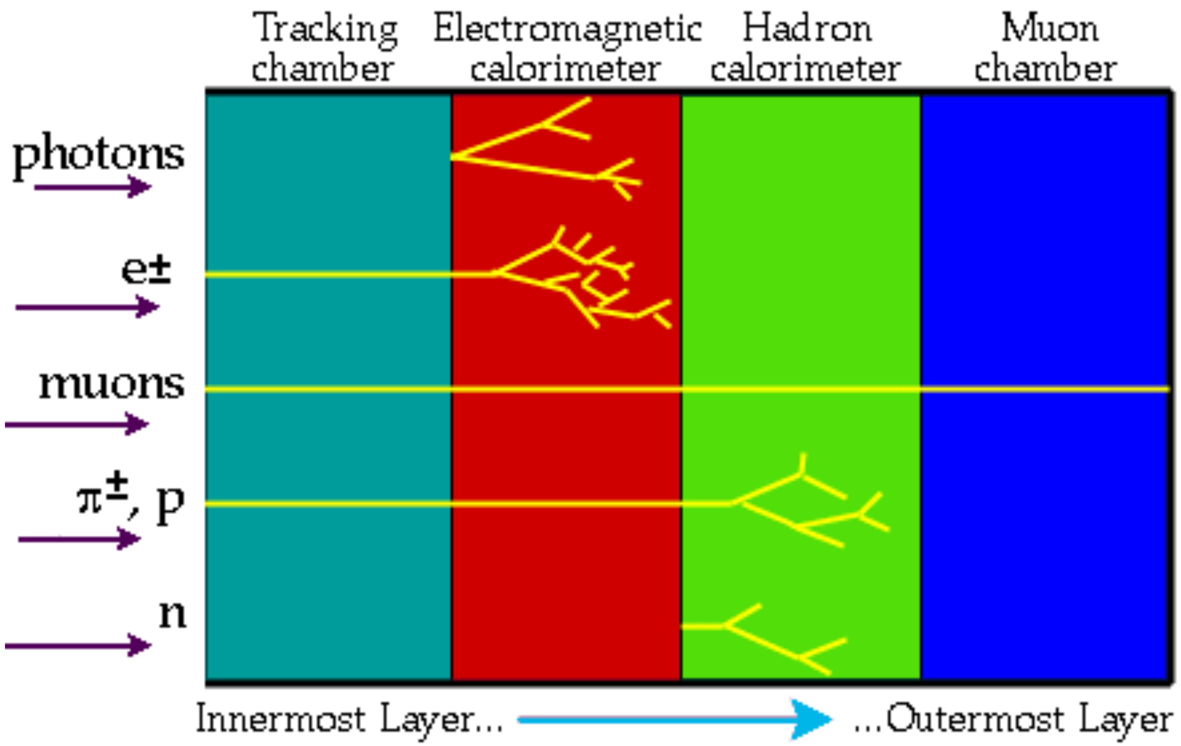
- **Pros:**
  - A list of particles is closer to the collision than a list of detector-level information
  - Leads to a more precise measurement:
    - Use the best sub-detector to perform a measurement
      - Example: Use the tracker to measure low-energy electrons
    - Calibration of individual particles according to their ID
  - Some analyses require a particle flow approach → enables new measurements!

# Why do Particle Flow?

- **Pros:**
  - A list of particles is closer to the collision than a list of detector-level information
  - Leads to a more precise measurement:
    - Use the best sub-detector to perform a measurement
      - Example: Use the tracker to measure low-energy electrons
    - Calibration of individual particles according to their ID
  - Some analyses require a particle flow approach → enables new measurements!
- **Cons:** It is hard.
  - The reconstruction software becomes complicated
  - *It requires our detectors to be designed with Particle Flow in mind*

# Detector Design for Particle Flow

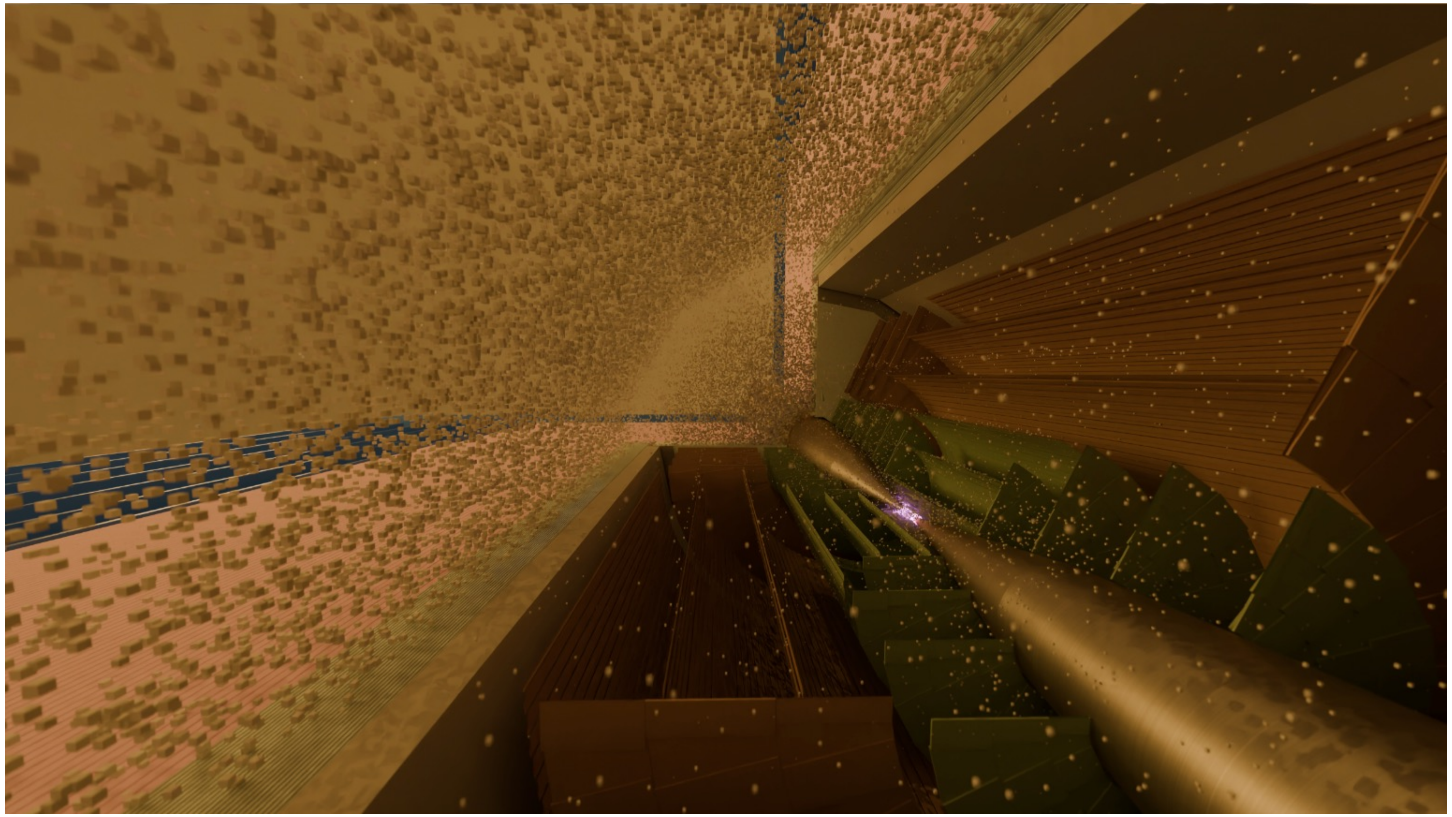
- Most important: The ability to follow a particle through the detector




high granularity detectors + high B-field → spatially separated particles → high performance Particle Flow

# Detector Design for Particle Flow

- Most important: The ability to follow a particle through the detector



Question for us: How can we write Particle Flow in a BIB environment?

Strategies for answering this today

# The Pandora Particle Flow Algorithm

- Particle flow algorithm designed for a linear $e^+e^-$ collider (ILC)
- It reads and accounts for detector geometry → it is *flexible*!

In a nutshell:

## Event Preparation

- Track selection
- Hit preparation

## Clustering

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

## Particle Flow Object Creation

Set of basic ID algorithms

# The Pandora Particle Flow Algorithm

- Particle flow algorithm designed for a linear $e^+e^-$ collider (ILC)
- It reads and accounts for detector geometry → it is *flexible*!

Resources

(ask me too!)

arXiv:0907.3577

## Particle Flow Calorimetry and the PandoraPFA Algorithm

M. A. Thomson

*Cavendish Laboratory, JJ Thomson Avenue, Cambridge CB3 0HE, United Kingdom.*

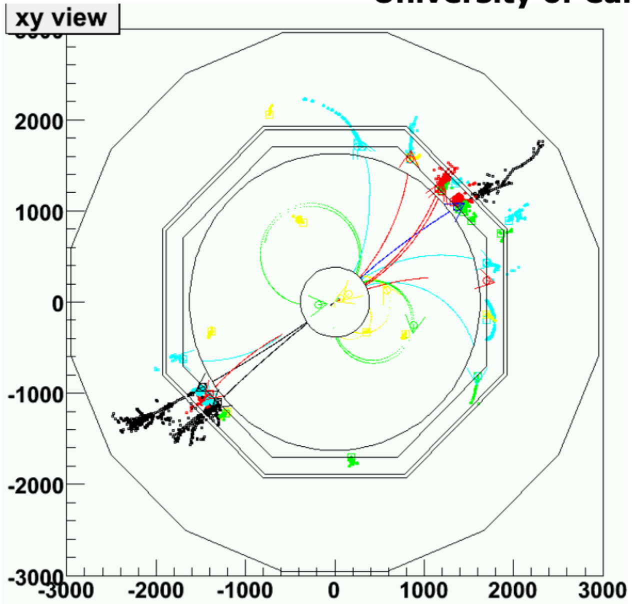
**Abstract**

The Particle Flow (PFlow) approach to calorimetry promises to deliver unprecedented jet energy resolution for experiments at future high energy colliders such as the proposed International Linear Collider (ILC). This paper describes the PandoraPFA particle flow algorithm which is then used to perform the first systematic study of the potential of high granularity PFlow calorimetry. For simulated events in the ILD detector concept, a jet energy resolution of $\sigma_E/E \lesssim 3.8\,\%$ is achieved for 40 – 400 GeV jets. This result, which demonstrates that high granularity PFlow calorimetry can meet the challenging ILC jet energy resolution goals, does not depend strongly on the details of the Monte Carlo modelling of hadronic showers. The PandoraPFA algorithm is also used to investigate the general features of a collider detector optimised for high granularity PFlow calorimetry. Finally, a first study of the potential of high granularity PFlow calorimetry at a multi-TeV lepton collider, such as CLIC, is presented.

*Key words:* Particle Flow Calorimetry, Calorimetry, ILC
*PACS:* 07.05.Kf, 29.40.Vj.+c

## A Topologic Approach to Particle Flow "PandoraPFA"

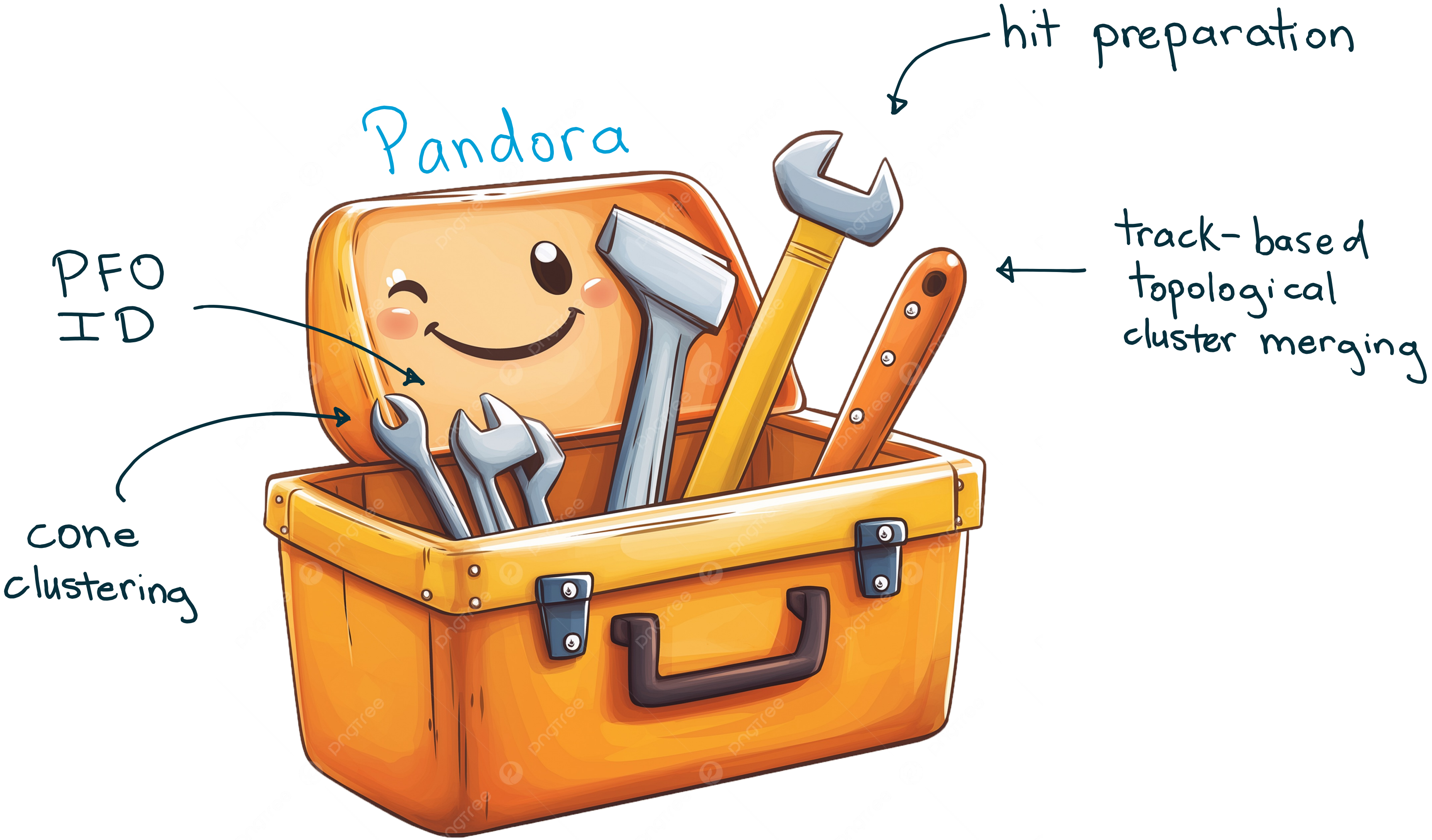
**Mark Thomson**
**University of Cambridge**




**This Talk:**

- ★ Philosophy
- ★ The Algorithm
- ★ Some First Results
- ★ Conclusions/Outlook

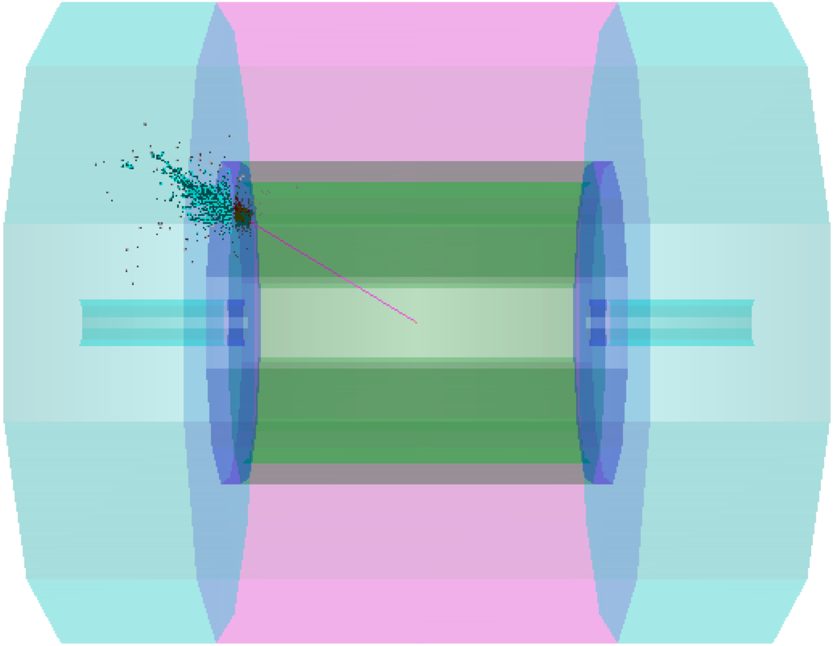
# Strategy: View Pandora as a toolbox!



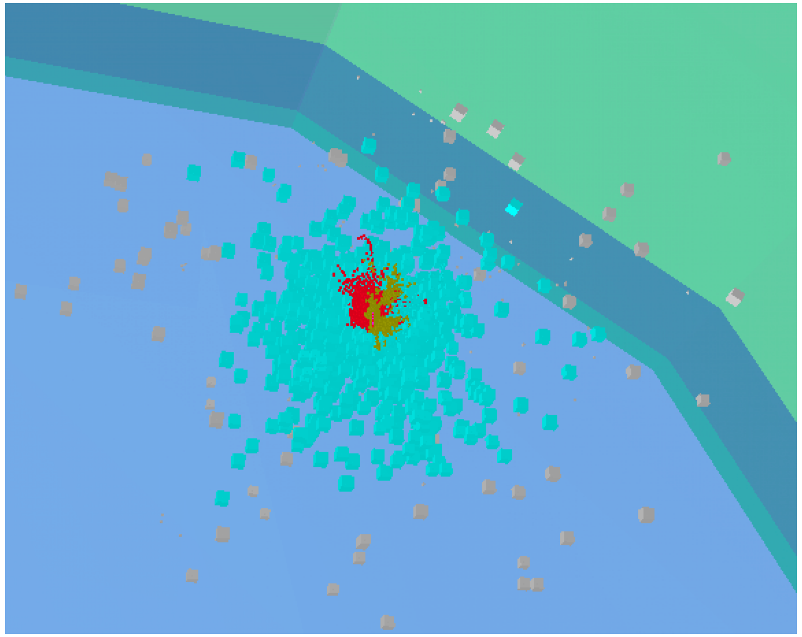
# Some extra tools

1. Installing Pandora locally
   - Generally not required
   - Instructions here
   - **Advantage:** Finding bugs
2. Event displays (PandoraMonitoring)
   - Installation may be required (similar to above instructions)
   - **Advantage:** Visual understanding of events that have "gone wrong"

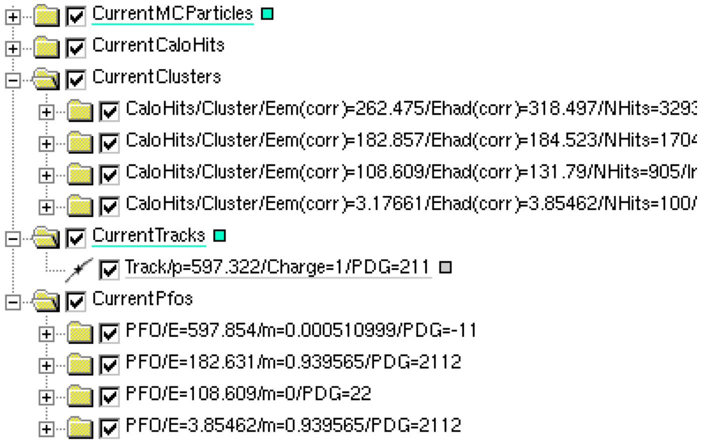
Single $\pi^+$: $E \sim 600$ GeV



View from origin



List of PFOs (mis-ID'd as $e^+$!)



# Build-a-Particle-Flow, MAIA

- **Foresight / from experience**: Difficult to interpret inefficiencies or poor resolution when running all of Pandora
  - *Particularly with BIB*
- **Goal:** Construct a Particle Flow algorithm by stacking sub-algorithms
  - Easier to debug
  - Easier to interpret
  - Reconstruction runs (~3x) faster
- Next few slides: $\pi^{\pm}$ gun in MAIA detector
  - 5 GeV < $E^{\pi}$ < 1 TeV
  - Restricted to central barrel region: 1 rad < $\theta$ < 2 rad
- Create the algorithm w/o BIB
  - Future: Test w/ BIB

# "Minimal Pandora", MAIA

**Track Selection** + **Hit Preparation** + **Cone Clustering** + **PFO Identification**

**Track Selection**

- consistency requirements
- $\frac{\sigma(p)}{p} < 0.15$

**Hit Preparation**

- define isolated hits

**Cone Clustering**

- main clustering algorithm

**PFO Identification**

- track-cluster matching
- basic ID algorithms

# "Minimal Pandora", MAIA

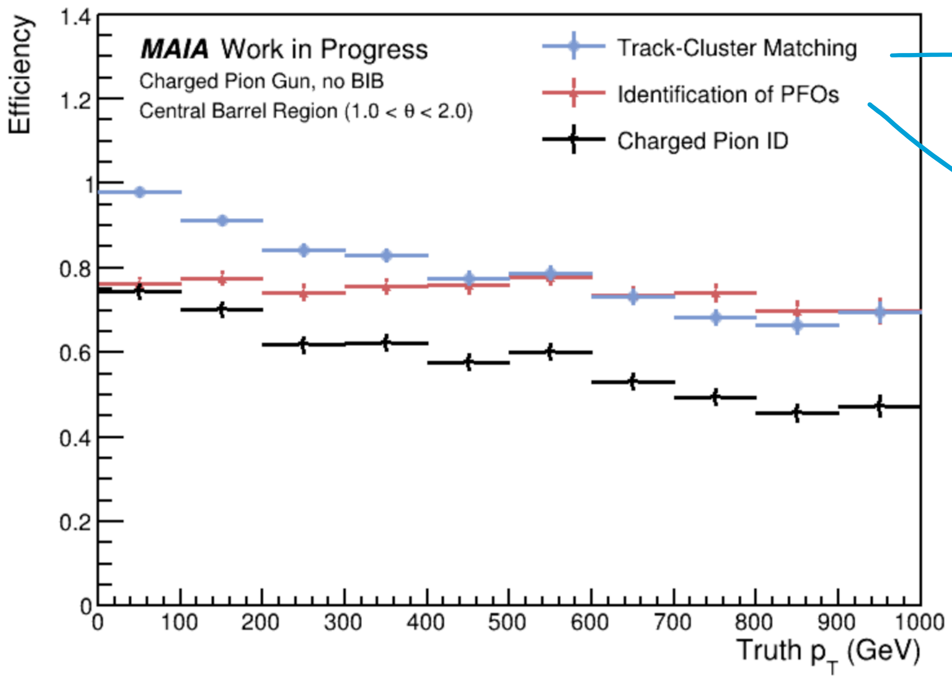
**Track Selection** + **Hit Preparation** + **Cone Clustering** + **PFO Identification**

**Track Selection**
- consistency requirements
- $\frac{\sigma(p)}{p} < 0.15$

**Hit Preparation**
- define isolated hits

**Cone Clustering**
- main clustering algorithm

**PFO Identification**
- track-cluster matching
- basic ID algorithms




Track-Cluster Matching → what fraction of events contain a charged particle?

Identification of PFOs → what fraction of reconstructed charged particles are identified as a $\pi^{\pm}$?

# "Minimal Pandora", MAIA

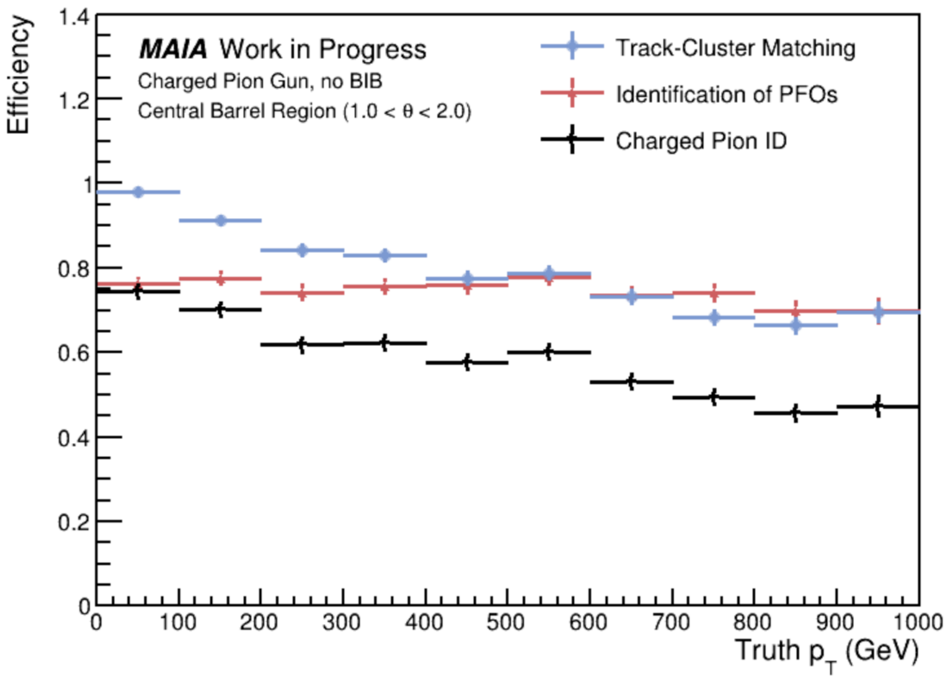
**Track Selection** + **Hit Preparation** + **Cone Clustering** + **PFO Identification**

**Track Selection**
- consistency requirements
- $\frac{\sigma(p)}{p} < 0.15$

**Hit Preparation**
- define isolated hits

**Cone Clustering**
- main clustering algorithm

**PFO Identification**
- track-cluster matching
- basic ID algorithms




does not match tracks to clusters or identify them as $\pi^{\pm}$'s well

# “Minimal Pandora”, MAIA

**Track Selection** + **Hit Preparation** + **Cone Clustering** + **PFO Identification**

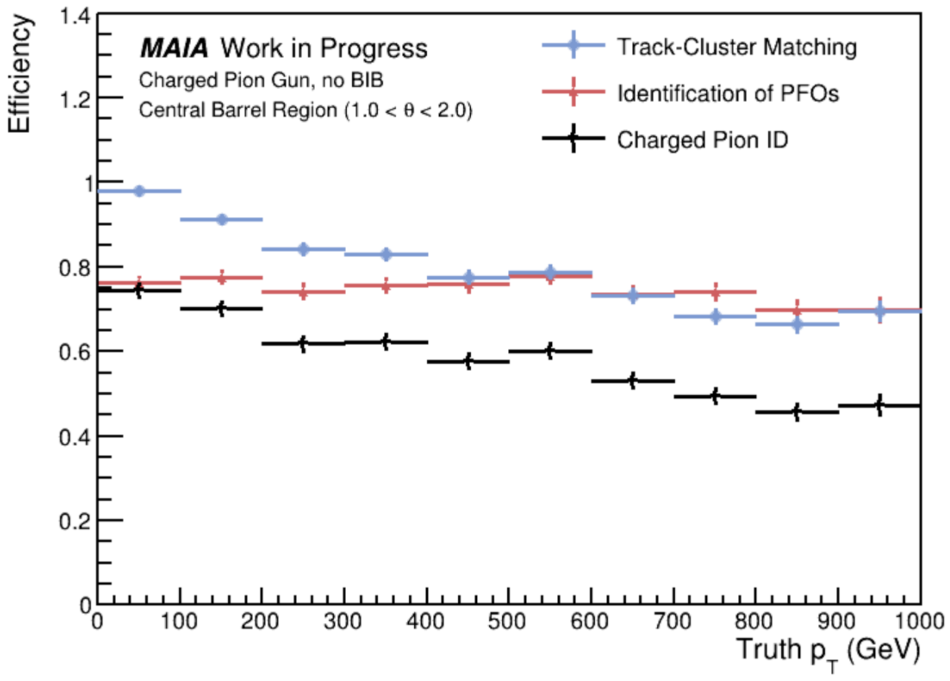
**Track Selection**
- consistency requirements
- $\frac{\sigma(p)}{p} < 0.15$

**Hit Preparation**
- define isolated hits

**Cone Clustering**
- main clustering algorithm

**PFO Identification**
- track-cluster matching
- basic ID algorithms

but easy to identify track selection as the culprit!




does not match tracks to clusters or identify them as $\pi^{\pm}$'s well

# "Minimal Pandora", MAIA

Track Selection + Hit Preparation + Cone Clustering + PFO Identification

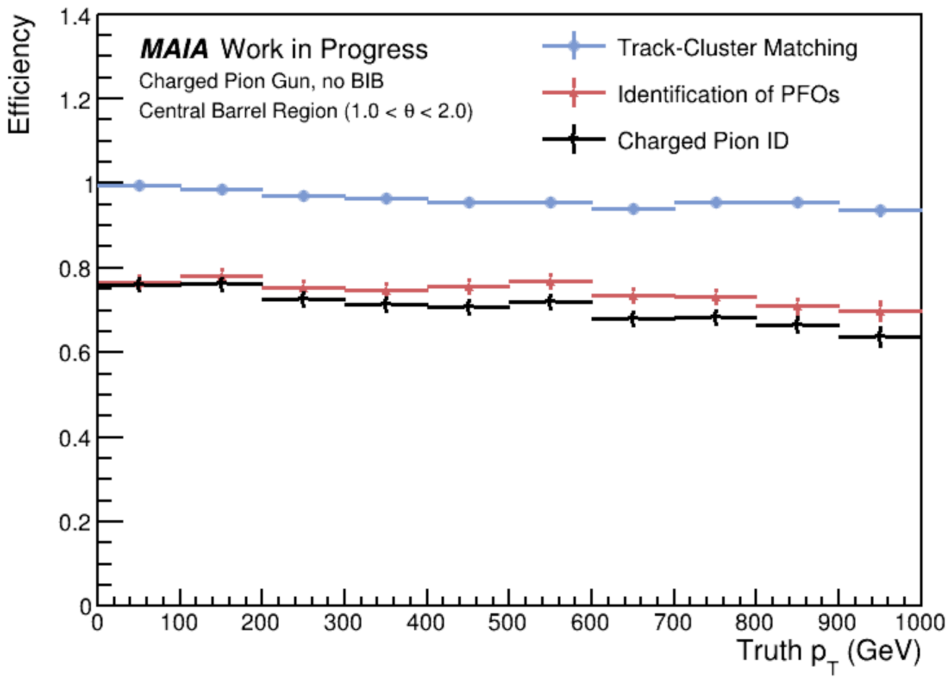
**Track Selection**
- consistency requirements
- $\frac{\sigma(p)}{p} <$ ~~0.15~~ → 0.30

**Hit Preparation**
- define isolated hits

**Cone Clustering**
- main clustering algorithm

**PFO Identification**
- track-cluster matching
- basic ID algorithms

but easy to identify track selection as the culprit!




still clustering challenges
↓
degrades PFO ID efficiency
↓
add another tool

# "Track-Driven, Minimal Pandora", MAIA

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

**Track Selection**
- consistency requirements
- $\frac{\sigma(p)}{p} < \sout{0.15} \rightarrow 0.30$

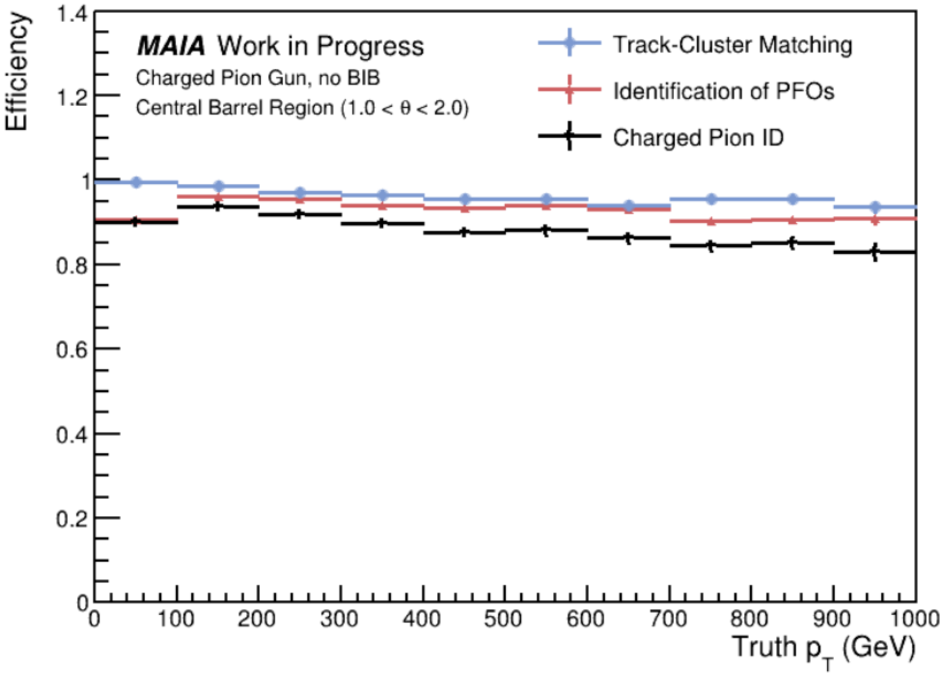
**Hit Preparation**
- define isolated hits

**Cone Clustering**
- main clustering algorithm

**Resolve Track Associations**
- topology-based algorithm
- reclusters so that $p_T^{track}$ compatible with $E^{cluster}$

**PFO Identification**
- track-cluster matching
- basic ID algorithms

reconstruction efficiency ~ 90%



# "Track-Driven, Minimal Pandora", MAIA

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

**Track Selection**
- consistency requirements
- $\frac{\sigma(p)}{p} < \sout{0.15} \rightarrow 0.30$

**Hit Preparation**
- define isolated hits

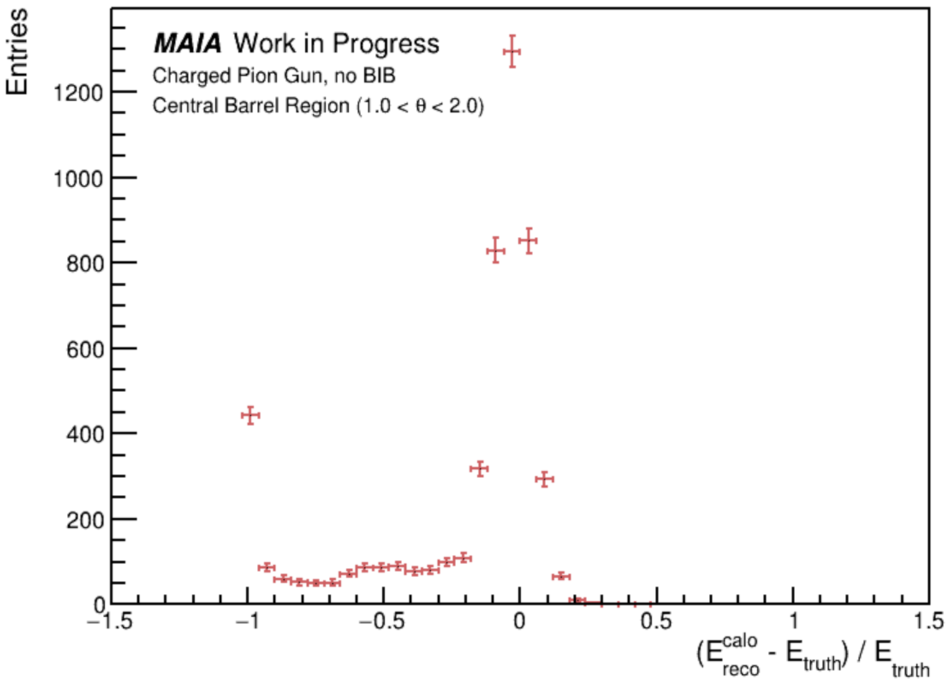
**Cone Clustering**
- main clustering algorithm

**Resolve Track Associations**
- topology-based algorithm
- reclusters so that $p_T^{track}$ compatible with $E^{cluster}$

**PFO Identification**
- track-cluster matching
- basic ID algorithms

Energy resolution looks OK

Peak @ low reco E: more work to do.



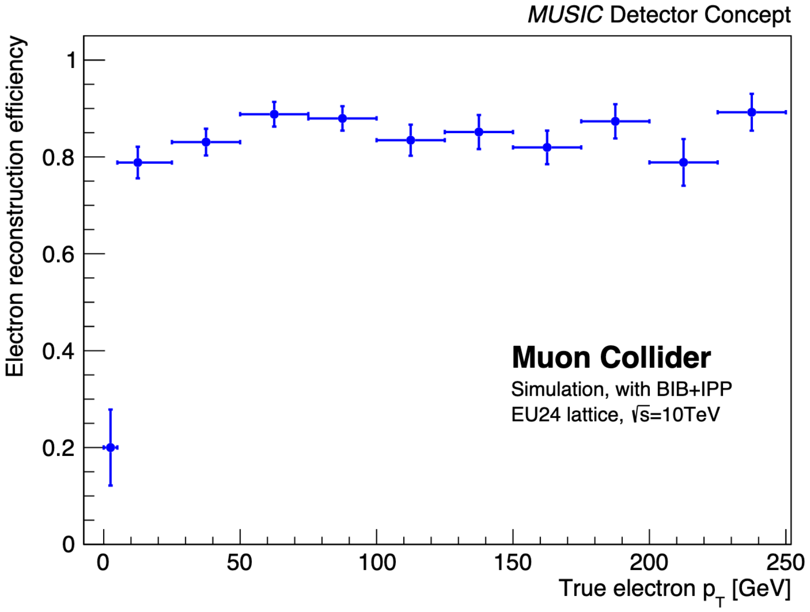
# Build-a-Particle-Flow, MUSIC

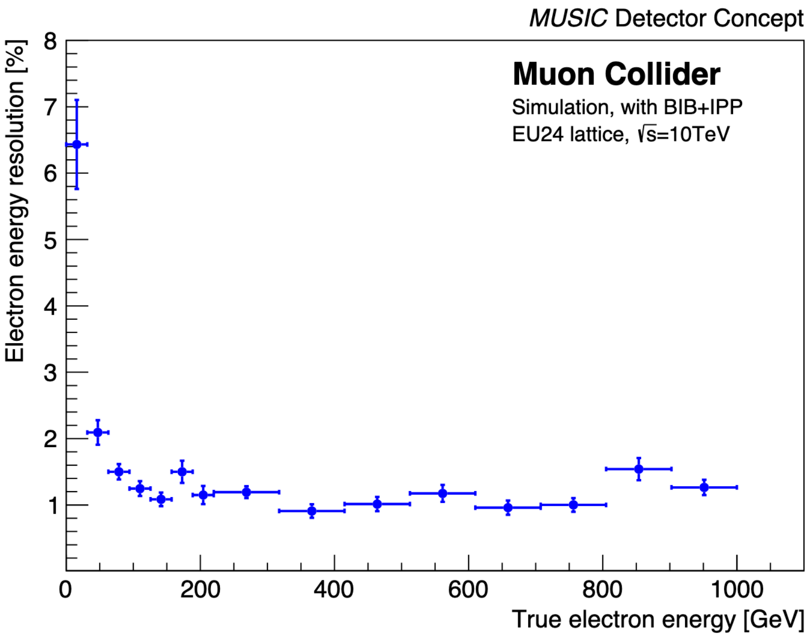
- “Minimal Pandora” constructed for electrons (slides):

Hit Preparation + Cone Clustering + PFO Creation

- define isolated hits
- main clustering algorithm
- track- cluster matching

- Optimize:
  - Definition of isolated hits → BIB rejection
  - Geometrical search parameters for Cone Clustering
  - Identify an electron as a charged PFO with center of mass in ECal



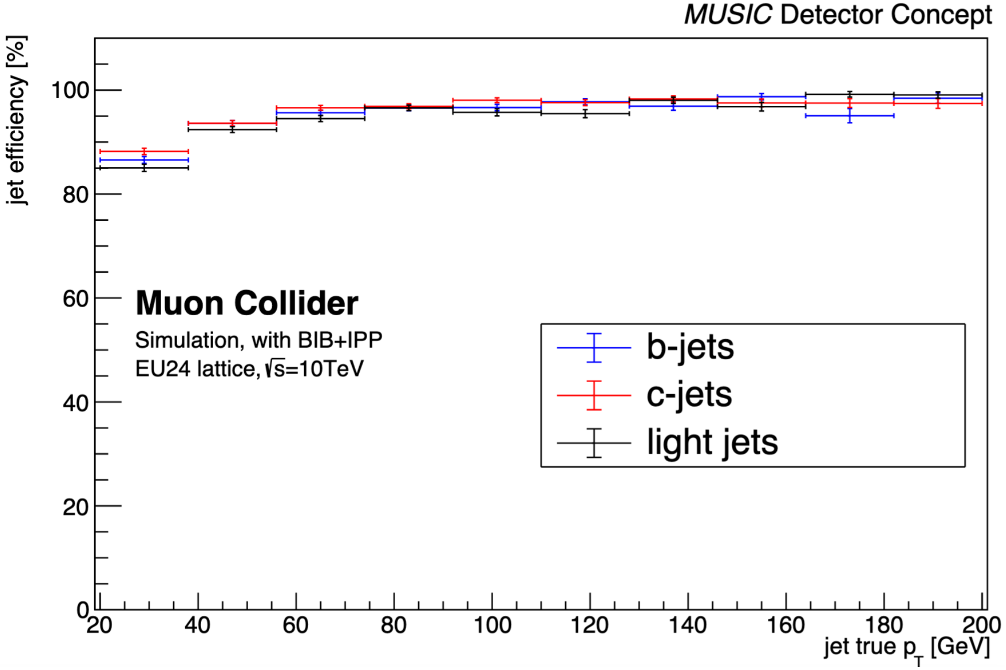




Signs of success for this strategy in a BIB environment!

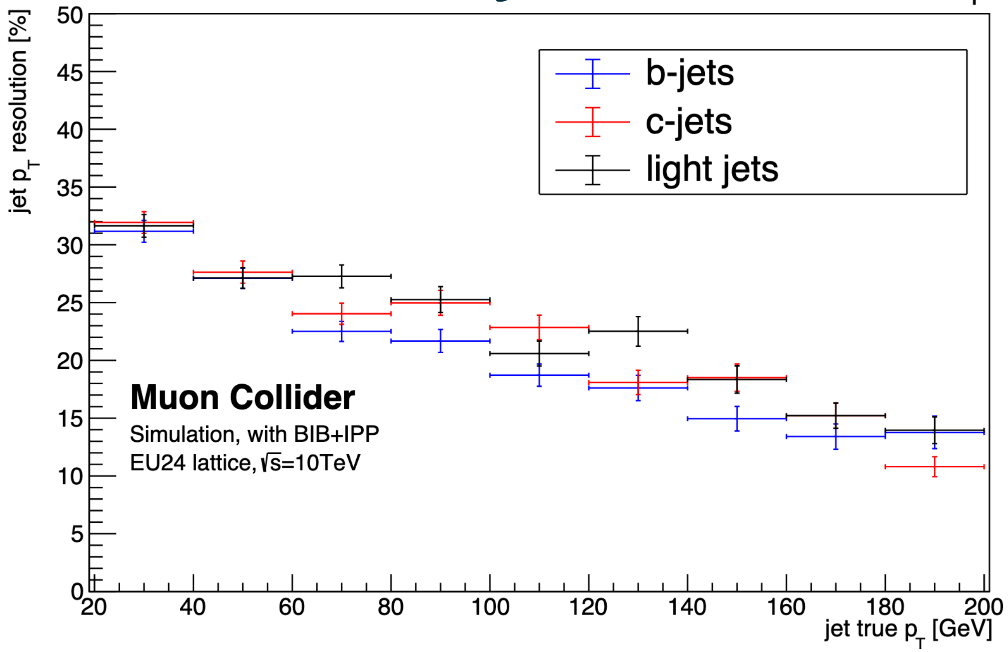
# Build-a-Particle-Flow, MUSIC

- Run *all* of Pandora for jets (slides):
  - "Full Pandora"
  - Jet clustering
  - Fake jet removal
  - Jet direction correction
  - Jet $p_T$ correction
  - Secondary vertex reconstruction
  - Jet tagging

Robust studies with "Full Pandora" demonstrates challenge of jet reconstruction with BIB




(60°< θ < 120°)



# Outlook

- High flux of BIB poses a challenge for particle flow algorithms
  - Jets w/ BIB is challenging
- Creating *simple, interpretable* particle flow algorithms as a test is crucial for developing understanding
  - What works? What doesn't?
- Plenty of ongoing work show promise for this approach:
  - Examples: $e^-$, $\pi^\pm$ reconstruction with simple versions of Pandora

Thanks!