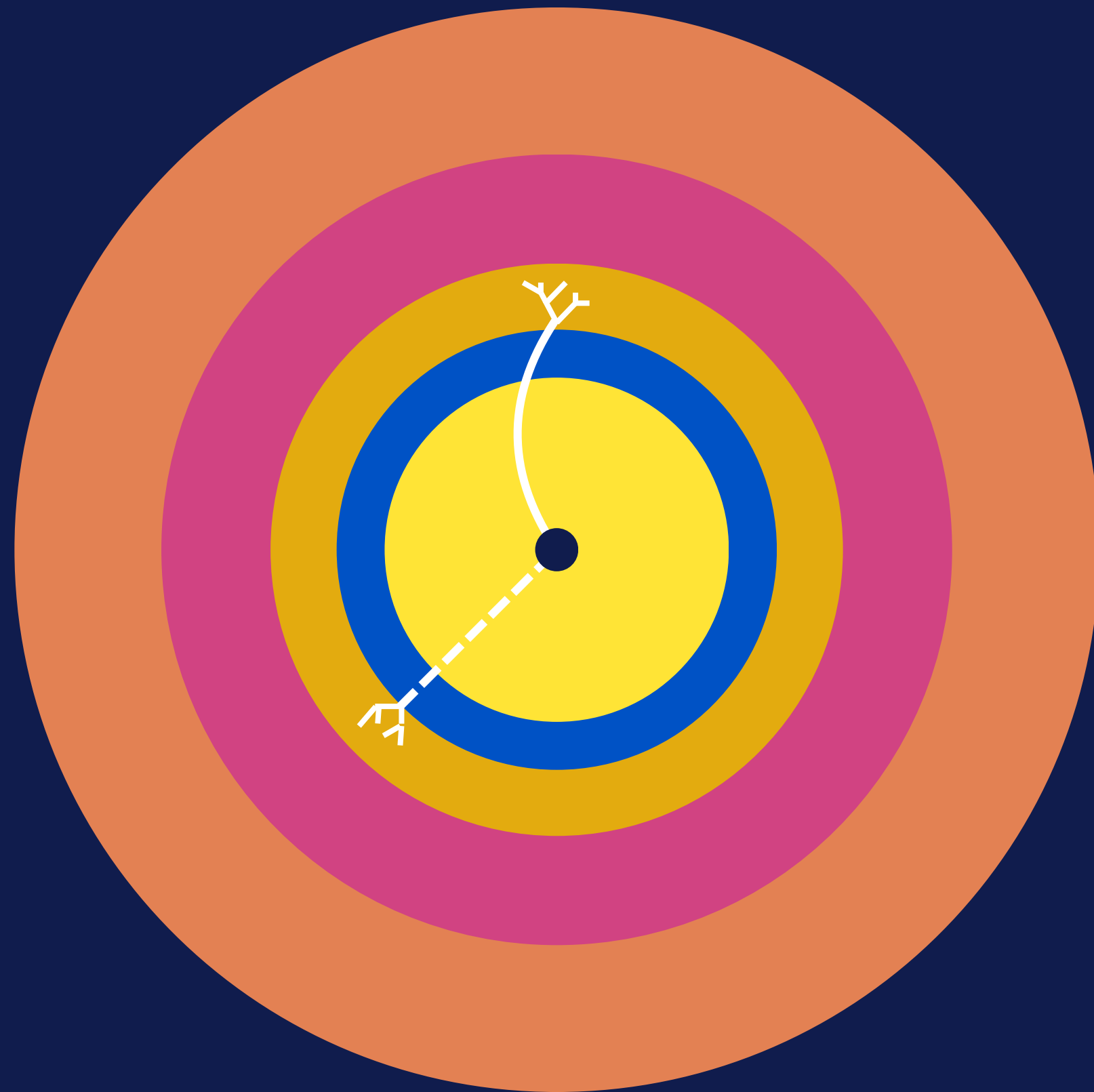


Electromagnetic Object Reconstruction In MAIA

Developing a software
environment for a 10 TeV
Muon Collider

Aidan Gardner-O'Kearny, Jullian Watts
On behalf of the MAIA Collaboration



Overview

Part I

- Motivation
- Challenges
- MAIA
- Historical Overview
- Pandora
- How does this work?
- Does this work?
- The MAIA solenoid
- Conclusions and next steps

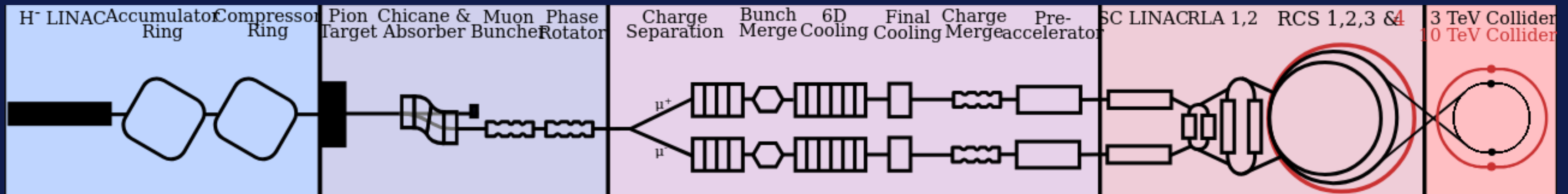
Part II

- Base electron reconstruction efficiency
- Calibration
- Electron PFOs
- Electron and pion discrimination
- Improved electron reconstruction efficiency
- Conclusions and next steps

Part I

Why A Muon Collider?

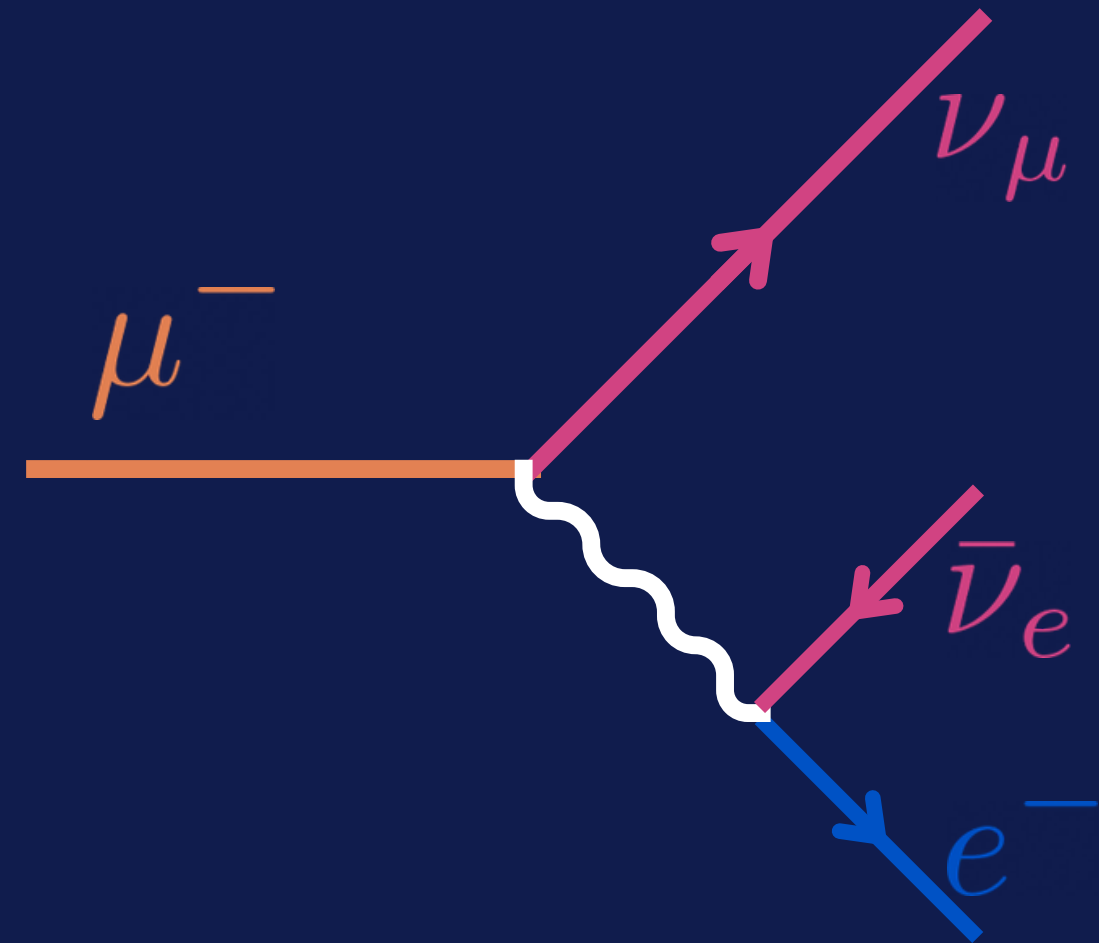
- New physics is *somewhere*
- Maybe not at LHC
- Want an energy-frontier candidate
- Also want to be able to do precision physics
- The muon collider is the only machine capable of both
- It's also a compact machine, similar in size to Fermilab campus



Credit: R. Taylor

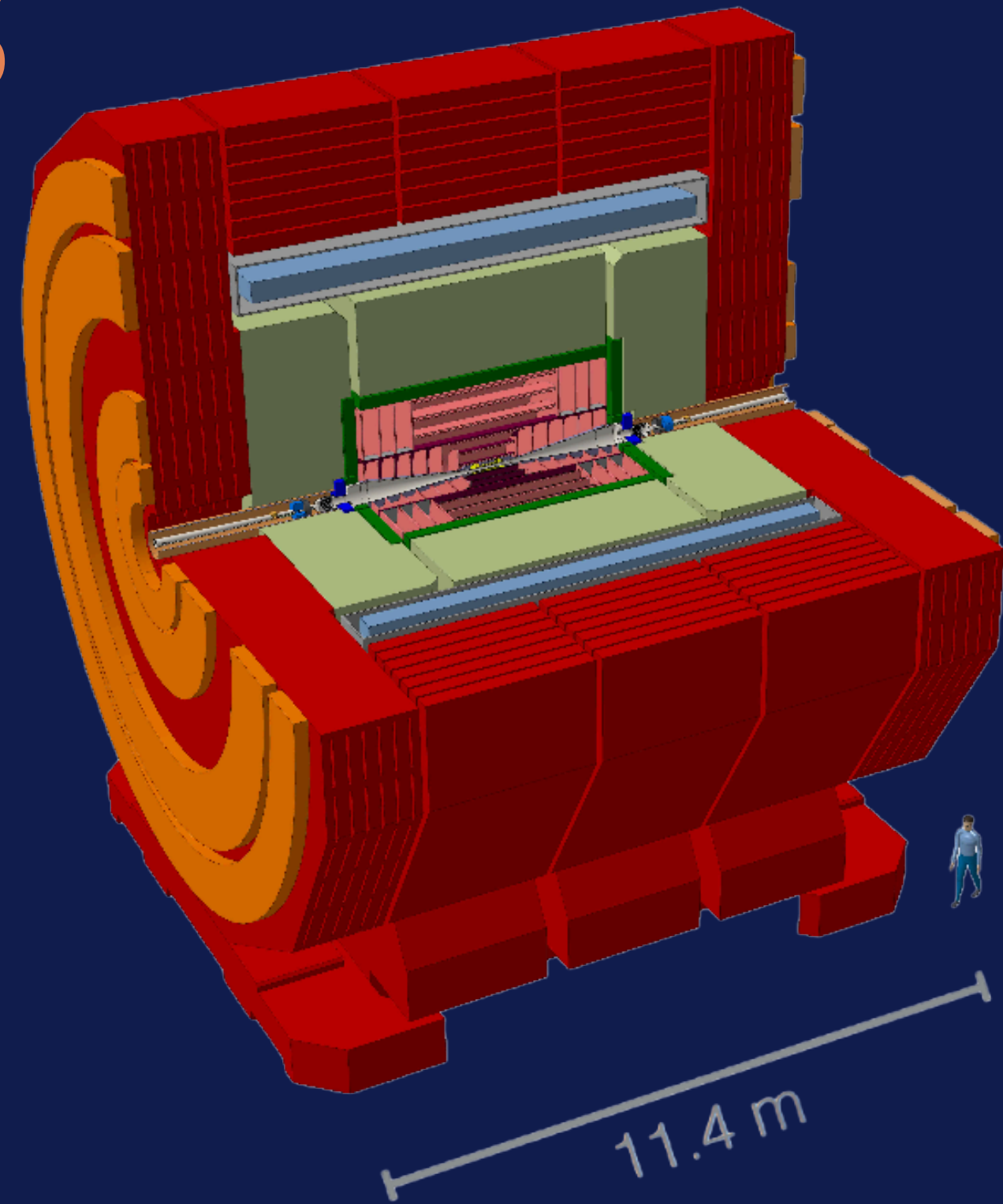
Okay, What's The Catch?

- “If something sounds too good to be true, it probably is”
- There are several significant challenges
 - Mainly derived from **muon** lifetime
 - Long due to highly virtual W, but still only $2\ \mu\text{s}$
- How do you get a beam of muons?
 - Not easy!
- How does a detector environment deal with a bath of high energy decay products?
 - Also non-trivial!



A Starting Point For Experimentalists

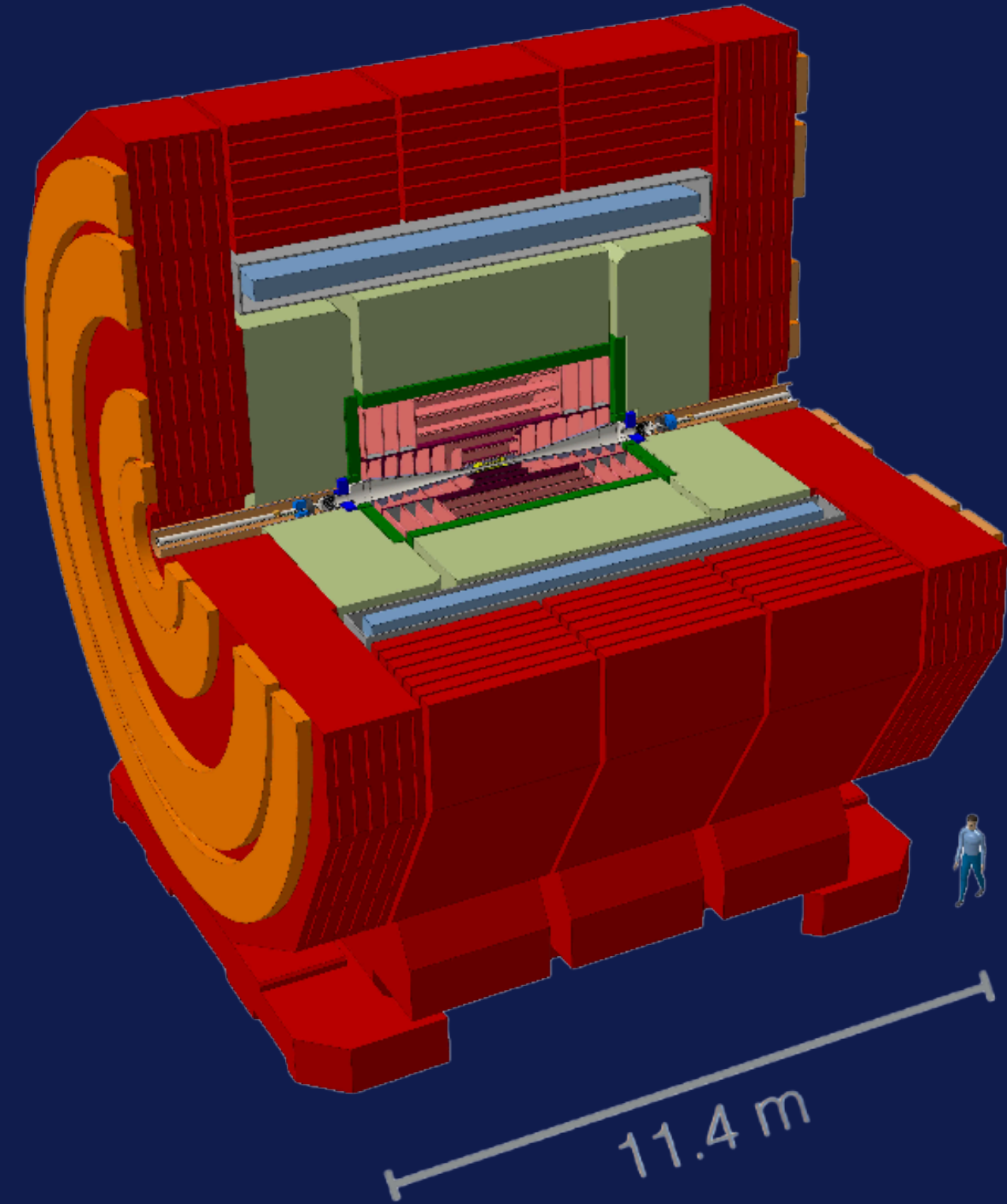
- Designing a detector is hard!
 - Many choices to make
 - Lots of things to consider and then optimize
- It can be helpful to have a starting place
- For us that was the CLIC detector



Credit: CLIC

MAIA, Some Historical Context

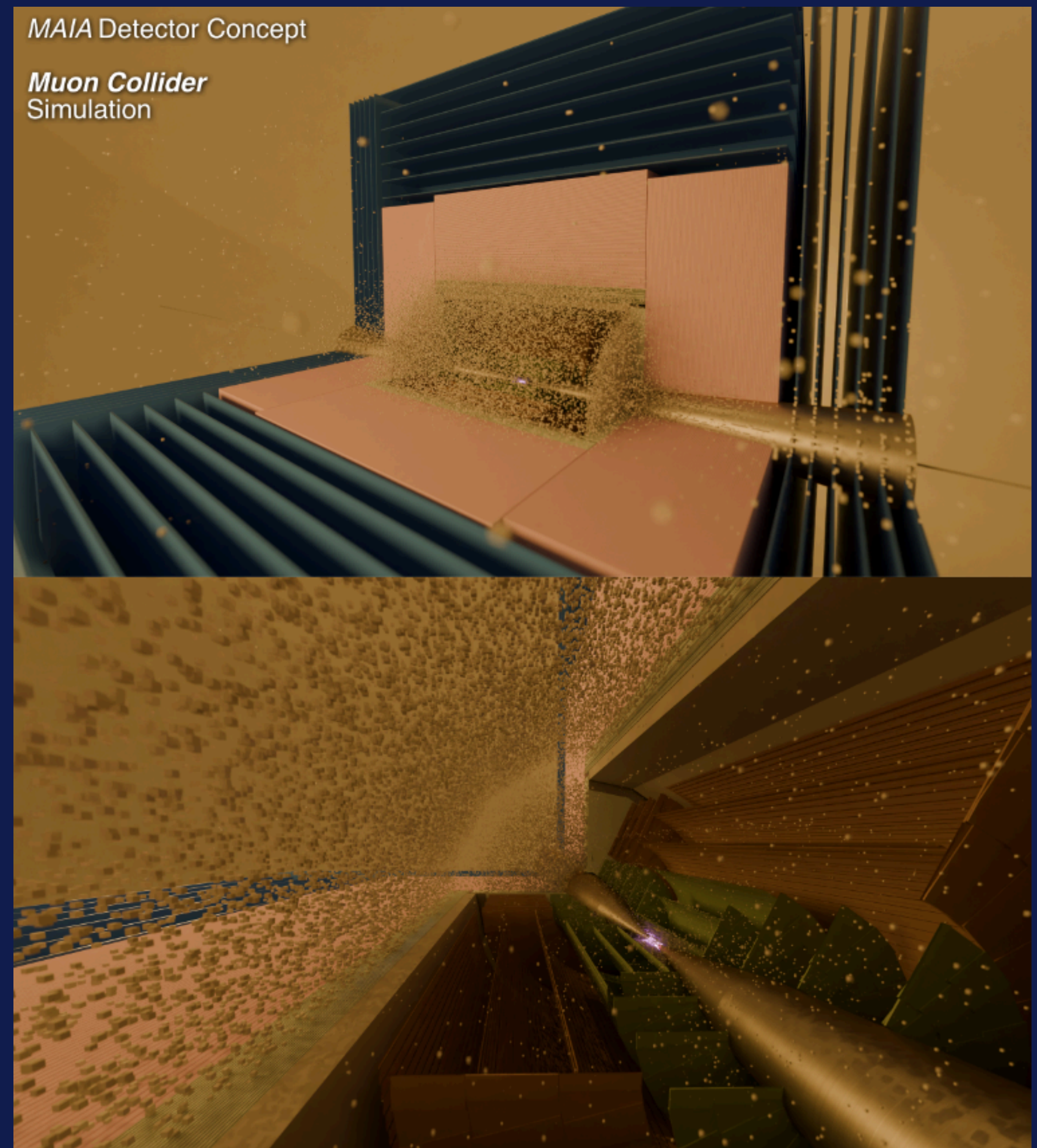
- CLIC detector
 - Optimized for lepton collider
- MAIA (3 TeV)
 - Take the CLIC geometry exactly as our starting point
- MAIA (10 TeV)
 - Larger energy scale → Larger detector
 - Everything got scaled up proportionally
- Took software directly from CLIC along the way
 - Necessitates validation of everything!



Credit: CLIC

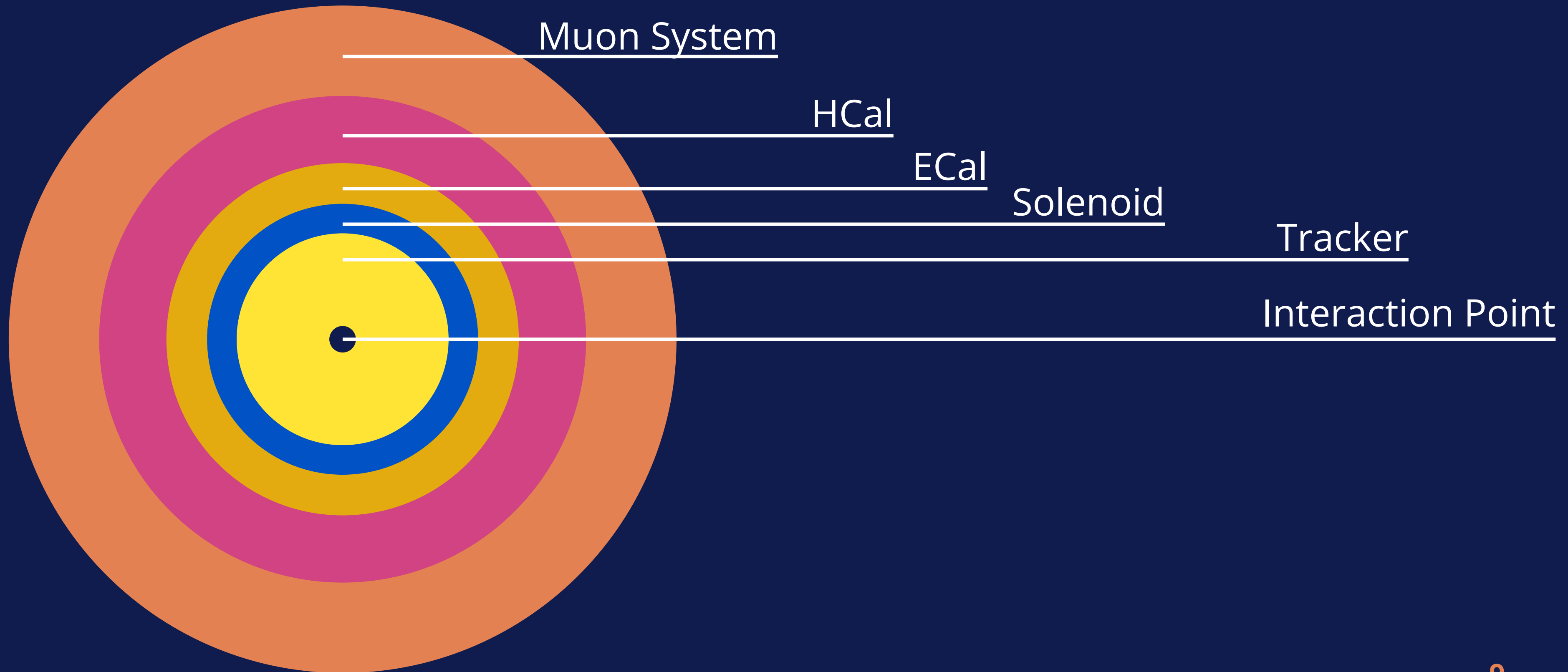
MAIA, Now

- Muon Accelerated Instrumented Apparatus
- One of the main detector concepts for a 10 TeV muon collider
 - Based off of CLIC detector design
- An “ATLAS-like” detector
 - Solenoid inside the calorimeters
- Active development community
 - New paper pushed to arXiv as of July 8th, 2026
 - O(30) members, many undergrads and early grads

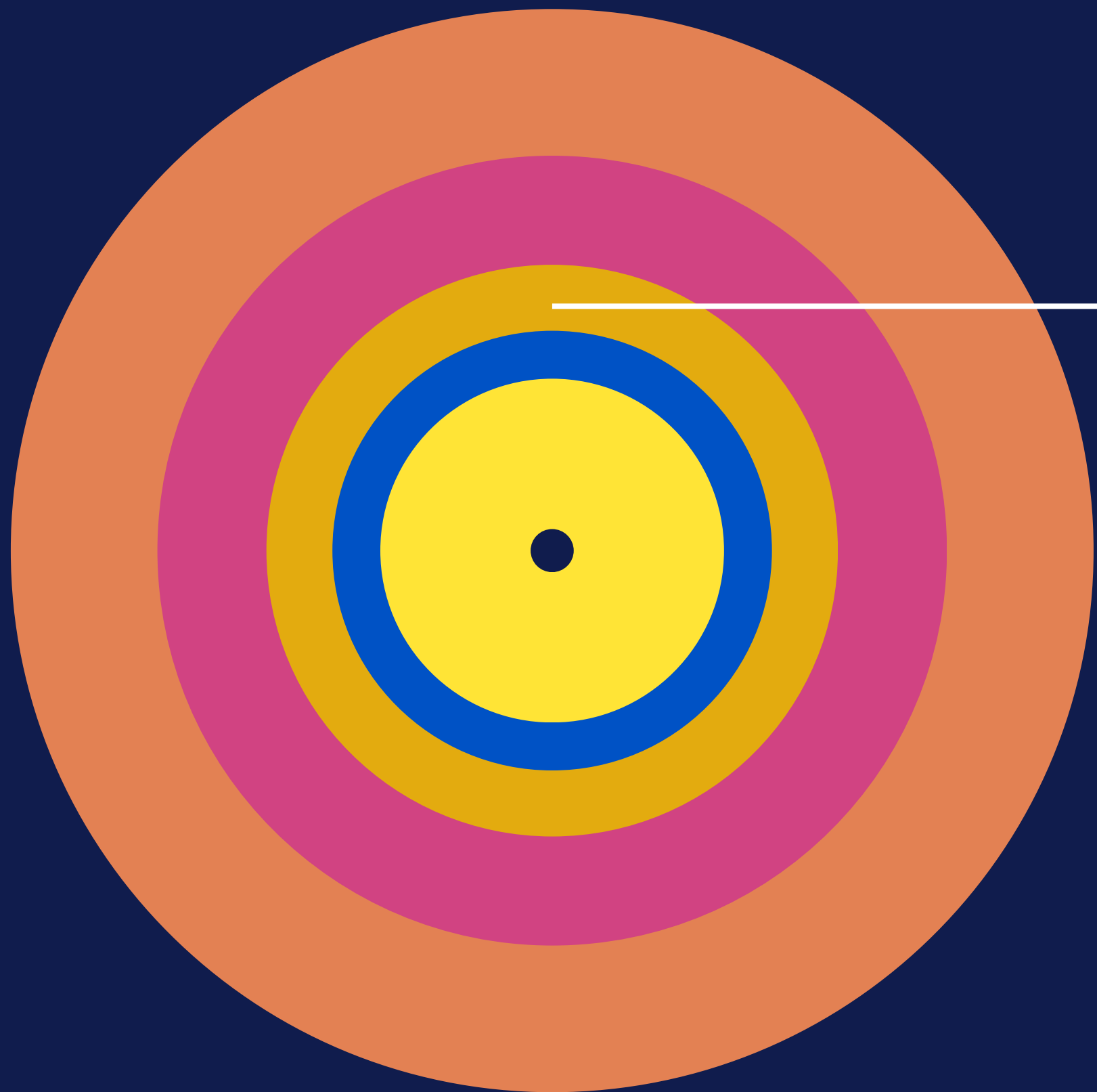


Credit: L. Lee, Charles Bell

MAIA, The Detector



MAIA, The ECal



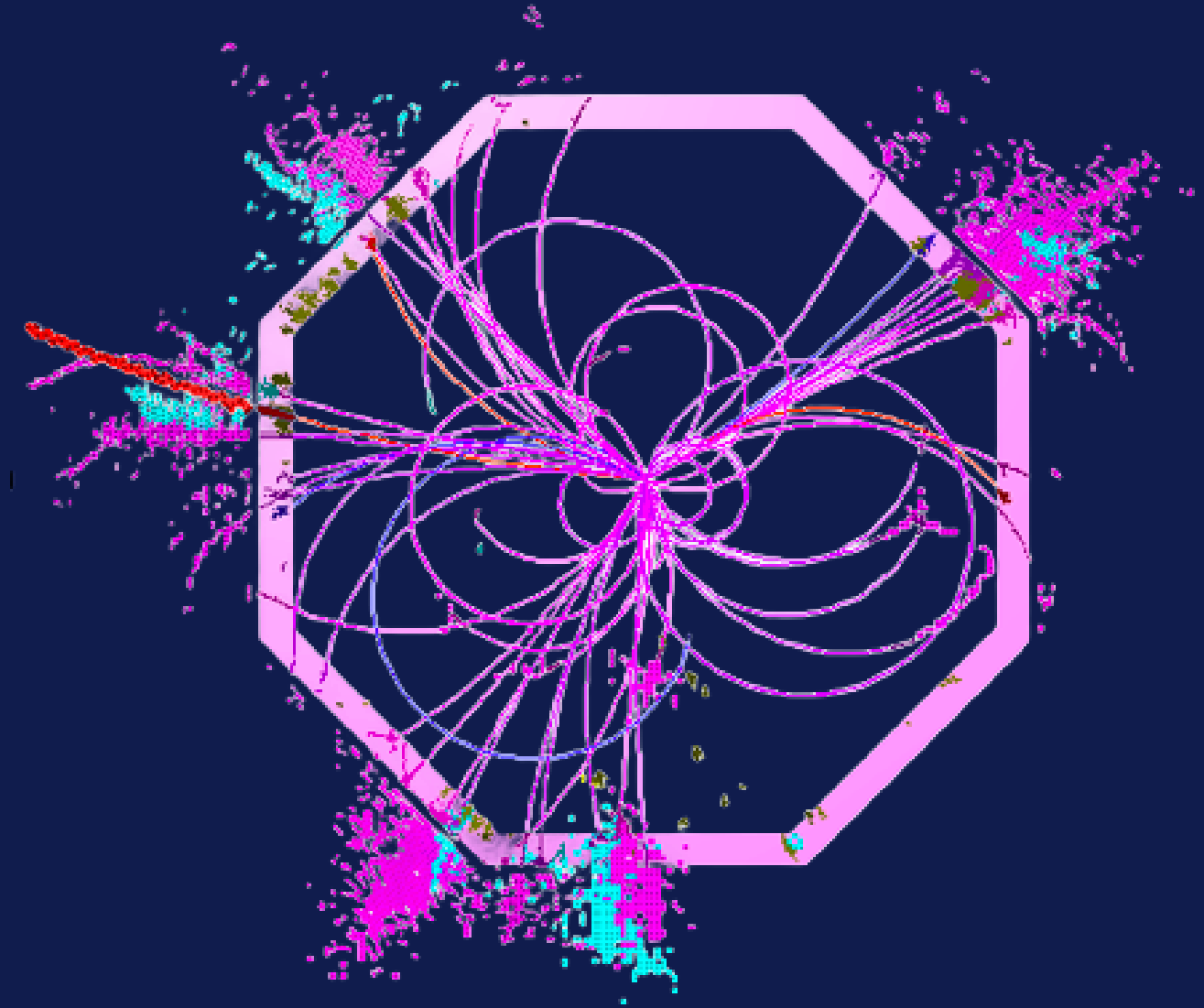
ECal

- Very HGCal-like
- Based on CLIC design and scaled up for increased energy

Cell Type	Si-W
Cell Size	5.1 x 5.1 mm
Sensor Thickness	0.5 mm
Absorber Thickness	2.2 mm
Number of Layers	50

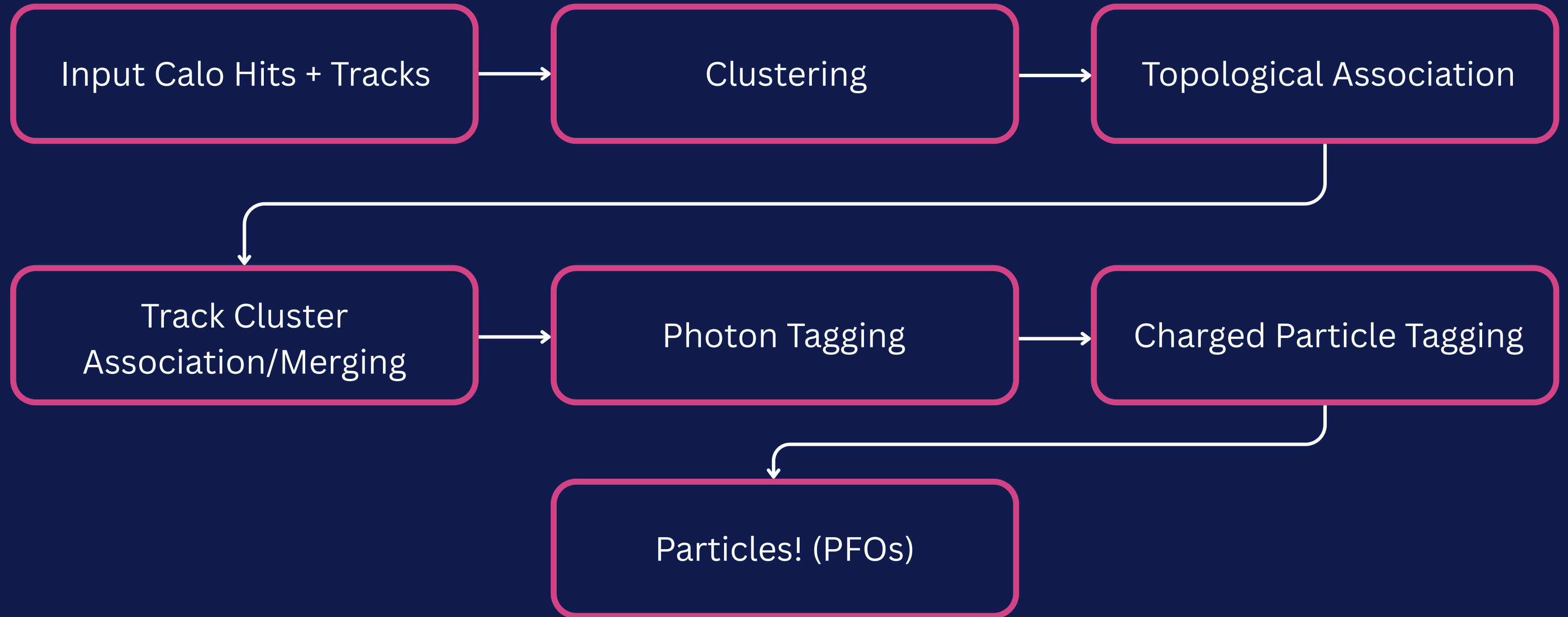
What Software Should You Use?

- As per our lepton collider heritage, we use PandoraPFA
- Pandora is a Particle Flow Algorithm
 - Similar idea to the CMS Particle Flow Algorithm
 - Lightweight! Maps well to design stage
- We have to validate along the way

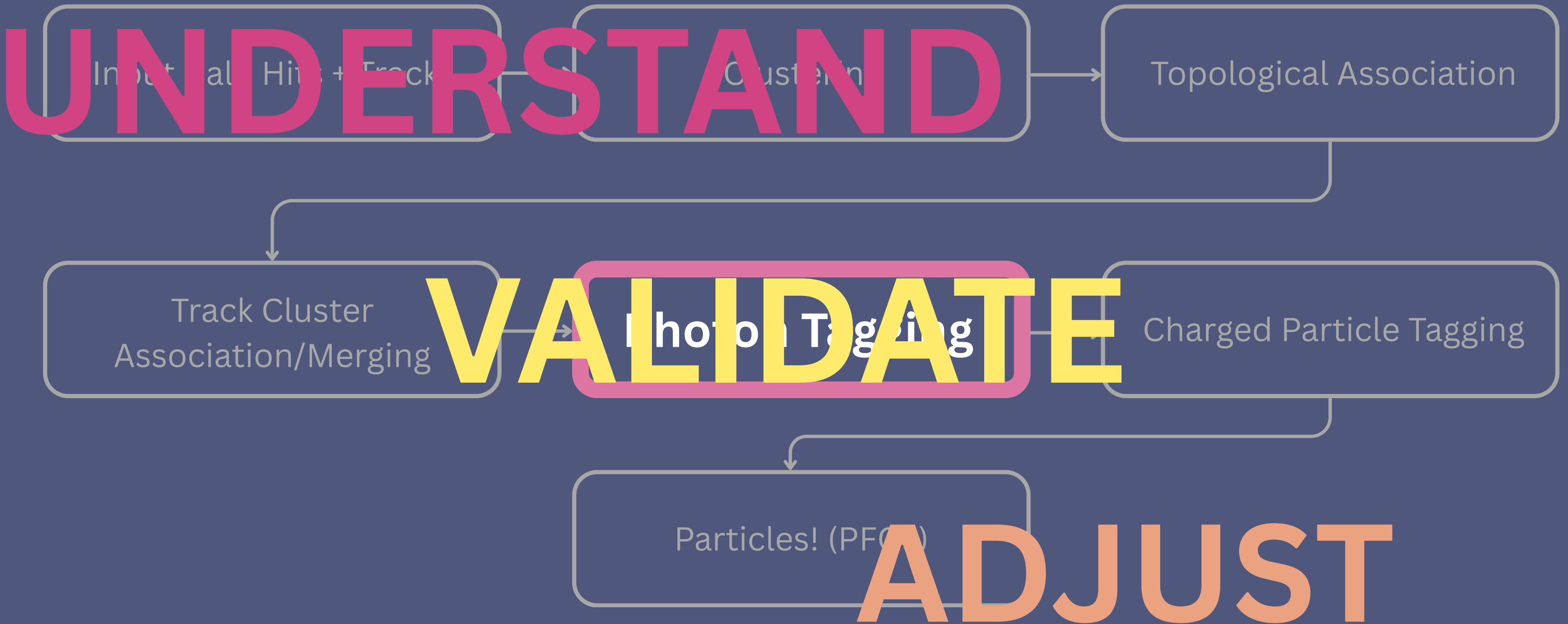


Credit: PandoraPFA Group

Particle Flow: A Crash Course



Photon Reco: A Case Study



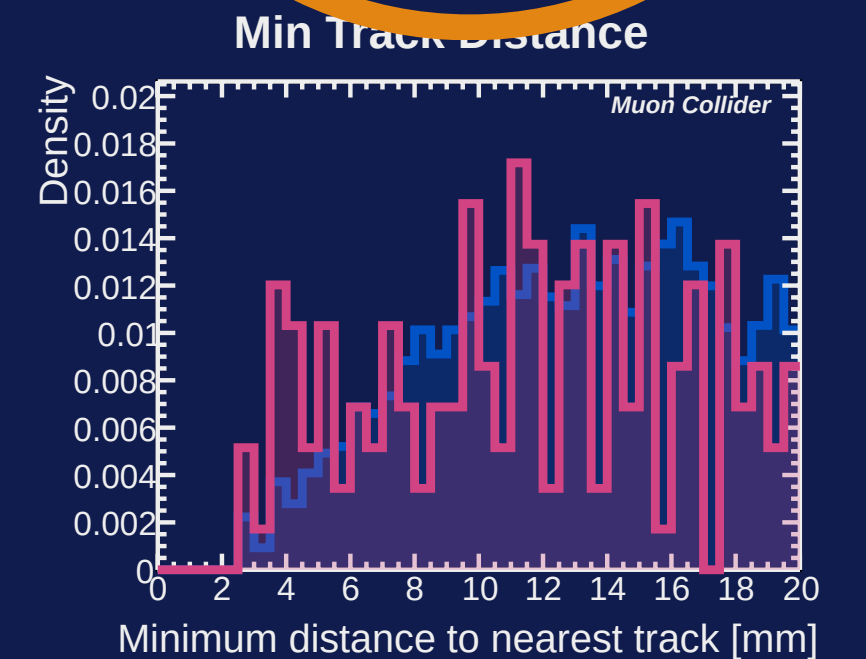
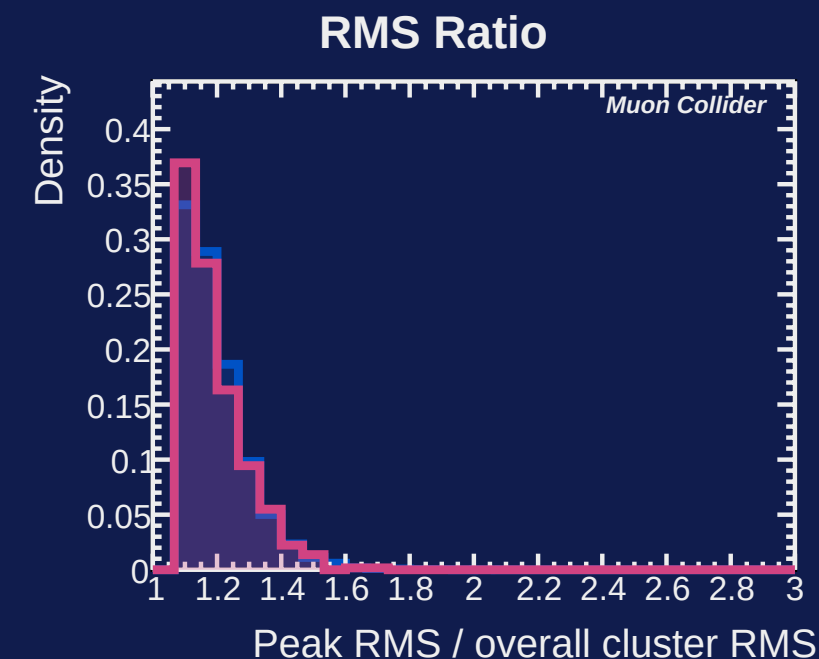
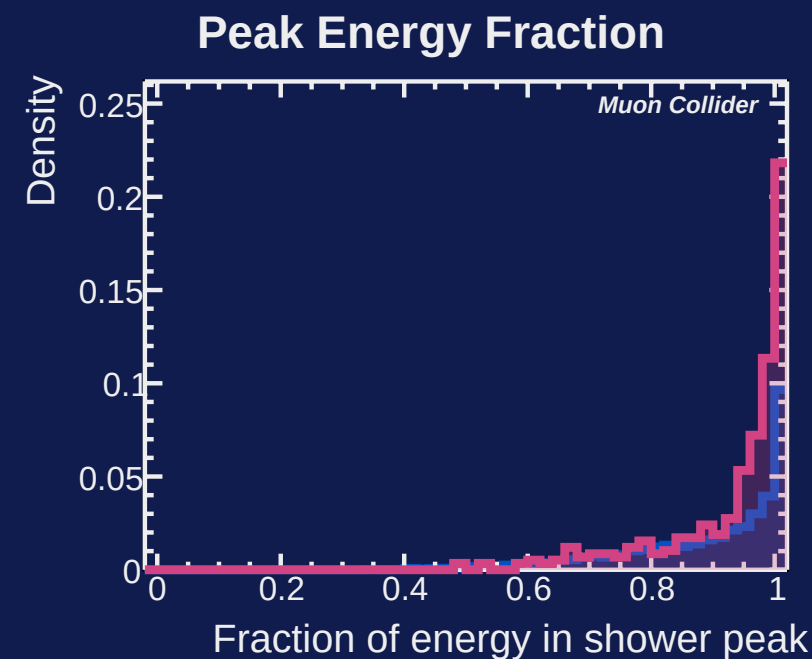
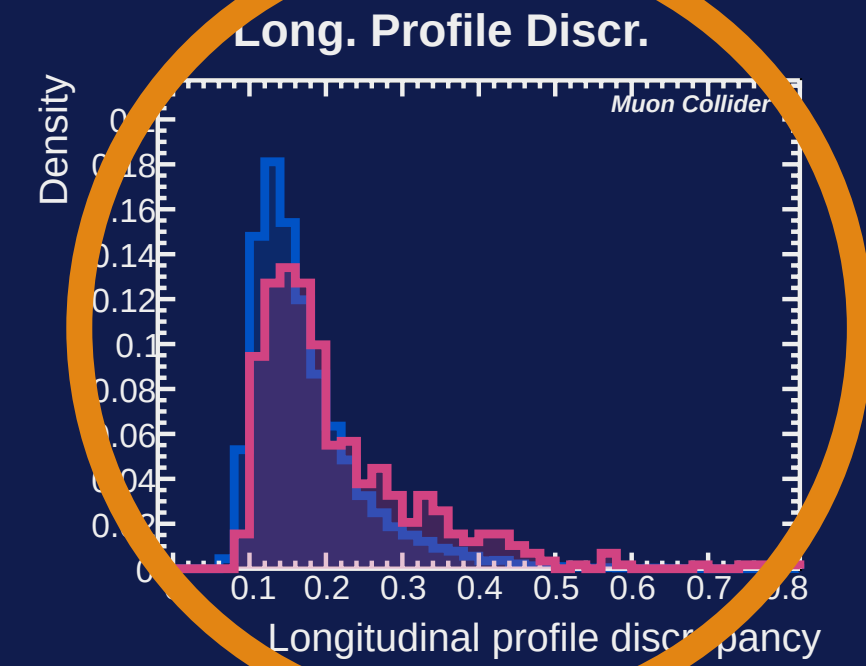
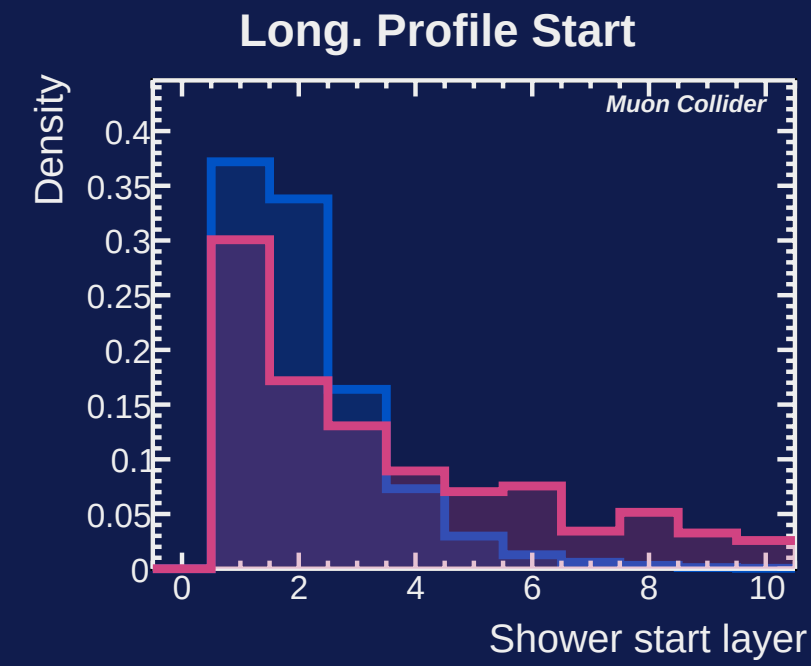
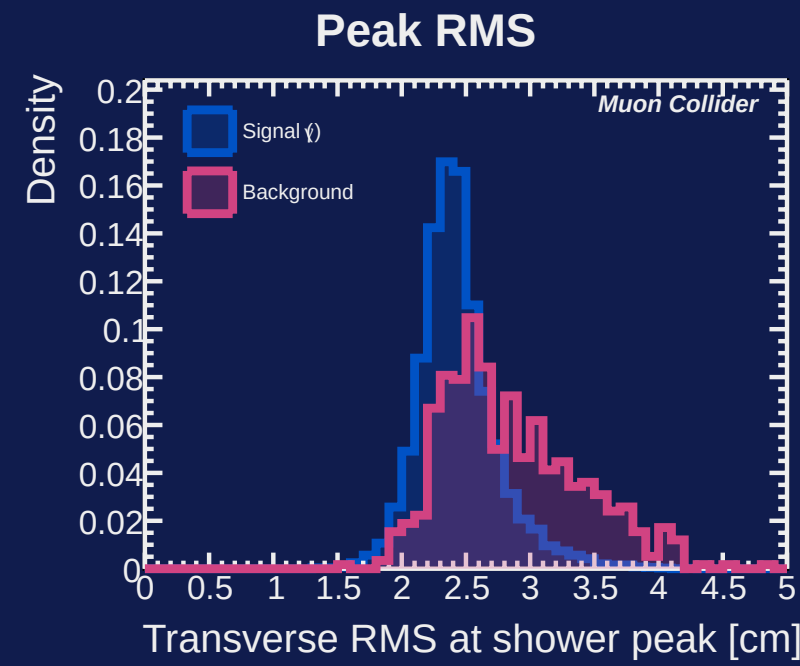
Anthropology With The Likelihood File

- As an example of this mode of work, let's take a look at [this file](#)
- Broad understanding of what the purpose was
 - Inputs to a classifier
 - Are these good choices?

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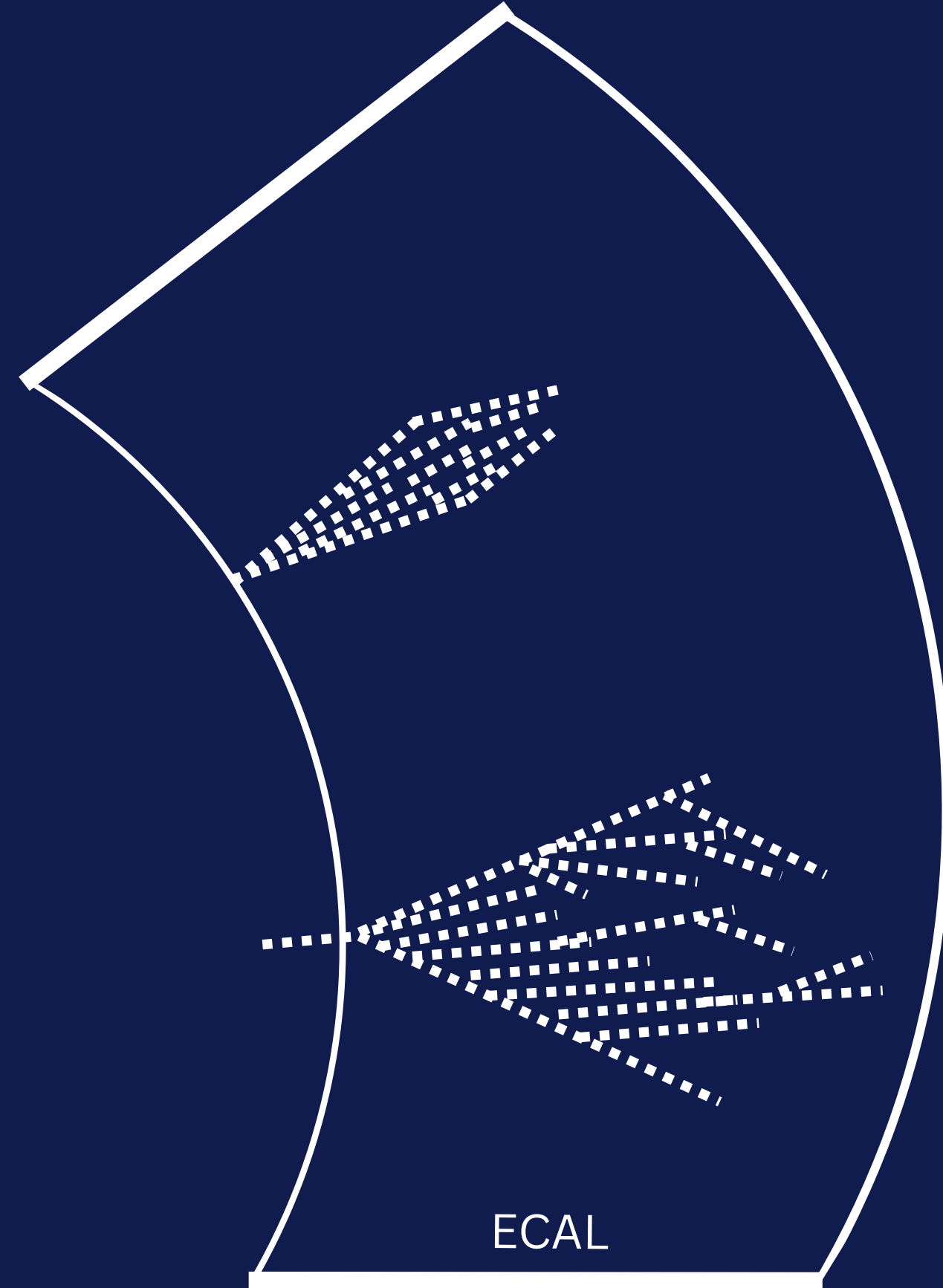
What Are These Variables?

- We can write a simple script to print out the contents of this file
- This spits out a bunch of histograms that look like this
- Doing this effectively kicks the can down the road
 - We know what's in this file, but not what it does



Electromagnetic Showers The Pandora Way

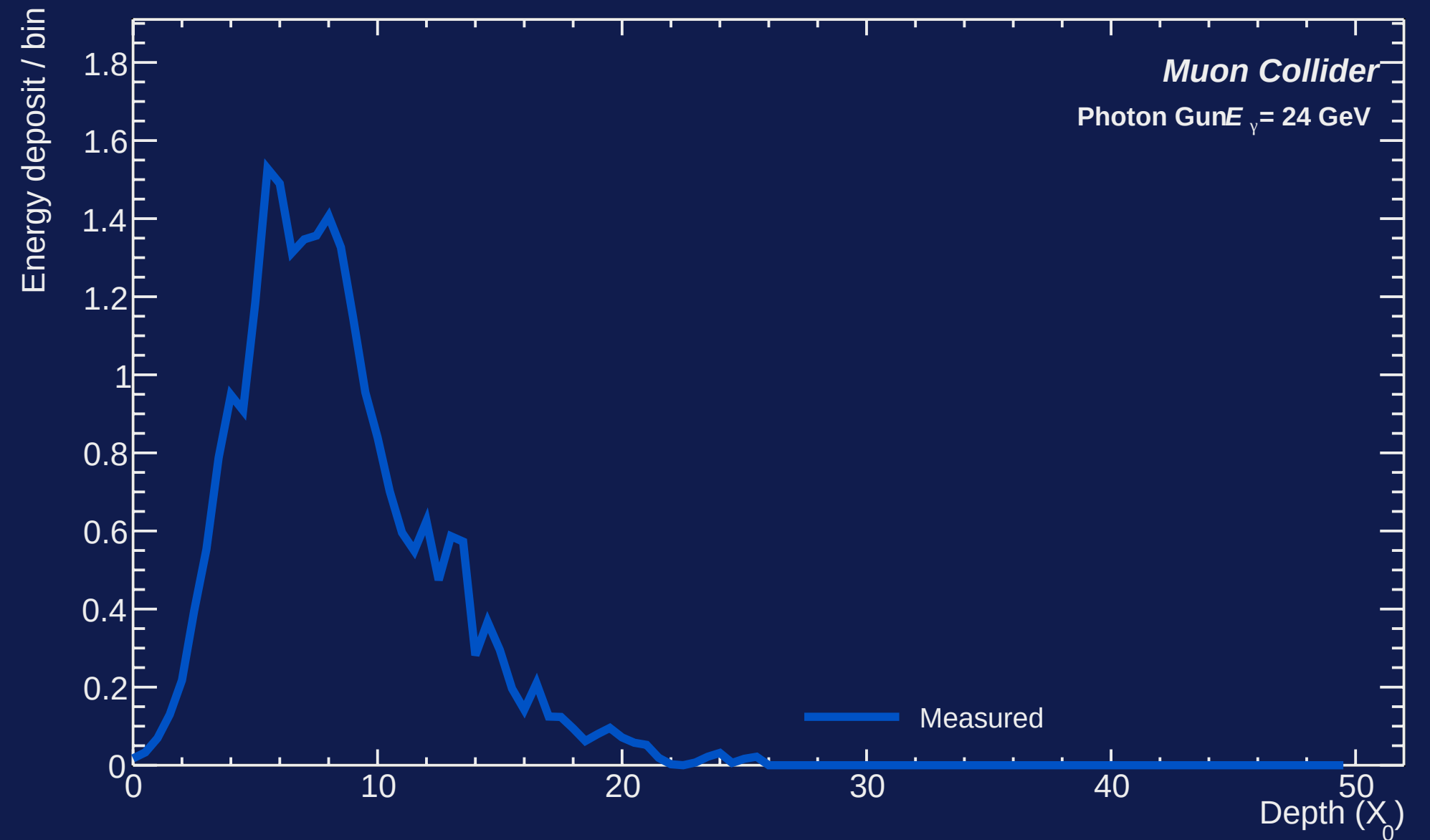
- Focusing in on the way we construct emag showers, we need to understand the process of deriving our inputs to the classifier
- Specifically how do we measure how “shower-like” a given cluster is?



Thank you Jullian for the graphic

Handling Showers

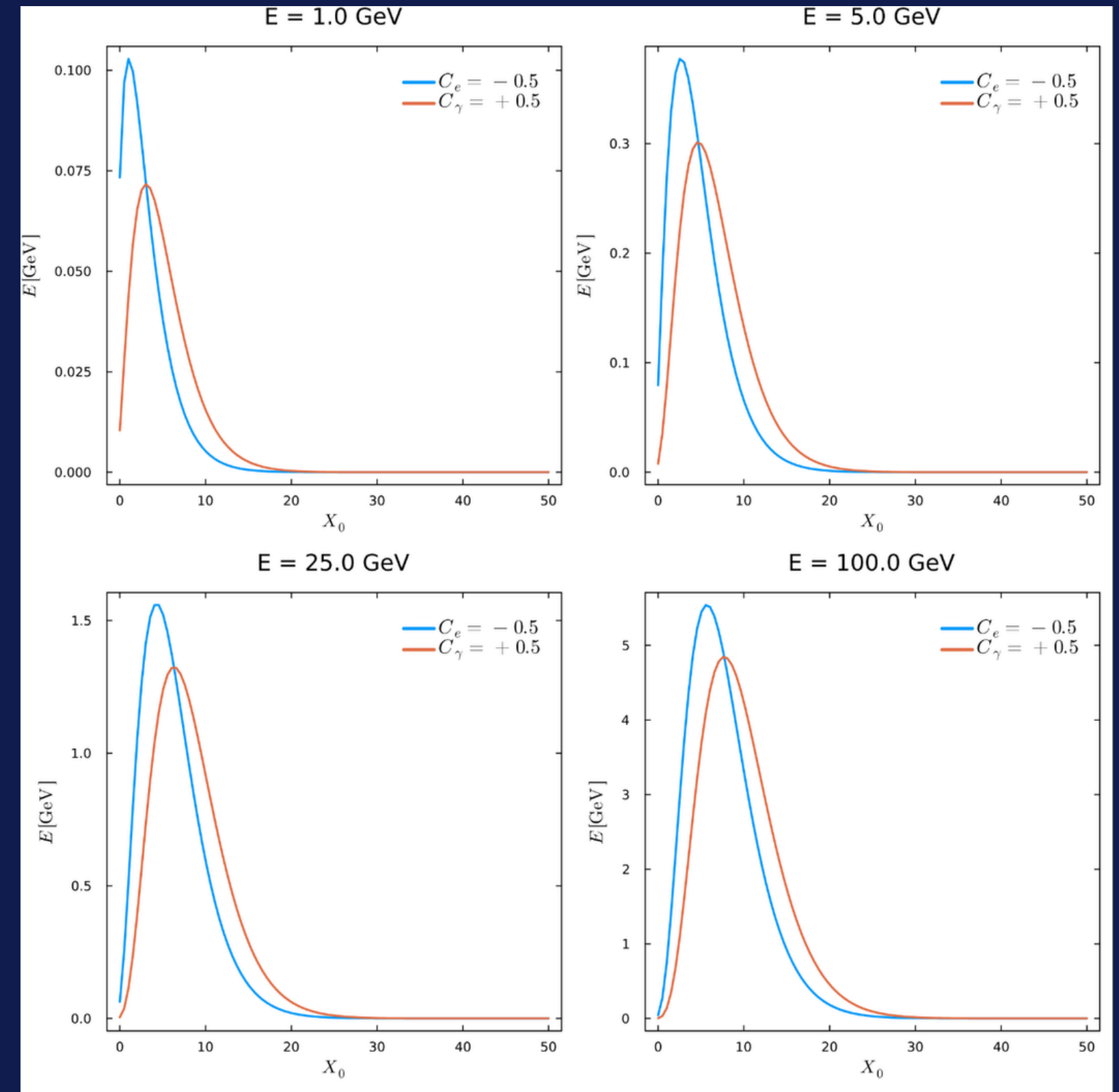
- Three step process
 - 1) Reconstruct the energy deposition of your shower



Handling Showers

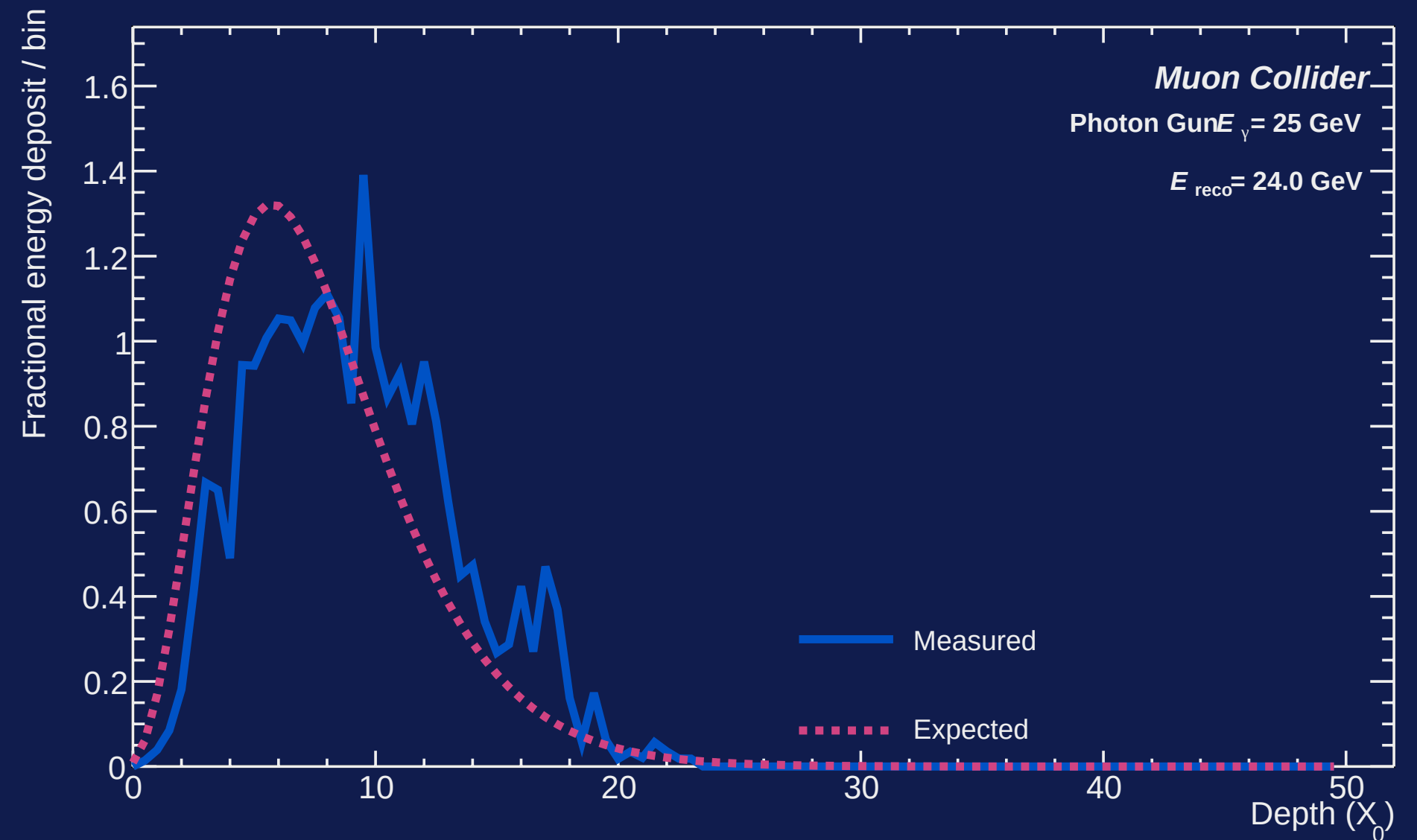
- Three step process
 - 1) Reconstruct the energy deposition of your shower
 - 2) Use total energy to construct a theoretical profile

$$\frac{dE}{dt} \propto E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$



Handling Showers

- Three step process
 - 1) Reconstruct the energy deposition of your shower
 - 2) Use total energy to construct a theoretical profile
 - 3) Compare these two curves and return a profile discrepancy score
 - I am going to refer to this as χ



Profile Discrepancy In Other Cases

- Let's consider the electron case
- Electron identification employs a simple-cut based identification approach
- In their case; a χ of < 0.6 is required

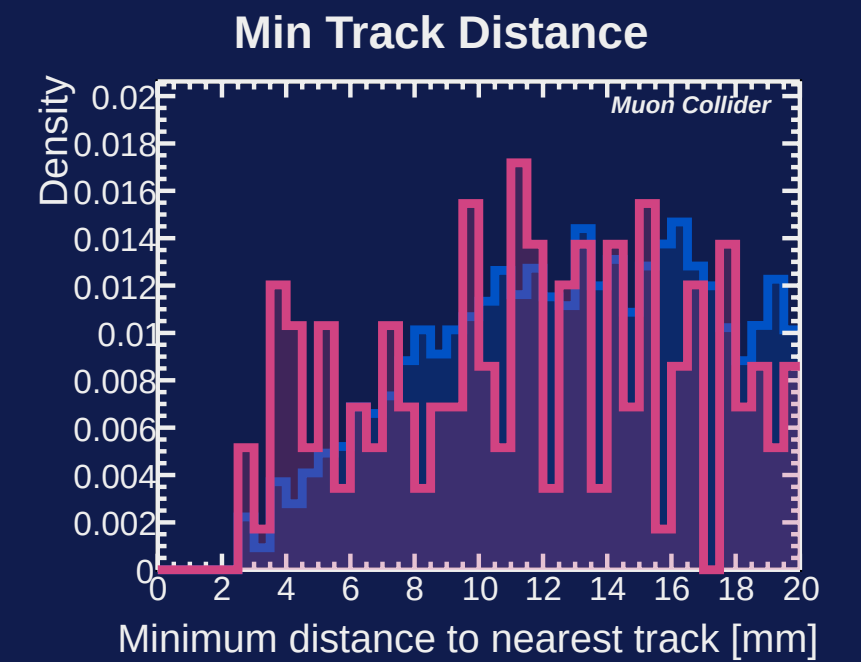
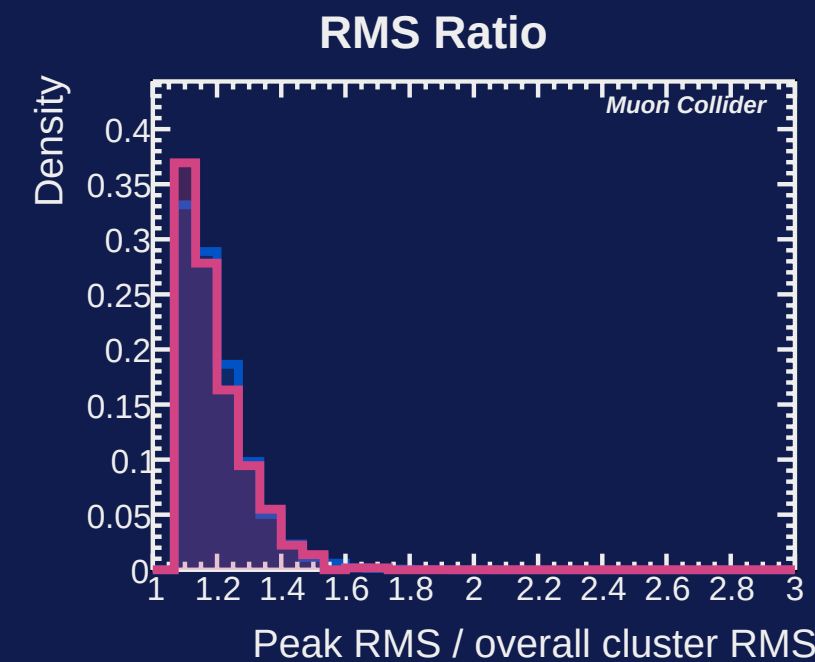
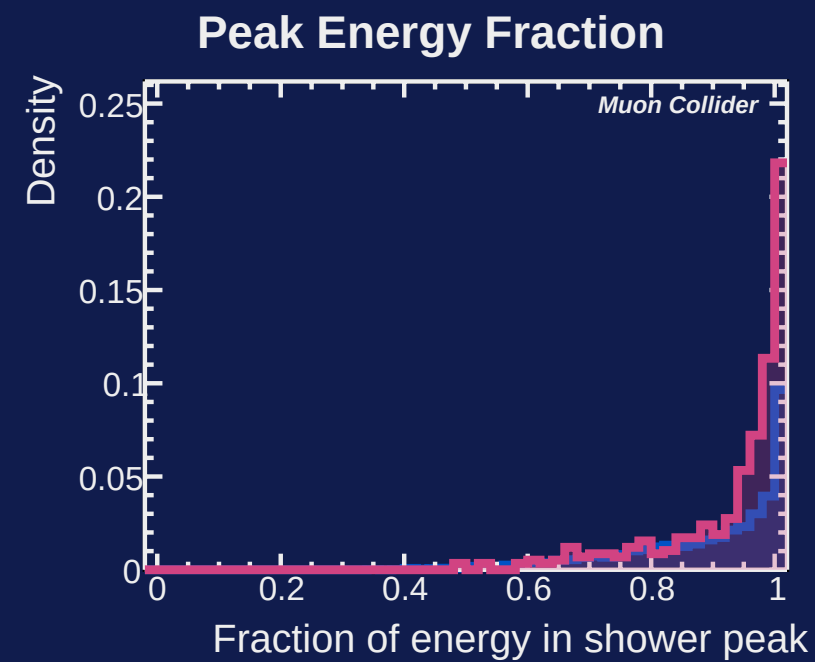
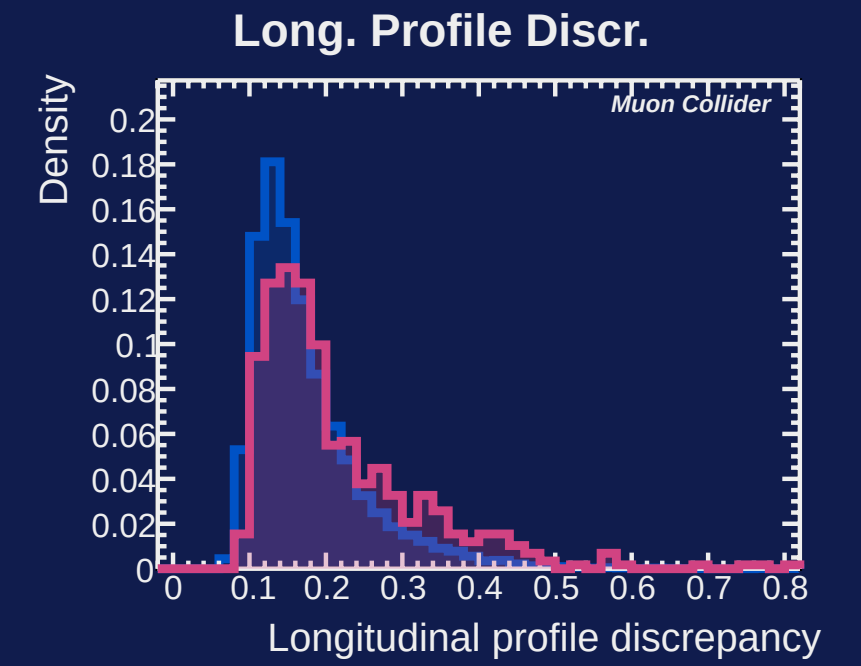
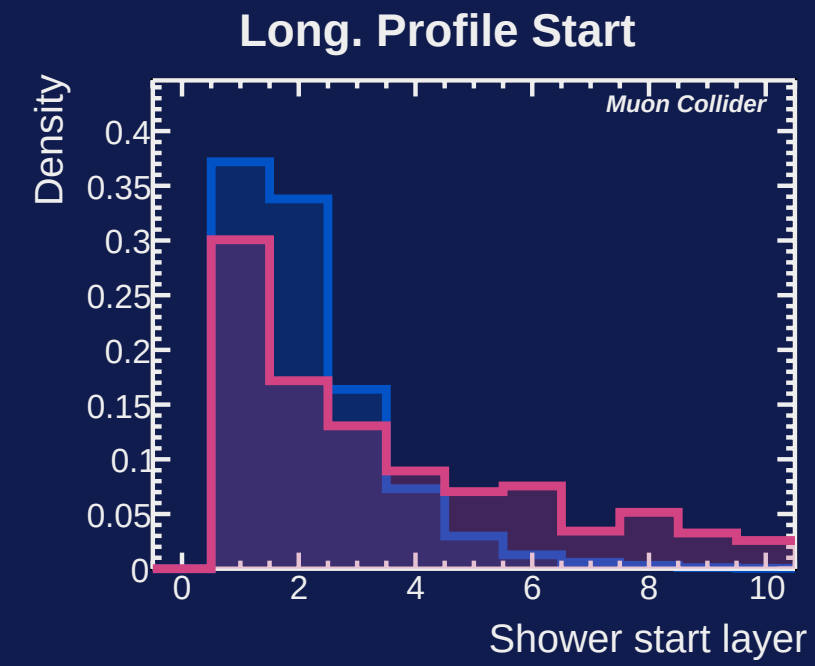
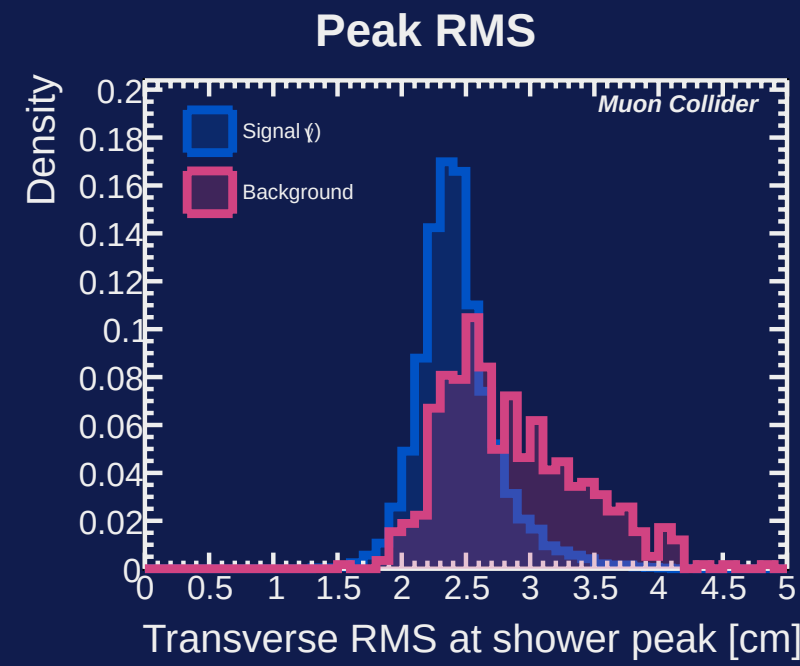
Pandora Default Electron ID

Variable	Value
Max inner layer	4
Max energy	5 GeV
Max profile start	4.5
Max profile discrepancy	0.6
Max E/p residual	0.2

What Are These Variables?

Redux.

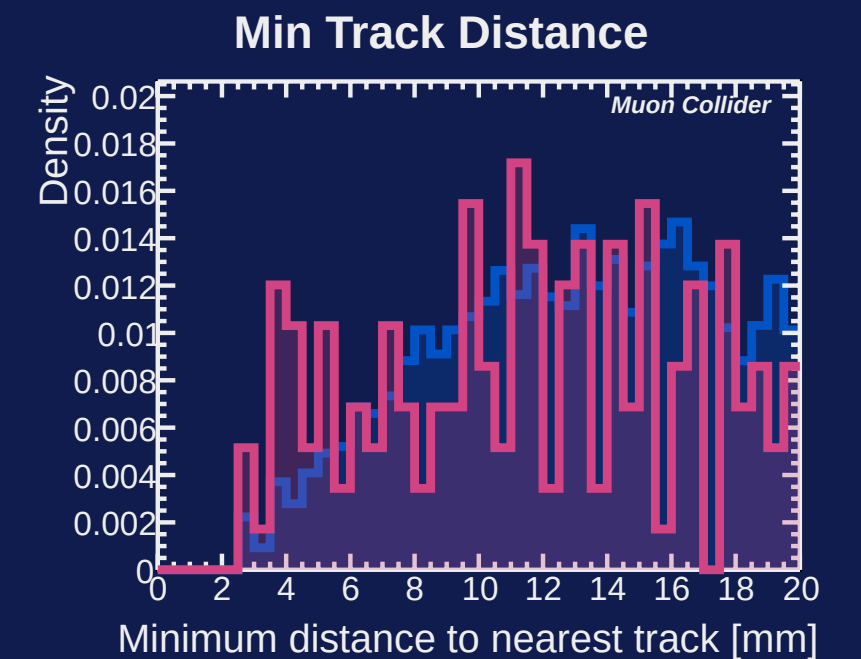
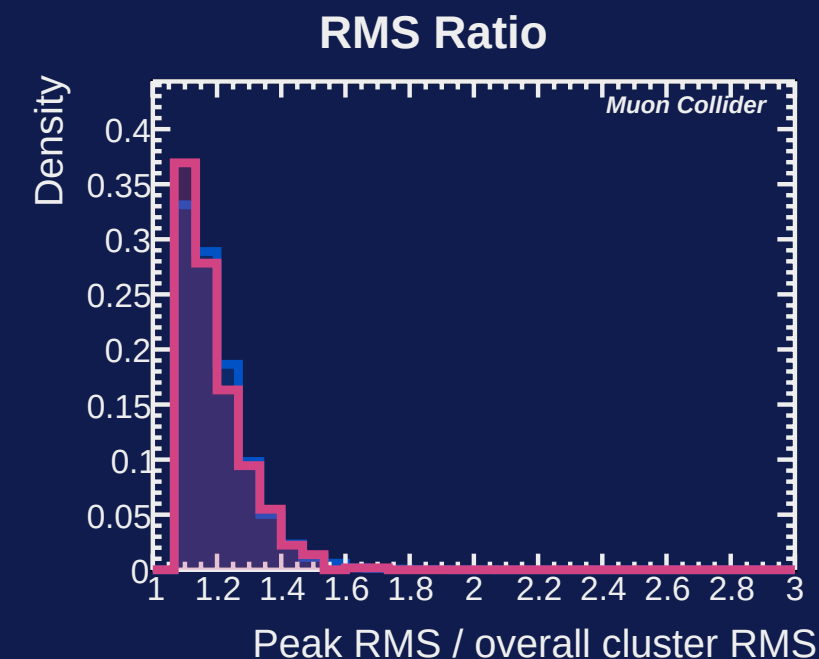
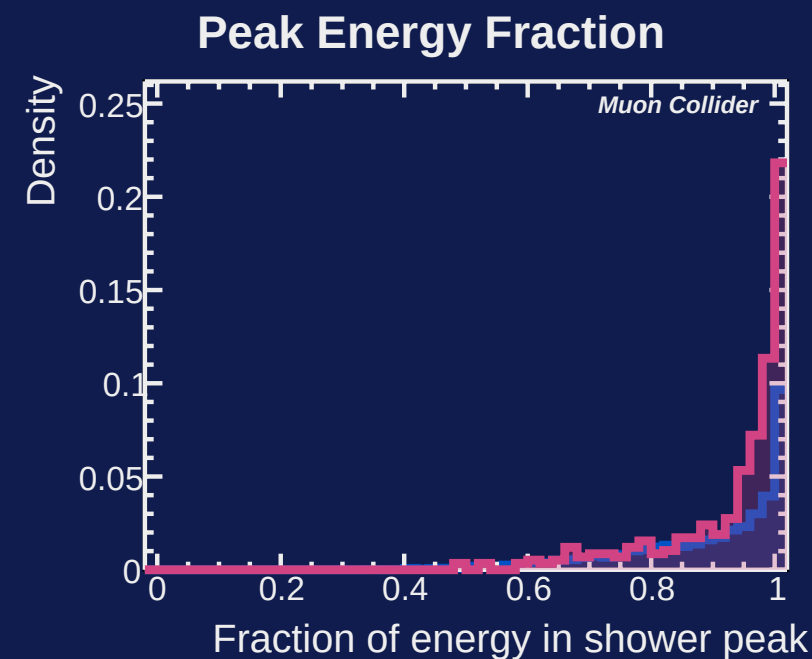
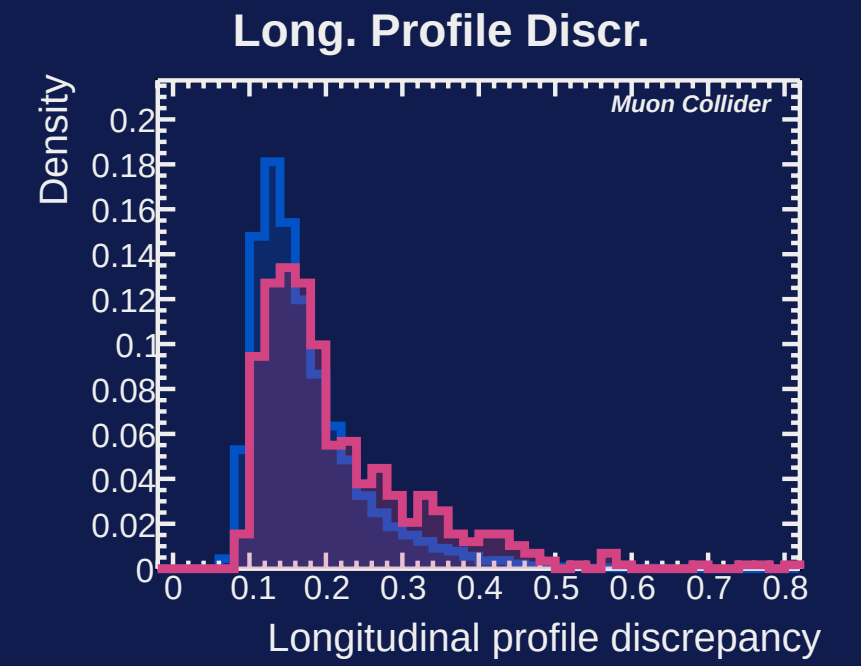
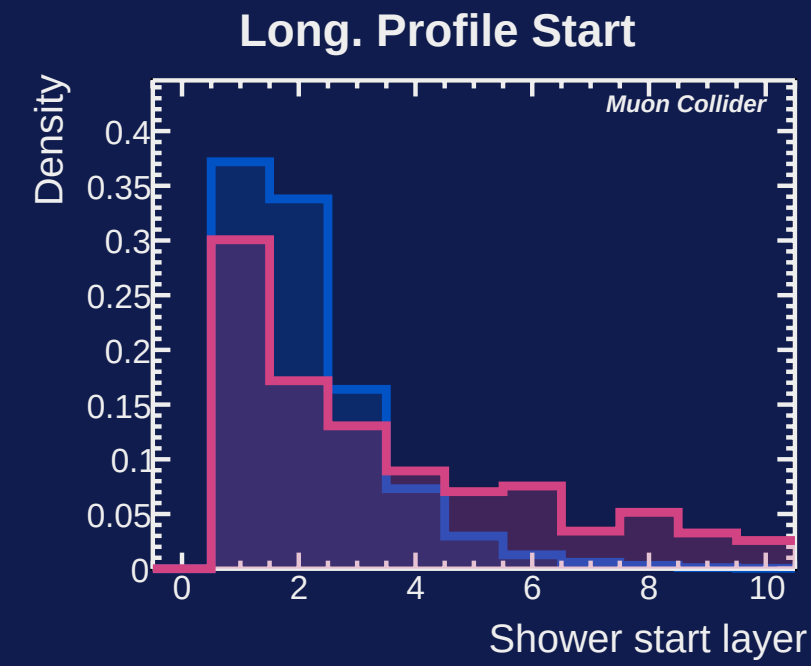
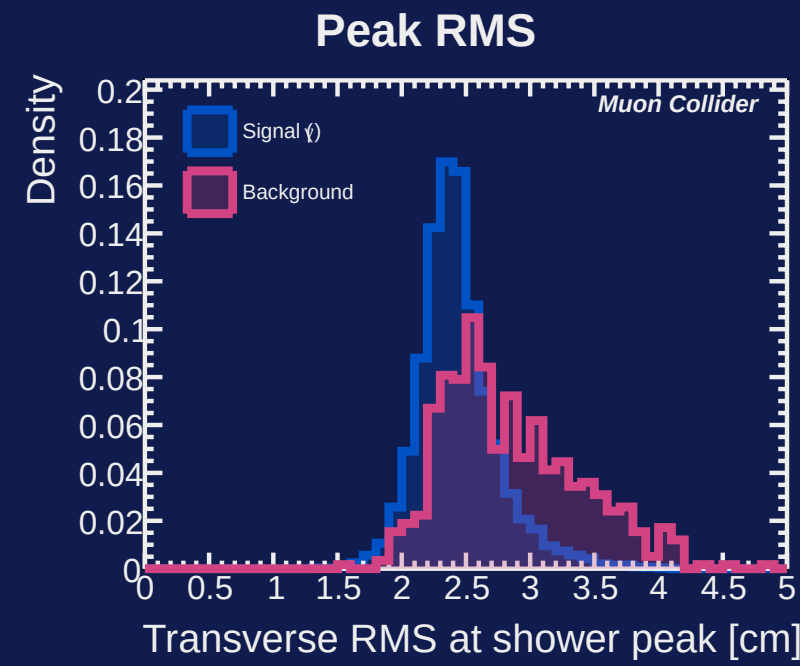
- Peak RMS
 - How big is the shower at its peak?
- Profile Start
 - Where in the calorimeter does the shower begin?
- Profile Discrepancy
 - How “ideal” is this shower?



What Are These Variables?

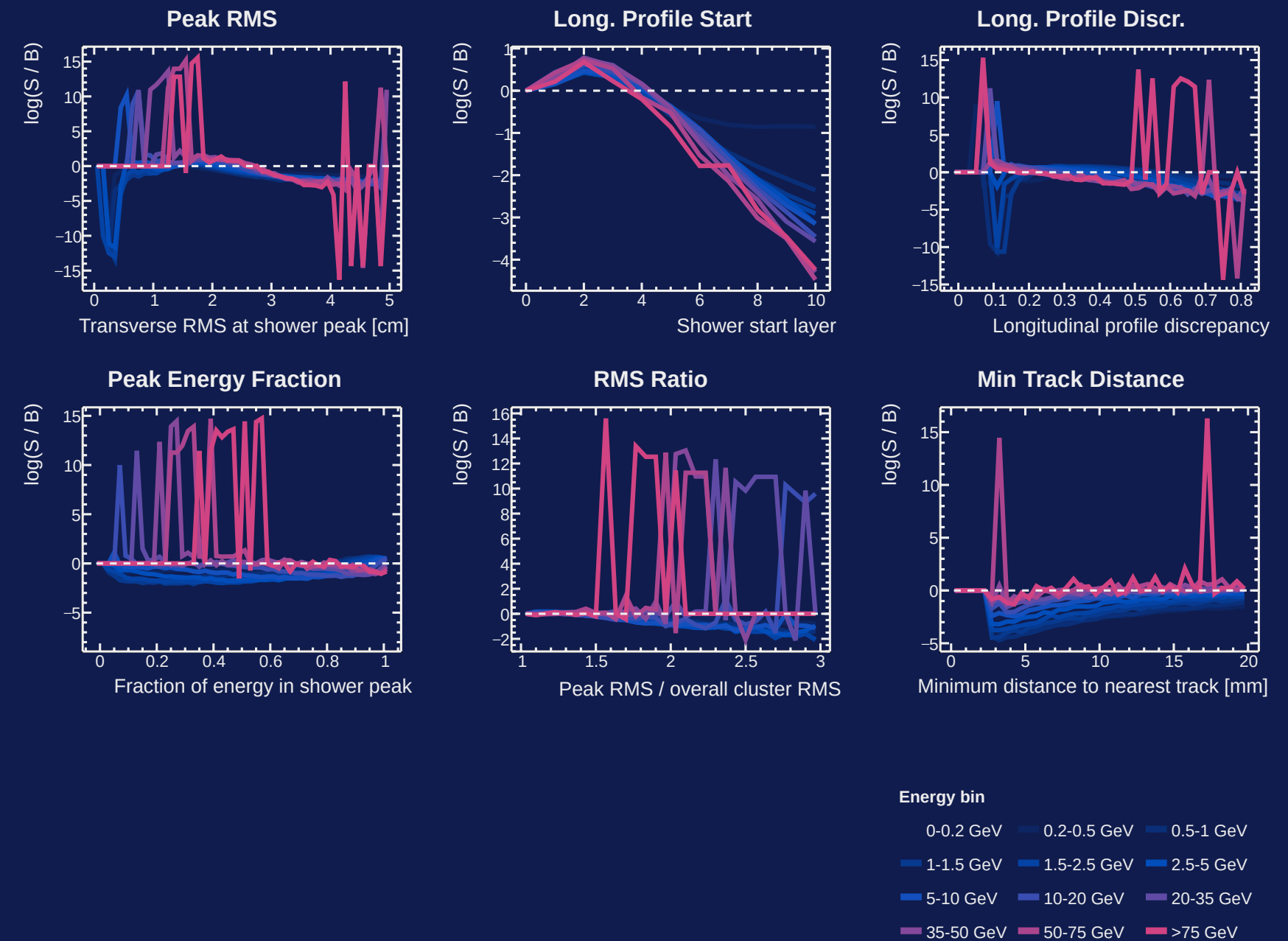
Redux.

- Peak Energy Fraction
 - How much energy is in the peak?
- RMS Ratio
 - How circular is this object?
- Distance-to-track
 - Is there a track nearby?
- All passed into 6-dimensional classifier to tag photons



What Does This Approach Look Like in Practice?

- For a given cluster we
 - a. Calculate all the relevant variables
 - b. Pass these variables to the classifier
 - c. Tag as a photon based on output
- With a rigorous understanding of this process, we can ask the question...



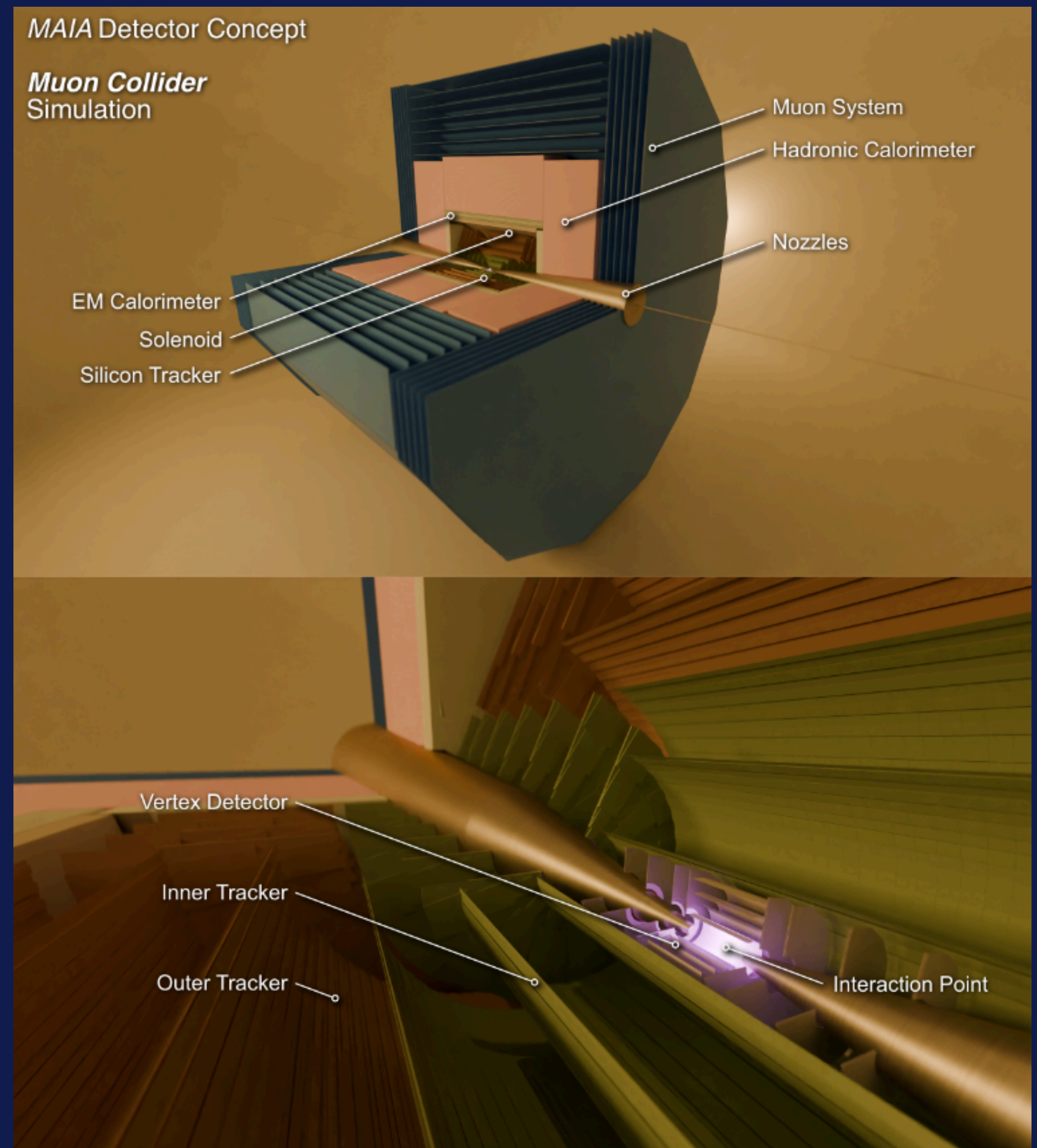
Does This Approach Make Sense?

- Sure
- But what does this approach mean for us in the context of a muon collider environment?
- More specifically, what sorts of issues arise in reconstruction because of our detector choices?
- E.g;

The Solenoid

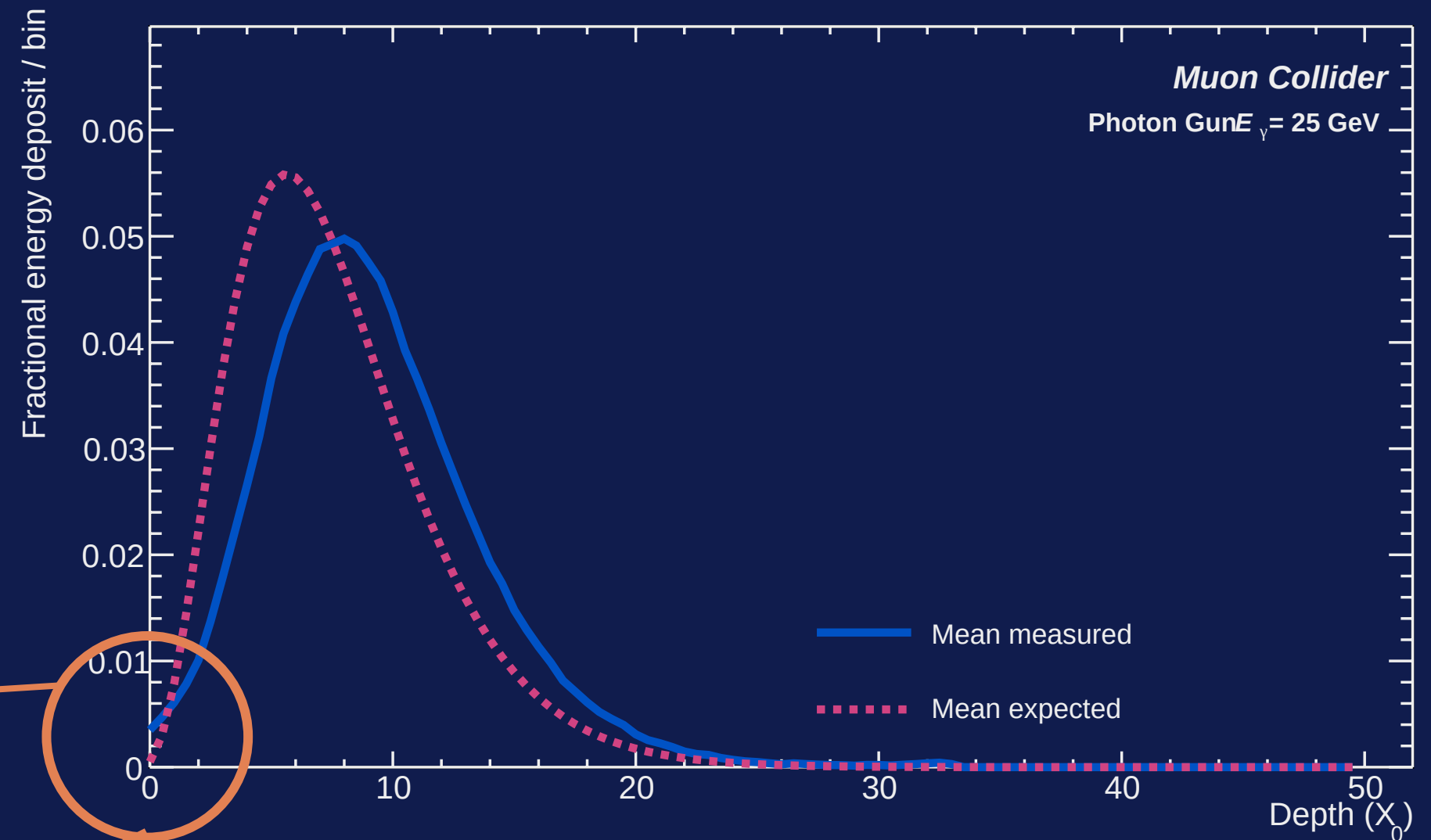
- We have a big solenoid in the middle of our detector
- Designed to shield the calorimeters from BIB
- Would be reasonable to expect that this material also gets in the way of things we want
 - E.g. photons
- This would be a big issue

A dedicated feasibility study is required for the solenoid. In these studies, we have assumed a 5T magnet with an inner radius of 150 cm simulated as a region of high-density materials, aluminum and steel. The feasibility of such a magnet needs to be evaluated, particularly given the sensitivity of the calorimetry to the amount of material in the magnet. A more realistic model of such a large high-field magnet should incorporate radiation tolerance requirements, and the structural and material design must be able to handle the large mechanical stresses from the field.



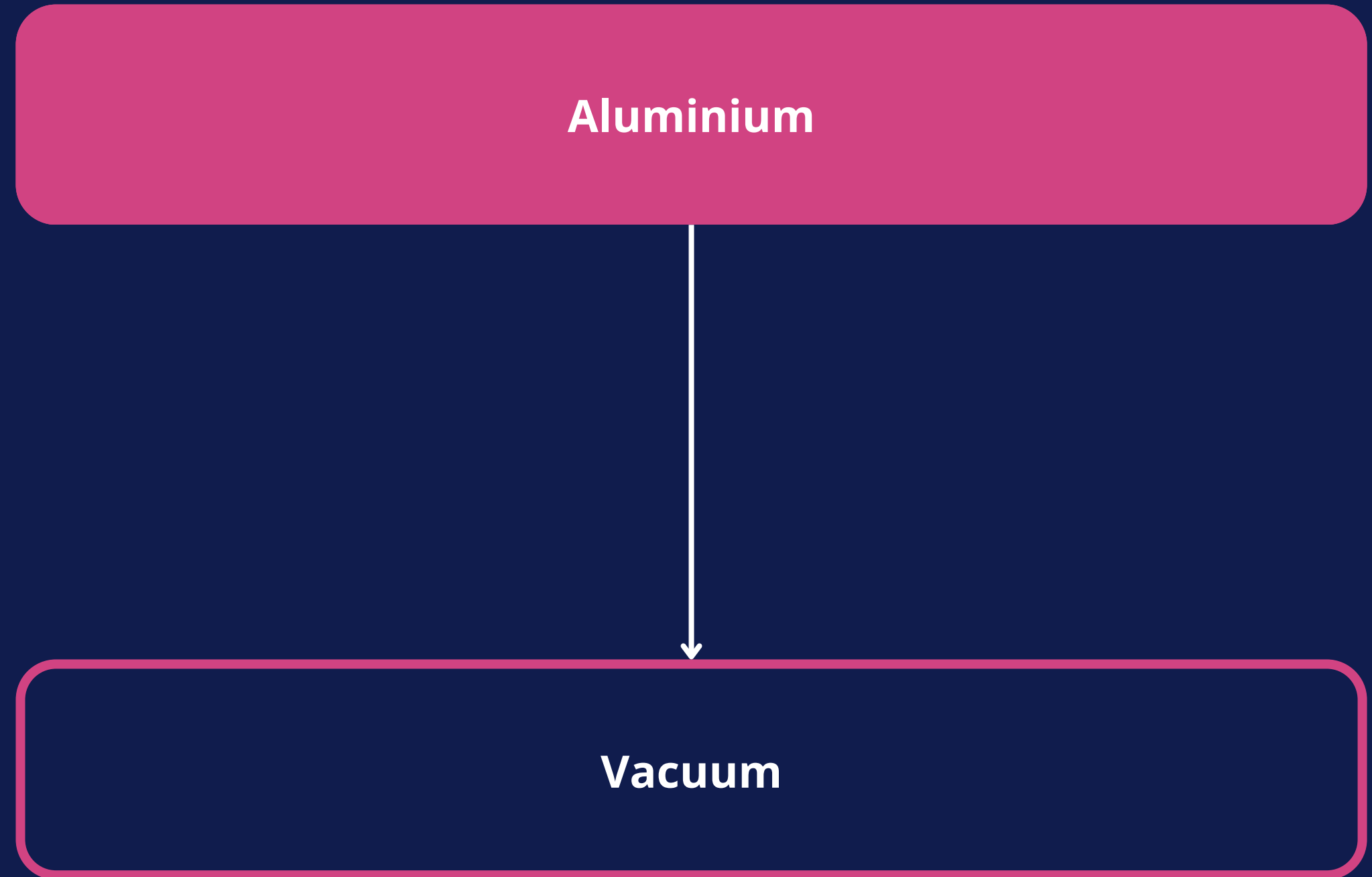
The Solenoid

- Let's return to our profile curve
- An eye test says that these two *do not* agree
- Let's focus in on this corner
- Can see that the measured curve has nonzero energy deposition at 0
- Could the solenoid be causing this?



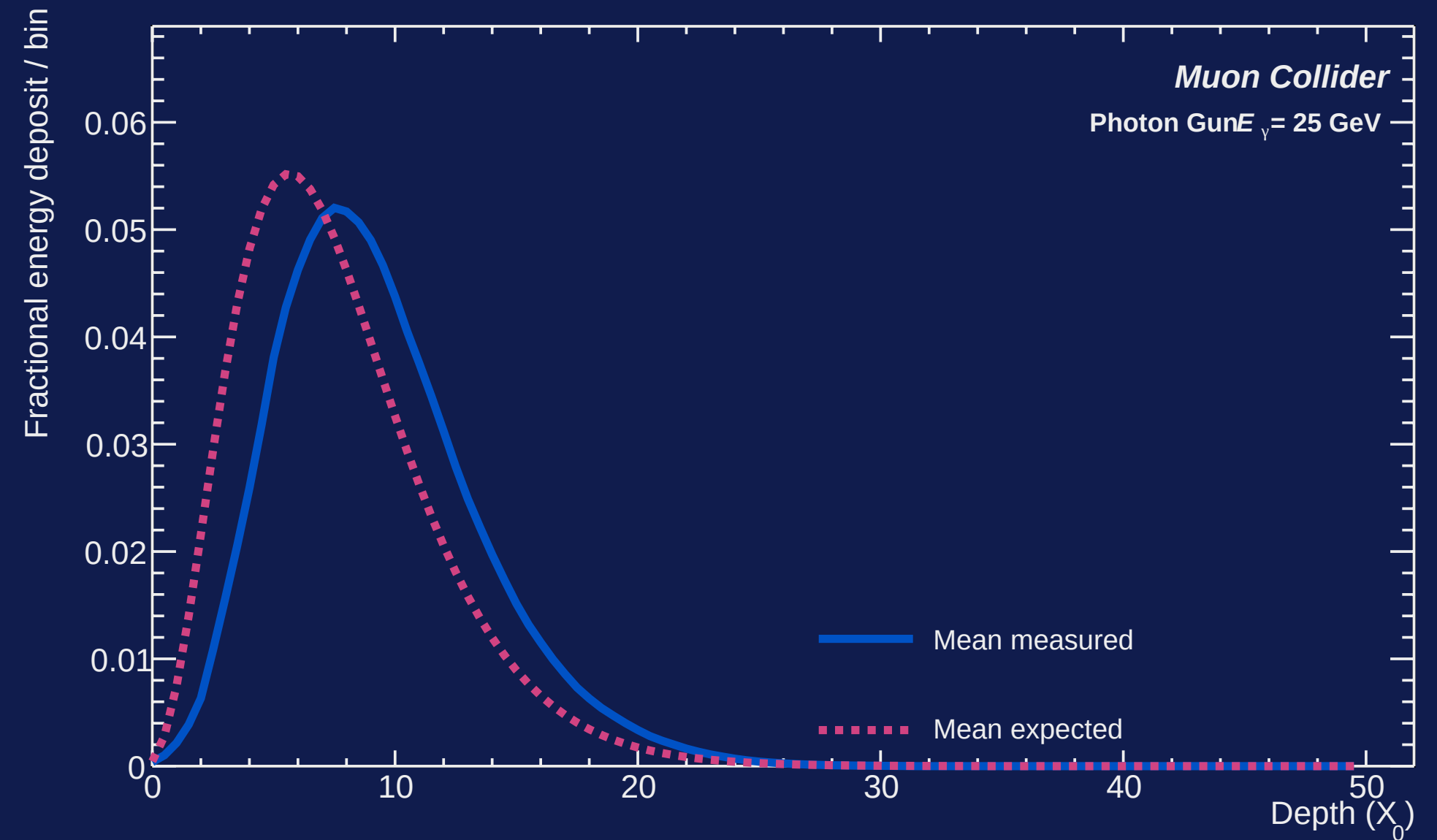
The Solenoid

- How do we test this?
- Go to magical simulation land where all things are possible
- Replace the solenoid material with vacuum
- Repeat the simulation and compare
- What do we see?



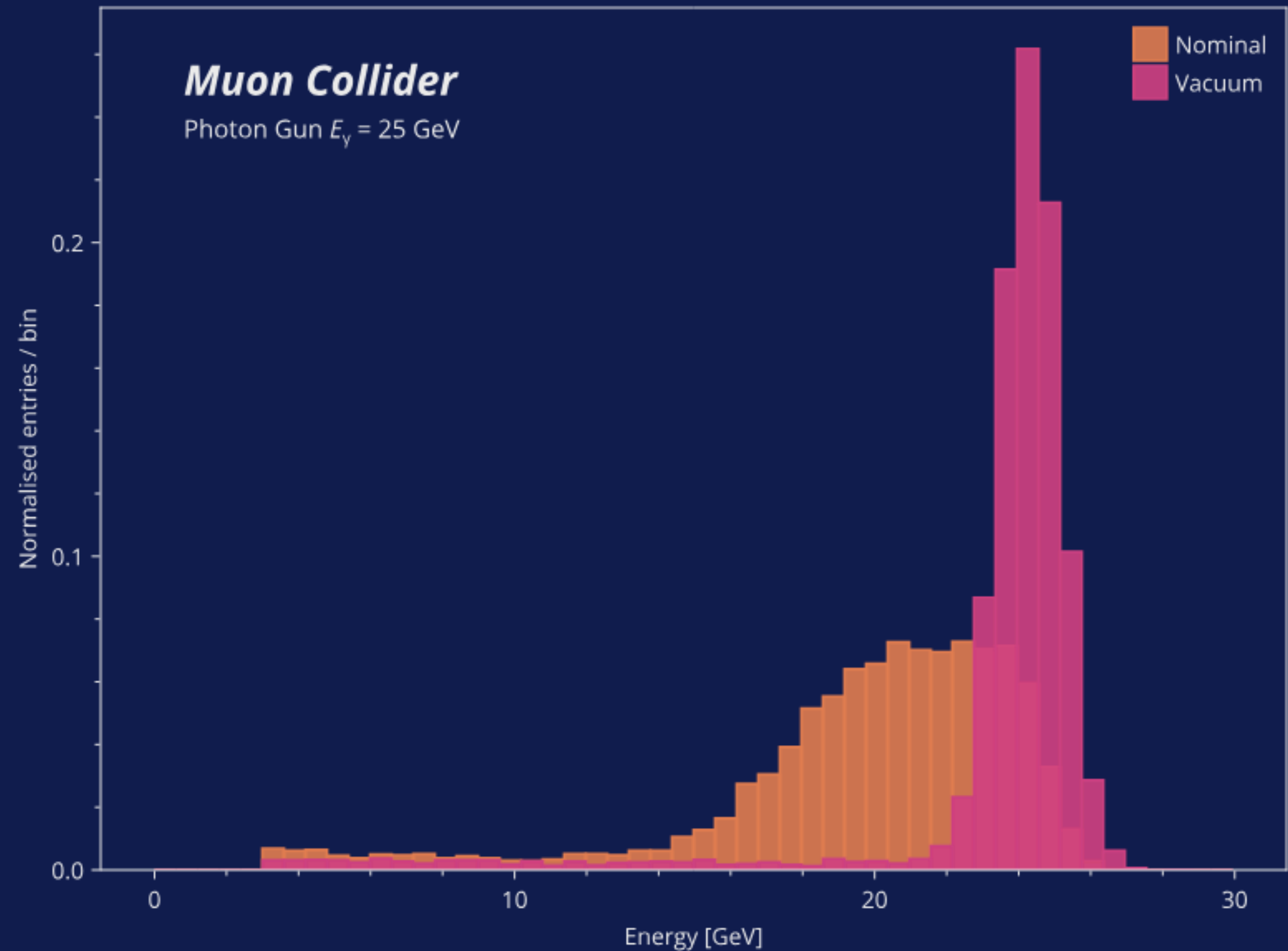
What Do We See?

- The curve start behavior in question disappears!
 - Still some disagreement, but a good first step



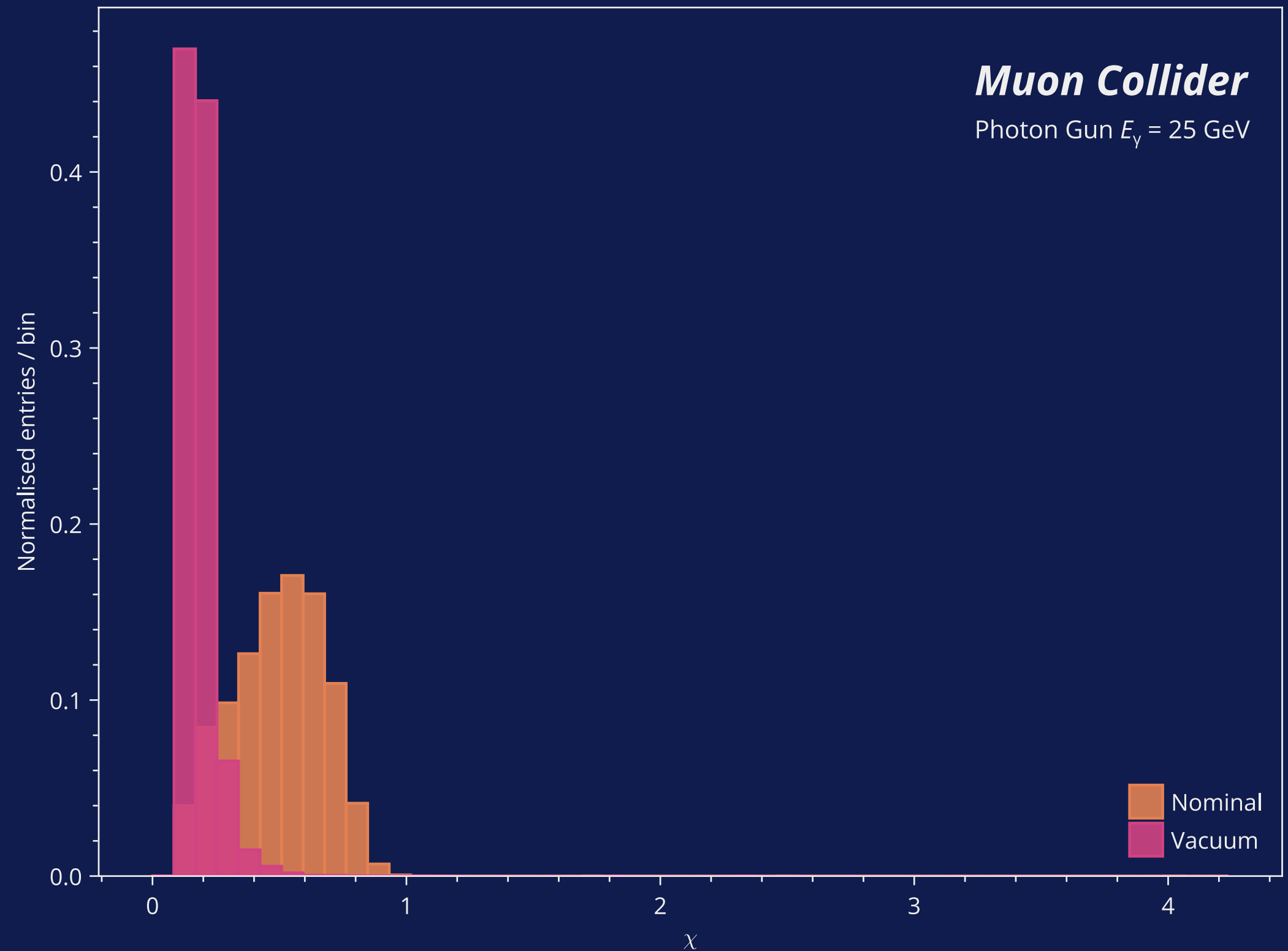
What Do We See?

- The curve start behavior in question disappears!
 - Still some disagreement, but a good first step
- Our energy reconstruction gets a lot worse!
 - The vacuum has a lovely 25 GeV peak while the actual geometry does not



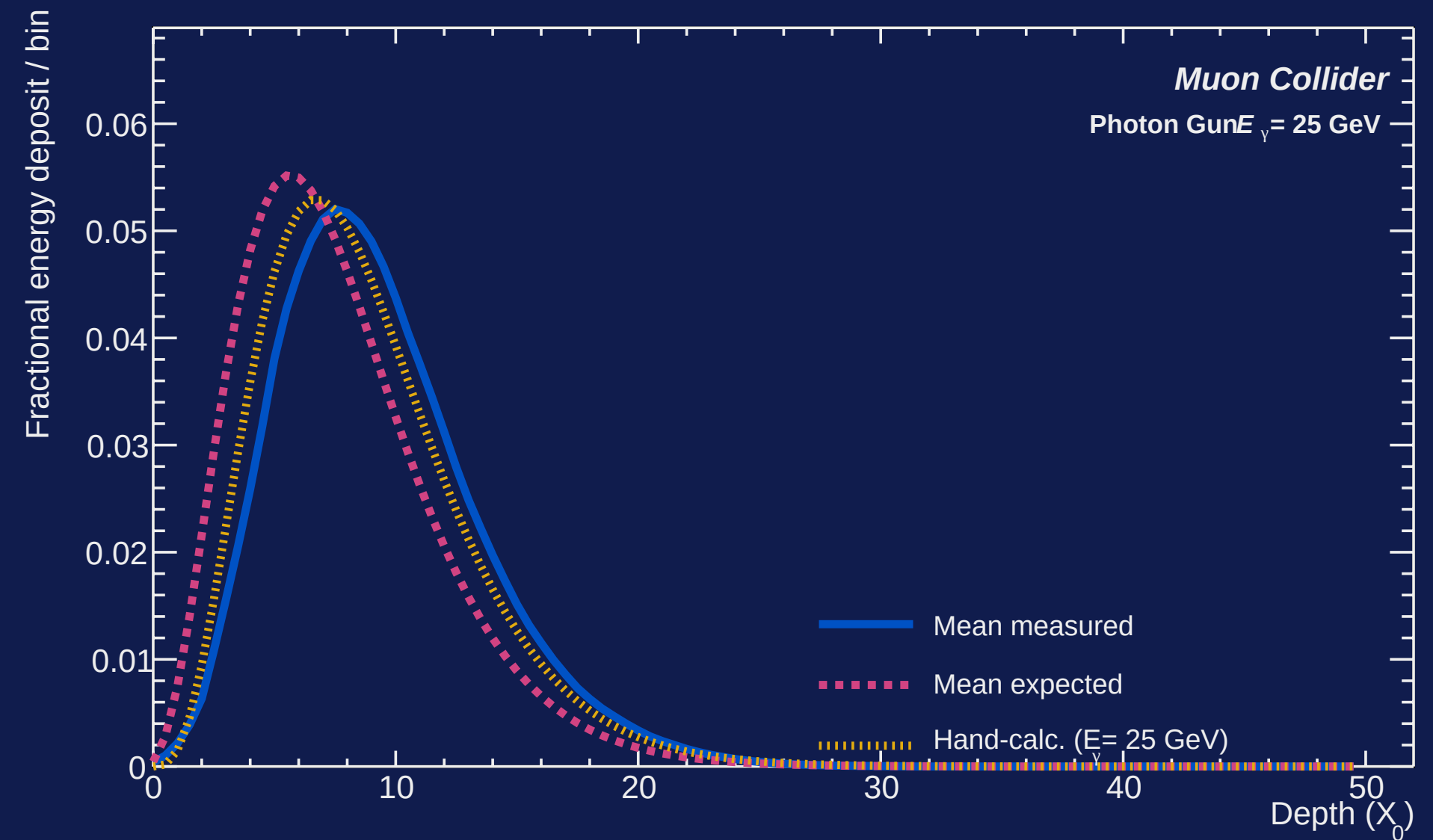
What Do We See?

- The curve start behavior in question disappears!
 - Still some disagreement, but a good first step
- Our energy reconstruction gets a lot worse!
 - The vacuum has a lovely 25 GeV peak while the actual geometry does not
- Our profile discrepancy scores also get worse!
 - Keeping in mind the ~ 0.6 breakpoint



What About The Other Offset?

- The measured curves appears to be overestimating the energy
 - We suspect this is due to potential material effects
- Working on confirming source of this behavior



Some Tentative Conclusions

- Pandora is a particle flow algorithm optimized for lepton collider environments
- We understand the photon reconstruction process
 - Calculate shower variables each cluster
 - Pass clusters into six-dimensional classifier for tagging
- Can confidently say that our solenoid is causing us to lose energy in photon showers
 - Additionally causes us to identify showers as “less ideal”

Some Tentative Next Steps

- Looking to add θ dependence to samples
 - Seeking to understand the way path length effects the noted reconstruction issues
- Digging into the nitty-gritty of how Pandora calculates everything
 - We suspect there might be a mismatch in the material properties we hand Pandora and what it actually does with them
- How do we fix this?
 - Is there a generic MC-based calibration technique we can use?
 - E.g; at some generic θ and E_0 results in a calibrated E
 - Failing that, looking at how ATLAS handles this sort of problem
 - A Presampler!
- Longer term: What background sources should we consider for our classifier?
 - The training data came to us prepackaged
 - We'll need to remake it, but with what?

Part II

Electron Reconstruction Efficiency

From a simulated electron gun
with no BIB

Electron Reconstruction Efficiency

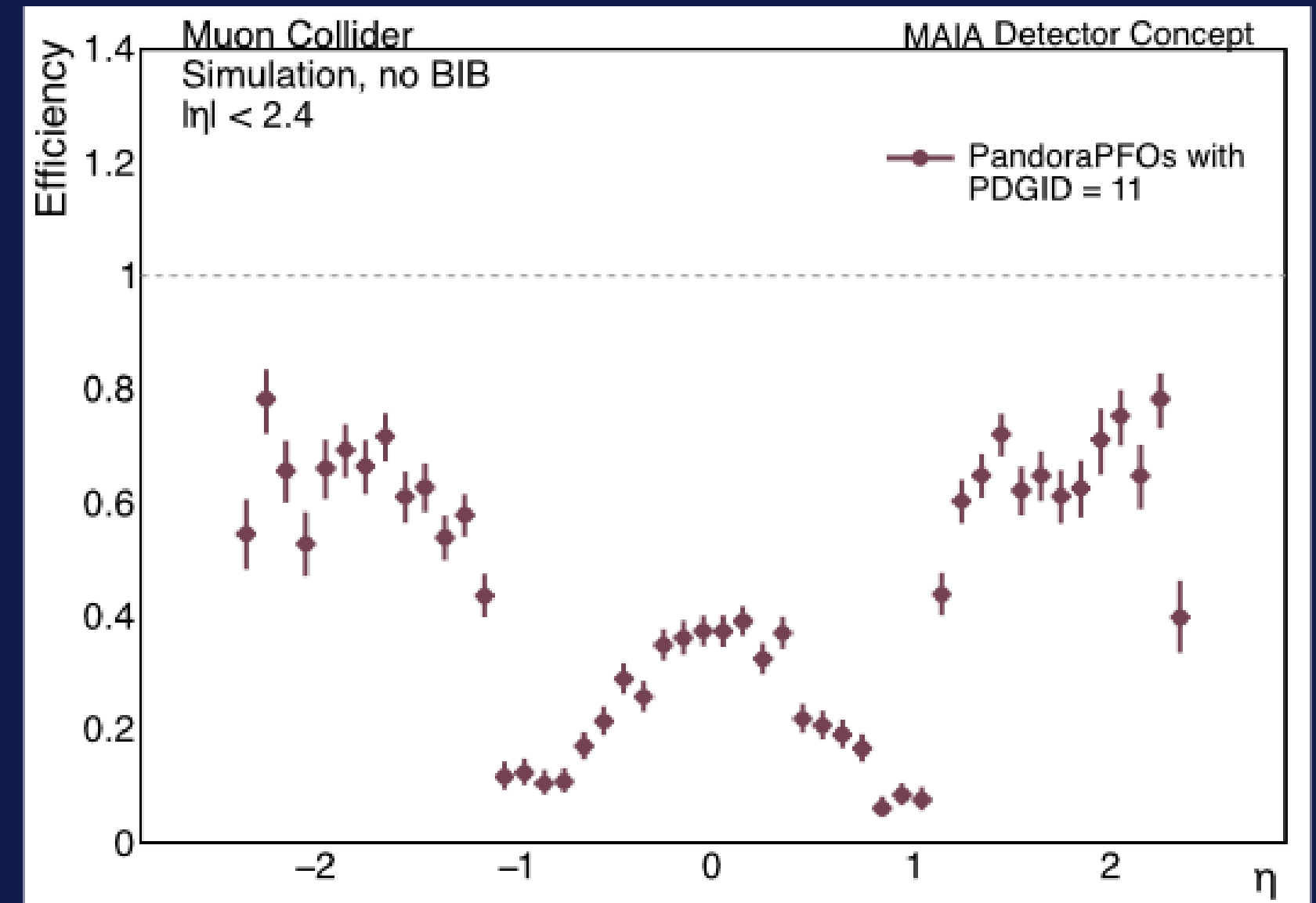
From a simulated electron gun
with no BIB

Pandora correctly reconstructs
36.9% of electrons

Electron Reconstruction Efficiency

From a simulated electron gun
with no BIB

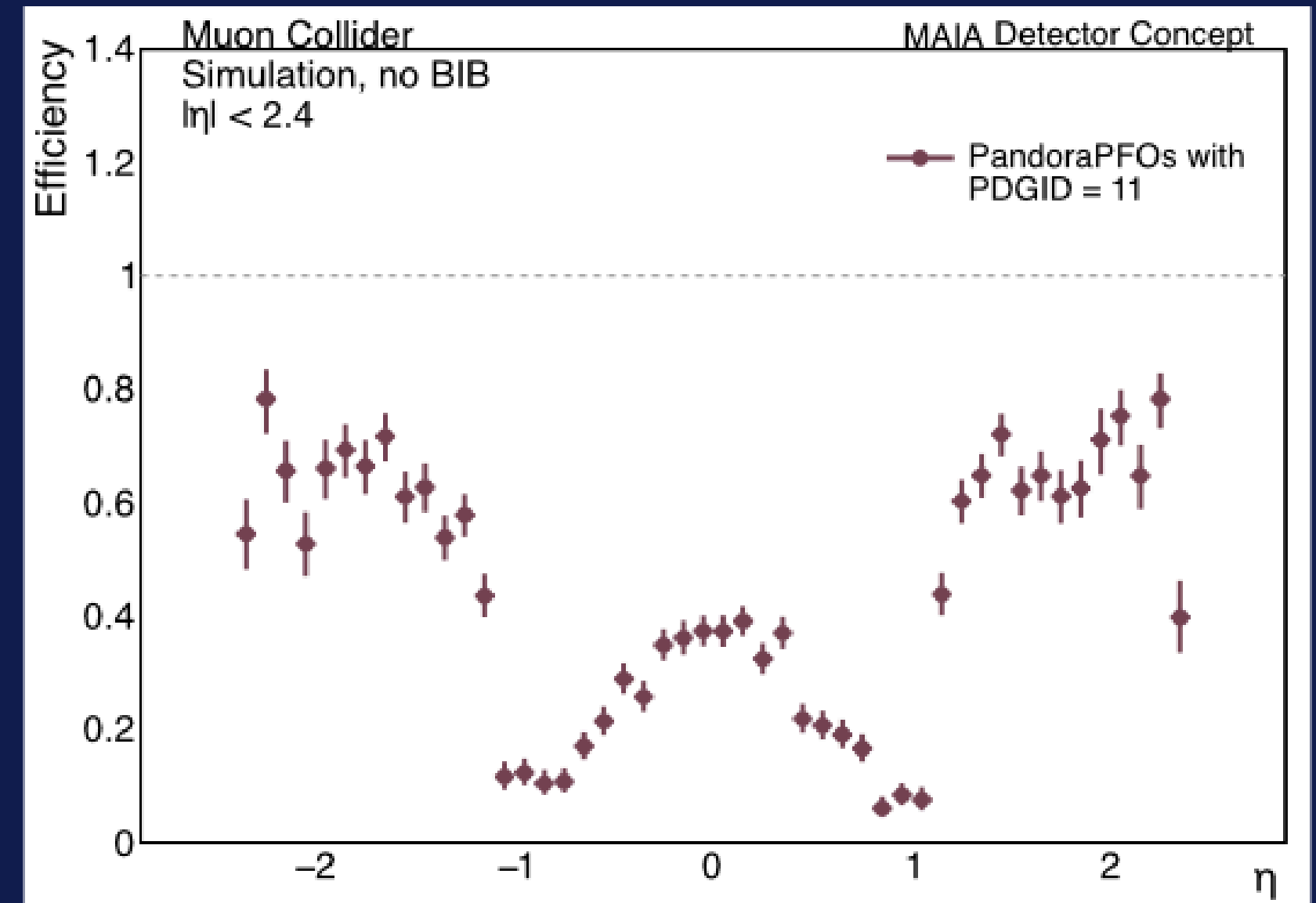
Pandora correctly reconstructs
36.9% of electrons



Efficiency of Pandora IDing PFOs as electrons. Denominator: total # of truth electrons, $p_T > 10$ GeV. Numerator: Number of PFOs with PDGID == 11, $p_T > 2$ GeV.

Electron Reconstruction Efficiency

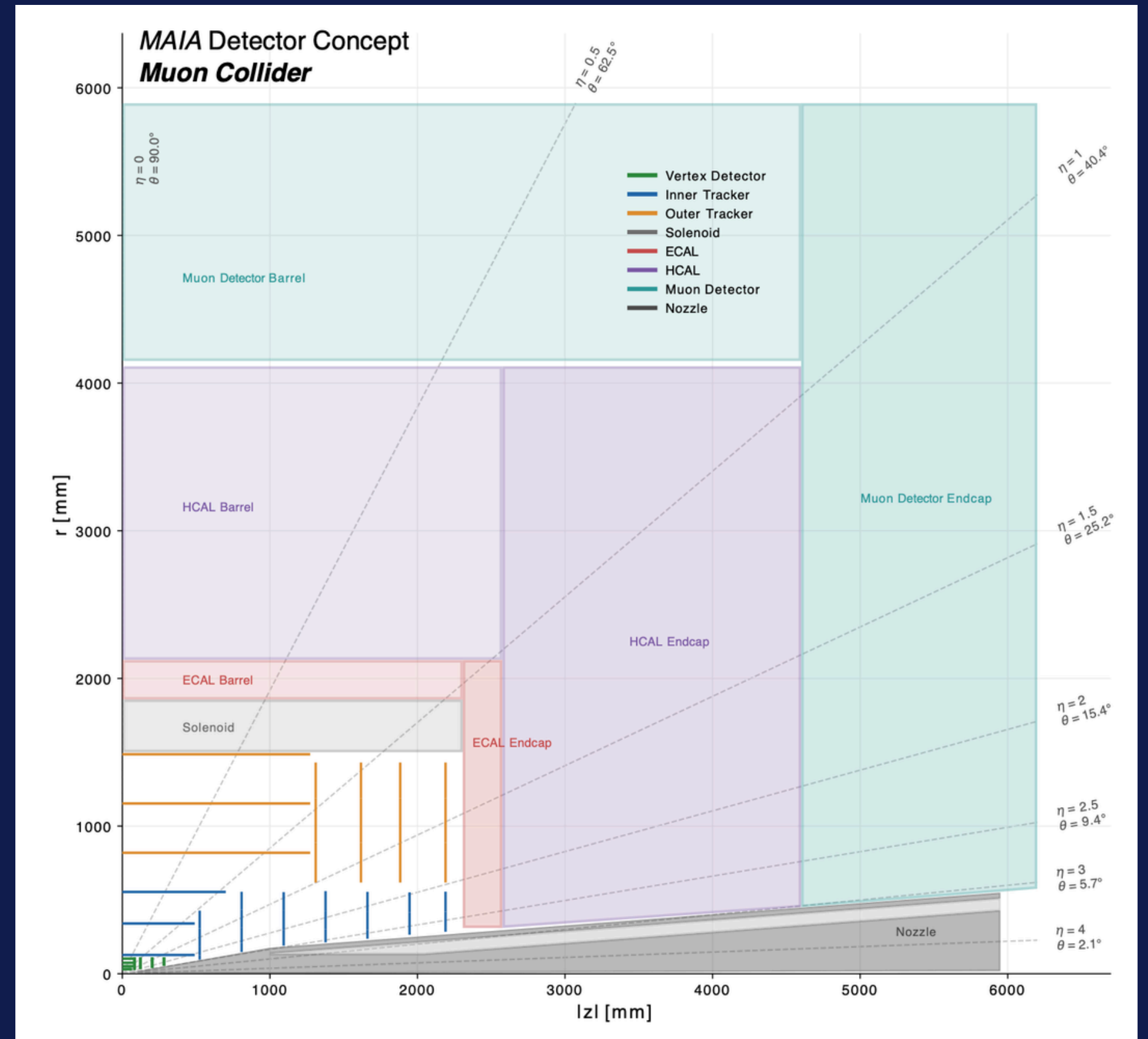
Region	Efficiency
$ \eta < 0.9$ — barrel	~38%
$ \eta \approx 1$ — transition region	< 10%
$1.5 < \eta < 2.4$ — endcap	60-80%



Efficiency of Pandora IDing PFOs as electrons. Denominator: total # of truth electrons, $p_T > 10$ GeV. Numerator: Number of PFOs with PDGID == 11, $p_T > 2$ GeV.

Electron Reconstruction Efficiency

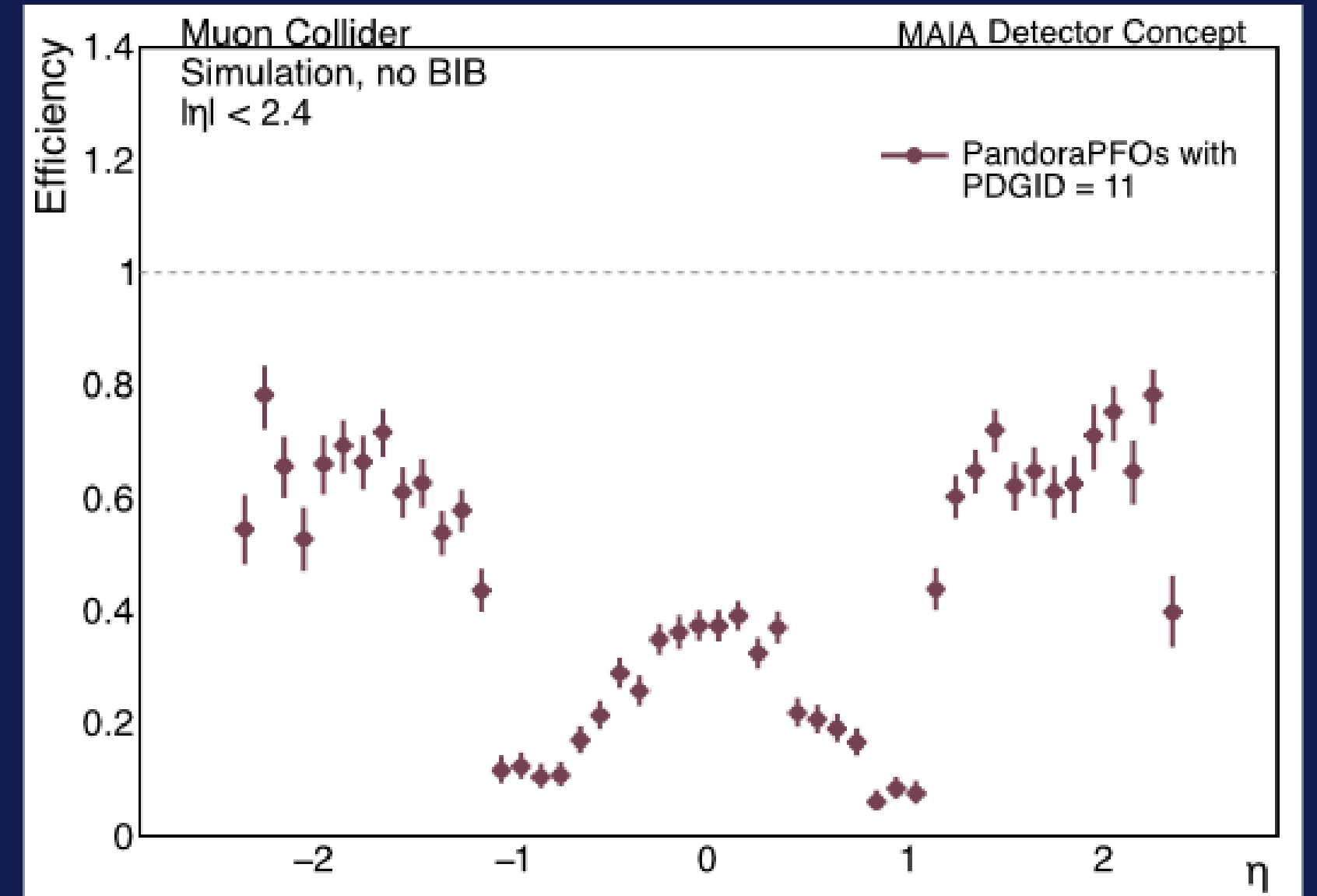
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$ \eta < 0.9$ — barrel	~38%
$ \eta \approx 1$ — transition region	< 10%
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Electron Reconstruction Efficiency

Pandora's Default Electron ID

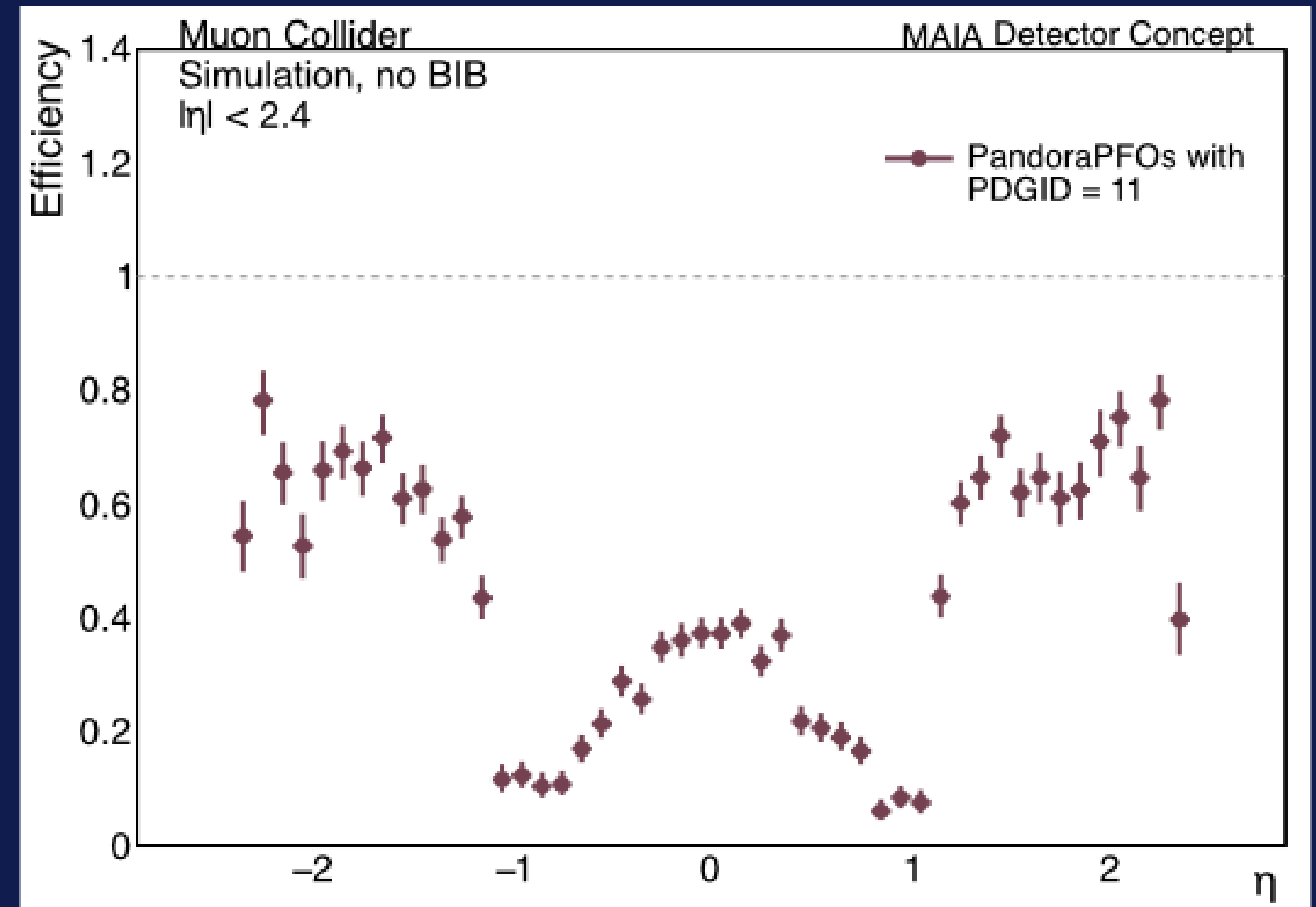
Variable	Value
Max inner layer	4
Max energy	5 GeV
Max profile start	4.5
Max profile discrepancy	0.6
Max E/p residual	0.2



Efficiency of Pandora IDing PFOs as electrons. Denominator: total # of truth electrons, $p_T > 10$ GeV. Numerator: Number of PFOs with PDGID == 11, $p_T > 2$ GeV.

Electron Reconstruction Efficiency

Since these variables are not optimized for MAIA yet, we need **another way to identify electrons rather than relying on Pandoras ID**



Efficiency of Pandora IDing PFOs as electrons. Denominator: total # of truth electrons, $p_T > 10$ GeV. Numerator: Number of PFOs with PDGID == 11, $p_T > 2$ GeV.

Electron Reconstruction Efficiency

Region

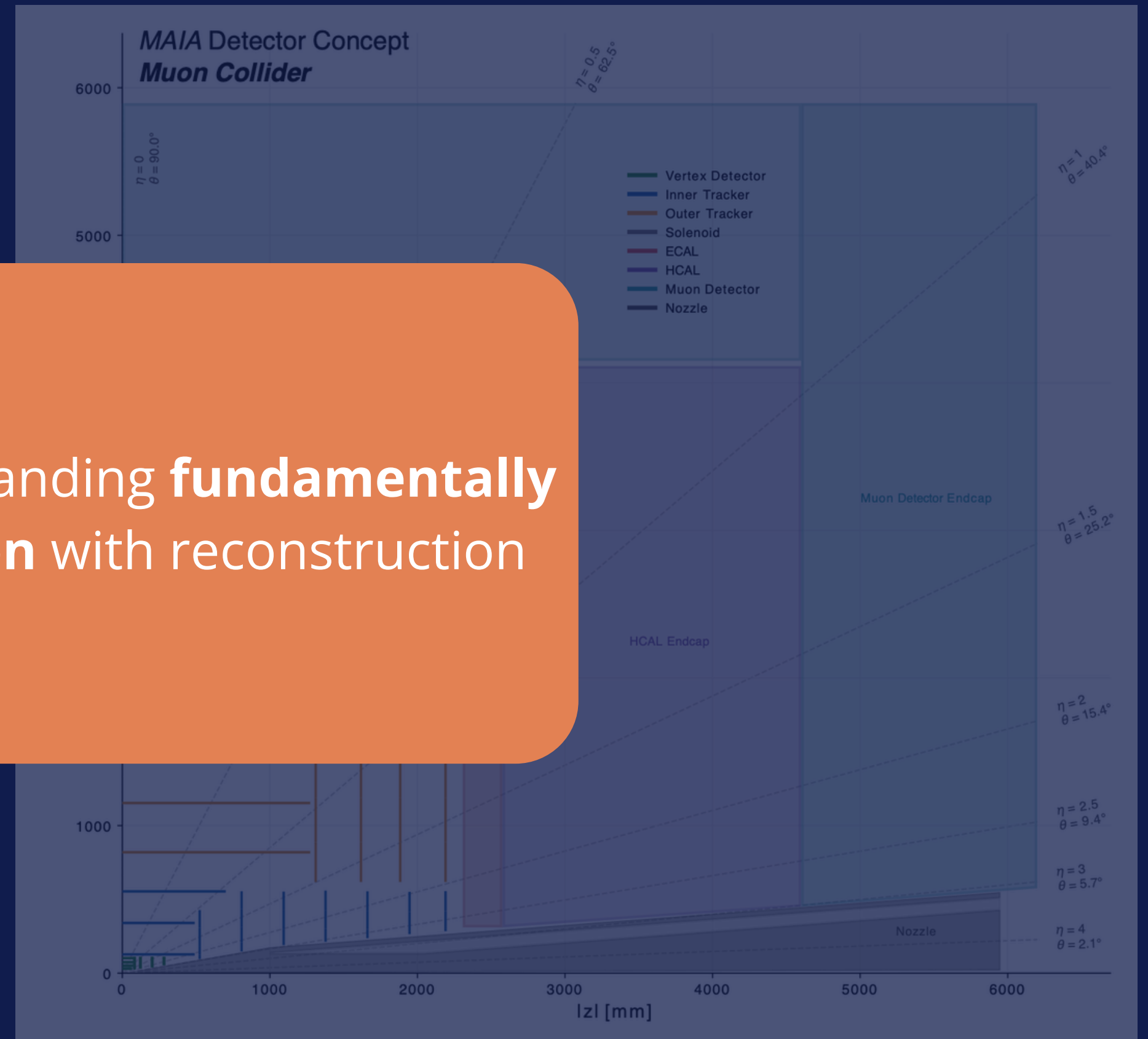
$|\eta| < 0.9$ — barrel

$|\eta| \approx 1$ — transition
region

$1.5 < |\eta| < 2.4$ —
endcap

Efficiency

Start by understanding **fundamentally**
what is going on with reconstruction



Electron Reconstruction Efficiency

Region

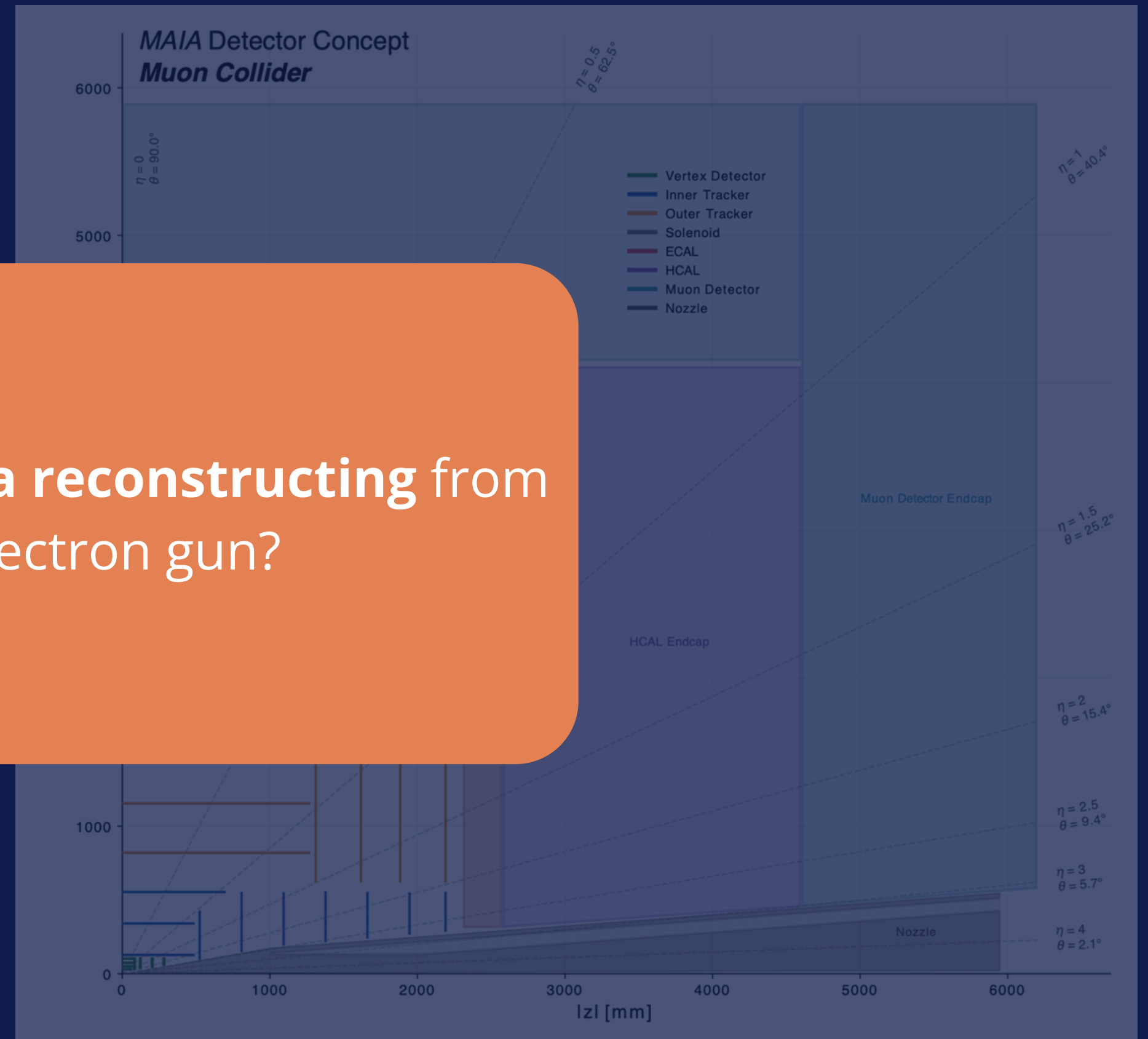
$|\eta| < 0.9$ — barrel

$|\eta| \approx 1$ — transition
region

$1.5 < |\eta| < 2.4$ —
endcap

Efficiency

What is Pandora reconstructing from
the electron gun?



What is being reconstructed?

Electrons, neutrons,
pions, and photons

What is being reconstructed?

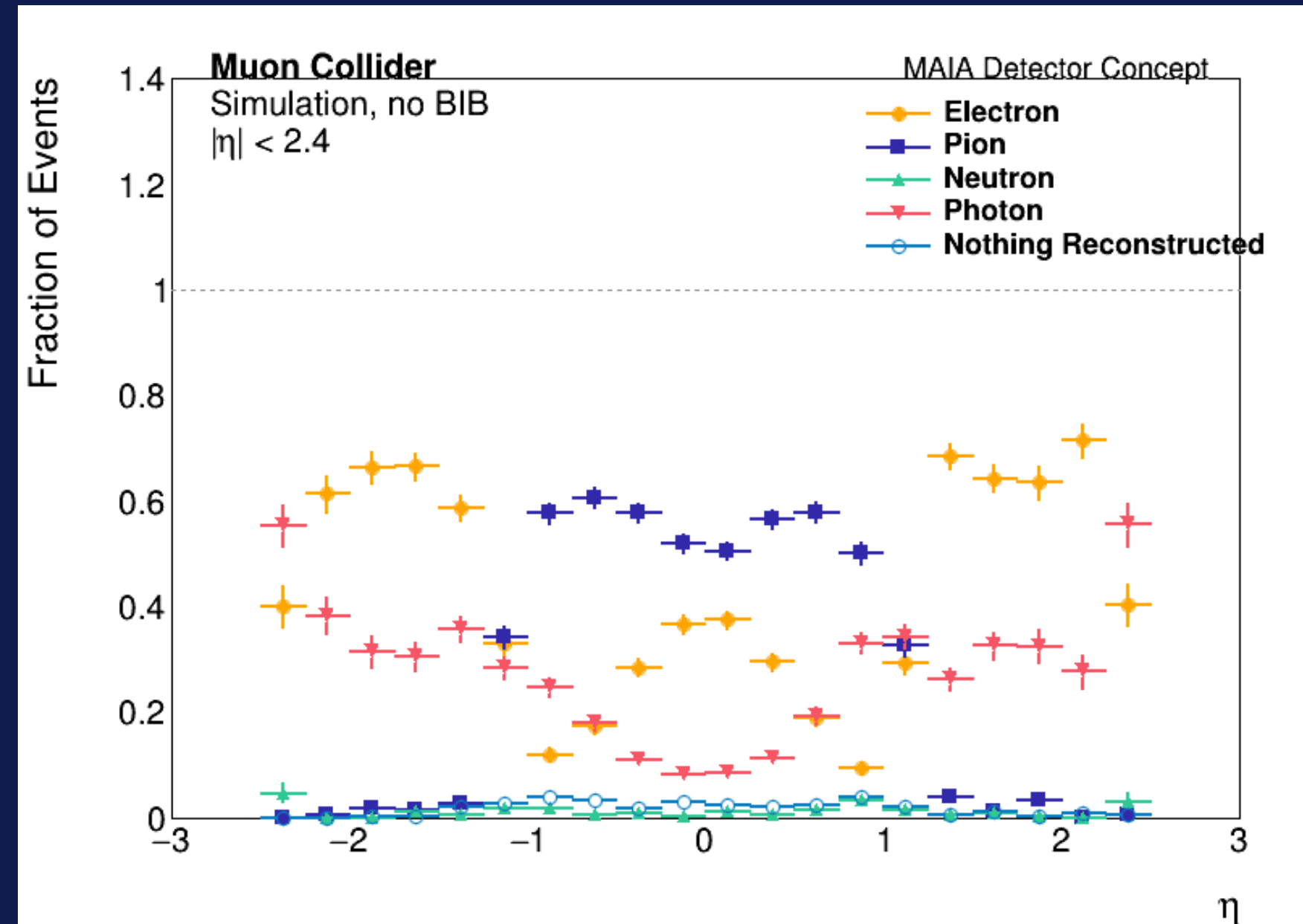
Electrons, neutrons,
pions, and photons

Majority of
misidentification
comes from electron
energy being **ID as
charged pions**

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Electrons, neutrons,
pions, and photons

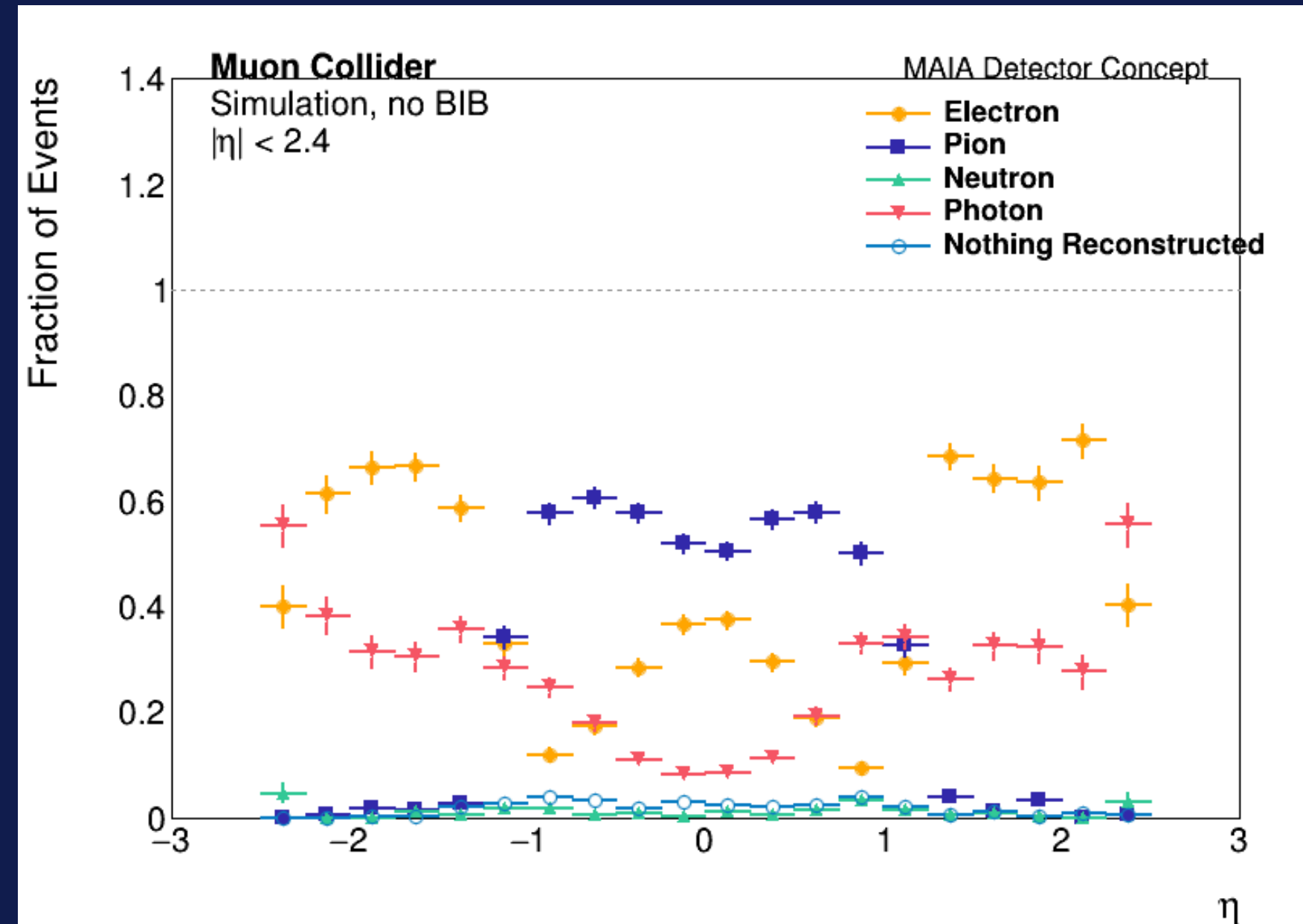
Majority of
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Electron gun sample, with leading PFO being plotted. The names “pion”, “neutron” etc are named based on what Pandora id the PFOs as, not what is actually there.

Why is this happening?

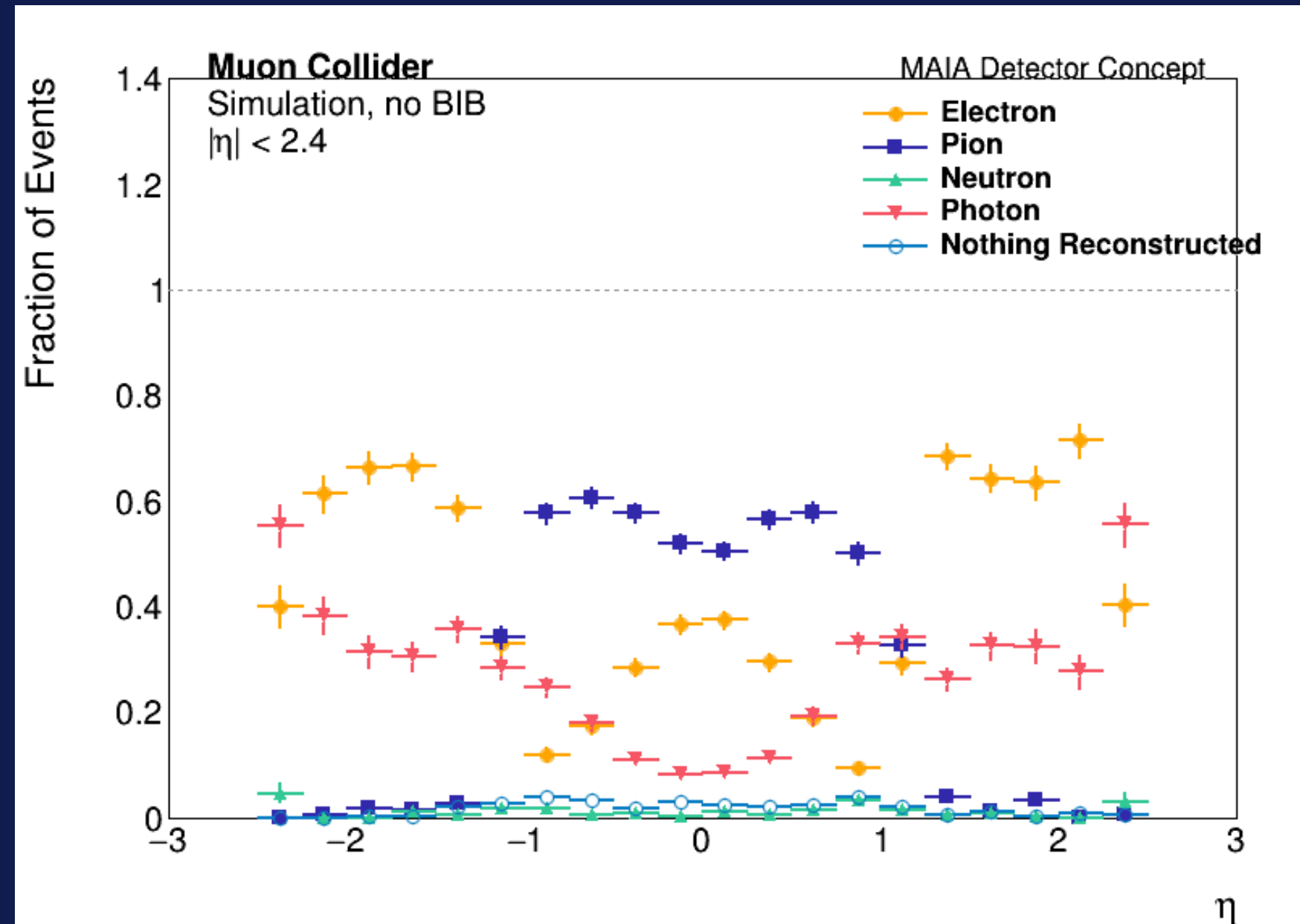
- In Pandora particle flow, there is no set pion ID



Electron gun sample, with leading PFO being plotted. The names “pion”, “neutron” etc are named based on what Pandora id the PFOs as, not what is actually there.

Why is this happening?

- In Pandora particle flow, there is no set pion ID
- The flow:
 - Muons and electrons are reconstructed
 - All other charged particles are identified as charged pions

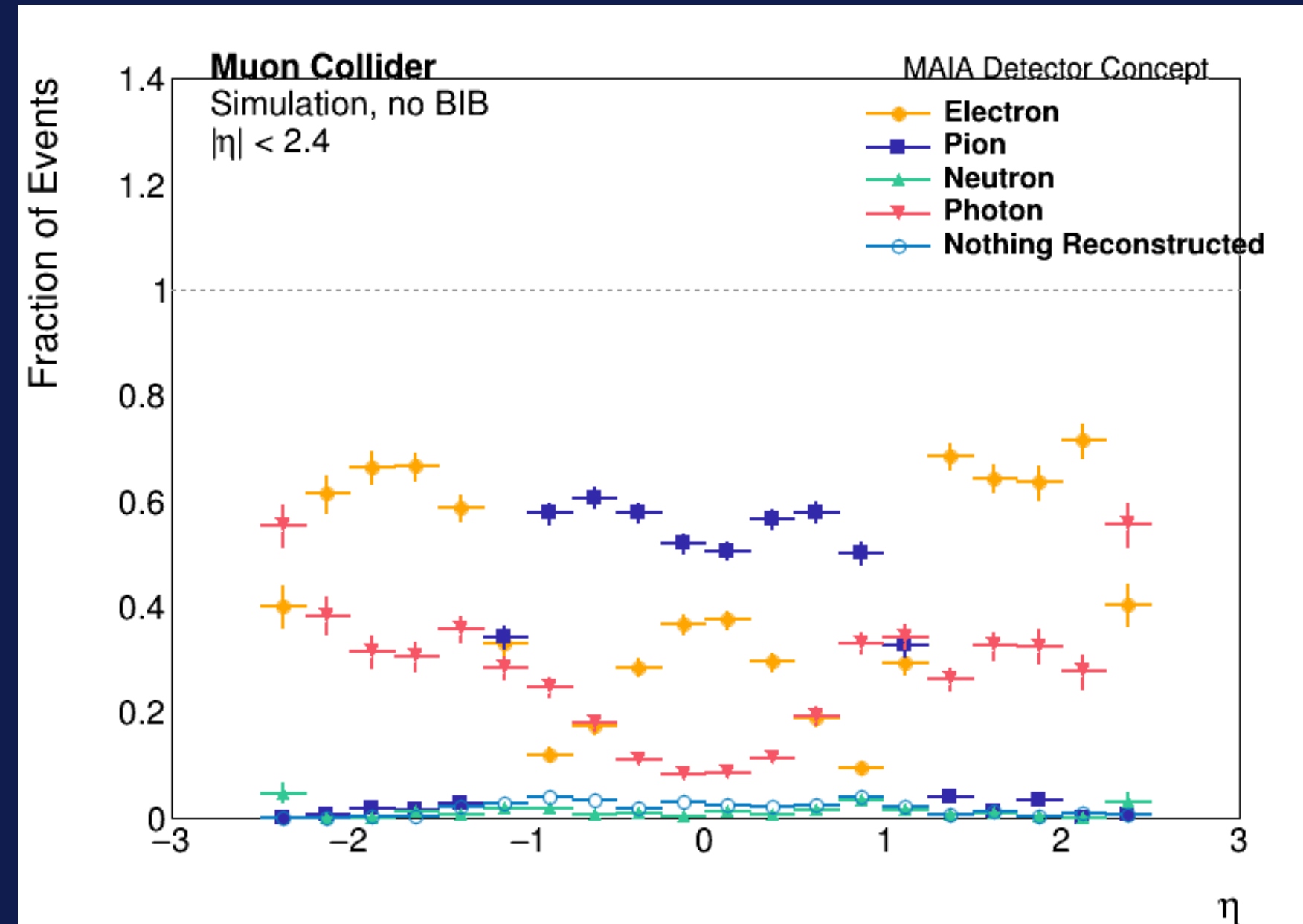


Electron gun sample, with leading PFO being plotted. The names “pion”, “neutron” etc are named based on what Pandora id the PFOs as, not what is actually there.

Why is this happening?

- In Pandora particle flow, there is no set pion ID
- The flow:
 - Muons and electrons are reconstructed
 - All other charged particles are identified as charged pions

So, we need an **electron and pion discriminator!**



Electron gun sample, with leading PFO being plotted. The names “pion”, “neutron” etc are named based on what Pandora id the PFOs as, not what is actually there.

Electron and Pion Discrimination

Similarities

Differences

Electron and Pion Discrimination

Similarities

- Charged particles that ionize as they pass through the detector
- Leaves hits in the tracker that form tracks
- Shower in the calorimeters producing clusters

Differences

Electron and Pion Discrimination

Similarities

- Charged particles that ionize as they pass through the detector
- Leaves hits in the tracker that form tracks
- Shower in the calorimeters producing clusters

Differences

- Electrons interact electromagnetically + lose energy through bremsstrahlung.
- Pions interact via the strong force and undergo nuclear interactions, which produces secondary hadrons
- The scale for electrons is the radiation length (X_0) while for pions it's the nuclear interaction length (λ), which is much longer

Electron and Pion Discrimination

Similarities

- Charge
- Ionization
- the
- Lead
- that
- Shower
- pro

Differences

The main differences stem from **how the showers shapes develop**

radiation length (X_0) while for pions it's the nuclear interaction length (λ), which is much longer

Electron and Pion Discrimination

Similarities

- Charge
- Ionization
- the
- Lepton
- that
- Shower
- pro

Differences

Shower development is dependent on energy, so the natural first step is to check if **energy is calibrated correctly**

lose energy
ng.
strong force
interactions,
dary

is the
radiation length (X_0) while for pions
it's the nuclear interaction length
(λ), which is much longer

Energy Reconstruction

- Cluster **energy** is used multiple times during particle reconstruction:
 - EM vs hadronic decision
 - Track + cluster association and cluster merging
 - Track momentum and cluster energy association

If cluster energy is initially wrong, Pandora reconstructs the wrong particle.

Is the cluster energy being calibrated correctly?

Calibration, Pandora's Way

- MAIA has a sampling calorimeter, meaning **calibration is needed** to convert the measured signal back to the true particle energy

Calibration, Pandora's Way

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- **Pandora originally used a global scale factor** to calibrate electromagnetic energy

Calibration, Pandora's Way

- MAIA has a sampling calorimeter, meaning **calibration is needed** to convert the measured signal back to the true particle energy
- **Pandora originally used a global scale factor** to calibrate electromagnetic energy



What Does This Mean?

Regardless of the position or energy
of the particle, if it was identified as EM
it would be **multiplied by 1.38**

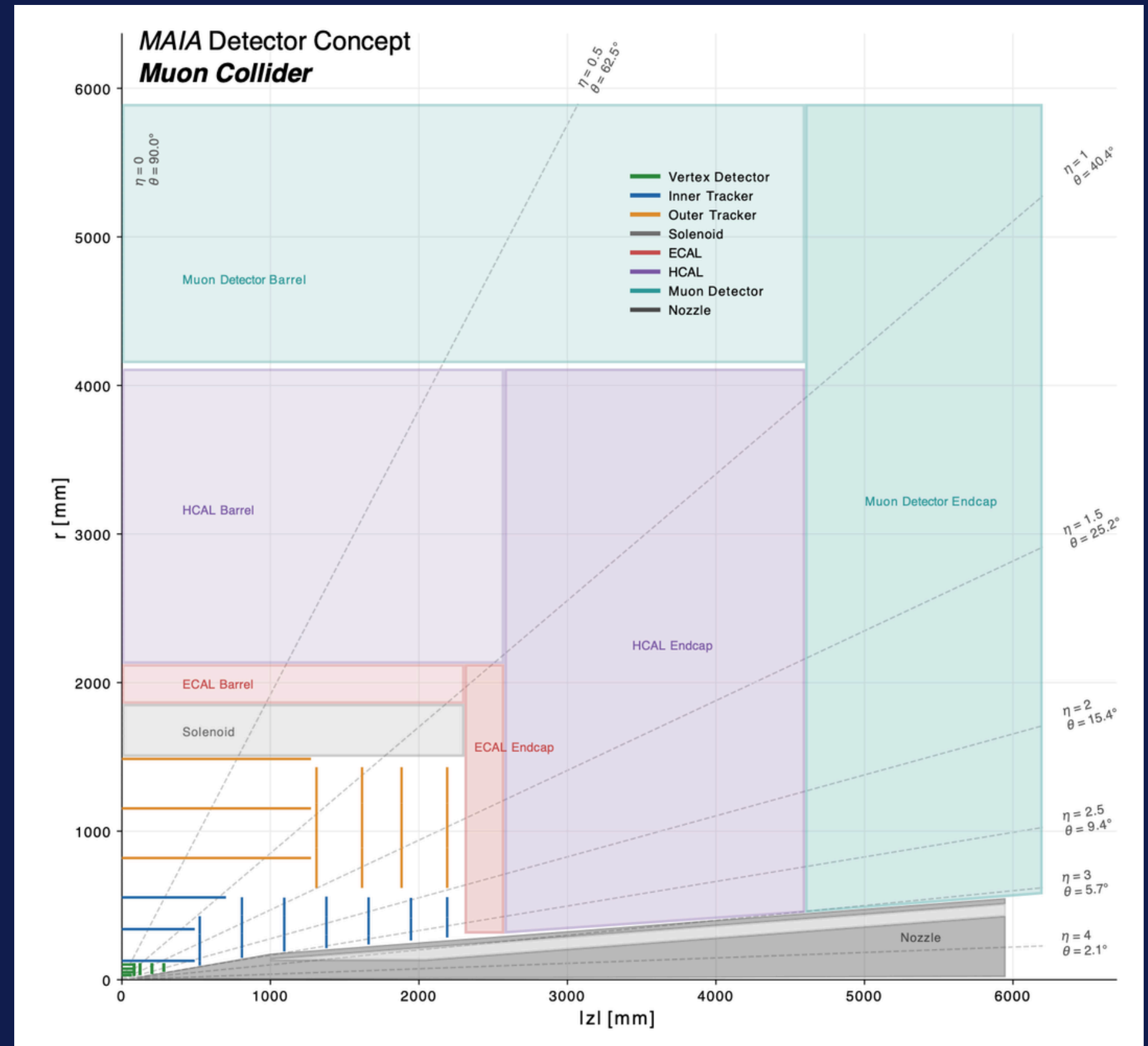
What Does This Tell Us?

If cluster energy is scaled incorrectly, Pandora is going to **mis-reconstruct the energy and misidentify the particle.**

Energy and Theta Dependent Calibrations

Theta dependence

Energy dependence

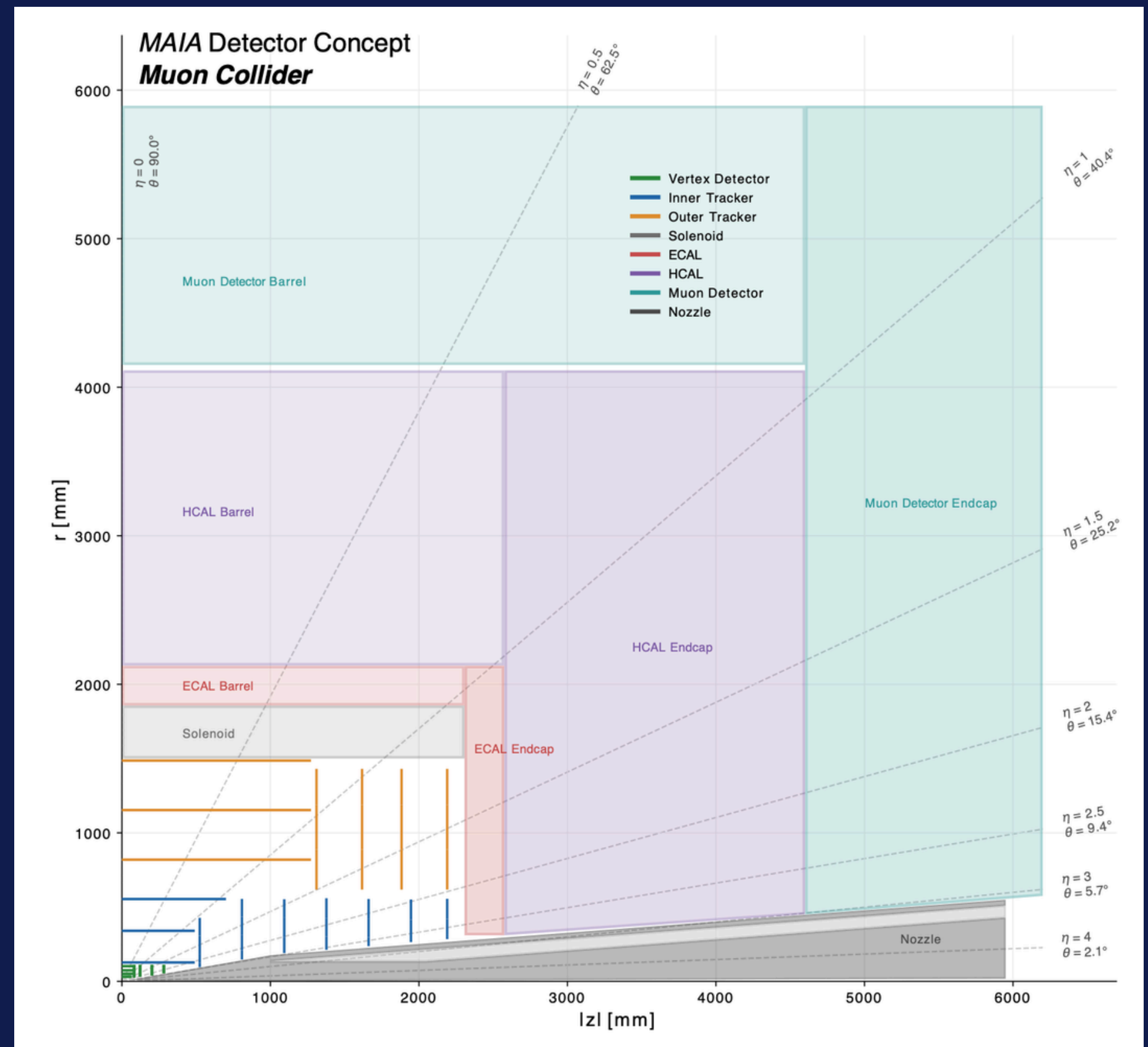


Energy and Theta Dependent Calibrations

Theta dependence

Depending on where in theta the particle is, it traverses through more or less material

Energy dependence



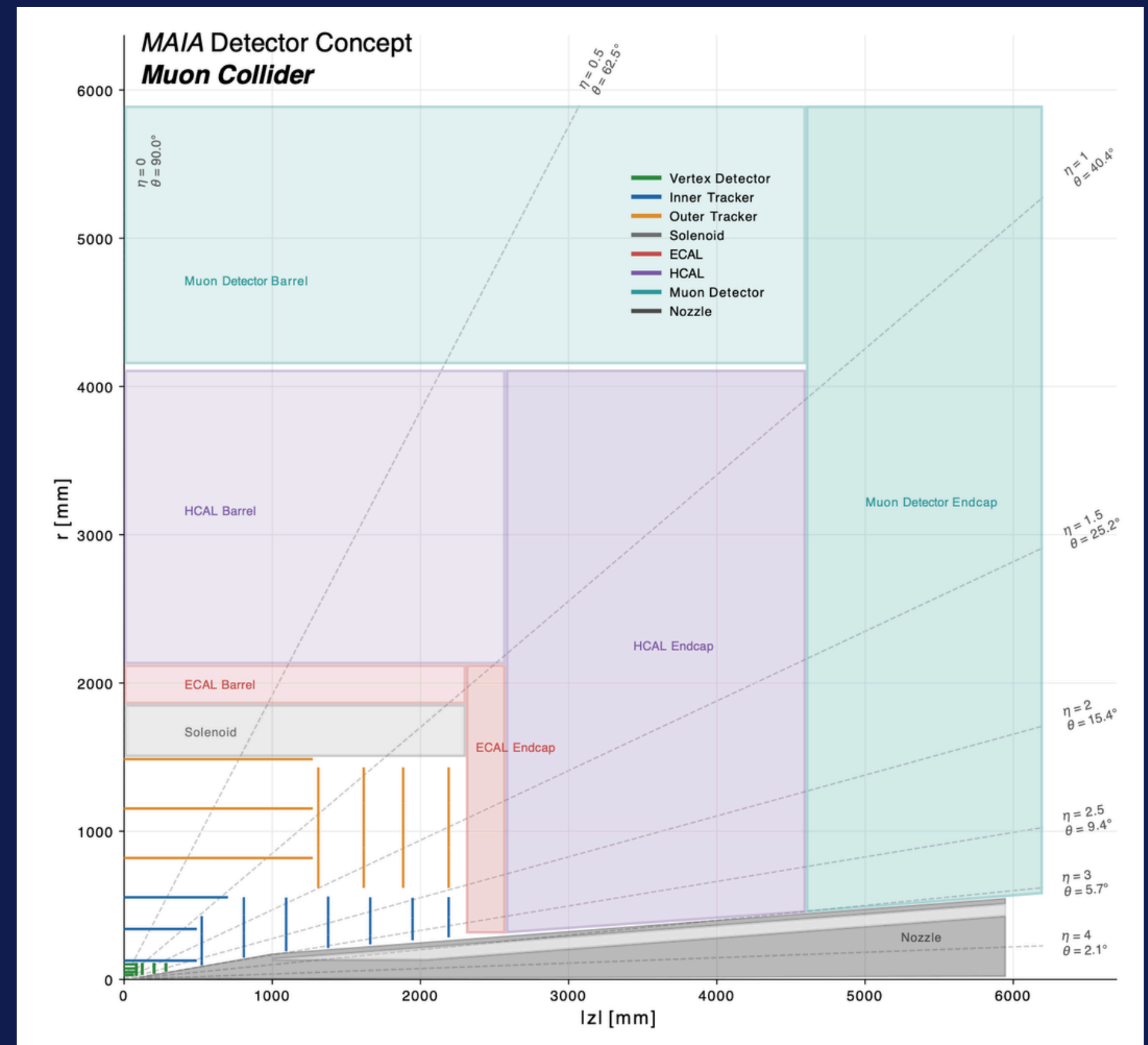
Energy and Theta Dependent Calibrations

Theta dependence

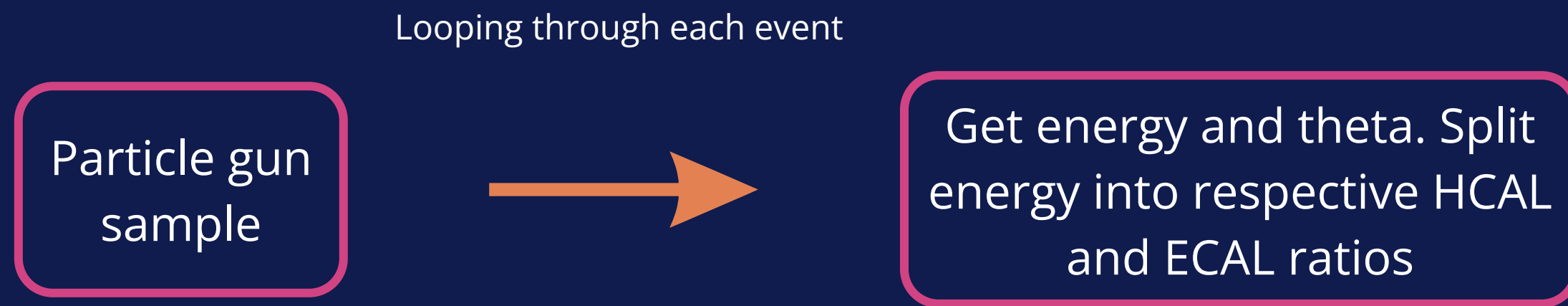
Depending on where in theta the particle is, it traverses through more or less material

Energy dependence

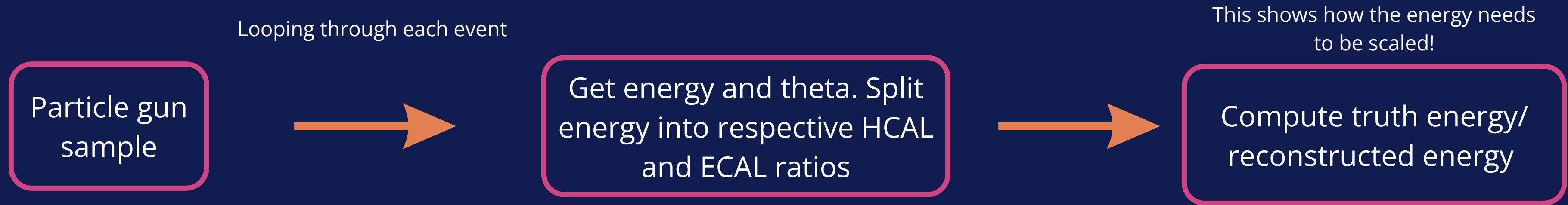
The fraction of the shower we measure changes with the energy of the particle



Calibration Factors



Calibration Factors



Calibration Factors

Looping through each event

Particle gun
sample



Get energy and theta. Split
energy into respective HCAL
and ECAL ratios



This shows how the energy needs
to be scaled!

Compute truth energy/
reconstructed energy



Put this ratio
into a theta and
energy bin



For each bin, take the median
of the ratio. **This is now the
scale factor for that bin!**

Calibration Factors

Looping through each event

Particle gun
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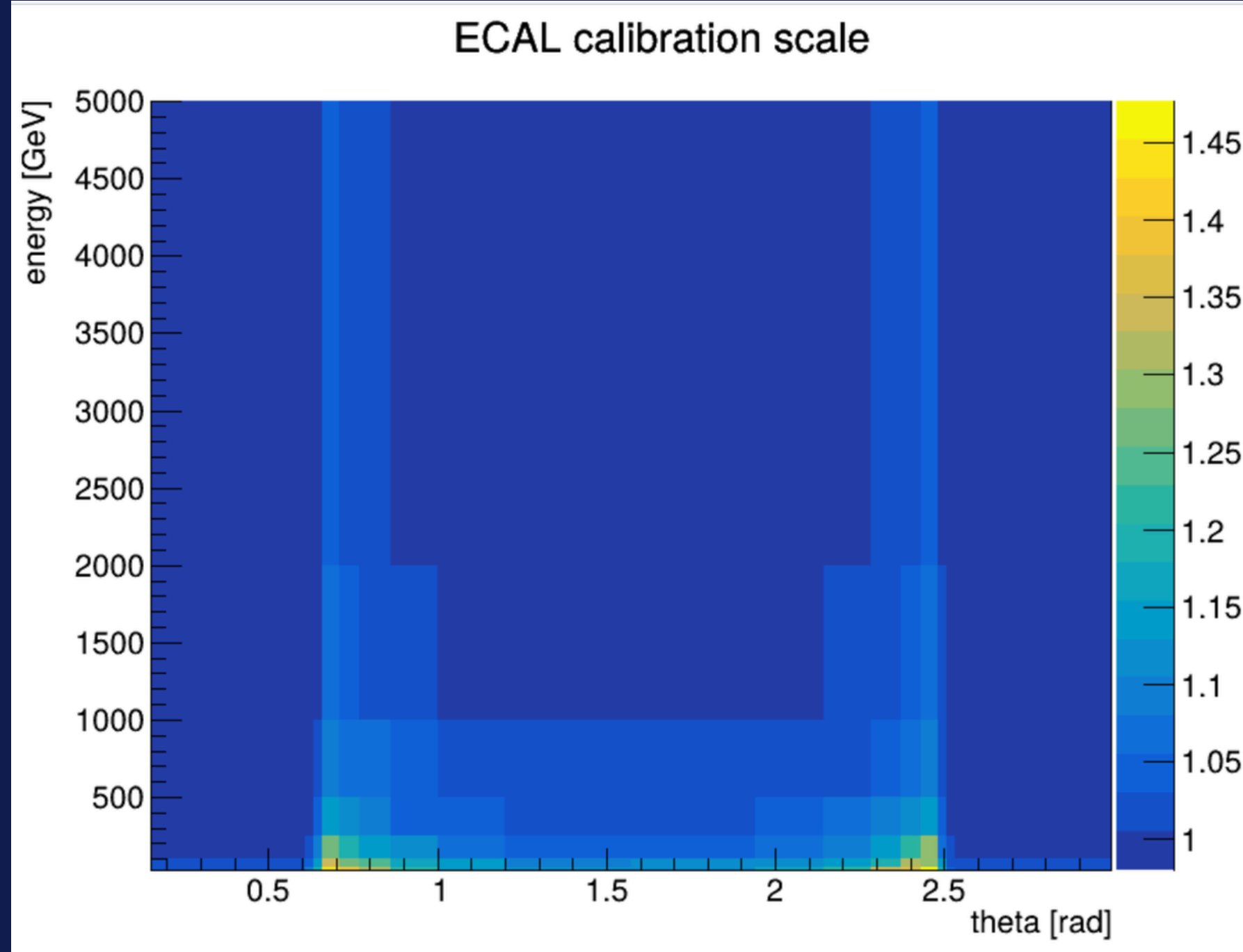


For each bin, take the median
of the ratio. **This is now the
scale factor for that bin!**



Scale factors are stored
and handed to Pandora
during reconstruction

Calibration Scale



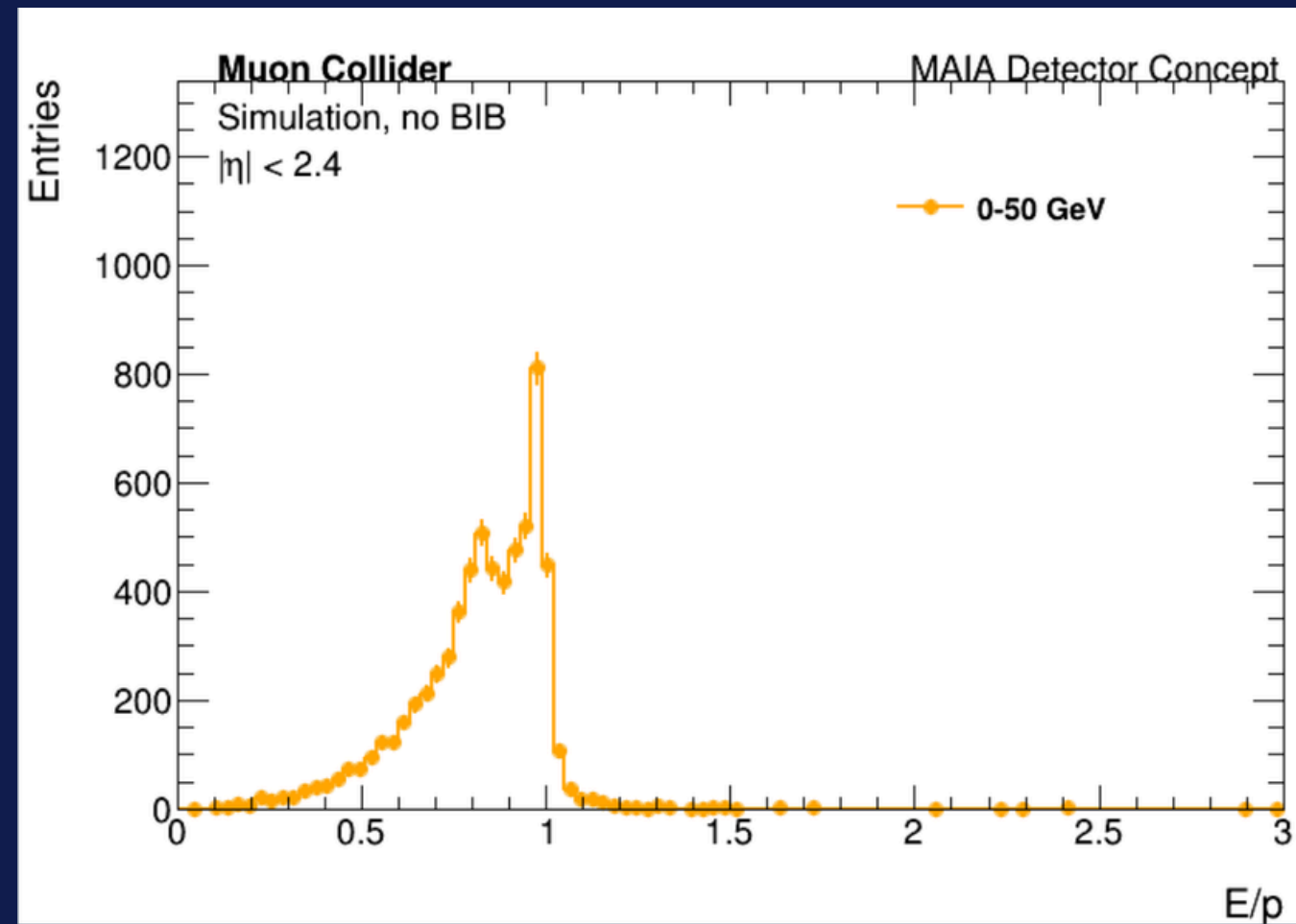
By using calibration factors during particle reconstruction, it allows for energy to be reconstructed more accurately. This calibration is trained on photons.

Results of Calibration

A way to tell if energy is closer to the expected value is by **studying the E/p** . For electrons, the E/p should be approximately 1.

Results of Calibration

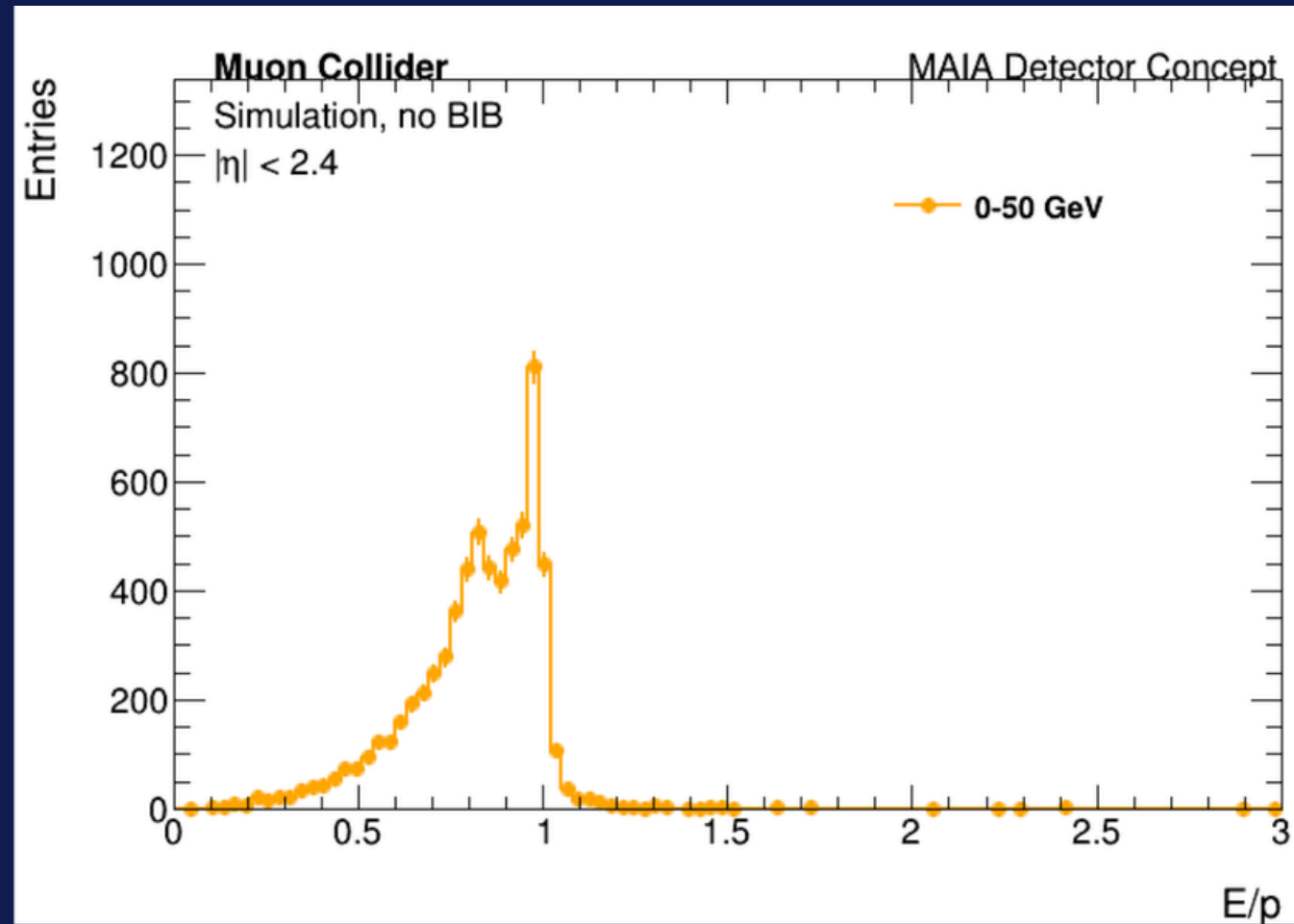
Before calibration



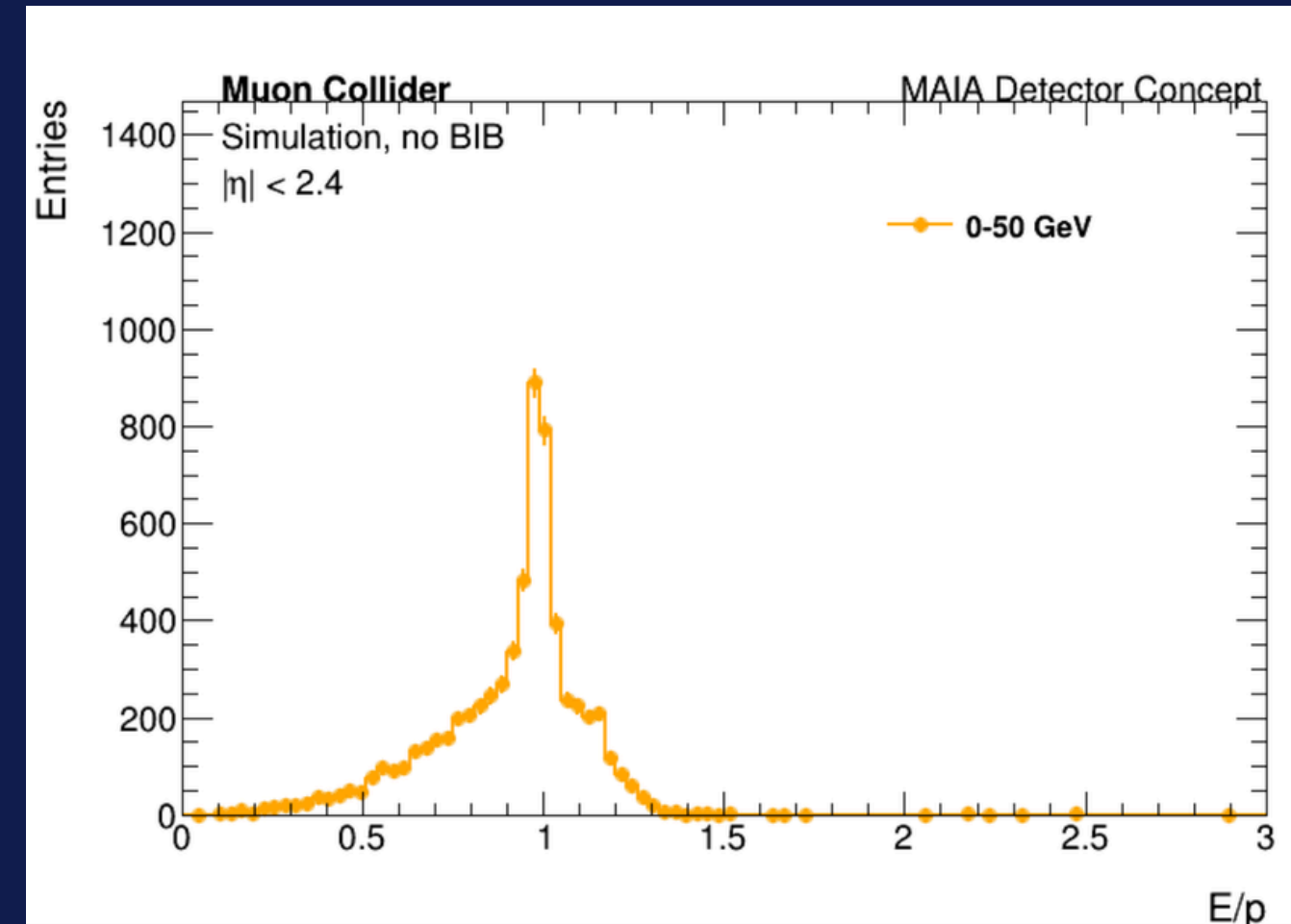
A way to tell if energy is closer to the expected value is by studying the E/p . For electrons, the E/p should be approximately 1.

Results of Calibration

Before calibration



After calibration



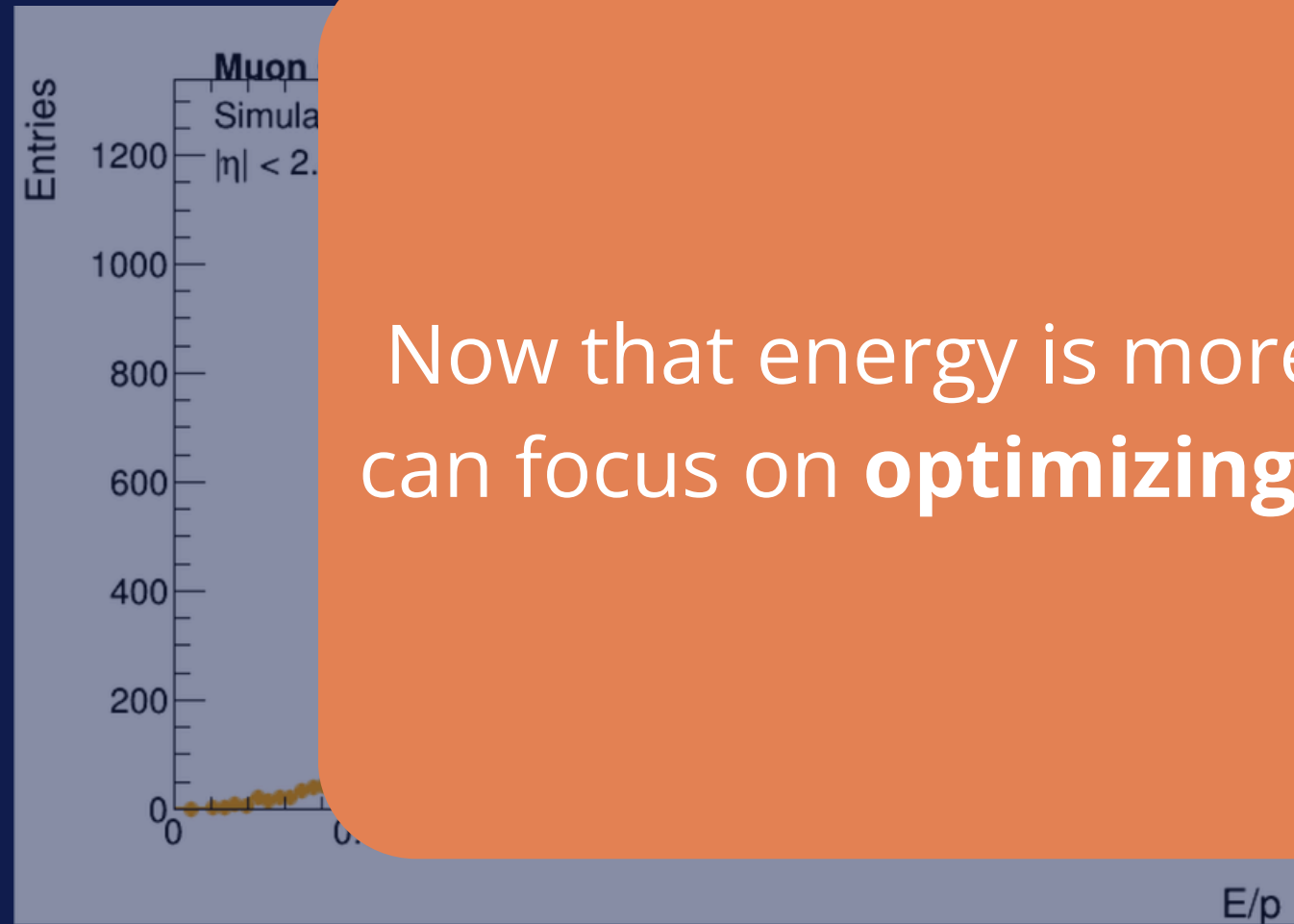
A way to tell if energy is closer to the expected value is by studying the E/p . For electrons, the E/p should be approximately 1.

Results of Calibration

Before calibration

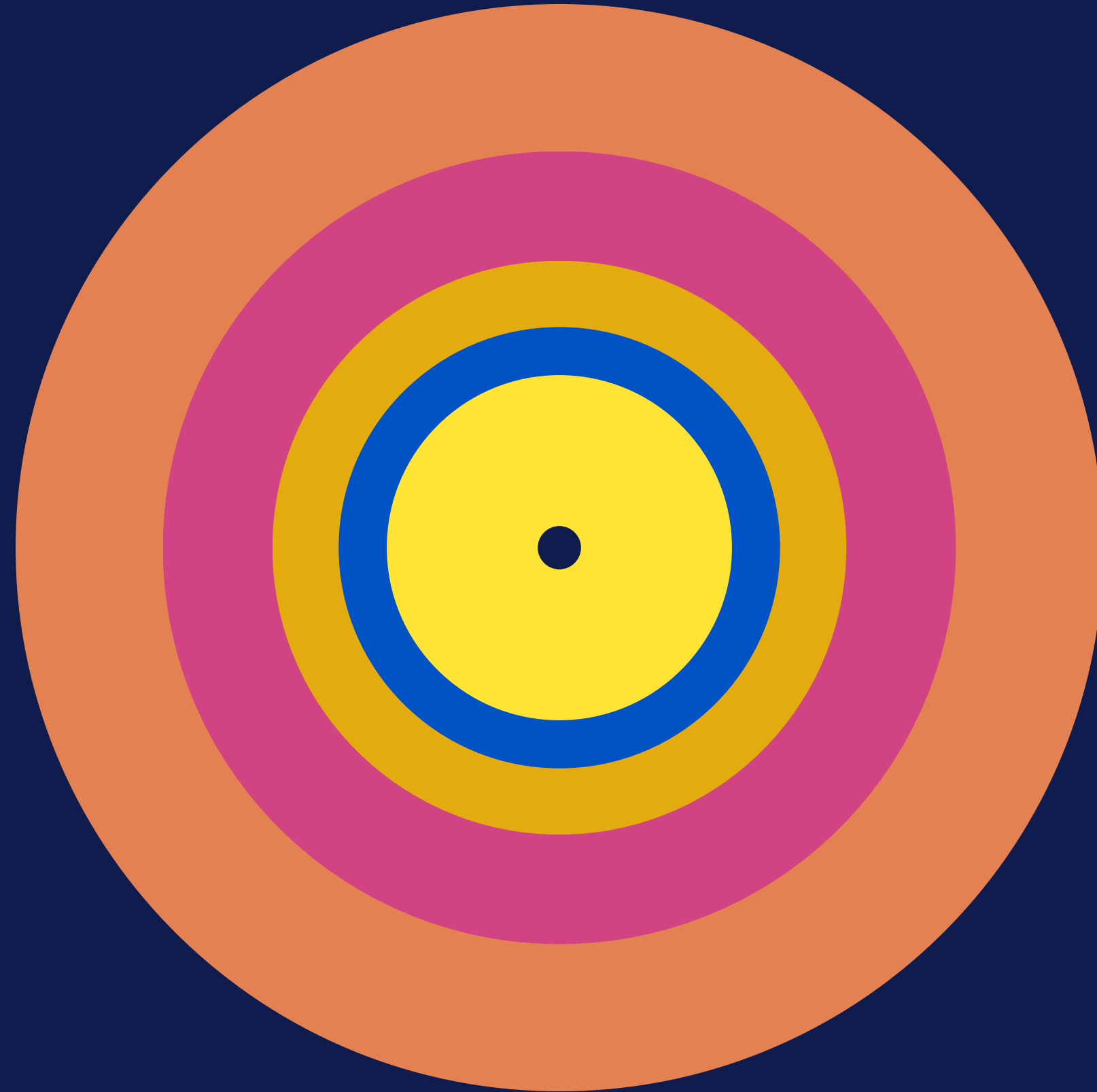
After calibration

Now that energy is more accurately reconstructed, we can focus on **optimizing how electrons are identified**

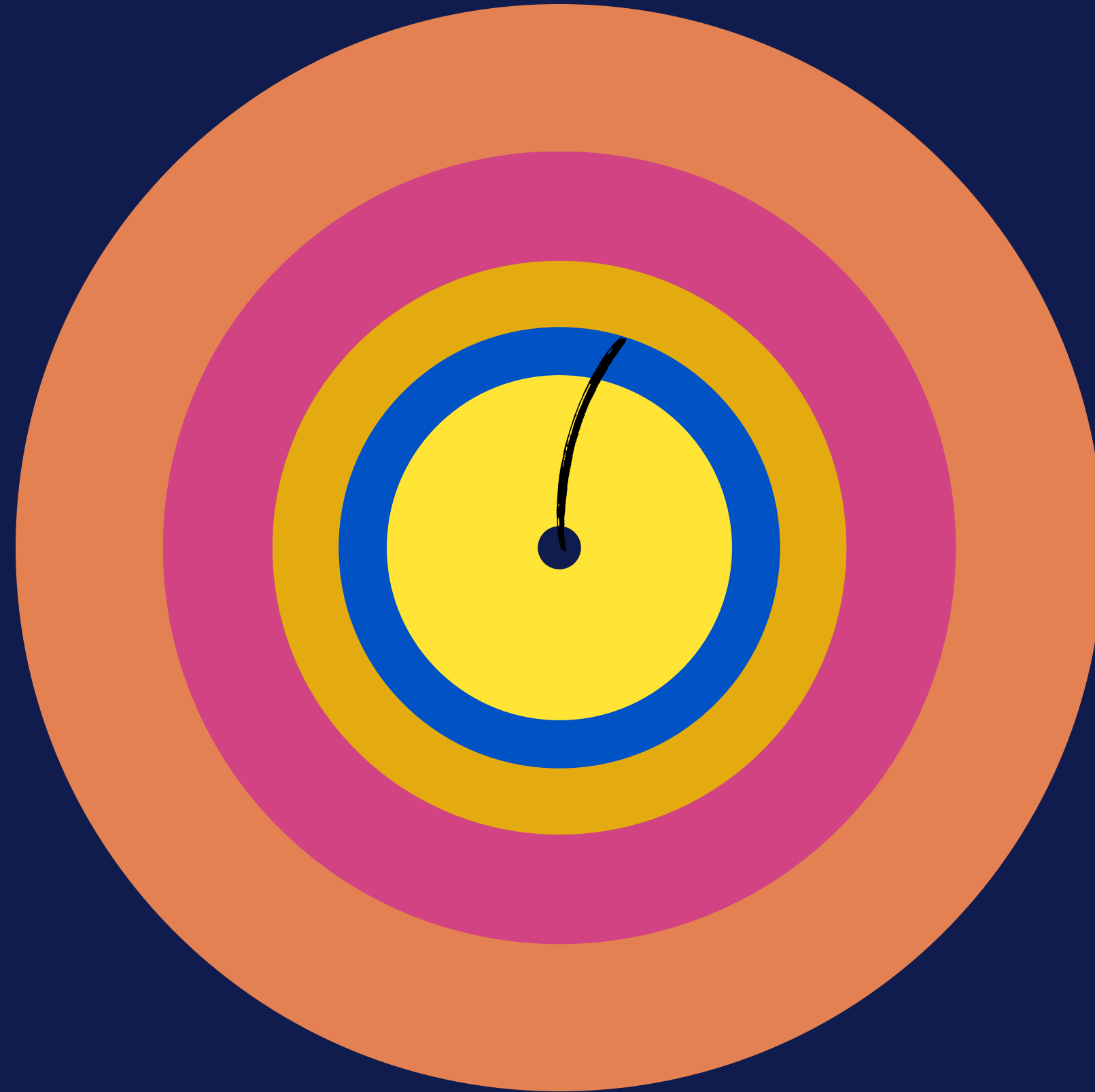


A way to tell if energy is closer to the expected value is by studying the E/p . For electrons, the E/p should be approximately 1.

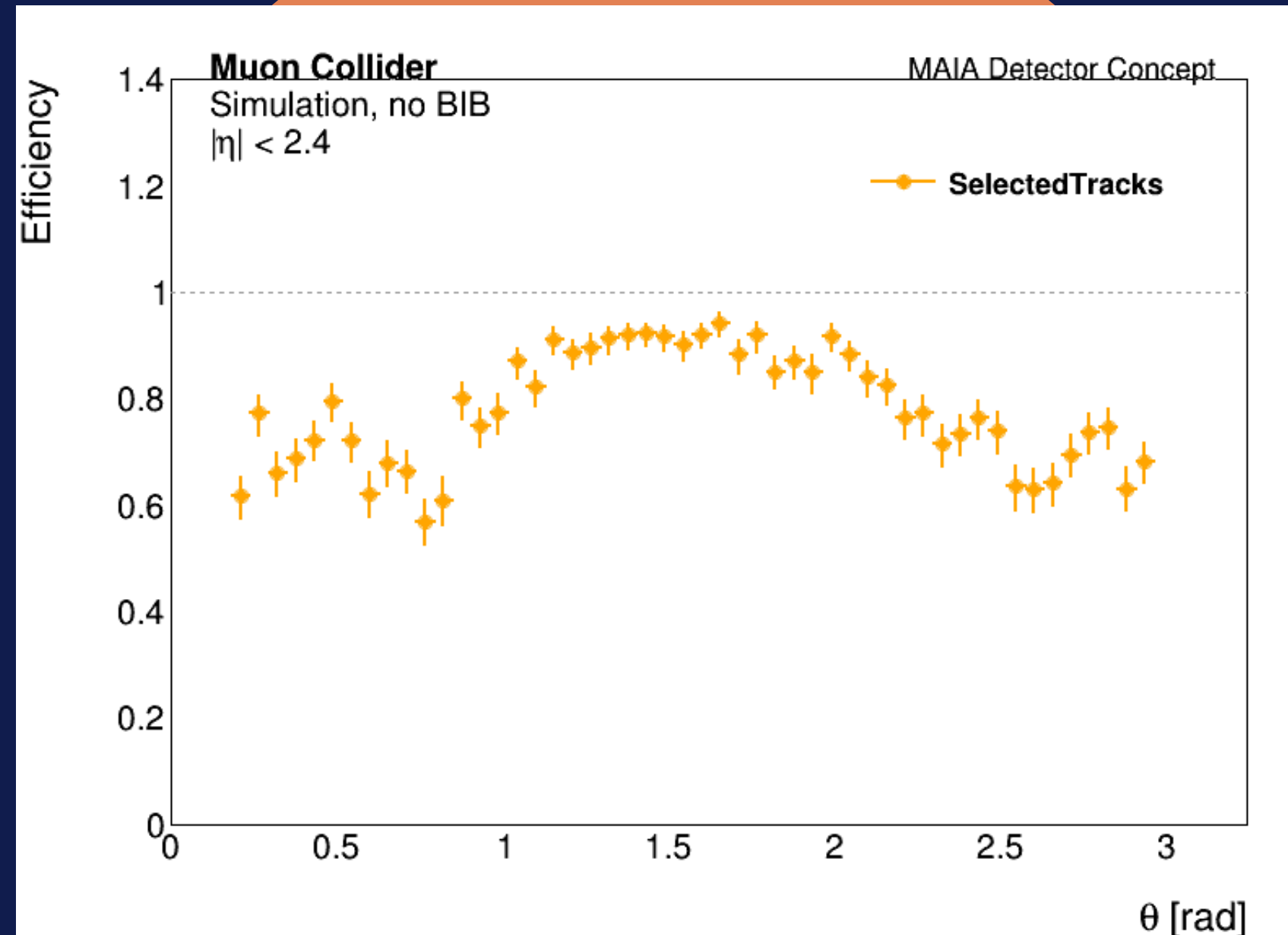
Components of Electron PFOs



Components of Electron PFOs

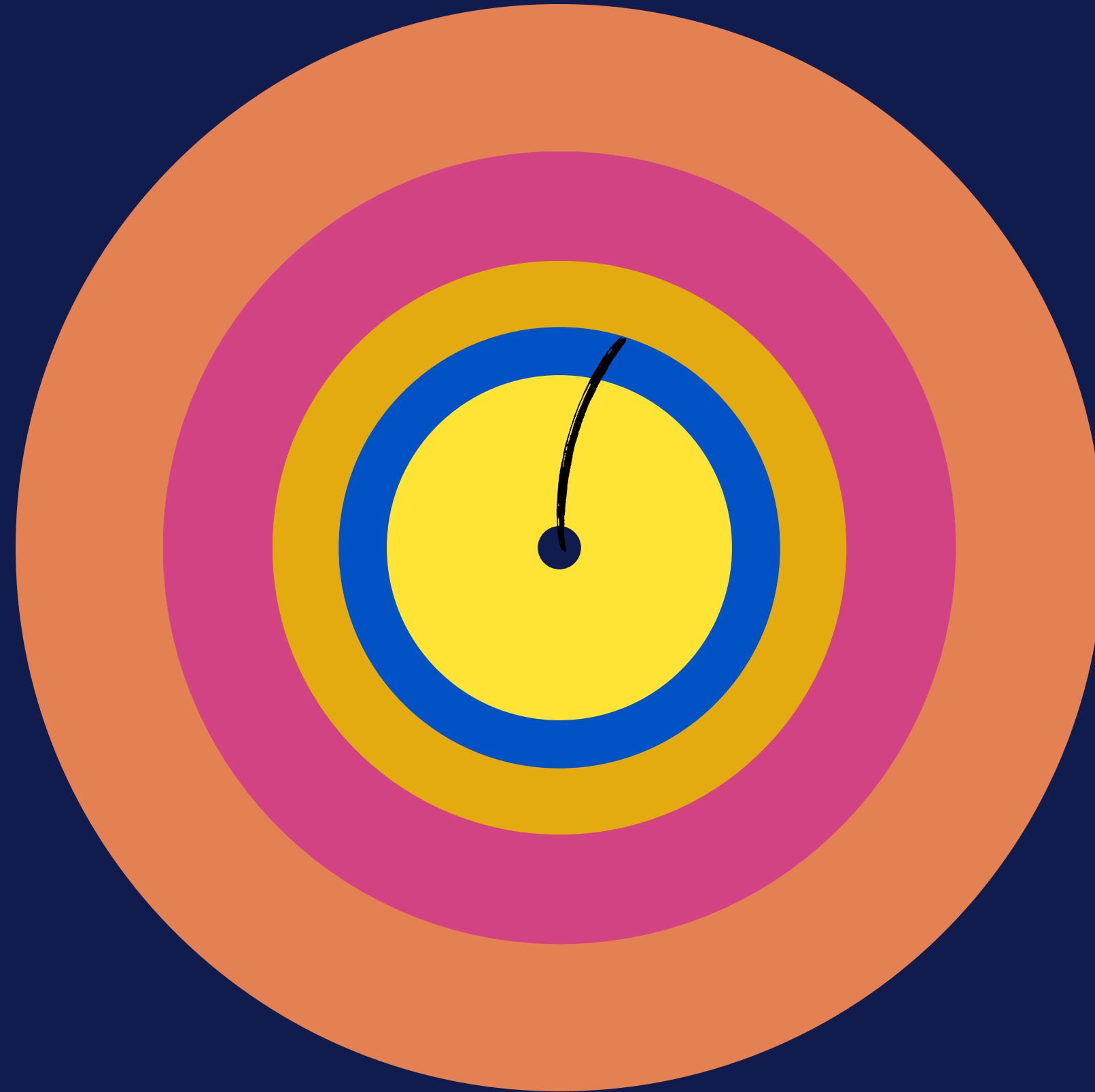


Components of Electron PFOs

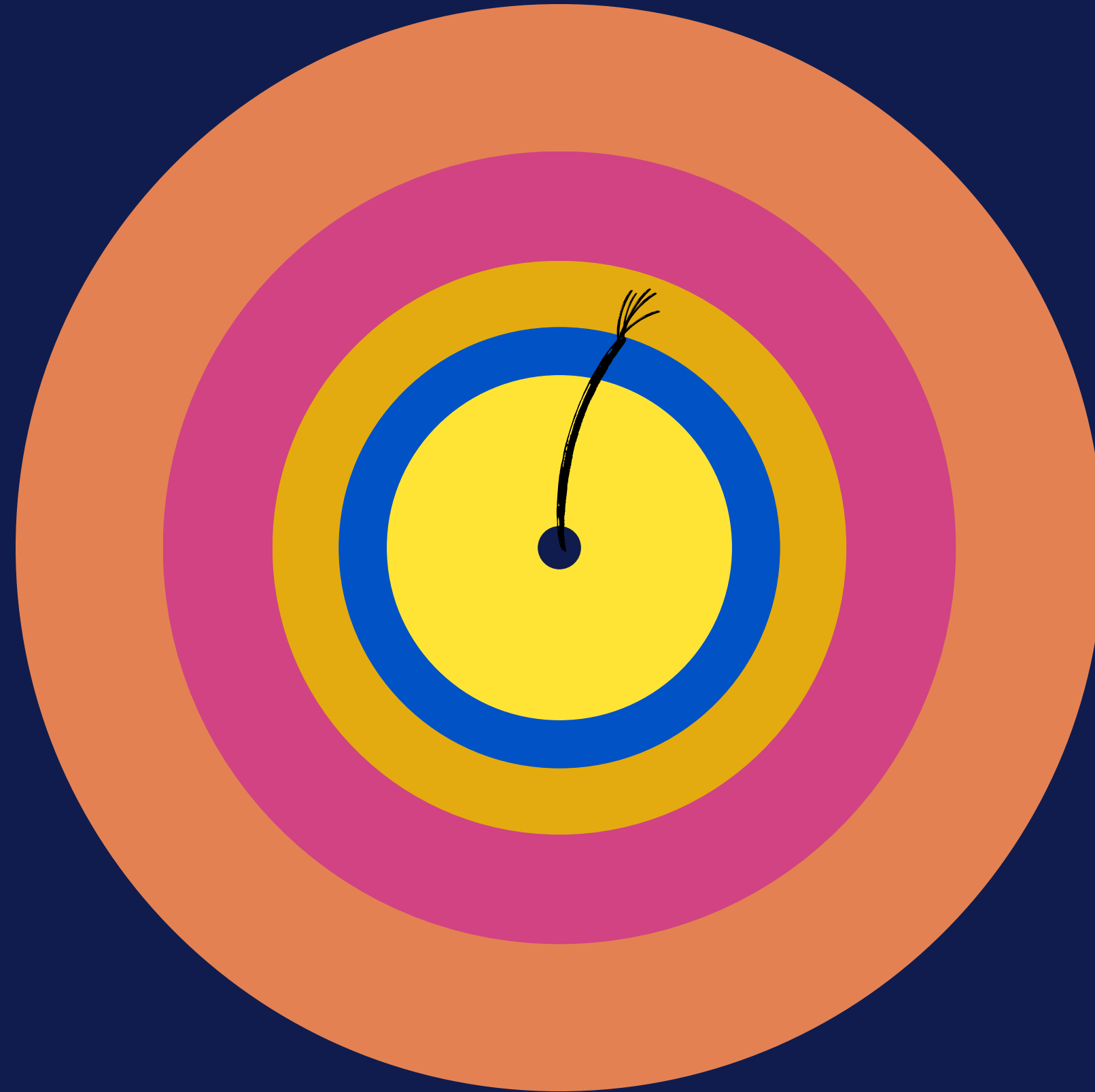


77.9% efficiency for reconstructing electron tracks.
Denominator: truth electron with $E > 10$ GeV, $|\eta| < 2.4$.
Numerator: tracks within $\Delta R < 0.2$ of the truth, $E > 2$ GeV, $|\eta| < 2.4$.

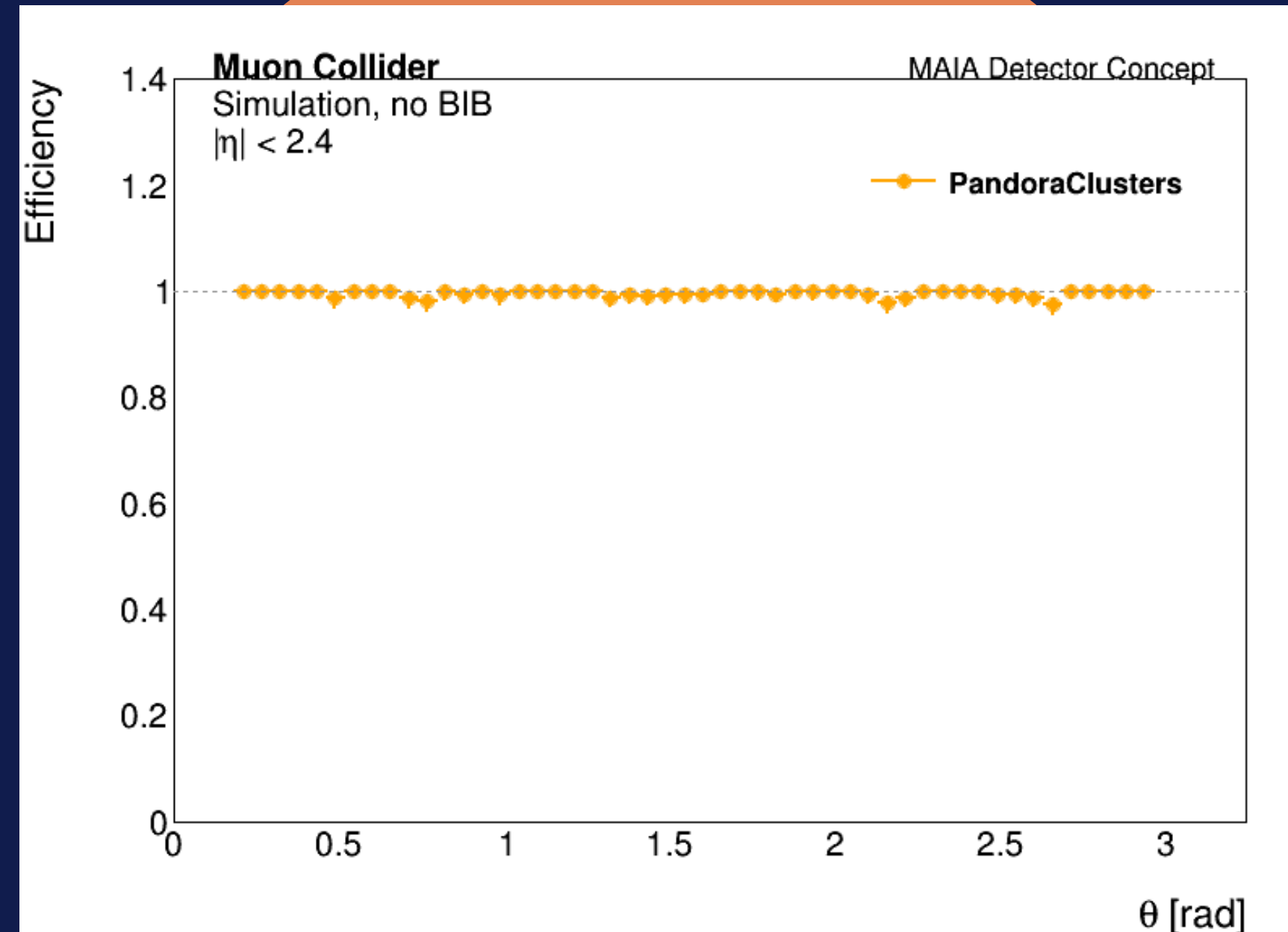
Components of Electron PFOs



Components of Electron PFOs



Components of Electron PFOs

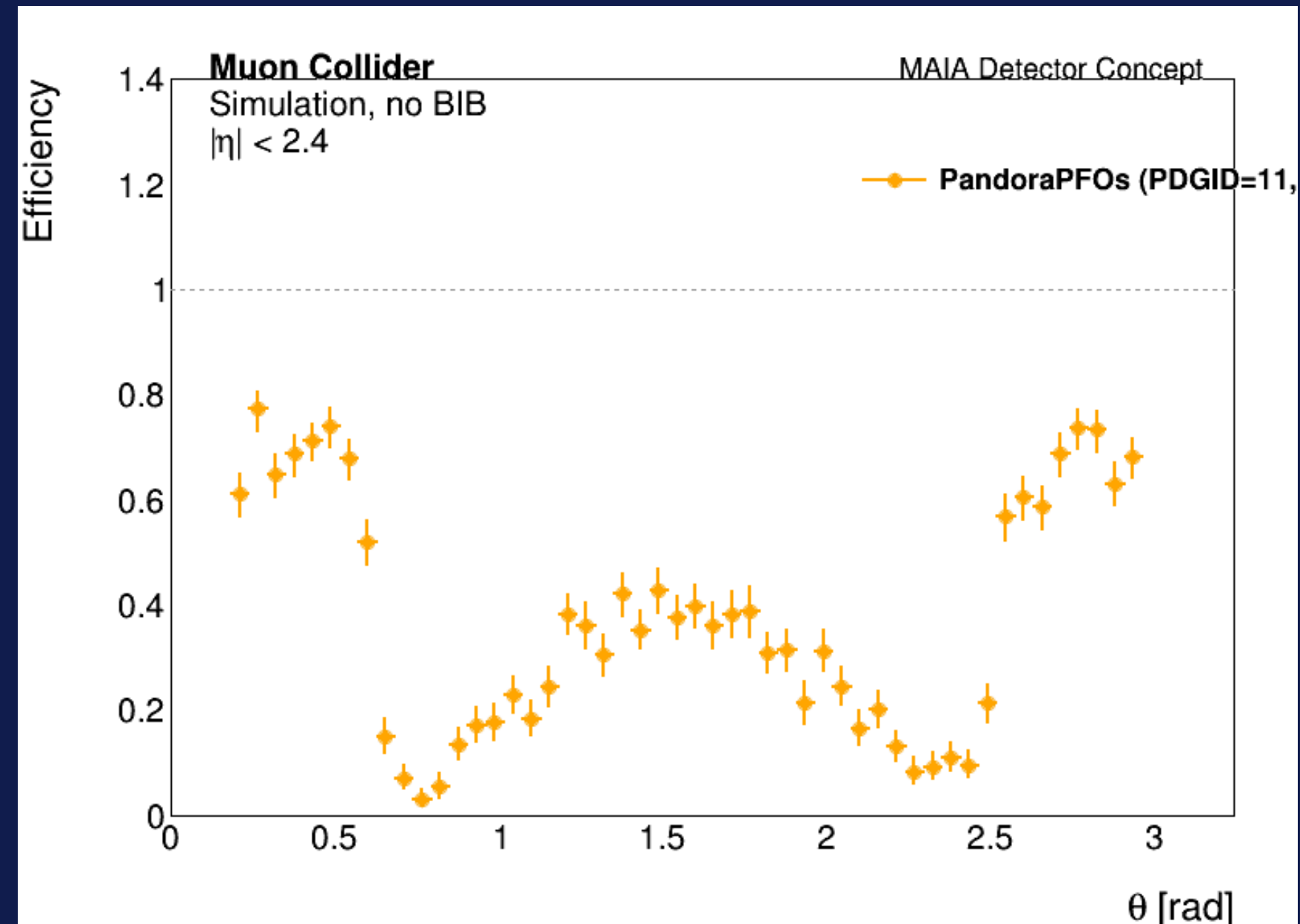


Efficiency of reconstructing electron clusters, with an efficiency of **99.5%** Denominator: truth electron with $E > 10$ GeV, $|\eta| < 2.4$. Numerator: a cluster with $E > 10$ GeV, $|\eta| < 2.4$, within $\Delta R < 0.2$ of the truth electron.

In Order to Reconstruct Electrons PFOs

- 1) The electron **track** and **cluster** need to be correctly **associated**
- 2) **Classified by Pandora as an electron** through a series of variables

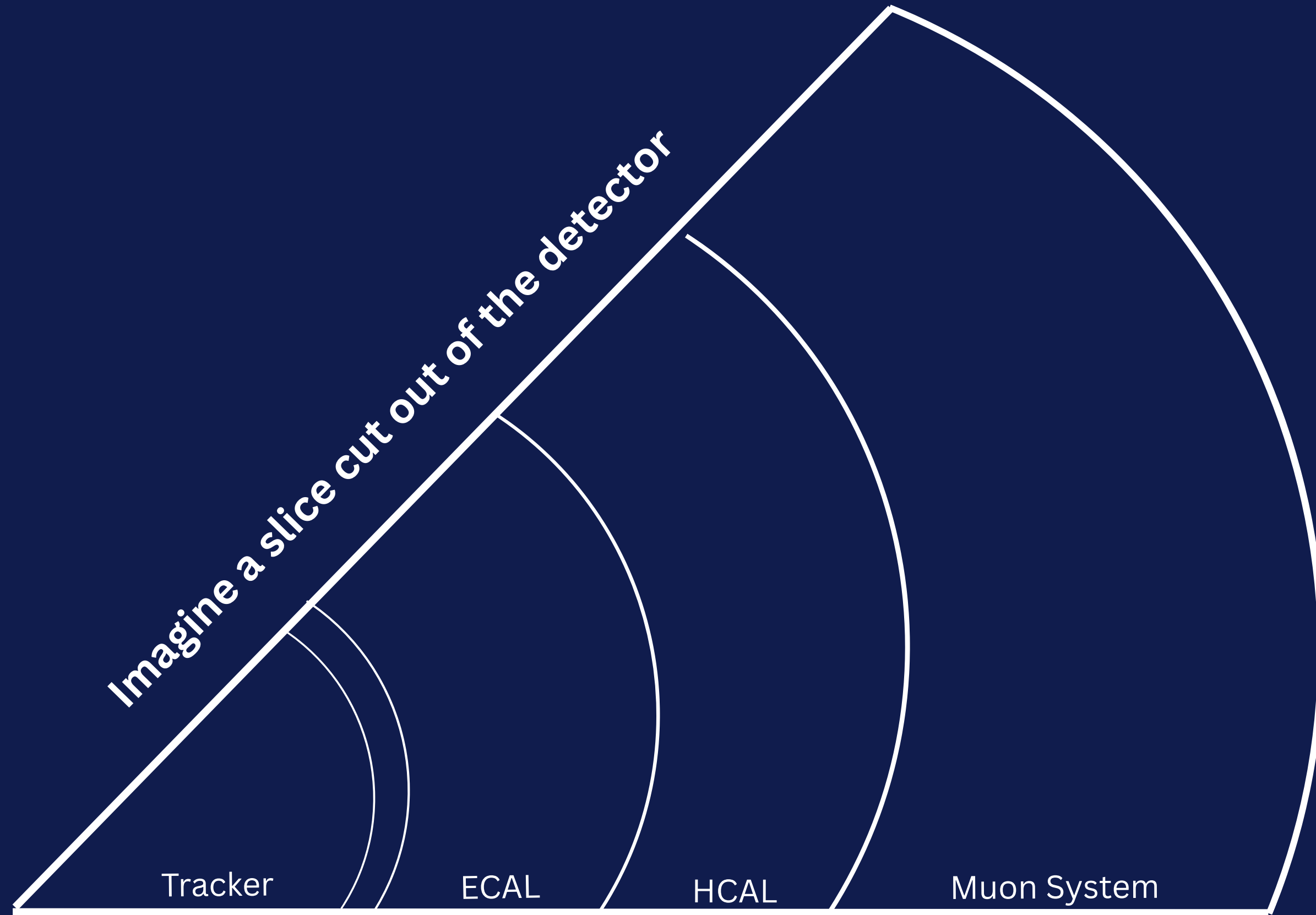
Electron PFOs



Initial electron reconstruction is low, at **36.8%**. The fact that reconstruction efficiency is low when we have 99.5% cluster efficiency and 77.9% track efficiency tells us it is **Pandora's electron ID failing**.

Since electron energy is commonly mis-IDed as charged pions, we can use **shower-based cuts to discriminate between the two, and therefore identify more electrons**

Electron and Pion Discrimination



Electron and Pion Discrimination

We are going to zoom in on the calorimeters, with the goal of **visualizing the 3 cuts we will make.**

Tracker

ECAL

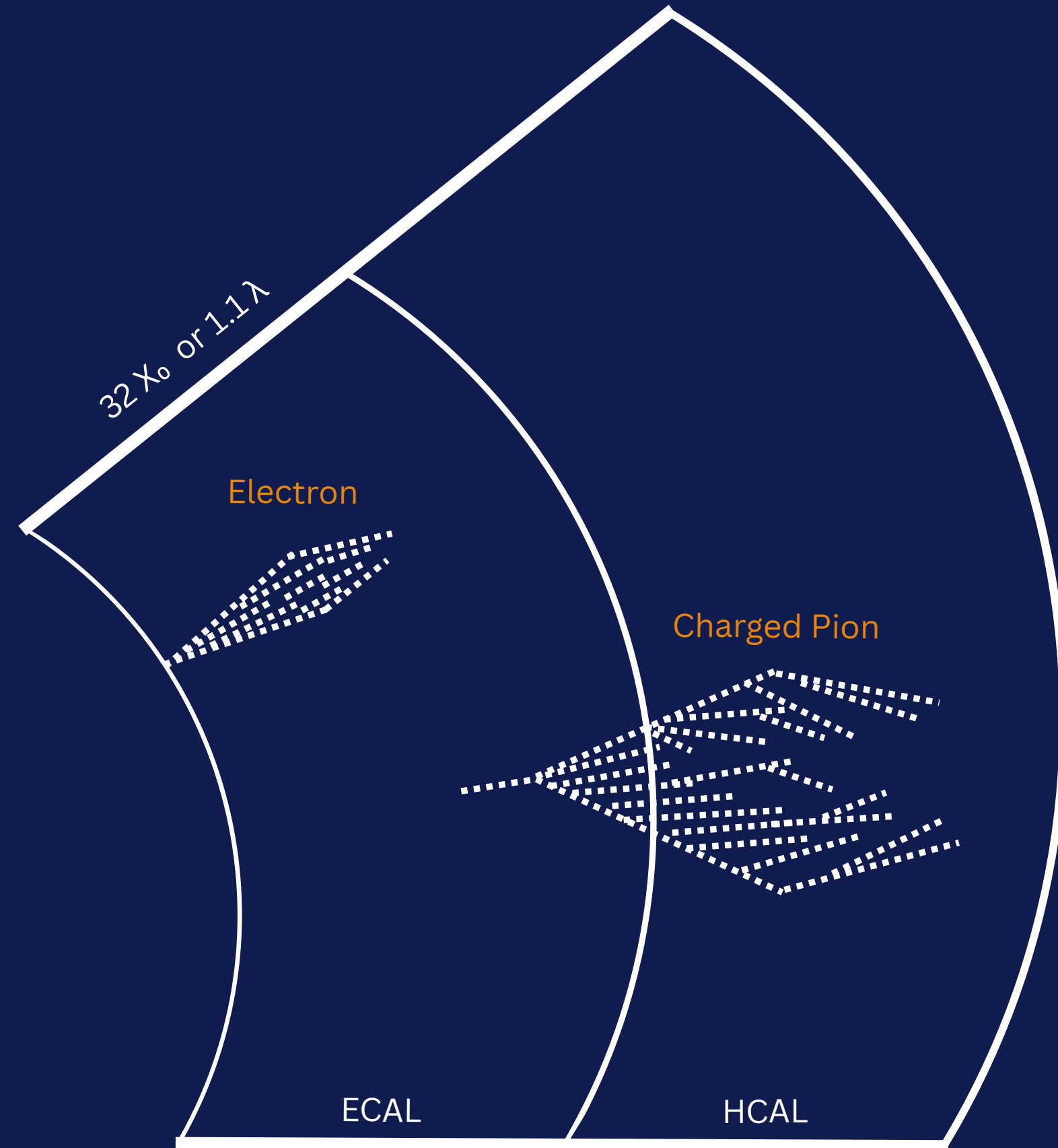
HCAL

Muon System

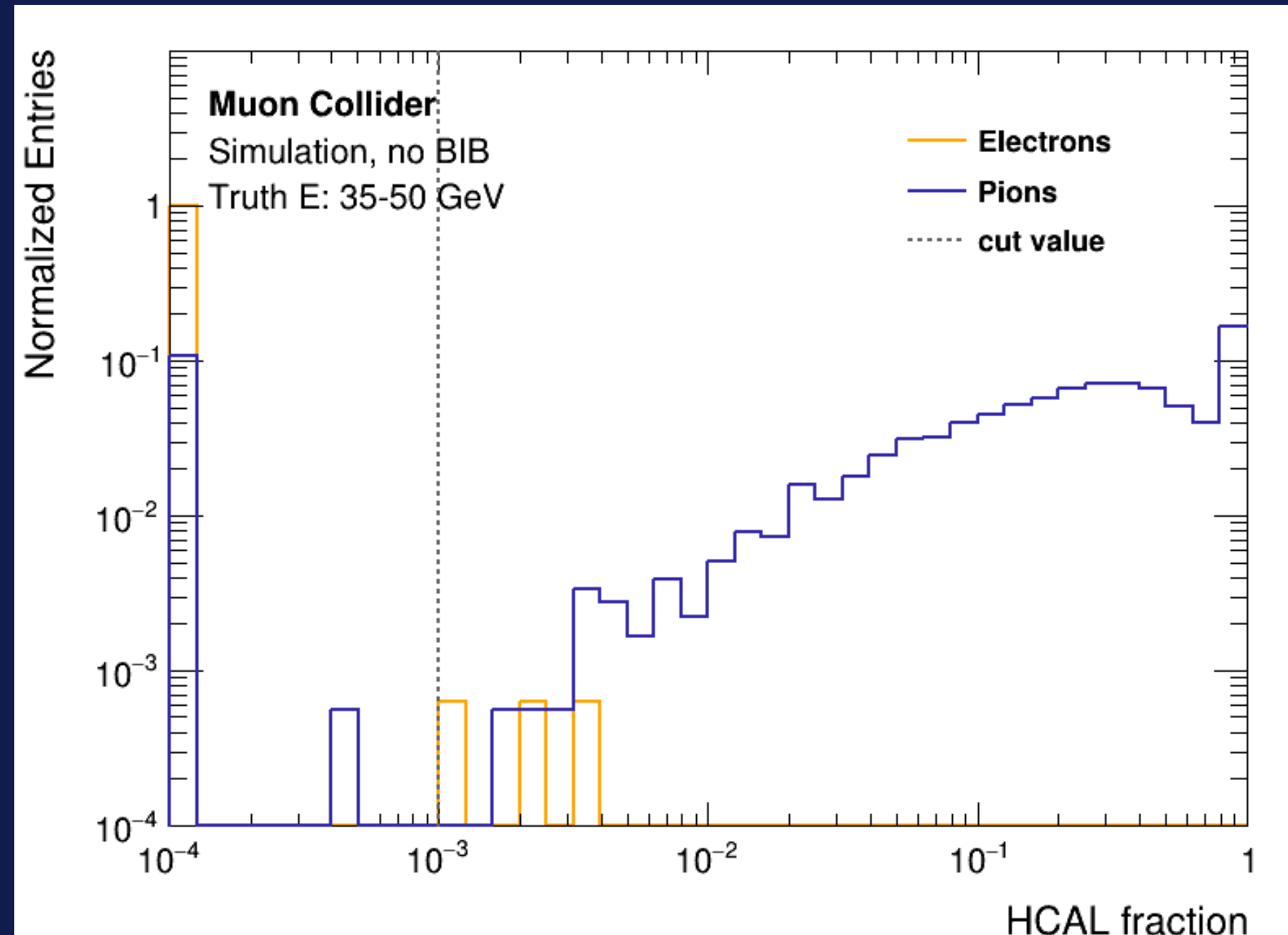
HCAL Fraction

- EM showers start developing by $1 X_0$, and the ECAL is $\sim 32 X_0$
- Pions develop around 1 nuclear interaction length, which is $\sim 28 X_0$.
- The ECAL is $\sim 1.1 \lambda$ thick

To discriminate between electrons and pions, we can **calculate the fraction of energy deposited in the HCAL for each, and use that to make a cut.**



HCAL Fraction



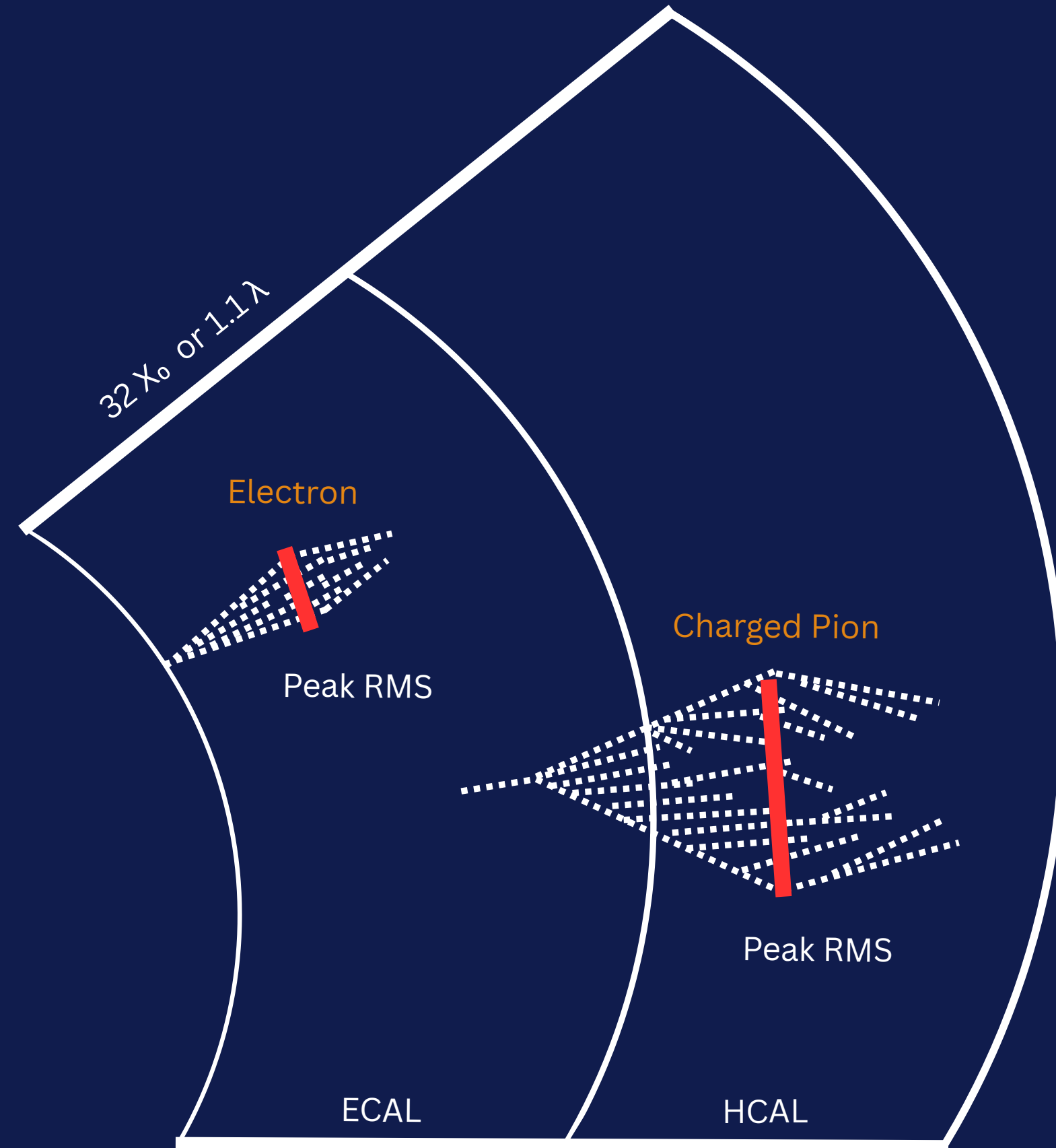
Raw HCAL energy / (raw ECAL + raw HCAL energy). This is summed over all PFO clusters.

From this plot, **HCAL fraction cut will be 0.001**

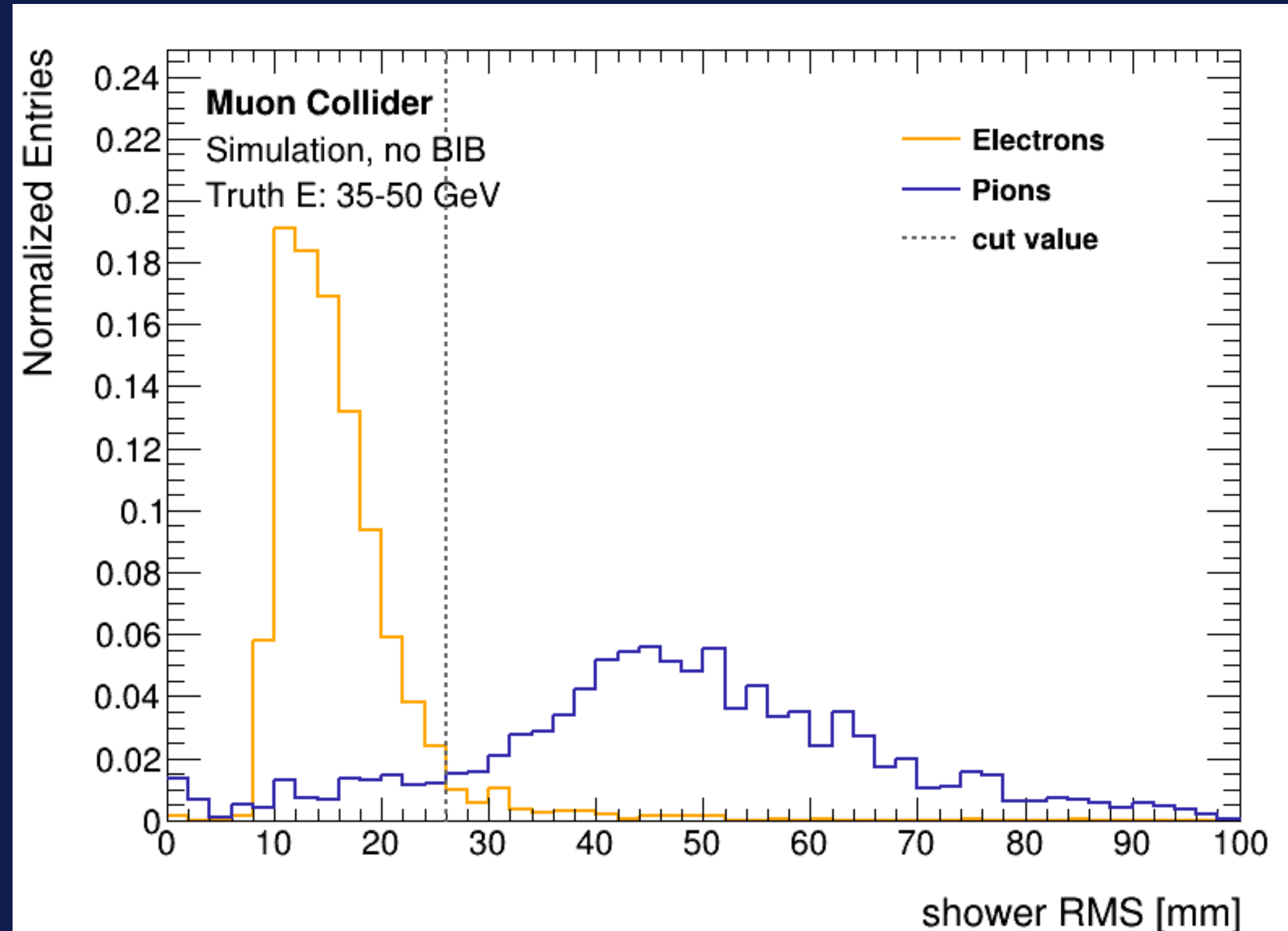
RMS

- EM shower width is set by the Molière radius, which is ~9 mm in tungsten,
 - wider in the actual ECAL due to Si
- Hadronic shower width is set by nuclear interactions and secondary production, a much larger scale

To discriminate between electrons and pions, we can **calculate the RMS of the showers and make a cut.**



RMS



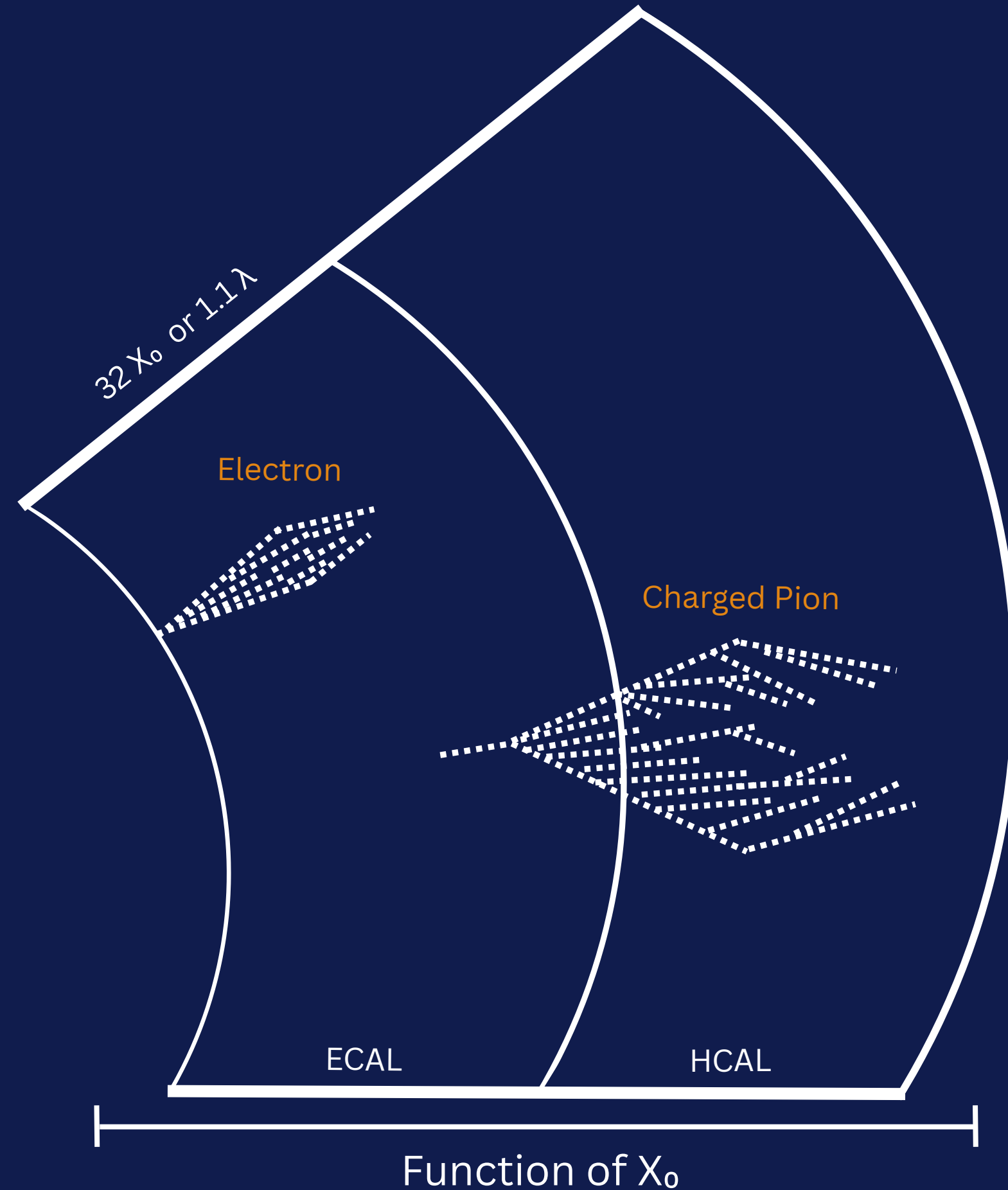
Energy-weighted transverse spread [mm] of the hits in the leading cluster around the cluster axis

From this plot, the **RMS cut will be 26mm**

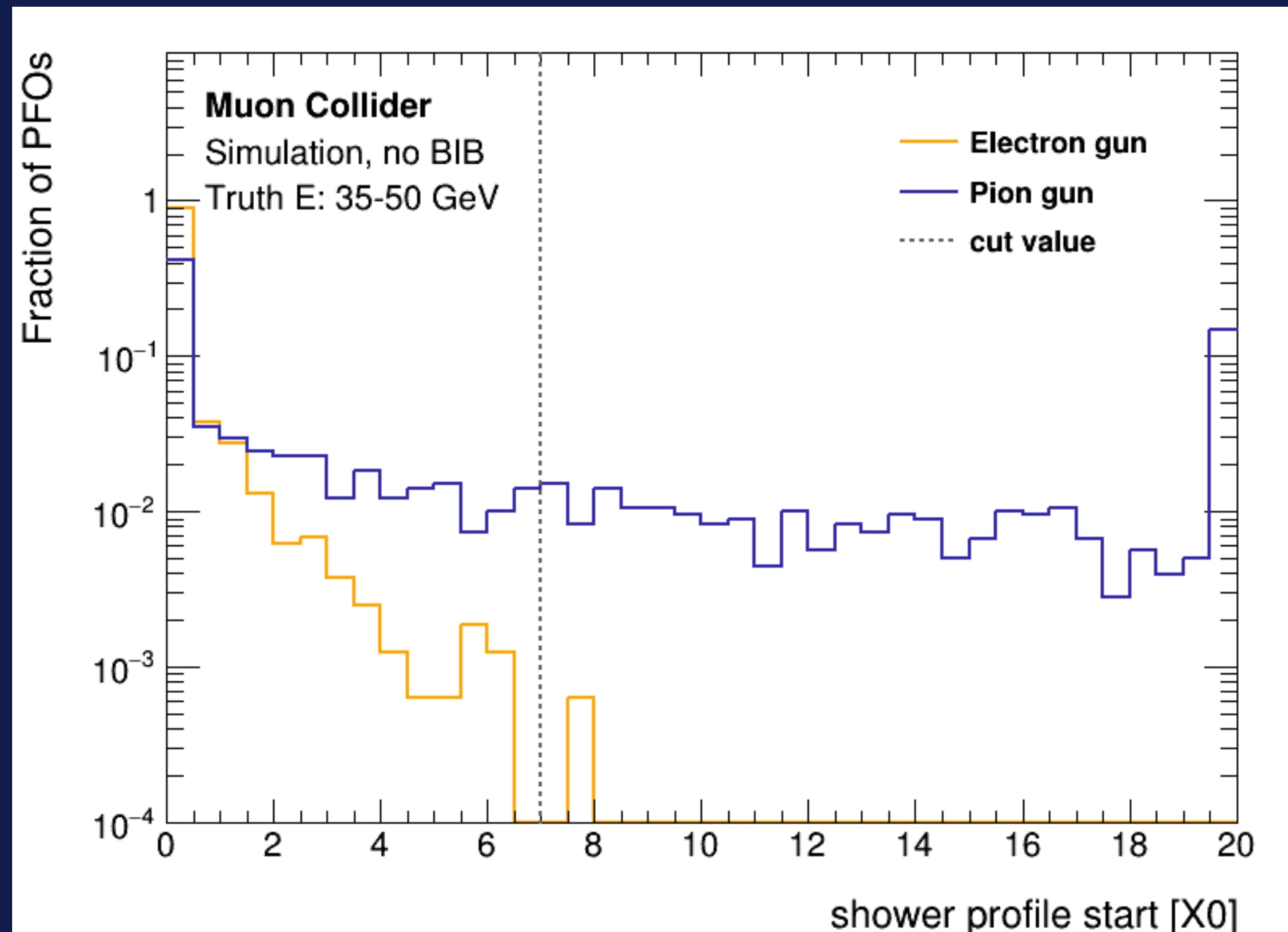
Shower Start Depth

- An electron starts showering within the first X_0
- A pion travels $\sim 28 X_0$ before its first nuclear interaction

To discriminate between electrons and pions, we can **calculate the shower start depth and determine a cut.**



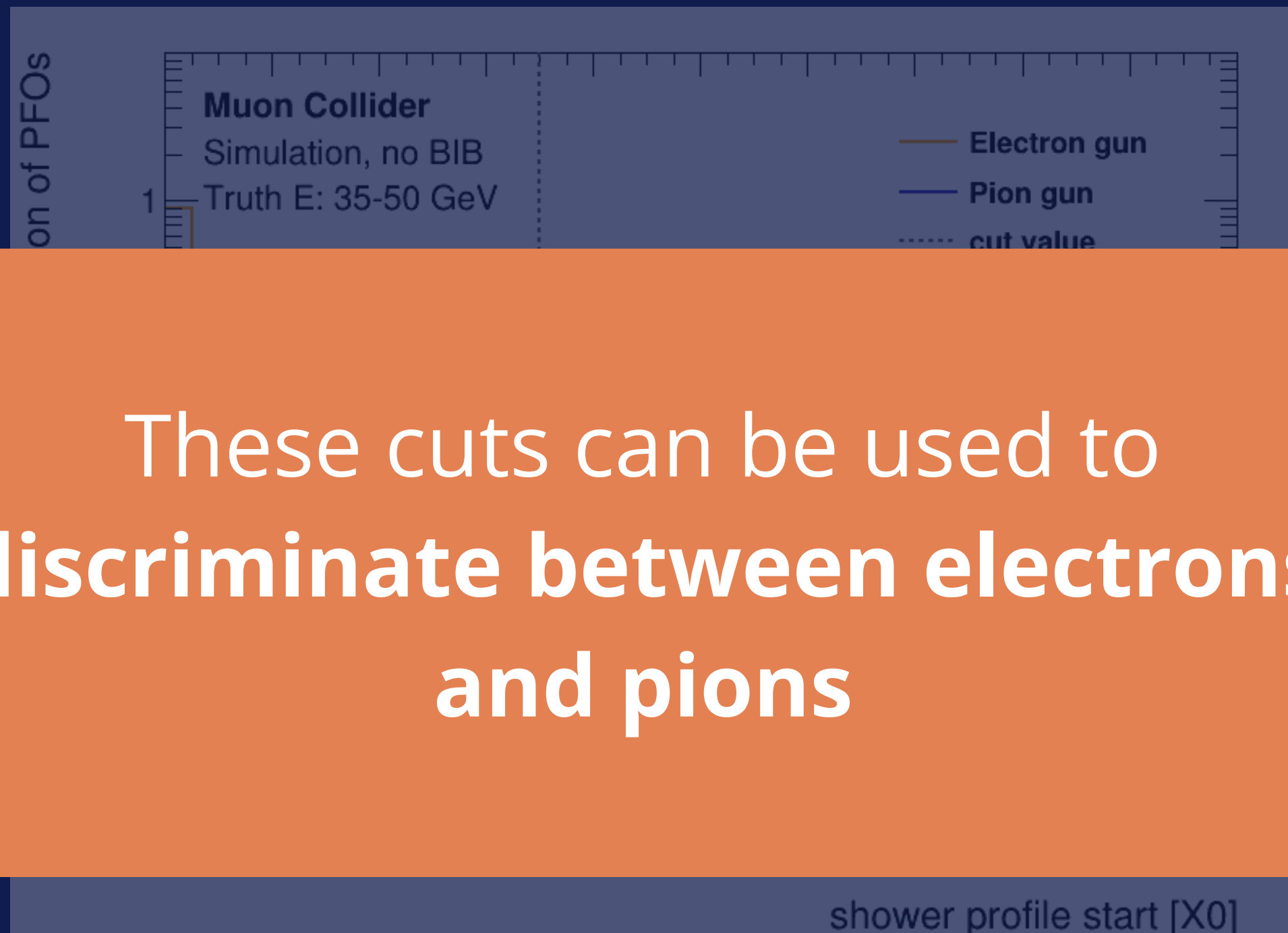
Shower Start Depth



Depth [X_0] at which the shower begins, found by sliding an expected EM profile along the layer-by-layer ECAL energy deposits until the showers best match — the same algorithm Pandora uses.

From this plot, the **shower start cut will be at 7 X_0**

Shower Start Depth



These cuts can be used to
**discriminate between electrons
and pions**

Depth [X_0] at which the shower begins, found by sliding an expected EM profile along the layer-by-layer ECAL energy deposits until the showers best match — the same algorithm Pandora uses.

From this plot, the **shower start cut will be at 7 X_0**

New Electron ID

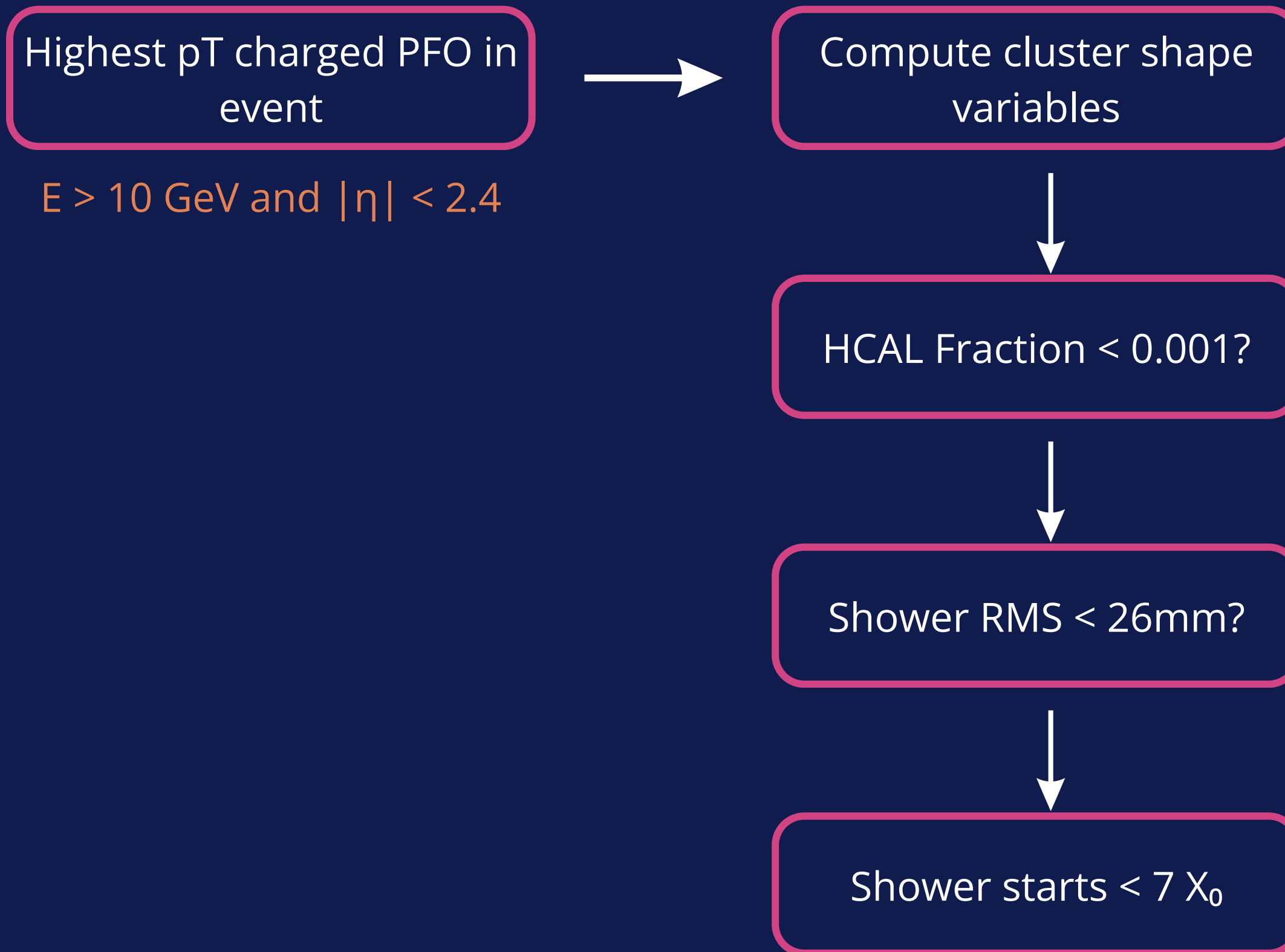
Highest pT charged PFO in
event



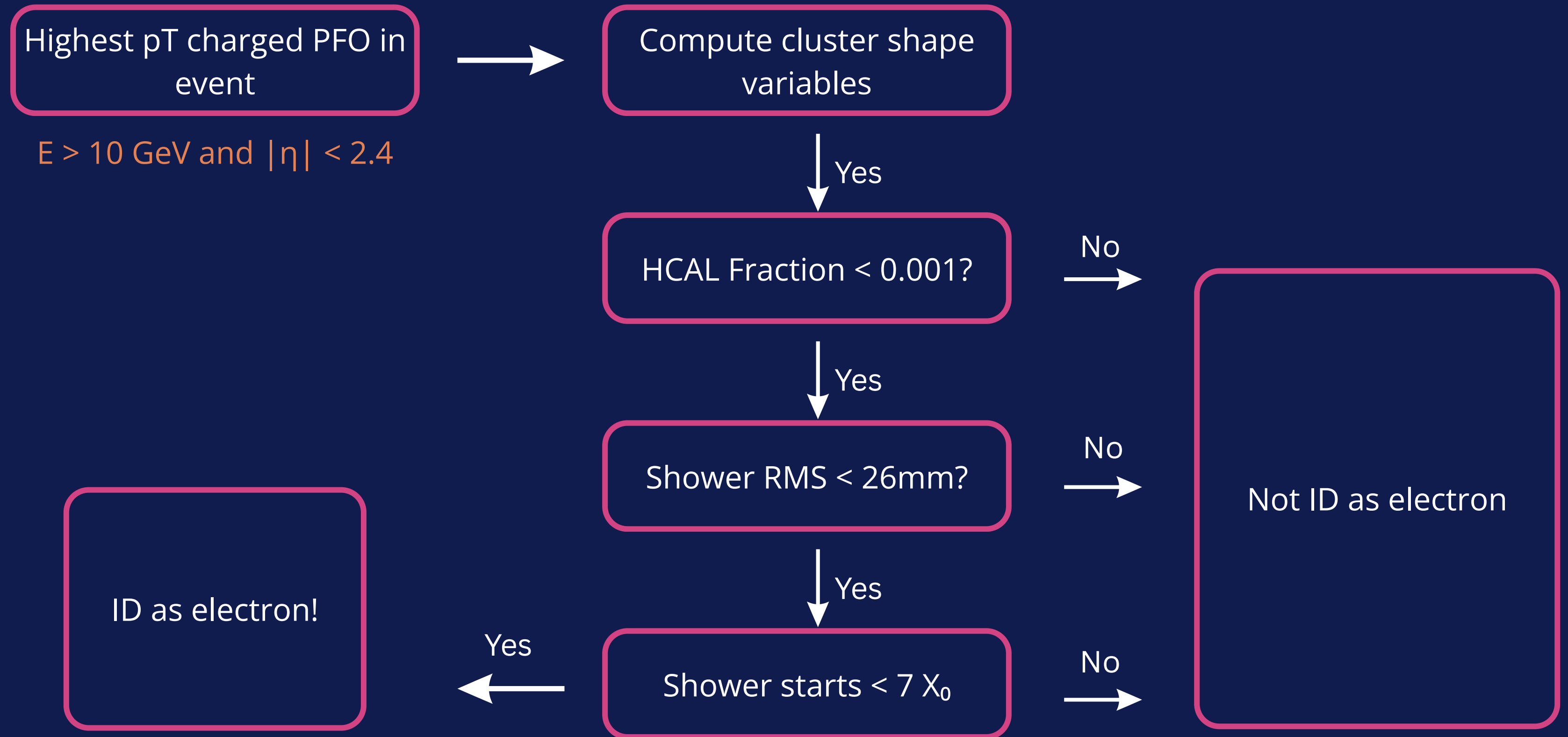
Compute cluster shape
variables

$E > 10 \text{ GeV}$ and $|\eta| < 2.4$

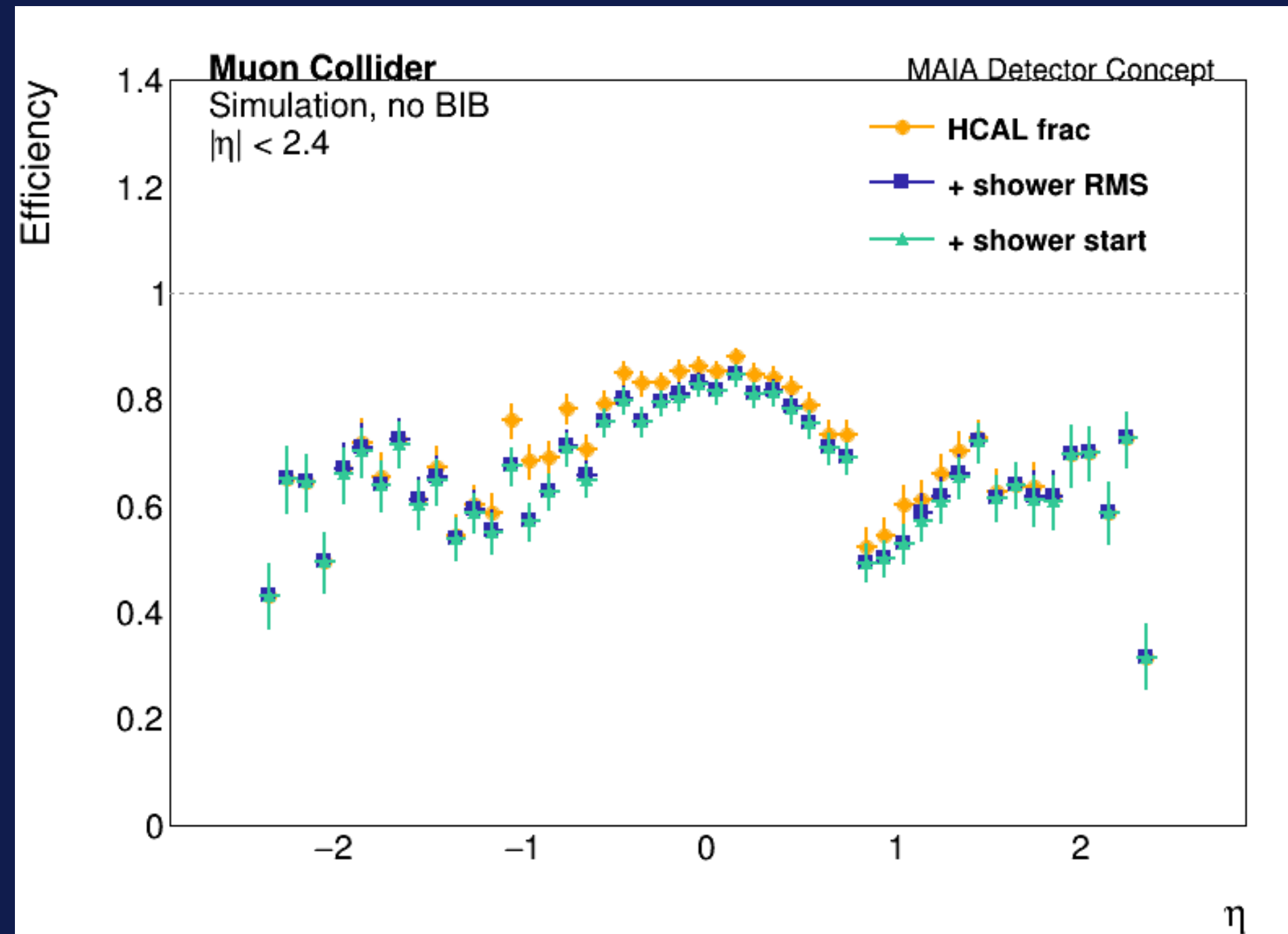
New Electron ID



New Electron ID

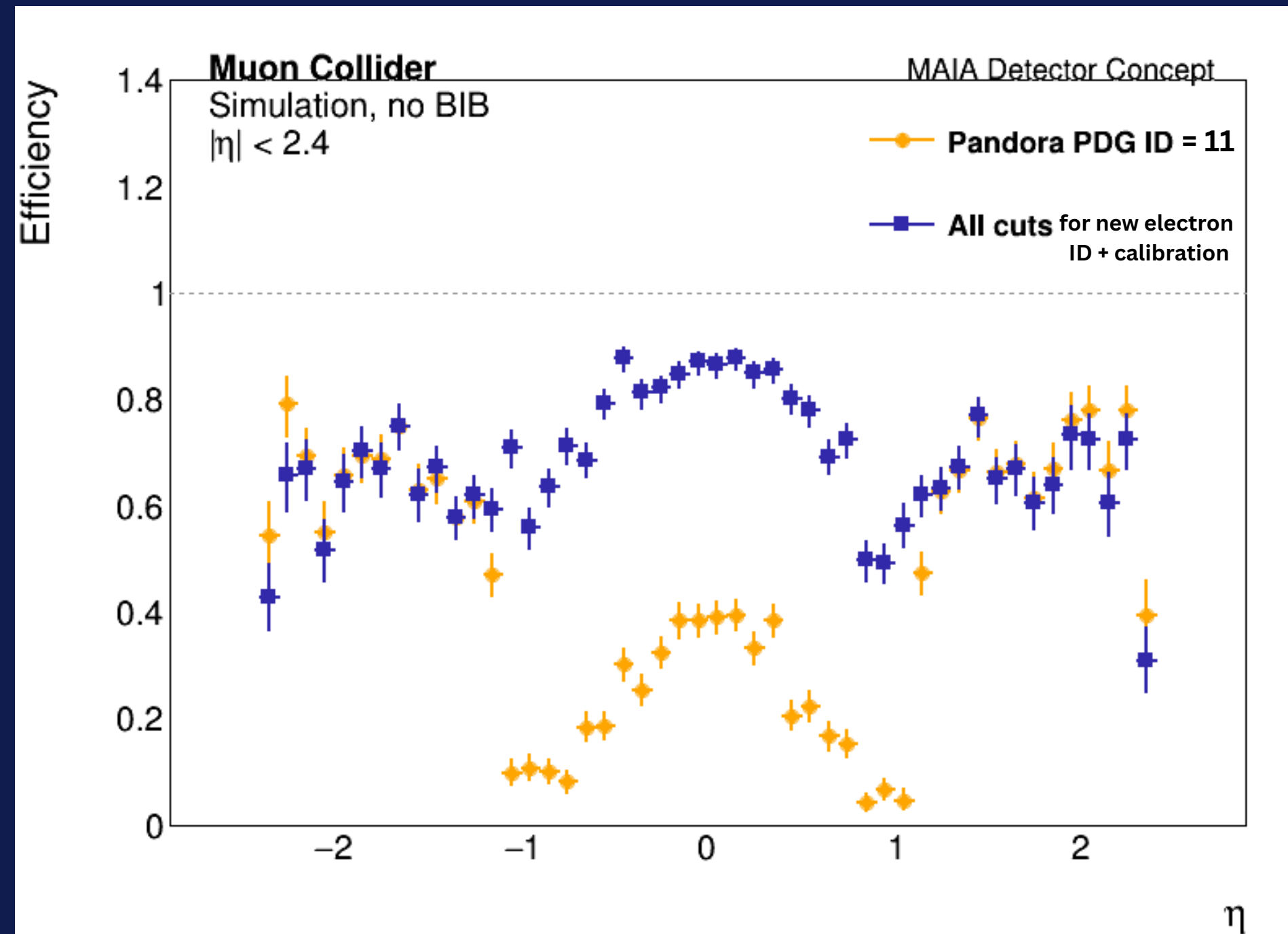


Results



From a combination of **calibration** and cuts that **discriminate between electrons and pions**, electron reconstruction efficiency is now **68.9%**

Results



The PFOs ID as electrons with the **updated electron ID + calibration** show an improvement from **36.9% to 68.9% reconstruction efficiency**.

Conclusions + Future Work

- EM shower and electron reconstruction are **improved but not complete**

Conclusions + Future Work

- EM shower and electron reconstruction are **improved but not complete**
- **Next Steps:**
 - Once Aidan is done optimizing how showers develop in MAIA, I can use the **updated shower profile discrepancy variable** for electrons
 - **Improved tracking efficiency** will also improve electron identification

Conclusions + Future Work

- EM shower and electron reconstruction are **improved but not complete**
- **Next Steps:**
 - Once Aidan is done optimizing how showers develop in MAIA, I can use the **updated shower profile discrepancy variable** for electrons
 - **Improved tracking efficiency** will also improve electron identification
- This is all very much a **work in progress**. Using machine learning could be helpful in the future, but we have one goal for now

Conclusions + Future Work

Validate the detector, physics, and reconstruction algorithms. **Understand what is fundamentally happening**

If you want to join USMCC, contact Tova
Holmes at tholmes@utk.edu



USMCC
Website



MAIA
Paper



If you want to join USMCC, contact Tova
Holmes at tholmes@utk.edu



Thank You!

USMCC
Website



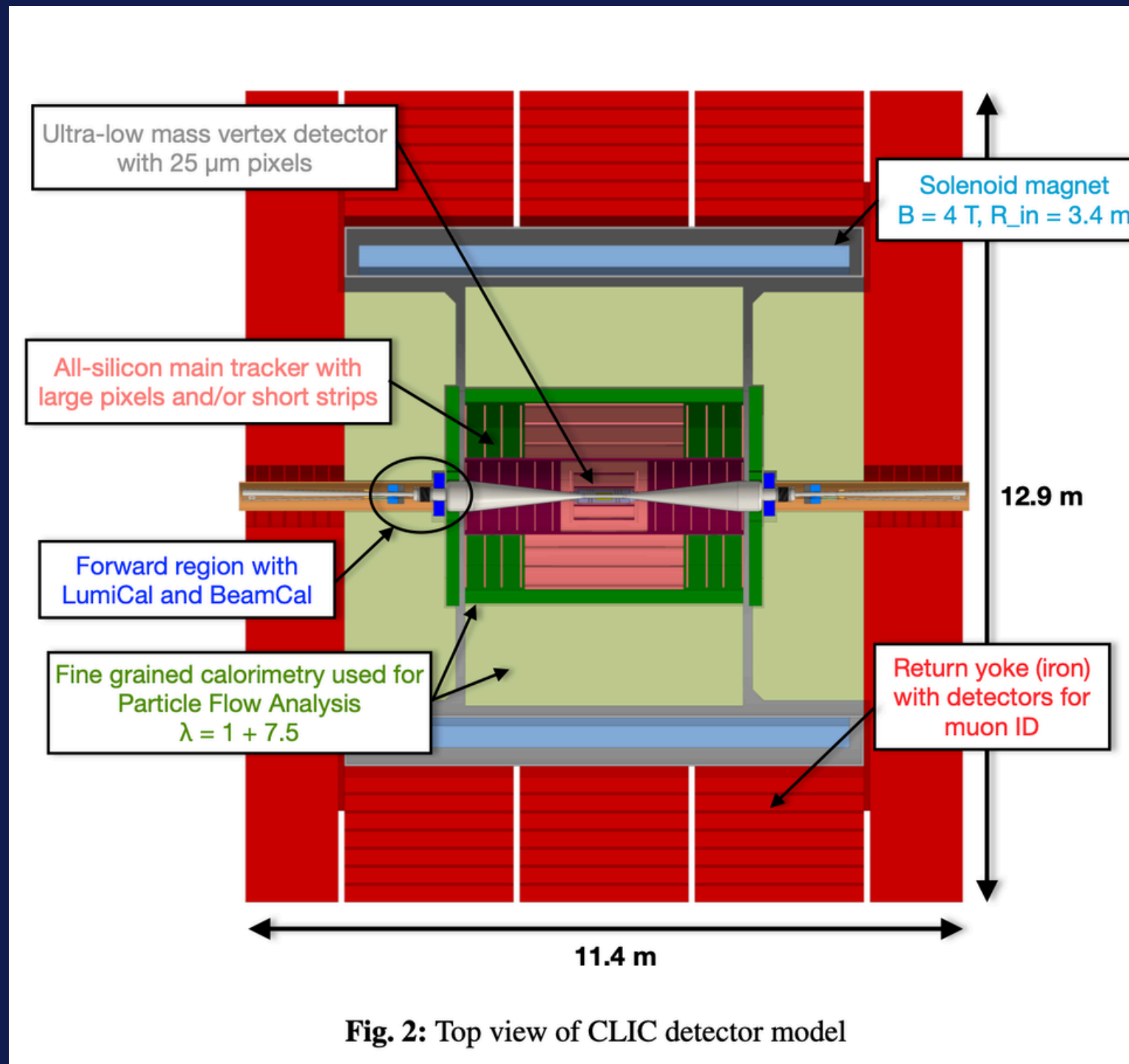
MAIA
Paper



Backup

CLIC Detector

<https://arxiv.org/pdf/1802.06008>



CLICdet

<https://cds.cern.ch/record/2254048/files/CLICdp-Note-2017-001.pdf>

Table 1: Comparison of key parameters of the different CLIC detector concepts. CLIC_ILD and CLIC_SiD values are taken from the CDR [3]. The inner radius of the electromagnetic calorimeter (ECAL) is given by the smallest distance of the calorimeter to the main detector axis. For the hadronic calorimeter (HCAL), materials are given separately for the barrel and the endcap.

Concept	CLICdet	CLIC_ILD	CLIC_SiD
Vertex inner radius [mm]	31	31	27
Tracker technology	Silicon	TPC/Silicon	Silicon
Tracker half length [m]	2.2	2.3	1.5
Tracker outer radius [m]	1.5	1.8	1.3
ECAL absorber	W	W	W
ECAL X_0	22	23	23
ECAL barrel $r_{\min}$ [m]	1.5	1.8	1.3
ECAL barrel Δr [mm]	202	172	139
ECAL endcap $z_{\min}$ [m]	2.31	2.45	1.66
ECAL endcap Δz [mm]	202	172	139
HCAL absorber barrel / endcap	Fe / Fe	W / Fe	W / Fe
HCAL λ_I	7.5	7.5	7.5
HCAL barrel $r_{\min}$ [m]	1.74	2.06	1.45
HCAL barrel Δr [mm]	1590	1238	1177
HCAL endcap $z_{\min}$ [m]	2.45	2.65	1.80
HCAL endcap Δz [mm]	1590	1590	1595
Solenoid field [T]	4	4	5
Solenoid bore radius [m]	3.5	3.4	2.7
Solenoid length [m]	8.3	8.3	6.5
Overall height [m]	12.9	14.0	14.0
Overall length [m]	11.4	12.8	12.8
Overall weight [t]	8100	10800	12500

ECAL for CLICdet

<https://cds.cern.ch/record/2254048/files/CLICdp-Note-2017-001.pdf>

Table 11: ECAL layout as implemented in the simulation model.

ECAL barrel $r_{\min}$ [mm]	1500
ECAL barrel $r_{\max}$ [mm]	1702
ECAL barrel $z_{\max}$ [mm]	2210
ECAL endcap/plug $z_{\min}$ [mm]	2307
ECAL endcap/plug $z_{\max}$ [mm]	2509
ECAL endcap $r_{\min}$ [mm]	410
ECAL endcap $r_{\max}$ [mm]	1700
ECAL plug $r_{\min}$ [mm]	260
ECAL plug $r_{\max}$ [mm]	380

The ECAL segmentation as implemented in the simulation model is given in Table 12, and shown in Figure 22. Note that the ECAL starts with an absorber layer, followed by a sensor/electronics layer, and so on. The last element in the ECAL stack is a sensor/electronics layer.

Table 12: Parameters for the ECAL segmentation as implemented in the simulation model, with a total of 40 SiW layers.

Function	Material	Layer thickness [mm]
absorber	tungsten alloy	1.90
Insulator	G10	0.15
Connectivity	mixed (86% Cu)	0.10
Sensor	silicon	0.50
Space	air	0.10
PCB	mixed (82% Cu)	1.30
Space	air	0.25
Insulator	G10	0.75
Total between W plates		3.15
Total SiW layer		5.05

Solenoid for CLICdet

<https://cds.cern.ch/record/2254048/files/CLICdp-Note-2017-001.pdf>

Table 15: CLICdet solenoid main parameters

Solenoid central field [T]	4.0	Nominal current [kA]	20
Maximum field on conductor [T]	4.6	Total ampere-turns solenoid [MA _t]	29.8
Inductance [H]	11.6		
Coil inner radius [mm]	3649	Stored energy [GJ]	2.32
Coil outer radius [mm]	3993	Stored energy per unit of cold mass [kJ/kg]	12.9
Coil length [mm]	7800		

Table 16: Description of the coil elements as implemented in the simulation model. For all elements the material, the longitudinal extent in one half of the detector $z_{\min/\max}$ and the radial extent $r_{\min/\max}$ are given.

Material	$z_{\min}$ [mm]	$z_{\max}$ [mm]	$r_{\min}$ [mm]	$r_{\max}$ [mm]
Steel	0	4129	3483	3523
Vacuum	0	4129	3523	3649
Aluminium	0	3900	3649	3993
Vacuum	0	4129	3993	4250
Steel	0	4129	4250	4290
Vacuum	3900	4089	3649	3993
Steel	4089	4129	3483	4290