



MAIA: A Detector Concept for a 10 TeV Muon Collider

Rose Powers (Princeton University)

On behalf of the MAIA team

CPAD 2025 at University of Pennsylvania

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Outline

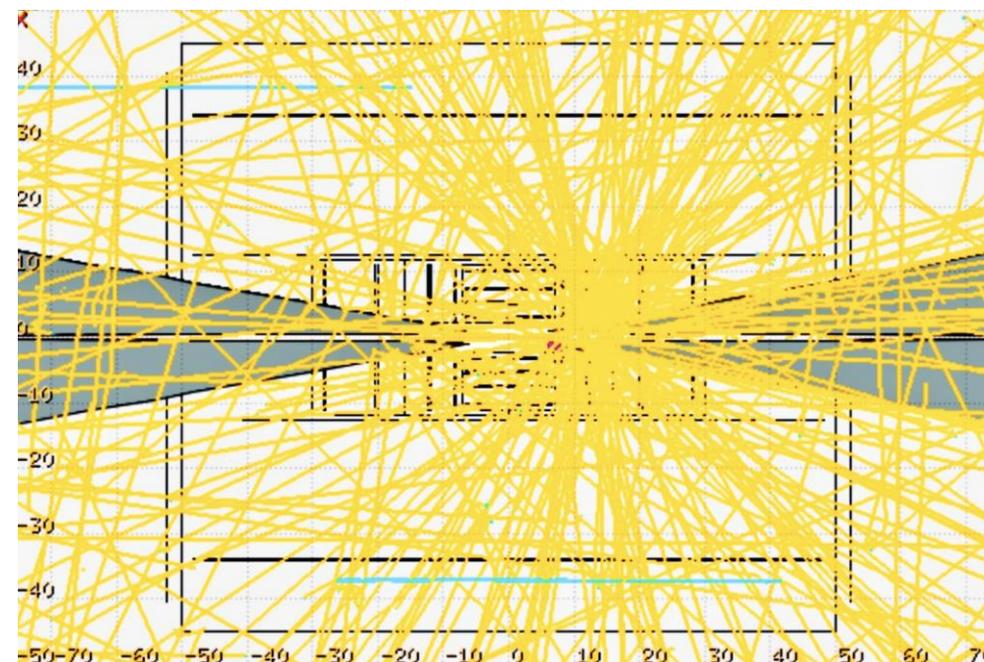
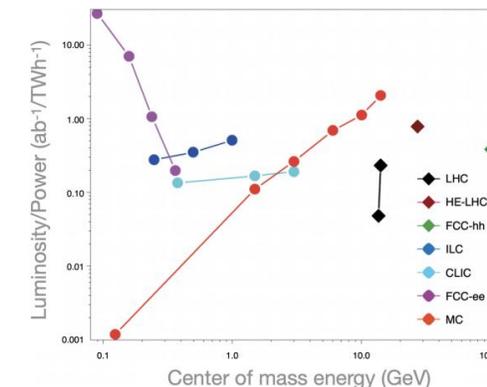
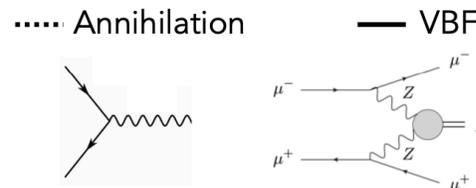
1. Introduction
2. The MAIA detector
3. Detector performance
 - I. Standard candles
 - II. More challenging objects
4. Reconstruction optimization progress
5. Conclusions and outlook

Introduction

10 TeV Muon Collider: Detector Priorities

- **Muons**: the perfect collider particle?
 - Fundamental, second-generation
 - Probes energy and intensity frontiers
 - Synchrotron radiation suppressed
 - However...
- Muons **decay** \rightarrow beam-induced background (**BIB**)
 - Decay products **flood** detector with low-energy secondaries
 - How to remain **robust** to interesting physics while **mitigating BIB**?

Multiple Production Modes



K. Kennedy

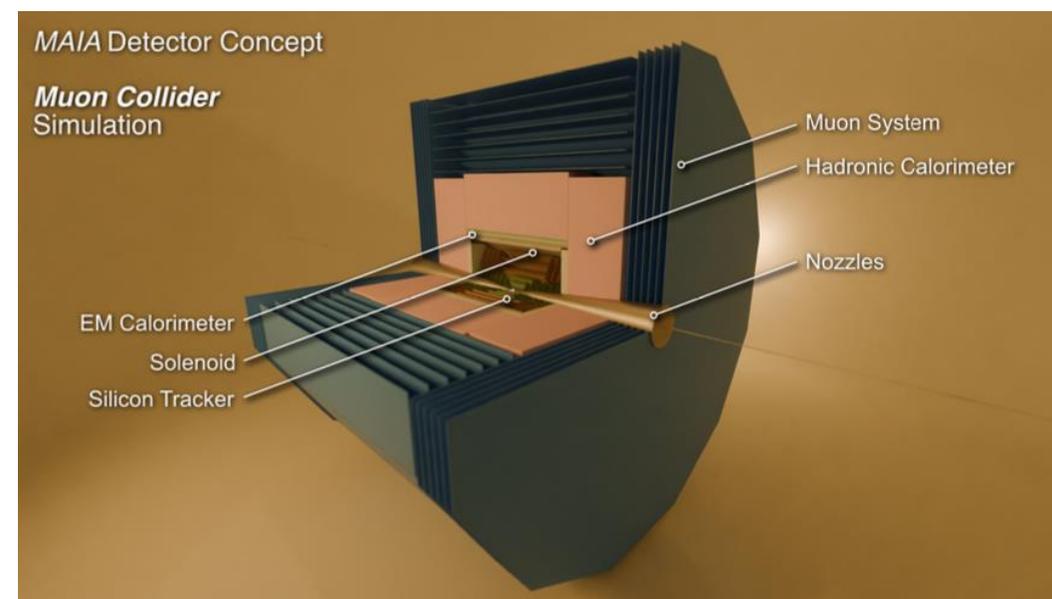
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What is **MAIA**?

- **Muon Accelerator Implemented Apparatus**
- One of two detector concepts proposed for a Muon Collider at $\sqrt{s}=10$ TeV
- Composed of shielding nozzles, trackers, a 5T solenoid, calorimeters, and a muon system



Introduction

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What is MAIA?

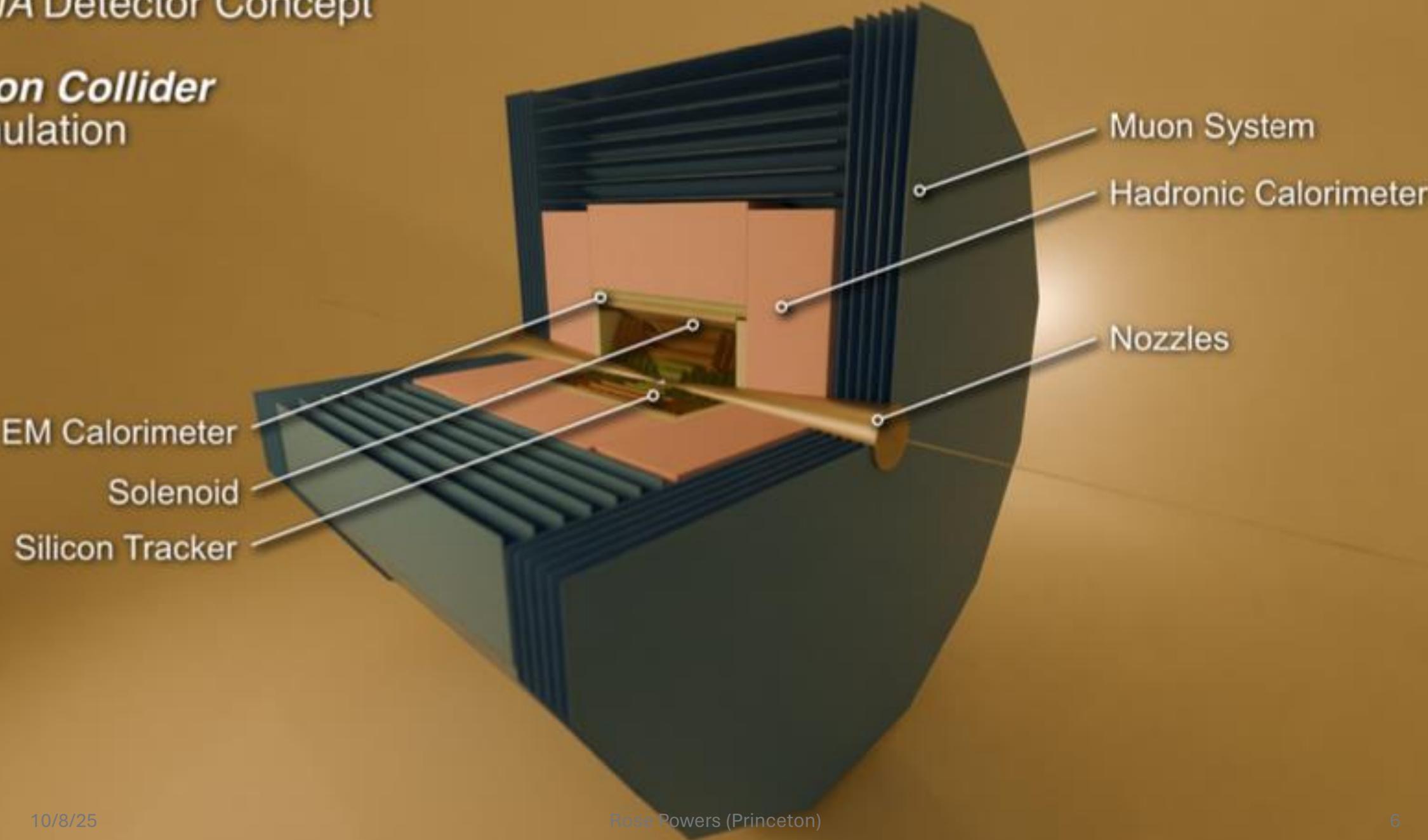
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How does MAIA address this challenge?

- **5T solenoid shields calorimeters**
- **High-granularity tracking and calorimetry**
- Excellent **timing precision**
- **Optimizing reconstruction software** for our high-background environment

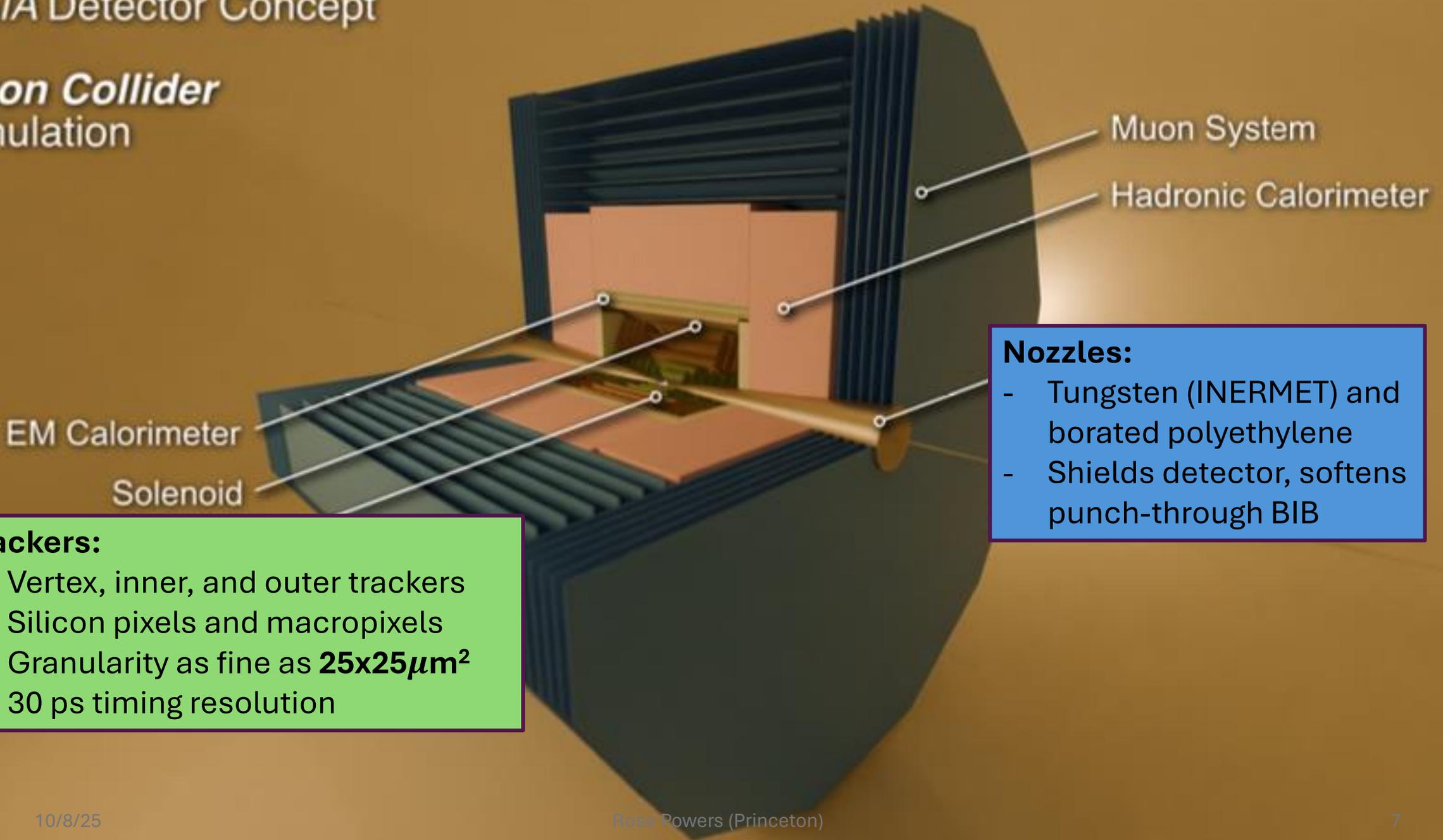
MAIA Detector Concept

Muon Collider Simulation



MAIA Detector Concept

Muon Collider Simulation



Nozzles:

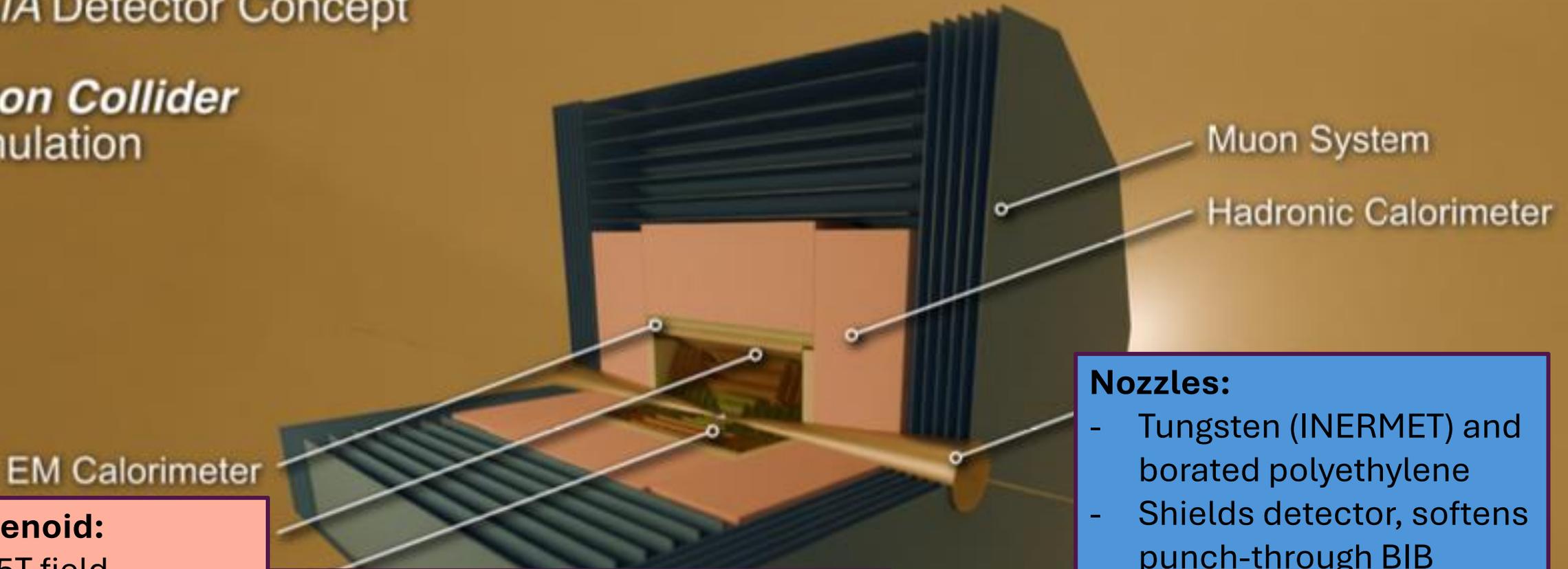
- Tungsten (INERMET) and borated polyethylene
- Shields detector, softens punch-through BIB

Trackers:

- Vertex, inner, and outer trackers
- Silicon pixels and macropixels
- Granularity as fine as **25x25 μm^2**
- 30 ps timing resolution

MAIA Detector Concept

Muon Collider Simulation



Solenoid:

- 5T field
- Aluminum
- Before ECAL for maximal shielding

Trackers:

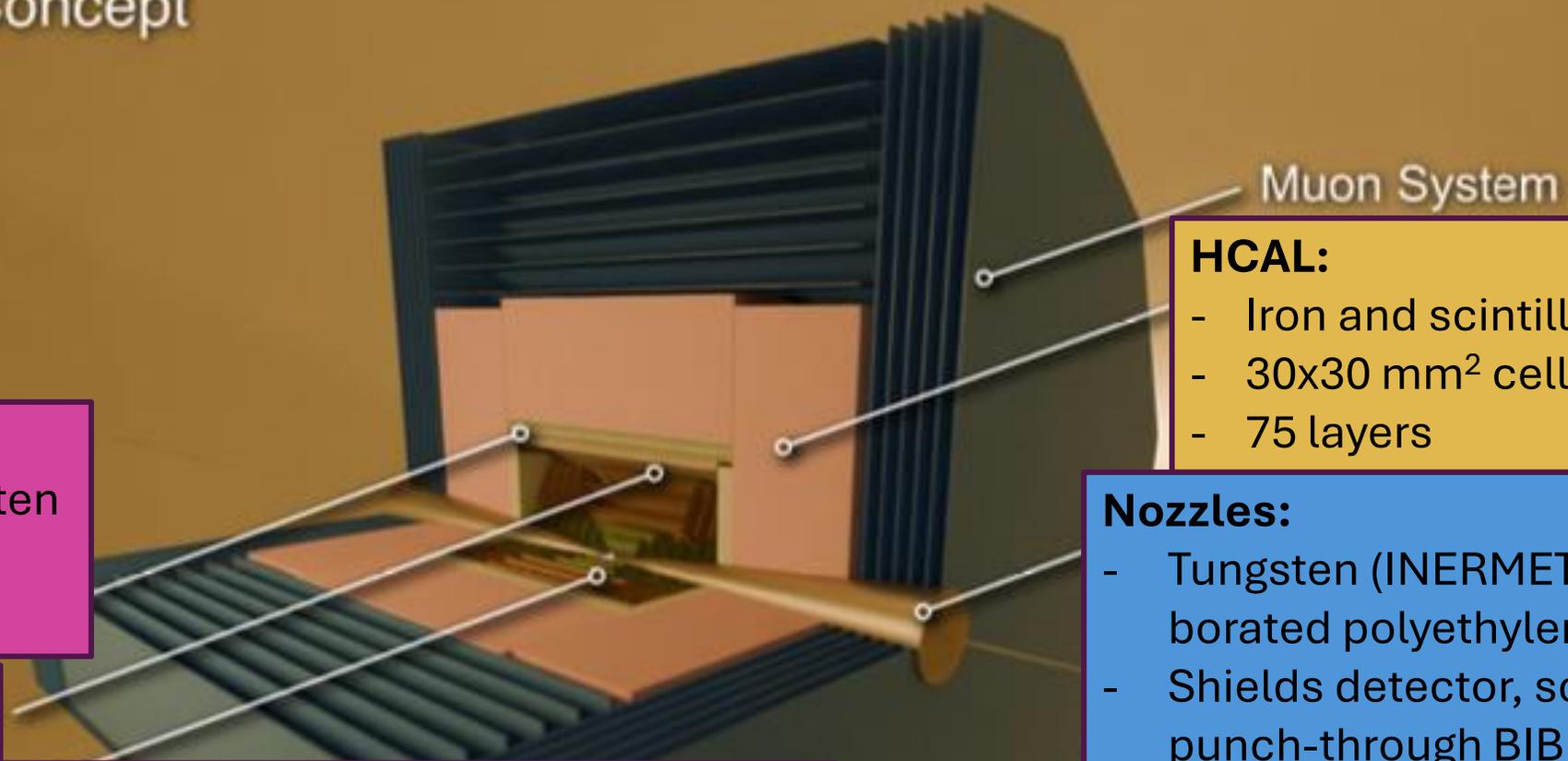
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MAIA Detector Concept

Muon Collider Simulation



ECAL:

- Silicon and Tungsten
- 5x5 mm² cells
- 50 layers

Solenoid:

- 5T field
- Aluminum
- Before ECAL for maximal shielding

Trackers:

- Vertex, inner, and outer trackers
- Silicon pixels and strips
- Granularity as fine as **25x25μm²**
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HCAL:

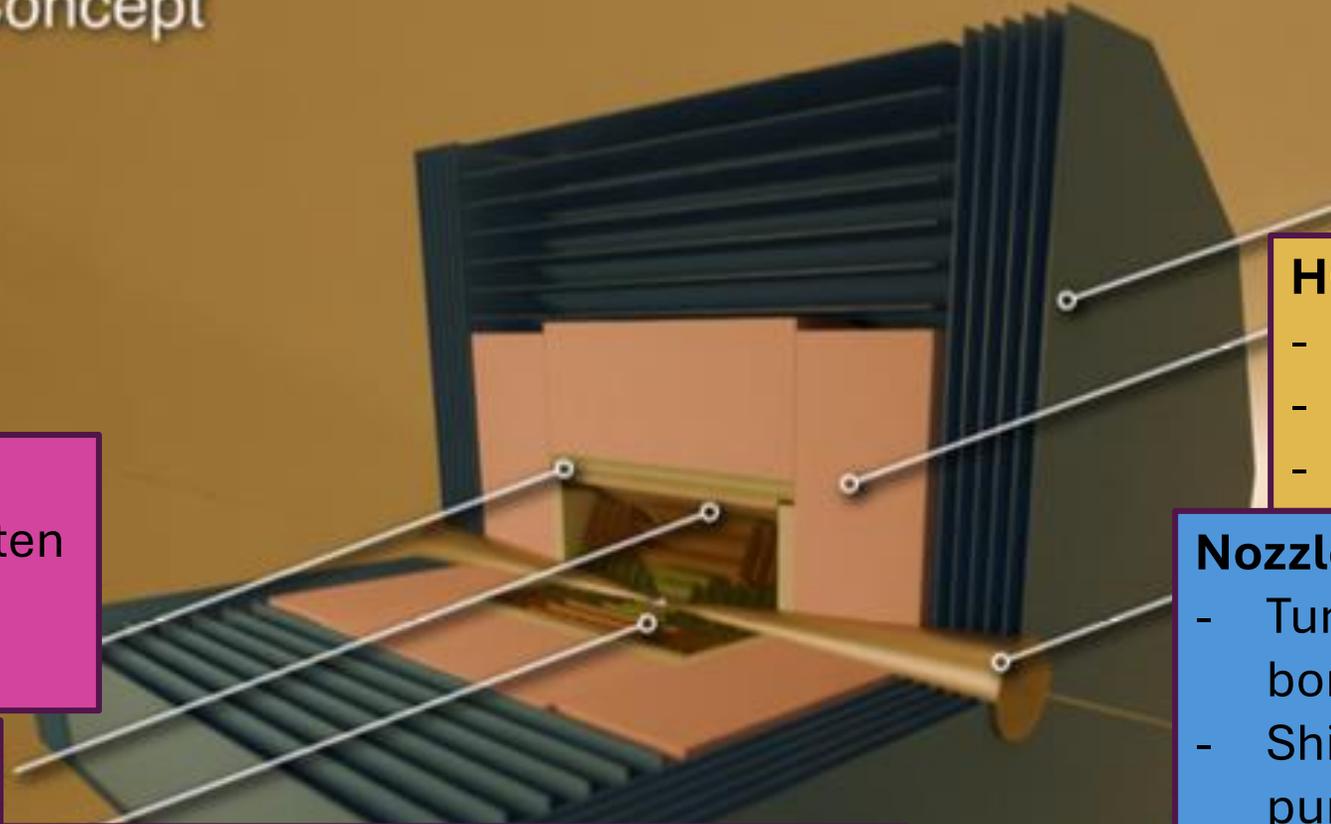
- Iron and scintillator
- 30x30 mm² cells
- 75 layers

Nozzles:

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- Shields detector, softens punch-through BIB

MAIA Detector Concept

Muon Collider Simulation



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Muon System:

- RPC (resistive plate chambers)

HCAL:

- Iron and scintillator
- 30x30 mm² cells
- 75 layers

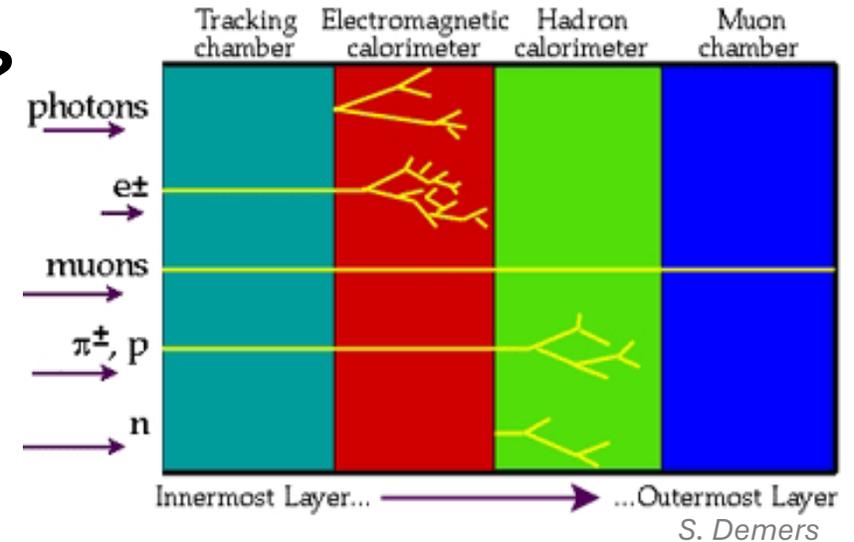
Nozzles:

- Tungsten (INERMET) and borated polyethylene
- Shields detector, softens punch-through BIB

Detector Performance

How do we assess detector performance?

- Basic objects as **standard candles** for each subdetector
- Tracker performance → muons
- ECAL performance → photons
- HCAL performance → neutrons

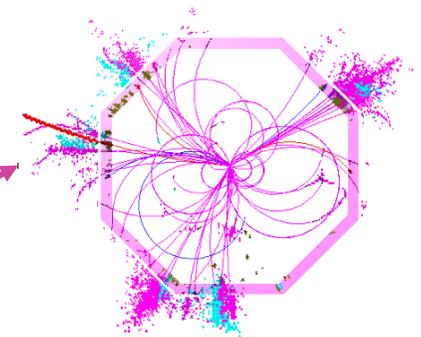


What is the simulation and reconstruction process?

- BIB is simulated in FLUKA, overlaid with signal Monte Carlo sample
- Tracking performed with ACTS
- Pandora particle flow used for full reconstruction
 - Still subject to optimization; see later slides!



acts

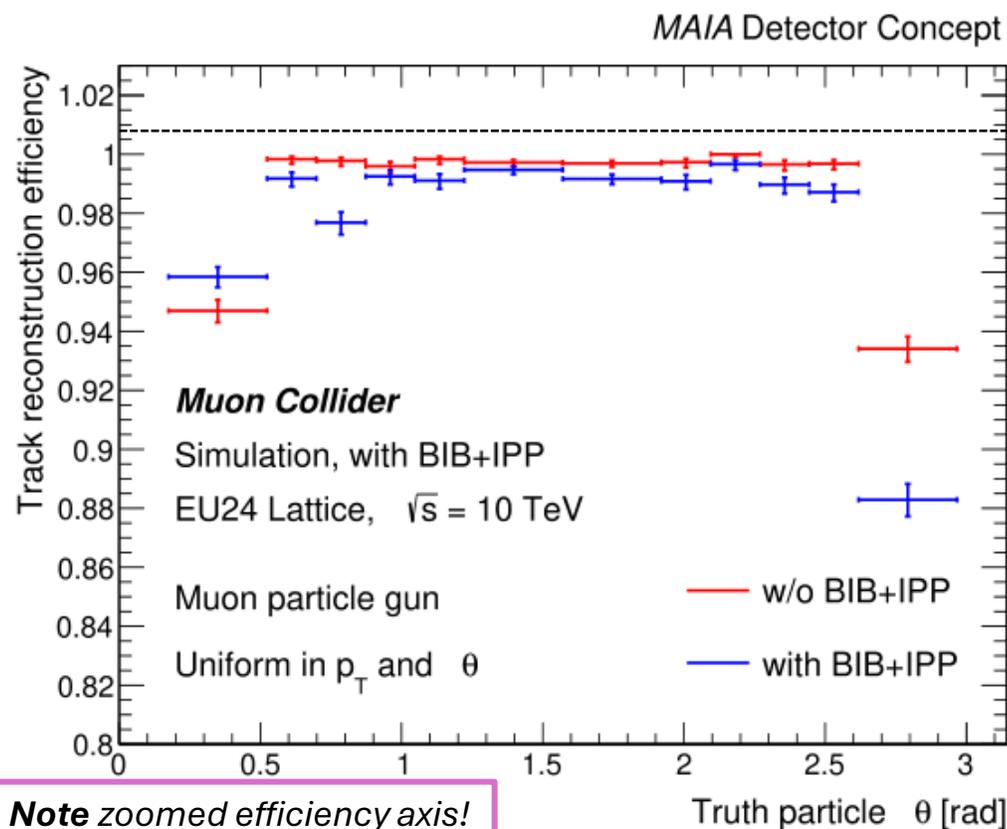


See [Ben Rosser's talk](#) for more!

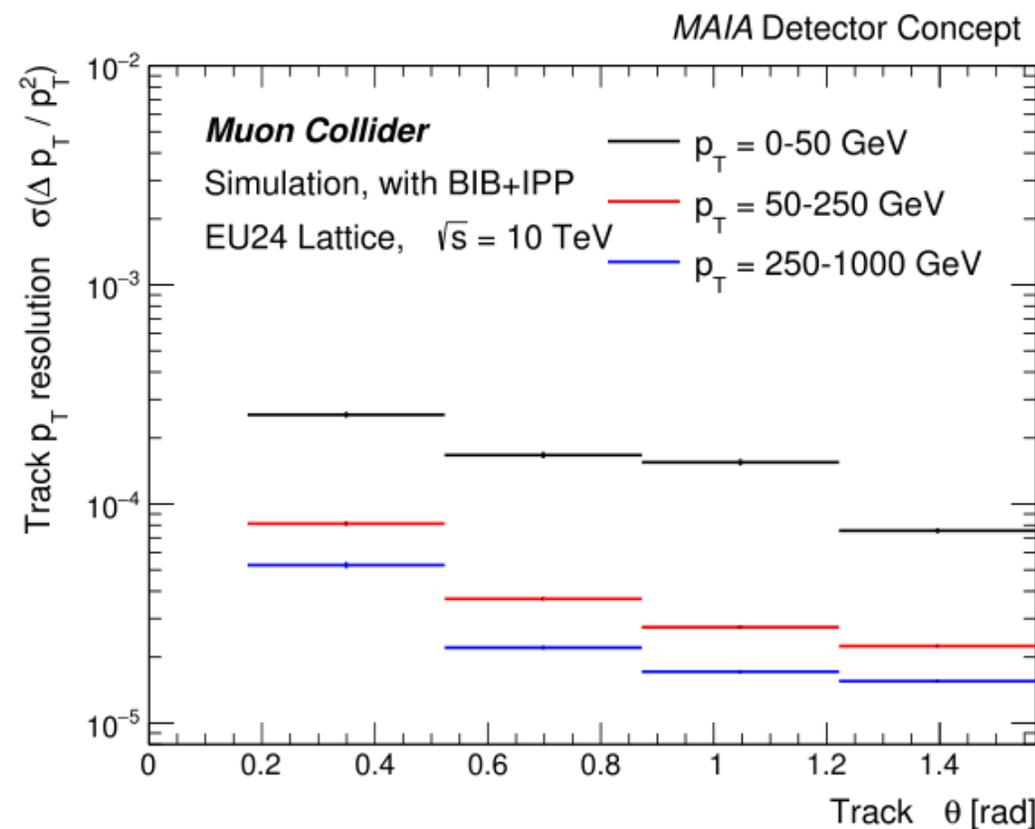
Tracker Performance

The tracker performs best in the barrel region, furthest from the nozzles

- Efficiency in this region above 98%, globally above 85%
- Resolution improves with p_T
- Excellent in the barrel; globally better than 0.02%/GeV



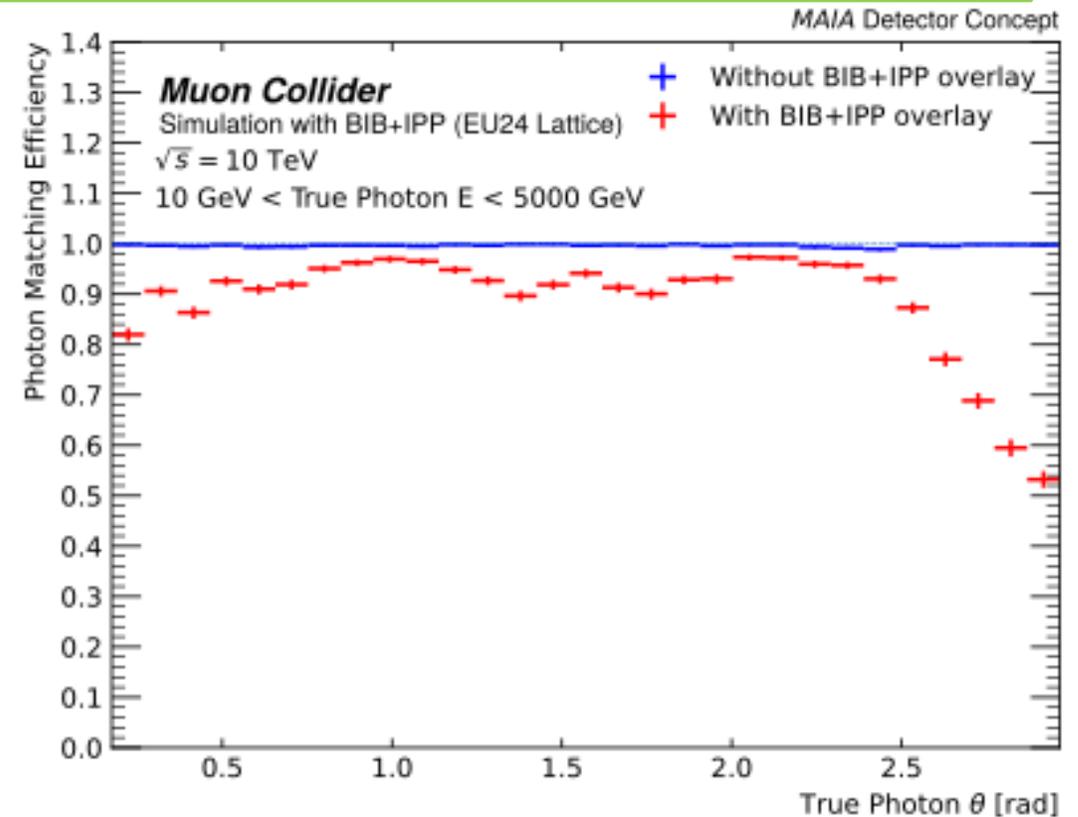
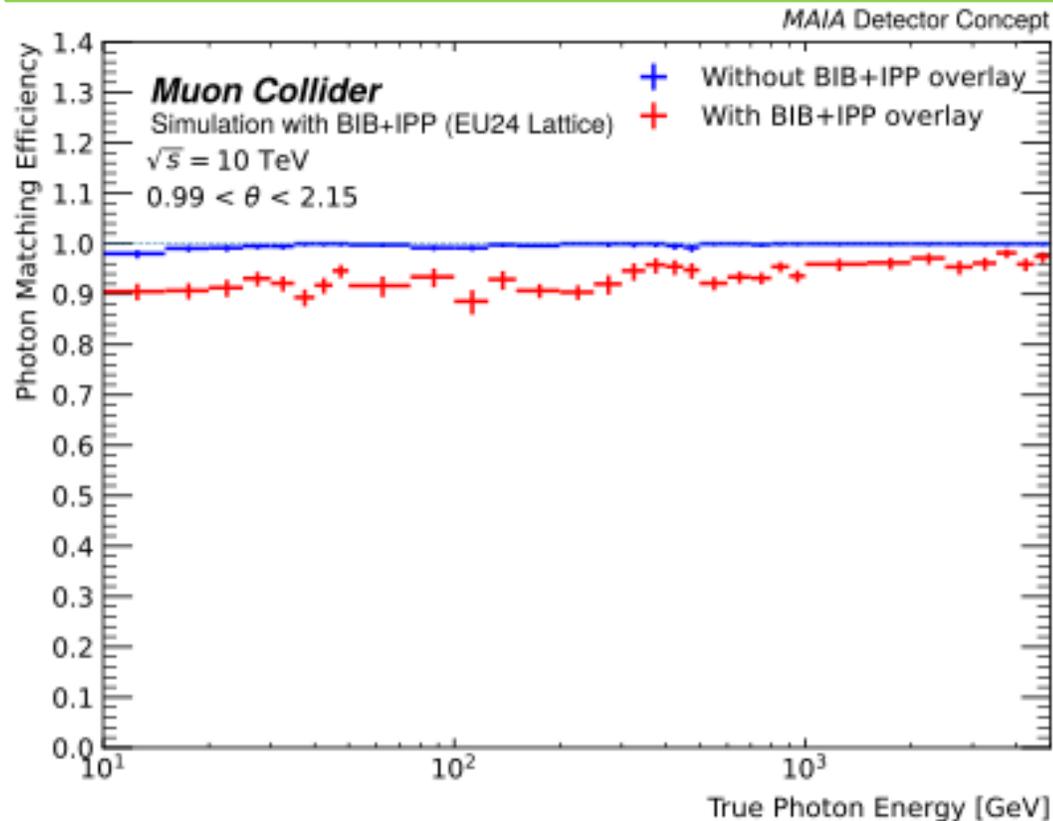
Note zoomed efficiency axis!



ECAL Performance: Photon Efficiency

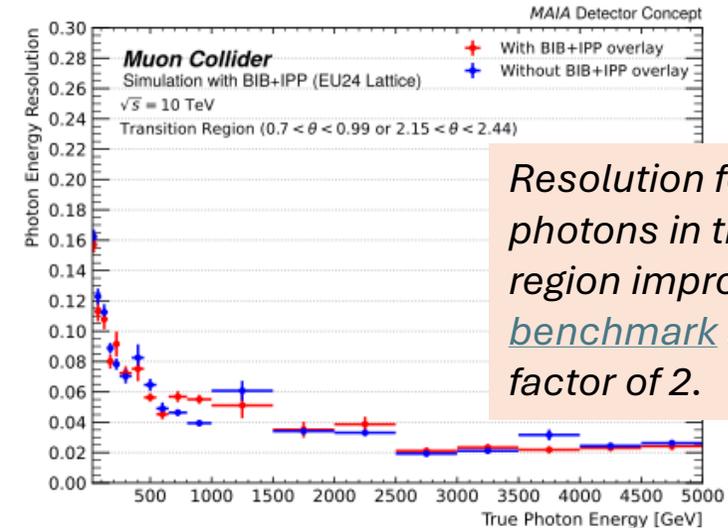
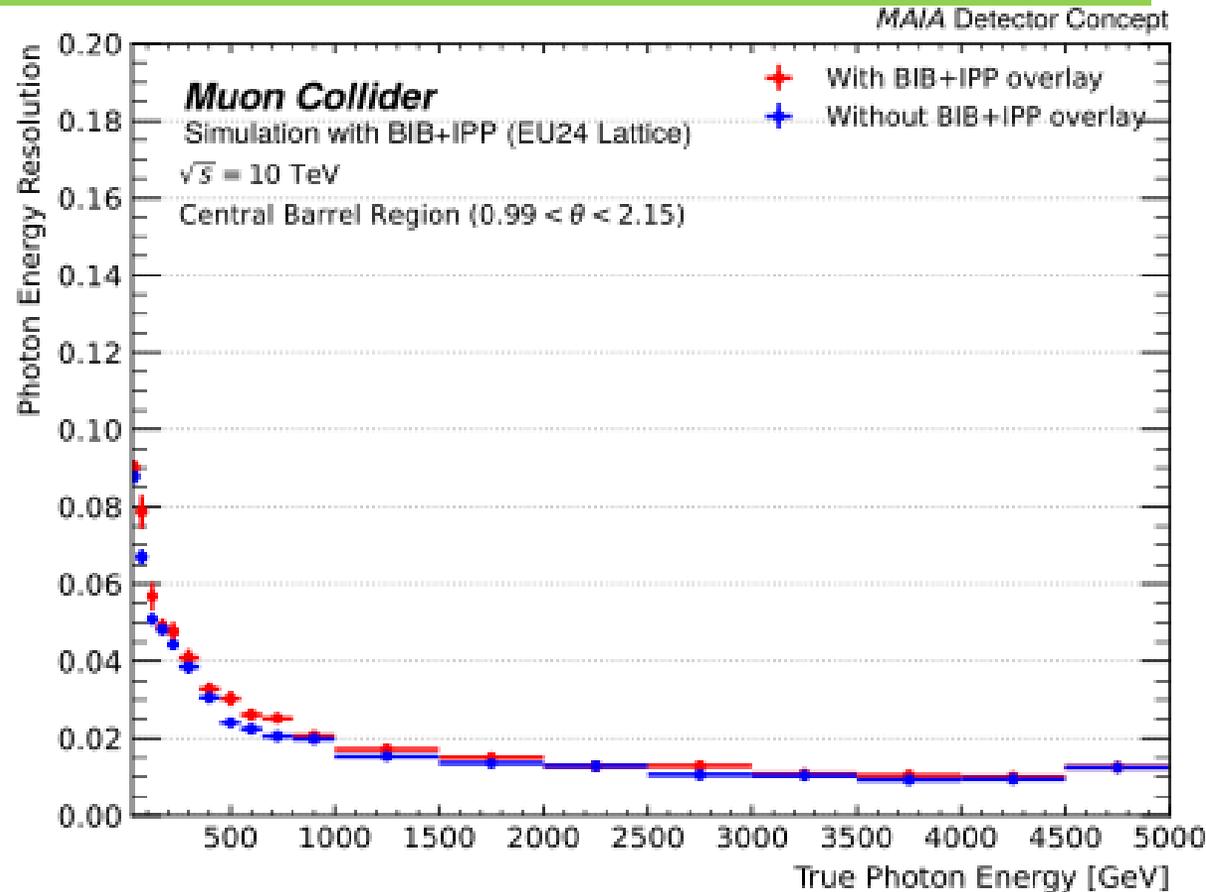
We match truth photons to the highest- p_T reconstructed candidate that is (a) tagged as a photon and (b) has $\Delta R < 0.1$.

- Efficiency in the barrel region better than **90%** with BIB at all energies
- We struggle to match in the endcap region—theta asymmetry under active investigation

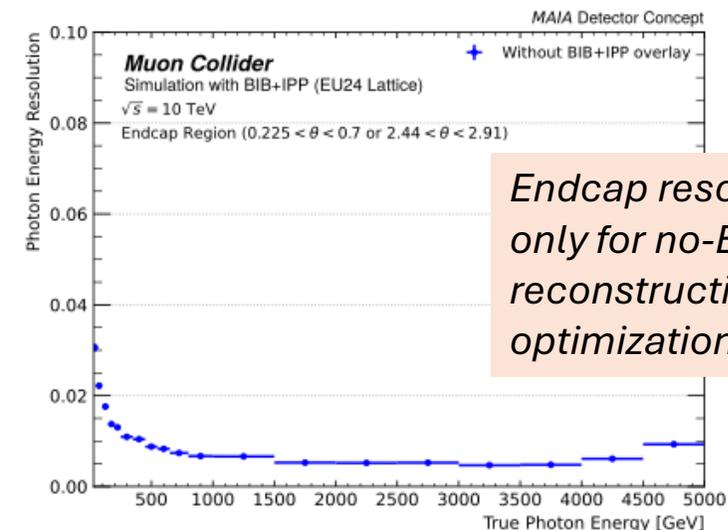


ECAL Performance: Photon Resolution

Energy resolution **below 10%** in the barrel at all energies, even in the presence of BIB!



Resolution for low-energy photons in the transition region improved over our benchmark by more than a factor of 2.

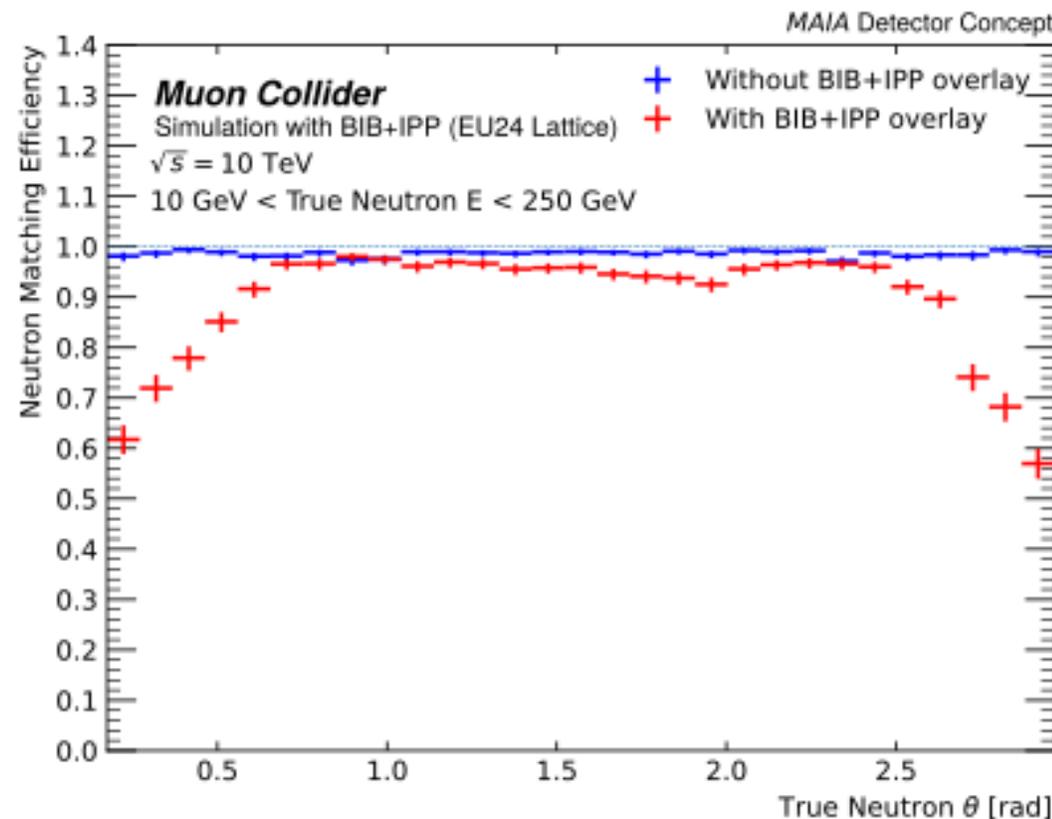
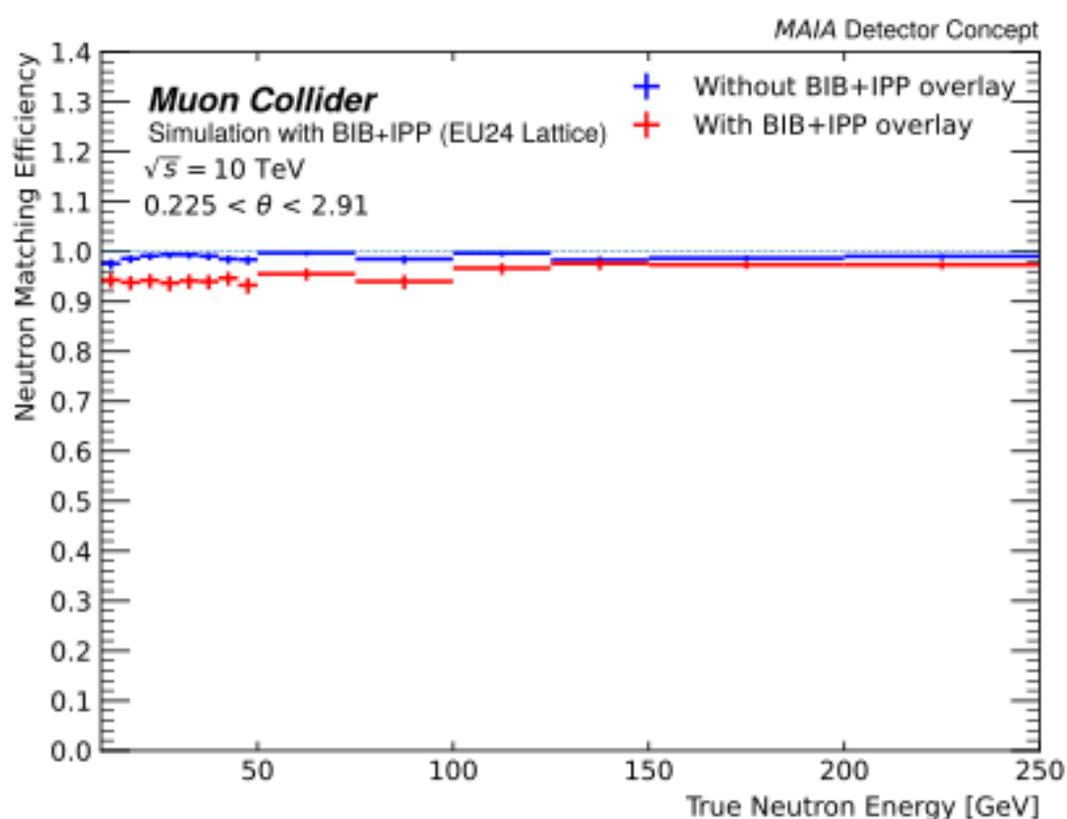


Endcap resolution shown only for no-BIB sample: reconstruction still needs optimization in this region.

HCAL Performance: Neutron Efficiency

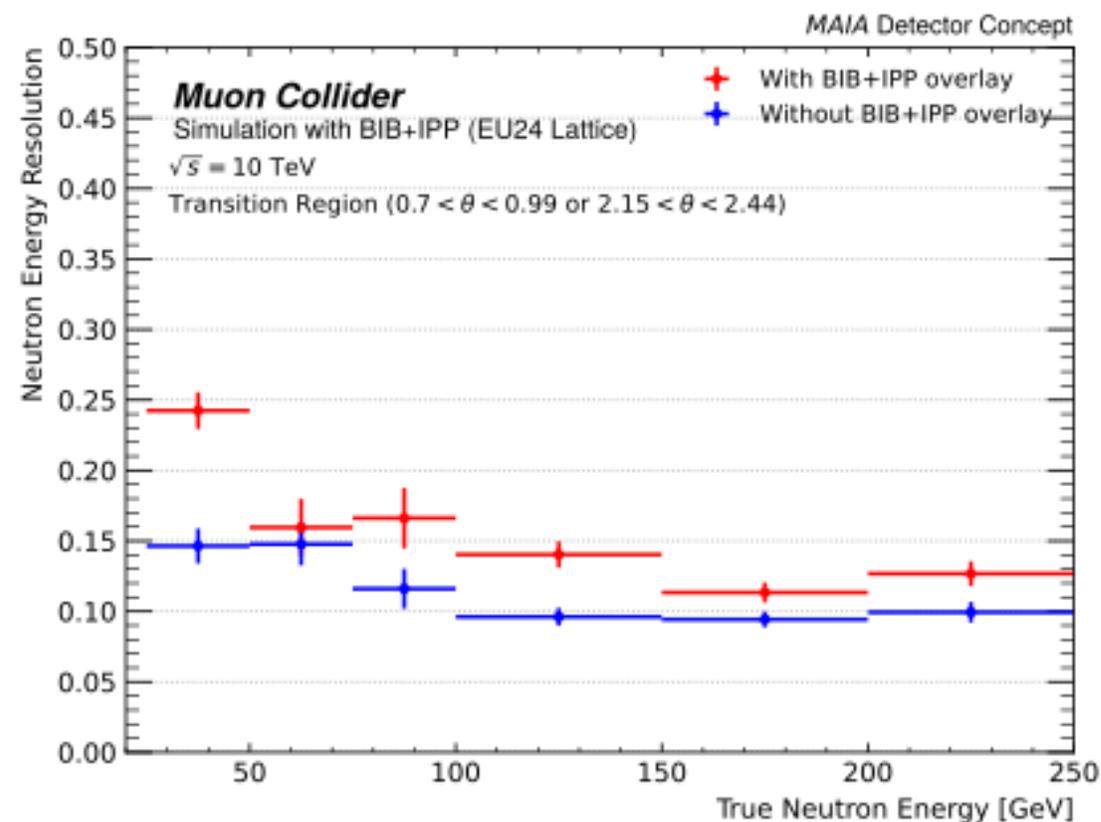
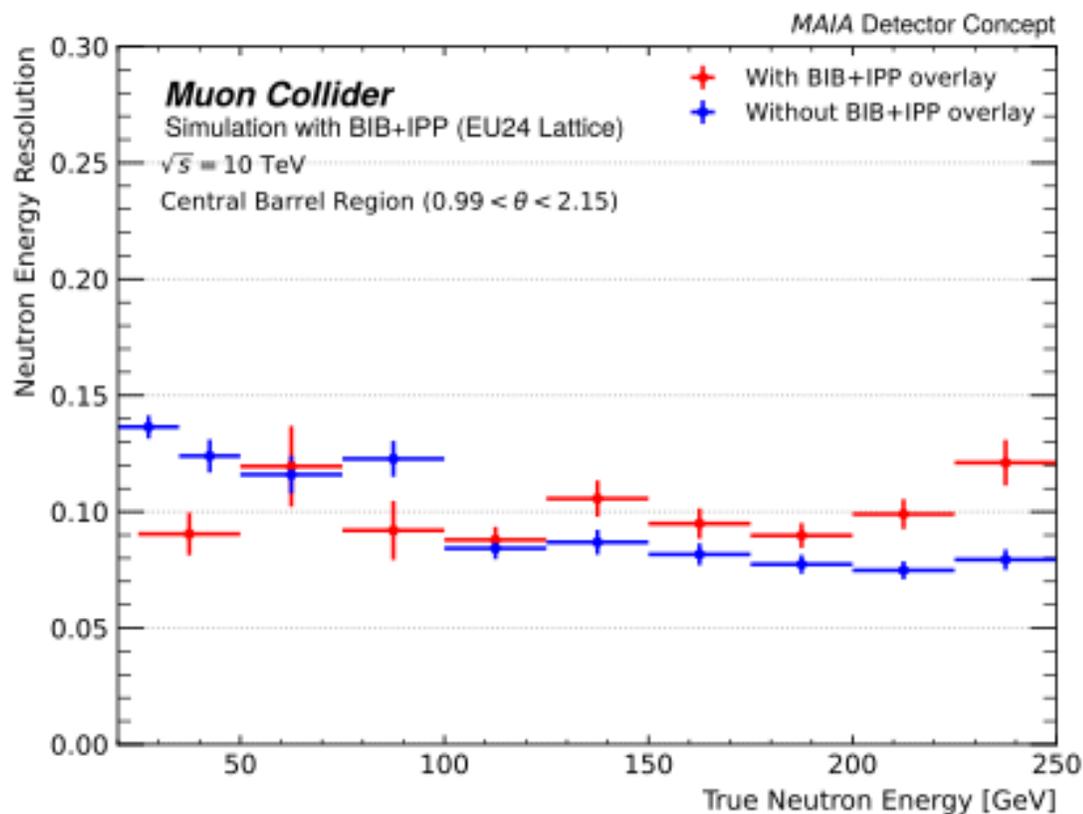
We match truth neutrons to the highest- p_T reconstructed candidate that is (a) tagged as a neutron and (b) has $\Delta R < 0.4$.

- Efficiency in the barrel region better than **95%** with BIB at all energies
- We struggle to match neutrons in the endcap region as well (no solenoid shielding in this region)



HCAL Performance: Neutron Resolution

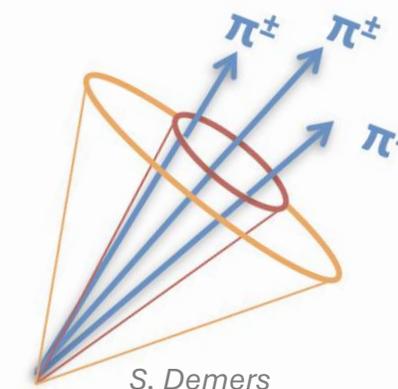
In the barrel and transition regions, vast improvement in neutron energy resolution over [benchmark](#)
 - (more than a factor of 3 at low energies!)



More Advanced Objects

Charged pions

- Need good performance from tracker, ECAL, HCAL
- Track-to-cluster matching (nontrivial process in Pandora!)

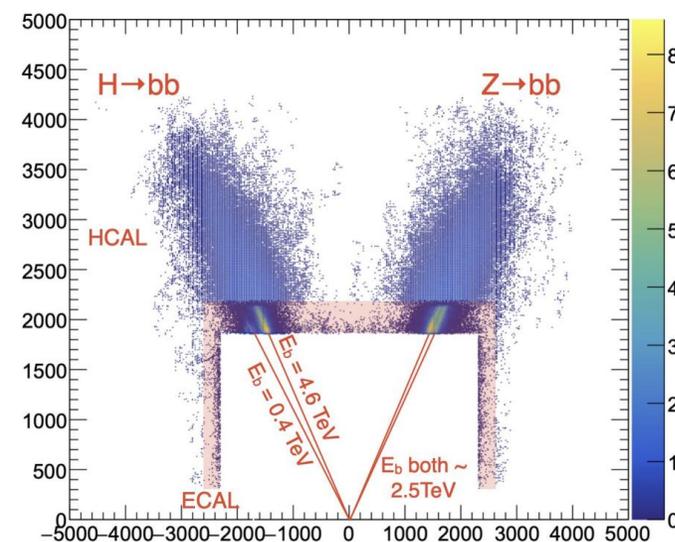


Taus

- Heavy third-generation leptons decay promptly
- Hadronic decay modes
- Need good pion reconstruction
- Group decay products to form a tau candidate

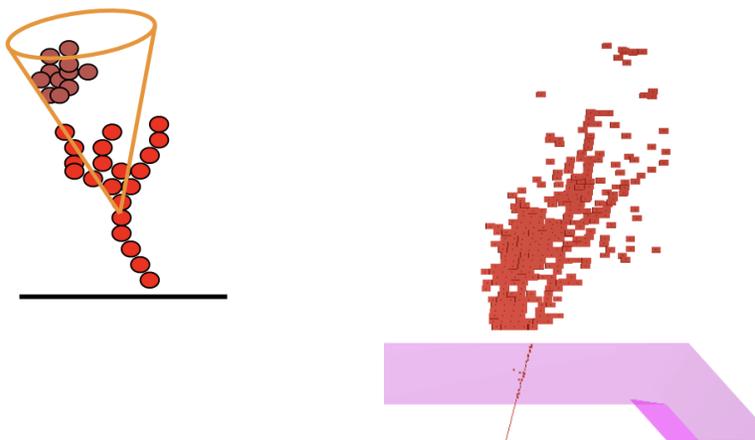
Di-jets, b-jet tagging, etc...

- Several studies currently underway on jets!

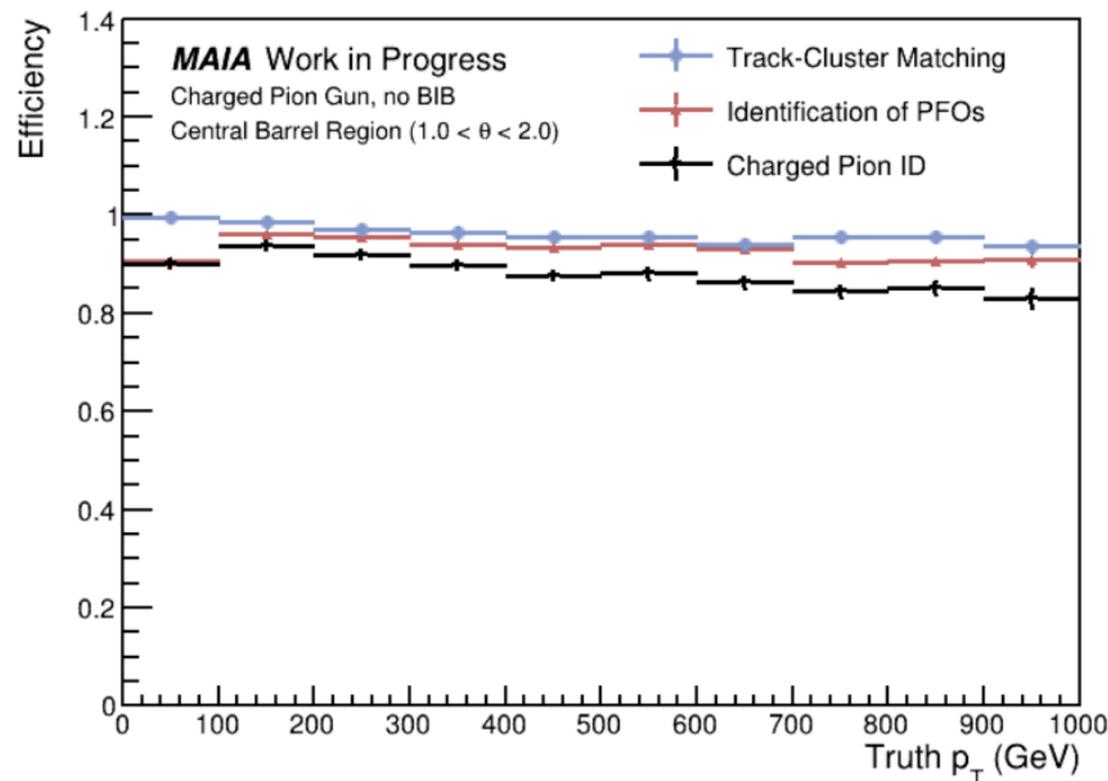


Charged Pion Reconstruction Performance

Charged pion reconstruction efficiency with three figures of merit: track-to-cluster matching, particle flow object ID, and charged pion ID. Results shown for a no-BIB environment.

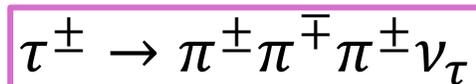
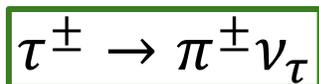
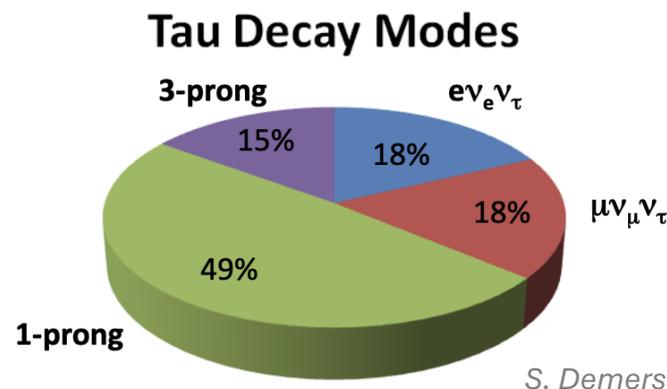


Challenges with track-to-cluster matching in pion samples inspired our current optimization of Pandora—see slide 21.

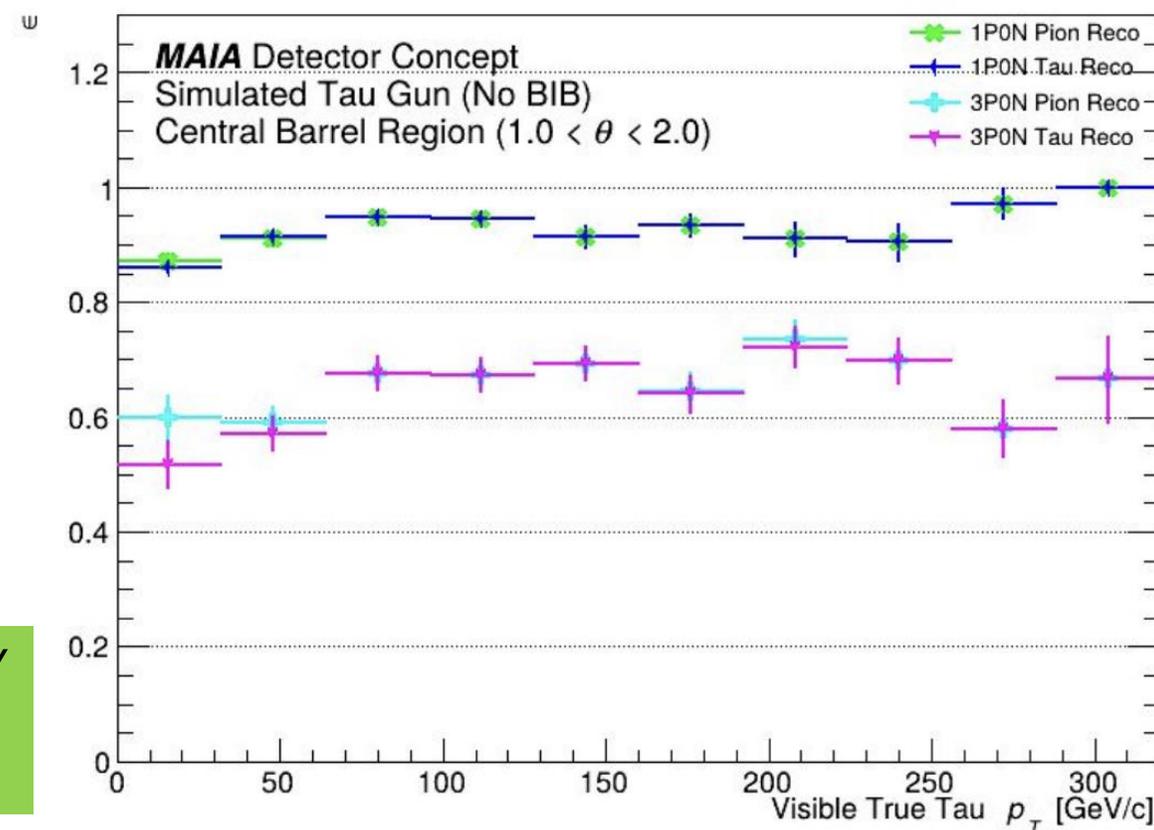


Tau Reconstruction Efficiency

The most common decay mode contains a single charged hadron (often a charged pion); alternatively, hadronic decays involve three charged hadrons about 15% of the time.



We reconstruct 1-prong taus with no neutral decay products in a no-BIB environment with a global efficiency of **~90%**!



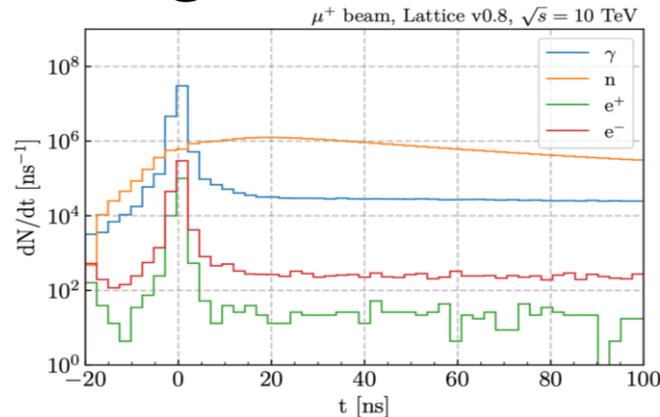
Reconstruction Optimization

The detector performance improvements displayed here are the result of a suite of recent optimization efforts. Among them...

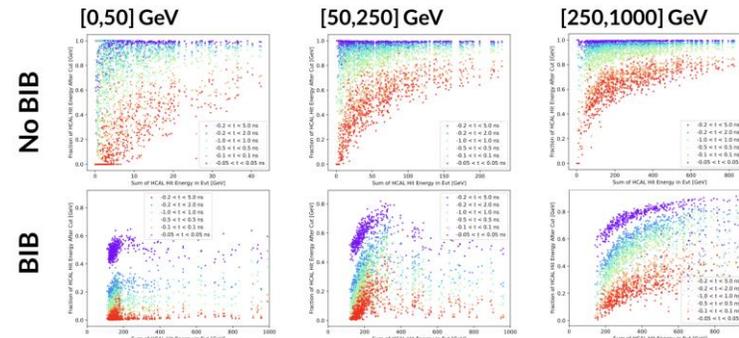
1. Pandora Particle Flow Optimization (see [Gregory Penn's talk](#))



2. BIB timing cuts → 5D Precision Calorimetry



D. Calzolari



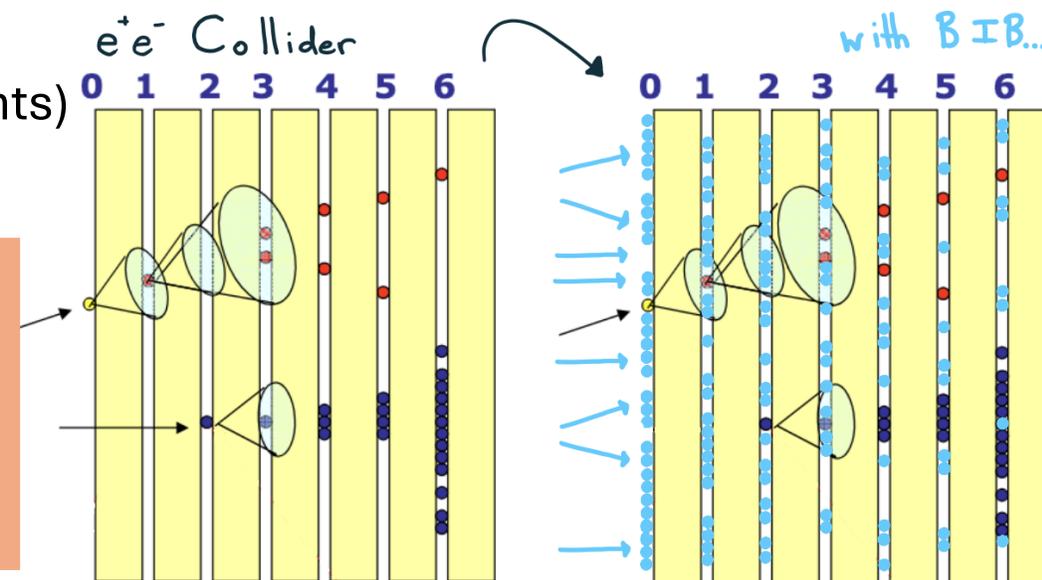
Rose Powers (Princeton)

Optimizing Pandora

PandoraPFA was originally developed for a linear electron-positron collider.

- Relies on a series of iteratively implemented algorithms to achieve...
 - Clustering
 - Track-to-cluster matching
 - Cluster “cleaning” (removing and merging fragments)
 - Particle ID

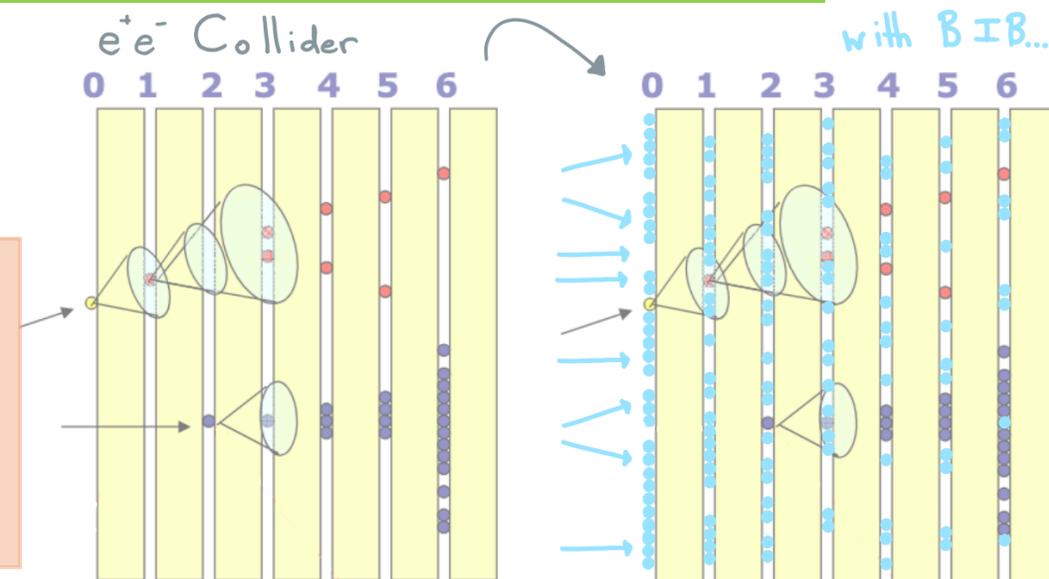
*In a high-background environment, this iterative process creates **ballooning combinatorics** and is prohibitively computationally expensive.*



Optimizing Pandora

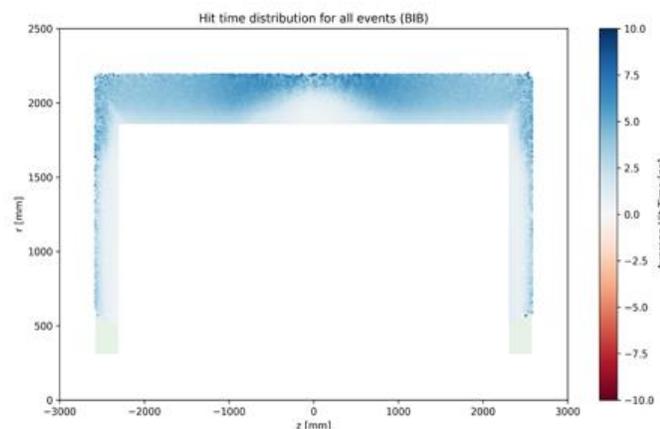
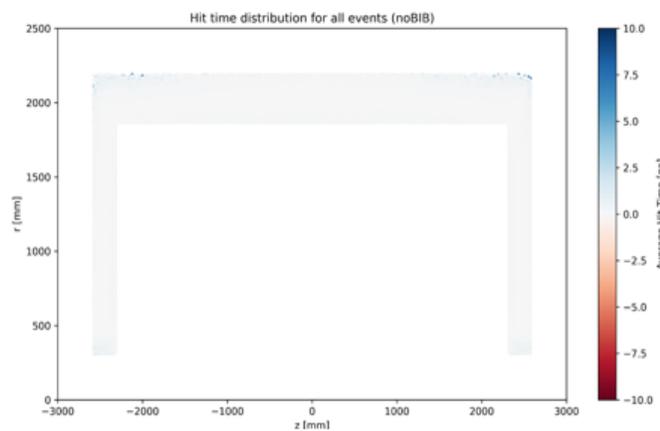
We have pared down the extensive list of algorithms called by Pandora and developed a “recipe” that reduces computational time by a factor of ~ 10 without significant degradation to reconstruction performance.

*In a high-background environment, this iterative process creates **ballooning combinatorics** and is prohibitively computationally expensive.*

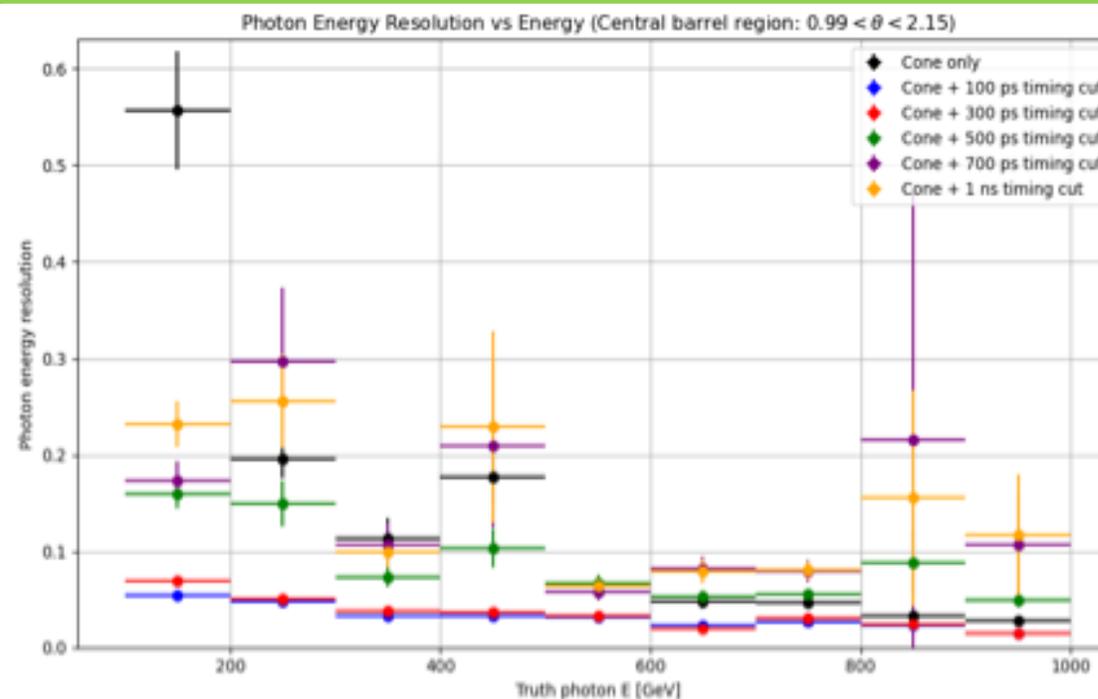


BIB Timing Cuts

Most BIB arrives out-of-time. Assuming cutting-edge timing precision from ECAL, we can use timing info to our advantage.



Study of BIB timing distribution determined range of feasible time cuts on calo hits → **300 ps** chosen as optimal value



Conclusions and Outlook

After several recent optimizations, we have achieved new benchmarks for simple object reconstruction in the MAIA detector.

- Still optimization to be done in the **endcap regions** for all subdetectors
 - Looking into **forward muon tagging** at very edges of endcap acceptance
- Simulating the BIB remains a **computational bottleneck**; studies underway into the possible use of generative AI to produce full-BIB samples
- We can now study more complicated objects – such as the pions, taus, and jets mentioned here
- It is an exciting time for the MAIA detector concept, with many ways to get involved in research!

*Link to the MAIA Software Tutorial: <https://mcd-wiki.web.cern.ch/software/howto/maia/>
Please reach out if you are interested in joining the effort!*

Backup – Muon Collider Requirements

10 TeV Muon Collider Beam Requirements

Parameter	Symbol	$\sqrt{s} = 10 \text{ TeV}$
Particle energy [GeV]	E	5000
Luminosity [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$]	\mathcal{L}	20
Bunch population [10^{12}]	N_p	1.8
Transverse normalized rms emittance [μm]	ε_n	25
Longitudinal emittance ($4\pi \sigma_E \sigma_T$) [eVs]	ε_l	0.314
Rms bunch length [mm]	σ_z	1.5
Relative rms energy spread [%]	p_T	0.1
Beta function at IP [mm]	β^*	1.5
Beam power with 10 Hz repetition rate [MW]	P_{beam}	14.4

Backup – MAIA Dimensions

Subsystem	Region	R dimensions [cm]	Z dimensions [cm]	Material
Vertex Detector	Barrel	3.0 – 10.4	65.0	Si
	Endcap	2.5 – 11.2	8.0 – 28.2	Si
Inner Tracker	Barrel	12.7 – 55.4	48.2 – 69.2	Si
	Endcap	40.5 – 55.5	52.4 – 219.0	Si
Outer Tracker	Barrel	81.9 – 148.6	124.9	Si
	Endcap	61.8 – 143.0	131.0 – 219.0	Si
Solenoid	Barrel	150.0 – 185.7	230.7	Al
ECAL	Barrel	185.7 – 212.5	230.7	W + Si
	Endcap	31.0 – 212.5	230.7 – 257.5	W + Si
HCAL	Barrel	212.5 – 411.3	257.5	Fe + PS
	Endcap	30.7 – 411.3	257.5 – 456.2	Fe + PS
Muon Detector	Barrel	415.0 – 715.0	456.5	Air + RPC
	Endcap	44.6 – 715.0	456.5 – 602.5	Air + RPC

Backup – Tracker Specifics

	Vertex Detector	Inner Tracker	Outer Tracker
Sensor type	pixels	macro-pixels	micro-strips
Barrel Layers	4	3	3
Endcap Layers (per side)	4	7	4
Cell Size	$25\ \mu\text{m} \times 25\ \mu\text{m}$	$50\ \mu\text{m} \times 1\ \text{mm}$	$50\ \mu\text{m} \times 10\ \text{mm}$
Sensor Thickness	$50\ \mu\text{m}$	$100\ \mu\text{m}$	$100\ \mu\text{m}$
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	$5\ \mu\text{m} \times 5\ \mu\text{m}$	$7\ \mu\text{m} \times 90\ \mu\text{m}$	$7\ \mu\text{m} \times 90\ \mu\text{m}$

Backup – Calorimeter Specifics

	Electromagnetic Calorimeter	Hadron Calorimeter
Cell type	Silicon - Tungsten	Iron - Scintillator
Cell Size	5.1 mm × 5.1 mm	30.0 mm × 30.0 mm
Sensor Thickness	0.5 mm	3.0 mm
Absorber Thickness	2.2 mm	20.0 mm
Number of layers	50	75