MAIA 10 TeV Detector Concept

Kiley Kennedy, Princeton University

On behalf of many people

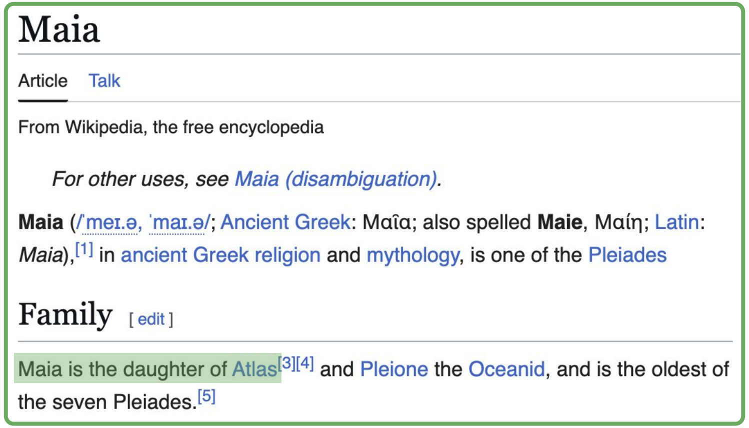
IMCC Annual Meeting, 14 May 2025

Title: L. Lee, C. Bell

Overview

- Introduction and motivation
- Simulation of beam induced background (BIB)
- Tracker design and performance
- Calorimeter design and performance
- Conclusions & Outlook

arXiv:2502.00181
In ESPPU Submission



Maia

Article Talk

From Wikipedia, the free encyclopedia

For other uses, see Maia (disambiguation).

Maia (/ˈmeɪ.ə, ˈmaɪ.ə/; Ancient Greek: Μαῖα; also spelled **Maie**, Μαίη; Latin: *Maia*),[1] in ancient Greek religion and mythology, is one of the Pleiades

Family [edit]

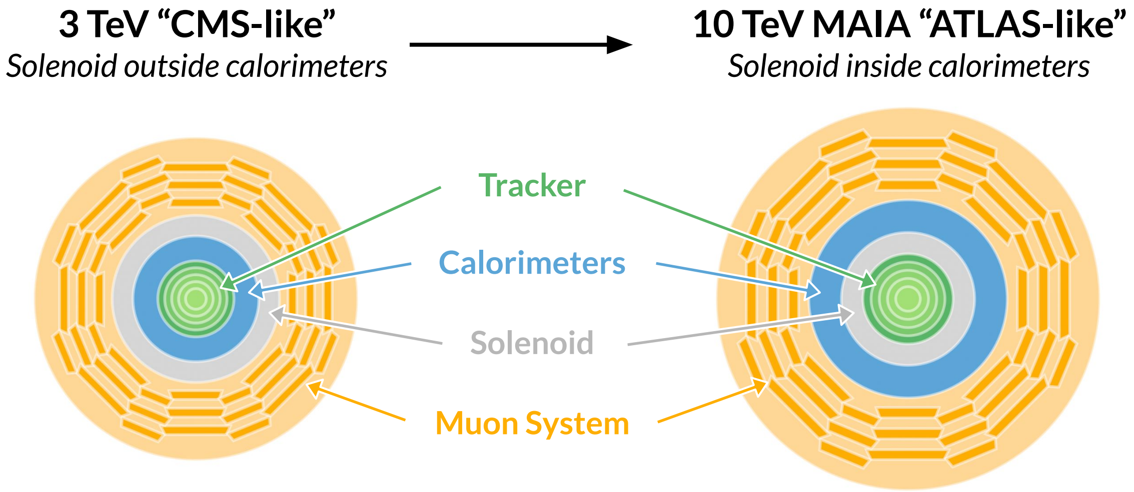
Maia is the daughter of Atlas[3][4] and Pleione the Oceanid, and is the oldest of the seven Pleiades.[5]

Results today include contributions from many, including:

Charles Bell, Daniele Calzolari, Christian Carli, Sarah Demers, Karri Folan Di Petrillo, Micah Hillman, Tova R. Holmes, Sergo Jindariani, Ka Hei Martin Kwok, Anton Lechner, Lawrence Lee, Thomas Madlener, Ethan Martinez, Federico Meloni, Isobel Ojalvo, Priscilla Pani, Gregory Penn, Rose Powers, Benjamin Rosser, Leo Rozanov, Kyriacos Skoufaris, Elise Sledge, Alexander Tuna, Junjia Zhang

Introduction + Motivation

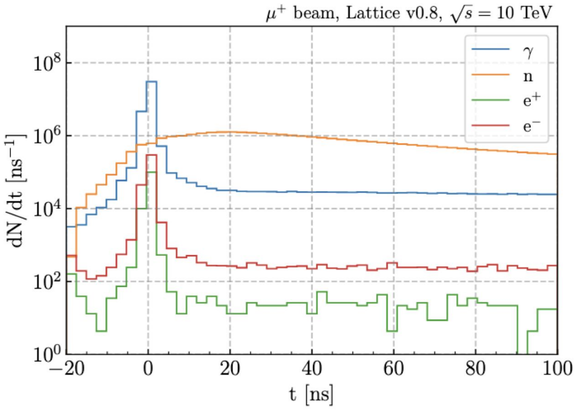
- Extensive detector studies for 1.5 and 3 TeV muon colliders
  - Critical to determine if (and how) 10 TeV detector concepts can handle high BIB
- MAIA designed for 10 TeV, based on 3 TeV design
  - Updated to updated nozzle design, deeper calorimeters, move solenoid inside the calorimeters



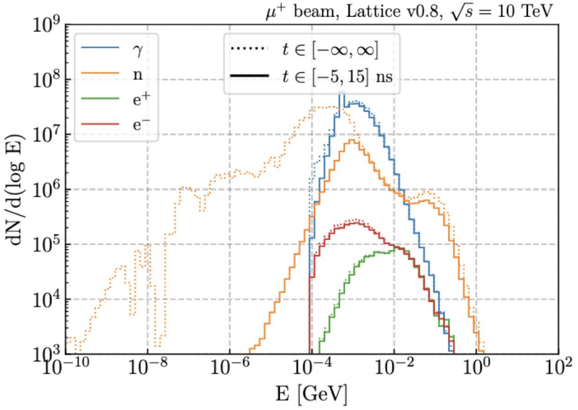
BIB Simulation, Assumptions, and Mitigation

- Latest results with EU24 (v0.8) accelerator lattice
  - Significantly higher BIB fluxes than with v0.4 lattice
- Assume dominant BIB from muon decays near the interaction region
  - Only consider muon decays in the final focusing region
  - Ignore beam halo and incoherent pair-production (for now)
- Simulated in FLUKA + overlaid with hard collision processes

BIB Distributions vs. t



BIB Distributions vs. E



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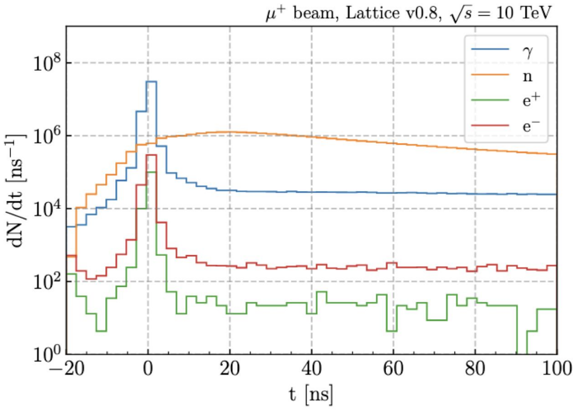
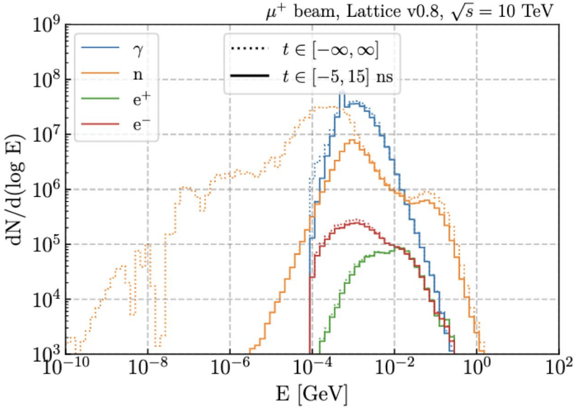
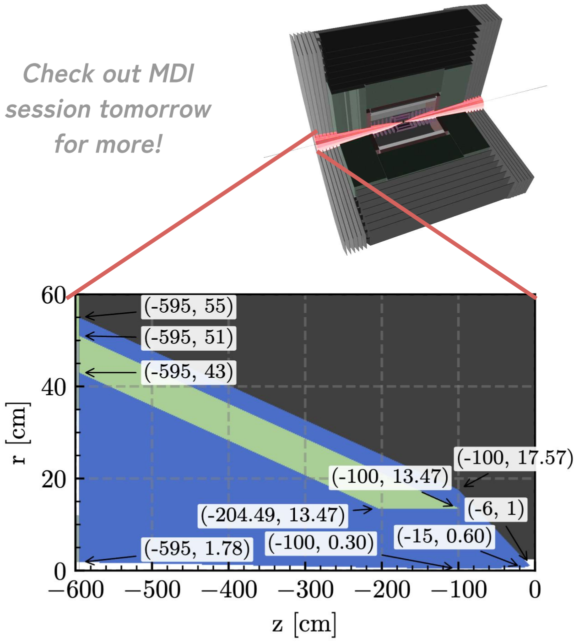


BIB Distributions vs. E



- Nozzles in the forward regions
  - INTERMET: mitigate EM
  - Borated polyethylene: neutron capture

Check out MDI session tomorrow for more!



Solenoid

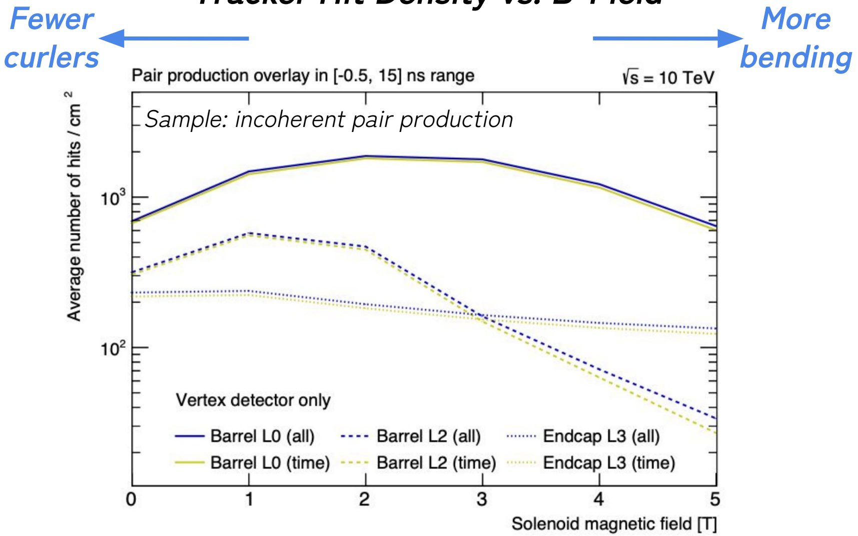
Move solenoid inside calorimeters due to increased B-field requirements

- MAIA increases solenoid field to 5 T (up from 3.57 T for 3 TeV detector)
- Adds approximately to ~4X_0 upstream of the calorimeter

Higher solenoid B-field significantly reduces fluence and occupancy

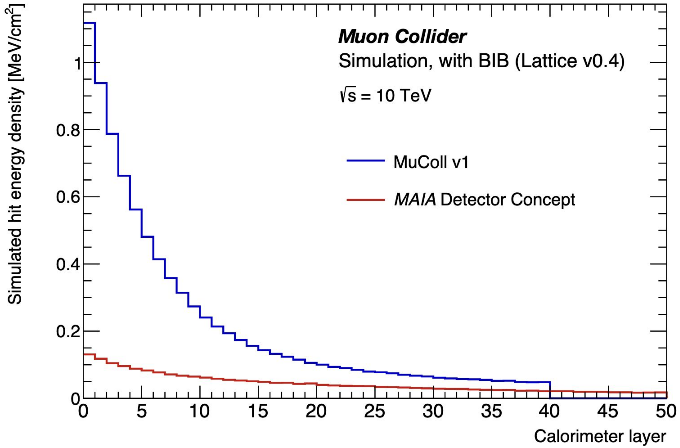
- BIB shielding for calorimeters, although this also degrades resolutions of hard scatter processes

Tracker Hit Density vs. B-Field



Energy Density of BIB in ECAL

~3-10x lower than 1.5 TeV due to solenoid shielding



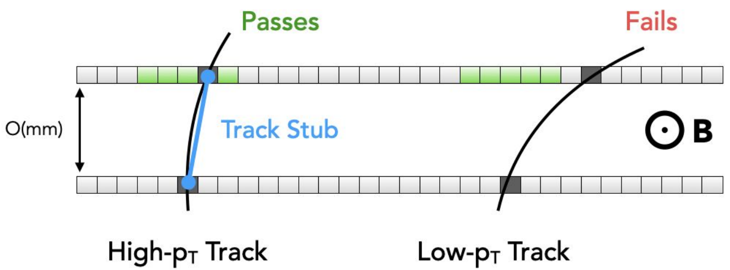
Tracker Design

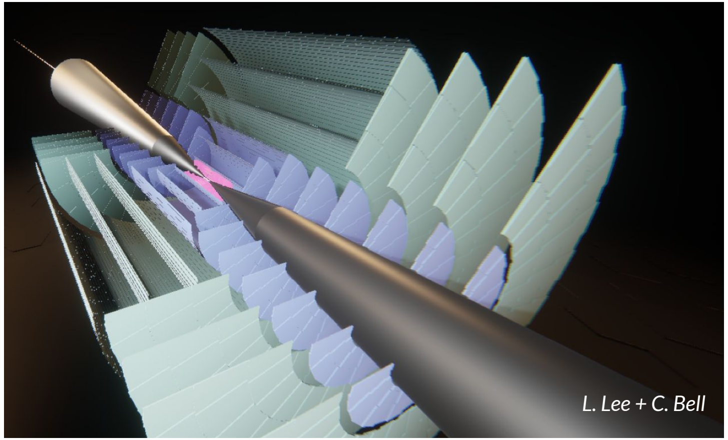
Major update w.r.t. 3 TeV design: reduction in number of doublet layers, which produce track ("stubs")

- Removed all but one doublet layer in vertex detector

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

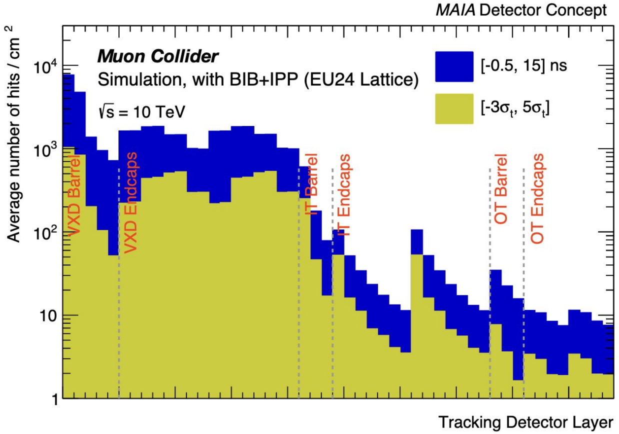
Tracking based on ACTS library led to significant improvements → many doublet layers redundant

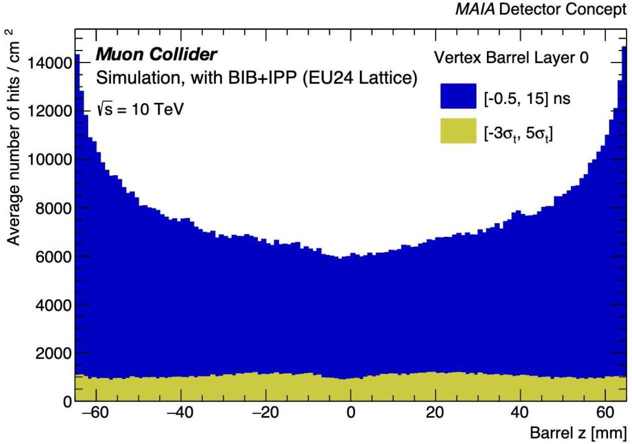




Tracker: BIB Occupancies

- Occupancies ~10x higher with realistic nozzle and lattice (v0.8/EU24) compared to previous versions (v0.4)
  - Highly dependent on accelerator lattice and nozzle
- Applying timing cuts significantly reduces BIB:
  - Broad time window → [-0.5, 15] ns
  - Narrow time window → [-3 σ_t, 5 σ_t]
- Sub-100 ps timing resolution critical to reduce hit occupancy in vertex layers



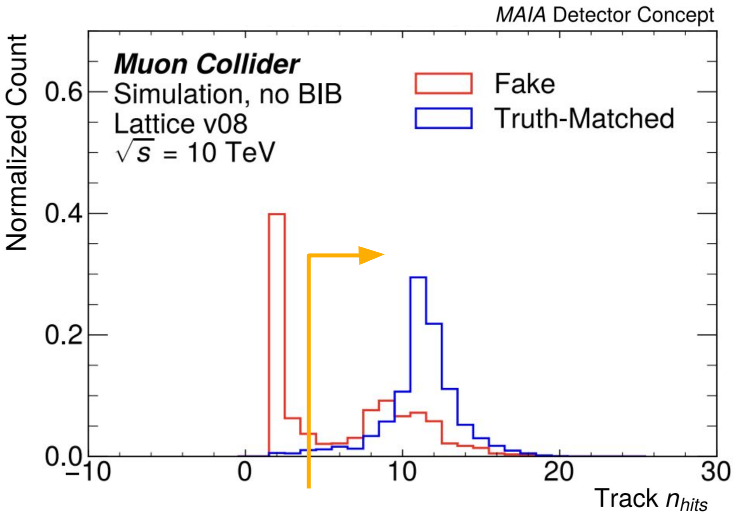


Track Reconstruction Performance

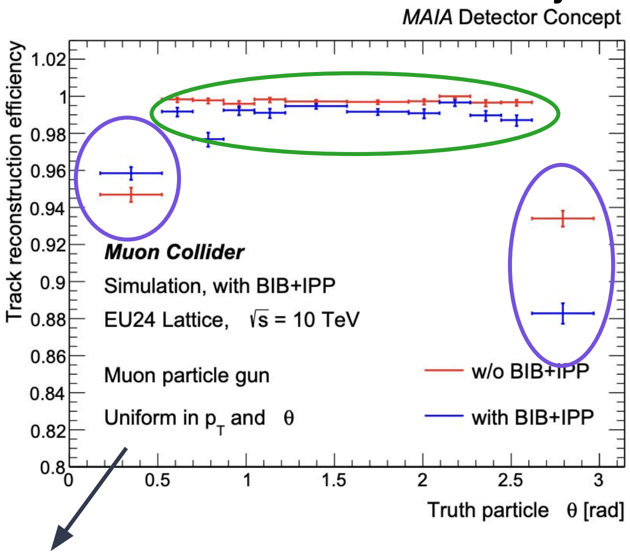
Use single muon gun sample to evaluate tracking performance

- Track cleaning: $p_T > 1$ GeV, $|d_0| < 0.1$ mm, $N_{hits} > 5$

Track Hit Multiplicity



Track Reconstruction Efficiency

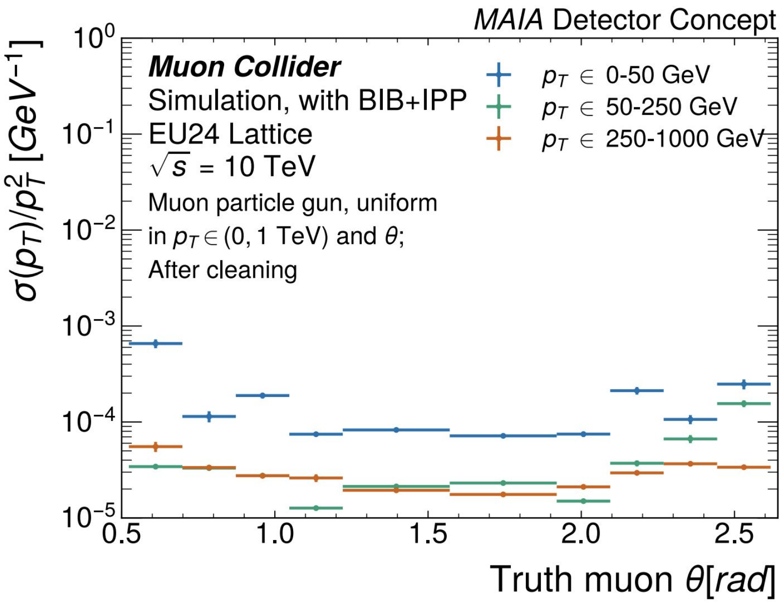


Reconstruction efficiency with BIB excellent in the barrel; degrades in the forward region

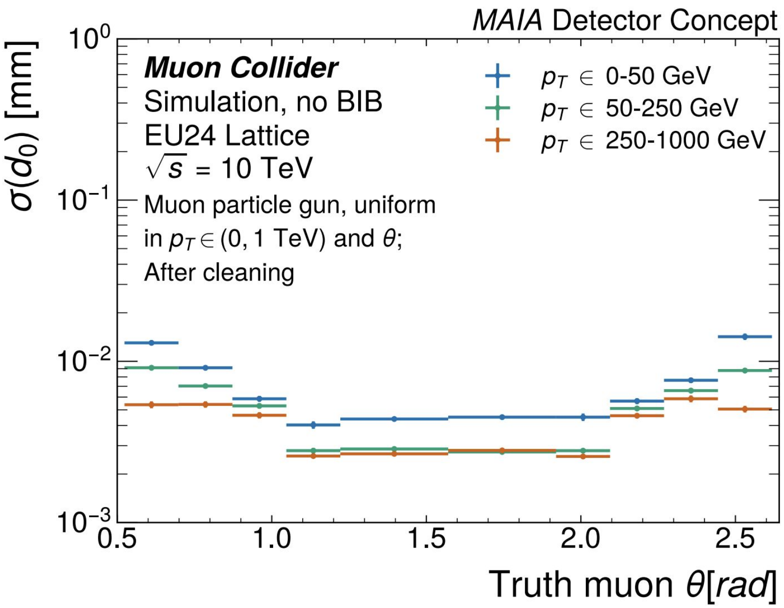
Track Reconstruction Performance

Excellent track p_T and impact parameter resolution, especially for harder tracks in the barrel

Track p_T Resolution



Track Impact Parameter Resolution

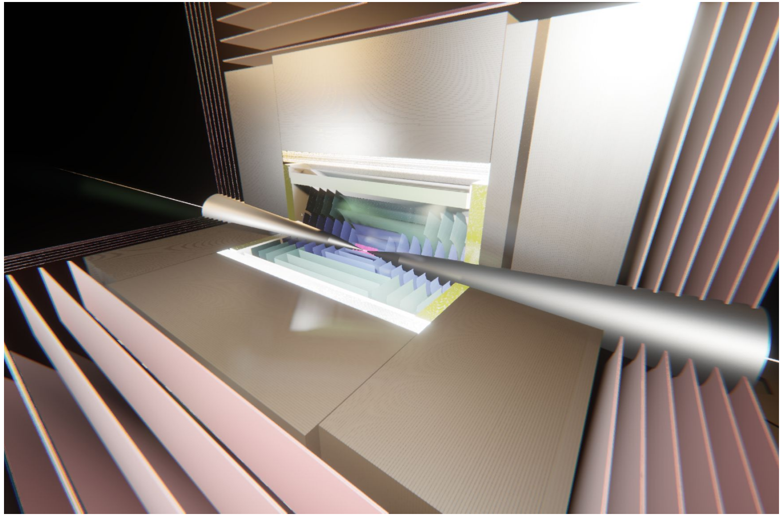


Calorimeter Design

	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

MAIA design increases number of ECAL and HCAL layers by 25% w.r.t. 3 TeV design to accommodate for harder final states

- Resolution Targets:
  - ECAL energy resolution target: 10% $/\sqrt{E}$
  - HCAL energy resolution target: 35% $/\sqrt{E}$



ECAL: Impact of BIB

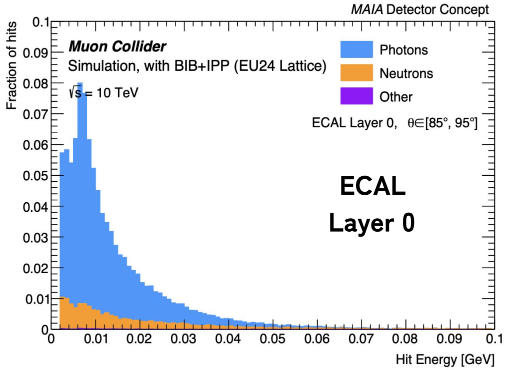
BIB in the ECAL mostly due to photons and neutrons

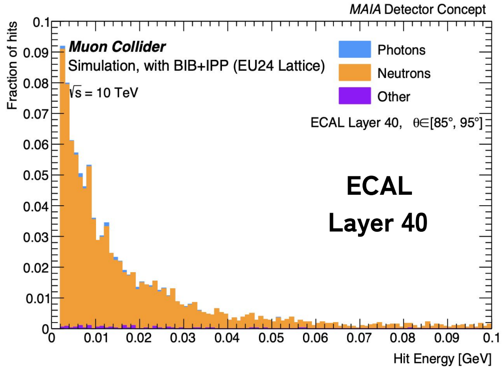
- Most BIB so soft and diffuse that it is not possible to reconstruct
- Lower layers photon-dominated, deeper layers neutron-dominated

BIB deposits up to ~6 MeV/cell

- Varies across θ and depth, with higher energies in the more forward region (due to solenoid)

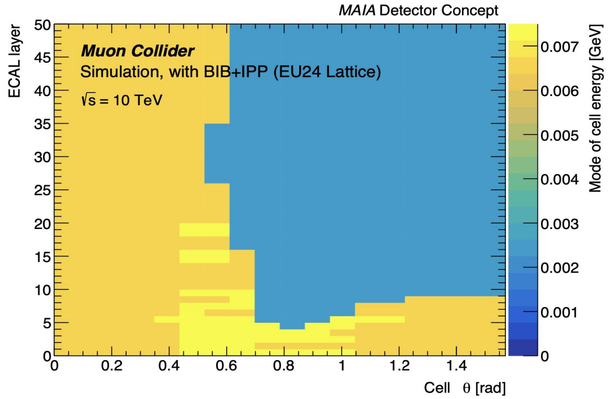
Composition of BIB Across ECAL Layers





Mode of Energy per ECAL Cell

Deeper into the ECAL

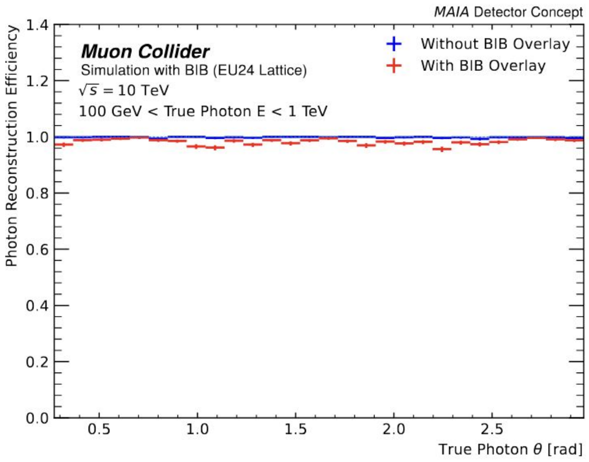


more forward ⟷ more central

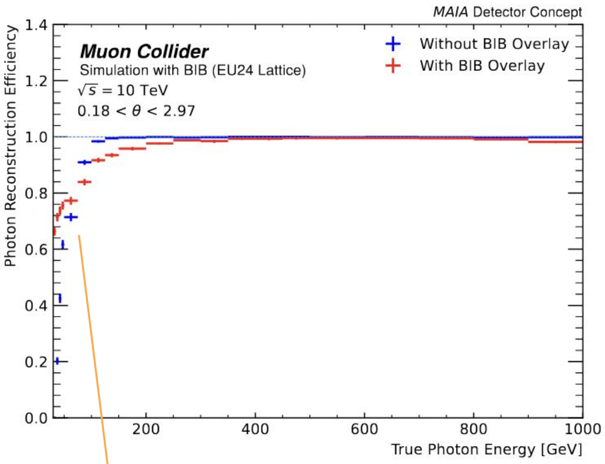
Photon Reconstruction Efficiency

- Use photon objects to evaluate ECAL performance
- Excellent (>95%) reconstruction efficiency across the barrel and endcaps for high-energy (>200 GeV) photons
- Challenging to reconstruct low-energy photons, many fakes

Efficiency vs. θ



Efficiency vs. E



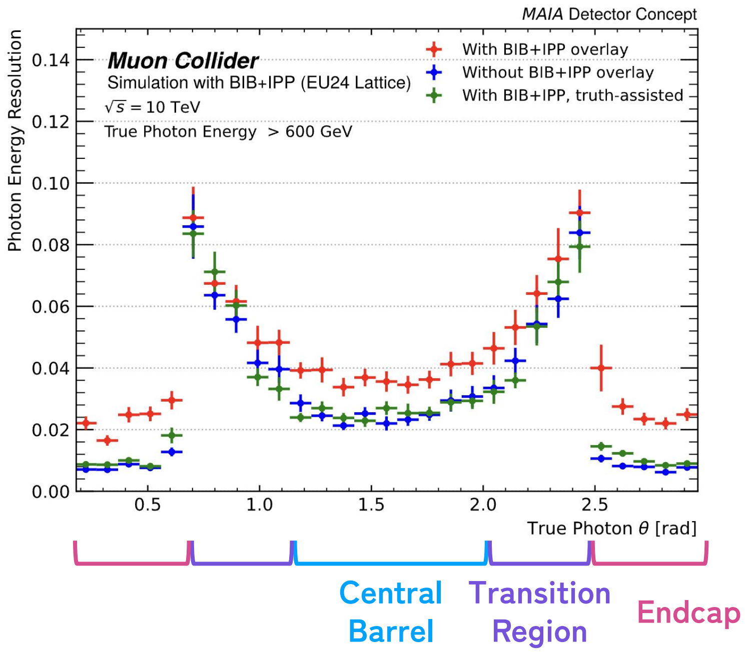
Reco efficiency with BIB is higher than without BIB → lots of fakes, improved algorithms needed

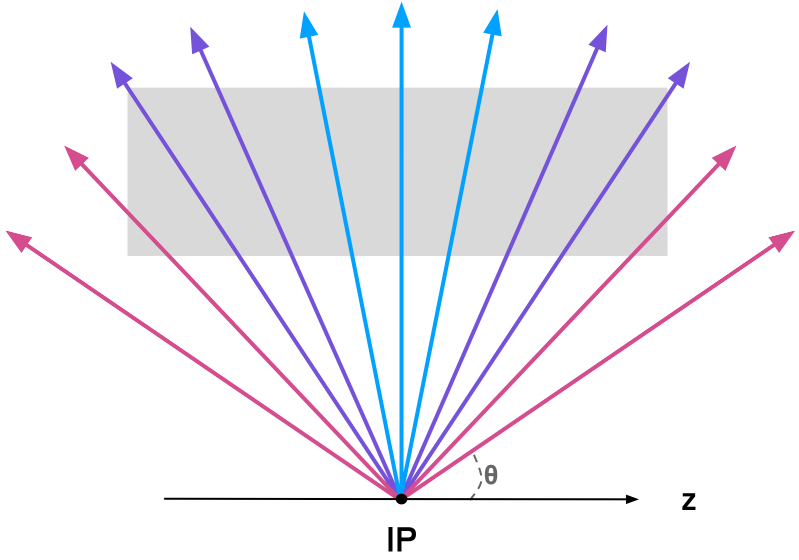
Photon Reconstruction Performance

Photon energy resolution highly dependent on position in theta – excellent in the central barrel and endcap

- Worse resolution for particles most impacted by the material of the solenoid

Photon Energy Resolution vs. Theta





Photon Reconstruction Performance

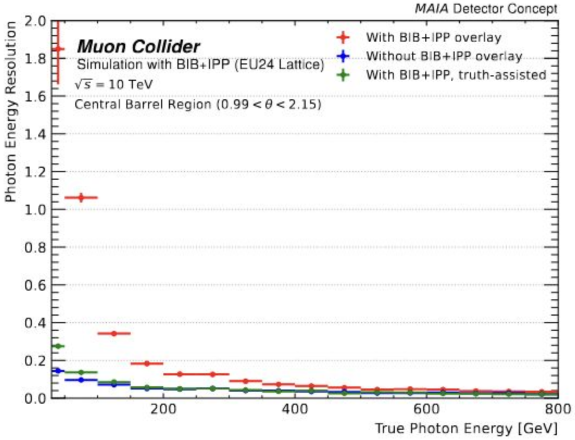
Results for no BIB and truth-assisted case ~meet specification requirements in the endcap

- Truth-assisted reconstruction: all ECAL cells within ΔR cone of 0.1 around truth particle
- Best results minimal or no interaction with solenoid

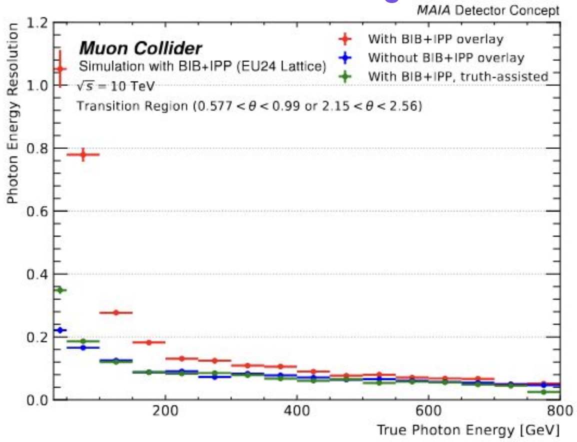
Results with BIB show significantly degraded resolutions – reconstruction algorithm improvements crucial

- Roughly ~similar results across the detector, regardless of upstream solenoid material

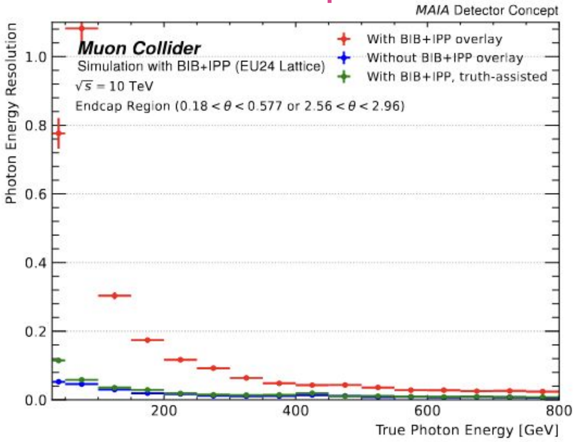
Central Barrel



Transition Region



Endcap



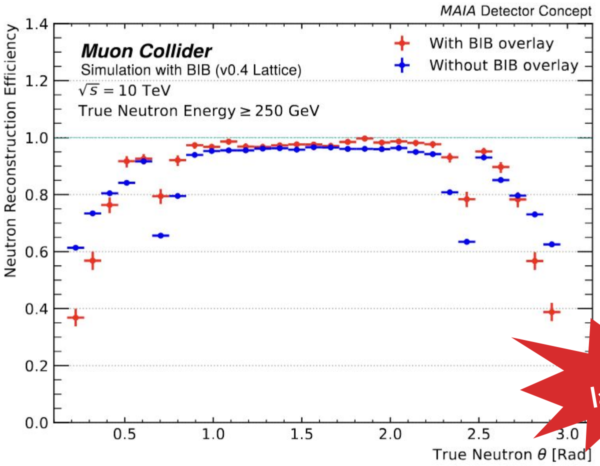
E. Sledge, R. Powers

Neutron Reconstruction Performance

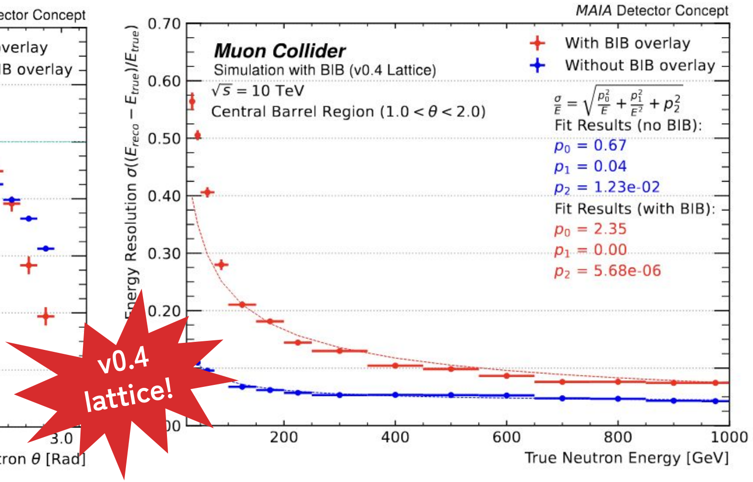
Very good results for lattice v0.4, especially for high-energy neutrons in the barrel

- Significant reconstruction challenges in v0.8 (not shown) – improvements to reconstruction algorithms critical
- Use neutron objects to evaluate HCAL performance

Efficiency vs. θ



Energy Resolution (Barrel)

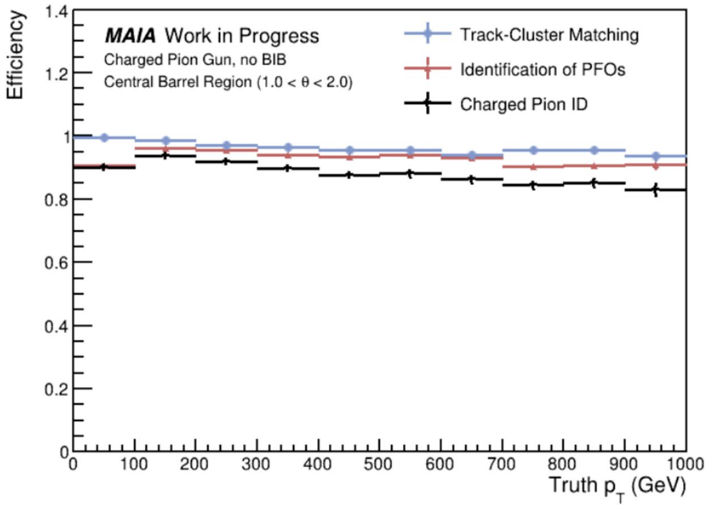


G. Penn, E. Martinez

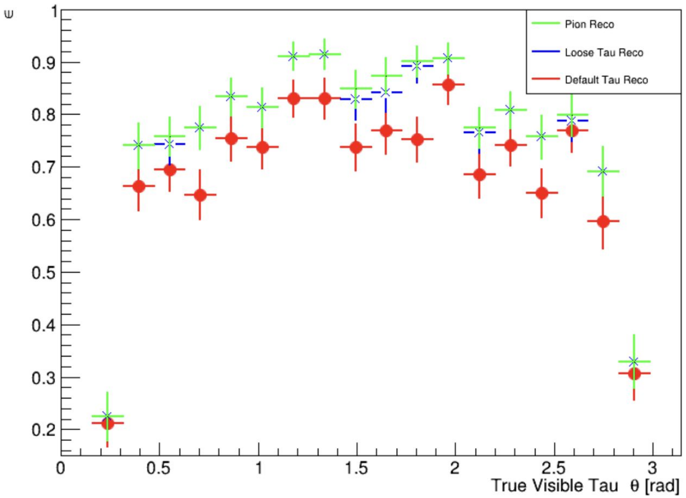
Towards Complex Objects: Pion + Tau Reconstruction

Ongoing investigations into more complex objects have already started to lead to significant algorithmic improvements and reveal promising results (without BIB)

Charged Pion Reconstruction Efficiency



Single-Prong Tau Reconstruction Efficiency



Ongoing + Future Work

- Detector optimization
  - Tracker: endcaps/forward region; doublet layer considerations
  - Solenoid material budget challenges
  - Muon spectrometer: in-air RPC centrally, forward region not yet integrated into design
- Machine-detector interface → see Rose's MDI talk tomorrow!
  - Nozzle design and interplay with collider lattice
- Software and reconstruction → see Greg's particle flow talk tomorrow
  - Integrating timing into calorimeter clustering could lead to significant BIB rejection
  - Many physics objects and tools designed for CLIC and need re-tuning for μμ collisions/BIB
- Longer term: DAQ, R&D, technological advancements, and feasibility studies

Conclusions + Outlook

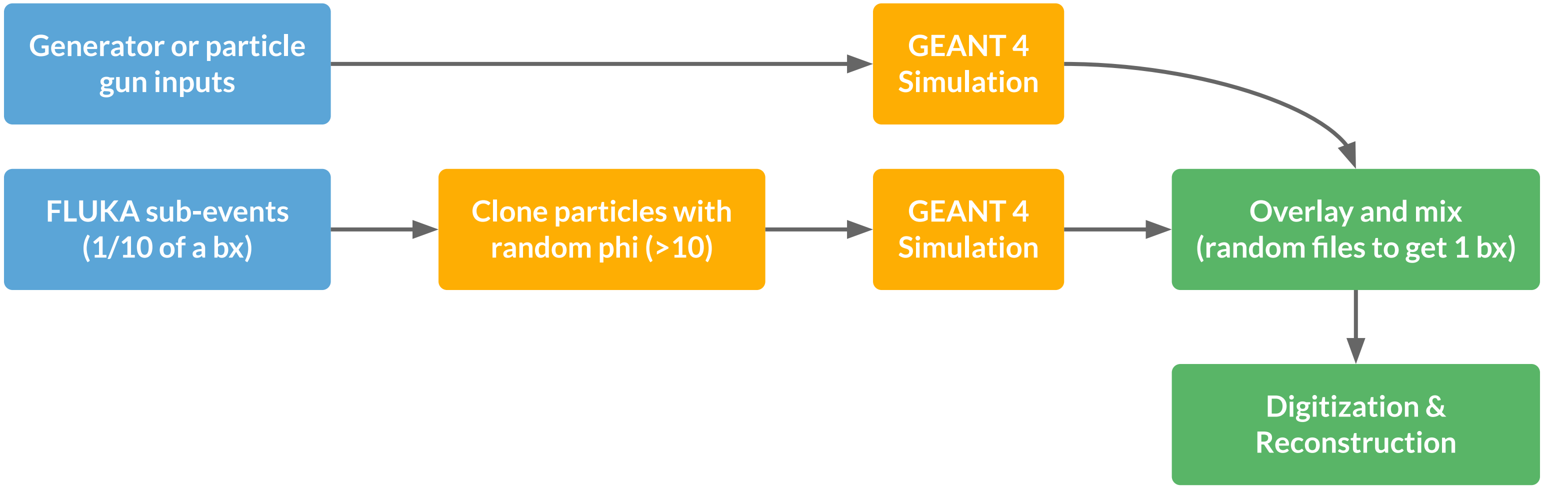
- **Conclusions**
  - MAIA demonstrates excellent tracking performance, even with BIB
  - More work needed to further refine and optimize calorimeter-based results
- **Outlook**
  - Many ongoing and future studies to continue to improve the MAIA detector concept and reconstruction algorithms
  - Encourage those who are interested in getting involved to please reach out!

Thank You!

L. Lee, C. Bell

BIB Simulation | *Workflow*

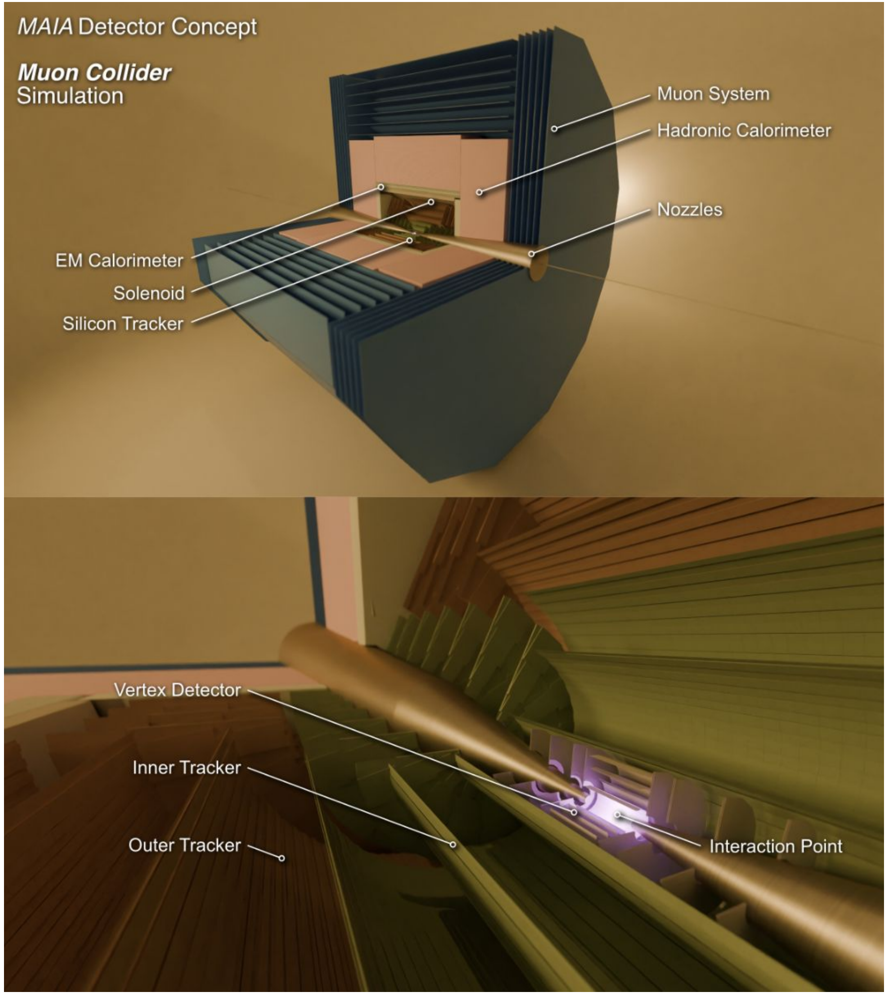
- ➔ Using updated FLUKA 10 TeV BIB
  - ◆ Kinematics look very similar to 3 TeV; but MDI, nozzle optimization extremely important (D. Calzolari)
- ➔ BIB simulation and overlay (N. Bartosik)
  - ◆ Simulating the BIB contributions in FLUKA is computationally expensive, so employ overlay strategy:



MAIA: Summary

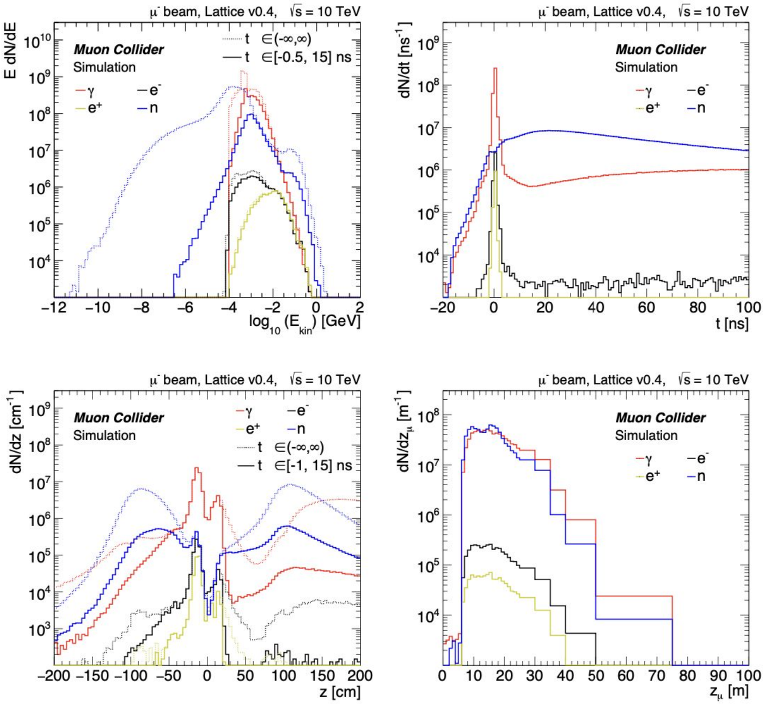
Subsystem	Region	R dimensions [cm]	|Z| dimensions [cm]	Material
Vertex Detector	Barrel	3.0 – 10.4	65.0	Si
	Endcap	2.5 – 11.2	8.0 – 28.2	Si
Inner Tracker	Barrel	12.7 – 55.4	48.2 – 69.2	Si
	Endcap	40.5 – 55.5	52.4 – 219.0	Si
Outer Tracker	Barrel	81.9 – 148.6	124.9	Si
	Endcap	61.8 – 143.0	131.0 – 219.0	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

Table 1: Boundaries and materials of individual subdetectors.

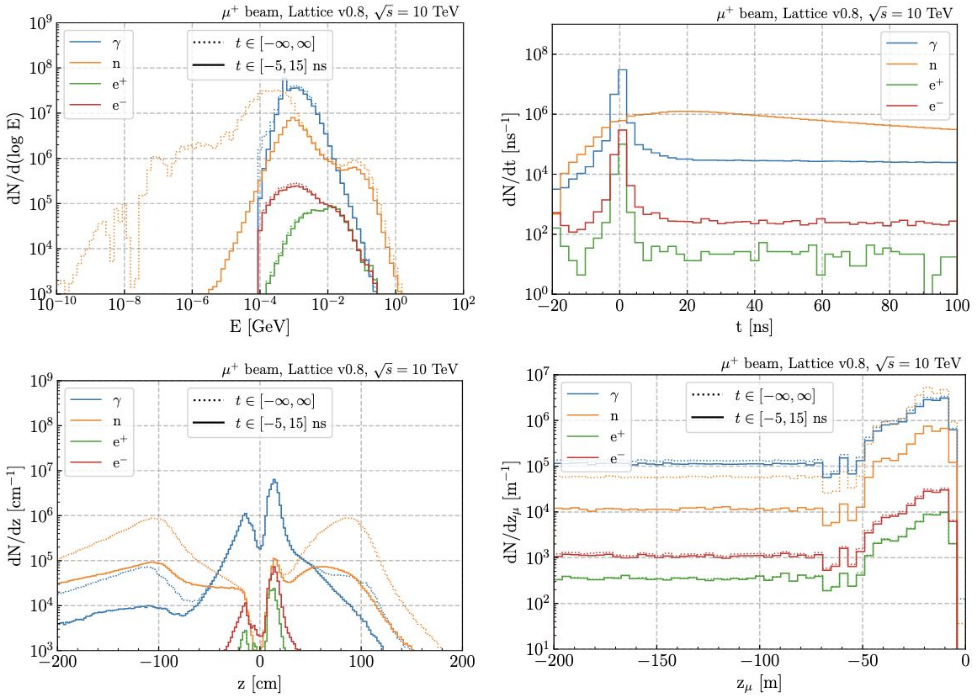


BIB: v0.4 vs v0.8 (EU24) Lattice

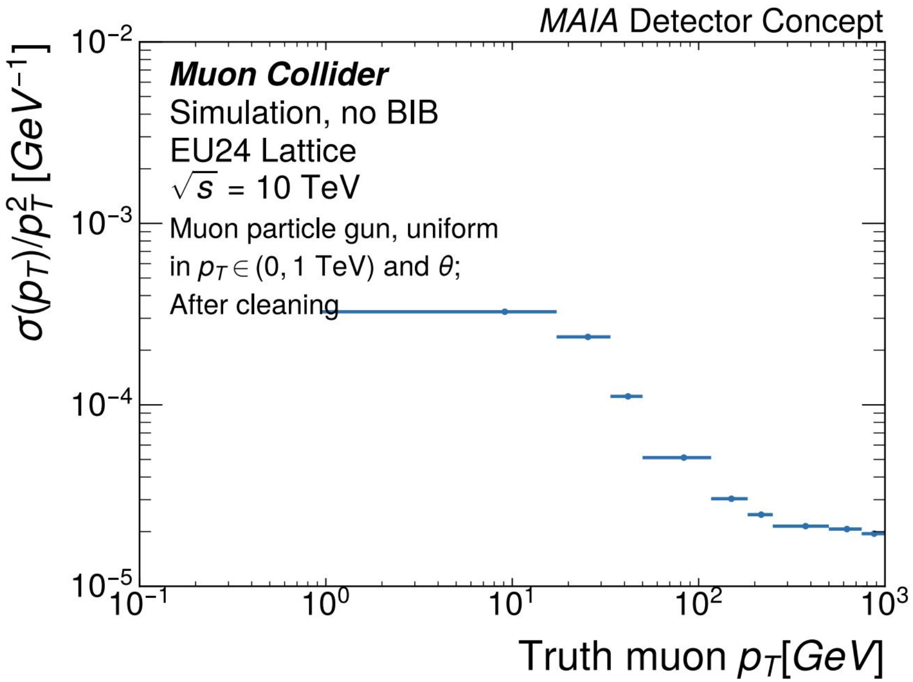
v0.4 Lattice



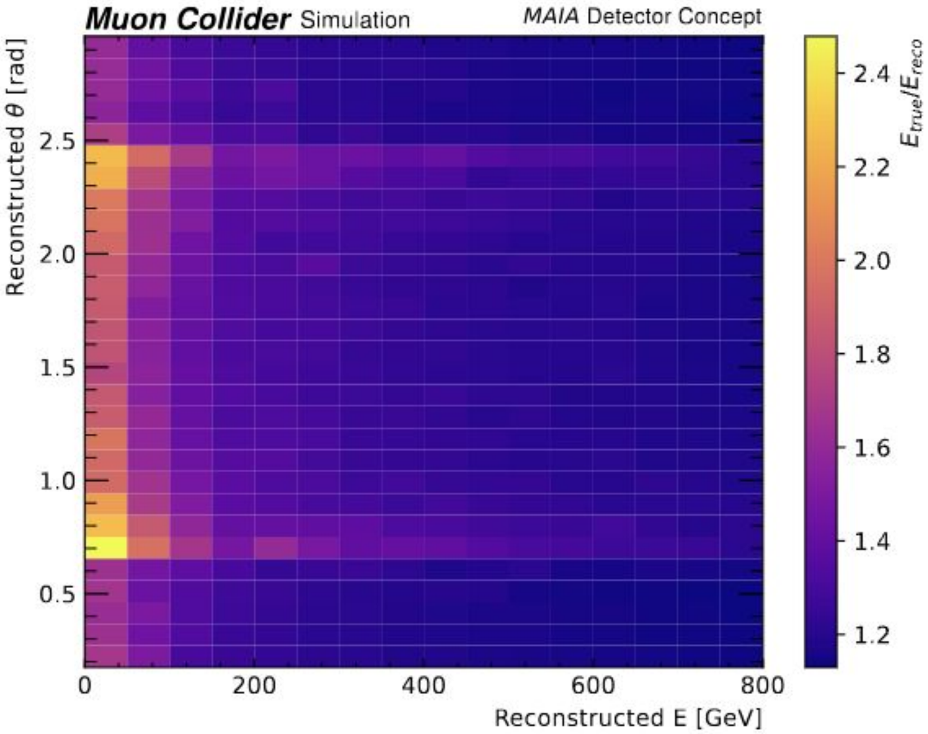
v0.8 Lattice



Track Reconstruction

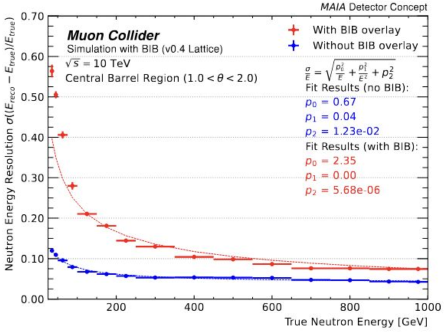


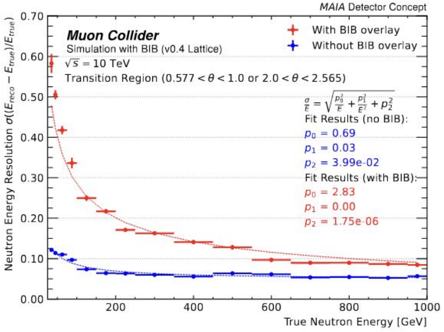
ECAL Calibration

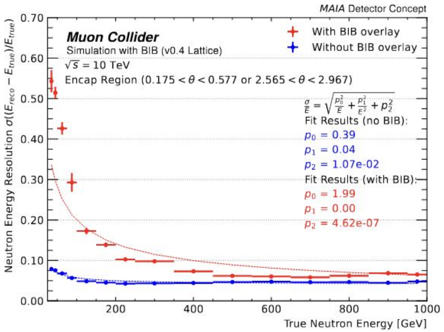


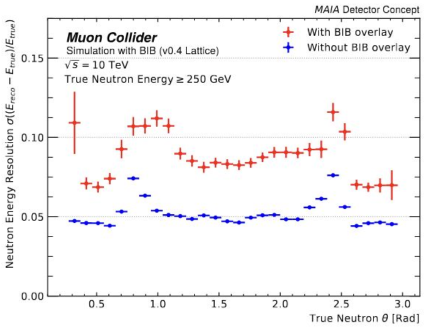
Neutron Reconstruction

v0.4 Lattice

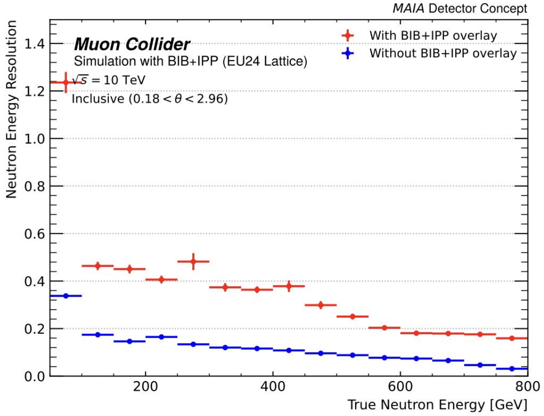








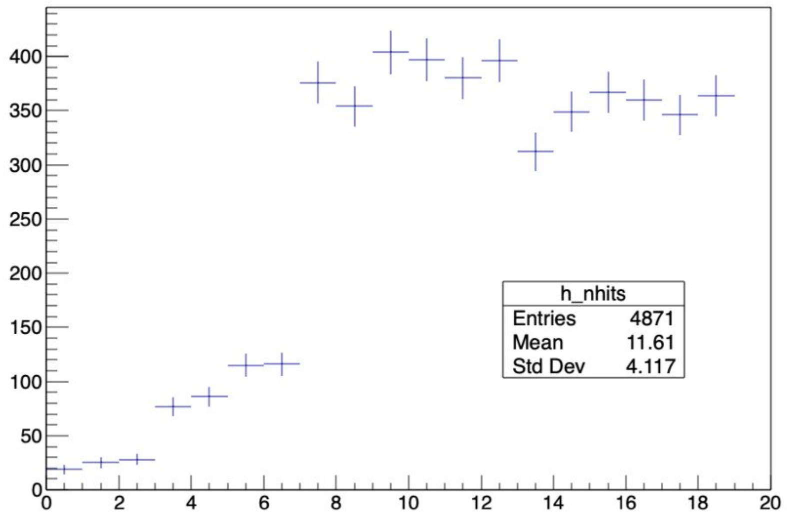
V0.8 (EU24) Lattice

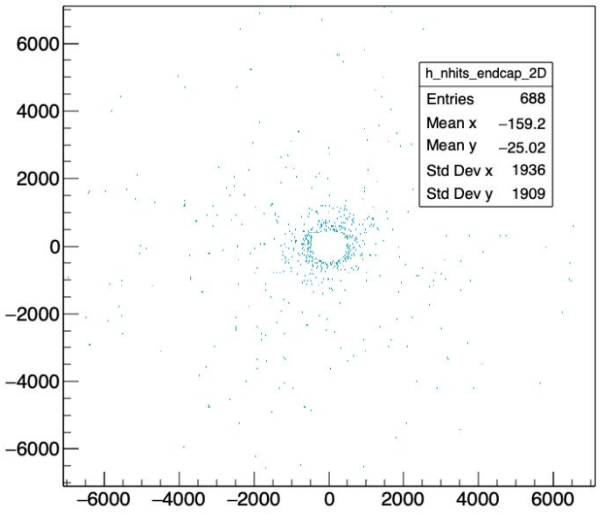


Muon System Results

B. Rosser

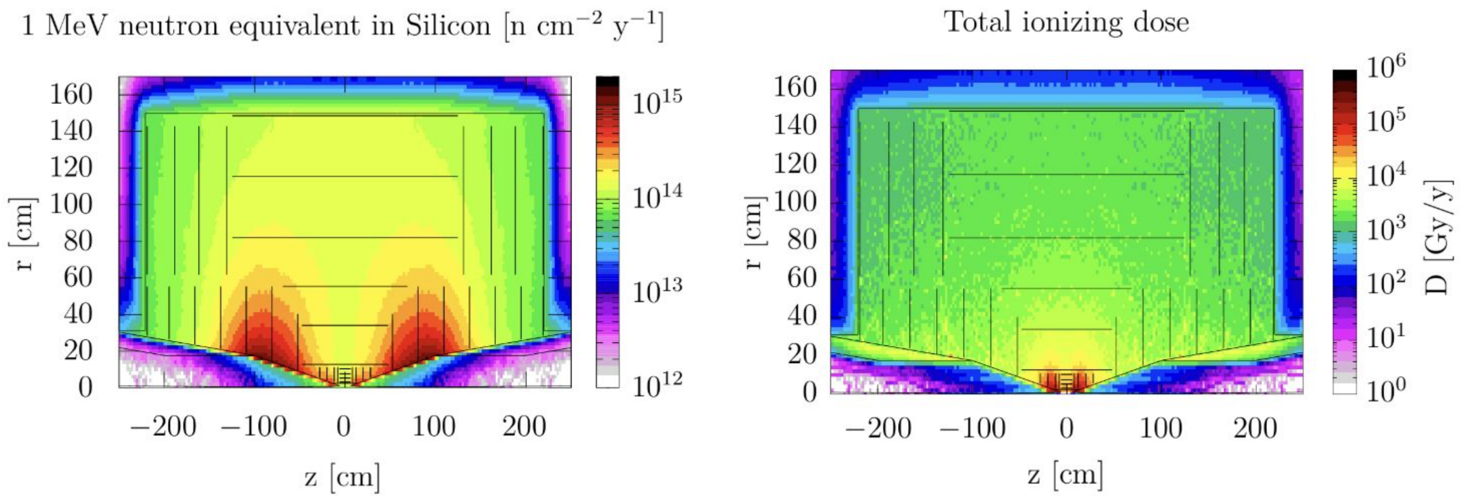
- **Muon detector should be the least affected by beam induced background:**
  - In general, BIB absorbed by solenoid and by calorimeters, so not a problem here.
  - Potentially some issues depending on nozzle geometry in far forward region.
- **Initial look at muon system occupancy: higher in endcap layers, but not an issue.**





Radiation Damage

- Radiation at 10 TeV comparable to HL-LHC and previous 3 TeV muon collider studies; much lower than FCC-hh (1018 1 MeV-neq/cm2) (2209.01318, 2105.09116)



	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider (3 TeV)	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}
Muon Collider (10 TeV)	20	0.2	3×10^{14}	10^{14}

Nozzle Configuration Optimization Studies

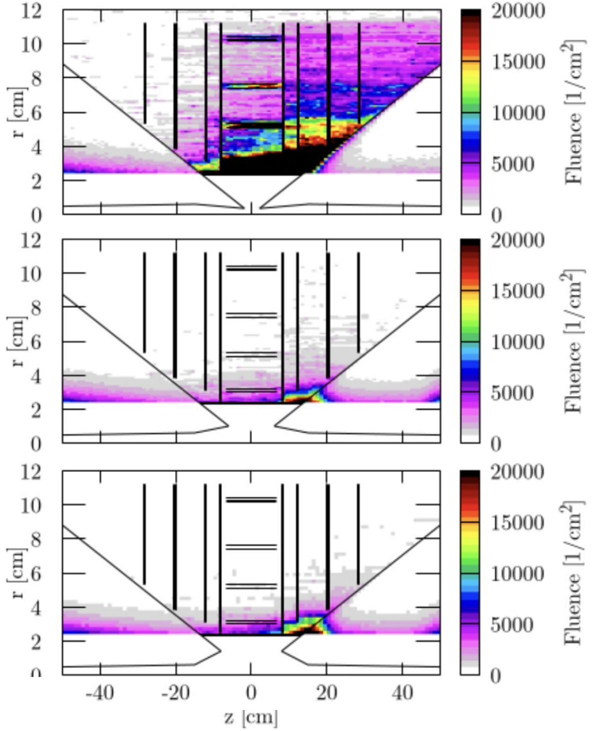
D. Calzolari

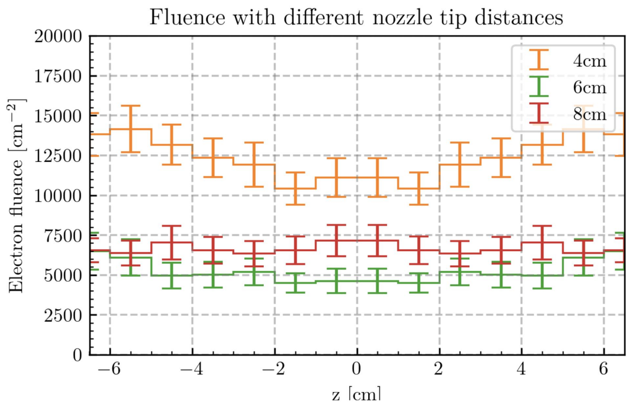
Simulate BIB fluence with nozzle tip at different distances

2 cm

6 cm

8 cm





- ➔ Nozzle tip has a strong influence on the electron fluences
- ➔ Require nozzle distance > 4 cm from origin to reduce EM showers
- ➔ Studies ongoing!