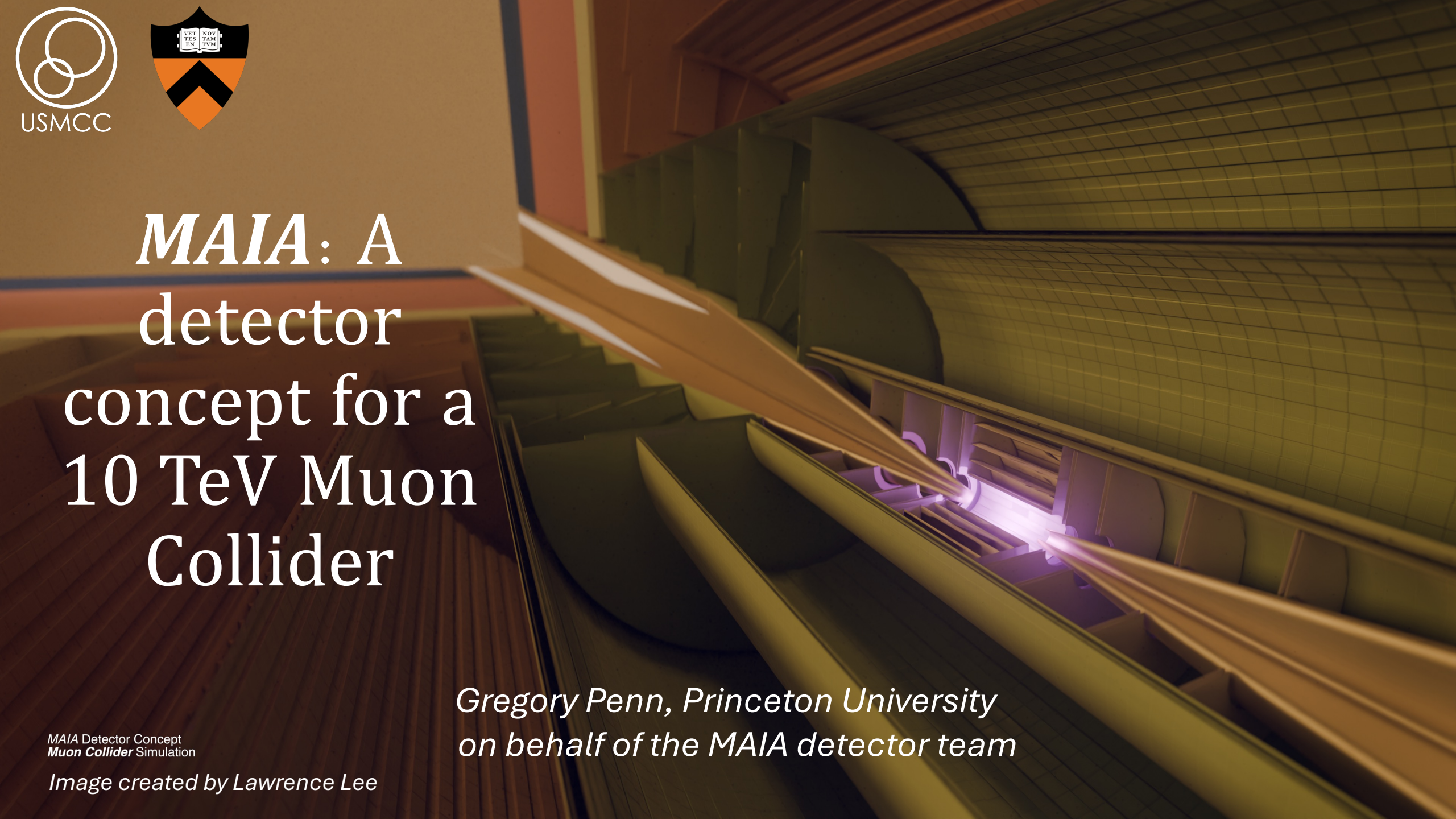
MAIA: A detector concept for a 10 TeV Muon Collider

Gregory Penn, Princeton University
on behalf of the MAIA detector team



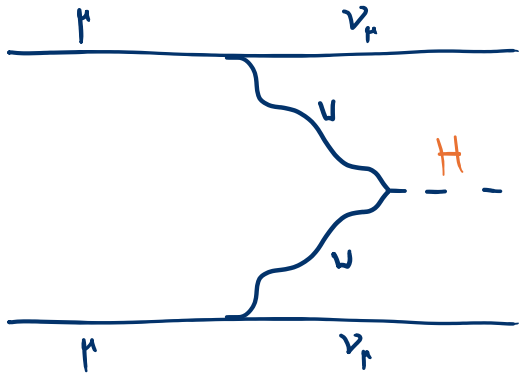
MAIA Detector Concept
Muon Collider Simulation

Image created by Lawrence Lee

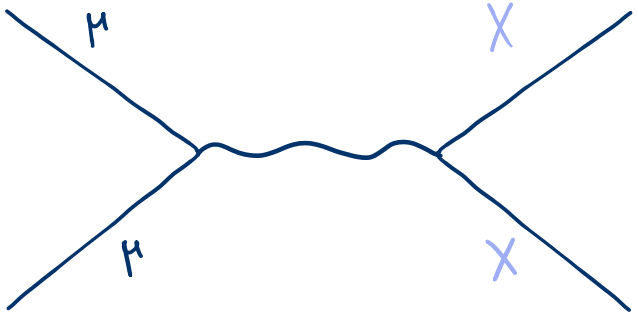
more details on the physics case here

Why a 10 TeV Muon Collider?

*A muon collider has potential to be both a **precision** and an **energy** frontier machine*



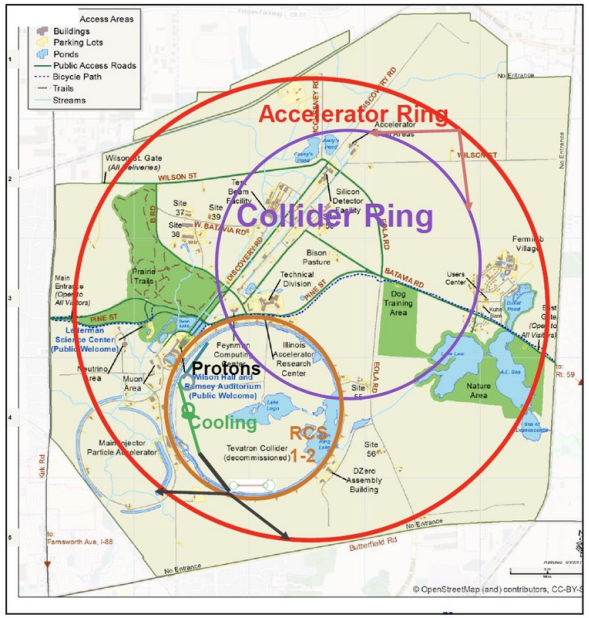
electroweak radiation enhances Higgs cross section



reach up to 10 TeV scale

All within a compact footprint;

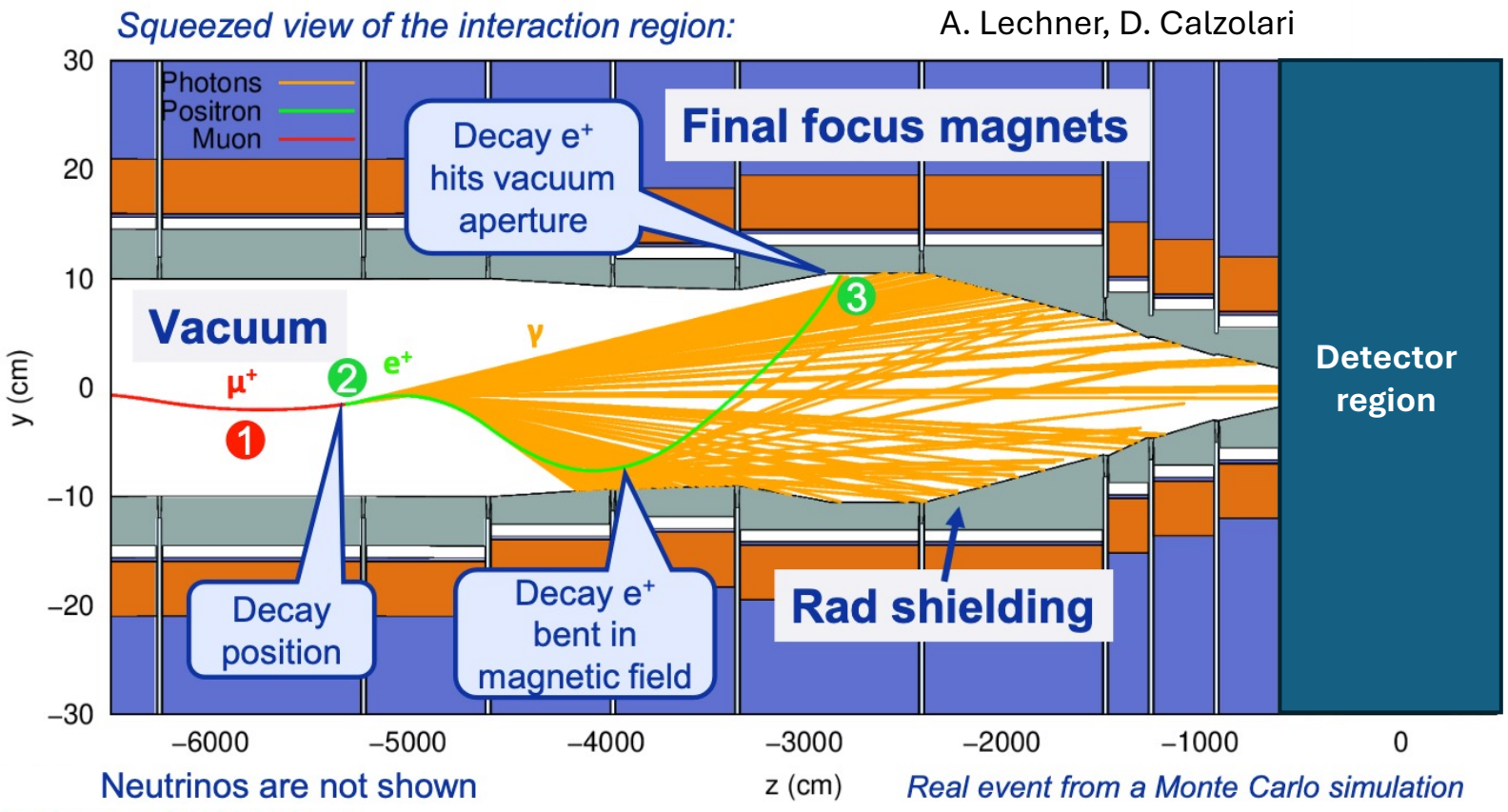
can fit within Fermilab complex!



What makes it experimentally difficult?

Muons decay, and their decay products enter the detector region

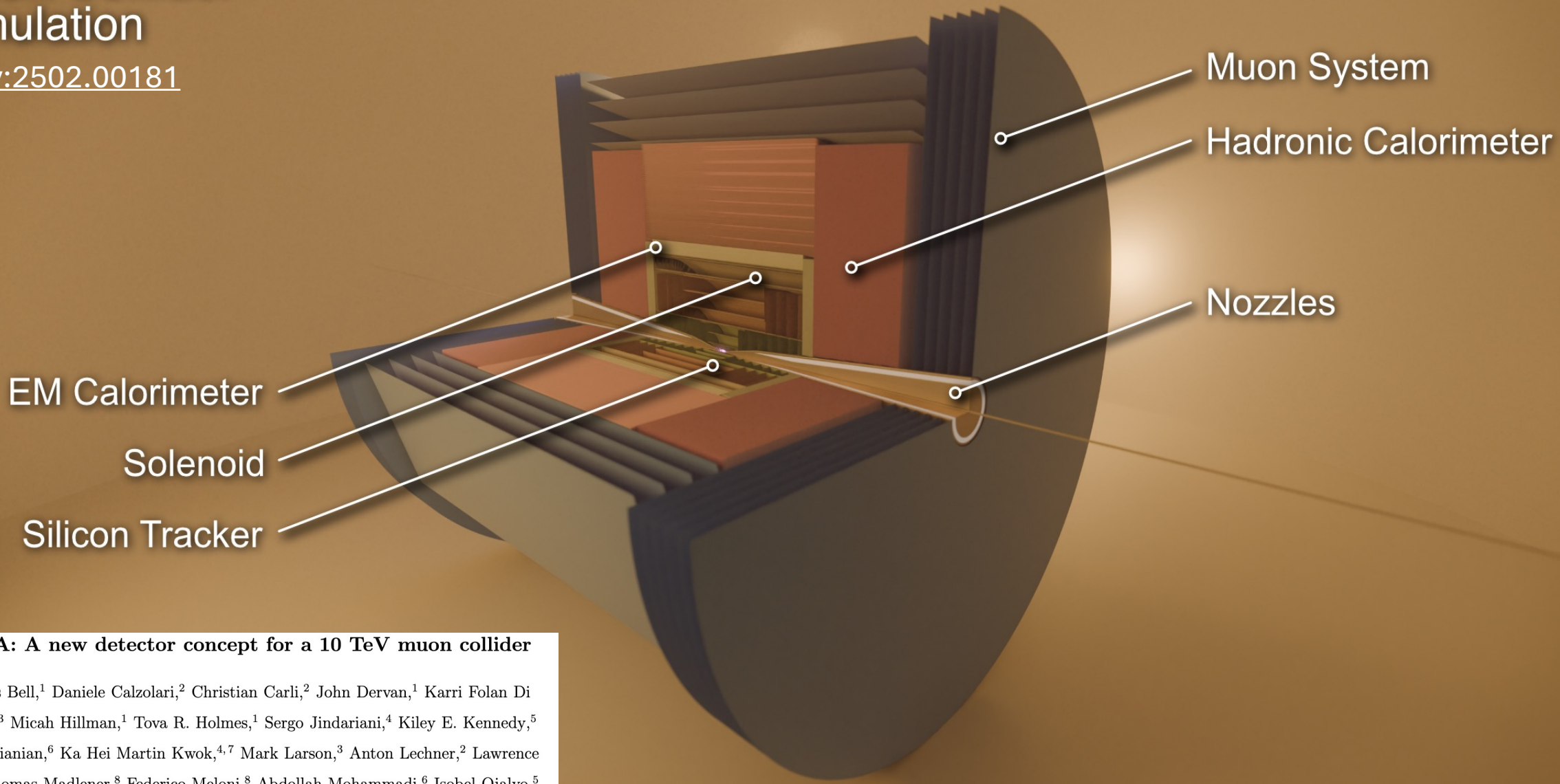
Beam Induced Background (BIB)



How can we design detectors to fulfill the physics program of a 10 TeV Muon Collider?

MAIA Detector Concept
Muon Collider
Simulation

arXiv:2502.00181



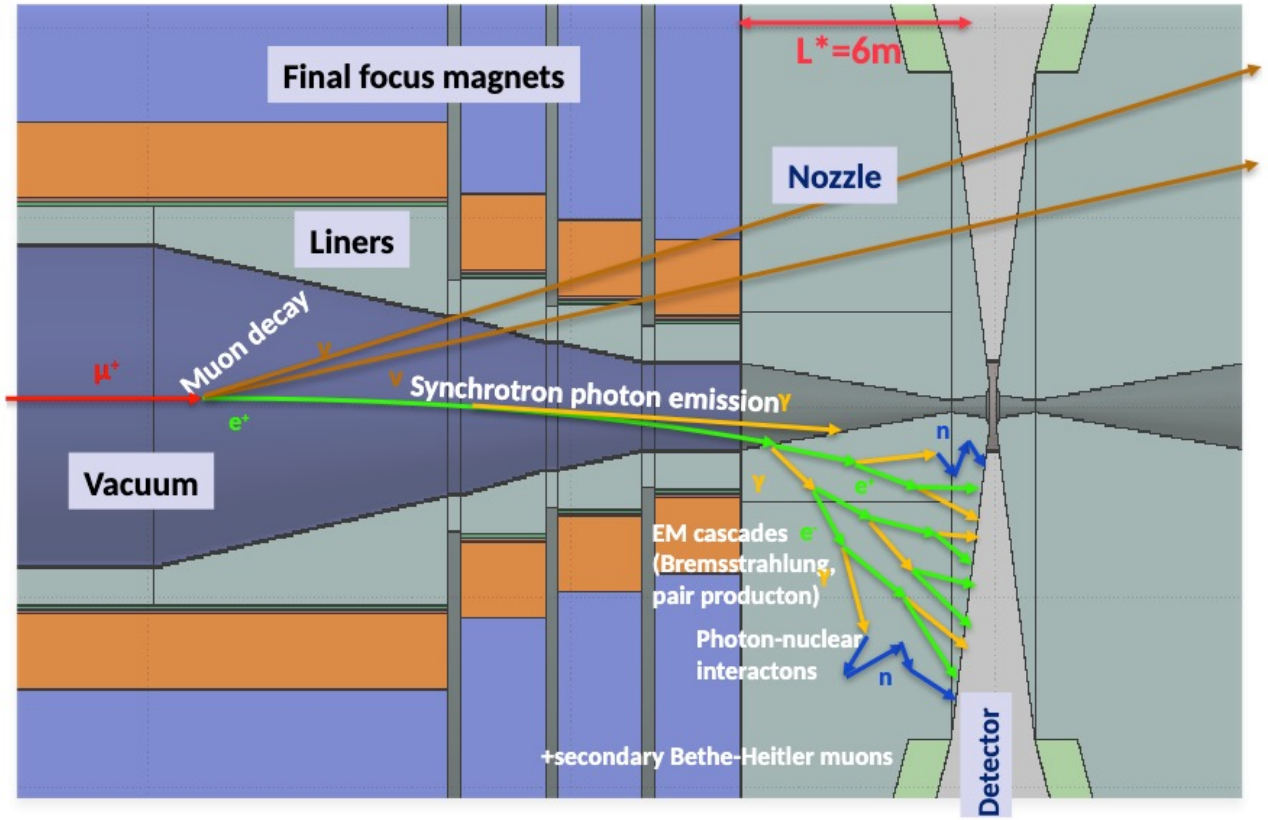
MAIA: A new detector concept for a 10 TeV muon collider

Charles Bell,[1] Daniele Calzolari,[2] Christian Carli,[2] John Dervan,[1] Karri Folan Di Petrillo,[3] Micah Hillman,[1] Tova R. Holmes,[1] Sergo Jindariani,[4] Kiley E. Kennedy,[5] Cyrus Kianian,[6] Ka Hei Martin Kwok,[4,7] Mark Larson,[3] Anton Lechner,[2] Lawrence Lee,[1] Thomas Madlener,[8] Federico Meloni,[8] Abdollah Mohammadi,[6] Isobel Ojalvo,[5] Priscilla Pani,[8] Gregory Douglas Penn,[9] Rose Powers,[5] Benjamin Rosser,[3] Leo Rozanov,[3,10] Kyriacos Skoufaris,[2] Elise Sledge,[5,11] Alexander Tuna,[1] and Junjia Zhang[5]

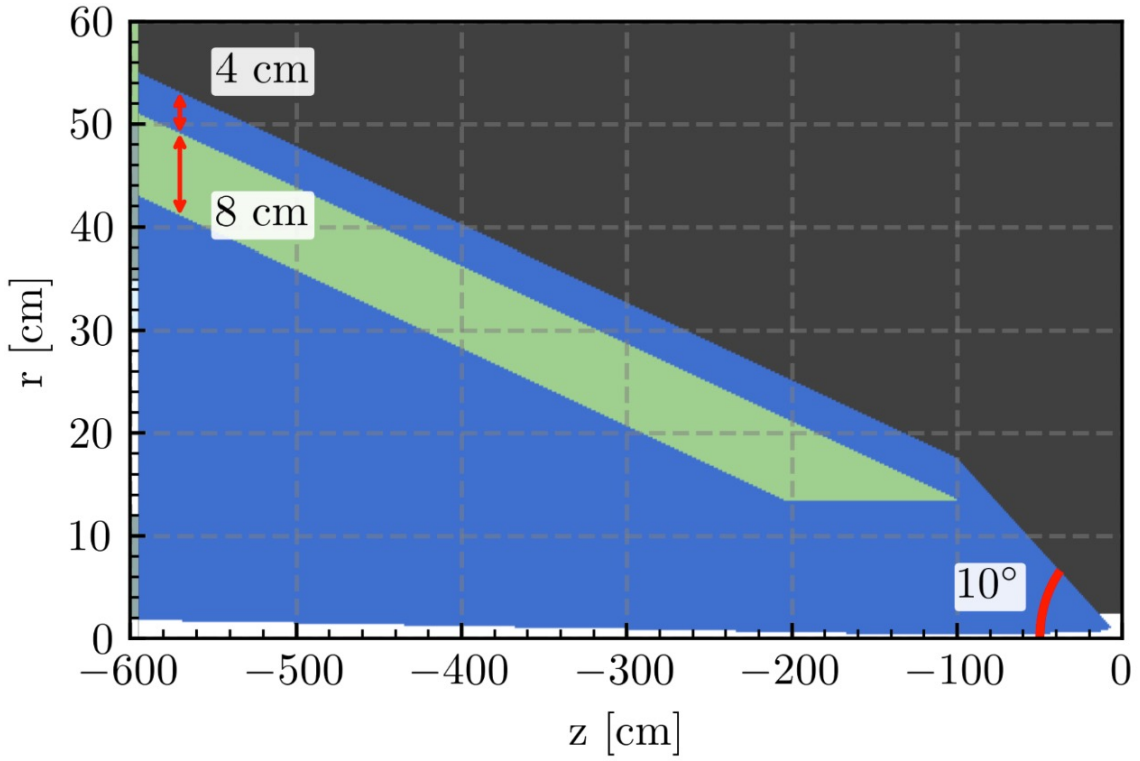
The Nozzle

Nozzles convert TeV-scale electrons and photons from BIB into a high multiplicity of low energy particles

Composed of **tungsten** to contain electromagnetic showers, and **borated polyethylene** to slow neutrons



A. Lechner, D. Calzolari

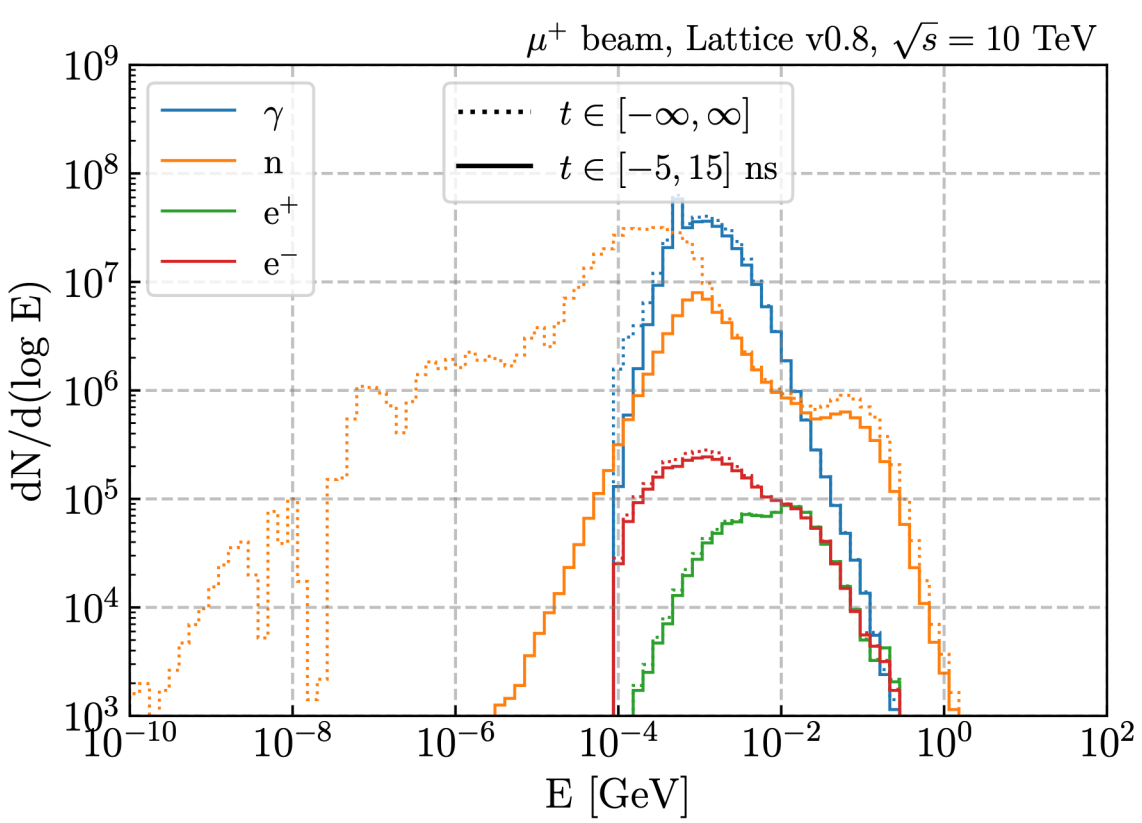


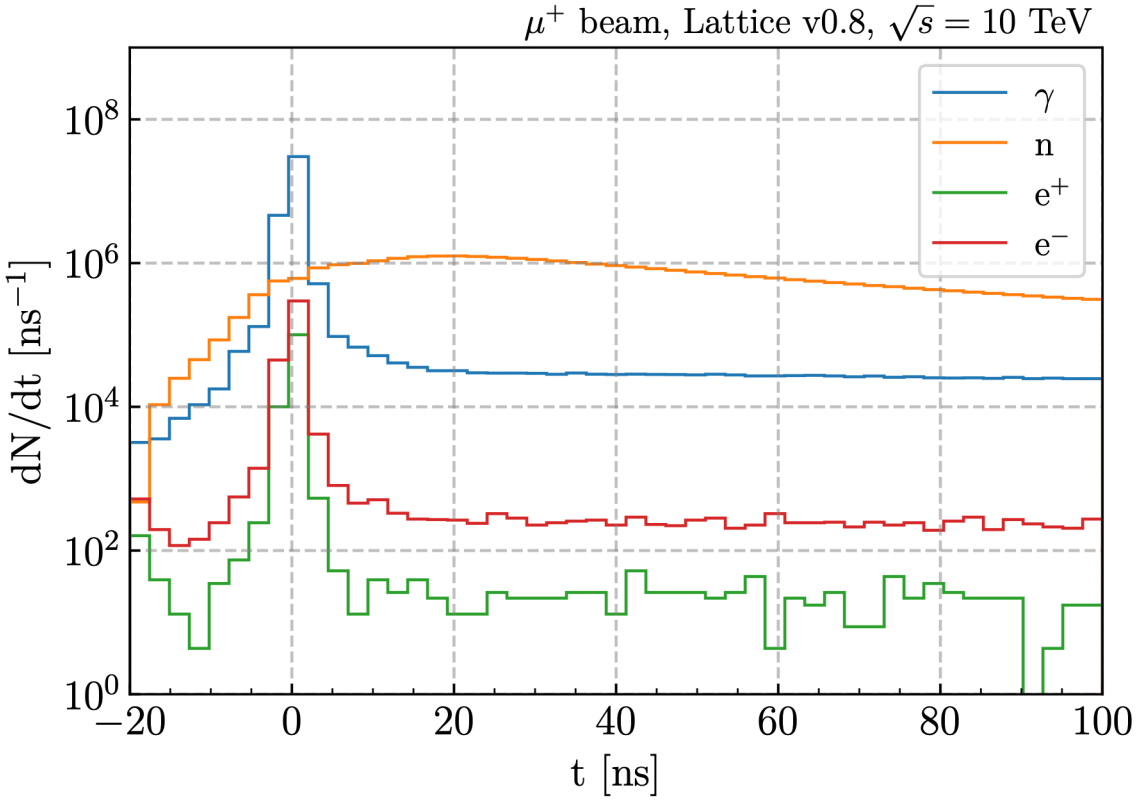
The Nozzle

Nozzles convert TeV-scale electrons and photons from BIB into a high multiplicity of low energy particles

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*Detector background is mostly **sub-GeV**, and contains a large **out-of-time** component*

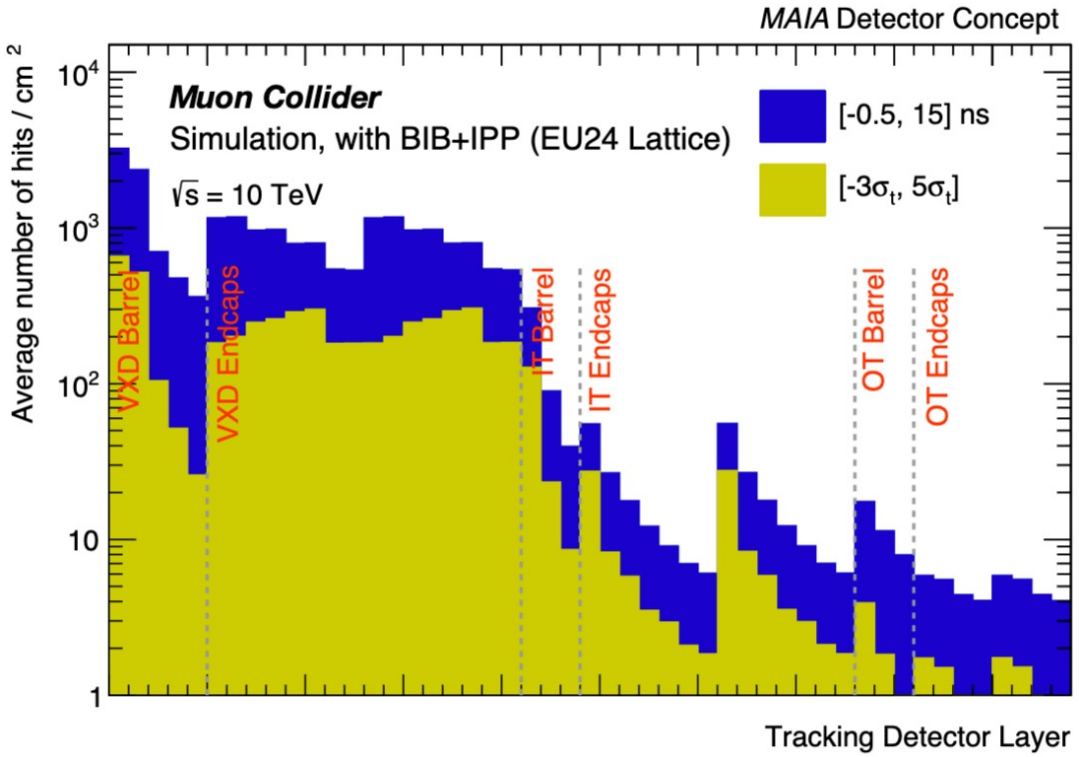


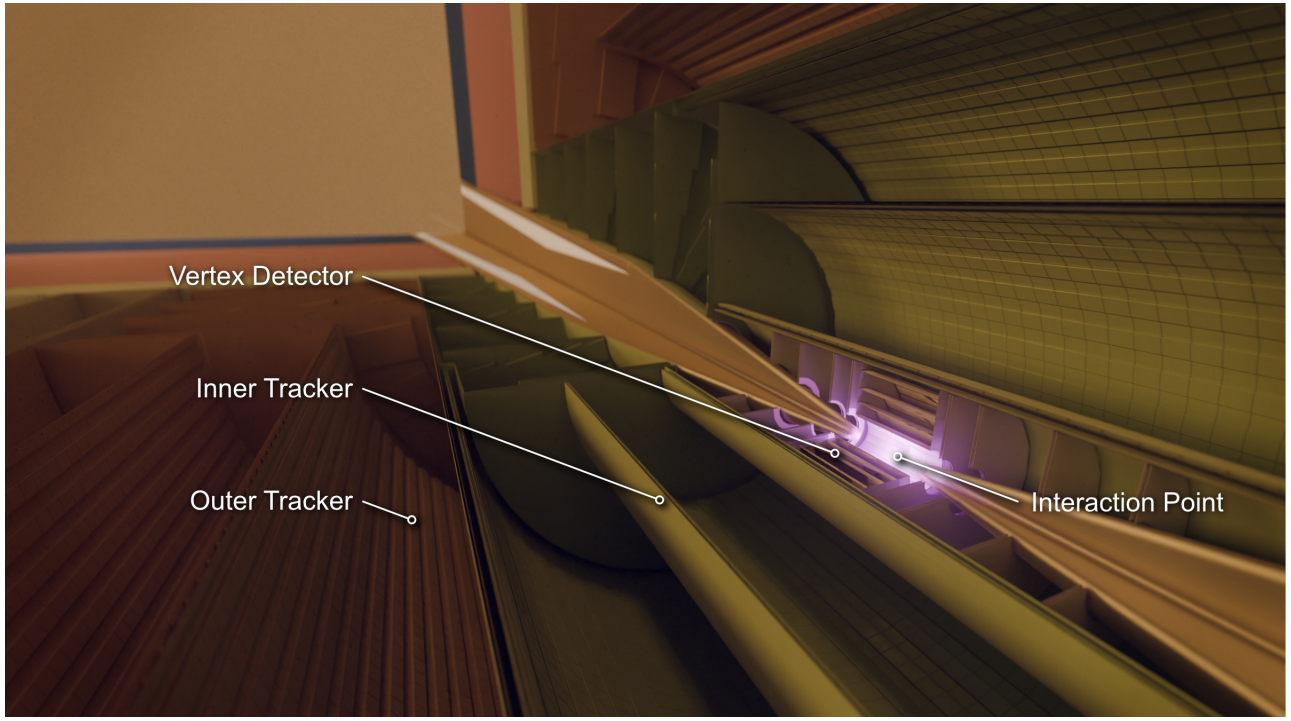


Tracker

- All-silicon tracker
- Innermost vertex layer is a doublet
- Timing resolution on par w/ ATLAS, CMS Phase-II LGAD-based timing detectors

	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 µm × 25 µm	50 µm × 1 mm	50 µm × 10 mm
Sensor Thickness	50 µm	100 µm	100 µm
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	5 µm × 5 µm	7 µm × 90 µm	7 µm × 90 µm

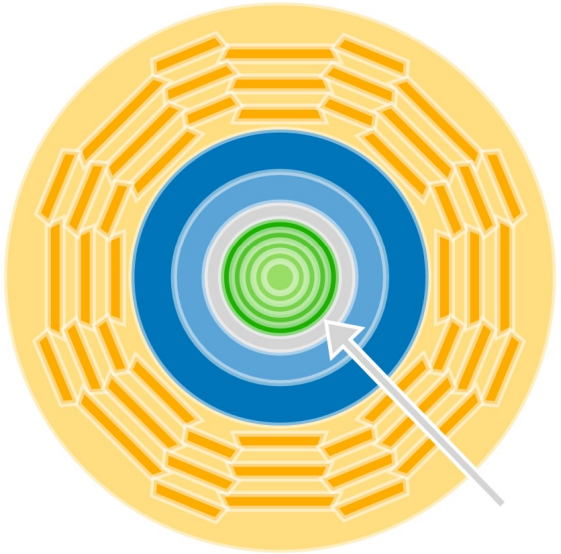




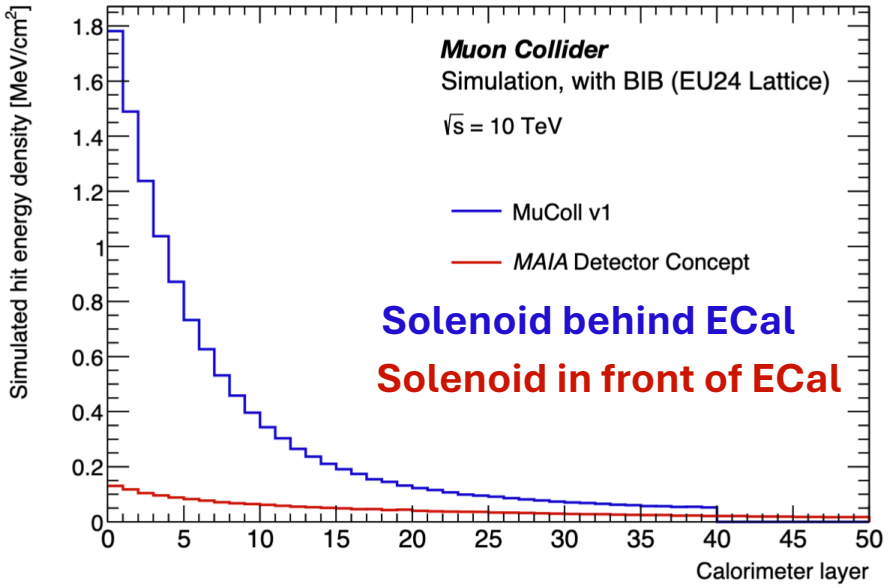
Solenoid

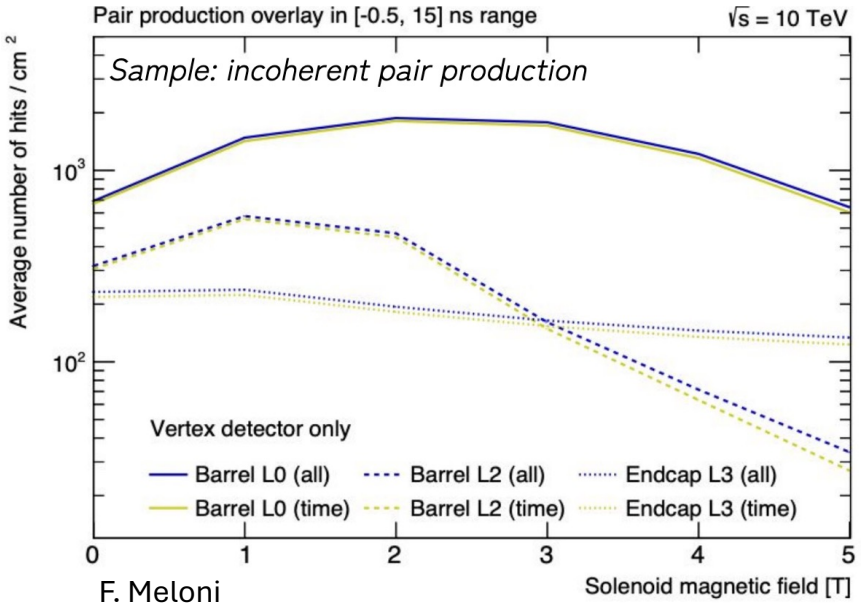
Solenoid placement and parameters reduce detector occupancy from machine backgrounds.

- 5T minimizes tracker occupancy from incoherent e^+e^- pair production and aids high-p_T tracking
- Solenoid is placed between tracking system and calorimeters
  - Provides shielding for calorimeters ($X_0 \sim 4, \lambda = 1$)
    - *Causes downstream effects on calorimeter resolution*



Solenoid** inside **Calorimeters



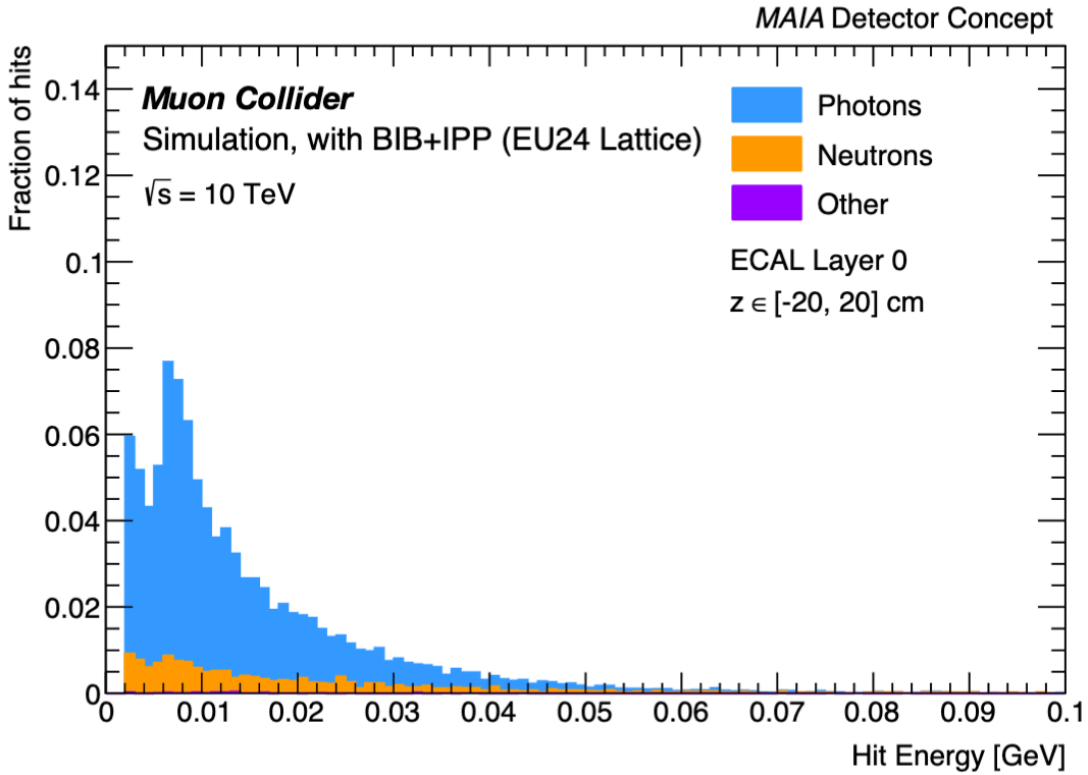


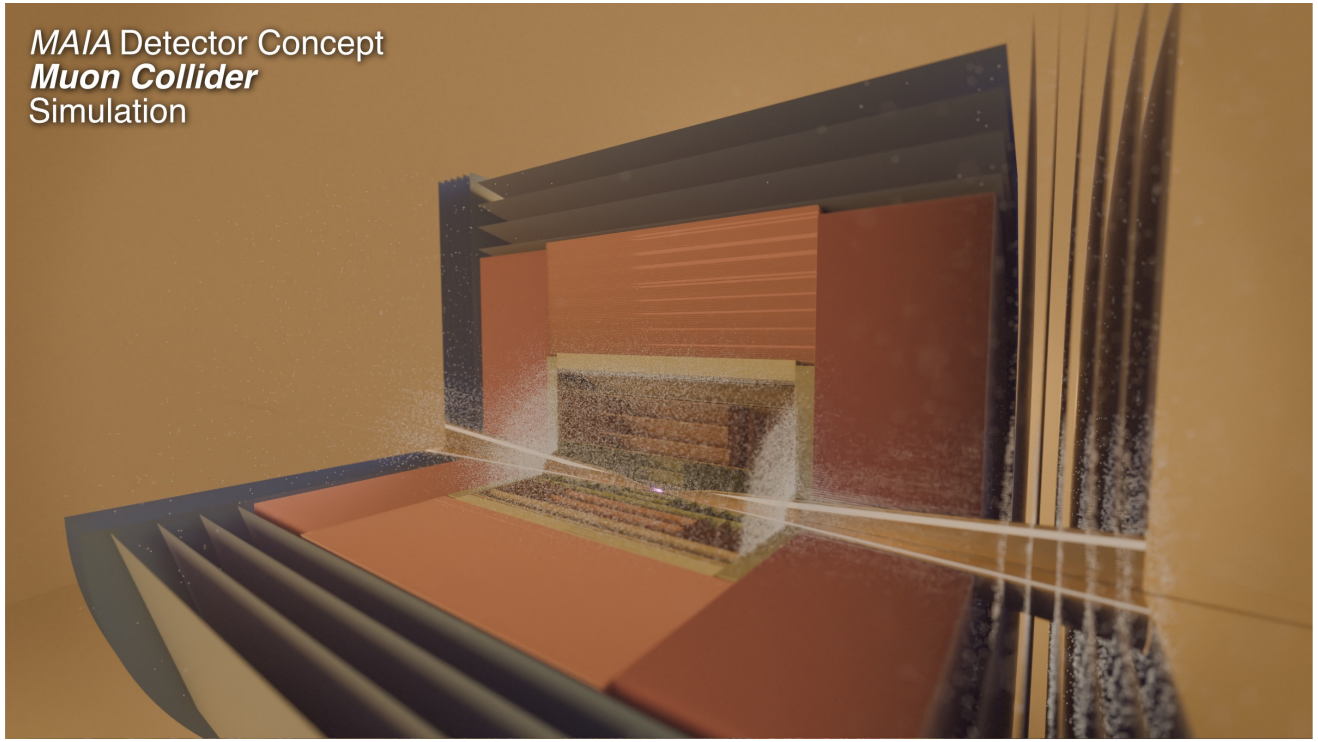
F. Meloni

Calorimeters

- Design based on CLIC (3 TeV e^+e^- linear collider)
- ***Deeper*** to accommodate signals @ 10 TeV
- BIB contribution reduced by variable cell energy (2 – 7 MeV) and timing ($\pm$ 300 ps) thresholds

	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





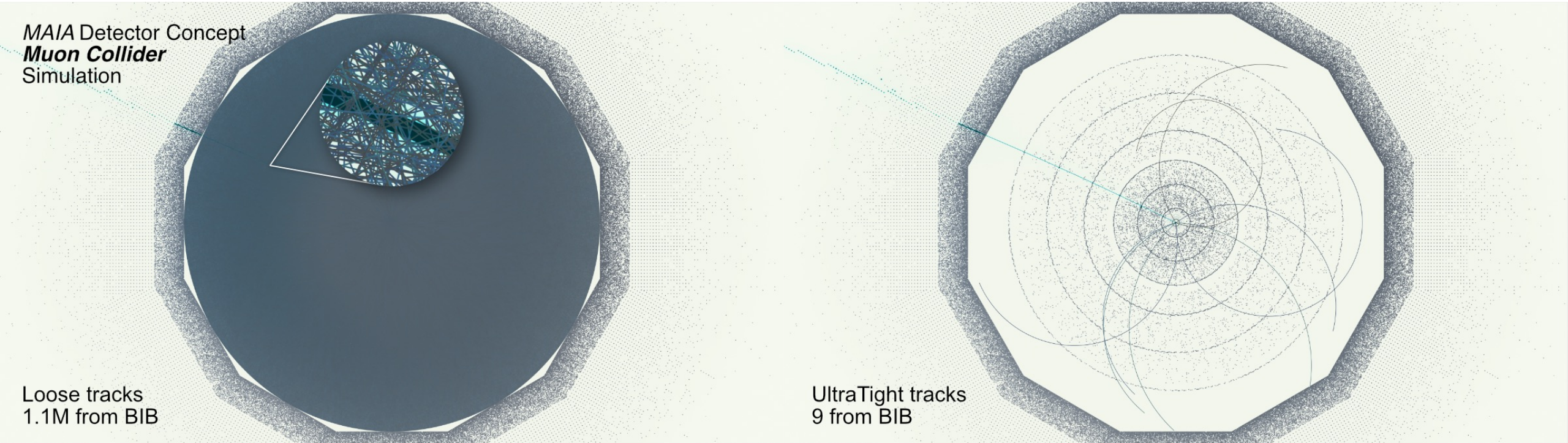
Tracking Performance

"A Common Tracking Software" (ACTS) is used for tracking

"Loose tracks"
- Directly from Combinatorial Kalman Filter
- $O(10^6)$ fakes / event

"UltraTight tracks"
- Additional requirements:
  $\boldsymbol{p_T > 0.5\ GeV, n_{hits} \geq 9, n_{holes} \leq 3, n_{outliers} \leq 4, \chi^2 / n_{dof} < 3}$
- $O(10)$ fakes / event

These definitions are chosen to demonstrate the range of knobs we have for track tuning

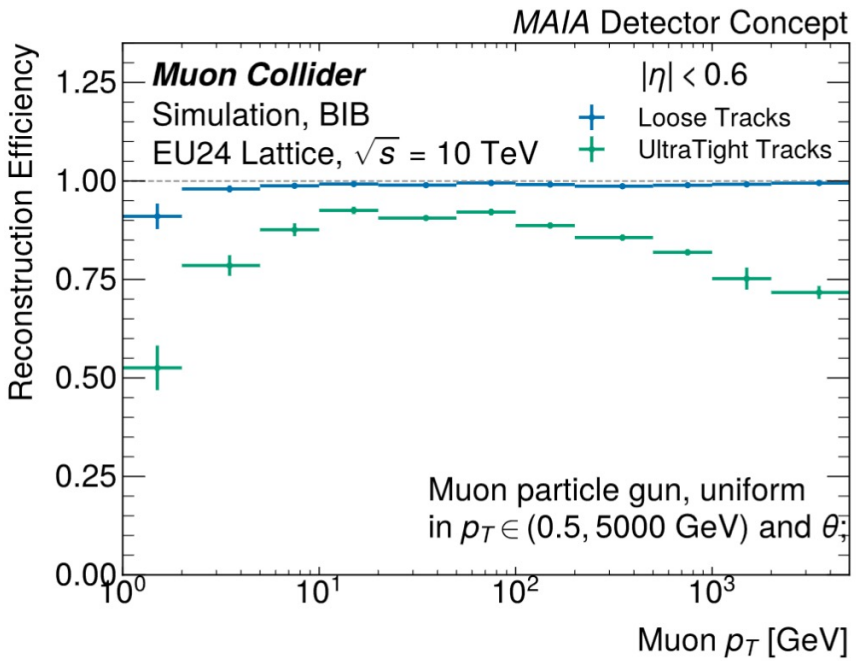


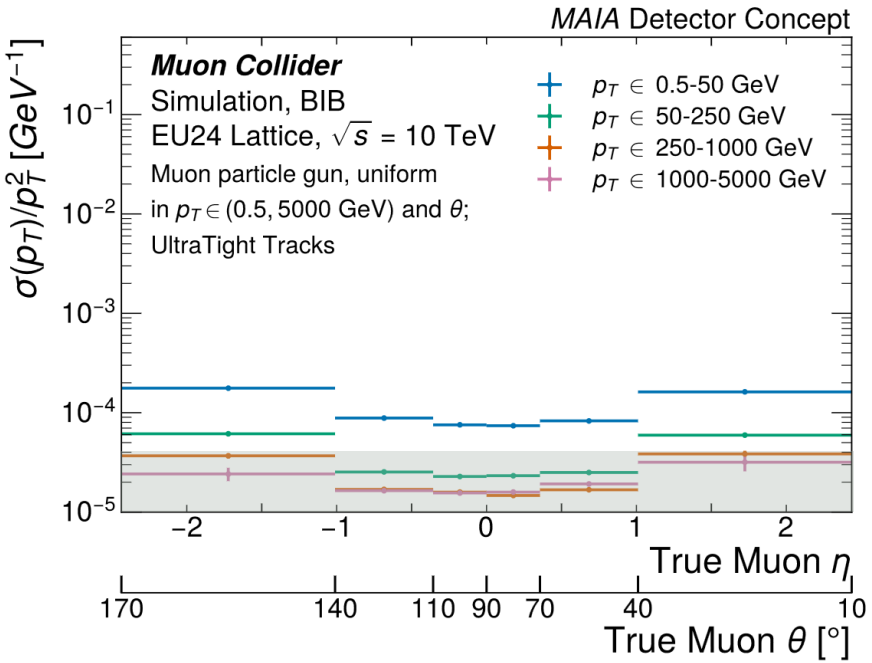
Tracking Performance

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- $O(10)$ fakes / event

- *Tracks are considered matched if >50% of their hits originate from the generated muon*
- **99% (87%) efficiency reached in the barrel region for Loose (UltraTight) tracks**
- **$\sigma(p_T)/p_T^2 < 10^{-4}\ \mathrm{GeV}^{-1}$ through the barrel region**





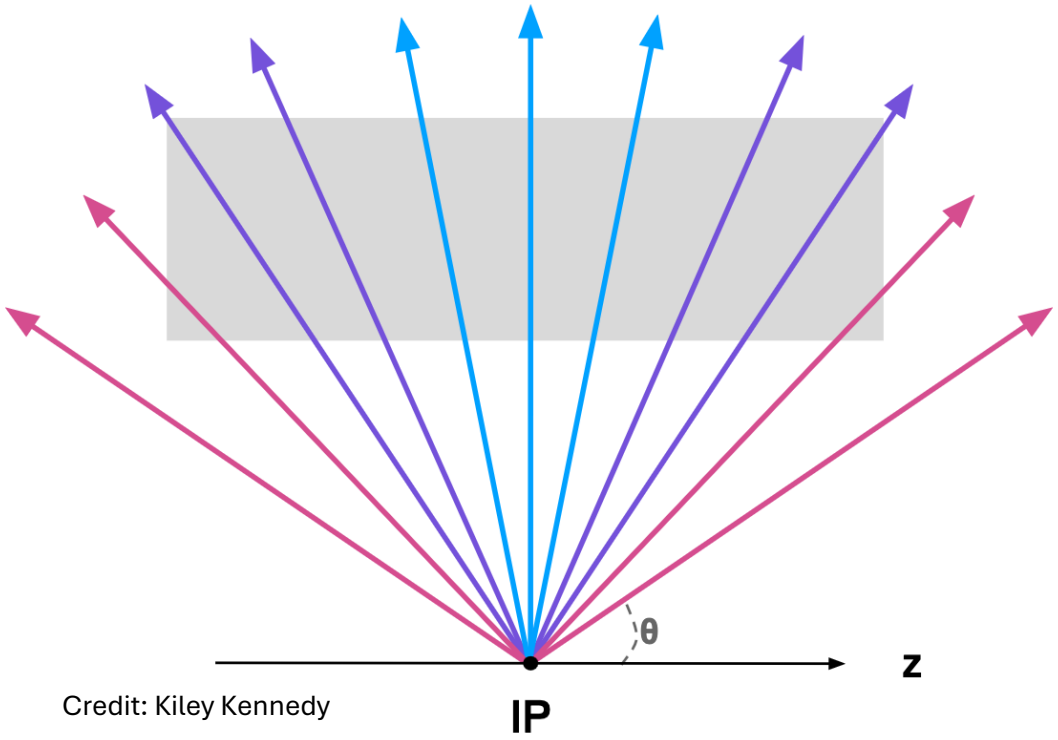
benchmark!

Calorimeter Performance

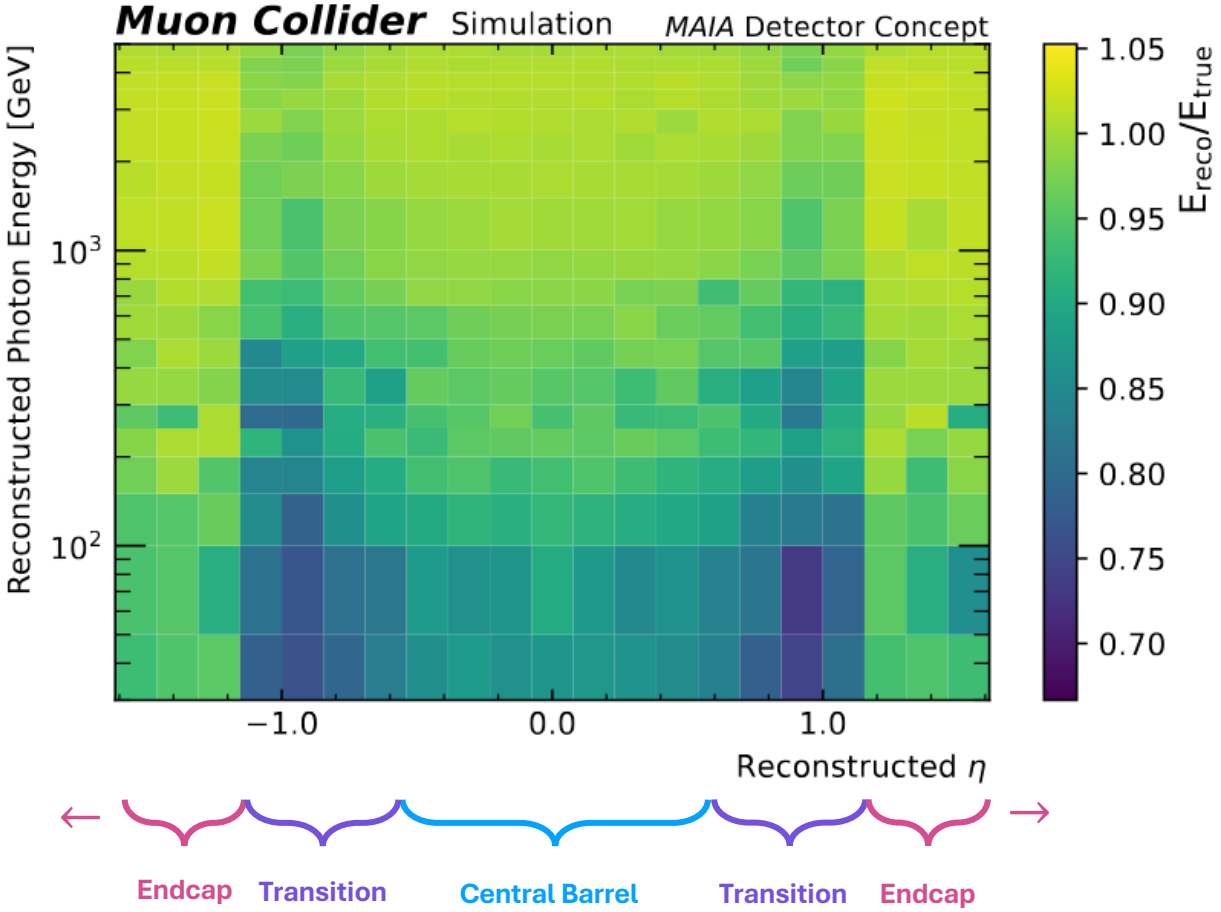
Calorimeter performance is influenced by the solenoid's placement

Differing path lengths through solenoid introduces θ-dependence

Motivates splitting into: **Central Barrel**, **Transition**, and **Endcap** regions



Credit: Kiley Kennedy

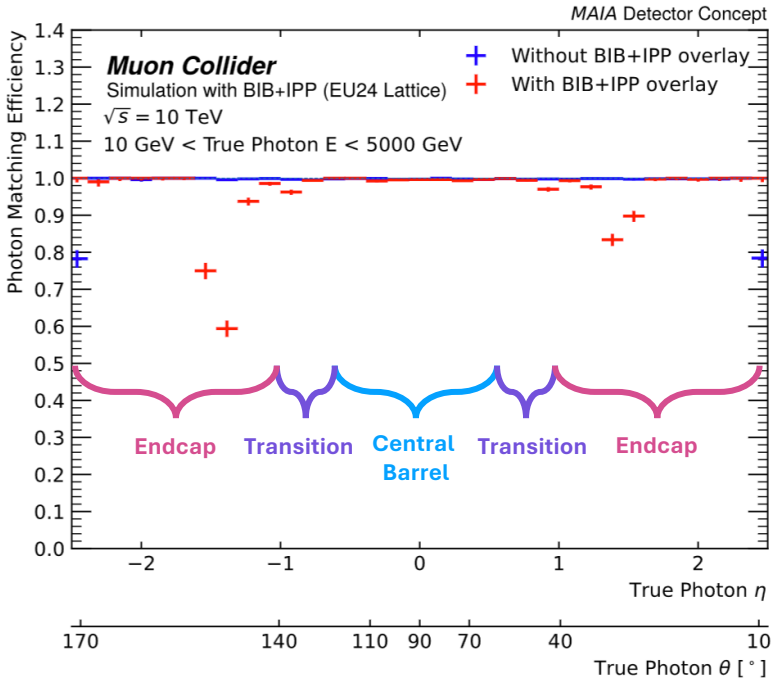


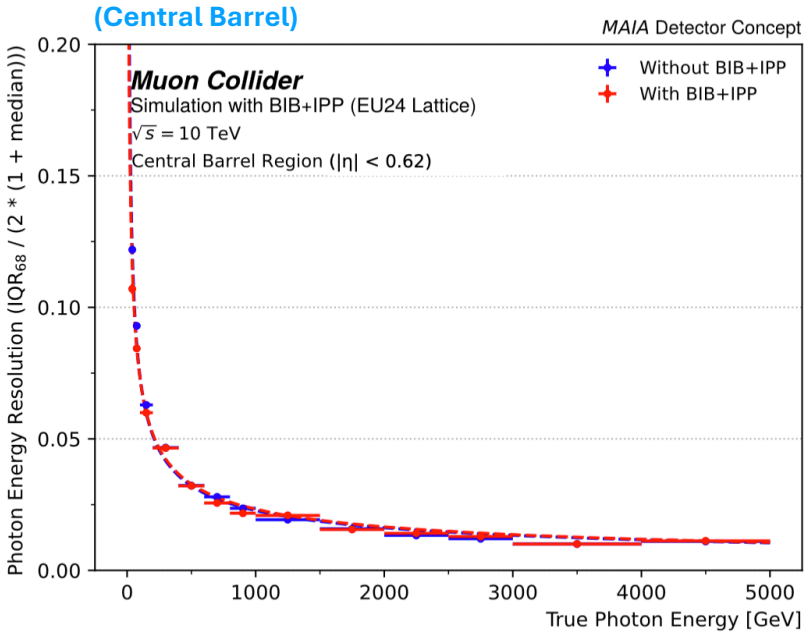
Photon Reconstruction

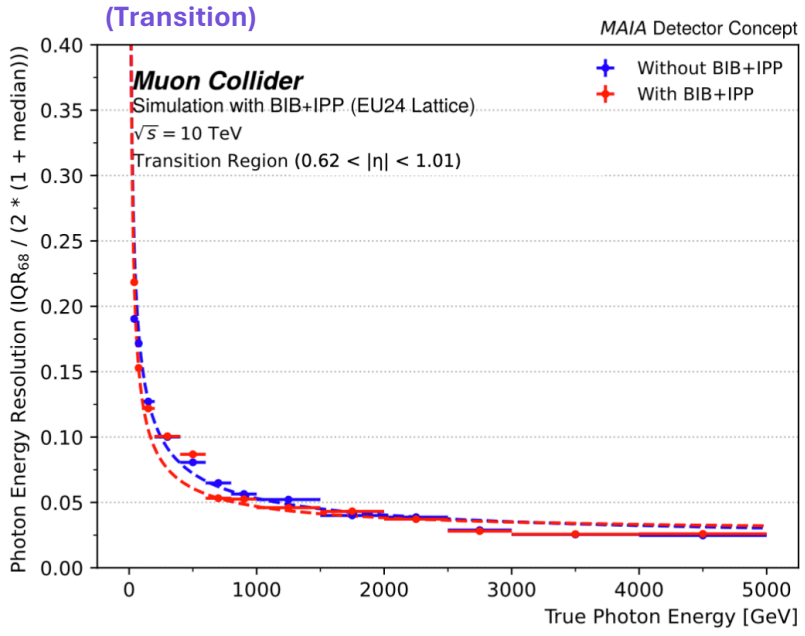
Pandora algorithm used for particle flow reconstruction

Highest-E identified photon within $\Delta R < 0.1$ of generated photon is matched

- **Matching efficiency > 96% in the barrel and transition regions**
- Endcaps dominated by matching to BIB clusters – asymmetry caused by low statistics of underlying BIB sample
- **Resolution below 15% (22%) in barrel (transition region) for E > 10 GeV**





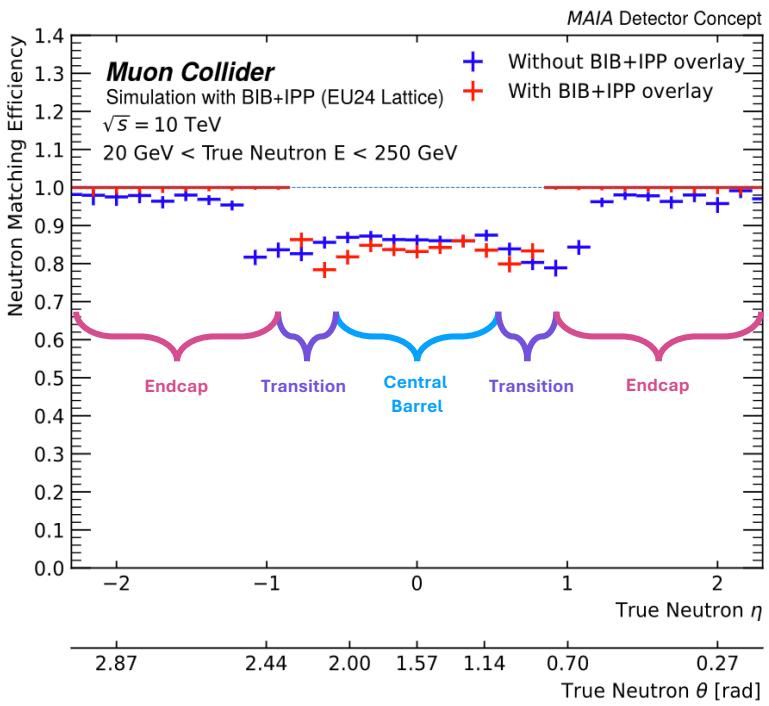


Neutron Reconstruction

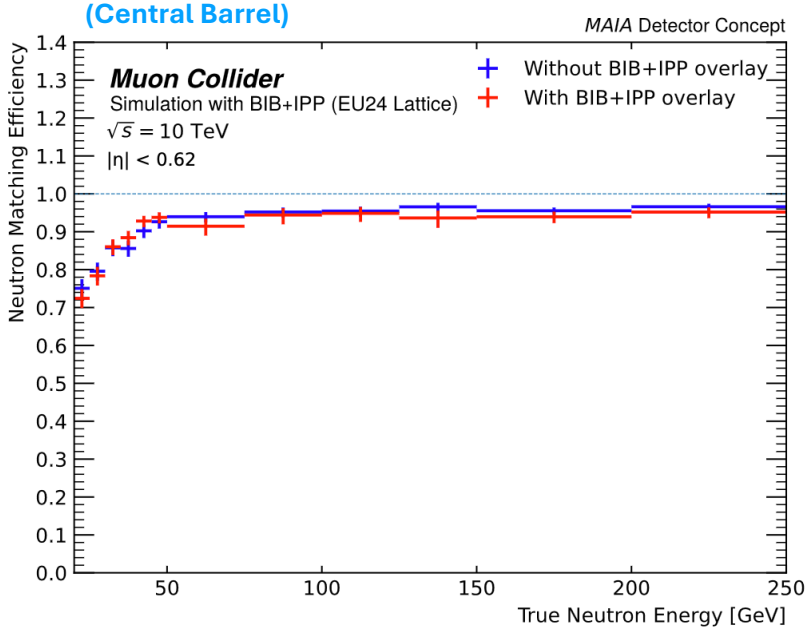
Pandora algorithm used for particle flow reconstruction

Highest-E identified neutron within $\Delta R < 0.4$ of generated neutron is matched

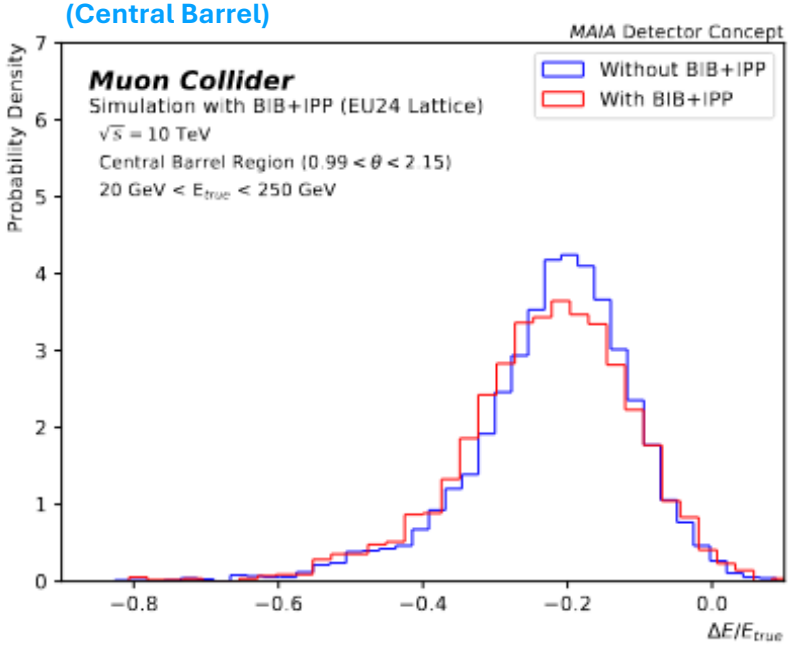
- **Matching efficiency > 90% from 50 GeV to 250 GeV in central barrel**
- Similar challenges in the endcap region
- Inclusive energy slice exhibits good resolution and robustness against BIB



(Central Barrel)



(Central Barrel)



Charged Pion Reconstruction

Pandora algorithm used for particle flow reconstruction

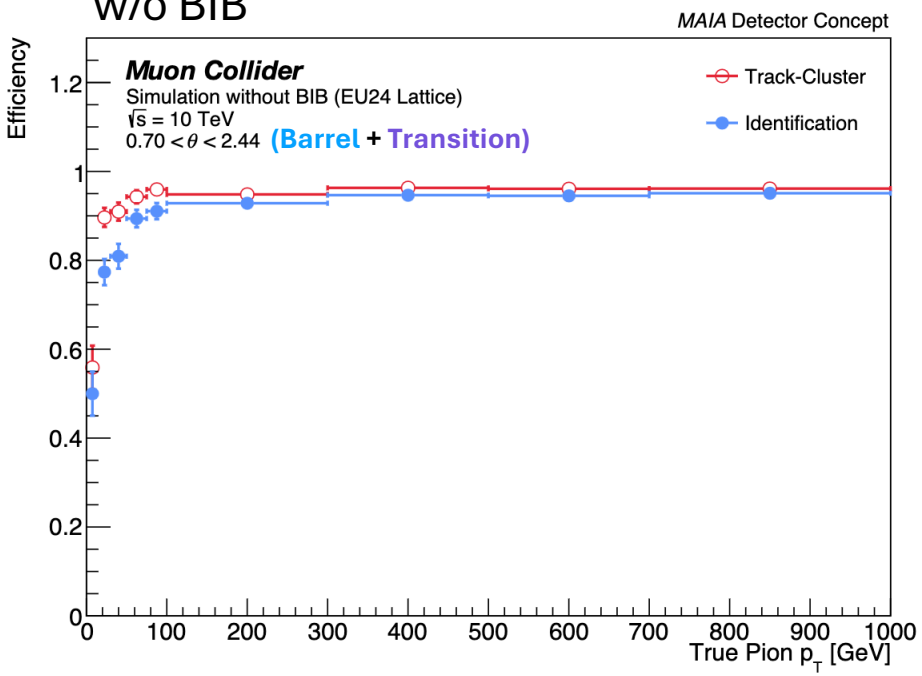
"Track-Cluster" Efficiency

- Require an ID'd charged particle $(e, \mu, \pi^{\pm})$ within $\Delta R < 0.1$
- **>85% efficiency above 20 GeV in barrel + transition**
- Inefficiency due to matching to low-E cluster fragments

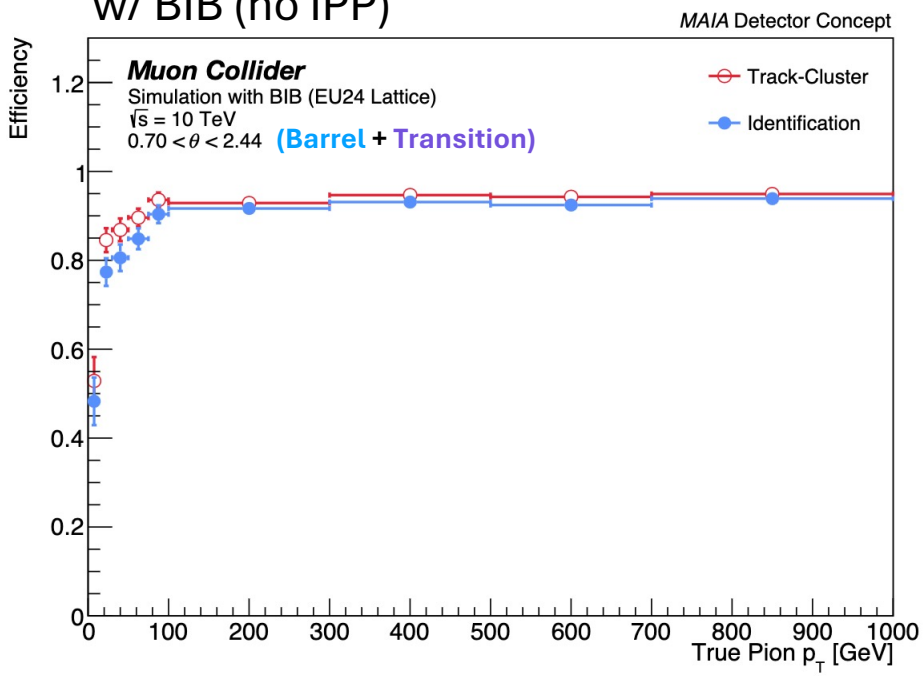
"Identification" Efficiency

- Require a $\pi^{\pm}$ within $\Delta R < 0.1$
  - Tracking efficiency in denominator
- Inefficiency arises from mis-ID as electron
  - 5% effect at maximum

w/o BIB



w/ BIB (no IPP)



Tracker R&D

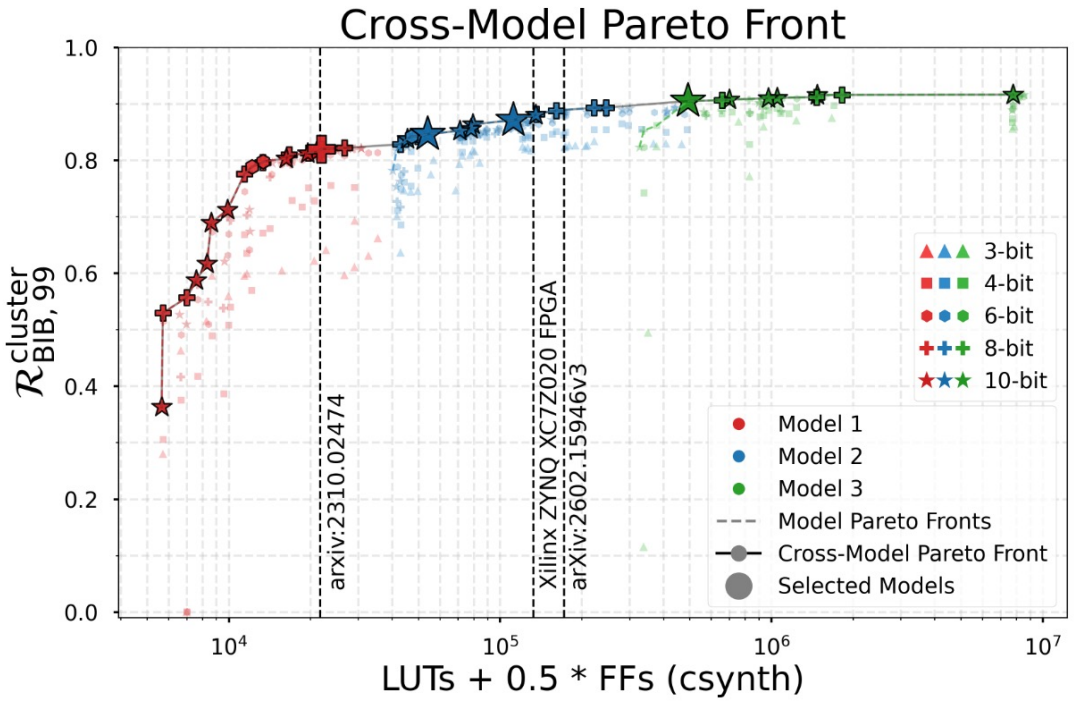
Smartpixels

D. Abadjiev, et al., arXiv:2608.21327

more on Smartpixels in CPAD from H. Gupta, B. Weiss

Discriminate BIB hits based on pixel cluster shape

NN implementation studied over many models



Hardware resource usage on FPGA

BIB hit rejection

Feasible implementations exhibit >80% rejection at 99% signal

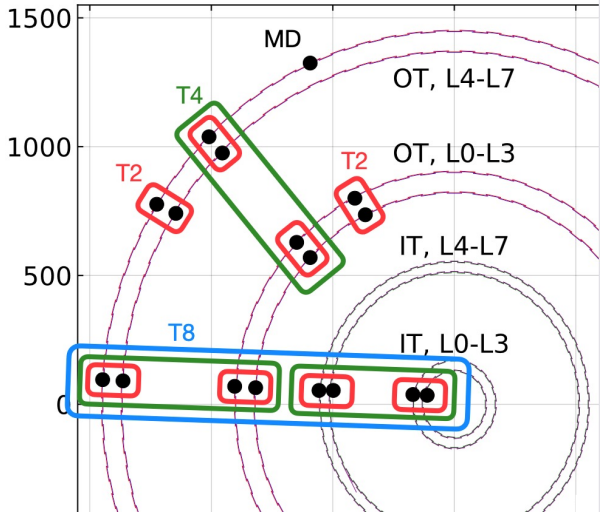
Line Segment Tracking

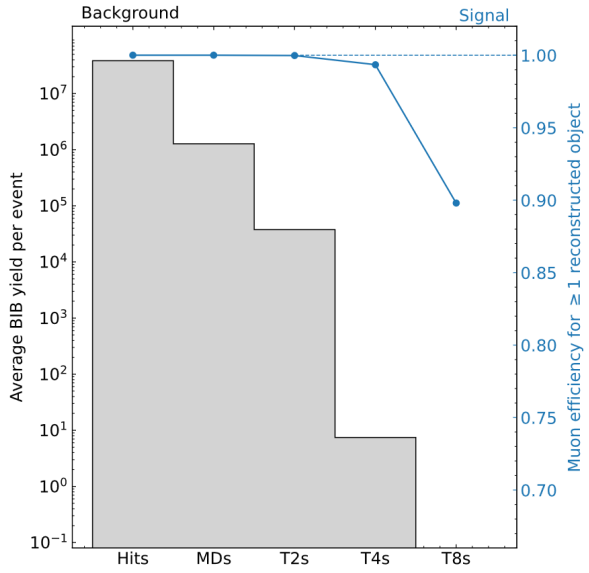
CMS style!

Y. Gu, A. Tuna, et al. (see more @ ICHEP presentation)

Redesign tracker to contain doublet layers

Reject BIB based on doublet hit geometry





Building pairs of doublets (T2) rejects BIB hits by a factor of 1000 at negligible signal loss

Summary

We have established an initial benchmark for reconstruction of basic objects in the MAIA detector

- Tracks, photons, neutrons, charged pions

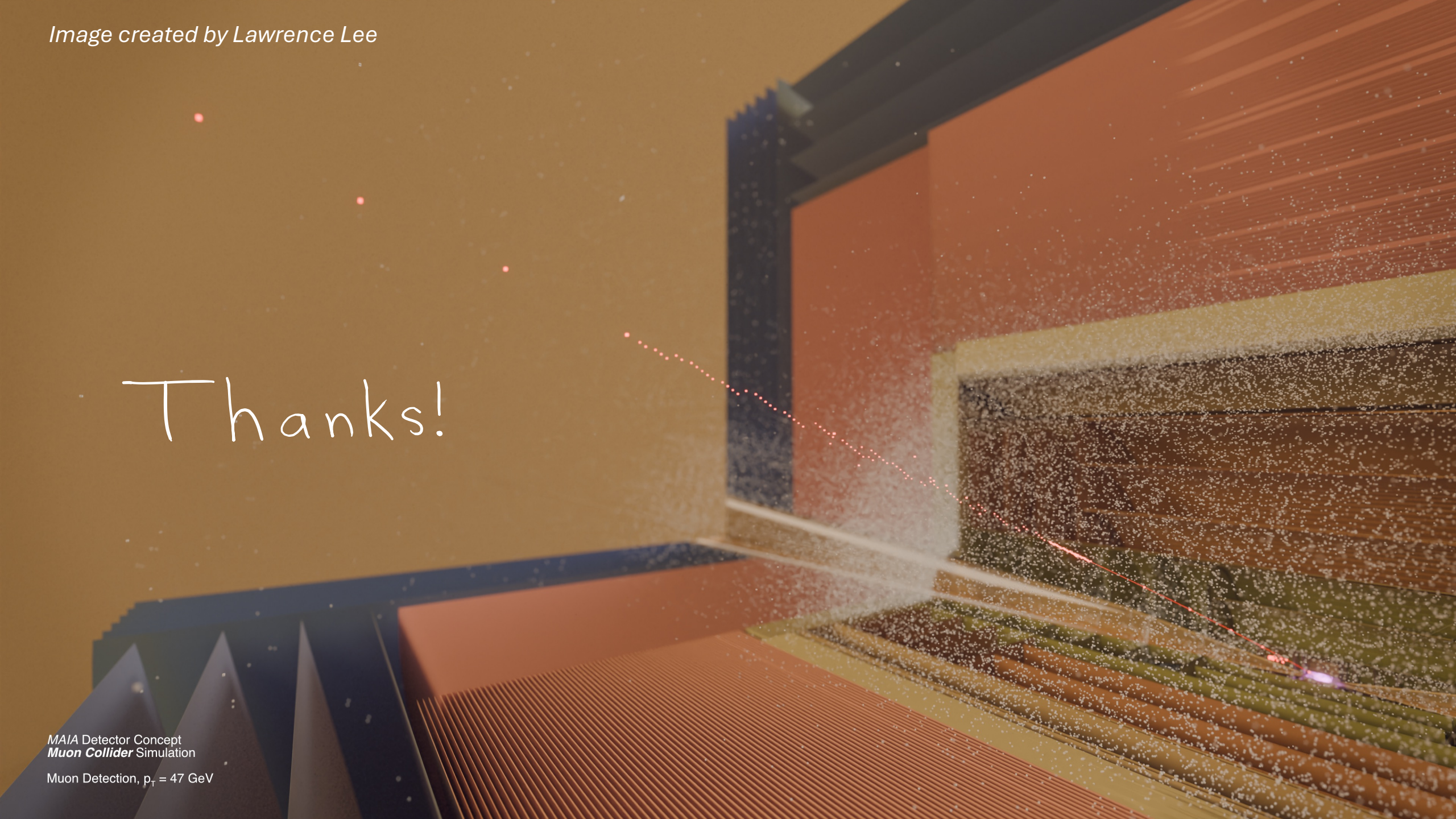
Optimization is yet to be done, particularly in the endcaps

Future work (partial list):

- Optimization of particle flow algorithms
- Study of muon system performance, particularly in the forward region
- Study of more complicated objects: jets, taus, flavor tagging

This is an excellent time to get involved!

See our recent tutorial for running MAIA simulation


Image created by Lawrence Lee
Thanks!
MAIA Detector Concept
Muon Collider Simulation
Muon Detection, p_T = 47 GeV

Target Detector Performance

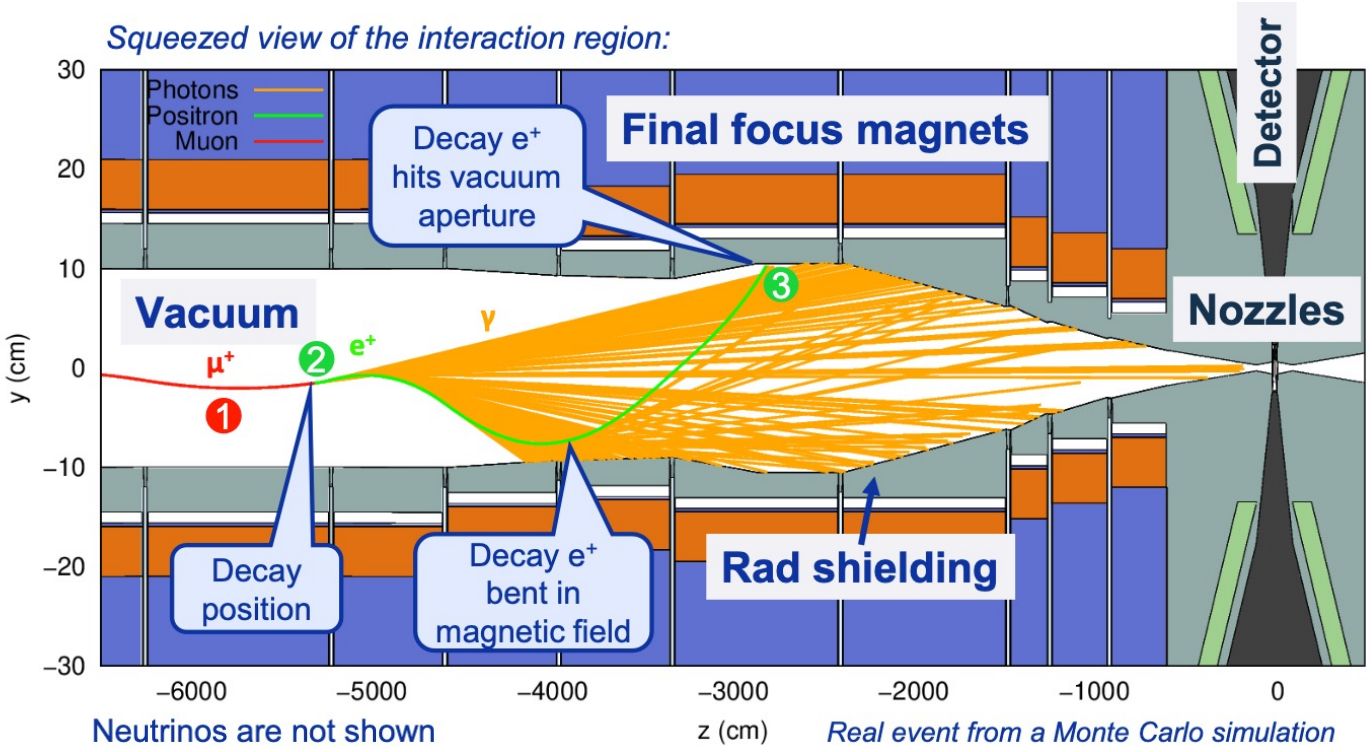
- Benchmarks set, targeting:
  - “Baseline”: Utilize physics potential of a 10 TeV Muon Collider
  - “Aspirational”: On par with H / Top / Electroweak factories

Requirement	**Baseline**	**Aspirational**
Angular acceptance $\eta = -\log(\tan(\theta/2))$	$\lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 4$
Minimum tracking distance [cm]	~ 3	< 3
Forward muons ($\eta > 5$)	tag	$\sigma_p/p \sim 10\%$
Track σ_{p_T}/p_T^2 [GeV^{-1}]	4×10^{-5}	1×10^{-5}
Photon energy resolution	$0.2/\sqrt{E}$	$0.1/\sqrt{E}$
Neutral hadron energy resolution	$0.4/\sqrt{E}$	$0.2/\sqrt{E}$
Timing resolution (tracker) [ps]	$\sim 30 - 60$	$\sim 10 - 30$
Timing resolution (calorimeters) [ps]	100	10
Timing resolution (muon system) [ps]	~ 50 for $\lvert\eta\rvert > 2.5$	< 50 for $\lvert\eta\rvert > 2.5$
Flavour tagging	b vs c	b vs c, s-tagging
Boosted hadronic resonance identification	h vs W/Z	W vs Z

10 TeV μC Machine Backgrounds

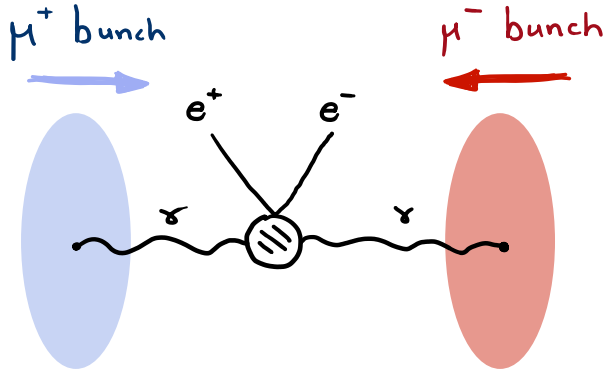
Two sources of background accounted for:

Beam Induced Background (BIB)



A. Lechner, D. Calzolari

Incoherent Pair Production

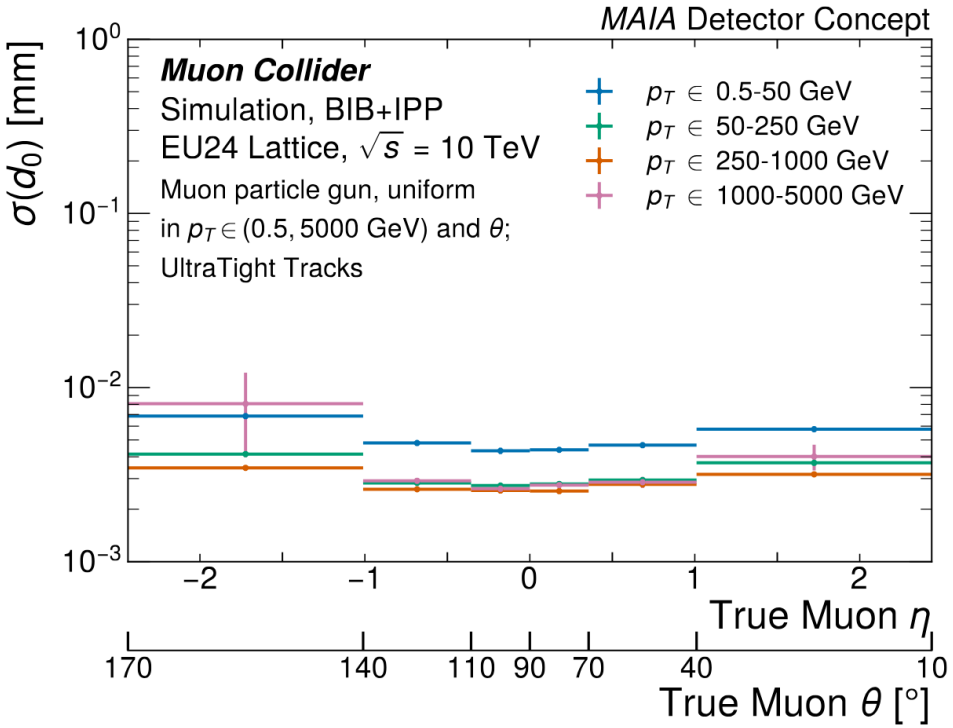


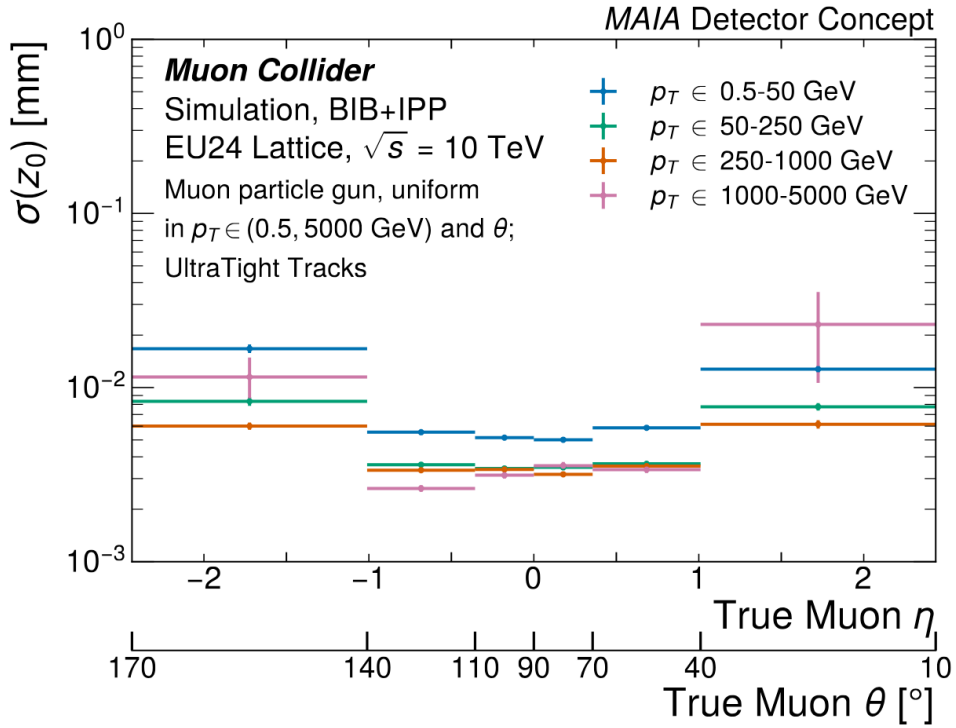
- *The bunches interact with each other's E-field*
  - *e^+e^- pair produced near interaction point*



Contributing diagrams

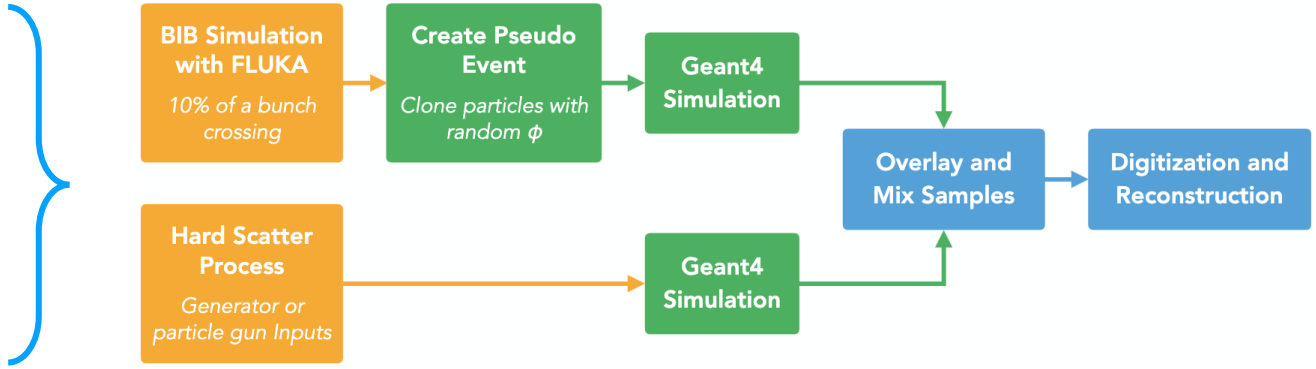
Track Impact Parameter Resolutions





Software

- BIB, IPP simulated w/ FLUKA + GUINEA-PIG
- Cloning and mixing process performed
  - Reduces BIB simulation
  - Statistical independence achieved



- Gaudi-based framework of Key4hep used across analysis chain
- Combinatorial Kalman Filter (CKF) based track reconstruction using ACTS
- Pandora used for particle flow
  - Configuration optimized to balance run-time and performance

Pandora Configuration

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

Hit Preparation
- Define isolated hits

Initial Clustering
- Fast photon clustering
- "Cone clustering"

Re-clustering
- "Broken Tracks"
- "ShowerMipMerging"
- "ProximityBasedMerging
- "ConeBasedMerging"
- Fragment removal

PFO Identification
- Set of basic ID algorithms