Detector Design for a Muon Collider

Kiley Kennedy, Princeton University

Early Career Researchers & Muon Colliders, 28 August 2024

International MUON Collider Collaboration

About Me

G. Fontana

Research Experience

- PhD, Physics, Columbia University, 2022
    - ATLAS Experiment – LLP analyses, LAr HL-LHC upgrade, Run 2/Phase I operations
- Postdoc, CMS Group, Princeton University, 2022–present

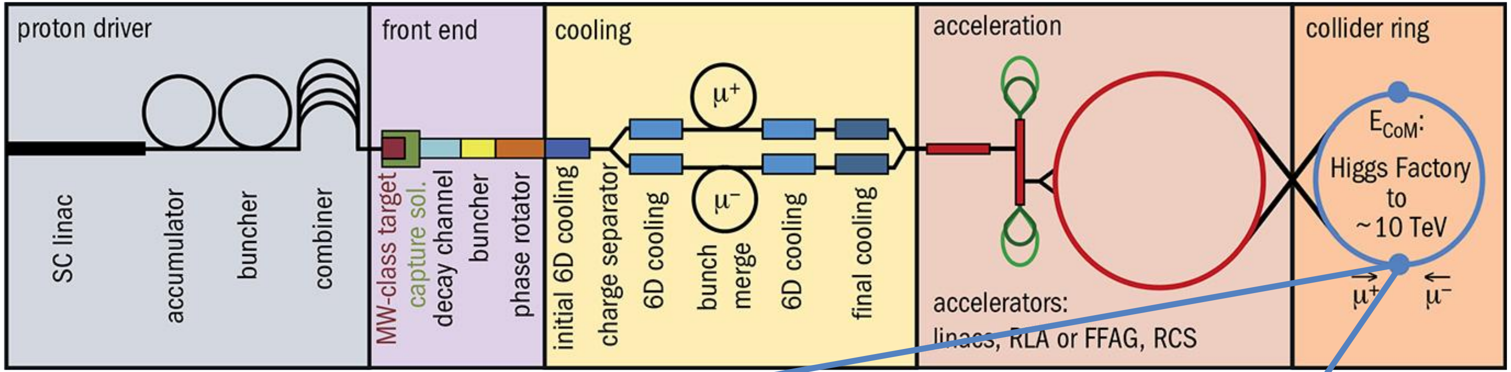
Research Interests and Activities

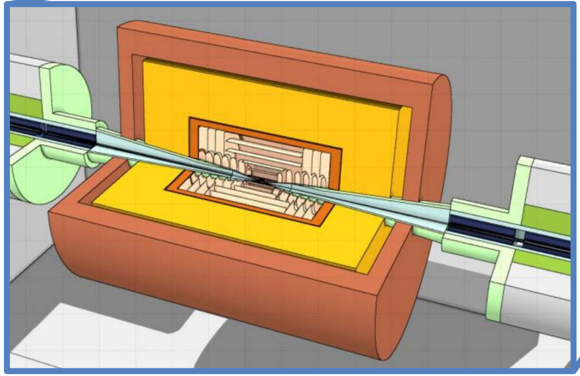
- CMS: LLP searches, outer tracker upgrade, trigger, ML
- Muon Collider: detector R&D studies

Excited about the fastest path to 10 TeV pCM and paving the way for the next era of particle physics!

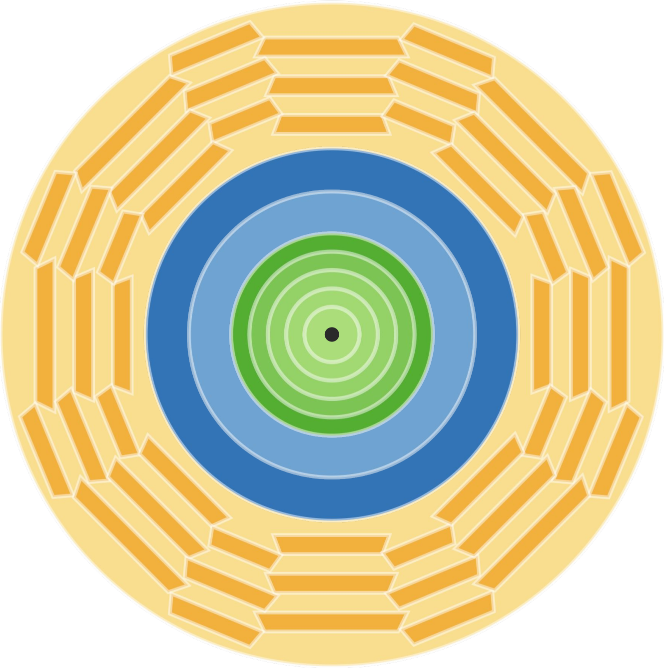
Muon Collider Infrastructure

Title page: L. Lee, C. Bell
3D renderings with Unreal Engine





Let’s Build a Detector!



Tracker

- Charged particles leave tracks
- Measure particle position & momentum, vertices

Calorimeters

- Dense materials stop particles
- Separate ECAL and **HCAL** systems
- Measure particle position, energy

Muon Spectrometer

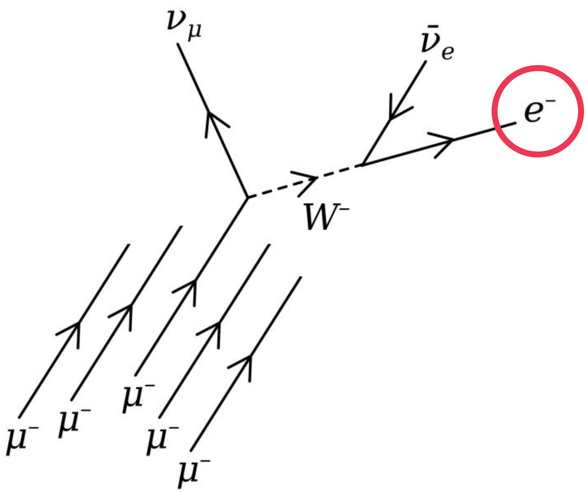
- Muon tracks escape detector
- Measure position & momentum

Magnet System (not shown)

- Superconducting magnets provide B-field in tracker, muon spec.

Impact of Muon Decays on the Detector

L. Lee, D. Calzolari

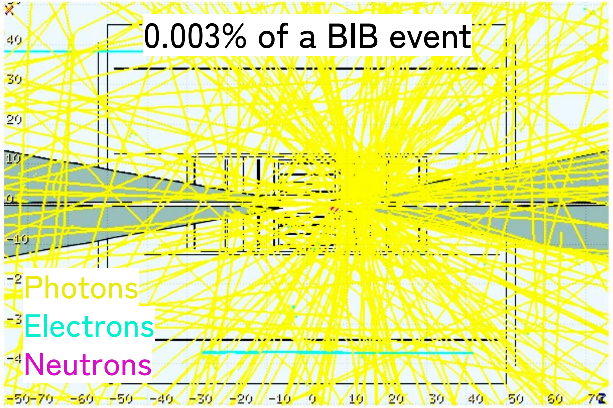


Multi-TeV muon decays produce <u>TeV-scale electrons</u>

Beam Induced Background (BIB)

Electrons shower and make an EeV-scale mess in the detector

(1 EeV = 1e9 GeV)

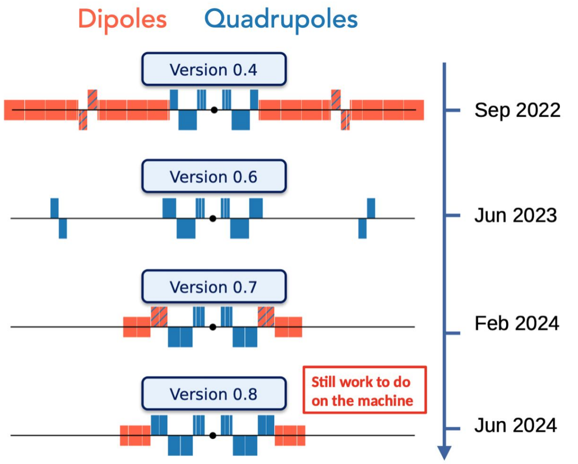


First Steps in BIB Mitigation

L. Lee, D. Calzolari

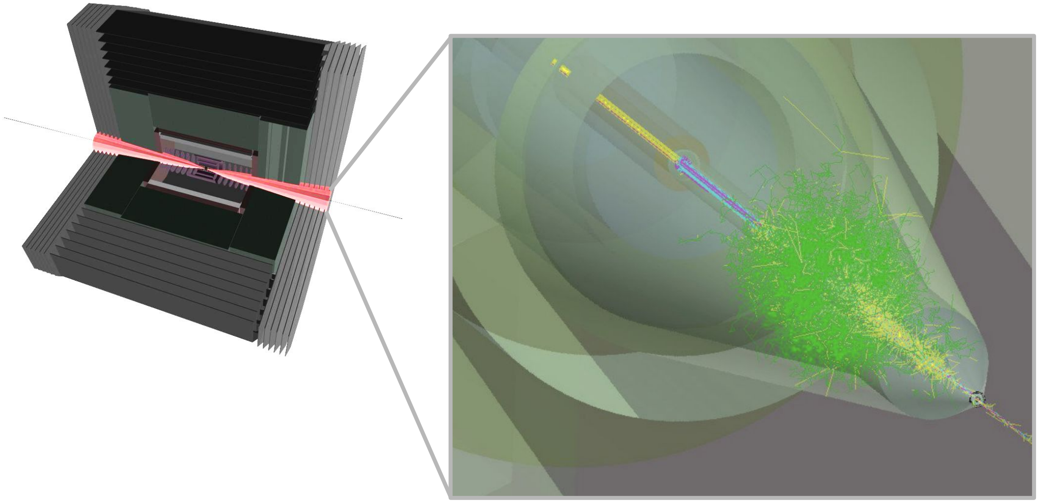
1. Collider lattice design

- Configure lattice near the interaction region (IR) to minimize BIB
- E.g. short straight section



2. Shielding via “nozzles”

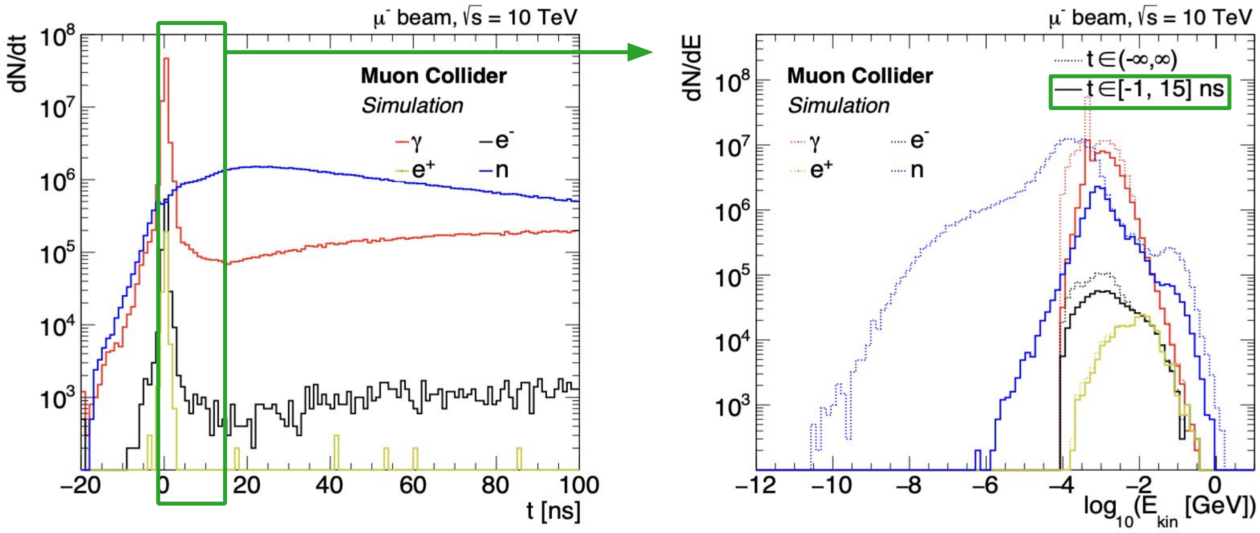
- Reduces BIB by several orders of magnitude
- Changes BIB composition (highly energetic particles → diffuse)



First Steps in BIB Mitigation

3. Apply timing selection

- Can reduce BIB by ~orders of magnitude, especially low-energy contributions
- Precision timing O(10-100) ps critical to perform meaningful physics analyses



Key Challenges + Goals for Detector Design

1. Robust against BIB
    - Dominated by MeV-scale γ/n, generally out-of-time + non-projective

2. Sensitive to physics signatures of interest
    - Multi-TeV objects from $\mu^+\mu^-$ annihilation processes
    - Exotic BSM physics signatures (e.g. long-lived particles)

Tracker Design + Performance

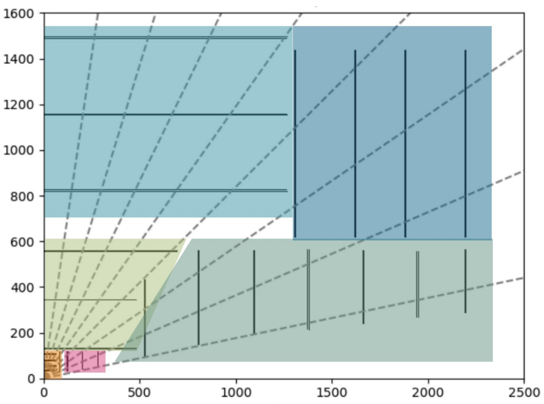
T. Holmes, F. Meloni, L. Rozanov

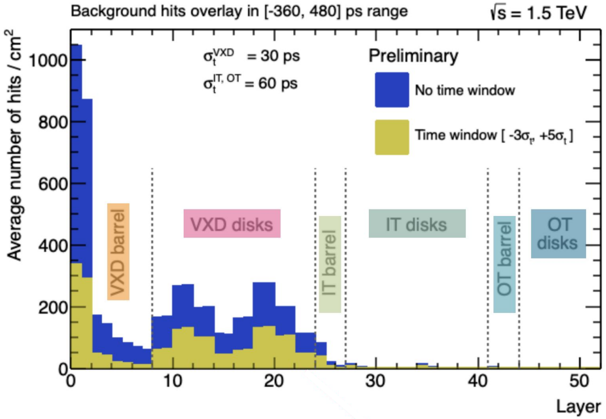
Three Si Tracking Sub-Detectors

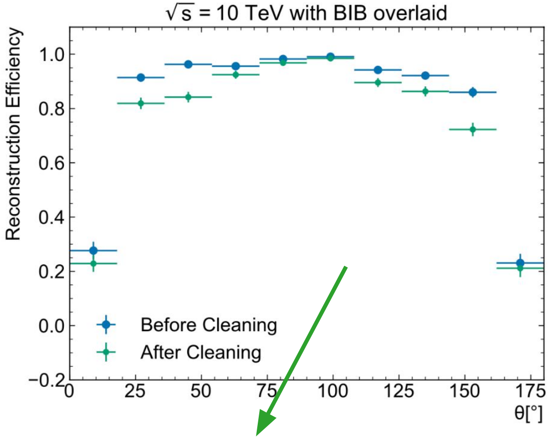
1. Vertex Detector (VXD) – Barrel, Endcap
2. Inner Tracker (IT) – Barrel, Endcap
3. Outer Tracker (OT) – Barrel, Endcap

Key Challenge: occupancy

- Single event: O(100k) BIB hits vs O(10-100) signal hits
- Varies per layer → informs size + timing requirements







Excellent tracking reconstruction efficiency in the barrel, even with BIB!

ECAL Design + Performance

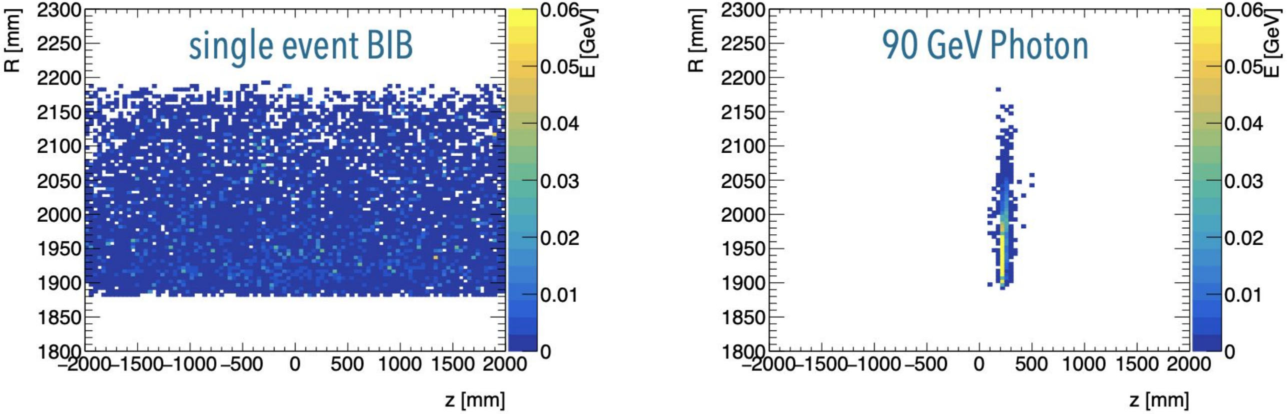
Various detector technologies being explored:

- W-Si: Tungsten-silicon
- Crilin: Lead fluoride crystal w/ depth segmentation

Key Challenge: large cell sizes + integration times

- 5D Calorimetry: high-granularity (eta/phi/depth), excellent timing, good energy resolution

High-energy signals "easy" to identify from diffuse BIB



HCAL Design + Performance

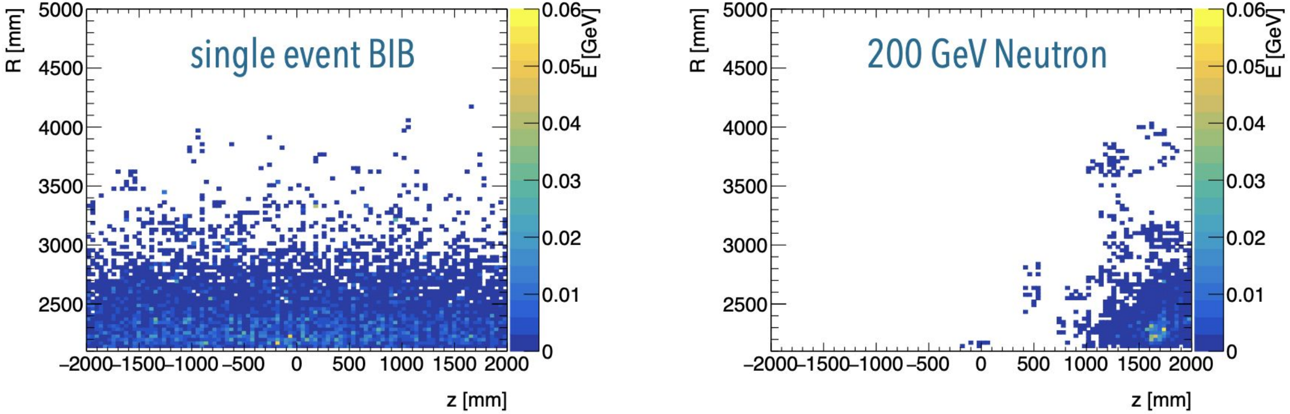
Detectors primarily using Fe/Steel+Scintillator

- 10 TeV: Iron as solenoid return yoke (magnet either inside ECAL or between ECAL/HCAL)

Key Challenge: large cell sizes + integration times

- 5D Calorimetry (same principles as ECAL)
- High-energy BIB neutrons tend to be out-of-time

Signal still distinct, but less pronounced than electromagnetic signatures

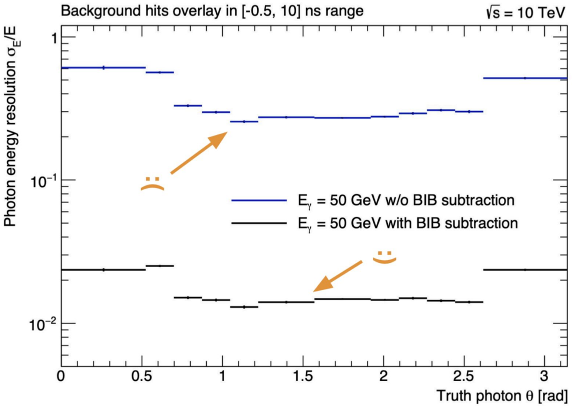


Physics Performance At-A-Glance

T. Holmes, Muon Collider Forum Report,
F. Meloni, D. Ally et al., M. Carsarsa

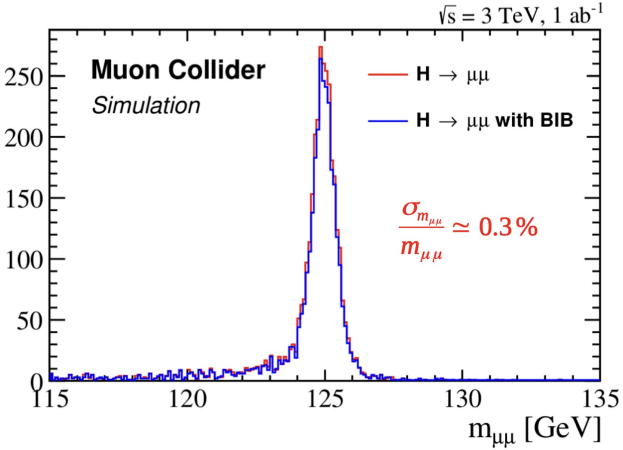
BIB Subtraction

Improves photon energy resolution by ~30x



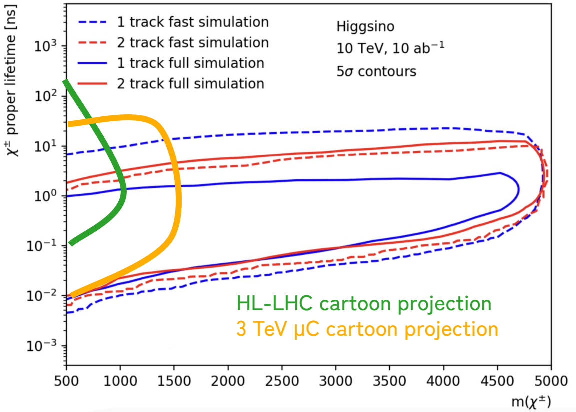
Higgs Measurements

Excellent reconstruction of H→μμ, even with BIB



Exotic BSM Signatures

Extend sensitivity to disappearing tracks signals



Many Open Questions + Ongoing Work!*

***A non-exhaustive list**

- Detector optimization
    - E.g. multiplicity and positions of various detector layers, magnet field strength(s) (at least for 10 TeV)
    - Must be done in conjunction with collider lattice design + nozzle optimization ("***Machine-Detector Interface***")

- Mechanical Requirements
    - Room for services, cooling, and support infrastructure
    - Physical support for the nozzle

- Software and Simulation
    - BIB simulation extremely computationally intensive
    - Latest SW release built on key4hep stack

- Physics in the forward region
    - Forward muon tagging very important for VBF processes – how to detect these muons?

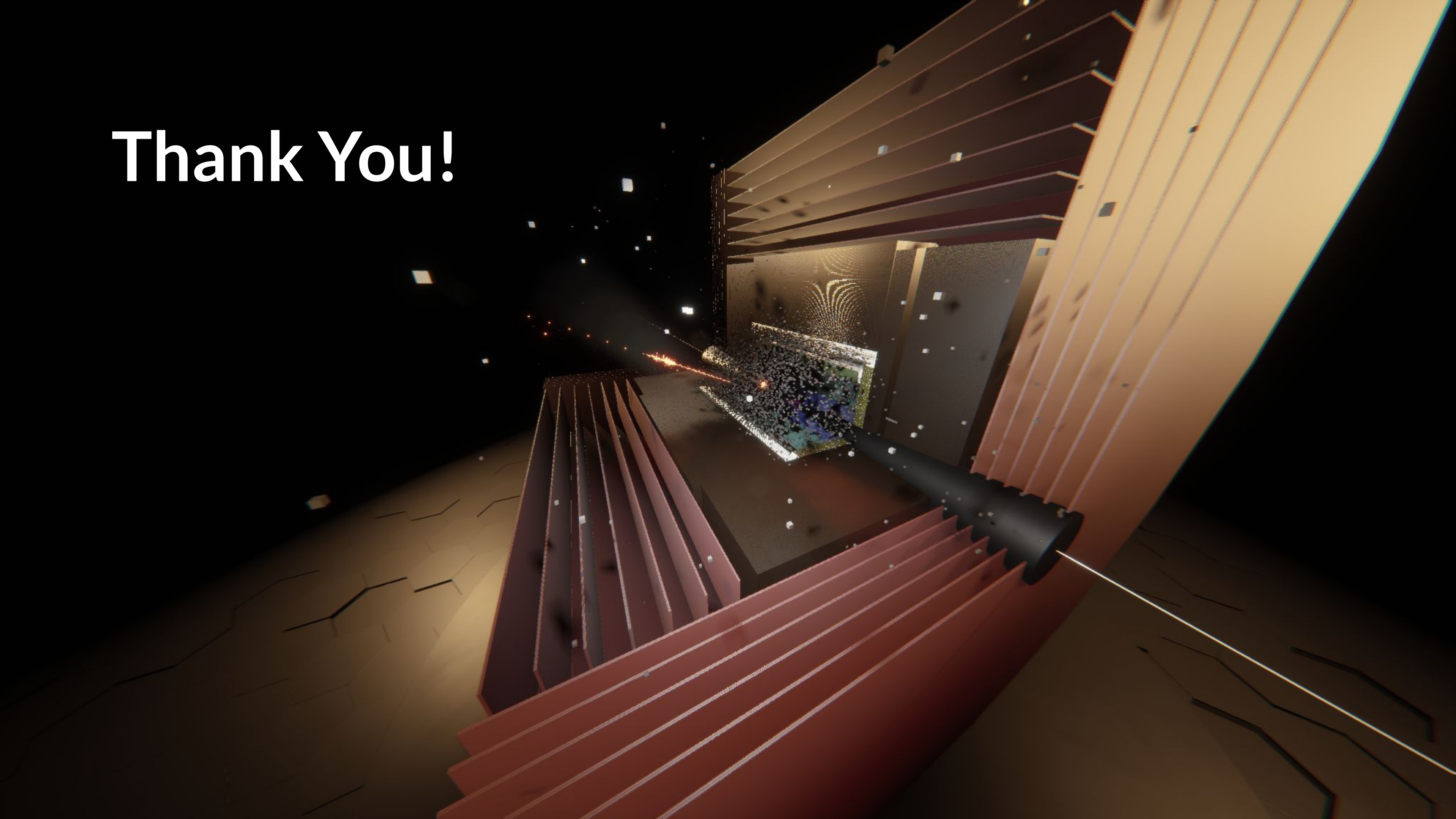
- DAQ system
    - Not much development done here yet…

Conclusions + Outlook

- Established configurations for 1.5 and 3 TeV detector concepts, with ongoing work on 10 TeV muon collider detector concepts
  - Detector technologies themselves an active area of R&D
- BIB mitigation is critical – requires precision timing across detector subsystems, small cell sizes, calorimeter depth segmentation
- Despite the challenging background conditions, **we can do physics**!
- Many exciting physics studies to be done by the European Strategy deadline on March 31, 2025! → **It's an excellent time to get involved**!

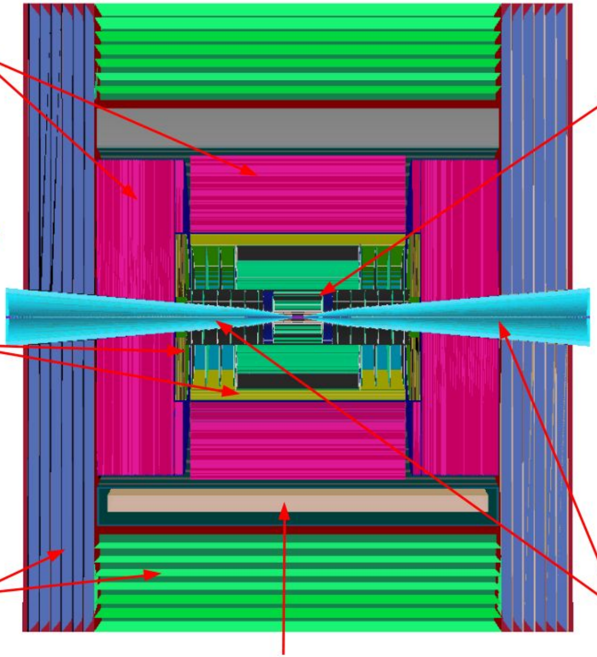
L. Lee, C. Bell

Thank You!



Backup

3 TeV Detector Design



hadronic calorimeter

- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_I.

muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet’s iron yoke;
- 30x30 mm^2 cell size.

tracking system

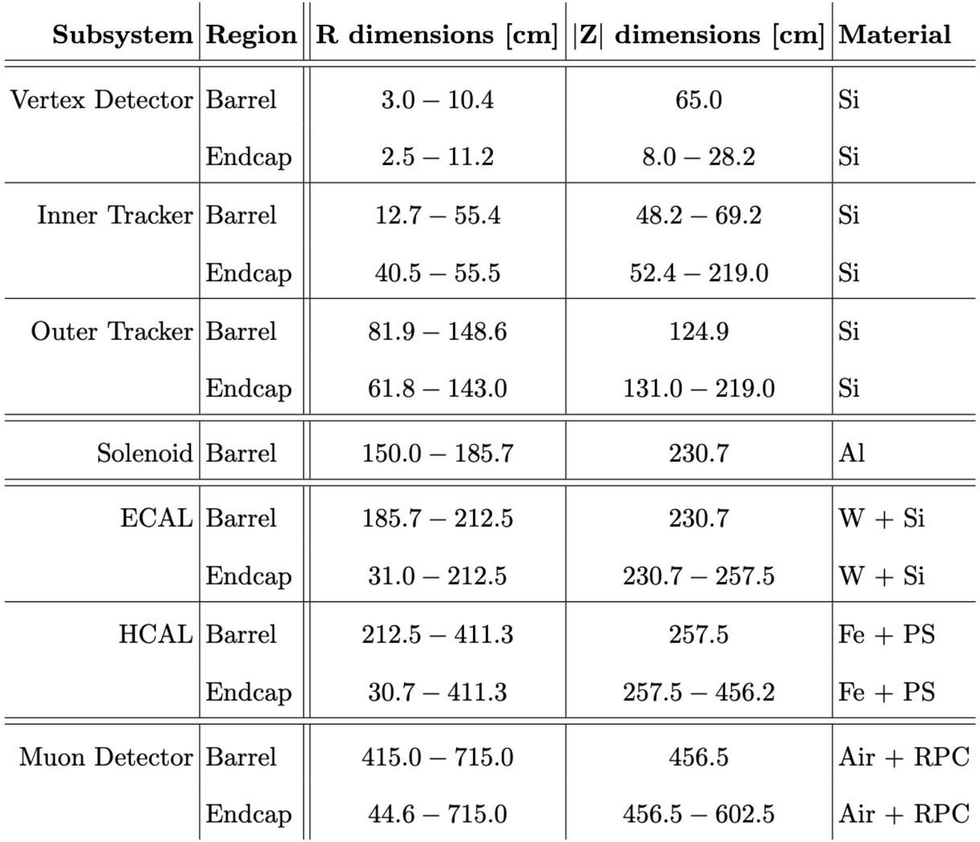
- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 μm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 μm x 10 mm micro-strip Si sensors.

shielding nozzles

- Tungsten cones + borated polyethylene cladding.

superconducting solenoid (3.57T)

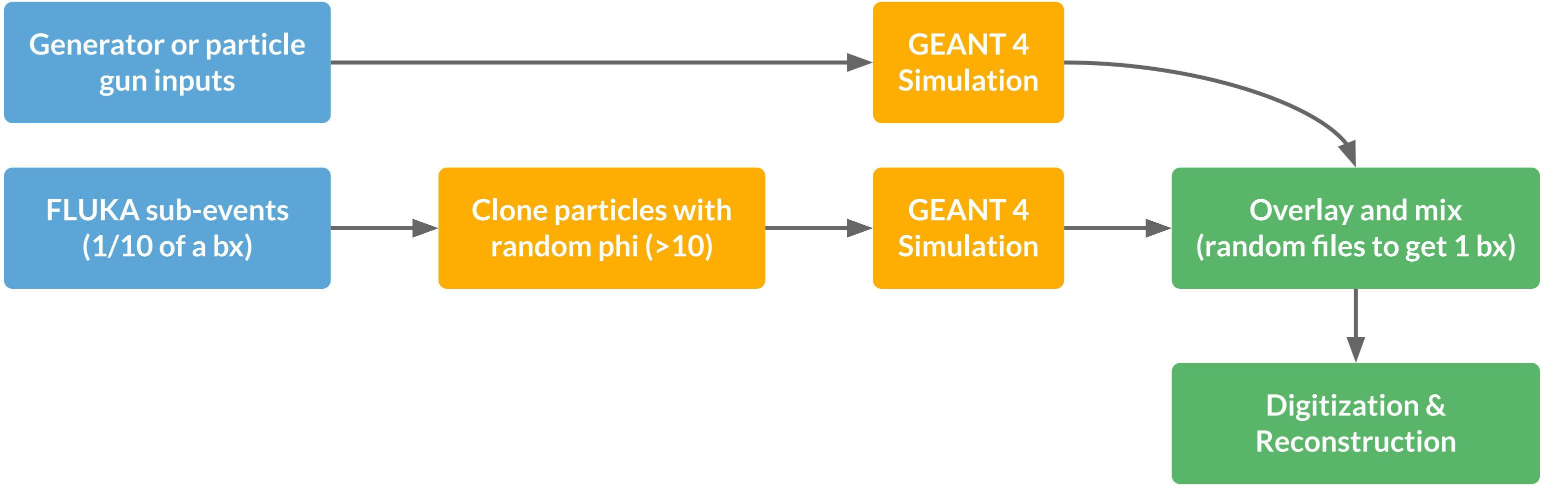
10 TeV MAIA Detector Design



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

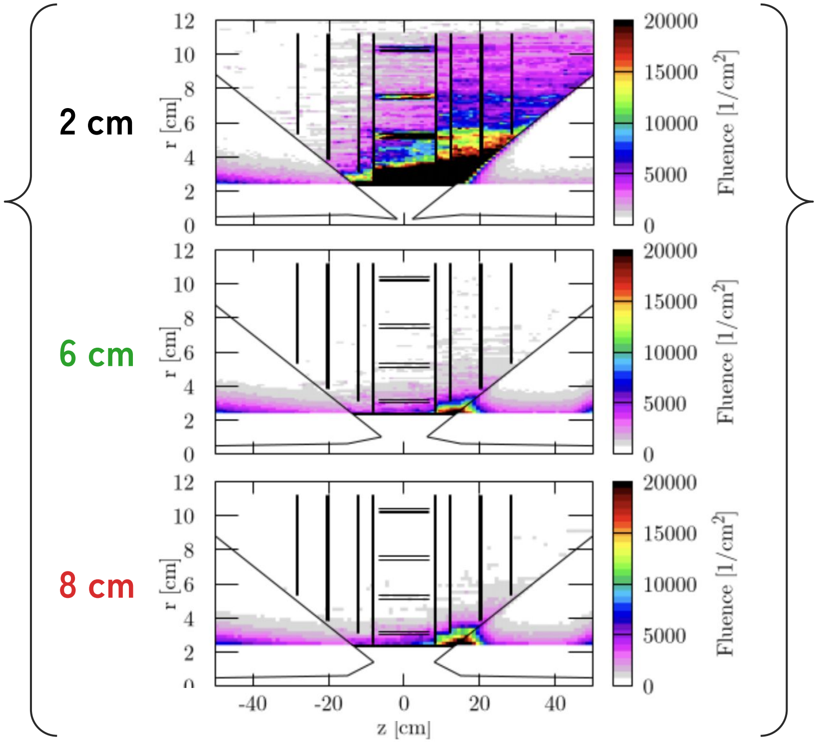
BIB Simulation Workflow

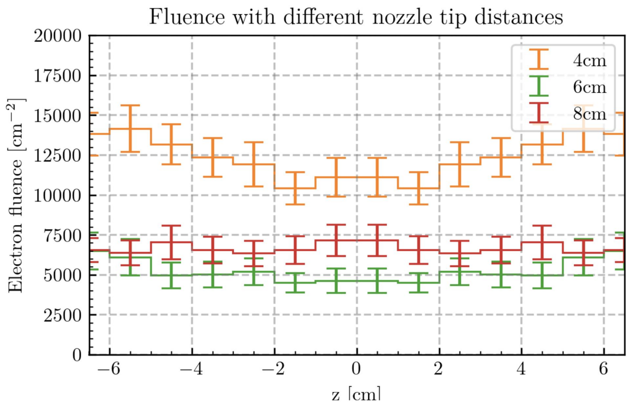
- Using updated FLUKA 10 TeV BIB
  - Kinematics look very similar to 3 TeV; but MDI, nozzle optimization extremely important (D. Calzolari)
- BIB simulation and overlay (N. Bartosik)
  - Simulating the BIB contributions in FLUKA is computationally expensive, so employ overlay strategy:



Nozzle Configuration Optimization Studies

Simulate BIB fluence with nozzle tip at different distances



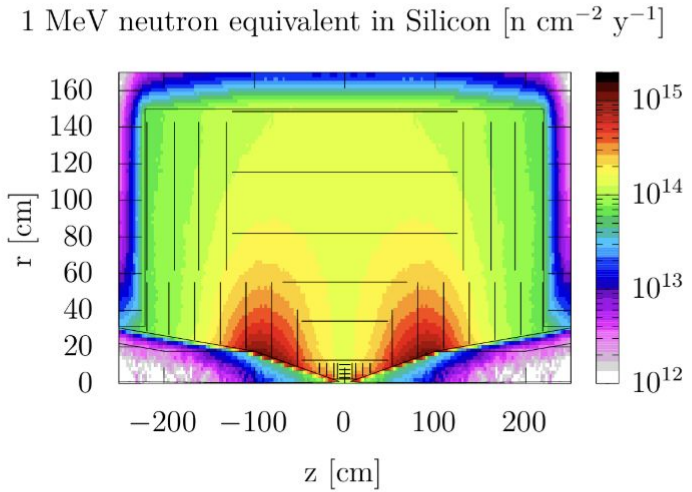


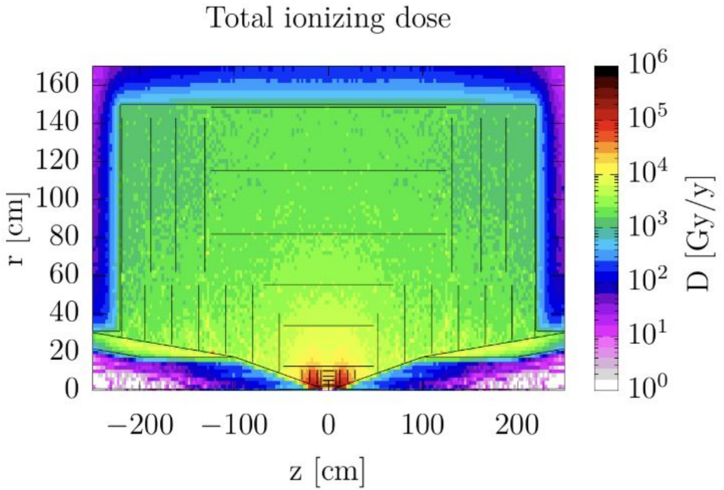
- Nozzle tip has a strong influence on the electron fluences
- Require nozzle distance > 4 cm from origin to reduce EM showers
- Studies ongoing!

Radiation Damage

B. Rosser

- 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)



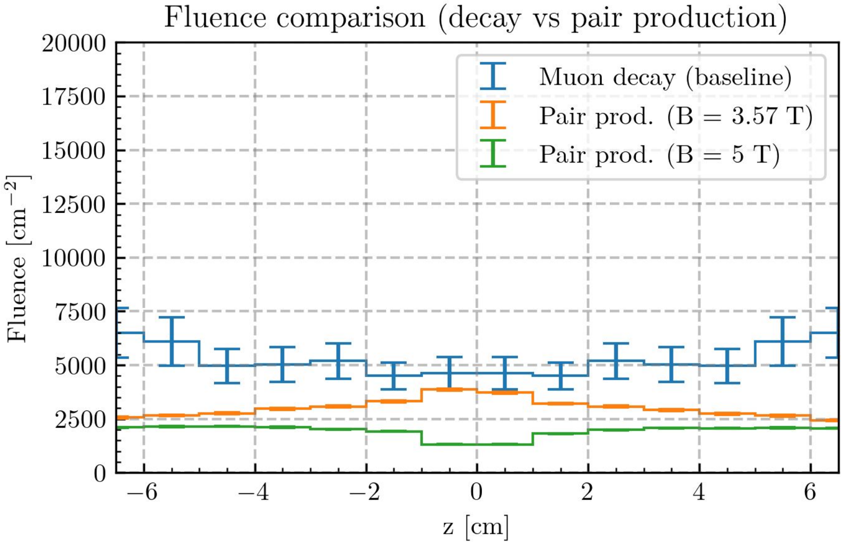


	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider (3 TeV)	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}
Muon Collider (10 TeV)	20	0.2	3×10^{14}	10^{14}

Solenoid – Design and Impact on Fluence

D. Calzolari

- **3 TeV design**: 3.57 T, outside calorimeters (“CMS-like”)
- **10 TeV design**: 5 T, inside calorimeters (“ATLAS-like”)
    - Higher solenoid B-field significantly reduces fluence (e+/e- results compared here)
    - BIB shielding for calorimeters
        - Adds ~265 mm of aluminum and thinner steel layers in barrel; additional steel layers in the endcap
        - Equivalent to ~4 X_0
    - Caveat: feasibility studies needed here!

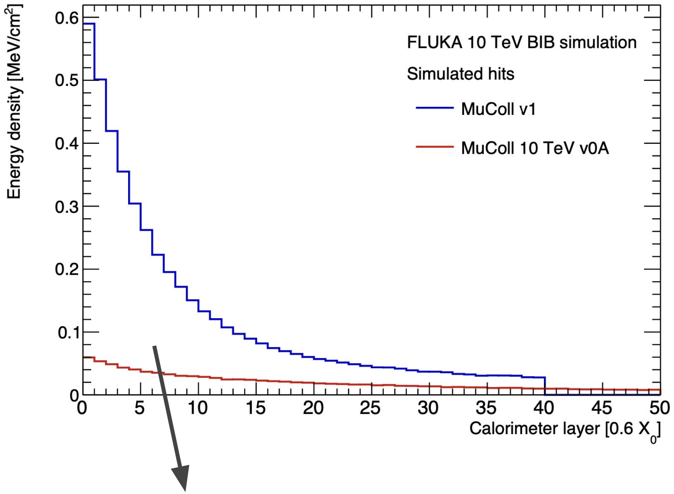


Calorimeter BIB Energy Densities

F. Meloni

Energy Density of BIB in ECAL:

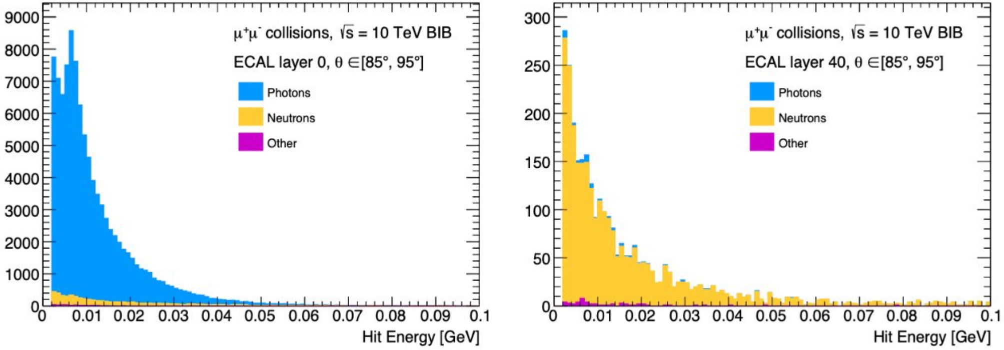
~3-10x lower than 1.5 TeV due to solenoid shielding



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



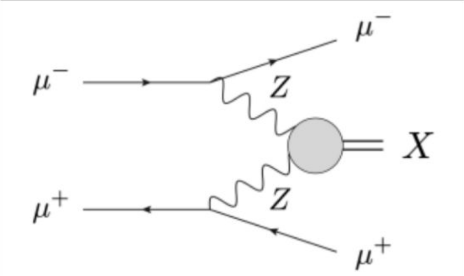
Further studies on impact of solenoid shielding needed, e.g.:

- ➔ Charged objects with particle flow
- ➔ Some clustering and track-cluster association issues in Pandora

L. Castelli, D. Lucchesi, D. Calzolari, F. Collamati

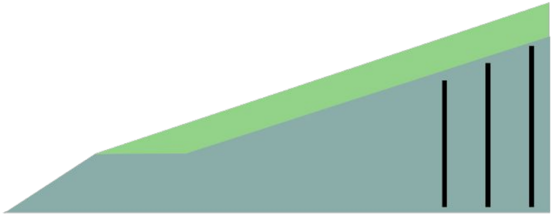
Muon Spectrometer

- **Barrel and Endcap**: least impacted by BIB given shielding from calorimeters
  - Simplified, Air + RPC (both 10 TeV detectors)
  - To potentially replace with scintillator (CERN rule)
- **Forward Region**: challenging given position of nozzle
  - Important physics (VBF) — e.g. Higgs boson width
  - Dedicated forward muon detector candidates



Silicon Layers in the Nozzle

Small detector, high BIB background



Separate Forward Cavern

Large detector, low background