A New Detector Concept for a 10 TeV Muon Collider

Quick Configuration Overview

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IMCC MDI Workshop, 26 June 2024

Overview

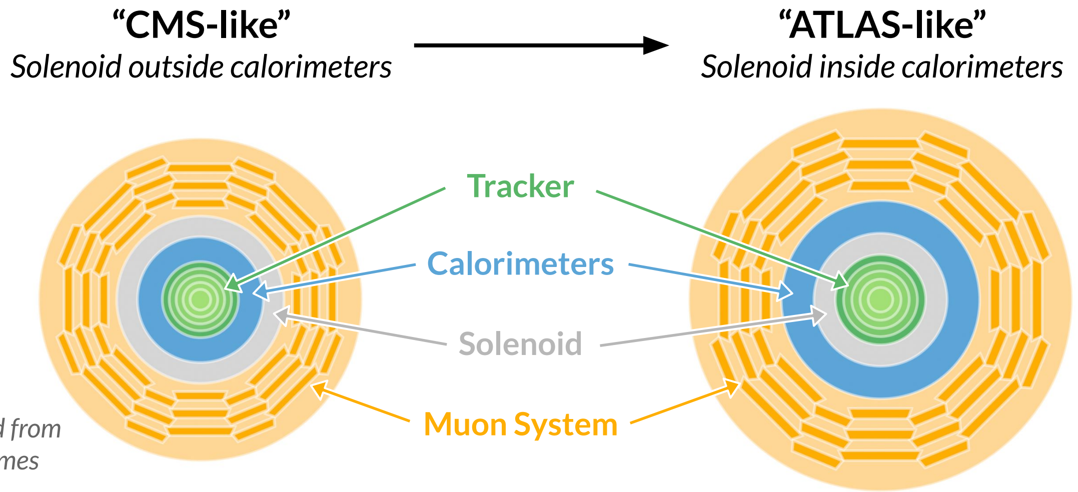
Title page: L. Lee, C. Bell
3D renderings with Unreal Engine

- ➔ Introduction and motivation
- ➔ Simulation of beam induced background (BIB)
- ➔ Tracker: 10 TeV conceptual design and performance
- ➔ Calorimeter: 10 TeV conceptual design and performance
- ➔ Conclusions & Outlook

Results today include contributions from many, including:
F. Meloni, T. Madlener, P. Pani (DESY); D. Calzolari (CERN); K. DiPetrillo, B. Rosser, L. Rozanov, I. Hirsch, N. Virani (Chicago); T. Holmes, L. Lee, B. Johnson, M. Hillman, A. Vendrasco, A. Tuna (Tennessee); S. Jindariani, K. Pedro, (FNAL); R. Powers (Yale); S. P. Griso (LBNL); I. Ojalvo, K. Kennedy, J. Zhang, E. Sledge (Princeton).

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
- ➔ BIB is the key challenge driving 10 TeV detector design
  - ◆ Similar nozzle strategy to as lower energy detector concepts
  - ◆ Some changes w.r.t. 3 TeV detector design, including ***moving solenoid inside the calorimeters*** (enabling higher B-field)

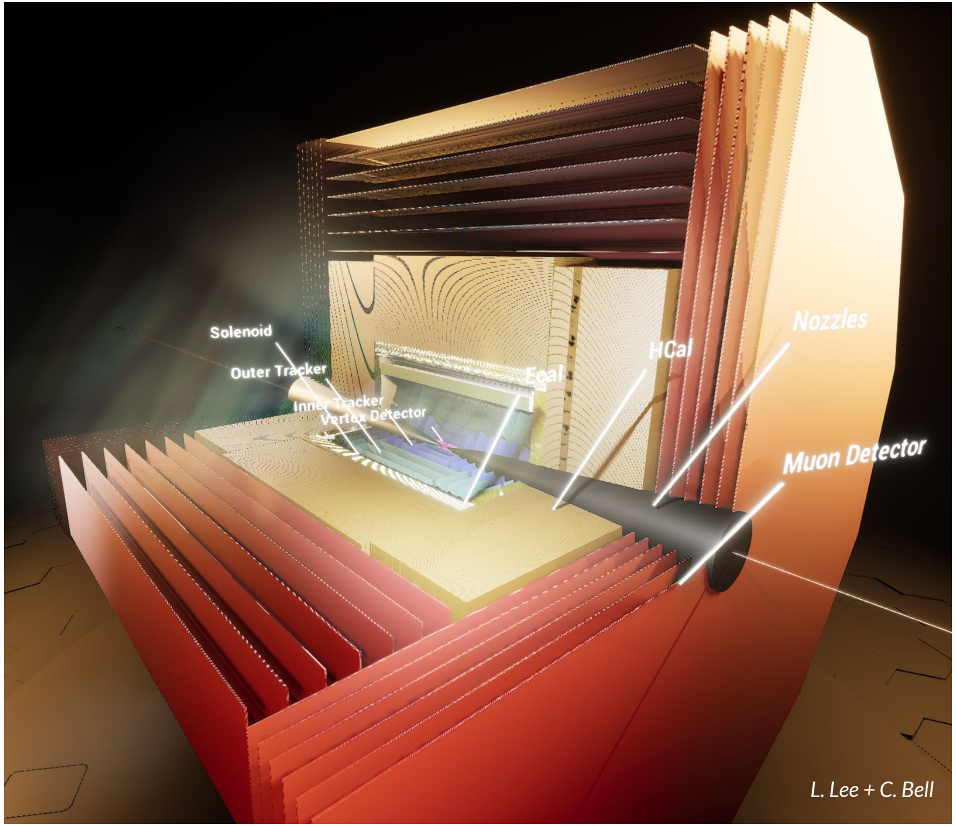


Adapted from T. Holmes

***Today**: update on progress towards a conceptual design for an "ATLAS-like" 10 TeV detector*

Overview of 10 TeV Detector Concept

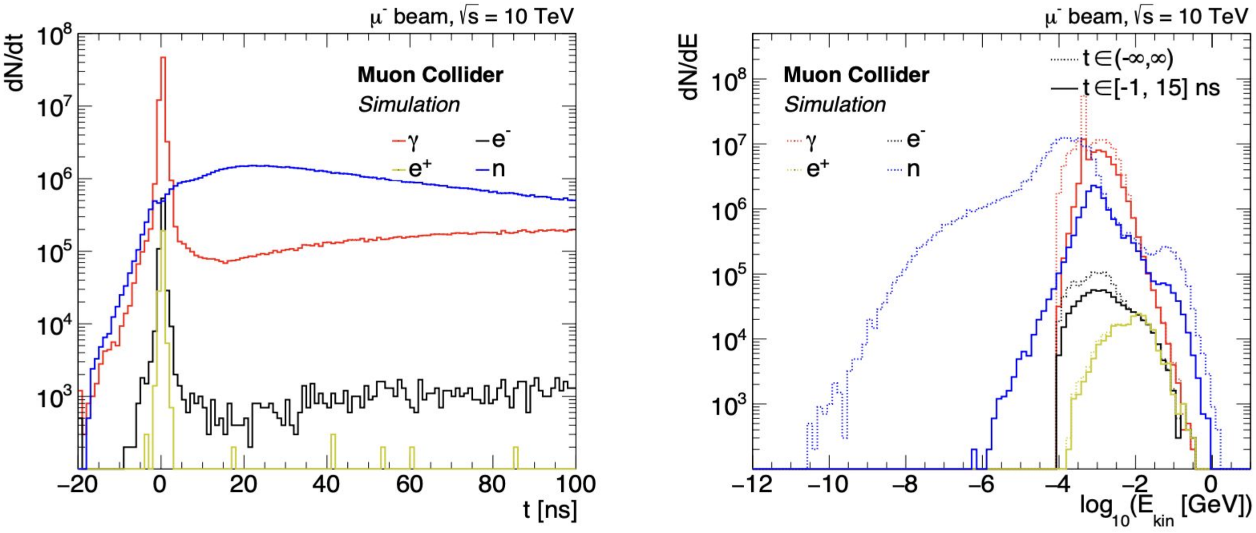
- ➔ **Nozzle** – Baseline: optimized design for 1.5 TeV
  - ◆ Tungsten + borated polyethylene
  - ◆ Major role in BIB mitigation
- ➔ **Tracker** – Vertex Detector, Inner + Outer Trackers
- ➔ **Solenoid** – 5 TeV, Aluminum
  - ◆ Higher B-field reduces tracker occupancy
  - ◆ Additional BIB shielding for calorimeters
- ➔ **Calorimetry** – High Granularity
  - ◆ ECAL – Silicon-Tungsten
  - ◆ HCAL – Iron-scintillator
- ➔ **Muon Spectrometer** – Simplified, Air + RPC
  - ◆ Not as impacted by BIB as other subsystems



BIB Simulation | *Assumptions*

➔ Assume dominant BIB from muon decays near the interaction region
  - Only consider muon decays in the final focusing region (otherwise deflected)
  - Ignore beam halo and incoherent pair-production for now

➔ Particles simulated down to 100 keV kinetic energy; neutrons down to thermal

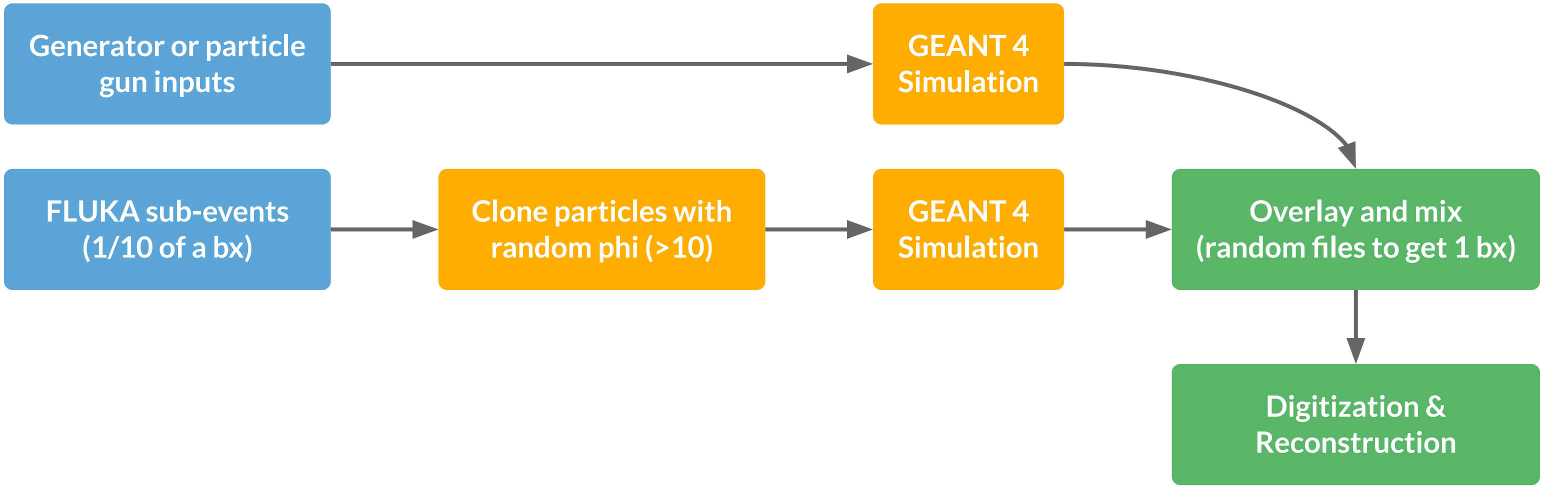


BIB Simulation | *Workflow*

F. Meloni

- Using updated FLUKA 10 TeV BIB
  - Kinematics look very similar to 3 TeV; but MDI, nozzle optimization extremely important (D. Calzolari)

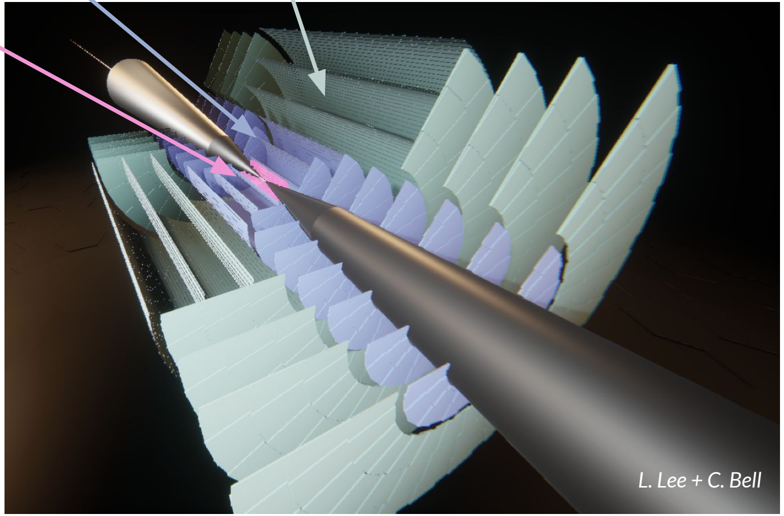
- BIB simulation and overlay (N. Bartosik)
  - Simulating the BIB contributions in FLUKA is computationally expensive, so employ overlay strategy:



Tracker | *Conceptual Design*

	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	$25\mu m \times 25\mu m$	$50\mu m \times 1mm$	$50\mu m \times 10mm$
Sensor Thickness	$50\mu m$	$100\mu mm$	$100\mu mm$
Time Resolution	30ps	60ps	60ps
Spatial Resolution	$5\mu m \times 5\mu m$	$7\mu m \times 90\mu m$	$7\mu m \times 90\mu m$

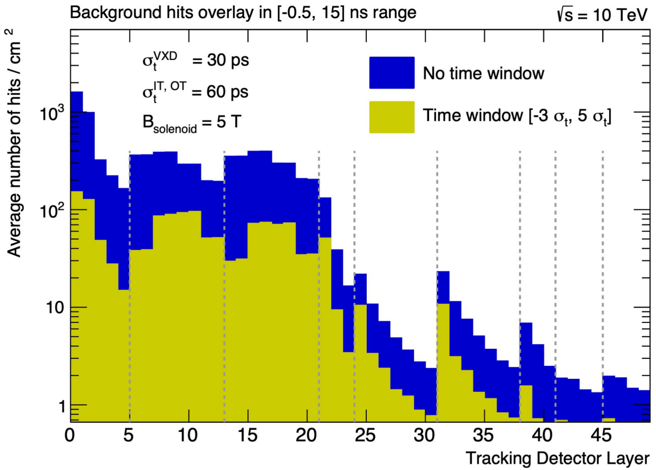
- ➔ **3 TeV design**: doublet layers in vertex det. to produce stubs
- ➔ **10 TeV design**: some doublet layers may not be needed
  - ◆ Removed all but one doublet layer in vertex detector
  - ◆ Tracking based on ACTS library led to significant improvements, found many doublet layers redundant
  - ◆ Additional considerations:
    - Higher B-field → fewer avg. hits per BIB particle
    - Fewer layers: less material and power

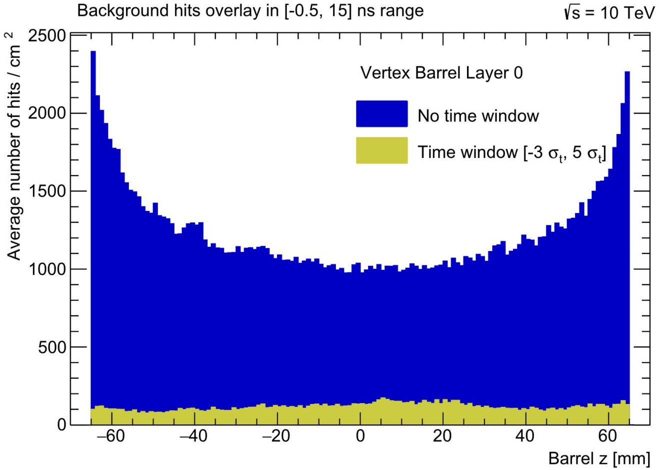


Tracker | *BIB Hit Densities*

F. Meloni

- ➔ Applying timing cuts significantly reduces BIB:
  - ◆ **Broad time window → [-0.5, 15] ns**
  - ◆ **Narrow time window → [-3 σ_t, 5 σ_t]**
  - ◆ With narrow time window, BIB hit densities ~flat in barrel
  - ◆ Sub-100 ps timing resolution critical to reduce hit occupancy in vertex layers
- ➔ Hit density ~lower than at 1.5 TeV
- ➔ Results here highly dependent on accelerator lattice and nozzle designs
- ➔ **Ongoing work**: investigate effect of incoherent pairs, which likely leads to additional particle flux (see F. Meloni's talk today)





Tracker | *Reconstruction Performance*

L. Rozanov

Samples

- ➔ Use single muon gun samples to assess tracking performance across a range of particle θ and p_T O(GeV – TeV)
- ➔ Tight track cleaning selection: p_T > 1 GeV, $|d_0|$ < 0.1 mm, N_{hits} > 5

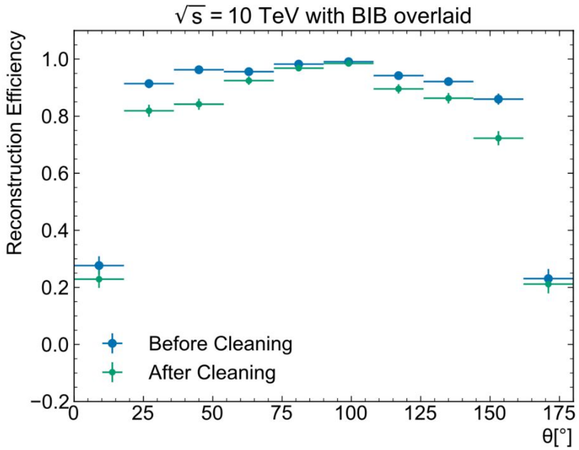
Reconstruction Efficiency

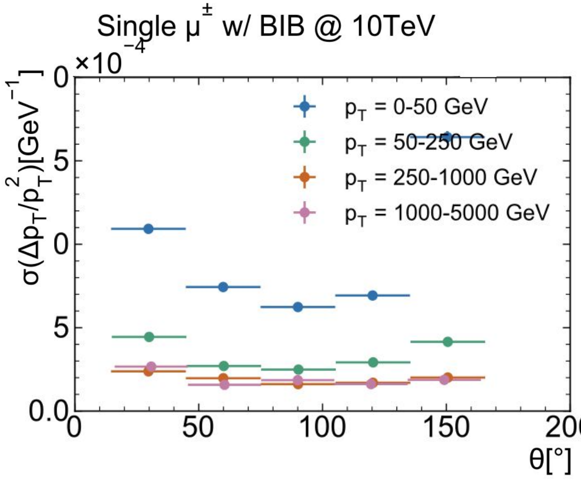
- ➔ Approx. flat as a function of p_T
- ➔ Lower efficiencies in more forward regions. With the addition of BIB:
  - ◆ Barrel – minimal drop in reco efficiency (~3.5%)
  - ◆ Endcap – moderate drop in reco efficiency (~20%) → ***future work to improve***

Track Parameter Resolutions

- ➔ Track p_T resolution better at higher pT and centrally
- ➔ Track d_0 resolution ~3-5 μm with BIB, stable as a function of pT and θ

Tracking performance very good, especially in the barrel



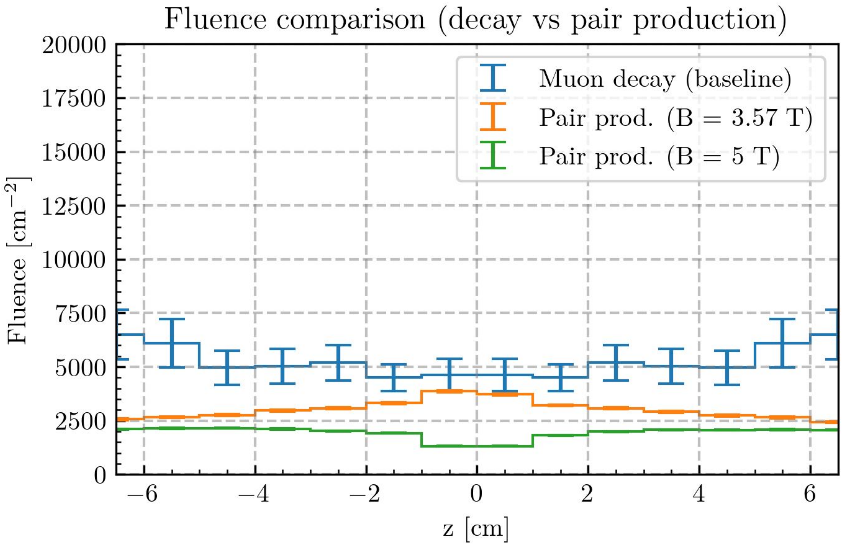


Solenoid | *Conceptual Design and Impact on Fluence*

D. Calzolari

Subsystem	Region	R dimensions [cm]	|Z| dimensions [cm]	Material
Solenoid	Barrel	150.0 – 185.7	230.7	Al

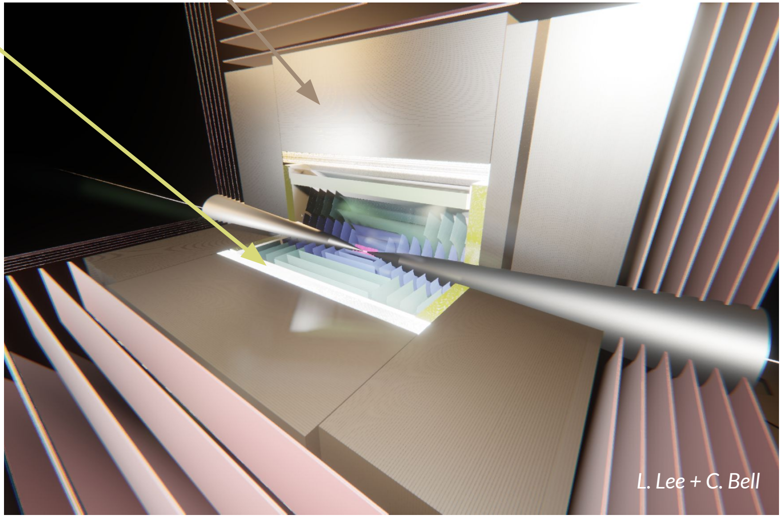
- ➔ **3 TeV design**: 3.57 T, outside calorimeters ("CMS-like")
- ➔ **10 TeV design**: 5 T, inside calorimeters ("ATLAS-like")
  - ◆ Higher solenoid B-field significantly reduces fluence (e+/e- results compared here)
  - ◆ BIB shielding for calorimeters
    - Adds ~265 mm of aluminum and thinner steel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



Calorimeters | *Conceptual Design*

	ECAL	HCAL
Cell type	Silicon - Tungsten	Iron - Scintillator
Cell Size	5.1mm × 5.1mm	30.0mm × 30.0mm
Sensor Thickness	0.5mm	3.0mm
Absorber Thickness	2.2mm	20.0mm
Number of layers	50	100

- ➔ **3 TeV design**: 40 layers (ECAL) and 60 layers (HCAL)
- ➔ **10 TeV design**: 50 layers (ECAL) and 75 layers (HCAL)
  - ECAL energy resolution target: 10% /√E
  - HCAL energy resolution target: 35% /√E

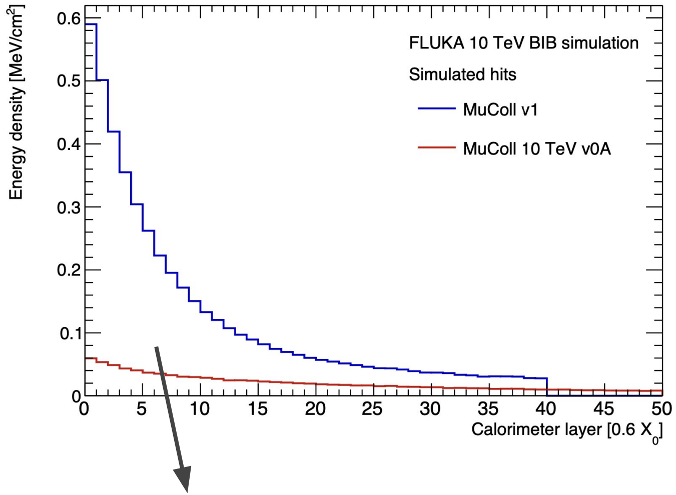


Calorimeters | *BIB Energy Densities*

F. Meloni

Energy Density of BIB in ECAL:

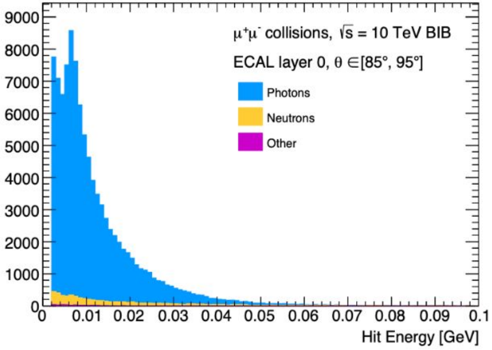
~3-10x lower than 1.5 TeV due to solenoid shielding

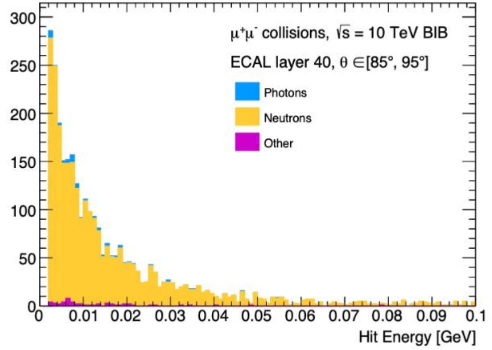


BIB in the ECAL mostly due to photons and neutrons

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

Calorimeters | *Photon Reconstruction*

Samples

- ➔ Single photon gun samples across a range of particle θ and p_T O(1 – 100 GeV)

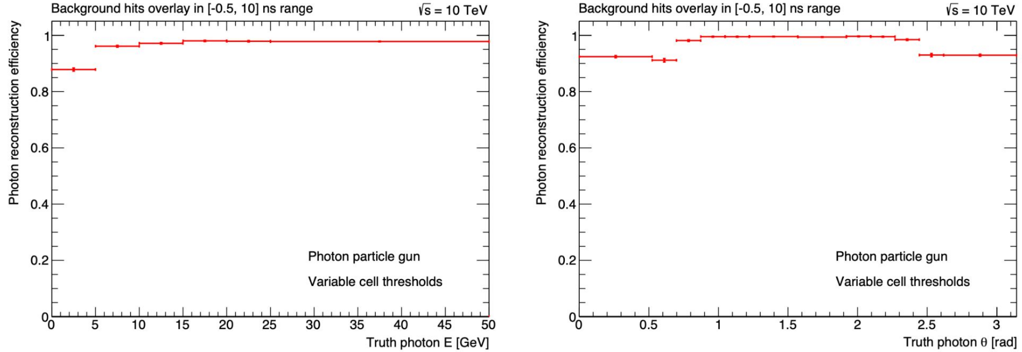
Reconstruction Efficiency

- ➔ Variable cell thresholds (in θ, depth) lead to ~100% efficiencies for photons in the barrel and with E > 15 GeV
- ➔ Efficiency still good (~90%) in the endcaps and at lower energies

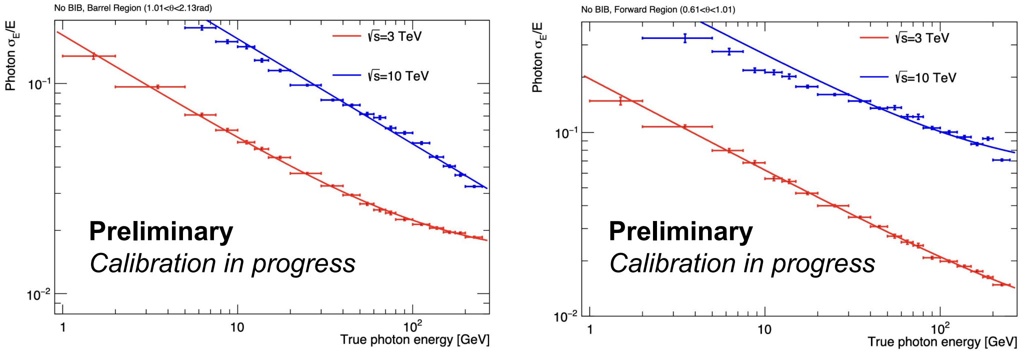
Energy Resolution – In Progress

- ➔ ECAL calibration following recent geometry update in progress; expect photon energy resolutions of **10 TeV** detector to be more comparable to those of **3 TeV**

Reconstruction Efficiency



Energy Resolution

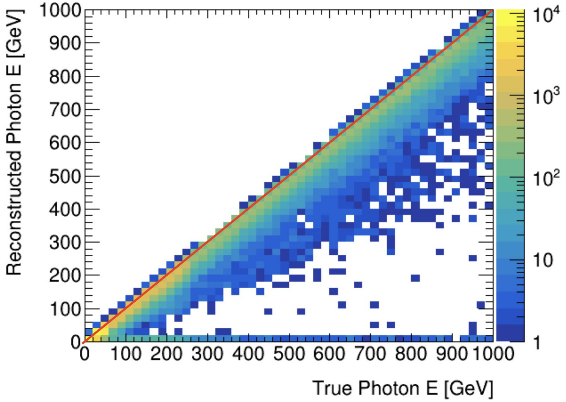


Calorimeters | *ECAL Calibration*

T. Holmes, R. Powers

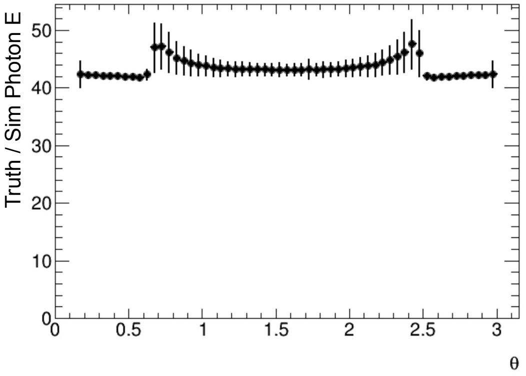
Summary of Issue:

- ➔ Updated detector geometry (more accurate) → increased material added to the ECAL barrel layers
- ➔ Observe strong eta-dependence in ECAL energy response, with energies underestimated
- ➔ Updated calibration needed



Calibration Studies:

- ➔ Analytic correction (piecewise-function) as a function of theta:
  - ◆ Inclusive in energy – does not significantly improve E resolution
  - ◆ Exclusive in energy – poor fits for high energies (>450 GeV)
  - ◆ Studies ongoing



Calorimeters | *Neutron Reconstruction*

Samples

- ➔ Single neutron gun samples across a range of particle θ and p_T O(10 GeV – TeV)

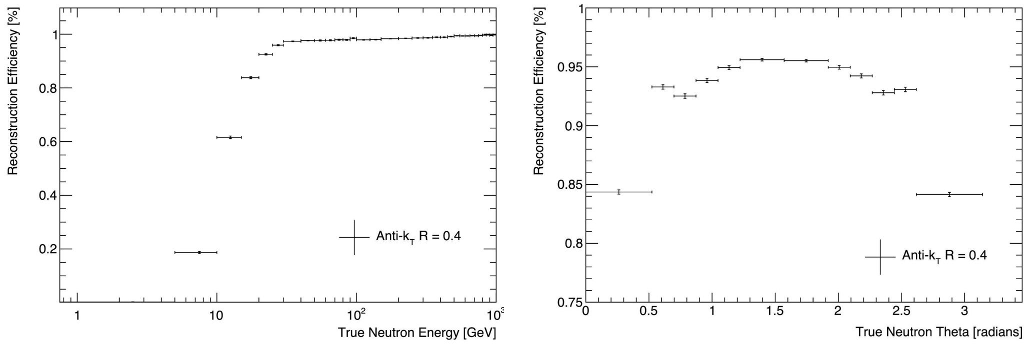
Reconstruction Efficiency

- ➔ Plateaus close to 1 for E > 30 GeV
- ➔ Better performance in the central (~95%) than forward region (~85%)

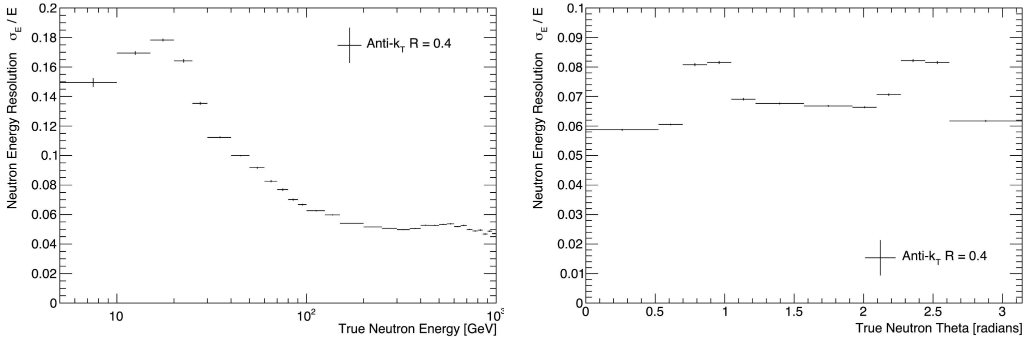
Energy Resolution

- ➔ Best at high energies, worst in the transition region

Reconstruction Efficiency



Energy Resolution



Conclusions + Outlook

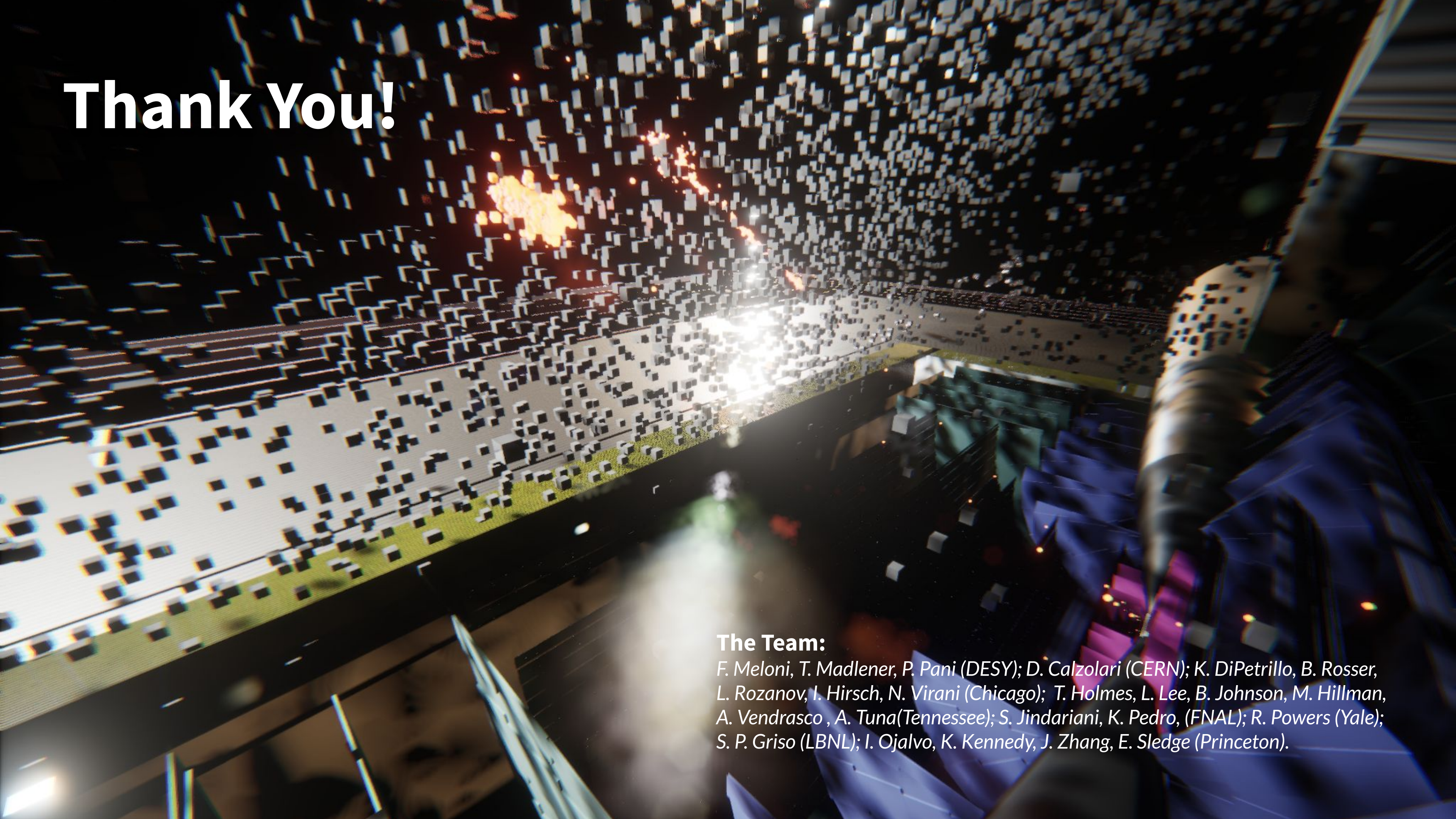
Conclusions

- ➔ Progress towards a detector concept for a 10 TeV muon collider
  - ◆ Started from a preliminary design concept a little over a year ago
- ➔ Excellent tracking performance even with BIB
- ➔ Calorimetry studies show promising results, but more work needed

Outlook

- ➔ Ongoing and future studies include:
  - ◆ Detector-level: ECAL calibration, endcap & nozzle optimization
  - ◆ Calorimetry performance with BIB, impact of solenoid shielding
  - ◆ Physics studies: more complex objects, test benchmarks

Thank You!



The Team:

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Backup | *Existing 3 TeV Detector Design*

hadronic calorimeter

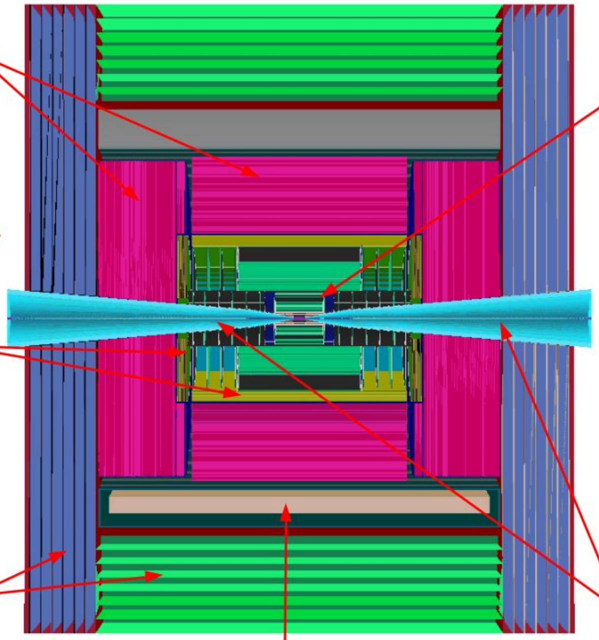
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

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.



superconducting solenoid (3.57T)

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

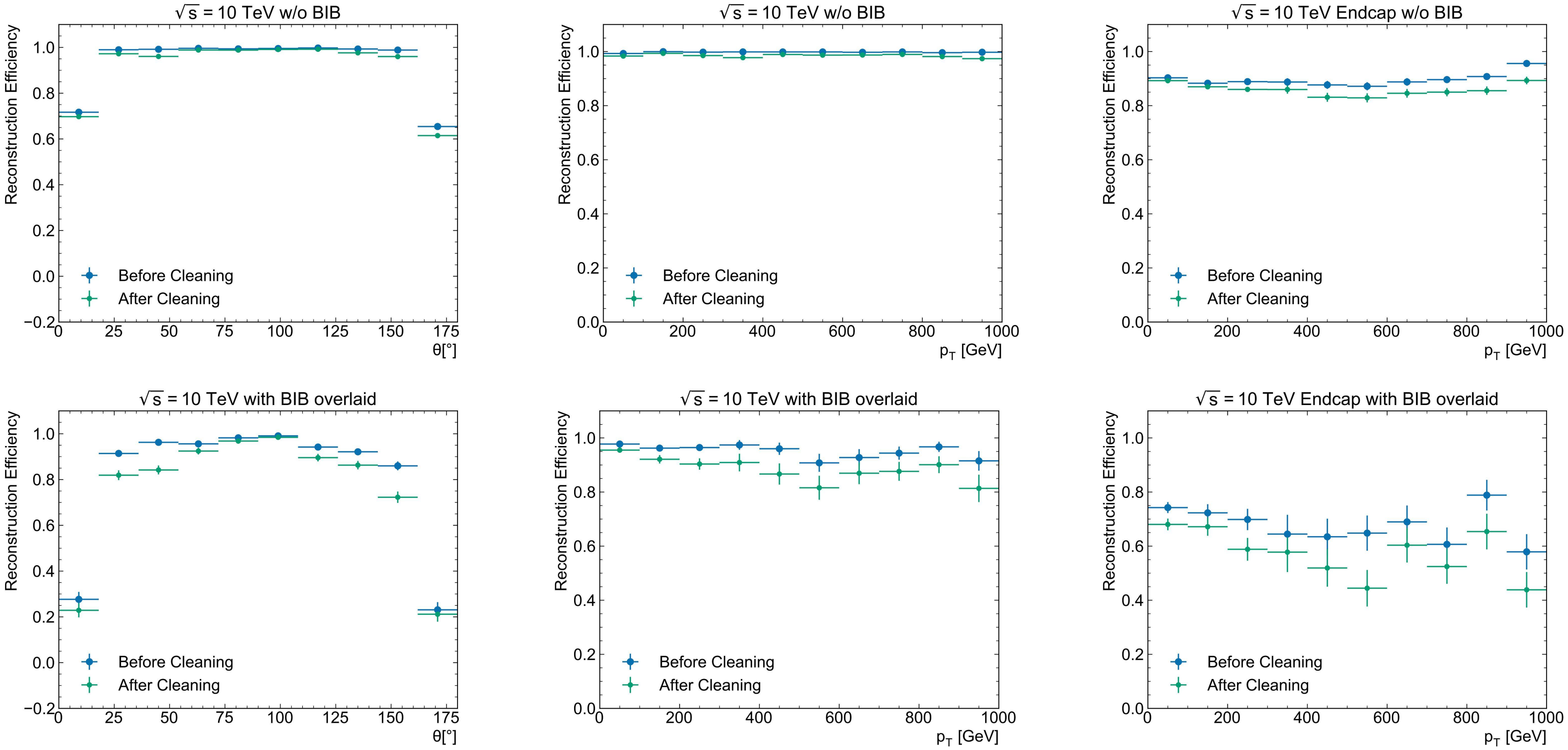
- Tungsten cones + borated polyethylene cladding.

Backup | *10 TeV Layout Table*

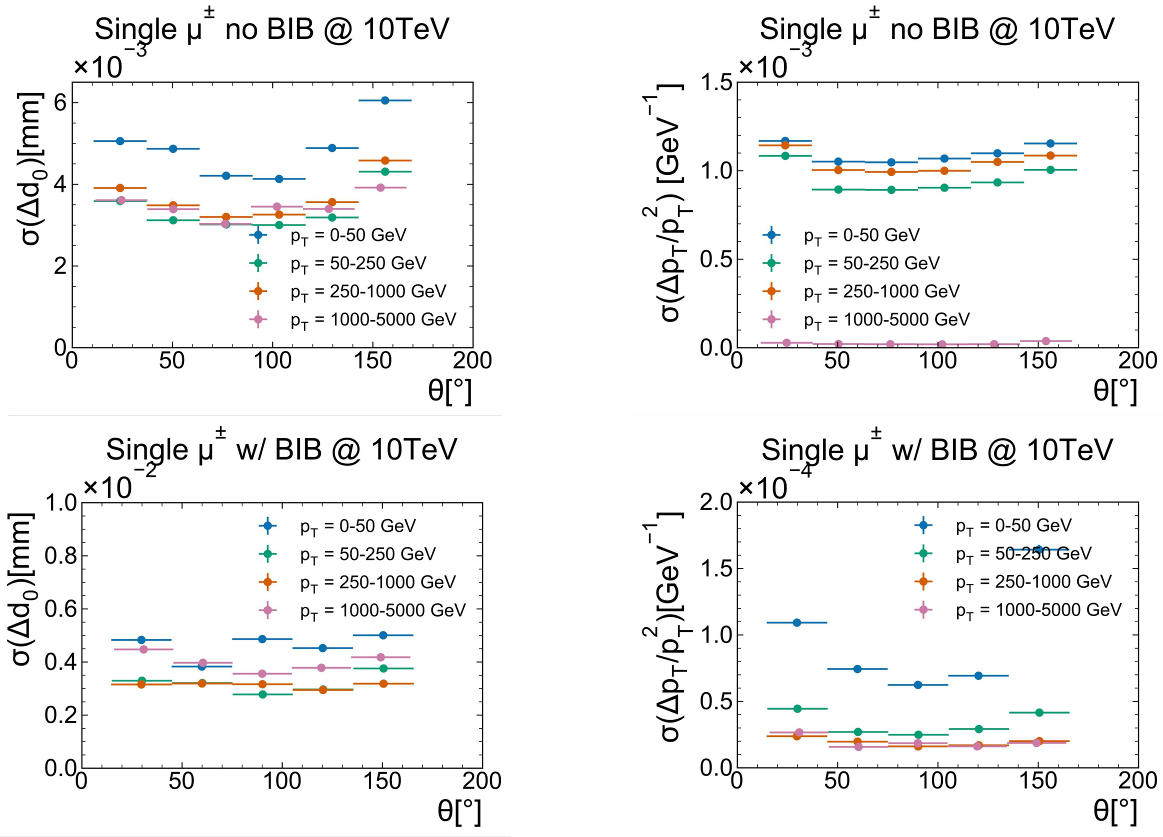
Subsystem	Region	R dimensions [cm]	|Z| dimensions [cm]	Material
Vertex Detector	Barrel	3.0 – 10.4	65.0	Si
	Endcap	2.5 – 11.2	8.0 – 28.2	Si
Inner Tracker	Barrel	12.7 – 55.4	48.2 – 69.2	Si
	Endcap	40.5 – 55.5	52.4 – 219.0	Si
Outer Tracker	Barrel	81.9 – 148.6	124.9	Si
	Endcap	61.8 – 143.0	131.0 – 219.0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

L. Rozanov

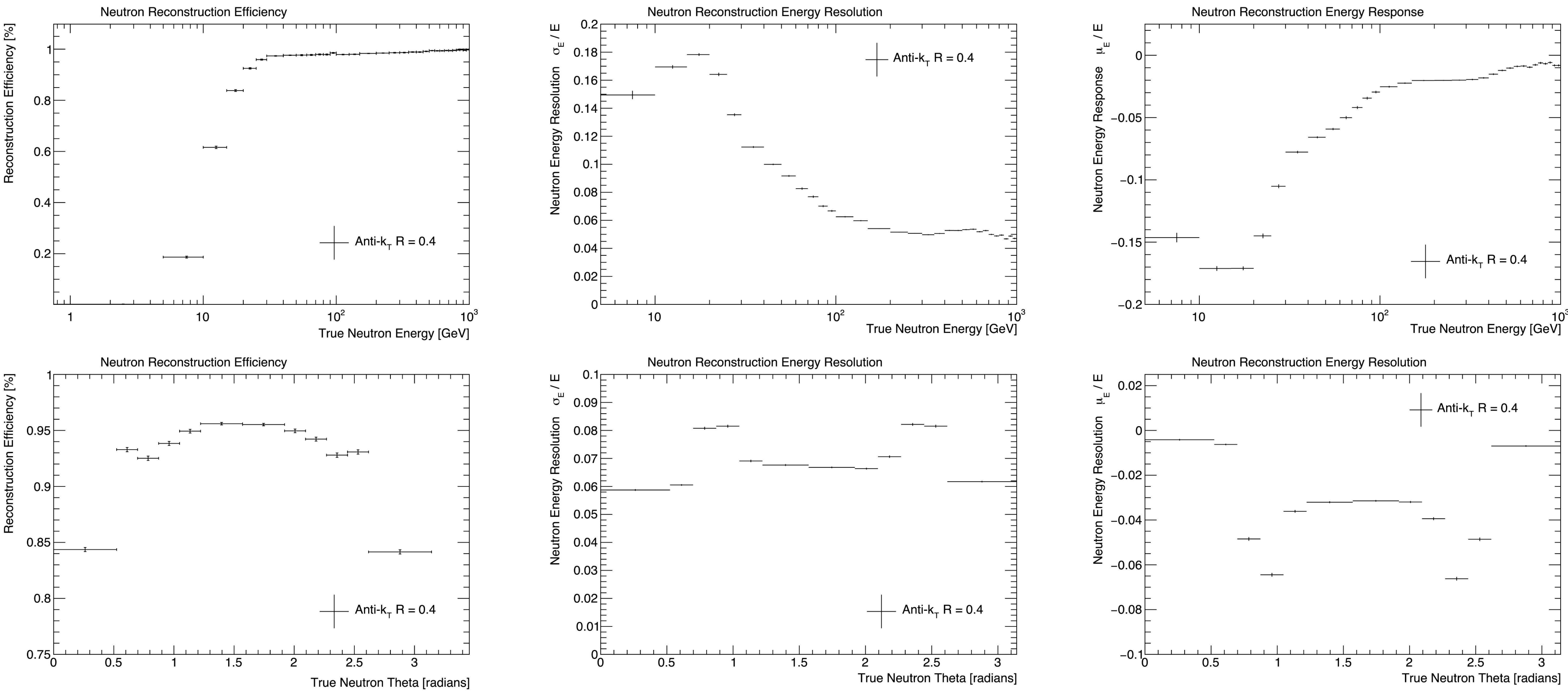
Backup | *Track Reconstruction Efficiency*



Backup | *Track Reconstruction Resolutions*

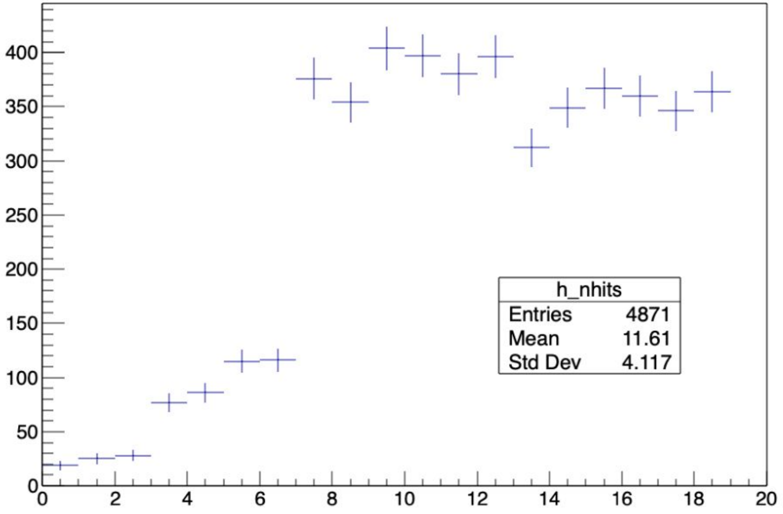


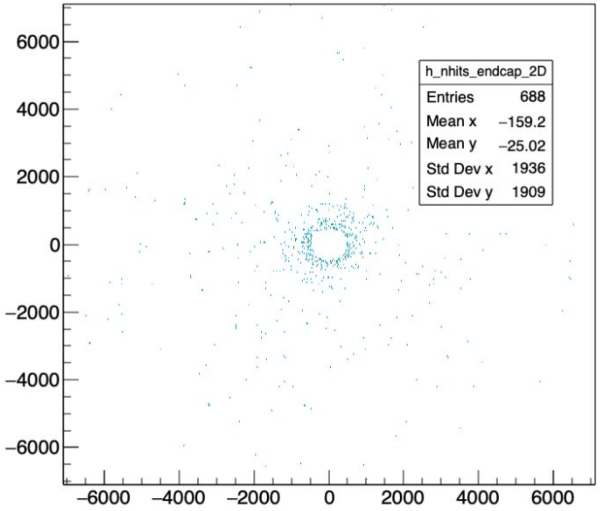
Backup | *Neutron Reconstruction*



Backup | *Muon System Results*

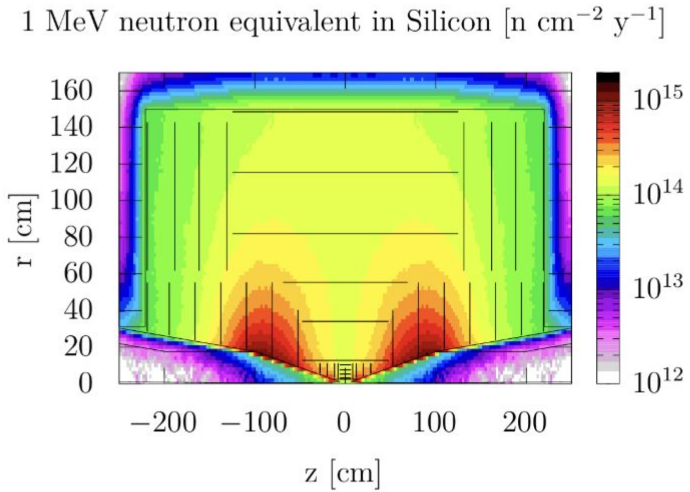
- ➔ Muon detector should be the least affected by beam induced background:
  - In general, BIB absorbed by solenoid and by calorimeters, so not a problem here.
  - Potentially some issues depending on nozzle geometry in far forward region.
- ➔ Initial look at muon system occupancy: higher in endcap layers,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

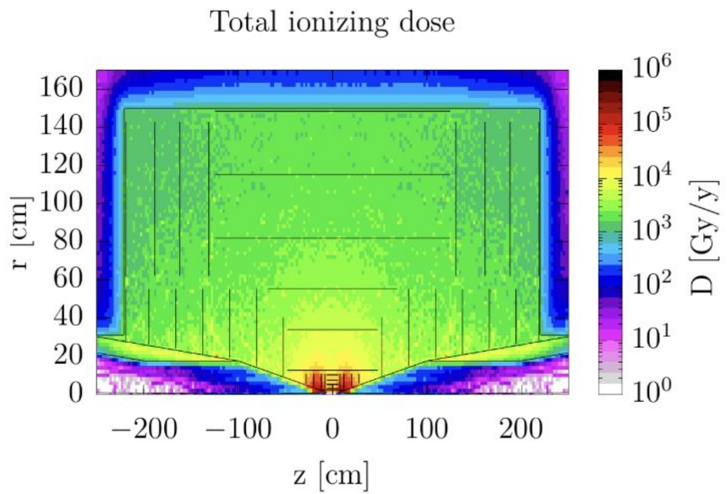




Backup | *Radiation Damage*

➔ 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}

D. Calzolari

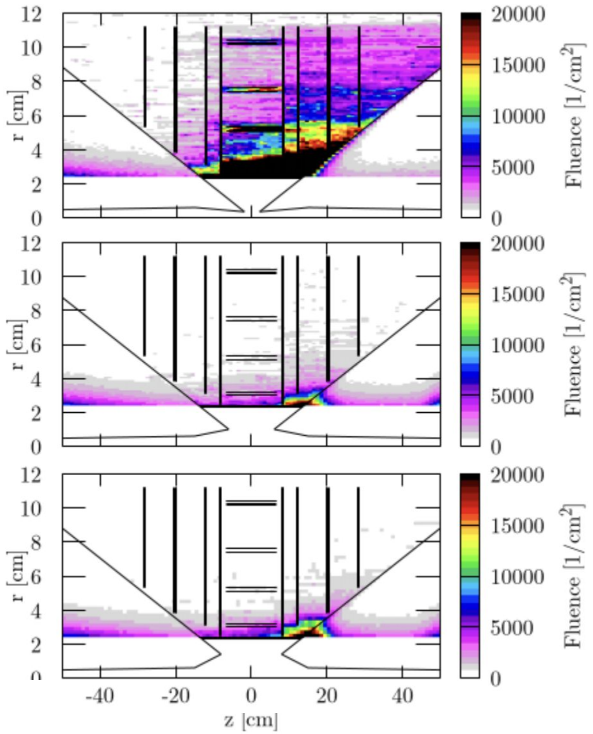
Backup | *Nozzle Configuration Optimization Studies*

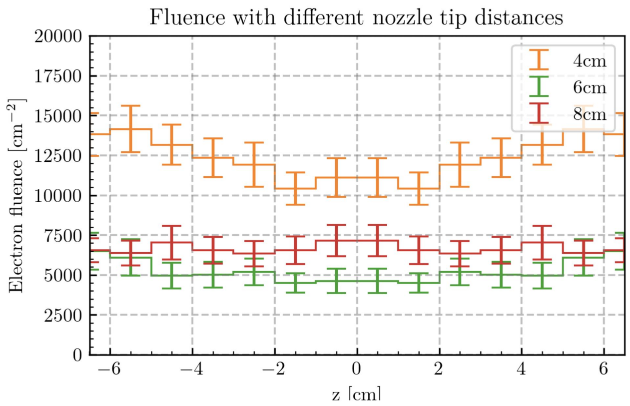
Simulate BIB fluence with nozzle tip at different distances

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!