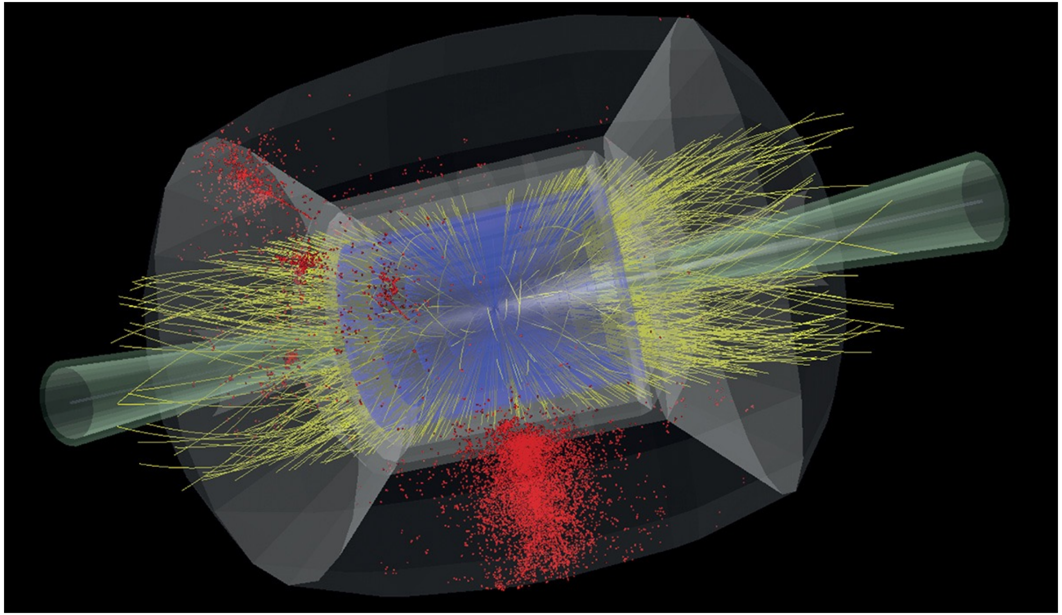


Muon Collider Detector

Sergo Jindariani (Fermilab)

IMCC Annual Meeting

October 2022

On behalf of the Muon Collider Physics and Detector and MDI Groups, with input from Snowmass

Thank you to all of the contributors!

Detector Parallel Sessions

Wed morning - MDI

Machine-induced background studies for 1…	*…cesco Collamati*	
40/S2-D01 - Salle Dirac, CERN		10:50 - 11:10
IR optics design for the 10 TeV Muon Collider	*Kyriacos Skoufaris*	
40/S2-D01 - Salle Dirac, CERN		11:10 - 11:30
Machine-induced background studies for the 10 TeV Muon Collider	*Daniele Calzolari*	
40/S2-D01 - Salle Dirac, CERN		11:30 - 11:50
How to use BIB data as input for the detector design	*Nazar Bartosik*	
40/S2-D01 - Salle Dirac, CERN		11:50 - 12:10
Magnetic field configurations for the detector	*John Hauptman*	
40/S2-D01 - Salle Dirac, CERN		12:10 - 12:30

Wed afternoon - reconstruction

	…rizka	
		…4:25
	…Aime'	
40/S2-D01 - Salle Dirac, CERN		14:25 - 14:50
Electrons and photons reconstruction	*Massimo Casarsa*	
40/S2-D01 - Salle Dirac, CERN		14:50 - 15:15
Jets reconstruction and b-tagging: leasson learned and new strategies	*Lorenzo Sestini*	
40/S2-D01 - Salle Dirac, CERN		15:15 - 15:55
Coffee Break		
CERN		16:00 - 16:20
Physics results with full sim and comparison with FastSim	*Luca Giambastiani*	
40/S2-D01 - Salle Dirac, CERN		16:20 - 16:45
Future collider framework (TBA)		
40/S2-D01 - Salle Dirac, CERN		16:45 - 17:10
Software status and future developments	*Alessio Gianelle et al.*	
40/S2-D01 - Salle Dirac, CERN		17:10 - 17:35
Simulated sample, shared resources, FastSim update (TBA)		
40/S2-D01 - Salle Dirac, CERN		17:35 - 17:55
BIB usage	*Nazar Bartosik*	
40/S2-D01 - Salle Dirac, CERN		17:55 - 18:15
Discussion		
40/S2-D01 - Salle Dirac, CERN		18:15 - 18:30

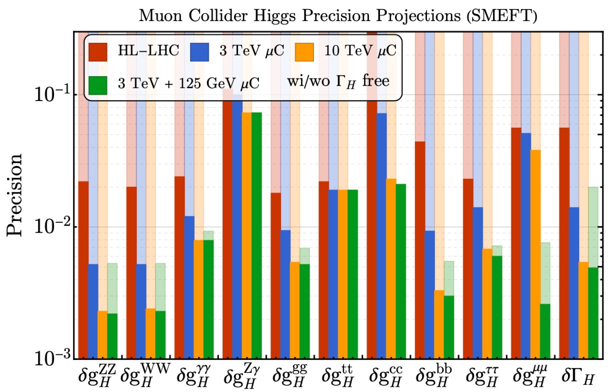
Thu morning – detector R&D

R&D studies on tracking detector	*Nicolo Cartiglia*	
42/3-032, CERN		09:00 - 09:15
R&D studies on calorimeter detector	*ivano sarra*	
42/3-032, CERN		09:20 - 09:35
R&D studies on muon detector	*Ilaria Vai*	
42/3-032, CERN		09:40 - 09:55
Physics opportunities with a muon "beam dump"	*Cari Cesarotti*	
42/3-032, CERN		10:00 - 10:30

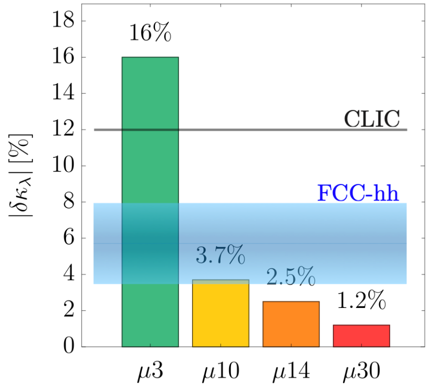
Thu afternoon – towards 10 TeV

Theory: status, needs and plans	*Prof. Fabio Maltoni*	
42/3-032, CERN		14:00 - 14:25
Toward 10 TeV detector studies	*Laura Buonincontri*	
42/3-032, CERN		14:25 - 14:45
Photon reconstruction	*Federico Nardi*	
42/3-032, CERN		14:45 - 15:05
Discussion on physics objects reconstruction in the forward region		
42/3-032, CERN		15:05 - 15:20
Discussion on needs to go to high energy		
42/3-032, CERN		15:20 - 15:35
LFUV at muon collider	*Admir Greljo*	
42/3-032, CERN		15:35 - 16:00

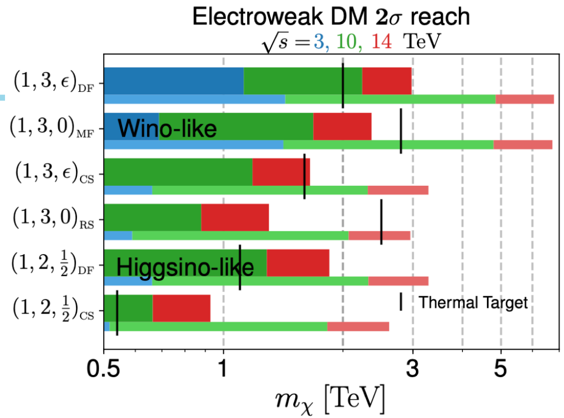
Muon Collider Physics



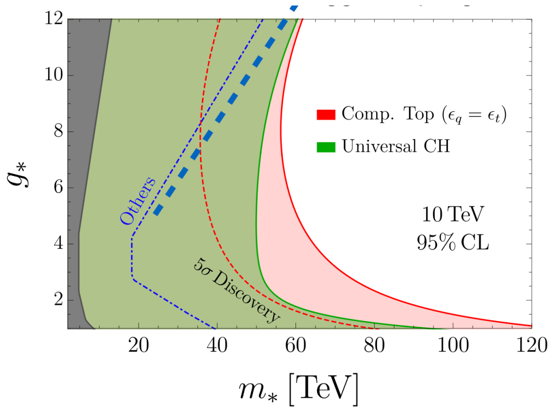
Order of magnitude in Higgs precision wrt HL-LHC and can directly probe *the scale implied in same machine!*



Self-coupling: at 3 TeV better than LHC. At 10 TeV similar or better than FCC-hh.



Covers *simplest* WIMP candidates hard or impossible with next gen DM direct detection



Unprecedented reach for strongly motivated BSM scenarios

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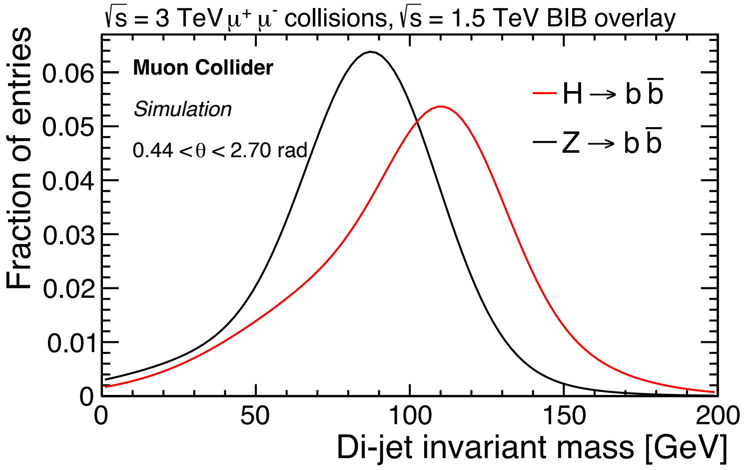
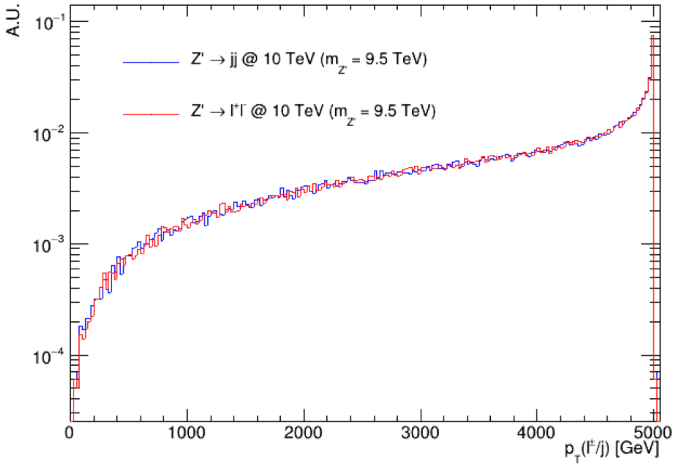
Muon Collider Detector Requirements

Muon Collider Physics program imposes stringent requirement on data reconstruction:

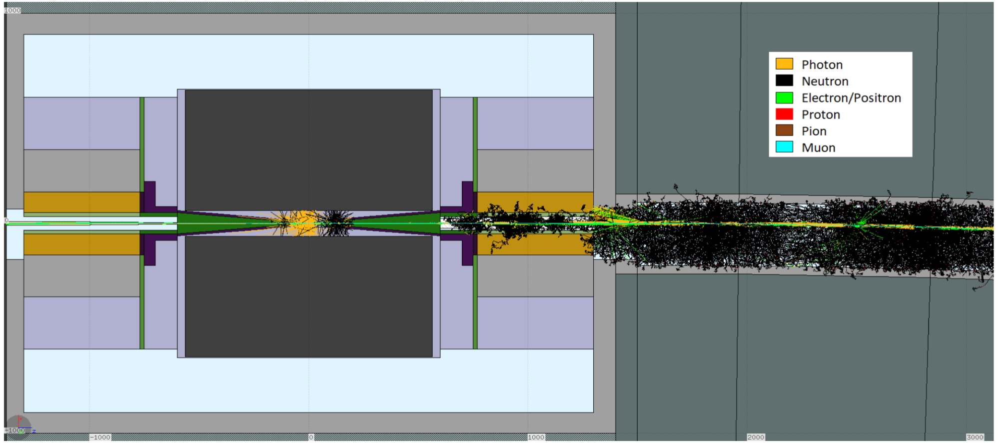
- High performance tracking for Particle Flow reconstruction
- + Good calorimetric energy resolution → need to separate Z from Higgs
- Performant heavy flavor tagging (e.g. H→bb/cc)
- Ability to reconstruct high energy leptons/jets for BSM physics
- Maintain acceptance/efficiency for unconventional signatures (LLP, HSCP, etc)

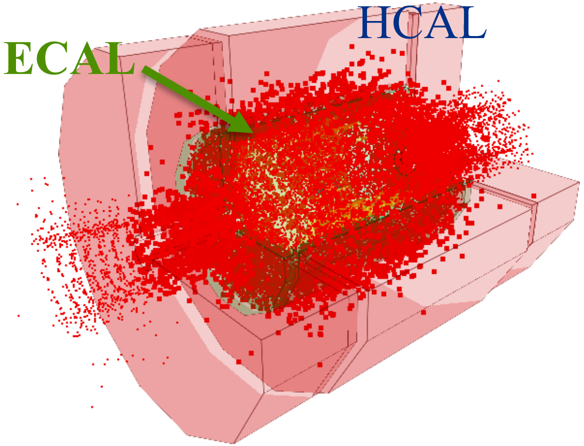




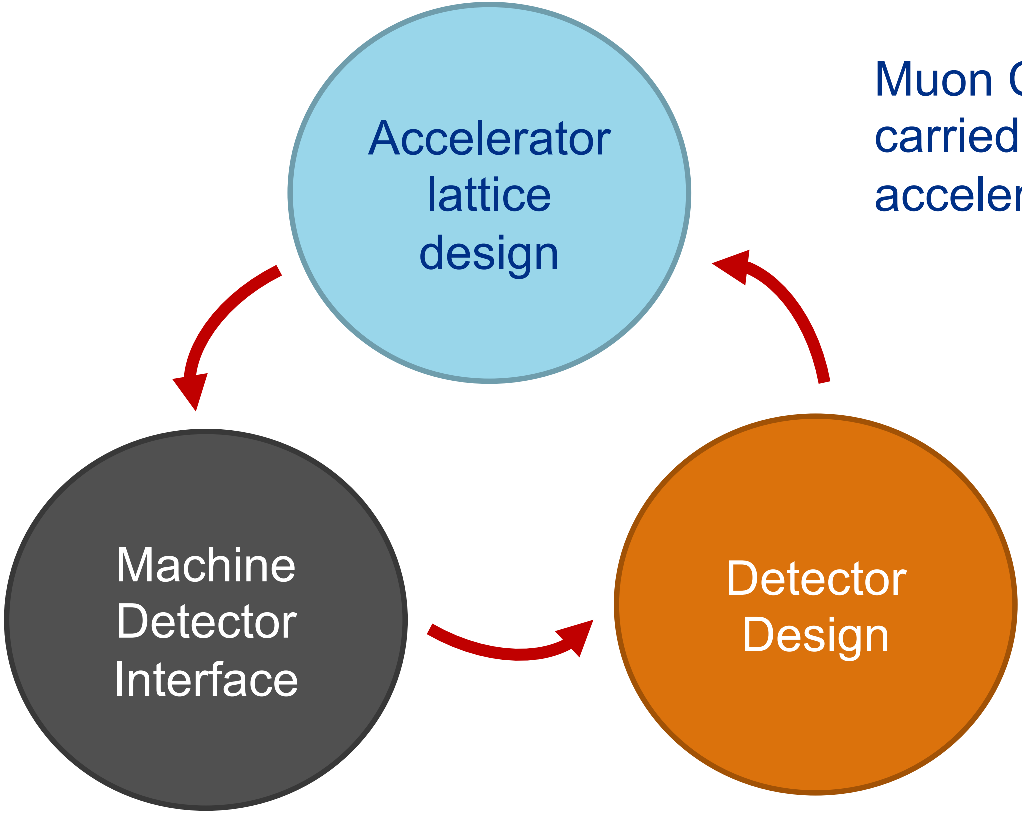
Beam Induced Background

- Beam background is one of the unique features/challenges of Muon Colliders
- Main Source of Beam Induced Background (BIB) are showers produced by electrons originating in beam muon decays
- The challenge is to separate collision particles from the BIB
- Detector environment and occupancy can be harsh





Machine Detector Interface



Muon Collider detector design has to be carried out in close collaboration with accelerator and MDI designers!

COM Energy	IP design	MDI	Detector
3.0 TeV	YES	Using 1.5 TeV	YES
10 TeV	In progress	In progress	Initial studies w/o BIB

Current Detector Configuration

Adopted from CLIC with some modifications
~10^0 acceptance limitation due to the nozzles

hadronic calorimeter

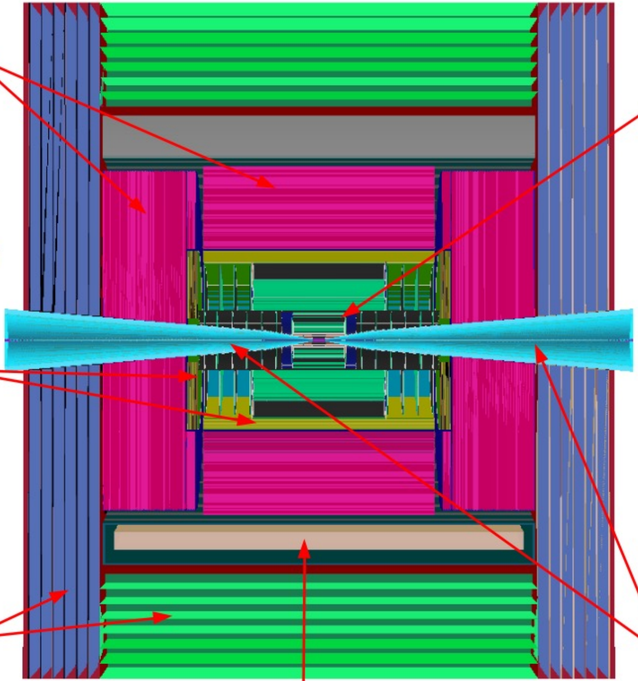
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

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)

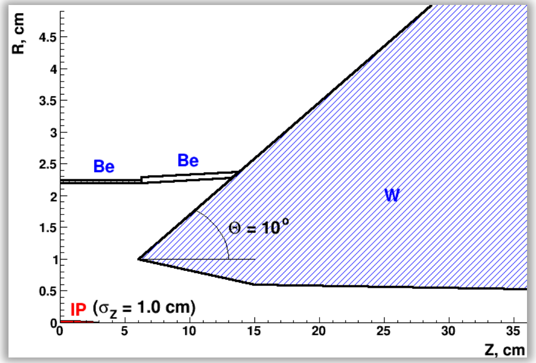
tracking system

- 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.

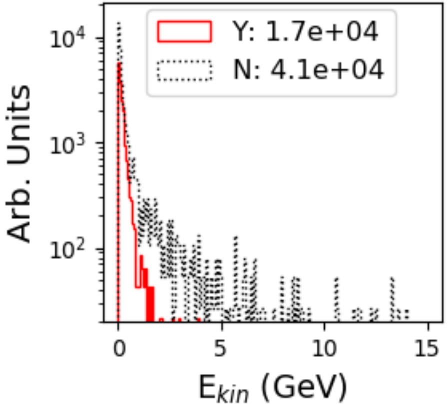
BIB properties



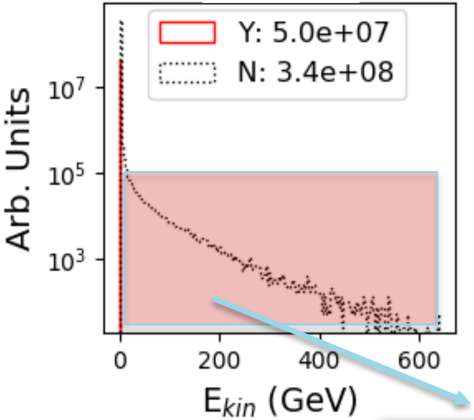
Di Benedetto et al., Journal of Instrumentation13(2018)

F. Collamati et al. 2021 JINST 16 P11009

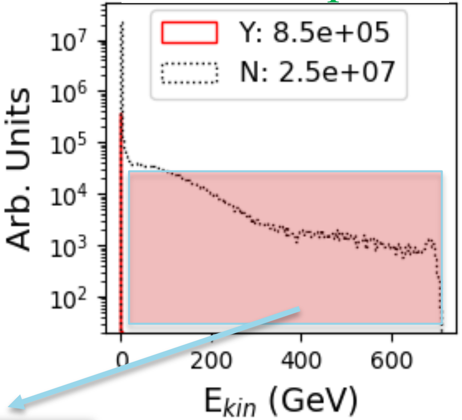
charged hadrons



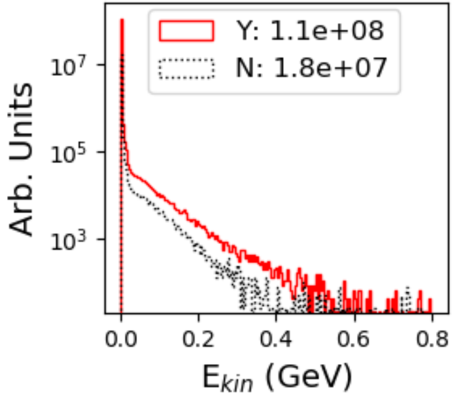
Photons



electrons/positrons



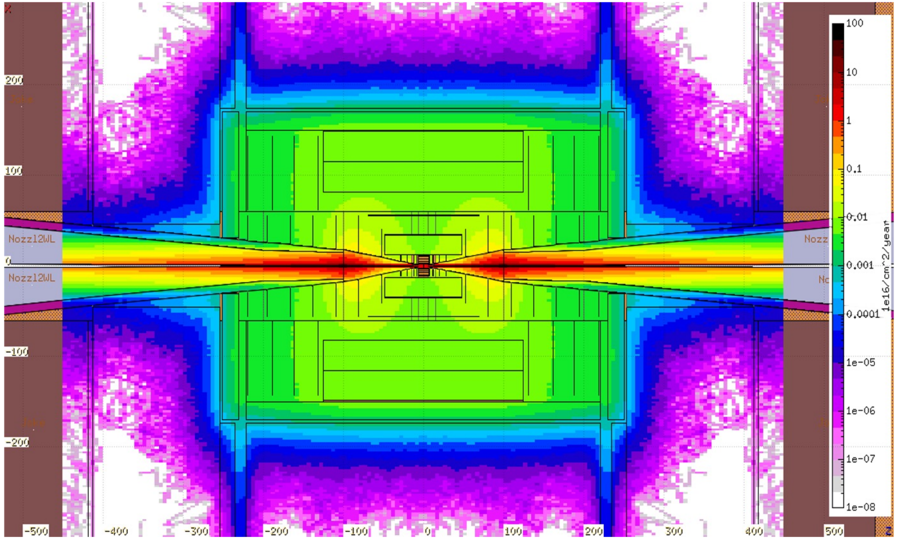
neutrons



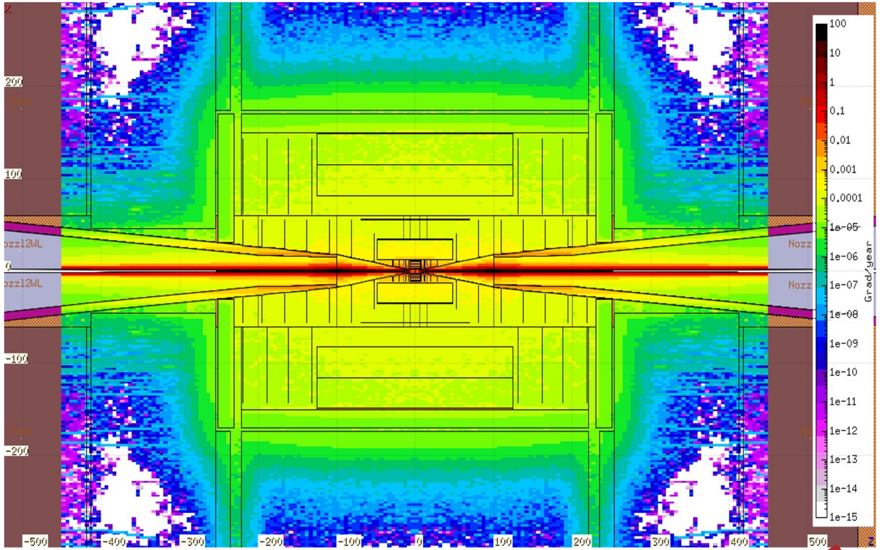
absorbed

Radiation Levels

1-MeV-neq fluence for one year of operation (200 days)



Total Ionizing Dose for one year of operation (200 days)



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

Much lower than FCC-hh

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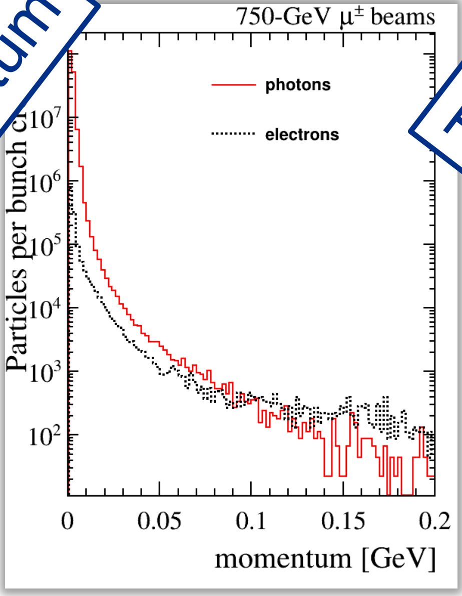
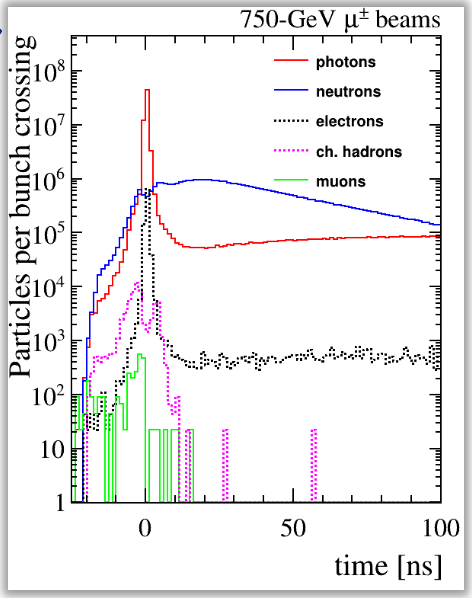
BIB properties

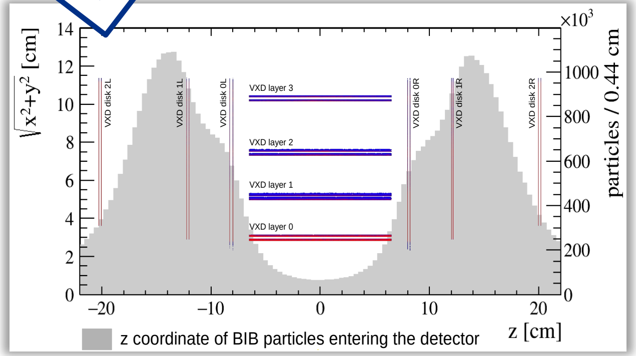
Momentum



Timing



Direction



- Low momentum particles
- Partially out-of-time with respect to the bunch crossing
- Often, not pointing to the interaction region

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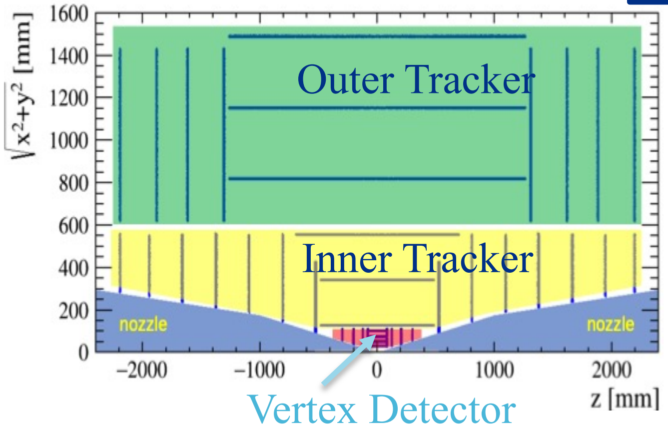
Tracker

- Goal: bring occupancy to <1% level. Pixel size and timing requirements optimized to achieve this goal
- Hit density in inner layers approximately 2-5 times higher than at the LHC
- Other requirements are not unique: low mass/power, radiation tolerance, low noise
- Correlation between layers
- Cluster shape

Detector Layer	ITk Hit Density [mm^{-2}]	Muon Col. Hit Density [mm^{-2}]
Pixel Layer 0	0.643	3.68
Pixel Layer 1	0.22	0.51
Strip Layer 1	0.003	0.03



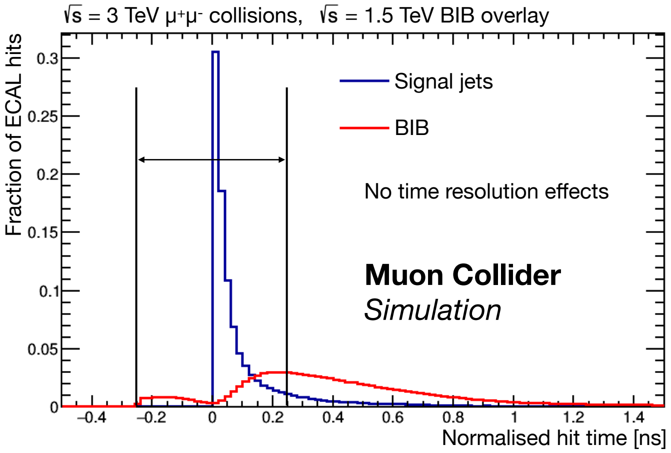
		cell size	sensor thickness	time resolution	spatial resolution	number of cells
VXD	B	25 µm × 25 µm pixels	50 µm	30 ps	5 µm × 5 µm	729M
	E	25 µm × 25 µm pixels	50 µm	30 ps	5 µm × 5 µm	462M
IT	B	50 µm × 1 mm macropixels	100 µm	60 ps	7 µm × 90 µm	164M
	E	50 µm × 1 mm macropixels	100 µm	60 ps	7 µm × 90 µm	127M
OT	B	50 µm × 10 mm microstrips	100 µm	60 ps	7 µm × 90 µm	117M
	E	50 µm × 10 mm microstrips	100 µm	60 ps	7 µm × 90 µm	56M

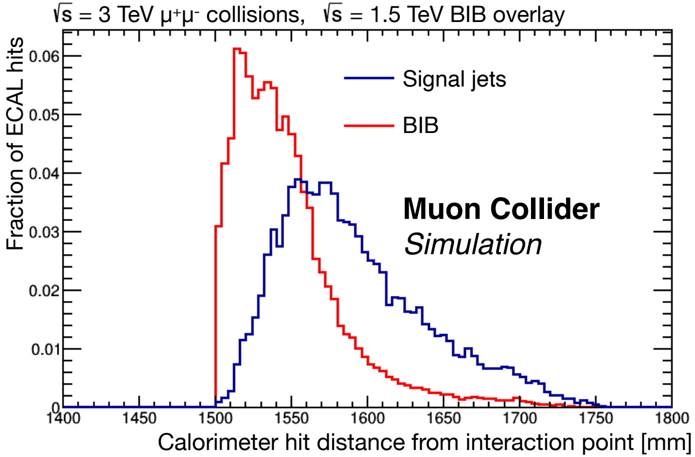
Calorimeters

- BIB dominated by neutrals: photons (96%) and neutrons (4%).
- Ambient energy about 50 GeV per unit area (~40 GeV in HL-LHC)

- high granularity
- precise hit time measurement O(100ps)
- longitudinal segmentation
- *good* energy resolution 10%/√E for photons and 35%/√E for jets or better

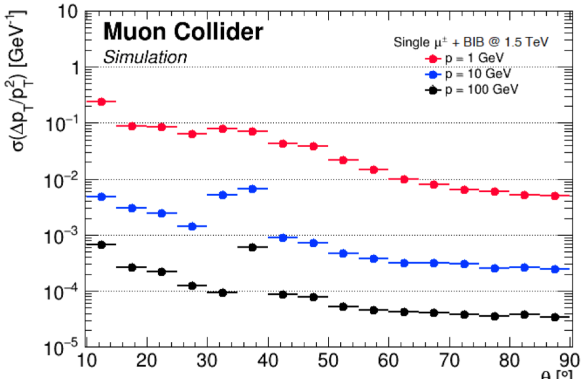
- Current Design:
  - ECAL: SiW with 22 X_0, 5x5 mm^2 pads
  - HCAL: Iron+Scintillator with 7.5λ
  - Study new options: Crilin, CalVision,…



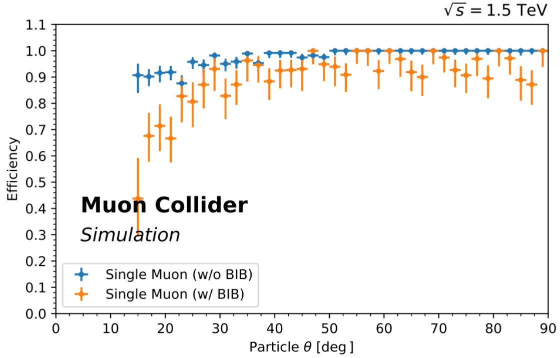


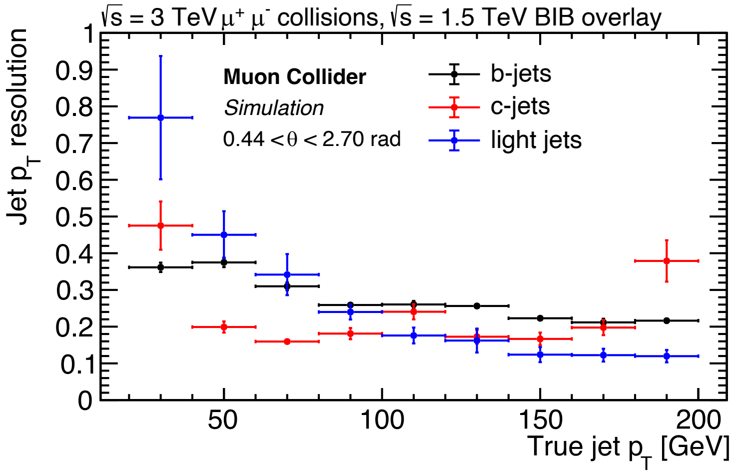
Reconstruction Performance Example

Preliminary



Transitioning from Conformal → CKF



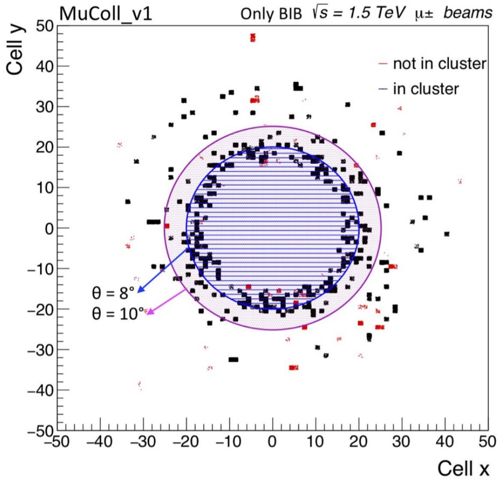


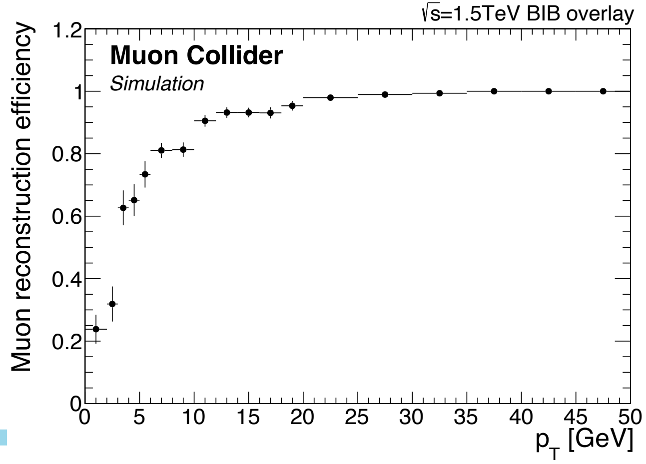
- LHC-level resolutions achieved
- Further improvements: better tracking, calo thresholds, fake jet removal

- Achieved performance specs in the barrel. Needs improvements next to the nozzle

Muon Detectors

- Muon system is the lest affected by the BIB
- Current design: gaseous detectors interleaved in an iron yoke
- Targets: 100 micron resolution and 1 ns timing
- High number of hits in the forward disks due to the BIB
  - Some technologies reaching rate limits
  - Some contain gas mixture which has a high Global Warming Potential
- New interesting technologies (MPGD, Picosec, mu-RWELL…)

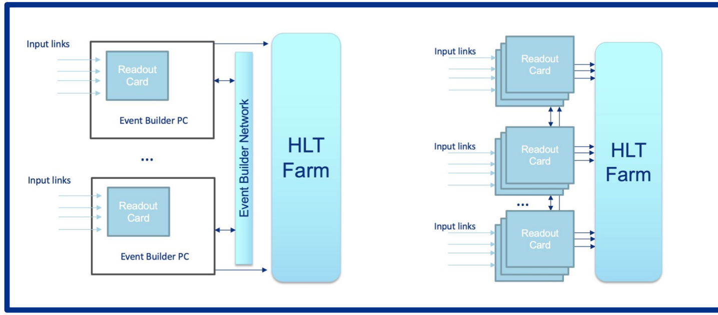




Readout/DAQ

- Key parameter - beam crossings every ~10 μs.
- Streaming approach: availability of the full event data → better trigger decision, easier maintenance, simplified design of the detector front-end...

	Hit	On-detector filtering	Number of Links (20 Gbps)	Data Rates
Tracker	32-bit	$t-t_0 < 1$ ns	~3,000	30 Tb/s
Calorimeter	20-bit	$t-t_0 < 0.3$ ns E>200 KeV	~3,000	30 Tb/s

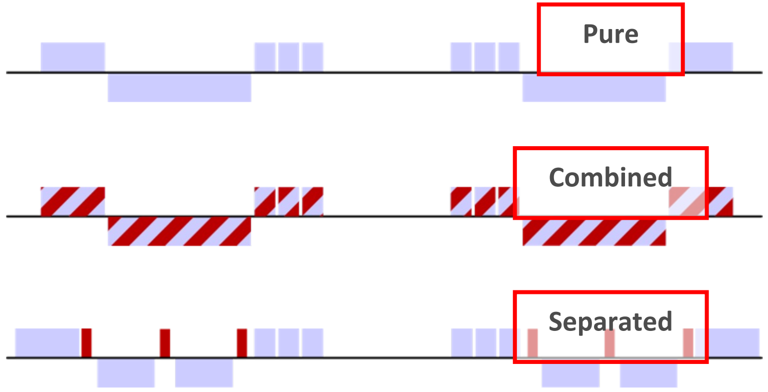


- Total data rate similar to HLT at HL-LHC ~ **streaming operation likely feasible**.
- Filtering based on event properties or event content

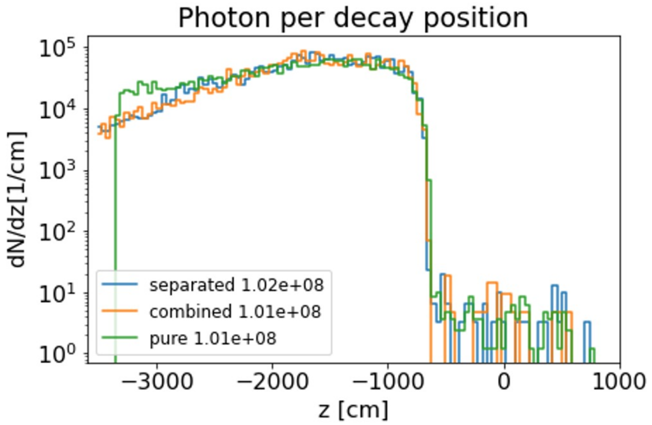
- High bandwidth and power efficient links, FPGA/GPU acceleration, advanced algorithms

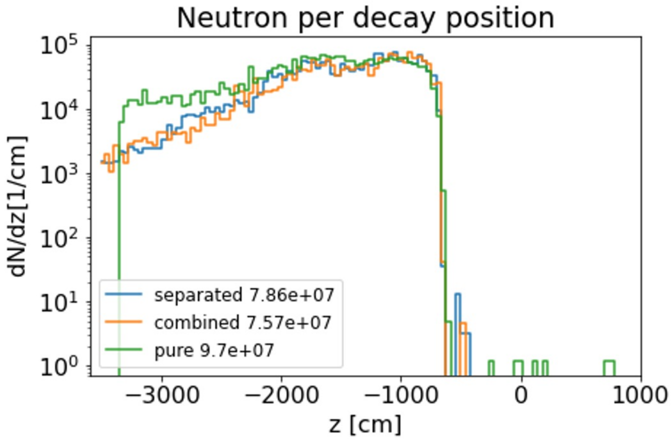
Towards 10 TeV Detector

Towards 10 TeV Lattice



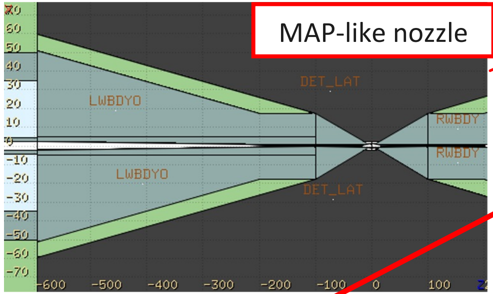
- Different final focus lattices have been investigated to understand the impact on the BIB.
- Having a dipolar contribution does not significantly reduce the overall BIB.
- The **contribution** of **different decay position** to the BIB for a positive muon beams is reported.

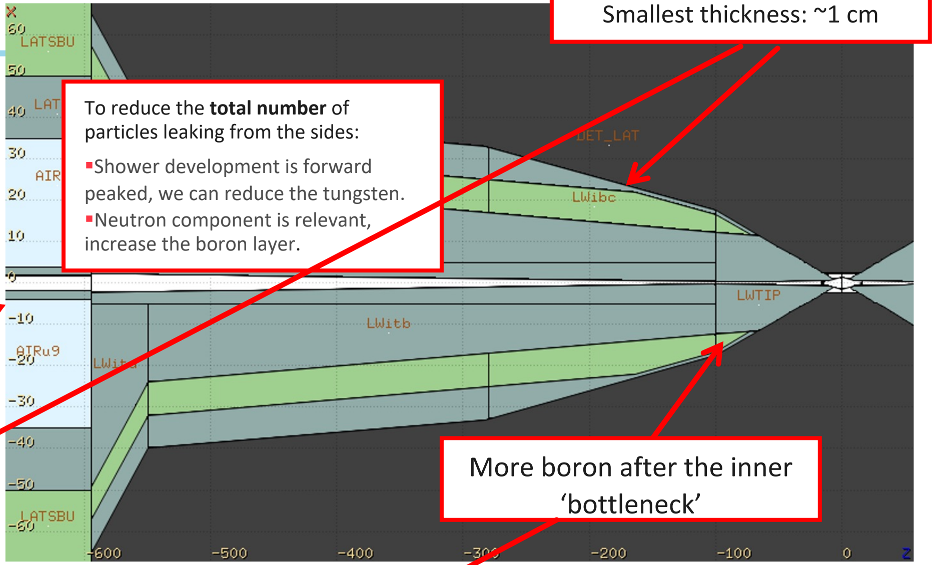


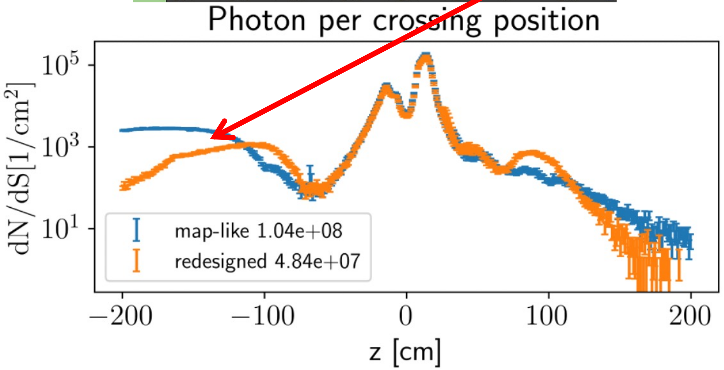


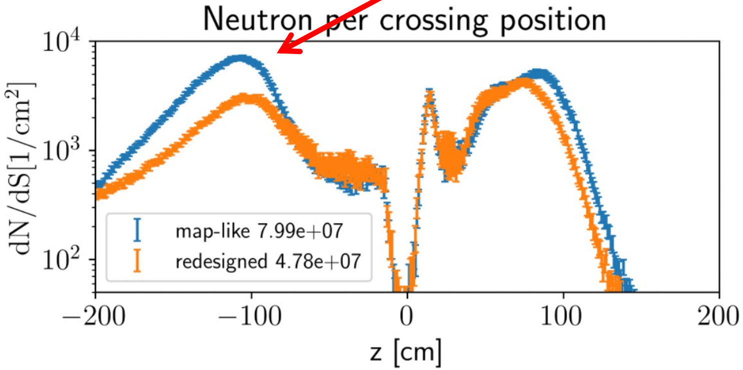
Towards 10 TeV Nozzle

- Considering the particles going in the detector area, a tentative **nozzle** geometry reshaping has been conducted based on the **1.5 TeV MAP nozzle**.
- From preliminary results, the possibility of reducing the BIB is **significant**.









BIB Evolution with Energy

Table 1: Multiplicities of different types of particles produced in a bunch crossing by the beam muon decays after the shielding structure, therefore arriving on the detector surface. In all cases, the MDI optimised for the centre-of-mass energy of 1.5 TeV is assumed.

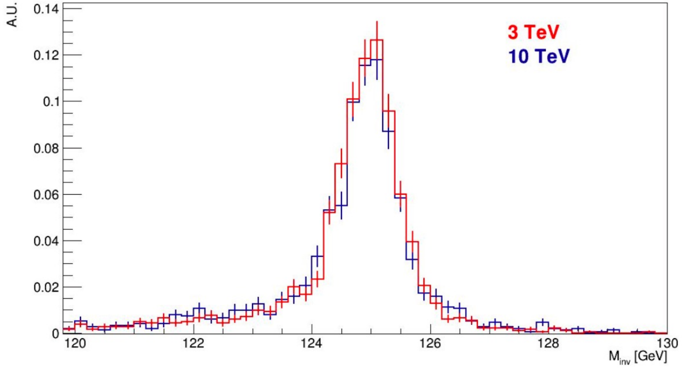
Monte Carlo simulator	MARS15	MARS15	FLUKA	FLUKA	FLUKA
Beam energy [GeV]	62.5	750	750	1500	5000
μ decay length [m]	$3.9 \cdot 10^5$	$46.7 \cdot 10^5$	$46.7 \cdot 10^5$	$93.5 \cdot 10^5$	$311.7 \cdot 10^5$
μ decay/m/bunch	$51.3 \cdot 10^5$	$4.3 \cdot 10^5$	$4.3 \cdot 10^5$	$2.1 \cdot 10^5$	$0.64 \cdot 10^5$
Photons ($E_\gamma > 0.1$ MeV)	$170 \cdot 10^6$	$86 \cdot 10^6$	$51 \cdot 10^6$	$70 \cdot 10^6$	$107 \cdot 10^6$
Neutrons ($E_n > 1$ MeV)	$65 \cdot 10^6$	$76 \cdot 10^6$	$110 \cdot 10^6$	$91 \cdot 10^6$	$101 \cdot 10^6$
Electrons & positrons ($E_{e^\pm} > 0.1$ MeV)	$1.3 \cdot 10^6$	$0.75 \cdot 10^6$	$0.86 \cdot 10^6$	$1.1 \cdot 10^6$	$0.92 \cdot 10^6$
Charged hadroms ($E_{h^\pm} > 0.1$ MeV)	$0.011 \cdot 10^6$	$0.032 \cdot 10^6$	$0.017 \cdot 10^6$	$0.020 \cdot 10^6$	$0.044 \cdot 10^6$
Muons ($E_{\mu^\pm} > 0.1$ MeV)	$0.0012 \cdot 10^6$	$0.0015 \cdot 10^6$	$0.0031 \cdot 10^6$	$0.0033 \cdot 10^6$	$0.0048 \cdot 10^6$

Approximately flat

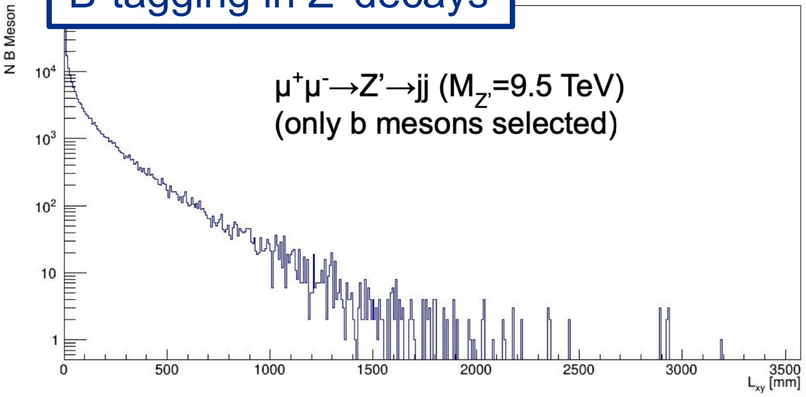
Early Detector Studies

Very preliminary!

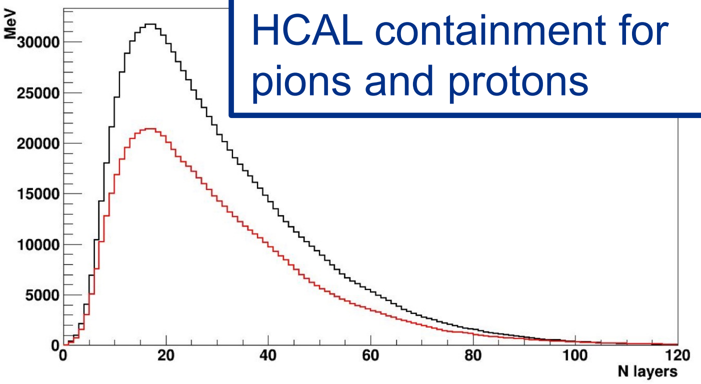
Higgs→mumu mass resolution



B-tagging in Z' decays



HCAL containment for pions and protons



- Early but already very interesting and promising studies
- Plenty of room to contribute
- You will hear a lot more during the week

Summary

- Established baseline detector design and performance at 3 TeV
  - paper to be submitted to journal
- Work on 10 TeV detector design has started
- Detector technologies have been rapidly advancing
- Minimum muon collider detector requirements are within reach or already technologically available
- A lot of work ahead of us with many avenues for improvements – come join us!

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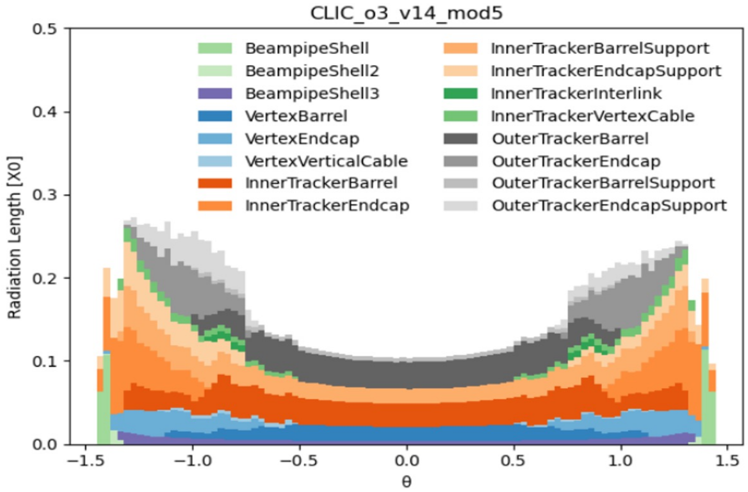
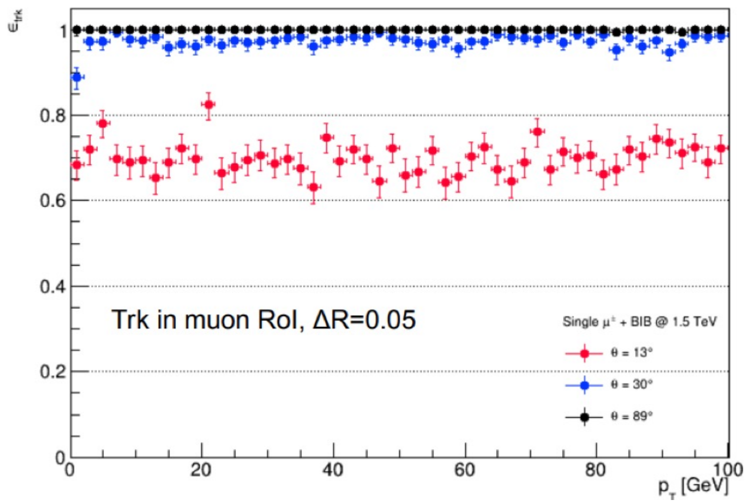
Backup

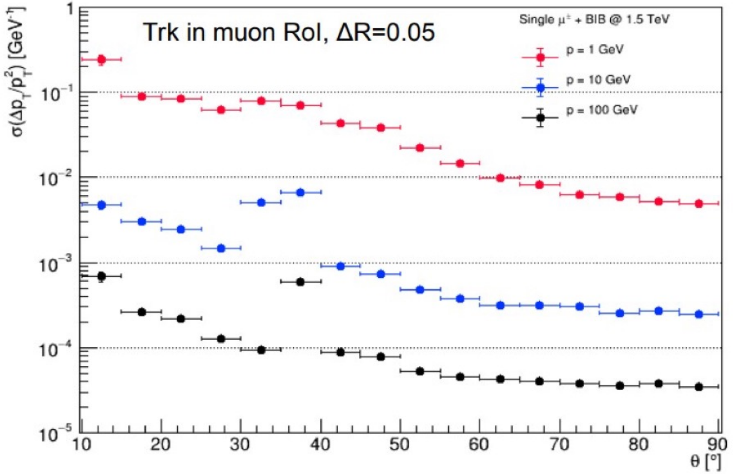
Tracking Performance

Preliminary

- With some basic hit suppression and track level cuts, get good offline track efficiency and resolutions
- Active work on tracking improvements, including Kalman based algorithm

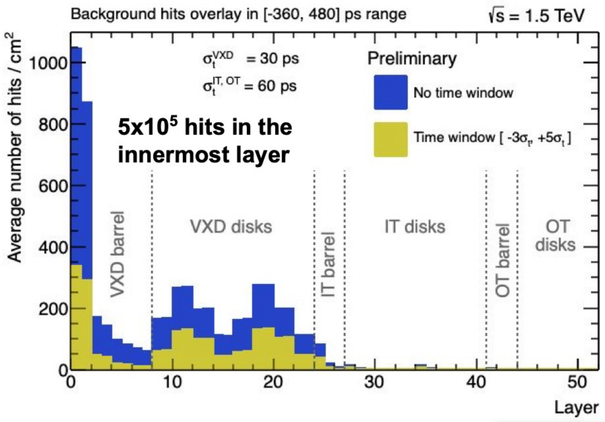






Tracker (2)

- Precision timing is critical for reducing the number of BIB hits. Up to a factor of x3 reduction in the inner layers
- Correlation between layers (a la CMS pT module) provides additional large reduction
- Other handles exist
- Some on-detector filtering may be needed



Example R&D:

- Monolithic devices
- AC-LGADs
- 3D hybrid pixels
- Intelligent sensors
- Common challenges: services, cooling, low-power ASICS