Cluster shape analysis of beam-induced background in the Muon Collider Tracking Detector

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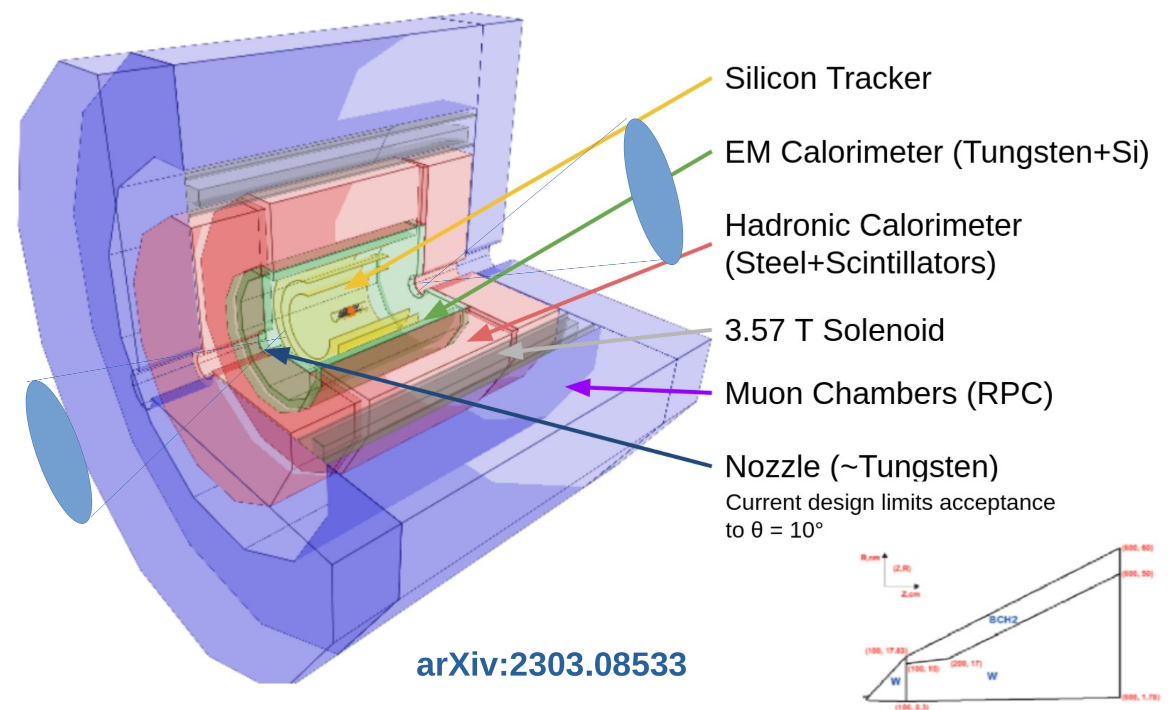
Abstract
The muon collider stands as one of the most promising prospects for next-generation high-energy particle physics experiments. However, it presents significant challenges, particularly in managing the beam-induced background (BIB) resulting from various muon decay sources. Currently, several mitigation strategies are under investigation, such as leveraging timing information from the innermost tracker detector to improve the tracking performance. On top of that, we are also exploring dedicated filtering based on the cluster shapes as well as hit multiplicity response from the realistic digitization to reject some of the in-time BIB from physics collision events.

Detector design



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Initially based on CLIC-detector, with modification for BIB suppression from shielding tungsten nozzles and removing the forward luminosity detectors.

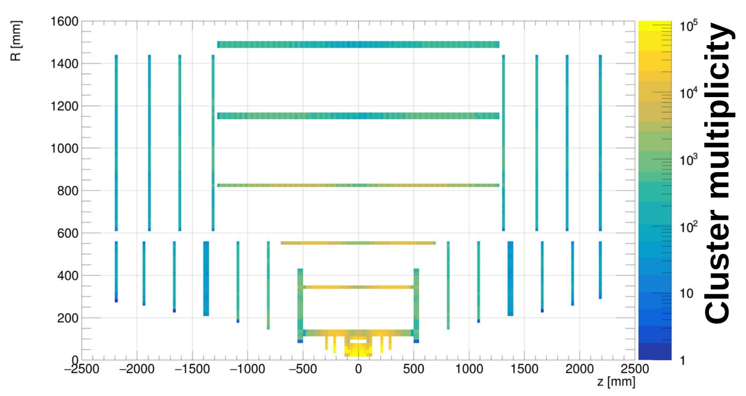
	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	$25\,\mu m \times 25\,\mu m$	$50\,\mu m \times 1\,mm$	$50\,\mu m \times 10\,mm$
Sensor Thickness	$50\,\mu m$	$100\,\mu m$	$100\,\mu m$
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	$5\,\mu m \times 5\,\mu m$	$7\,\mu m \times 90\,\mu m$	$7\,\mu m \times 90\,\mu m$
Layers	Double-sensor layers (4 barrel and 4+4 endcap disks)	3 barrel and 7+7 endcap disks	3 barrel and 4+4 endcap disks

Realistic digitization

Simplified digitization produces reconstructed hits from smearing of the simulated truth-level position, based on gaussian template of the position resolution.
For realistic digitization, actual particle-material interaction is emulated i.e. ionization losses with real sensor thickness, creating electron-hole pairs as well as the response of the front-end electronics for charge collection and timing information.

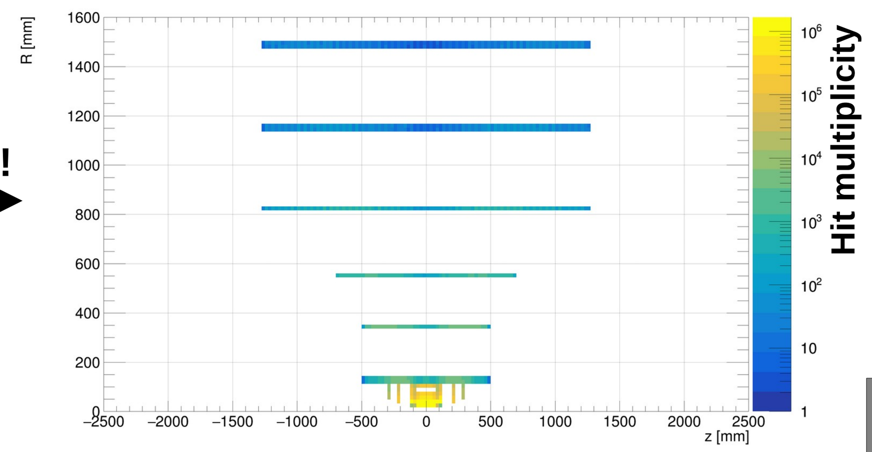
Pixel size and pitch as in detector table above

Sub-Detector	Typical <E> loss [e-]	Threshold [e-]	Threshold variation σ [e-]	Noise [e-]	#bits for charge	Max charge (overflow) [e-]
Vertex	4,000	500	25	80	4	15,000
Inner Tracker	8,000	1,000	25	80	4	60,000
Outer Tracker	8,000	1,000	25	80	4	60,000



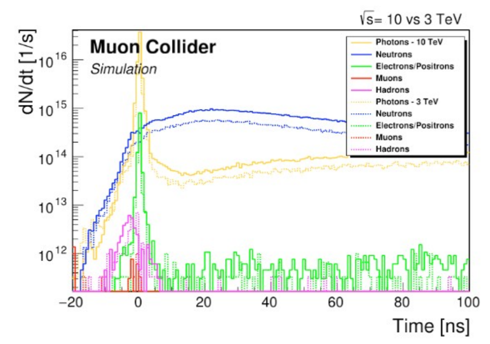
With realistic digitization, can look at actual pixel hits!

Not implemented for inner tracker and outer tracker endcap yet.

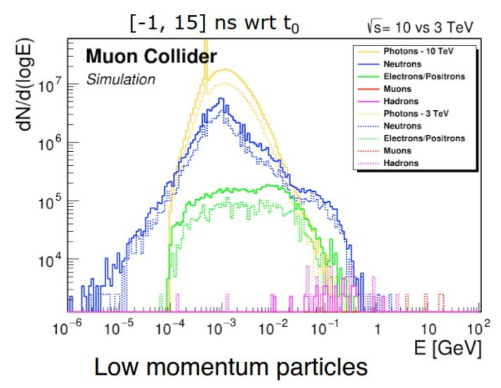


Sources of beam-induced backgrounds (BIBs)

In-flight decays of the muon beams and their interactions with beam line material and the detectors pollutes the otherwise clean collision environment. The ensemble of all these particles is usually known as "Beam Induced Backgrounds", or BIB.



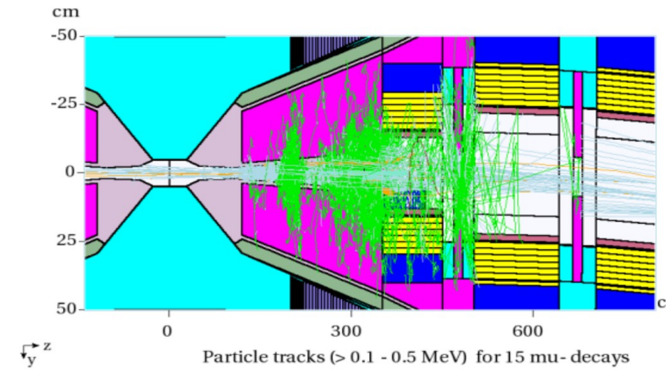
Partially out of time vs beam crossing



Low momentum particles

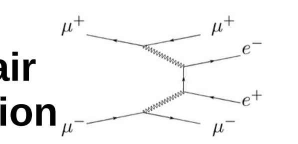
Background particles entering the detector per bunch crossing, with time window cut of [-1,15] ns:

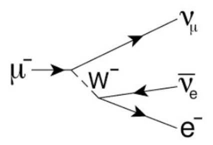
- O(10^8) ɣ (>100 KeV)
- O(10^7) n (>10^{-5} eV)
- O(10^6) e+, e- (>100 KeV)



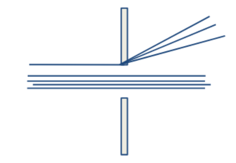
Large particle multiplicity entering the detector after showering on dedicated shielding.

e+e- pair production





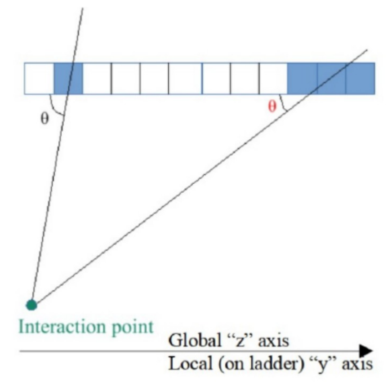
Muon beam decays



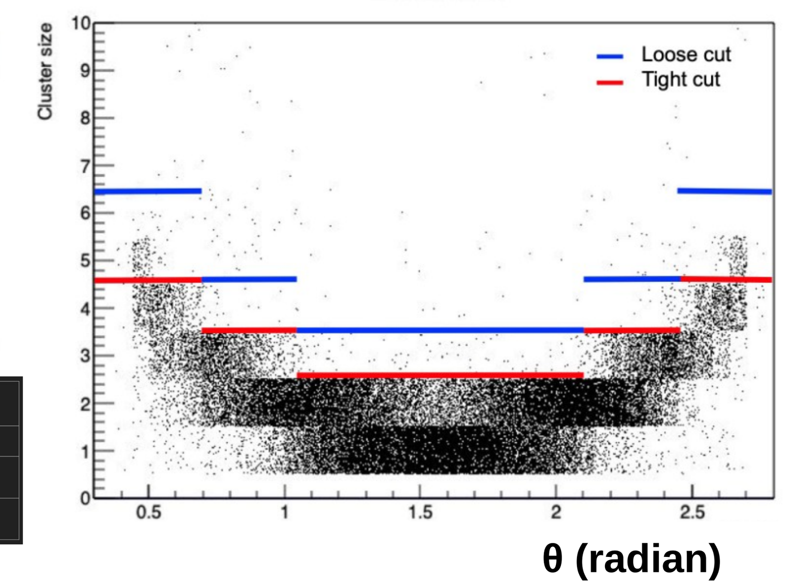
Beam halo loss on collimators

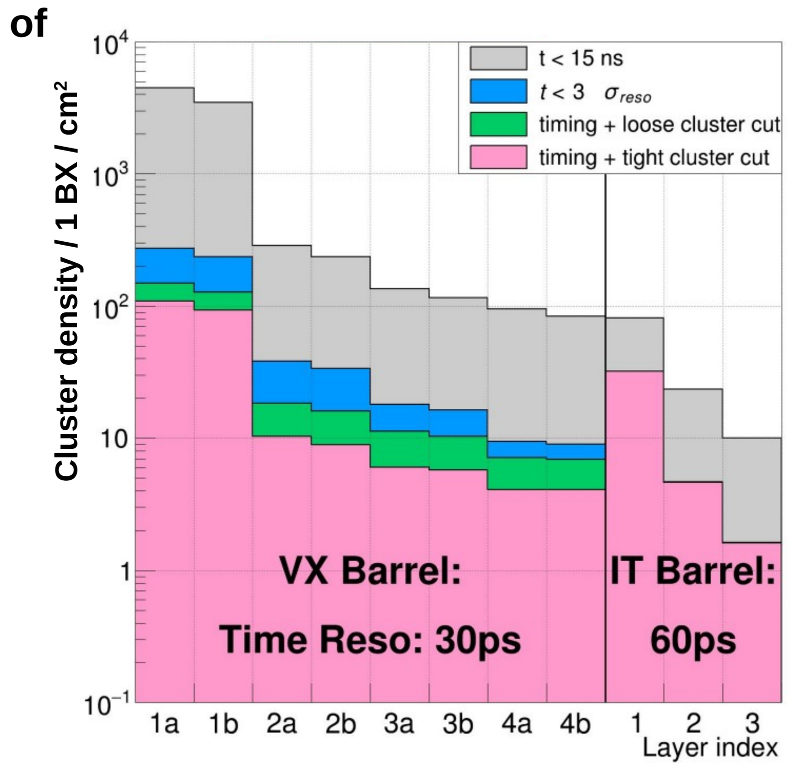
Cluster Shape Analysis for BIB rejection

Using correlation between incidence angle and number of pixel hits per cluster, we can reject long clusters which are characteristic of BIB particles from the muon collision events.



	% "Signal" Retained	% BIB Retained
No Cut	100	100
"Loose" Cut	98	65.7
"Tight Cut"	95	54.9



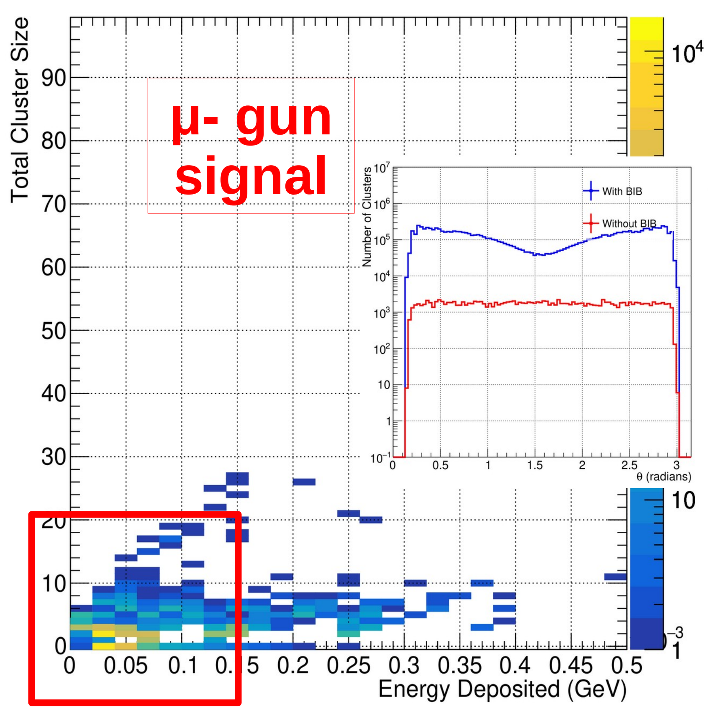


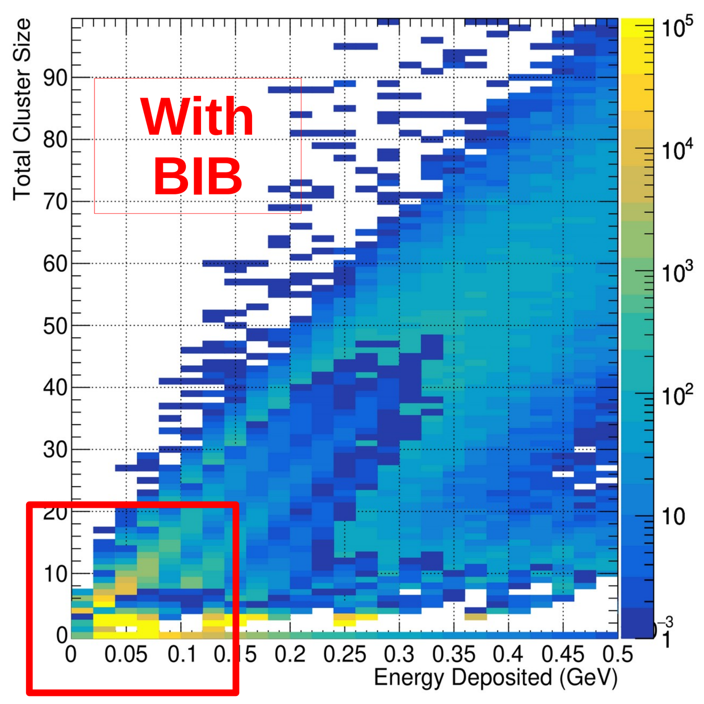
- Tighter time window selection reduces number of hits by 92% in vertex barrel, but only 74% in inner tracker barrel.
- The current cluster filter cuts give no additional BIB rejection in the inner tracker – scope for improvement!
- Also, need to extend to outer tracker barrel layers.

Ongoing work and future studies

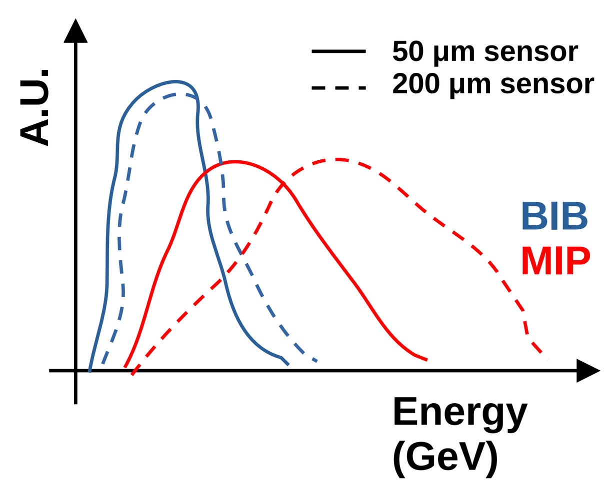
WORK IN PROGRESS

Currently, not much separation exists with thin sensors between muon signal and with BIB collision events. However, BIB produces several particles at higher incidence angles (longer clusters) which have lower energies.





1) Changing sensor thickness



Plan to increase sensor thickness to study the effect on the size of clusters from muon (MIP) signal vs BIB.

2) Improve the cluster shape filters to reject BIB even more efficiently, including for the inner tracker and outer tracker layers.
3) Implement the realistic digitization for tracker endcap layers.
4) Optimize the time window selection for out-of-time BIB rejection.

5) Assess DAQ bandwidth requirements towards a realistic front-end (FE) design. For example,
VXB Layer 1a, with tight time window cut:
- 270 clusters / BX / cm²
- 4000 hits / BX / cm² (based on current state-of-the-art pixel readout chip architecture)

6) Finally, study the impact of increasing FE threshold on the pixel hit multiplicity and cluster energy, with the optimum sensor thickness and time window.