Improving Tracker Digitization Performance in a Muon Collider Detector

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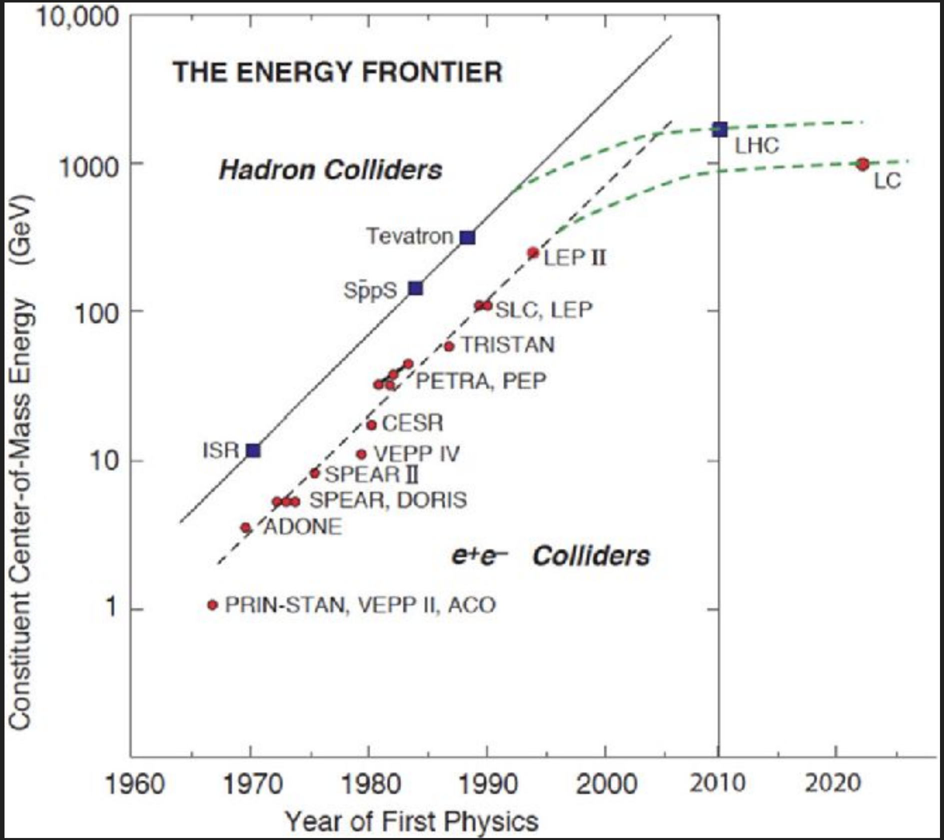
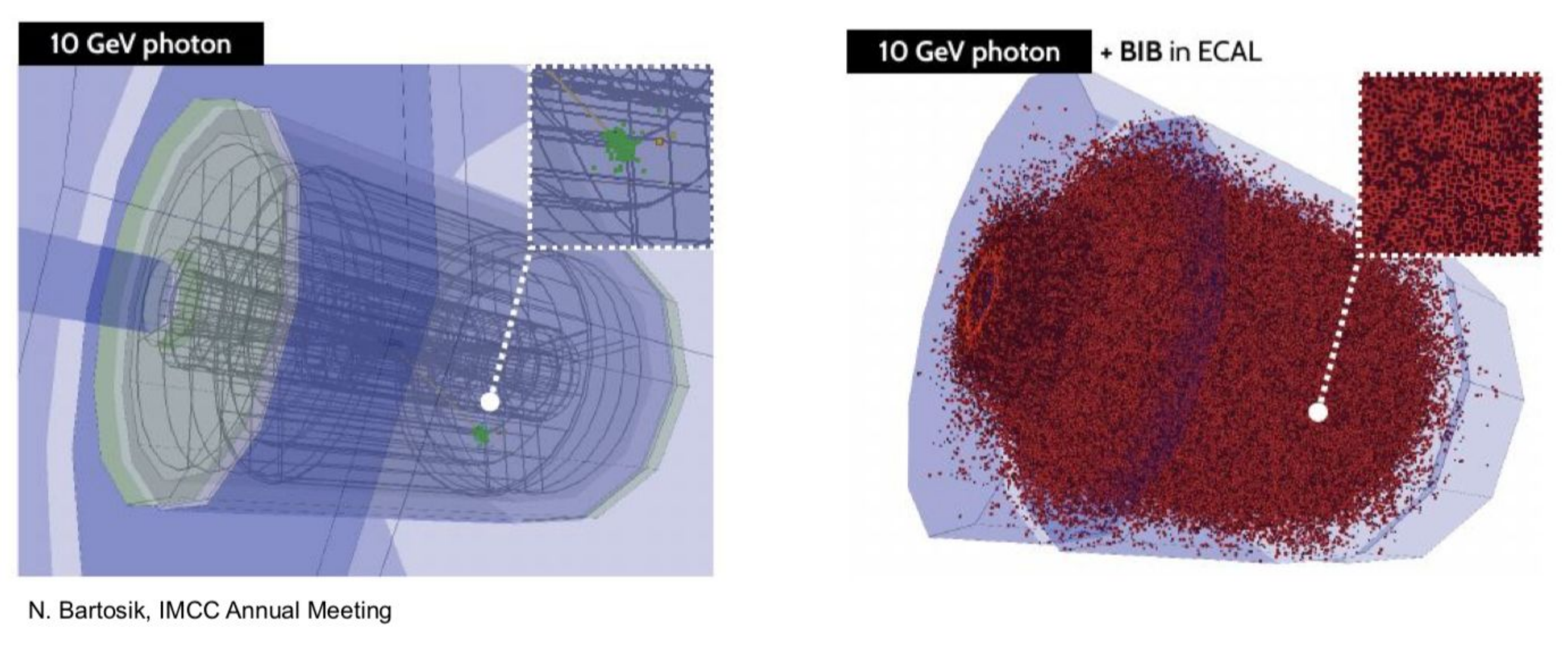
Motivation for a Muon Collider

- Muons lose less energy to radiation
- Overcomes historical divide between precision and energy frontier in HEP machines
- Best probe for new SM and BSM physics
- Compact and efficient design



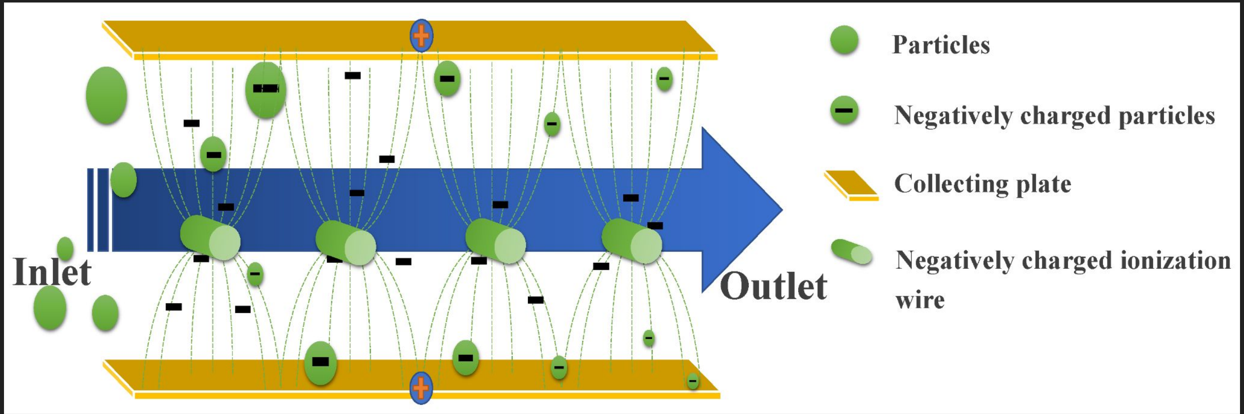
Challenges accompanying detector

- Short lifetime leads to novel challenges with beam production and cooling
- Large Beam Induced Background poses difficulty to detector design

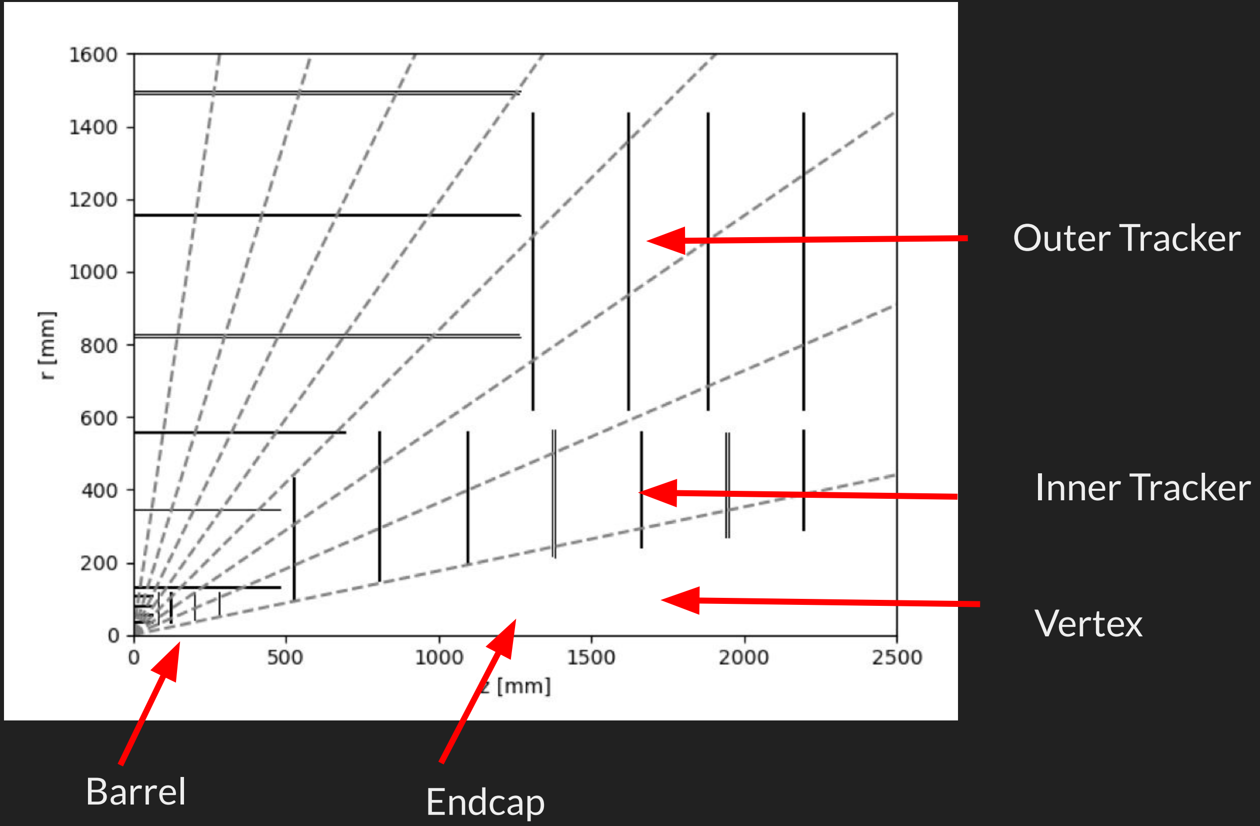


Digitization

- The conversion of charged particle interaction with matter -> electronic signal is a key element of all detector
- Initial muon collider studies used a simplified tracker digitizer with a Gaussian smear
- My project involved contributing to and studying a realistic digitizer algorithm that incorporated the correct physics

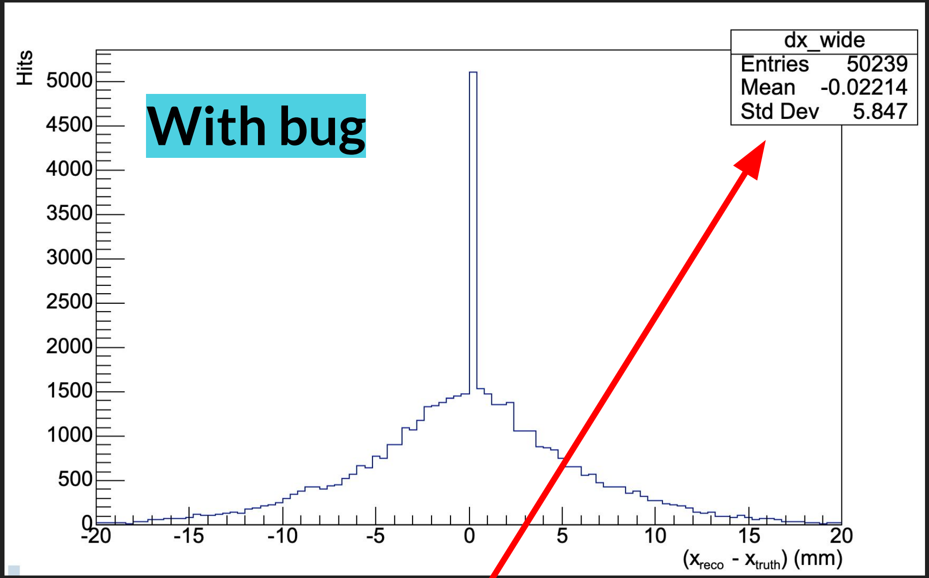


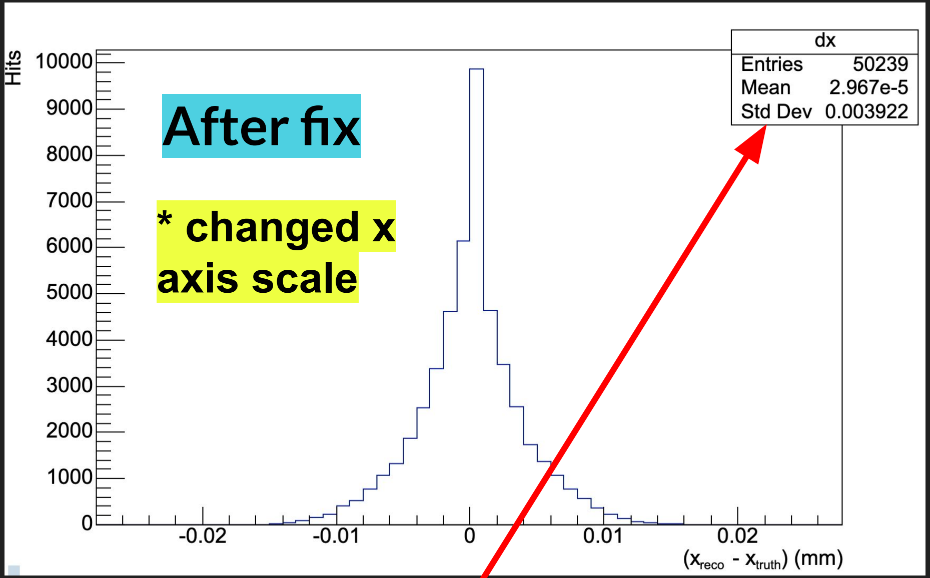
Extending realistic digitizer to new detector elements



- Out of 6 total detector elements for the tracker, realistic digitization had previously been incorporated in only 1
- The different geometries of the other layers formed a technical barrier
- I expanded the realistic digitization algorithm to handle 3 new elements
- Promising new potential study for tracking effiency

Finding an error in the digitization position reconstruction





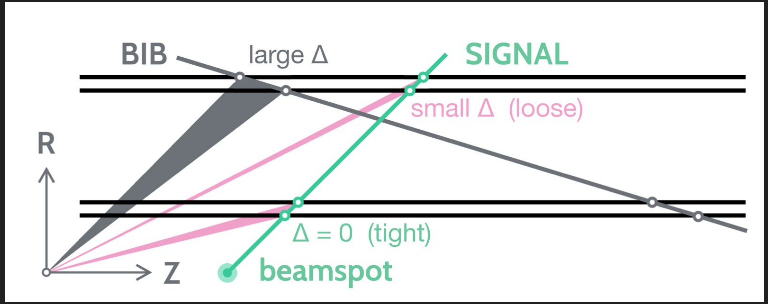
Before the fix, the spread in $x_{reco} - x_{truth}$ was ~6mm

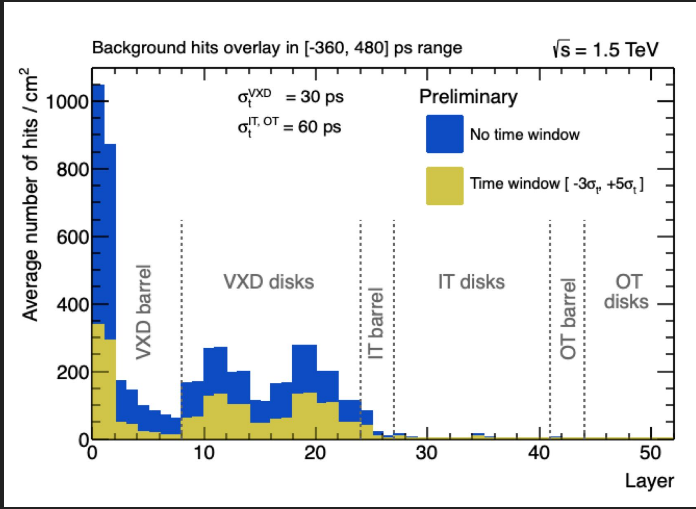
After the fix, the spread is ~4µm (pixel width is 25µm)

Using realistic digitization for background handles

- Detector needs filters to handle BIB
- Previously tested: double layer
  - Challenges: cost, construction
  - 10 TeV geometry only uses one DL layer

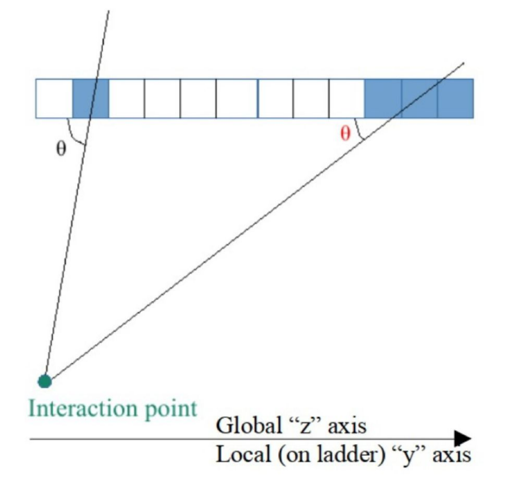
- Another important handle for filtering BIB hits is the hit time
- BIB particles travel through nozzle + lose energy
  - Have later arrival time

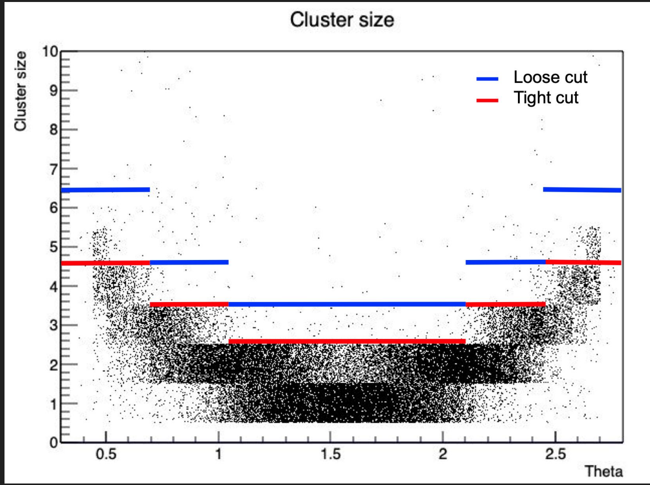




Cluster Size Filter

Use correlation between angle and # pixel detectors hit



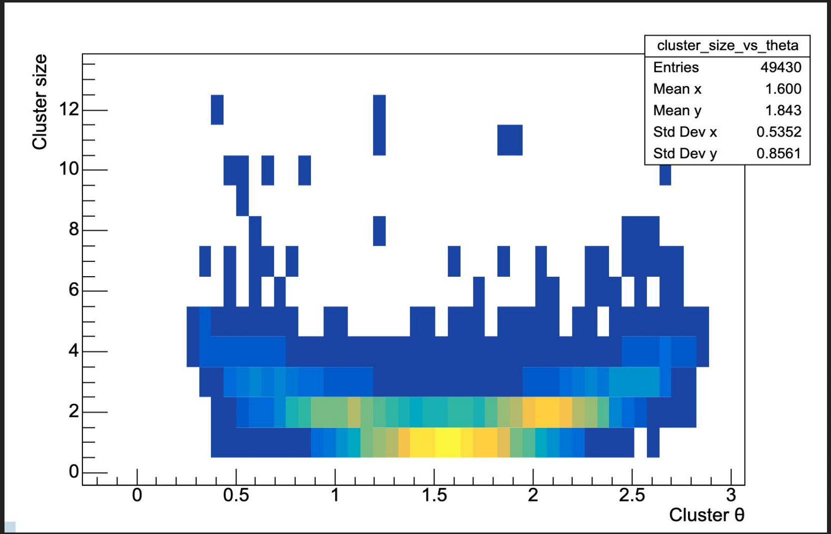


Cuts:

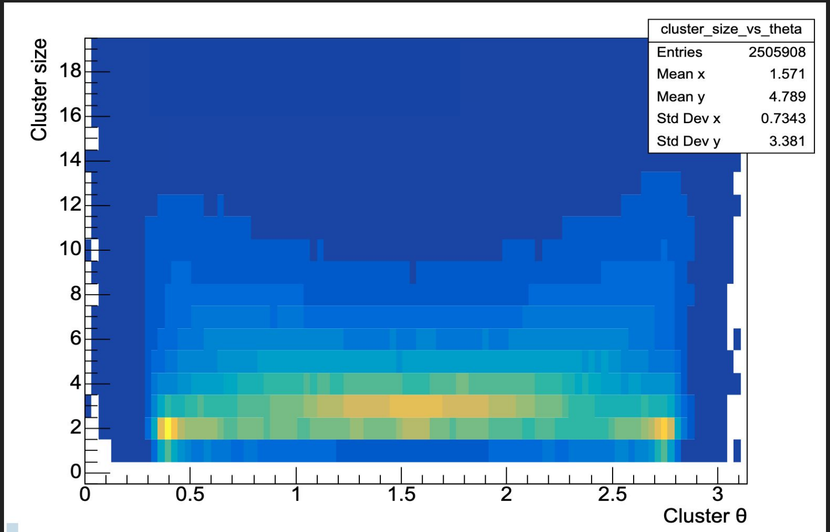
Theta Range (radians)	(0, 0.7)	(0.7, 1.05)	(1.05, 2.1)	(2.1, 2.5)	(2.5,3.2)
Max Cluster Size (Loose Cut)	6	4	3	4	6
Max Cluster Size (Tight Cut)	4	3	2	3	4

Effect of Cluster Filter in Vertex Barrel

Single 10GeV μ^- gun "signal" (10,000 events)

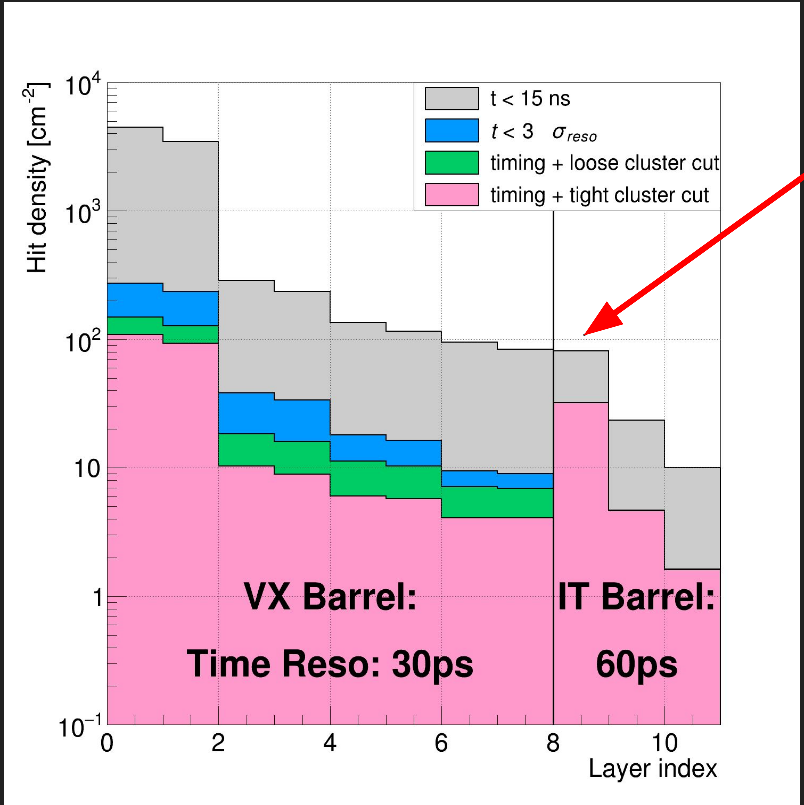


With BIB (1 event)



- Relative isotropy of BIB makes cluster cut effective for VX hits

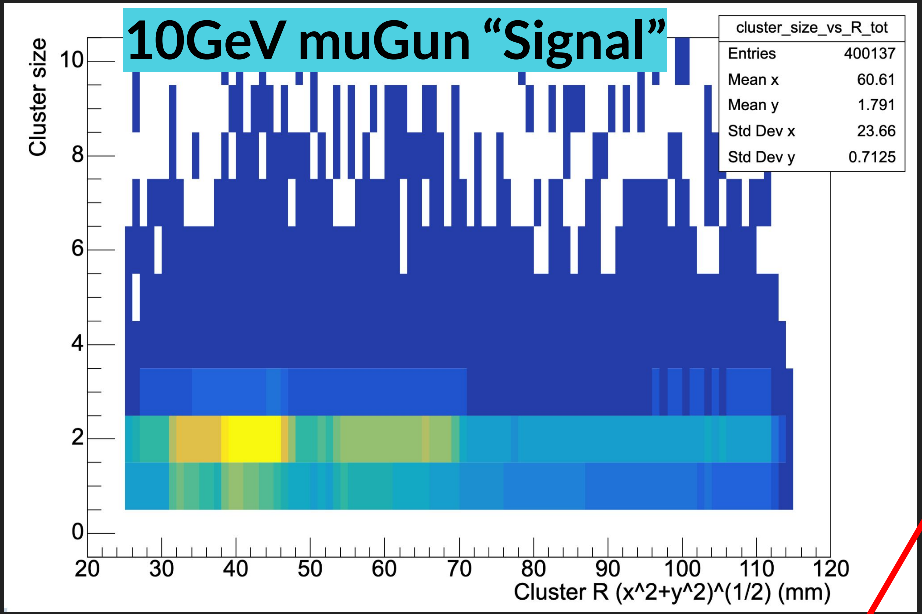
Updating occupancy with cluster shape filter

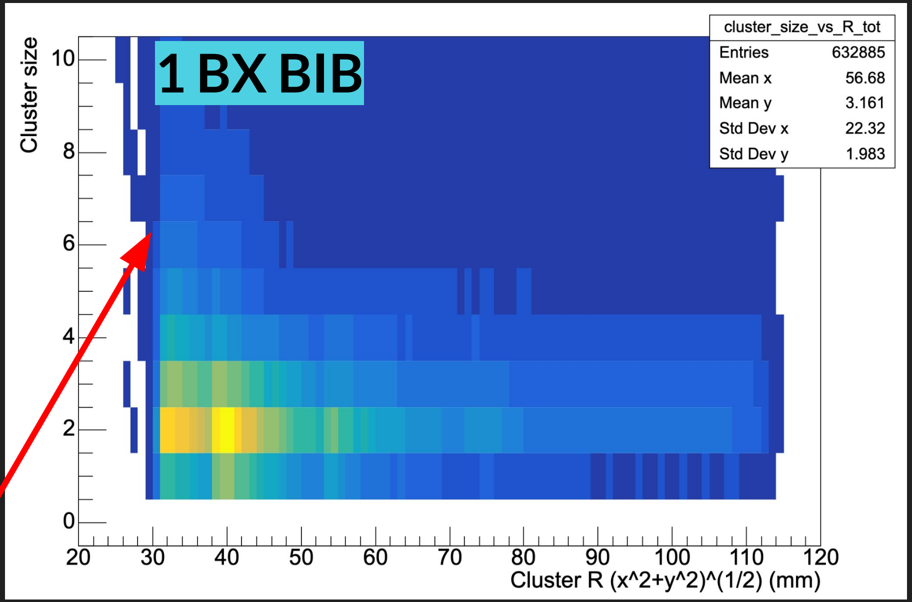


- The inner tracker barrel has comparable occupancy to the vertex barrel
- Timing cut in VX removes 92% of hits, only removes 74% in ITB

- As expected from the cluster shape of the BIB and signal comparison, the current cluster filter cuts have almost no additional veto power in the inner tracker

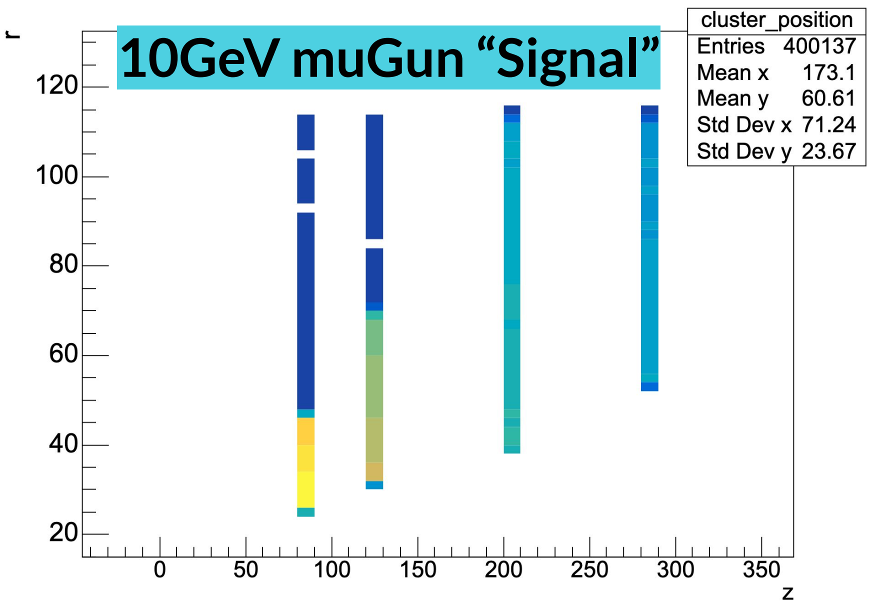
Cluster shapes for VX Endcap

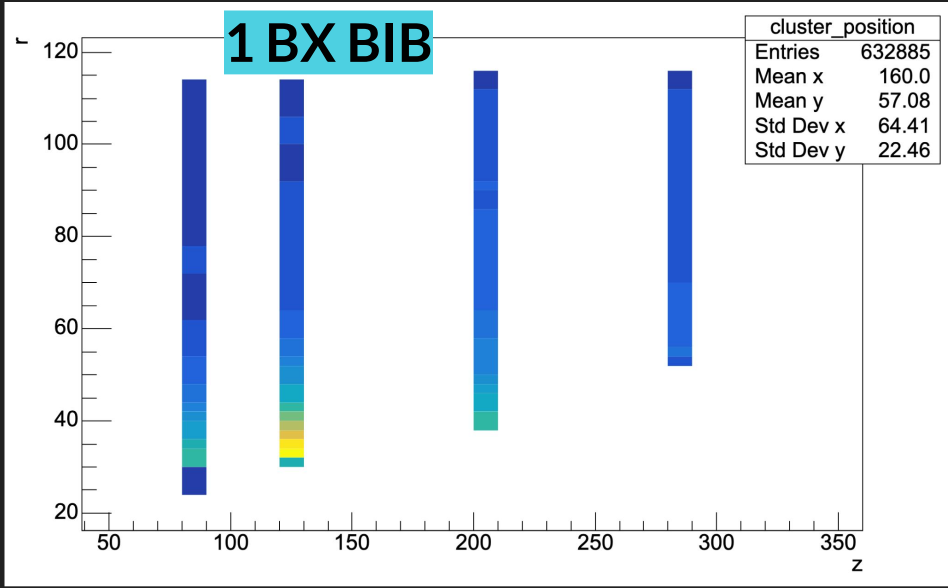




- As expected, many BIB particles leave large size clusters close to the nozzle.
- The two profiles are similar enough that making cuts on the entire profile only leads to ~20% hit reduction while retaining >95% "signal"

New approaches to cluster shape filter





- Filter needs to be adjusted to calculate cluster size in both x and y directions
- The hit profile differs when considering each layer independently
    - The cluster shape filter was redesigned to incorporate different cuts for each layer

Cluster cuts by layer

10GeV muGun "Signal"

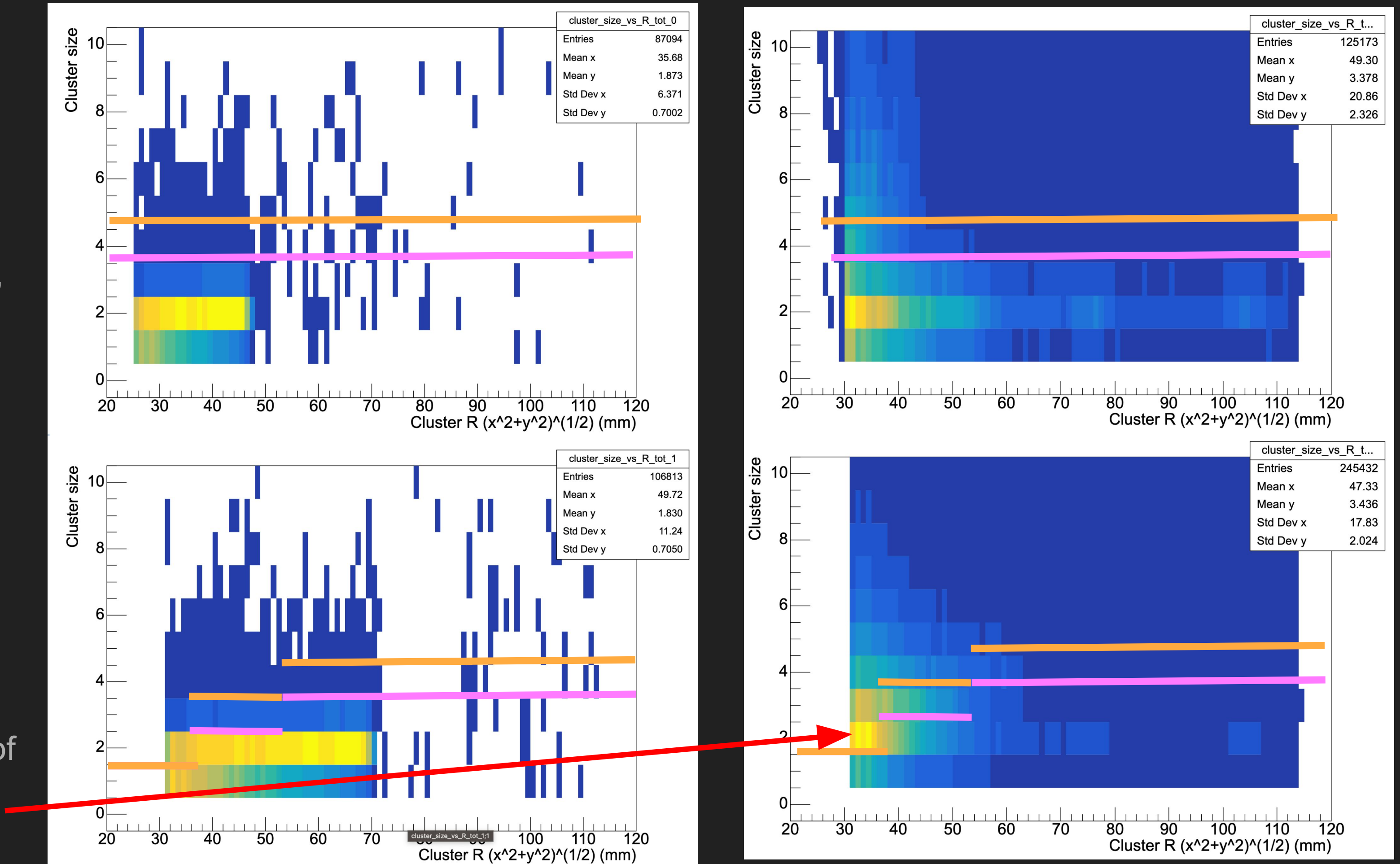
1 BX BIB

1st DL:

2nd DL:

Orange="loose cut"
pink = tight cut"

Almost 10% of all BIB hits created in this 10mm range of DL #2 alone!



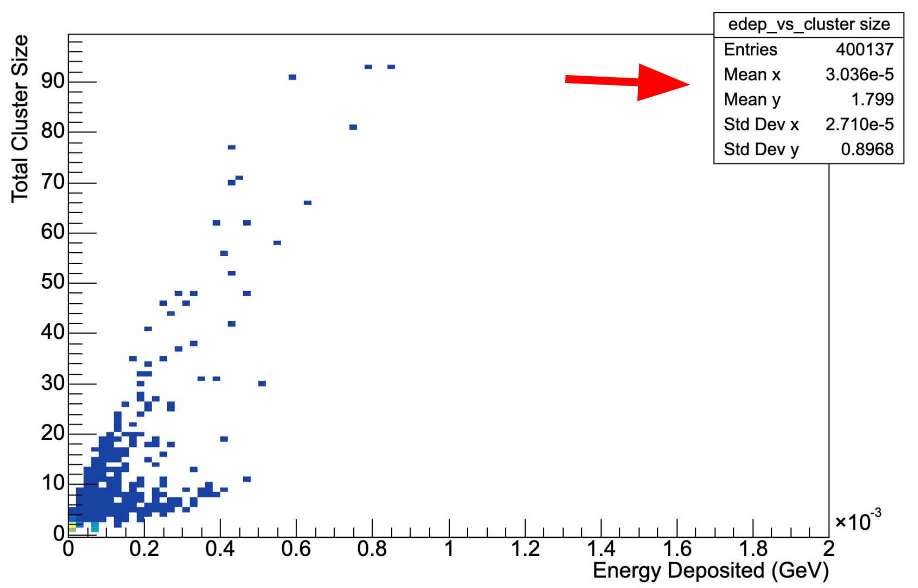
Results of differentiating cluster cut by layer

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

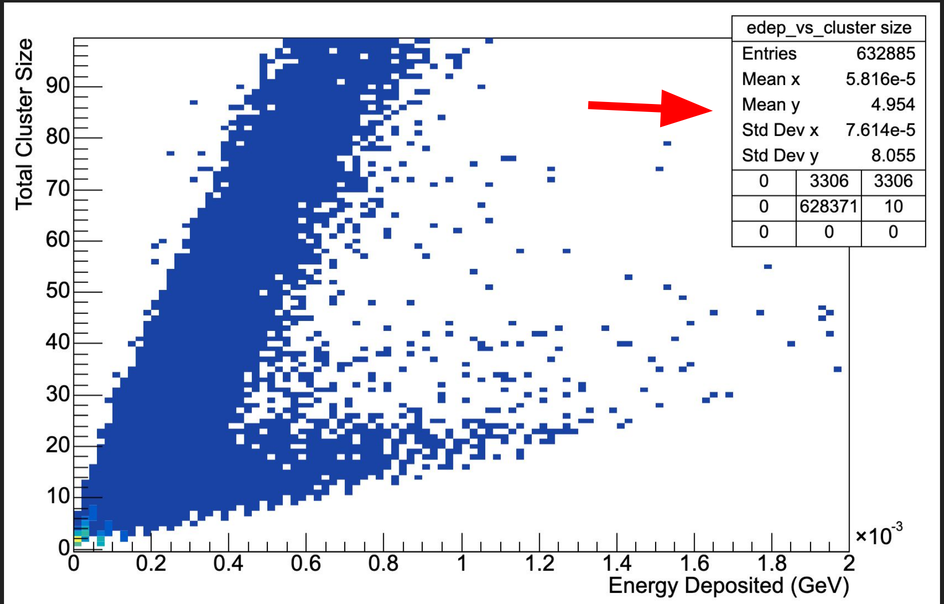
- New approach to differentiated cluster cut removes ~half background while maintaining >95% signal efficiency
- These cuts can be further optimized for better performance

Using Energy Deposition as an additional handle

10GeV Mu- Gun “signal”



1 BX BIB

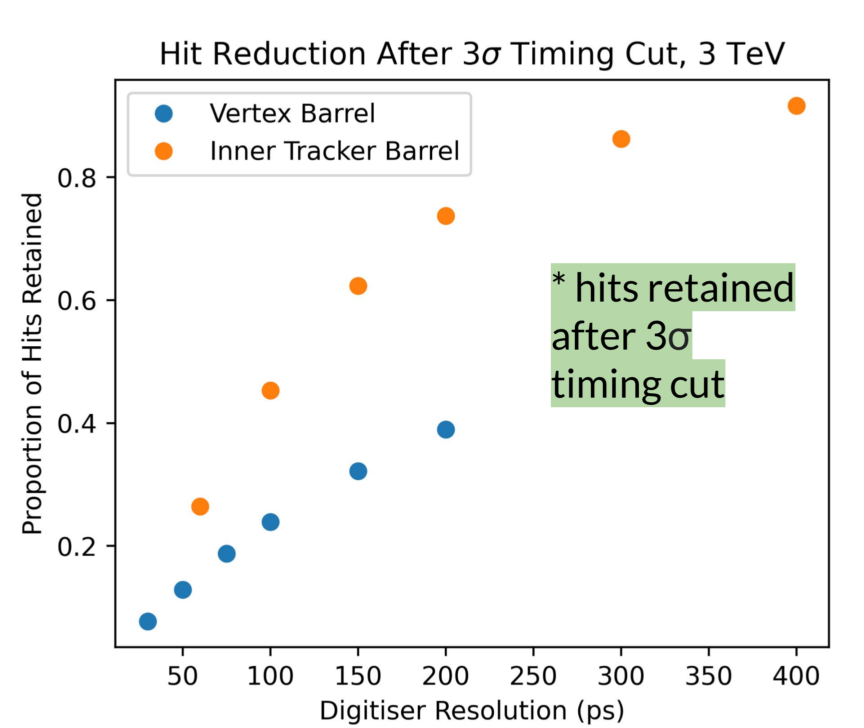


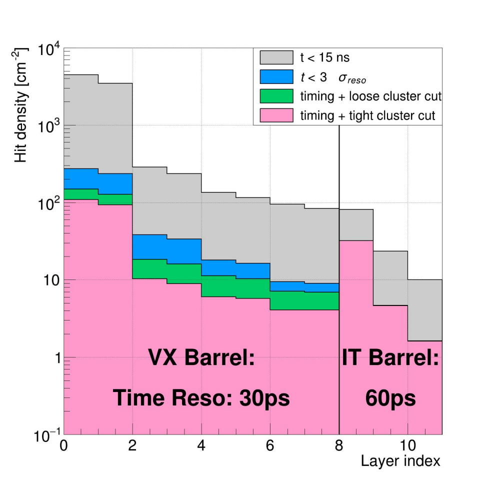
- BIB has many high energy deposition, larger cluster size events in the Vertex Endcap
- These could be low pT electrons that are spiraling around the endcap detector
- Vetoing these events could significantly improve tracking efficiency

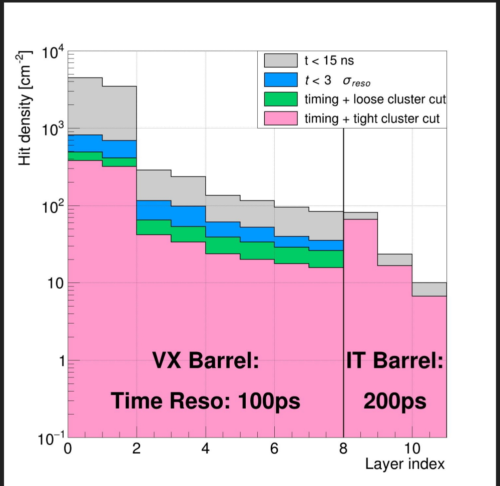
Additional Digitization studies

- Many of the digitization parameters have been chosen based on R&D projected goals
- Studying the effect of these parameters on detector performance can direct targets for hardware development

Effect of Changing Digitizer Timing Resolution





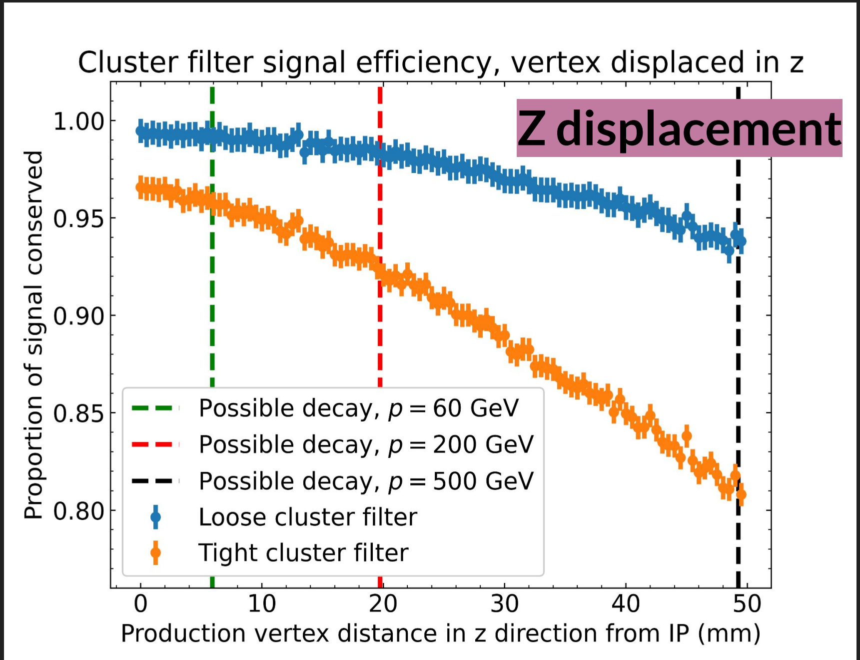


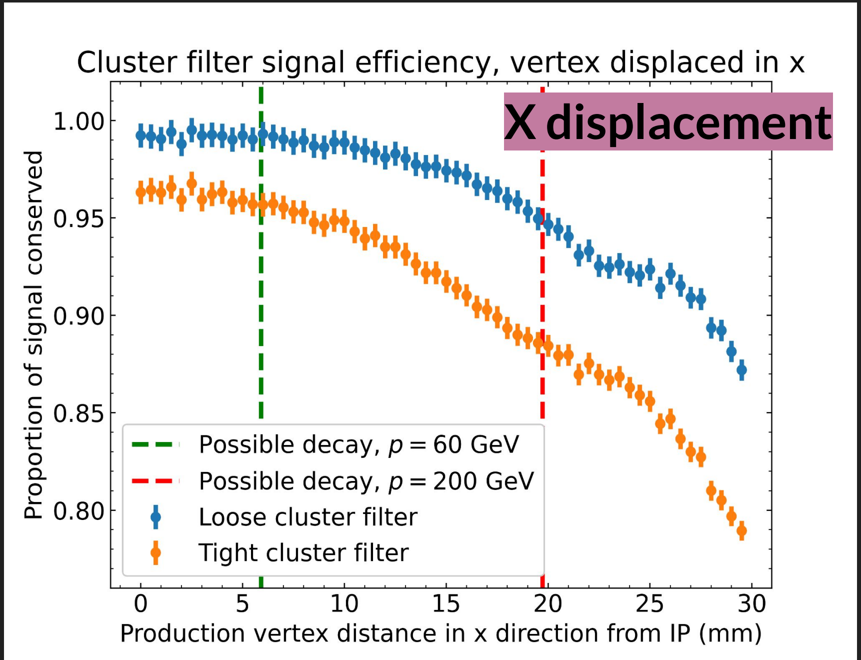
The effectiveness of the timing cut depends strongly on the resolution of the pixel detectors. The fraction of hits retained increases ~linearly with the time resolution.

Effect of timing cut with 30ps resolution = effect of loose cluster cut with 55ps resolution

= effect of tight cluster cut with 80ps resolution

Effect of cluster filter on particles created away from IP

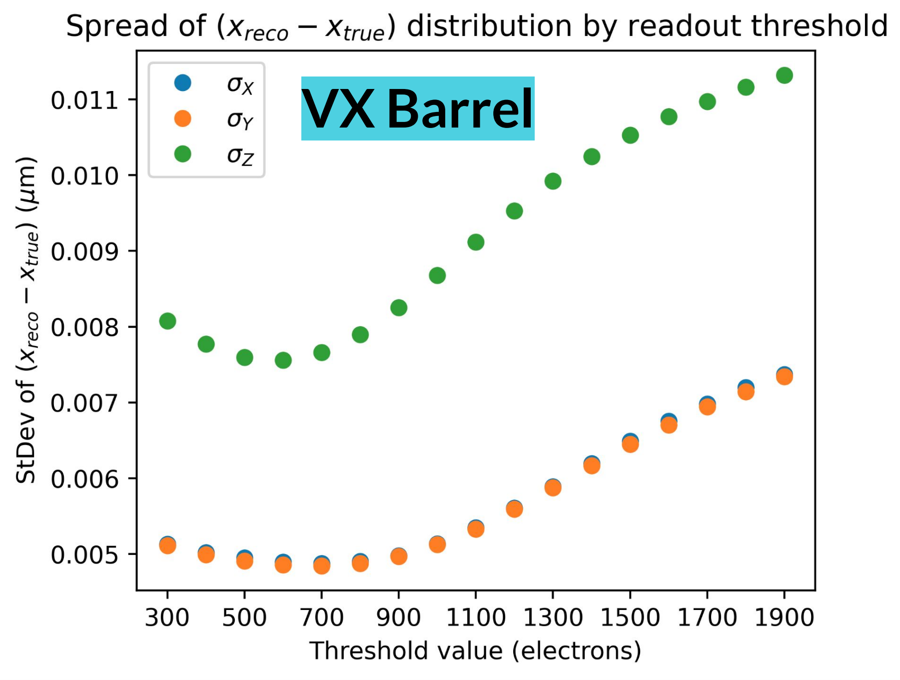


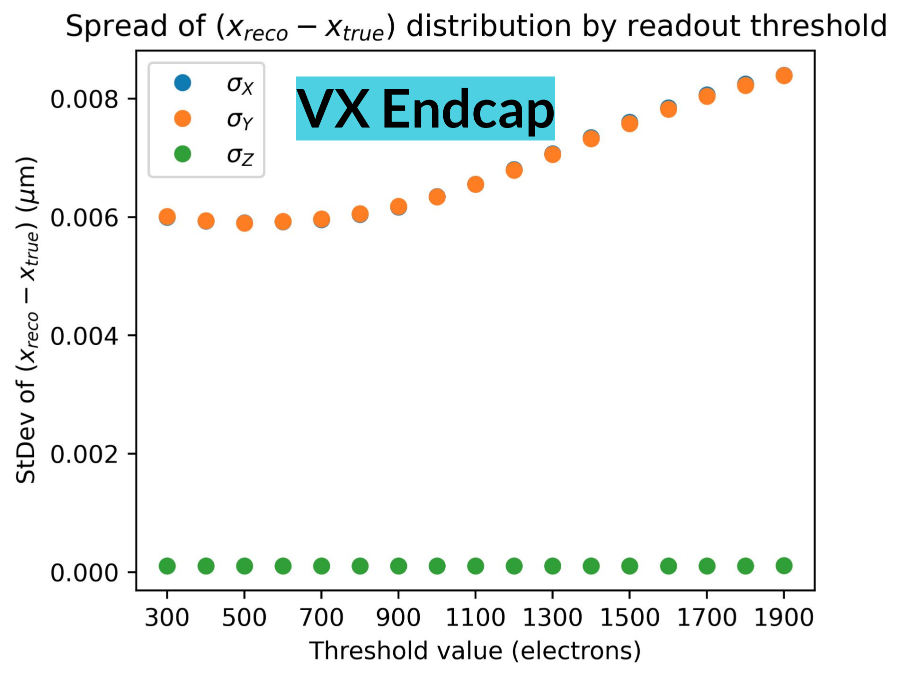


The “loose” cluster cut remains an important consideration because of signal processes whose production vertex is displaced from the (0,0,0) interaction point.

While the tight cluster will retain ~95% of hits for Δx, Δz < 10mm, some particles (B hadrons) can travel cm before decay. With tight cluster: ~20% chance of veto if decay is 30mm from IP

Effect of changing readout threshold

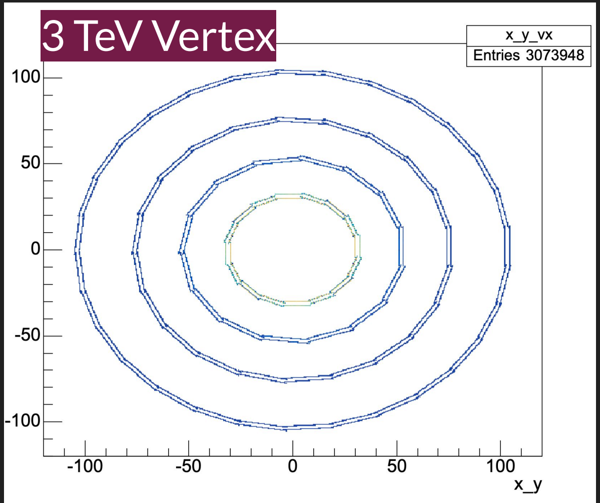


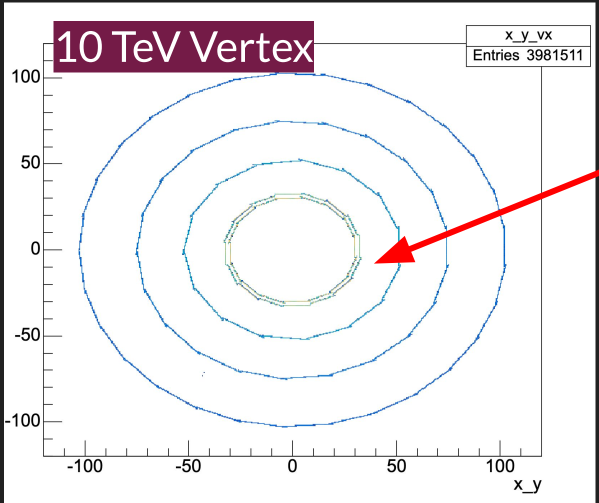


The optimal readout threshold for the pixel digitizers (with the updated position reconstruction method) appears to be 500-700 electrons. Raising the threshold slightly does not dramatically decrease reco accuracy (good for R&D).

Comparing v1.1 (√s = 3 TeV) to 10TeV geometry

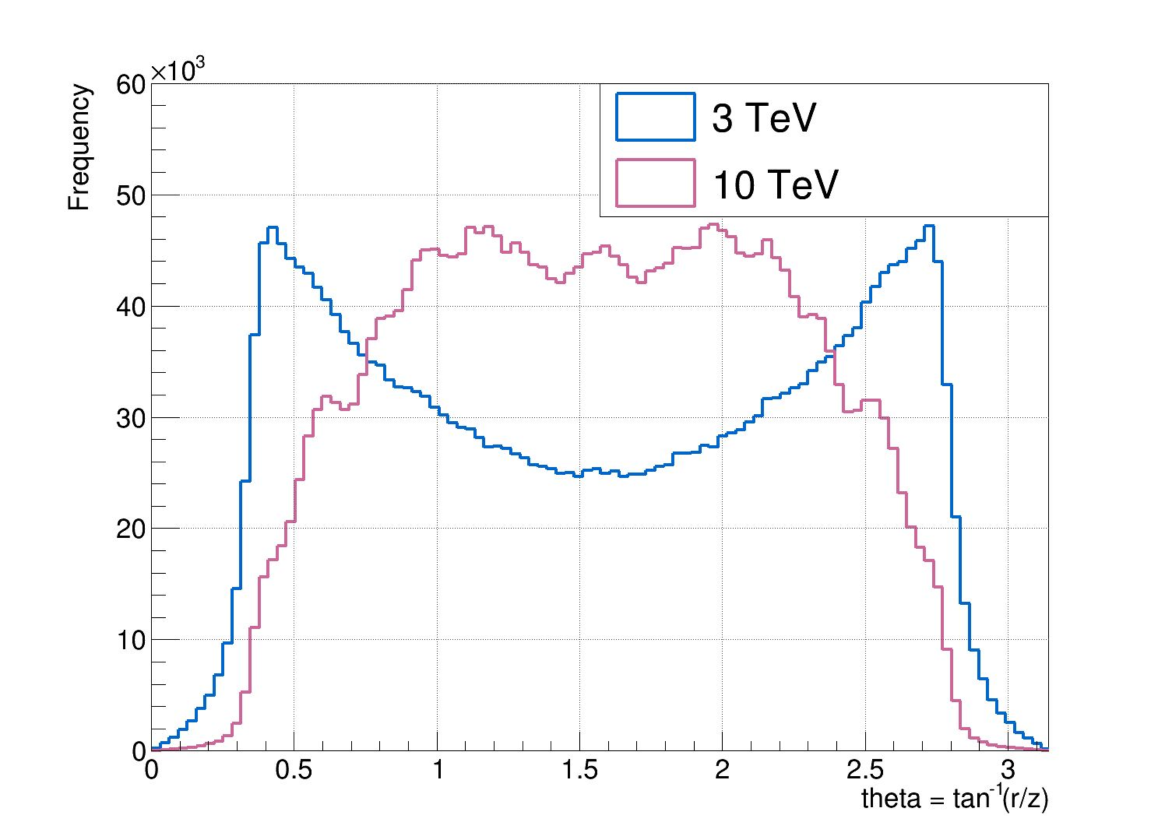
- Previous Muon Collider Detector simulations assumed a √s = 3 TeV beam
- New geometry testing √s = 10TeV beam (see Federico's May 16 talk)
- In 10TeV, two dominant changes cancel to first order
  - Longer lifetime beam particles -> fewer BIB muons
  - More energetic beam particles -> more BIB shower





One major change: only one double layer in 10 TeV geometry

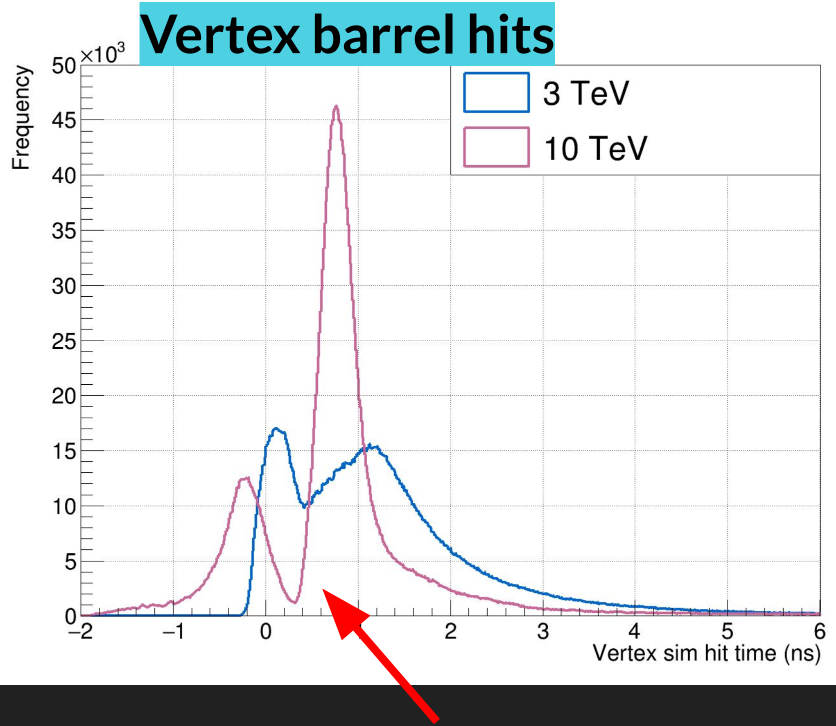
Comparing θ Distribution, 3 TeV vs 10 TeV BIB

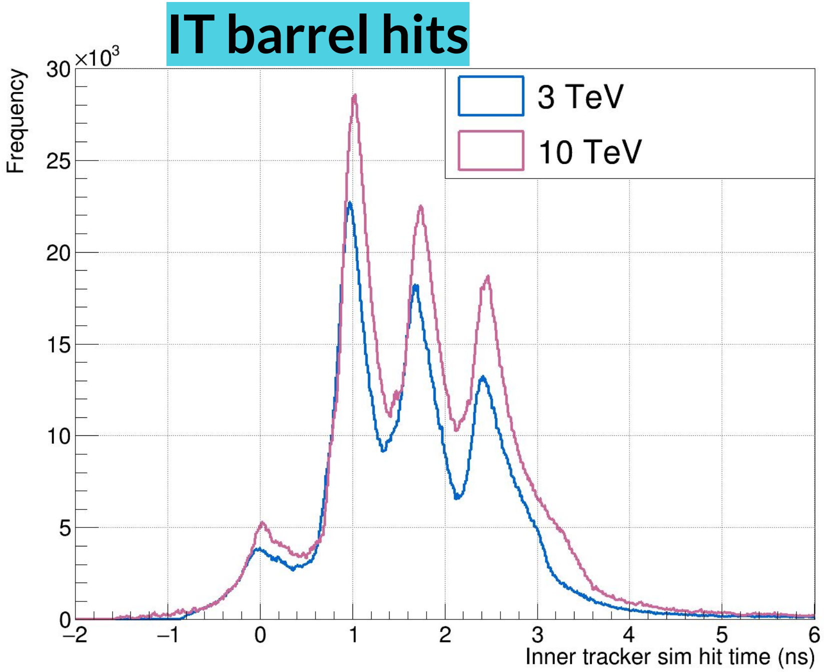


Comparing the distribution of hit angle for Vertex Barrel hits

The 10TeV BIB hits are more central, indicating that the cluster shape filter will lose effectiveness

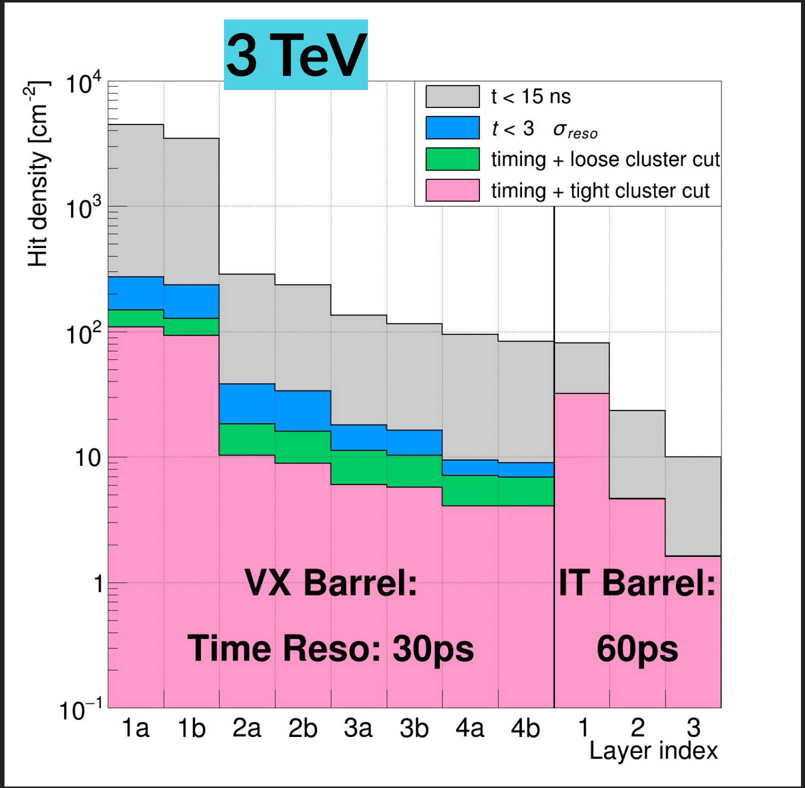
Comparing Sim Hit Timing

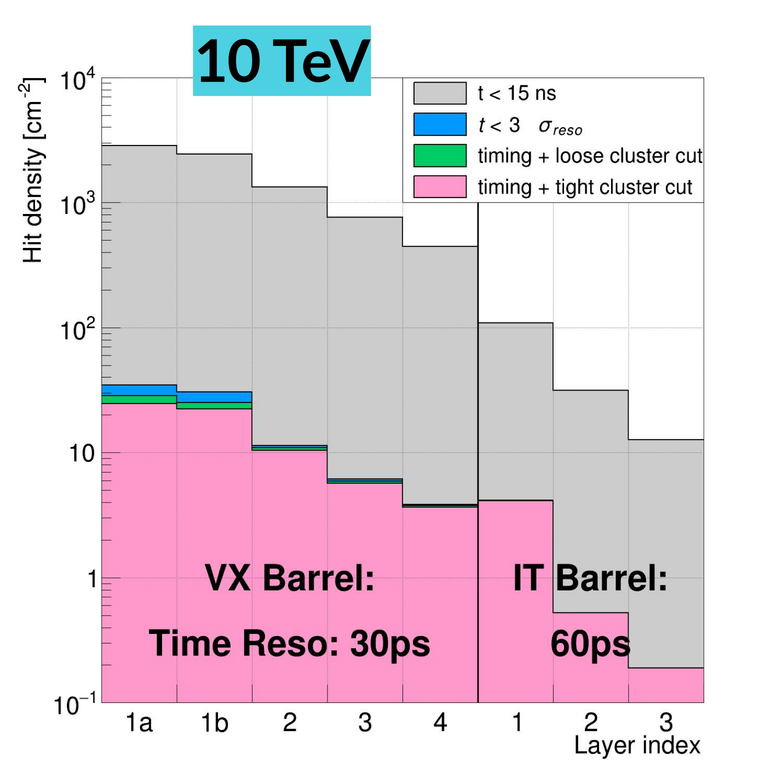




- Disparity in VXB hit timing affects efficiency of timing cut

Comparing 3TeV and 10TeV hit density





As expected from previous slides, cluster filter is less effective in 10TeV than 3TeV, but the timing cut is significantly more effective in 10TeV than 3TeV.

Summary

- Fixed bug and added support for realistic digitization in new detector elements
- Expanded cluster shape filter to account for new geometry considerations
- Studied effect of changing digitization parameters for R&D goals
- Studied changes in new 10TeV geometry design

Further work

- Effects of cluster filters tracking performance
- Using endcap digitization for further study, ex) pixel offline time
- Further developing cuts, including energy deposition

References and Specs

Original luster size cuts: Natalie Bruhwiler:

https://indico.cern.ch/event/1224307/contributions/5150454/attachments/2552372/4397311/Cluster_filtering.pdf

Double layer filter and original occupancy plot: Nazar Bartosik

https://indico.cern.ch/event/1277670/contributions/5366783/attachments/2631004/4550736/2023_04_18_bartosik_v0.pdf

- Muon Collider SW: Container 1.7-AlmaLinux9
- Config file (digitization): https://github.com/chrissellgren/MuCol/blob/master/config.xml
- Config files (plots): https://github.com/chrissellgren/MuCol/tree/master/trackperf
- Geometry: https://github.com/MuonColliderSoft/lcgeo/tree/master/MuColl/MuColl_v1.1
- BIB: https://nbartosi.web.cern.ch/simone_20230726/
- Realistic endcap digitizer: https://github.com/MuonColliderSoft/MuonCVXDDigitiser/tree/endcap-digi