Pixel-based BIB suppression and DAQ impact at a multi-TeV Muon Collider

Angira Rastogi, Lawrence Berkeley National Laboratory

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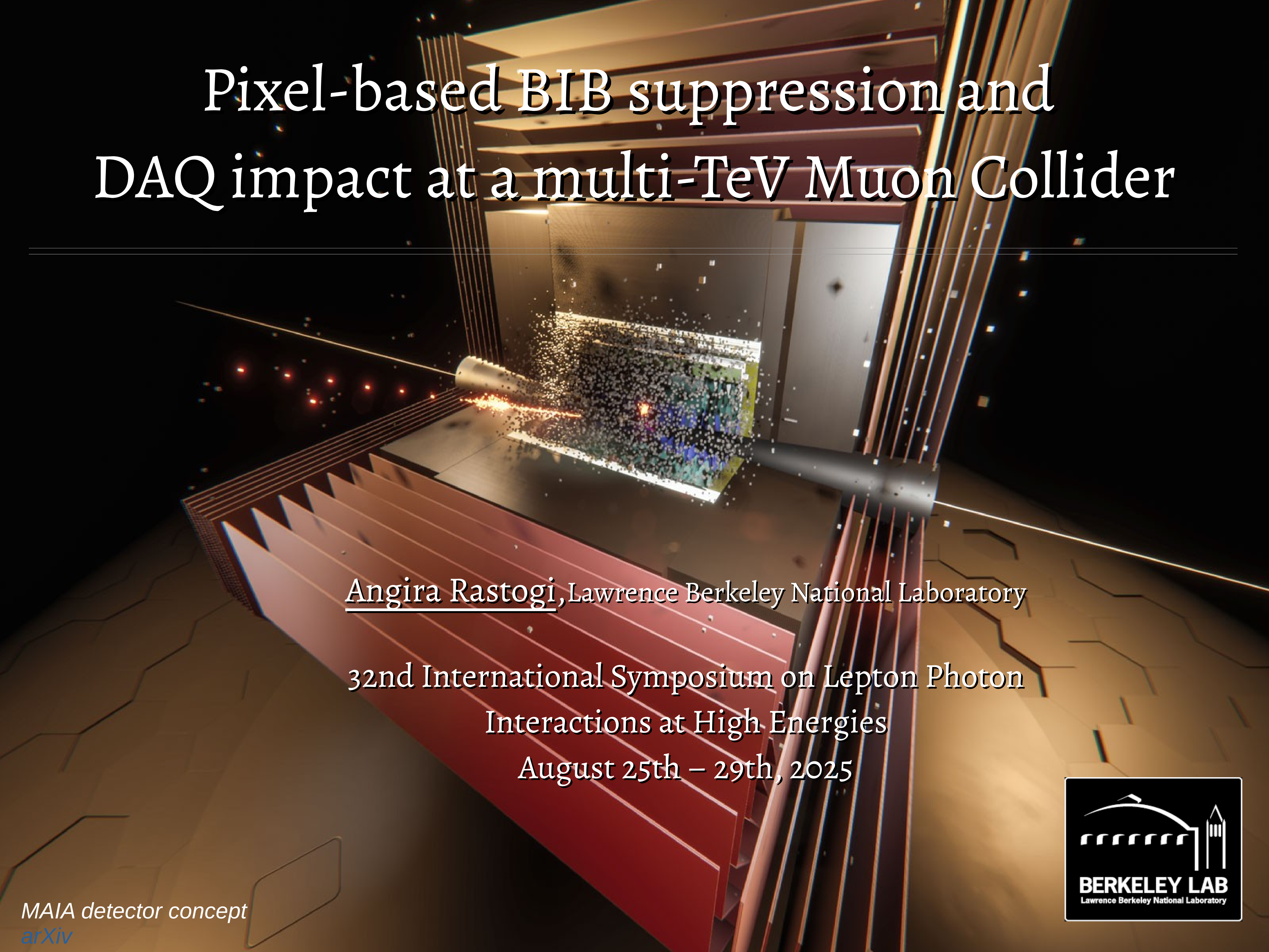
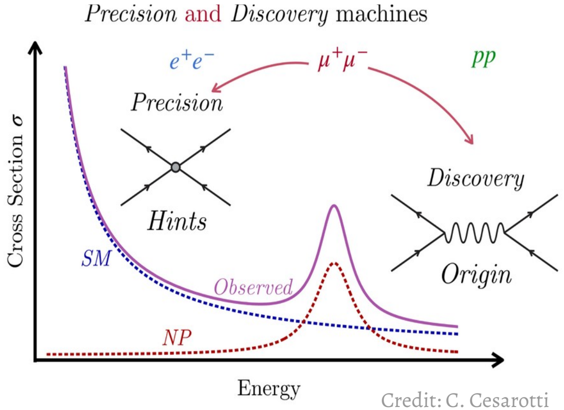


MAIA detector concept
arXiv

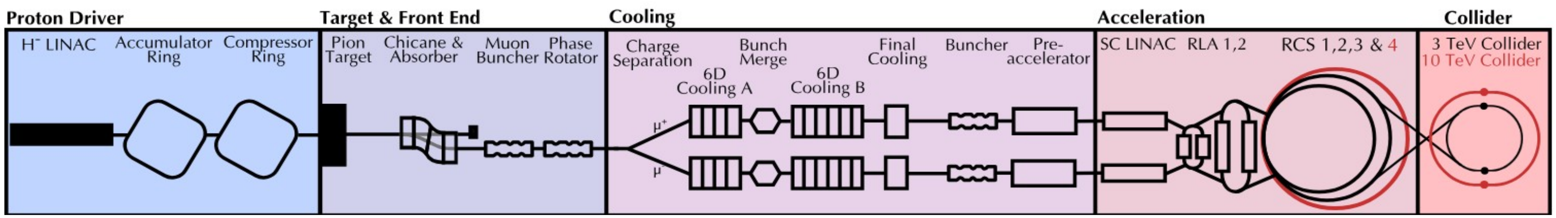
Brief introduction to Muon Collider

Muon collider is an attractive and exciting future collider option as:

- Advantages of "pp" collider due to high mass or low synchrotron radiation, hence provides us high energy reach for "discovery".
- Advantages of "e+e-" collider since muons are also fundamental particles, therefore high precision measurements for "hints" to new-physics.
- Compact machine hence more "cost-effective".



Credit: C. Cesarotti

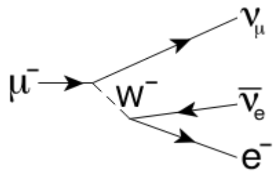


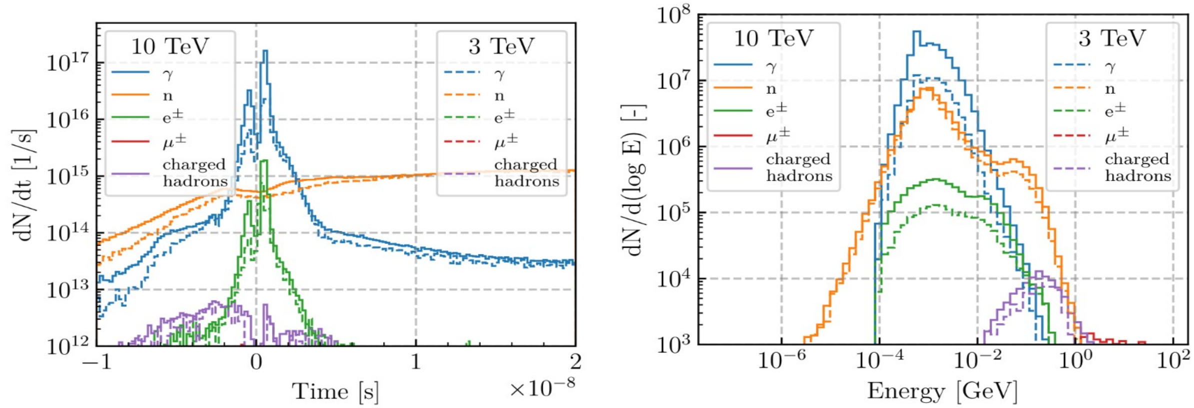
Conceptual layout of the muon collider (ESPPU submission)

For E_{COM} = 10 TeV: 10 km ring → 30 kHz bunch-crossing rate → instantaneous luminosty ~20 x 10^{34} $cm^{-2}s^{-1}$

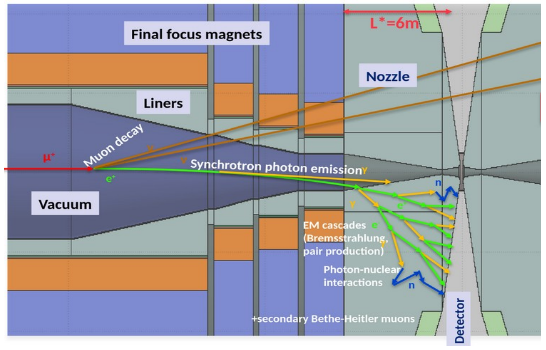
Beam Induced Backgrounds (BIB)

- Source: From decay of stored muons (τ ~ 0.1 s) around the collider ring.
- Impact: Very high energy electrons produced, interacting with the surrounding material.
- Consequently: Soft photons/neutrons/electrons secondaries from >O(10 m) from interaction point, entering the detector volume.
- Characteristics: Long out-of-time tail soft particles, not dramatic collider energy dependence.





Time window [-1, 15] ns: O(10^8) >100 KeV photons, O(10^7) >10^{-5} eV neutrons and O(10^6) >100 KeV e+/e-



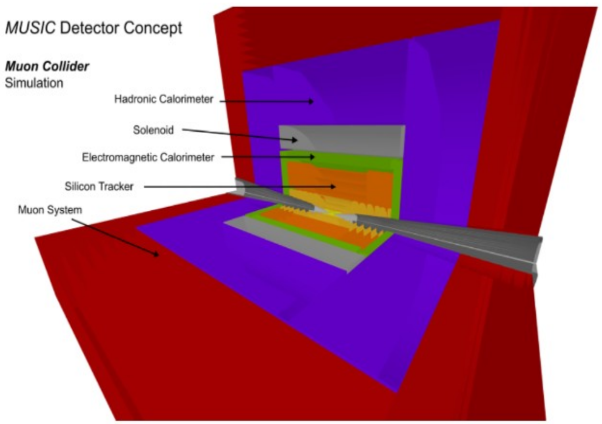
Dedicated shielding from tungsten nozzles to suppress large flux of high-energy electrons

10 TeV detector concepts

MUSIC detector

(Solenoid between ECAL and HCAL)

EU strategy input



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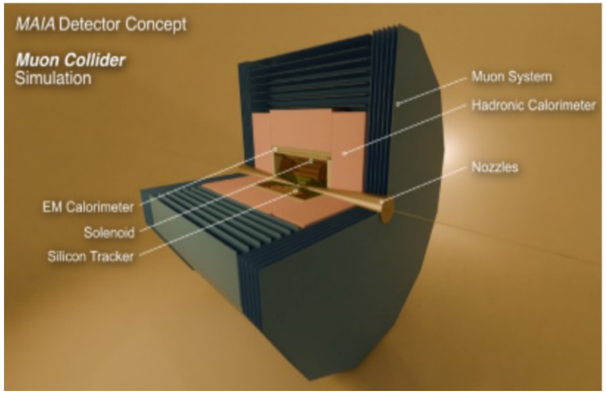
MAIA detector

(Solenoid inside Calorimeters)

arXiv: 2502.00181



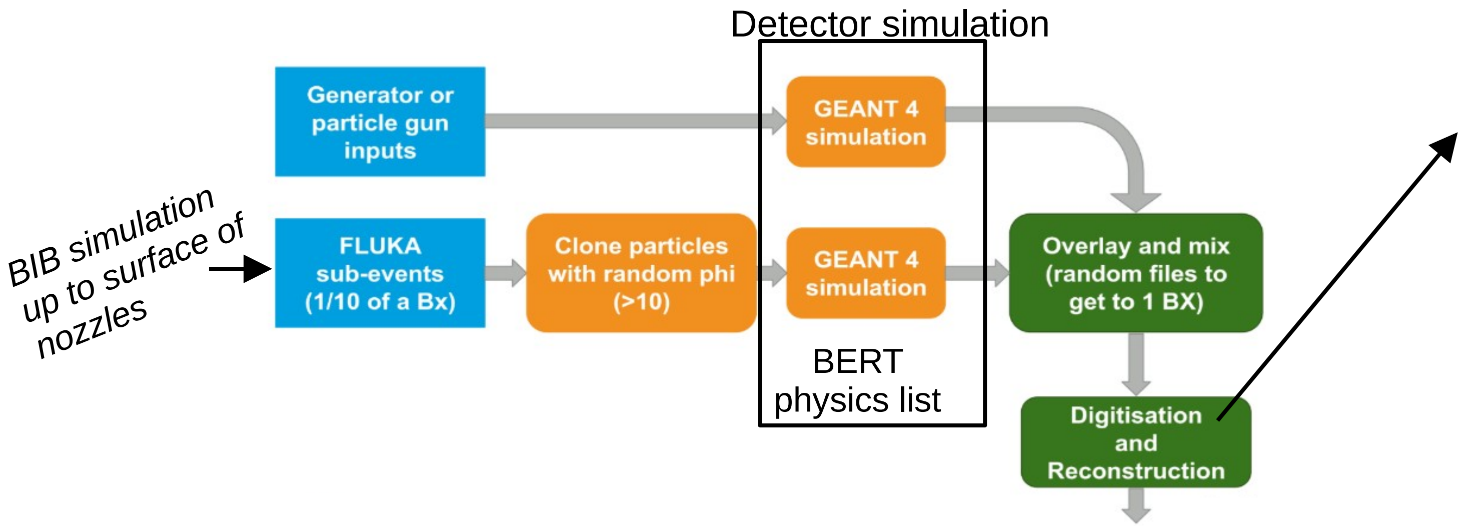
Sub-Detector MAIA/MUSIC Units	Technology	# Layers /Rings	"Cell" Size µm^2	Sensor Thickness µm	Hit Time Resolution ps	Signal Time Window ns
Vertex Barrel	Pixels	4*/5	25 x 25	50	30	[-0.18, 15.0]
Vertex Endcap	Pixels	4	25 x 25	50	30	[-0.18, 15.0]
Inner Barrel	Macro-Pixels	3	50 x 1000	100	60	[-0.36, 15.0]
Inner Endcap	Macro-Pixels	7	50 x 1000	100	60	[-0.36, 15.0]
Outer Barrel	Macro-Pixels	3	50 x 10000	100	60	[-0.36, 15.0]
Outer Endcap	Macro-Pixels	4	50 x 10000	100	60	[-0.36, 15.0]

Tracker design layout

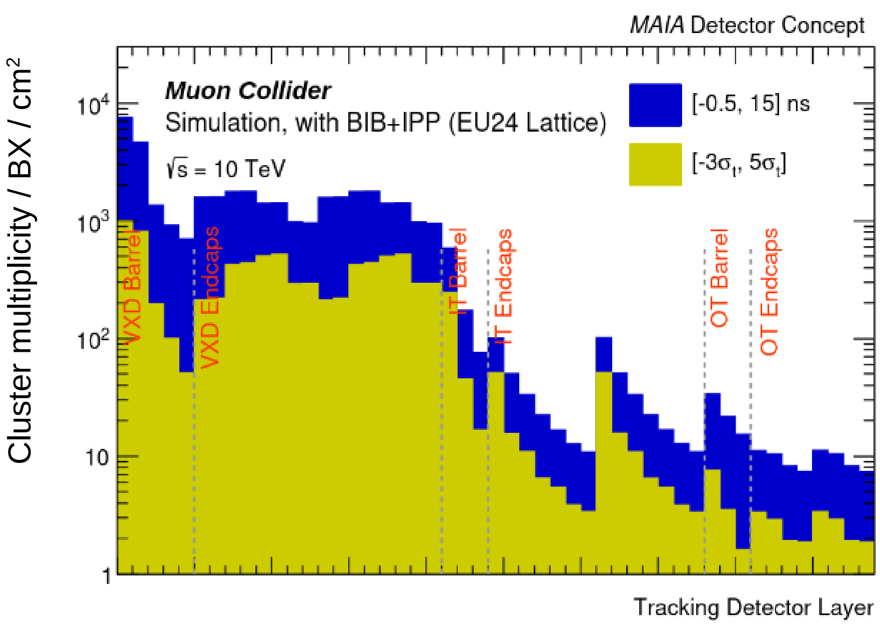
- All silicon-based
- Position precision
- Fast timing
- High radiation tolerance
- Low material budget

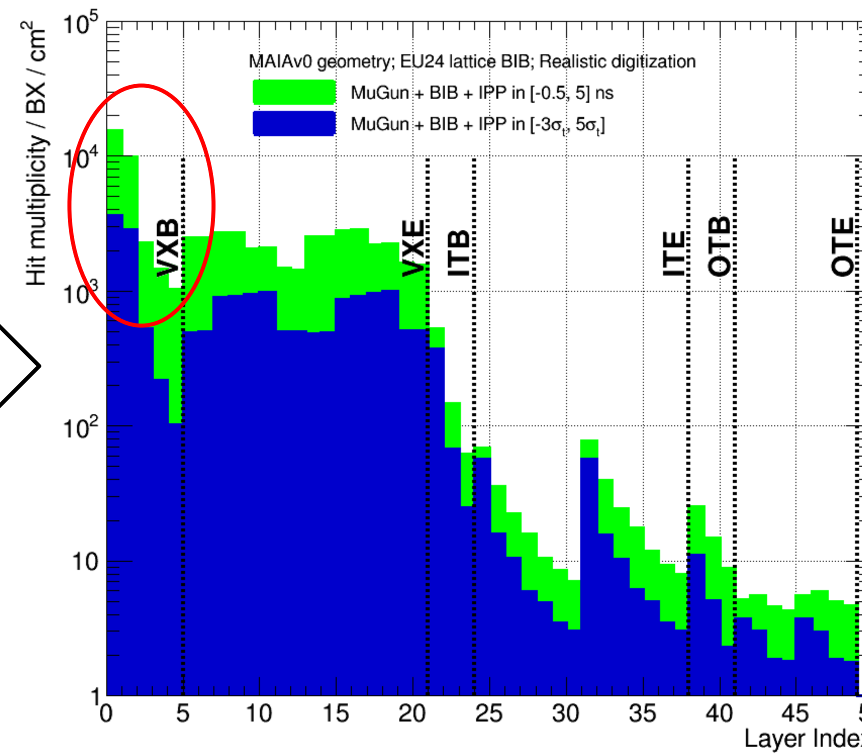
More details in previous talk

Simulating muon collider

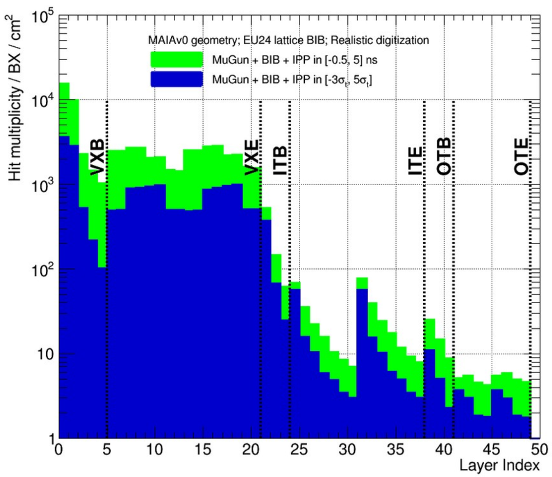


<u>Digitization:</u> real particle-material interaction and emulation of detector electronics response. Hence, information about individual pixel hits per reconstructed cluster position available.





Readout data volume



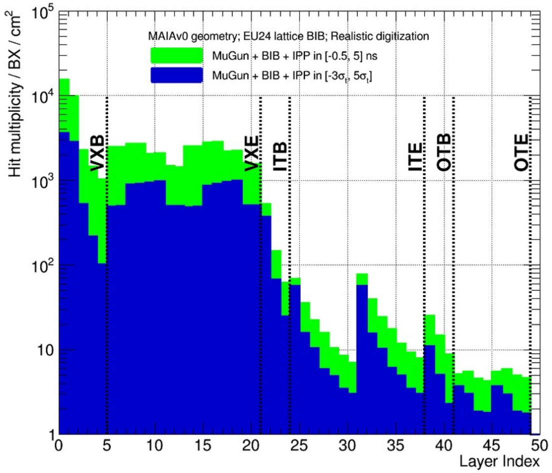
- Bunch crossing frequency, f_{BX} = 30 kHz
- Maximum hit data size ~ 40 bits = 5 Bytes
  (e.g. 8-bit pixel row within core, 8-bit pixel column within core, 10-bit BCID or timing info, 4-bit ToT, 8-bit pixel cluster pattern or hit-map, 2-bit core address)
- Let's take FE size of 2 cm x 2 cm (RD53B chip).
- Data rate / FE (Bytes per sec) = Occupancy x FE_area (cm^2) x f_{BX} x hit-size (Bytes)

Loose hit-time window → Data rate/FE (Gbps) with [-0.5, 5] ns

Tight hit-time window → Data rate/FE (Gbps) with [-3σT, 5σT]

Sub-detector layer	Occupancy (hits/BX/cm2) with [-0.5, 5] ns	Occupancy (hits/BX/cm2) with [-3σT, 5σT]	RAW data size (/FE/BX) (kB) with [-0.5, 5] ns	Data rate/FE (Gbps) with [-0.5, 5] ns	Data rate/FE (Gbps) with [-3σT, 5σT]
VXB L0 (σT=30 ps)	15422 (40%)	3600 (10%)	300	73.6	16.8
VXE L5 (σT=30 ps)	5541	1979	110	26.4	9.6
ITB L0 (σT=60 ps)	528	373	10	2.4	1.6
ITE L0 (σT=60 ps)	145	114	2.9	0.7	0.5
OTB L0 (σT=60 ps)	25	11	0.5	0.1	0.05
OTE L0 (σT=60 ps)	10	7.4	0.2	0.05	0.03

Readout data volume



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Loose hit-time window　　Tight hit-time window

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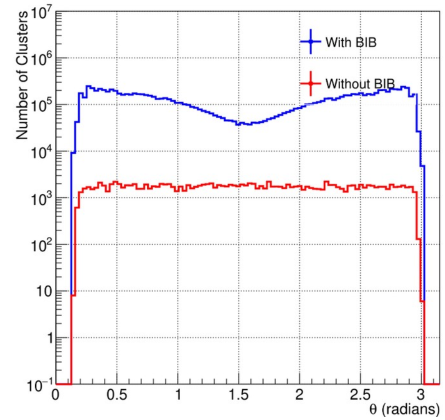
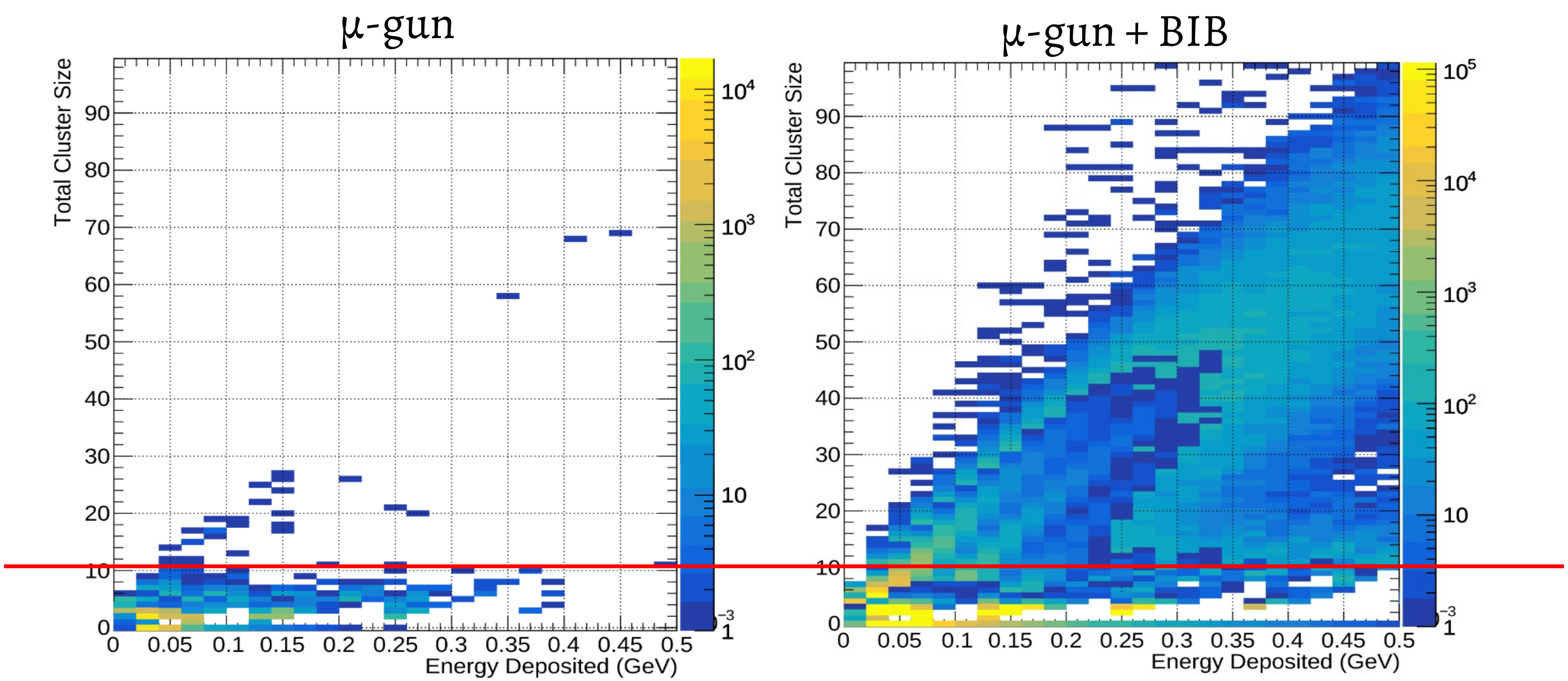
- Even the tight time-window constraints result in 10% tracker occupancy in innermost layer – 100x higher than ATLAS ITk for HL-LHC (with 1.28 Gbps FE links)!!
- However, not realistic for detector to maintain DAQ synchronization at picosecond-level (i.e. with tight hit-time window).

Pixel-based BIB suppression

- BIB produces several soft particles in the forward region.
- As a result, BIB intersects the tracker layers at shallow incidence angles, thereby hitting more pixels along the path.
- Signal undergoes normal incidence, hence shorter cluster sizes.

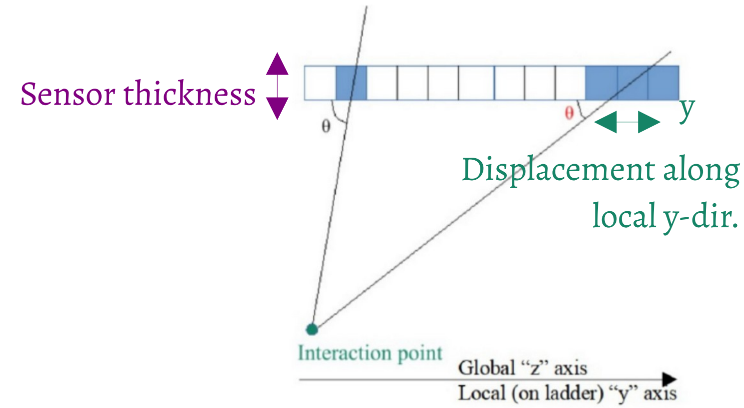




Can leverage this to remove BIB clusters from every BX → less data volume per FE to be readout.

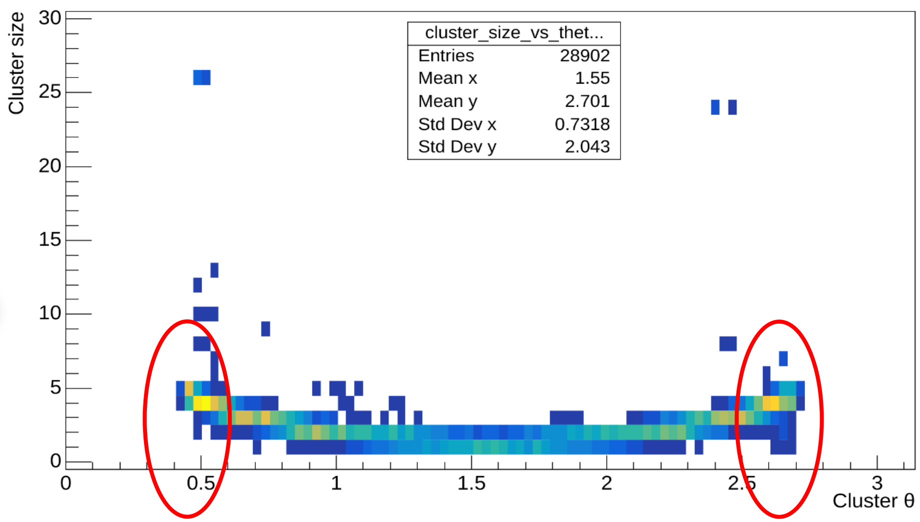
Cluster Shape Analysis for BIB rejection

Using correlation between incidence angle and number of pixel hits per cluster to reject long clusters.



MAIA: VXB Layer 1, sensor thickness = 50 μm, y-pitch = 25 μm

μ-gun



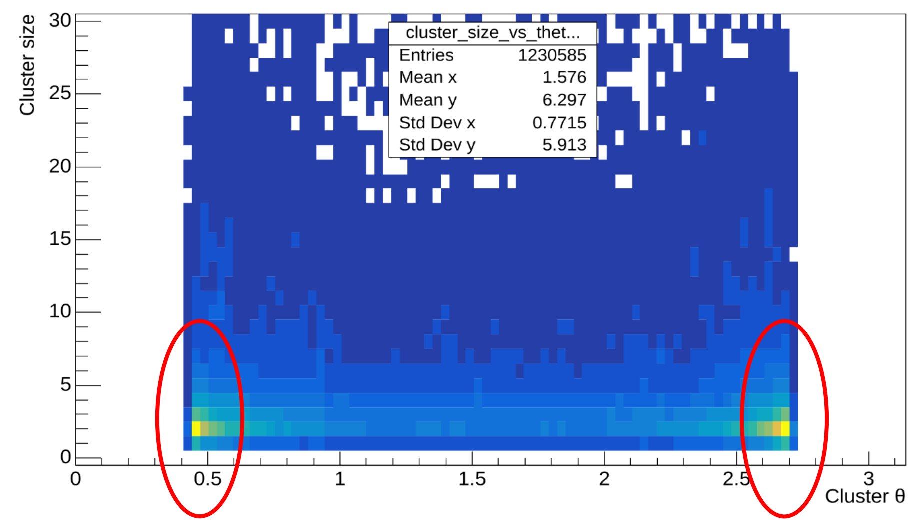
$\tan\theta = 50\mu m/y$

$\tan(0.5) \sim 0.5 = 50\mu m/y$

$y = 100\mu m$

y/pitch ~ 4 pixels

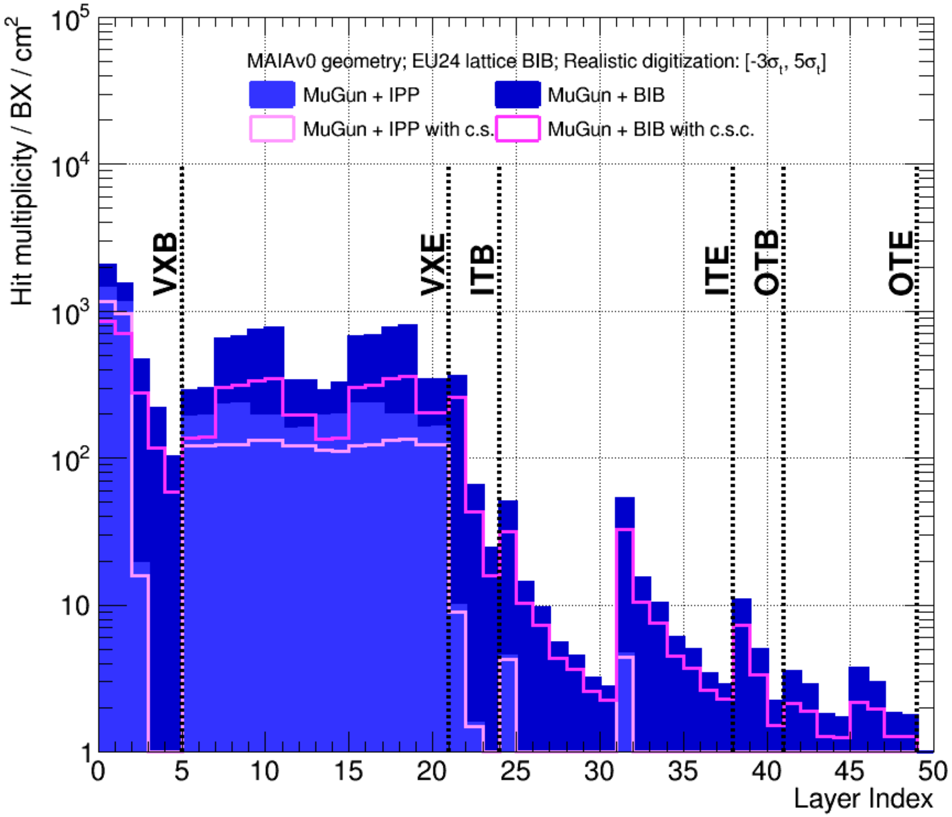
μ-gun + BIB



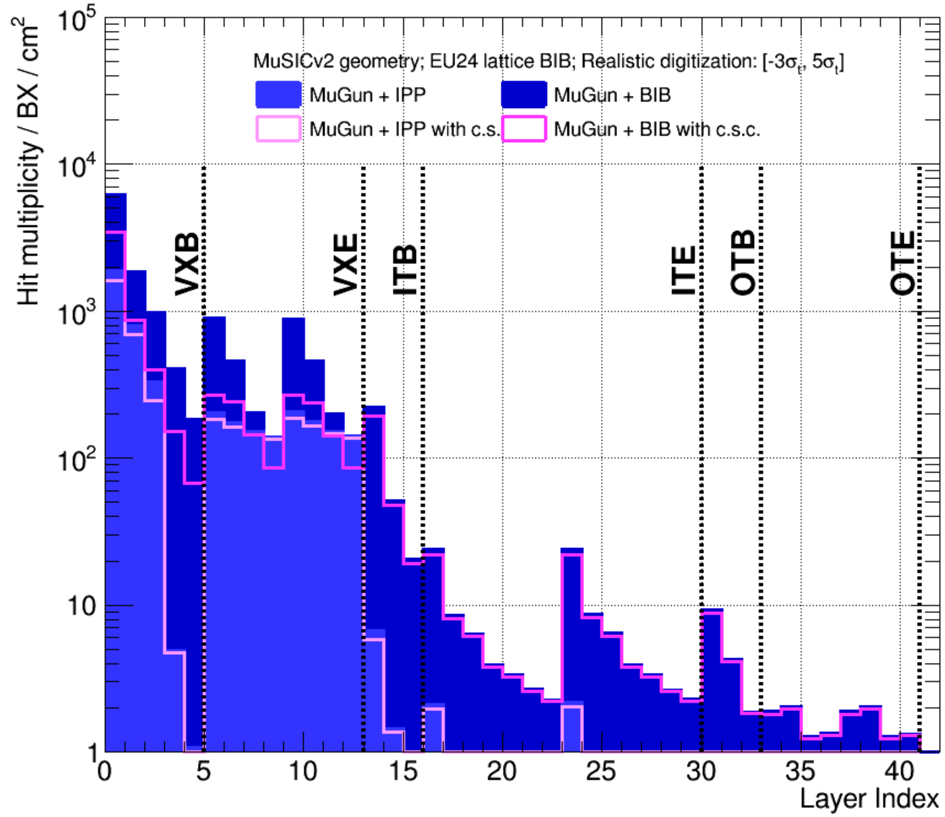
BIB particles either have very short clusters at same angles as signal (due to low-momentum particles) or excessively long clusters due to shallow incidences.

Results

MAIA detector



MUSIC detector

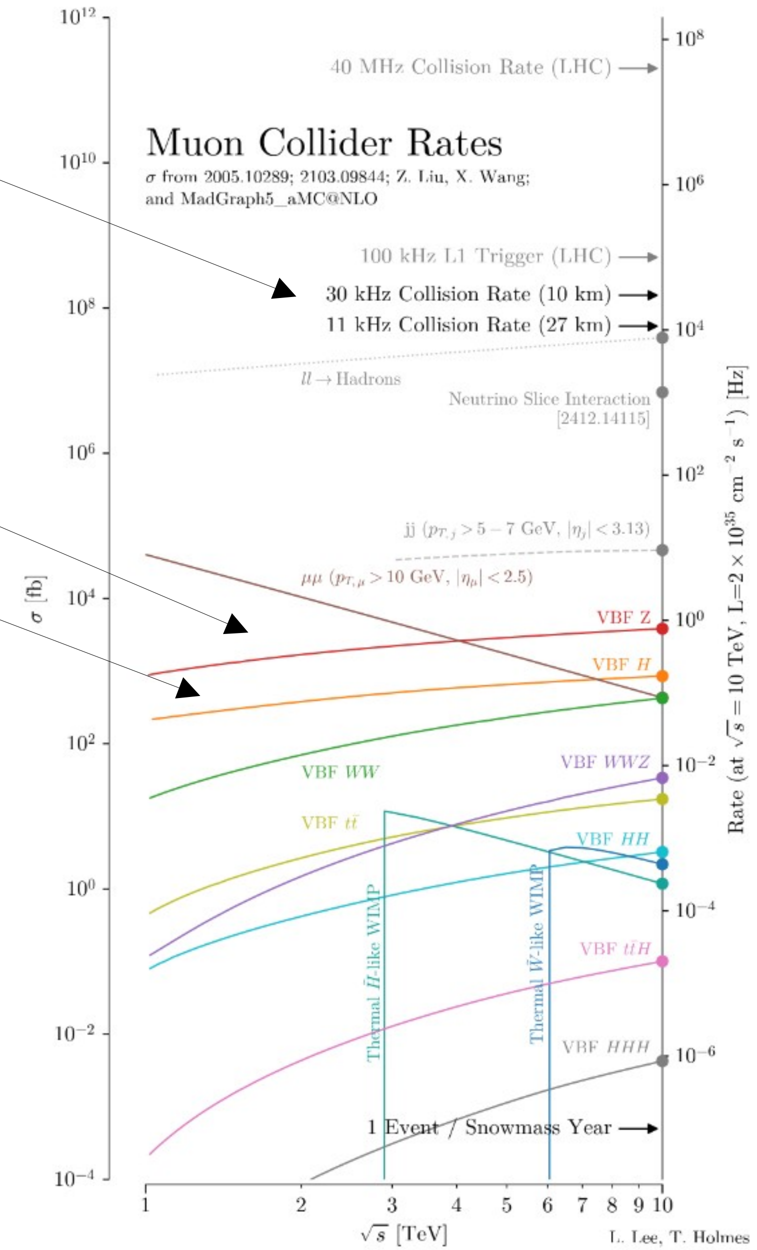


- From first principles, we can cut down up to 20-30% BIB clusters (with <5% loss for signal clusters) from each layer of subdetector!
- For ex, in VXB L0 of MAIA detector, tracker occupancy down from 2000 to 850 hits/BX/cm^2 → 50% reduction in bandwidth!
- Starting to explore MVA-based methods for better background rejection over signal.

Few thoughts on Trigger and Data Acquisition System…

Event rates of interesting physics

- **Bunch crossing (BX) rate ~ 30 kHz**
  - i.e. 30000 events/sec
- Physics processes at 10 TeV (in the order of decreasing rates):
  - **VBF Z** ~ 1 Hz i.e. 1 event/sec
  - **VBF H** ~ 0.1 Hz i.e. 1 event/ 10 secs
  - **VBF WW, μμ → μμ** ~ 0.08 Hz
  - **VBF WWZ, VBF tt** ~ 0.005 Hz
  - …
- Average number of interactions per BX (or effective pileup) = sum of rates of all processes/BX rate ~ 10^{-5} – 10^{-6} (ignoring inclusive jets production).
- That is, roughly 1-10 interesting physics events per million BXs!
- That is, most of the BXs are just … uneventful (ignoring ubiquitous muon decay backgrounds in every event).



So, do we need triggers for such few events?

↓

How much infrastructure (i.e. hardware, computing and cost) does it take to create a triggered-readout?

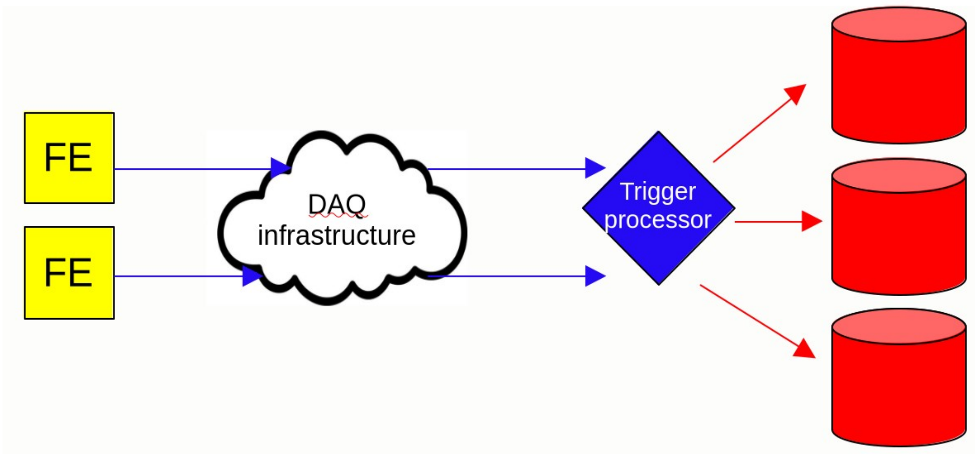
↓

Is triggerless-streaming possible at muon collider?

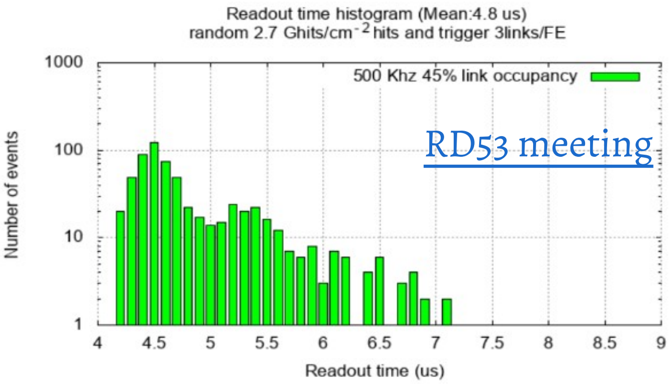
Depends on how fast we can process the data and move it out of FE, such that we keep up with the data volume and BX rate.

Triggerless streaming

A simplified illustration of triggerless scheme



- Very-high bandwidth required for continuous readout from each detector link.
- No buffers (hit-memories) needed on chip but need to implement smart methods (e.g. timing-based and/or cluster shapes-based) to do data reduction at FE-level.
  - Need to keep a check on the chip processing time and power budget. E.g. for 2.7 Ghit/cm^2 hit-rate in the innermost 25 µm x 25 µm pixels at 500 kHz rate (15% occupancy), RD53B chip can take up to 7 µs with 3 links @ 1.28 Gbps to fully readout.
- Can throw away uninteresting events at the “software-level” and split streams into different data-types for storage.



RD53 meeting

Conclusion

- Muon collider is a very attractive future collider option, with huge potential for both SM precision measurements and new discoveries.
- Many exciting challenges ahead to make sure TDAQ is not the precision bottleneck.
- Rates of interesting physics events are below O(1 Hz) for instantaneous luminosity of 2 x 10^{35} $cm^{-2}s^{-1}$ at 10 TeV, with average pileup interactions per BX of 10^{-5}-10^{-6}.
- Triggerless-streaming can be a workable overall choice for tracker detector, with some on-chip processing (e.g. based on hit time-of-arrival and cluster sorting), without significantly increasing the timing and power budget.
- AI/ML tools should be employed wherever necessary in meeting these challenges.
- Simultaneously, we must develop and maintain versatile heterogeneous frameworks and platforms for faster and higher-capacity readout, including new technologies such as wireless network to reduce material budget.