

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

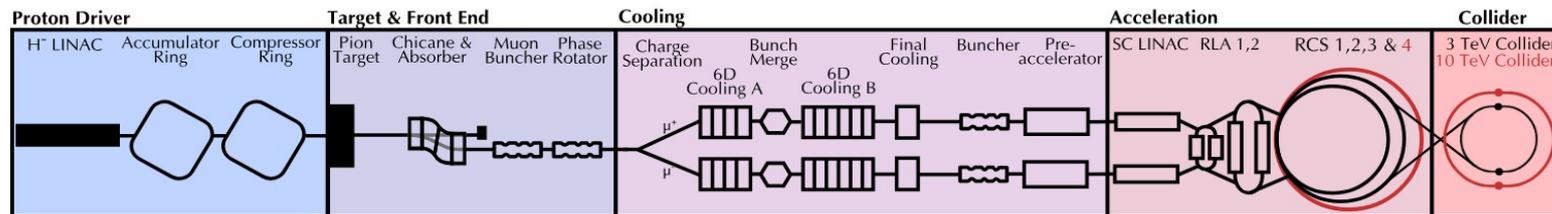
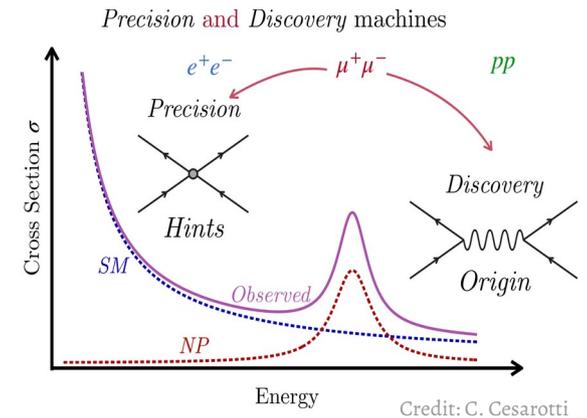
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Interactions at High Energies  
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# Brief introduction to Muon Collider

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

- 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”.



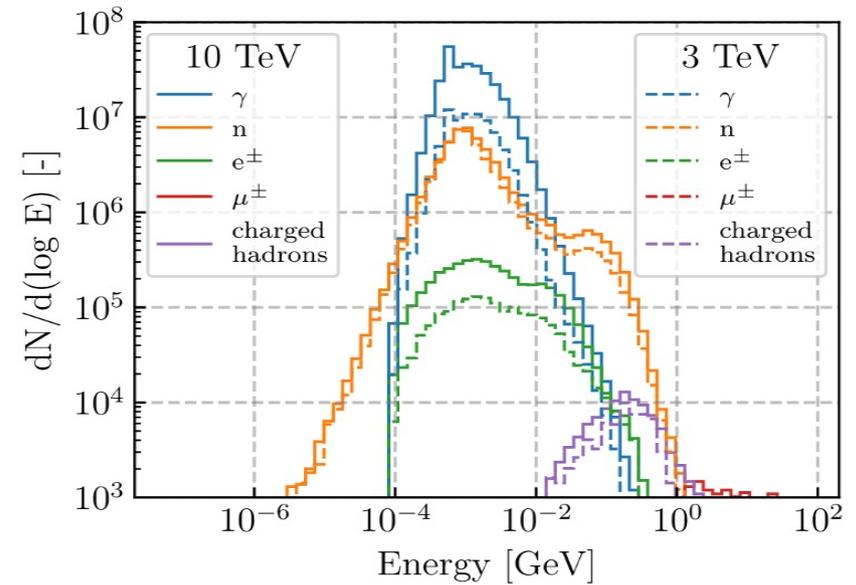
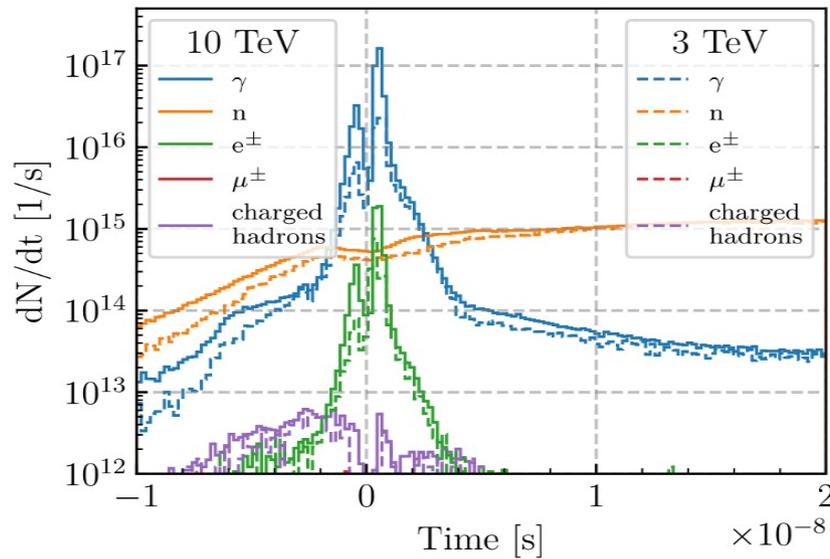
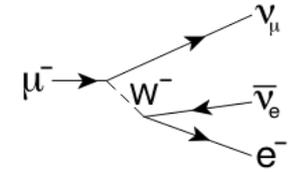
Conceptual layout of the muon collider (ESPPU submission)

For  $E_{\text{COM}} = 10 \text{ TeV}$ : 10 km ring  $\rightarrow$  Single-bunch  $\mu^+/\mu^-$  beams ( $\sim 2 \times 10^{12}$  muons/bunch)  $\rightarrow$  30 kHz bunch-crossing frequency  $\rightarrow$  instantaneous luminosity  $\sim 20 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

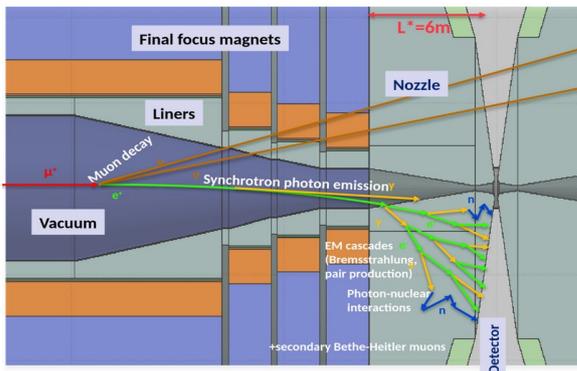
More on muon colliders in Sergo's [talk](#)

# Beam Induced Backgrounds (BIB)

- Source: Mainly from decay of stored muons around the collider ring ( $\sim 6.4 \times 10^8$  decays/turn).
- Impact: Very high energy electrons produced, interacting with the surrounding material.
- Consequently: Soft photons/neutrons/electrons secondaries produced far away, traveling towards the interaction point.
- Characteristics: Long out-of-time tail soft particles without much dependence on collider energy, entering the detector volume.



Time window [-1, 15] ns w.r.t. BX:  $O(10^8)$   $>100$  KeV photons,  $O(10^7)$   $>10^{-5}$  eV neutrons and  $O(10^6)$   $>100$  KeV  $e^\pm$



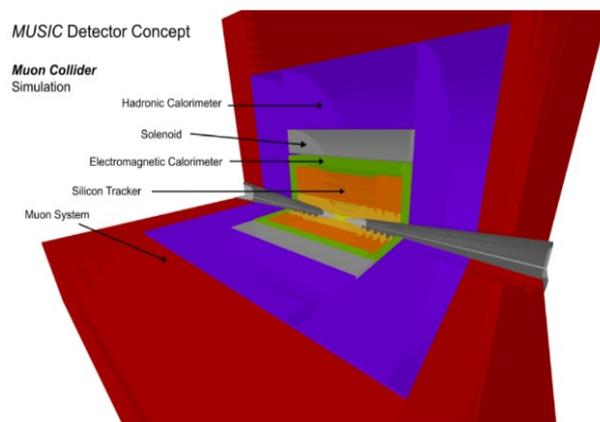
Dedicated shielding from tungsten nozzles to suppress large flux of high-energy electrons.

# 10 TeV detector concepts

## MUSIC detector

(Solenoid between ECAL and HCAL)

EU strategy input



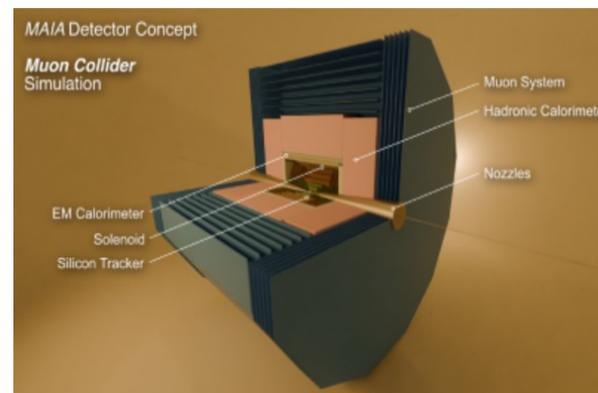
Massimo's [talk](#)

&

## MAIA detector

(Solenoid inside Calorimeters)

arXiv: 2502.00181



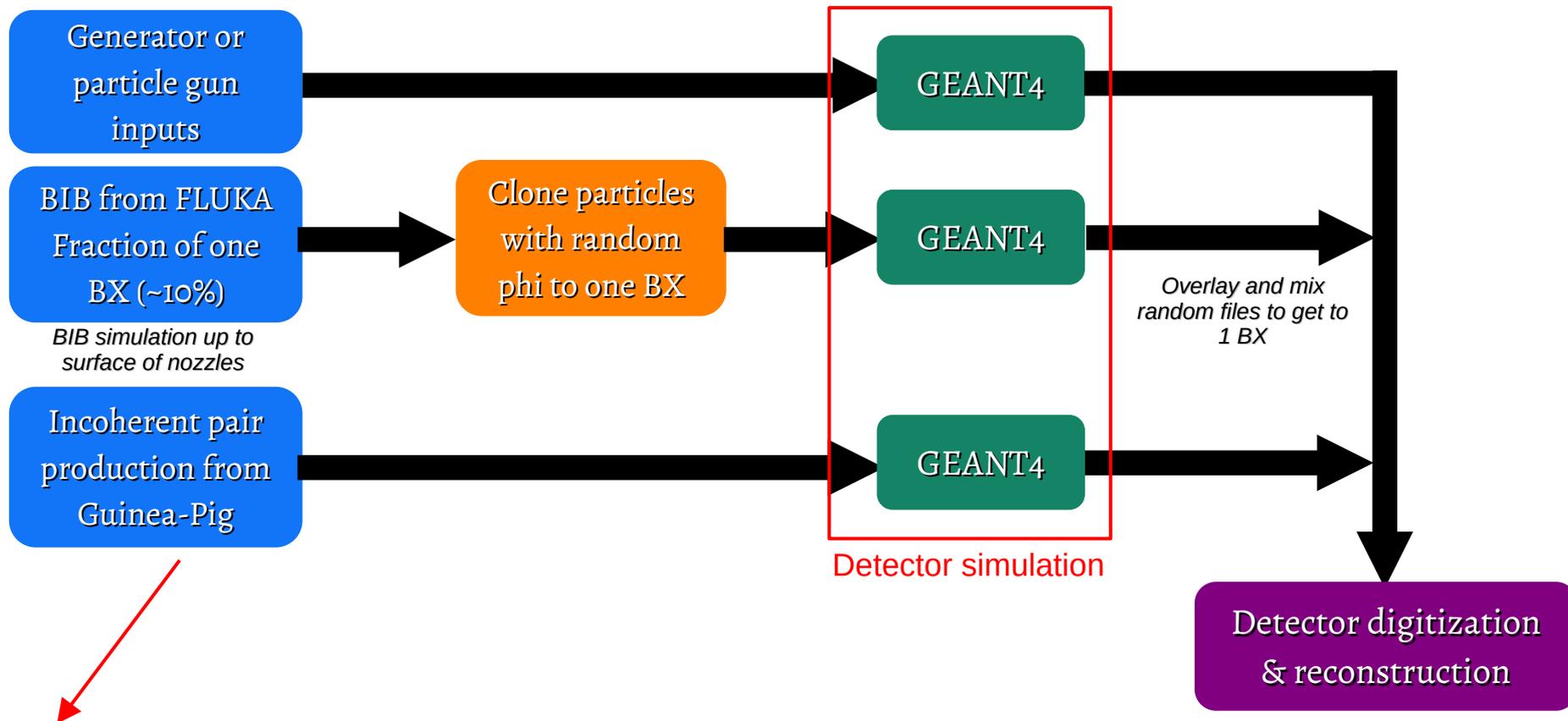
Sub-Detector MAIA/MUSIC Units	Technology	# Layers /Rings	"Cell" Size $\mu\text{m}^2$	Sensor Thickness $\mu\text{m}$	Hit Time Resolution ps	Signal Time Window ns
Vertex Barrel	Pixels	4*/5	25 x 25	50	30	[-0.18, 15.0]
Vertex Endcap	Pixels	4	25 x 25	50	30	[-0.18, 15.0]
Inner Barrel	Macro-Pixels	3	50 x 1000	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

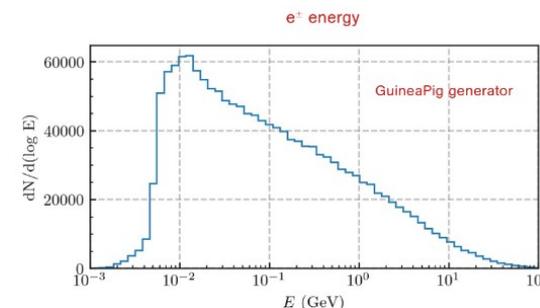
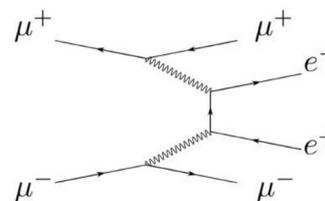
More details in previous [talk](#)

# Simulating muon collider



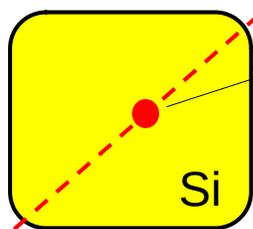
## Incoherent Pair Production (IPP) background

- Low energy  $e^+e^-$  pair production from real or virtual photons emitted by muons in the counter-rotating bunches.
- Produced at the interaction point, hence higher time-coincidence with signal.
- Higher energy tail as compared to BIB.



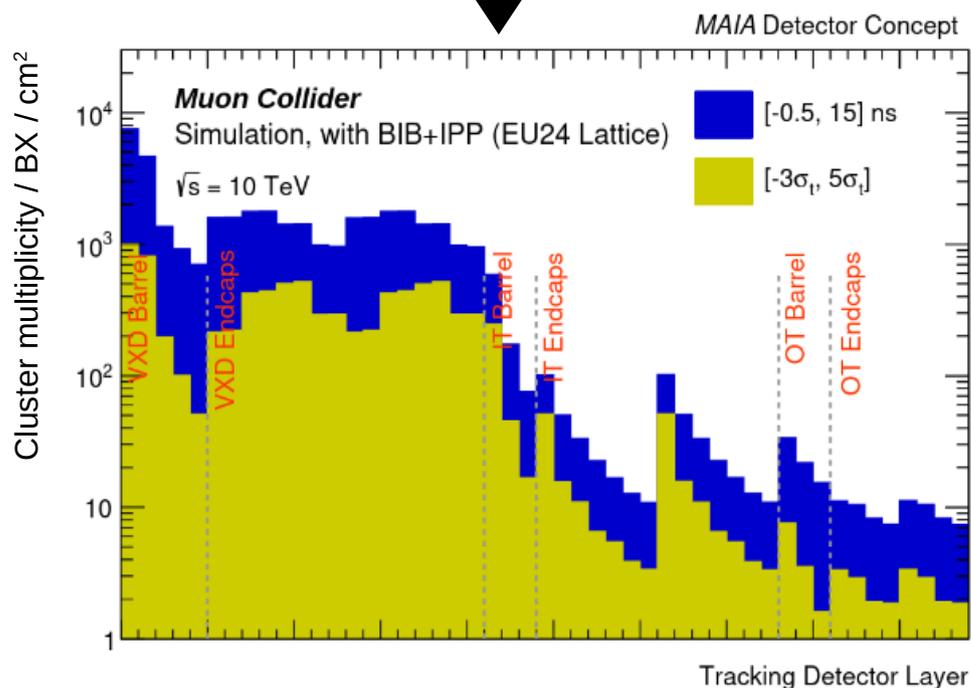
# Detector digitization

Simplified

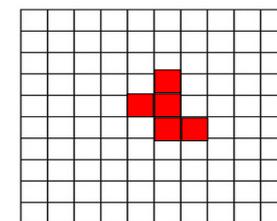
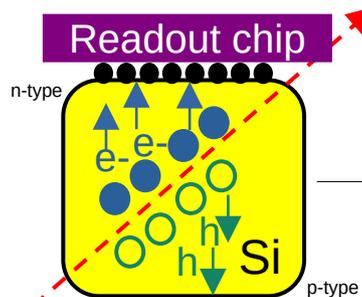


Average reconstructed "cluster" position from Geant4 energy deposit

Charged particle

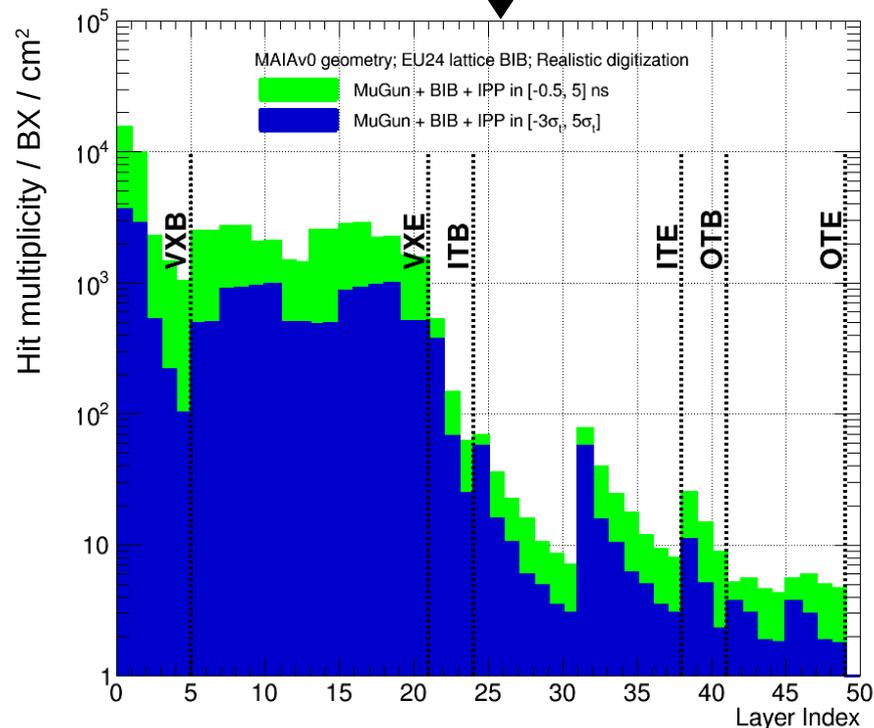


Realistic



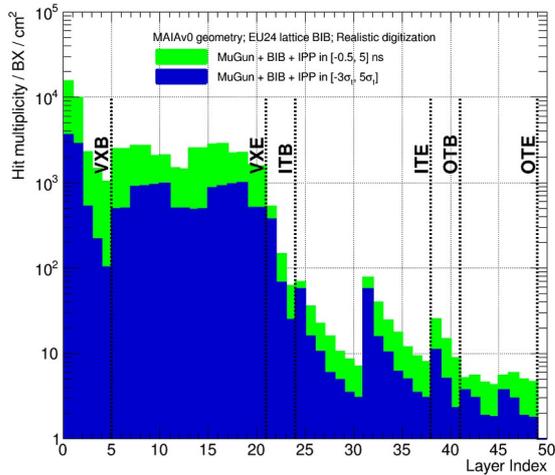
Pixel hits on ROC

Charged particle



Very high hit multiplicities per BX in the innermost layers of the detectors.

# Readout data volume



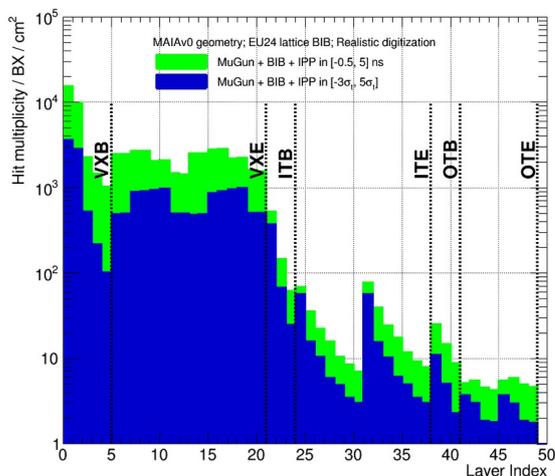
- Bunch crossing frequency,  $f_{\text{BX}} = 30 \text{ kHz}$
- Maximum hit data size  $\sim 40 \text{ bits} = 5 \text{ Bytes}$   
(e.g. 8-bit pixel row within core, 8-bit pixel column within core, 10-bit BCID or timing info, 4-bit ToT, 8-bit pixel cluster pattern or hit-map, 2-bit core address)
- Let's take FE size of 2 cm x 2 cm (RD53B chip, 153600 pixels).
- Including both BIB & IPP backgrounds.
- Data rate / FE (Bytes per sec) = Occupancy x FE\_area x  $f_{\text{BX}}$  x hit-size

Loose hit-time window      Tight hit-time window

Sub-detector layer	Occupancy (hits/BX/cm <sup>2</sup> ) with [-0.5, 5] ns	Occupancy (hits/BX/cm <sup>2</sup> ) with [-3 $\sigma$ T, 5 $\sigma$ T]	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 [-3 $\sigma$ T, 5 $\sigma$ T]
VXB Lo ( $\sigma$ T=30 ps)	15422 (10%)	3600 (2%)	300	73.6	16.8
VXE L5 ( $\sigma$ T=30 ps)	5541	1979	110	26.4	9.6
ITB Lo ( $\sigma$ T=60 ps)	528	373	10	2.4	1.6
ITE Lo ( $\sigma$ T=60 ps)	145	114	2.9	0.7	0.5
OTB Lo ( $\sigma$ T=60 ps)	25	11	0.5	0.1	0.05
OTE Lo ( $\sigma$ T=60 ps)	10	7.4	0.2	0.05	0.03

\*\*very conservative estimate

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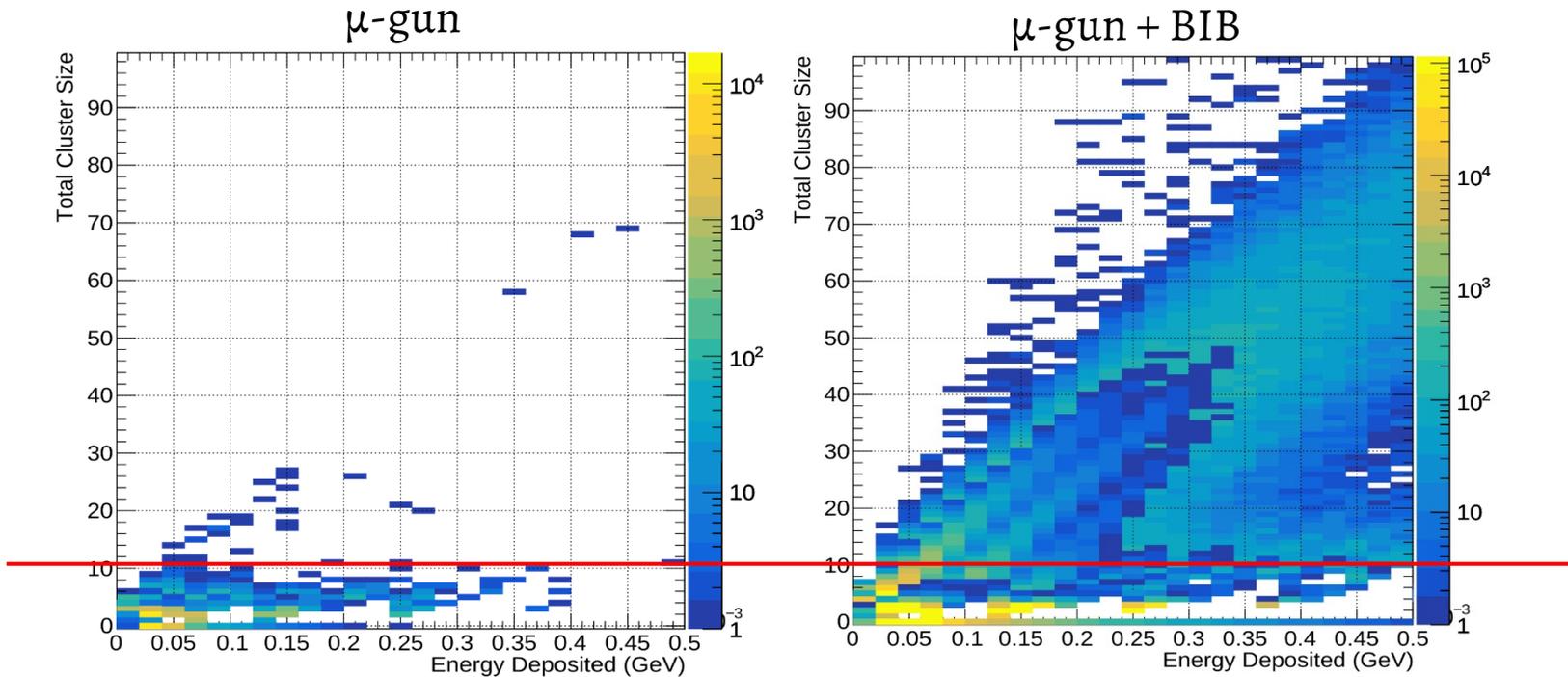
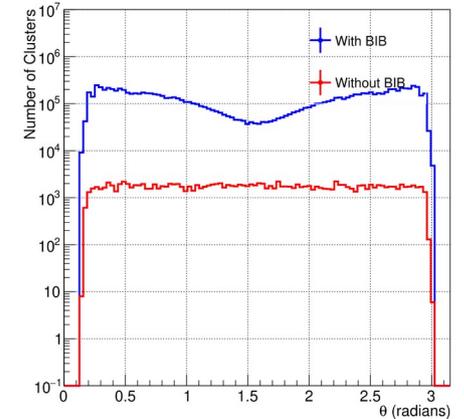
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- Even the tight time-window constraint results in 2% tracker occupancy in innermost layer – 20x higher than ATLAS Itk (with triggered-readout) for HL-LHC !!
- However, not realistic for detector to maintain DAQ synchronization for trigger-less readout at picosecond-level (i.e. with tight-time window requirement).

Need other ways than hit time-of-arrival purely to reduce data volume per FE to be readout!

# Pixel-based BIB suppression

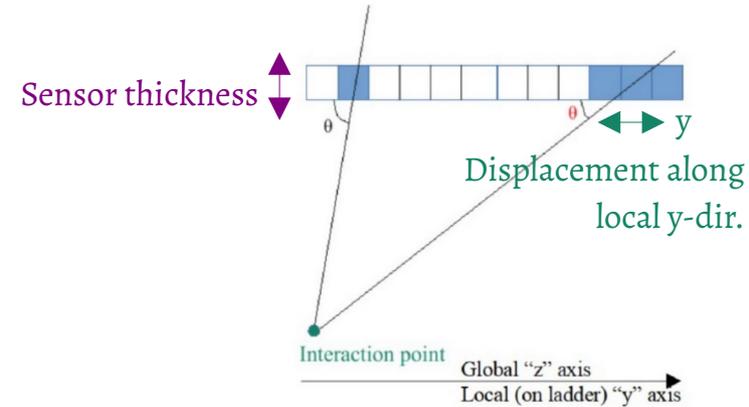
- BIB produces several soft particles in the forward region.
- As a result, BIB intersects the tracker layers at shallow incidence angles, thereby hitting more pixels along the path.
- Signal undergoes normal incidence, hence shorter cluster sizes.



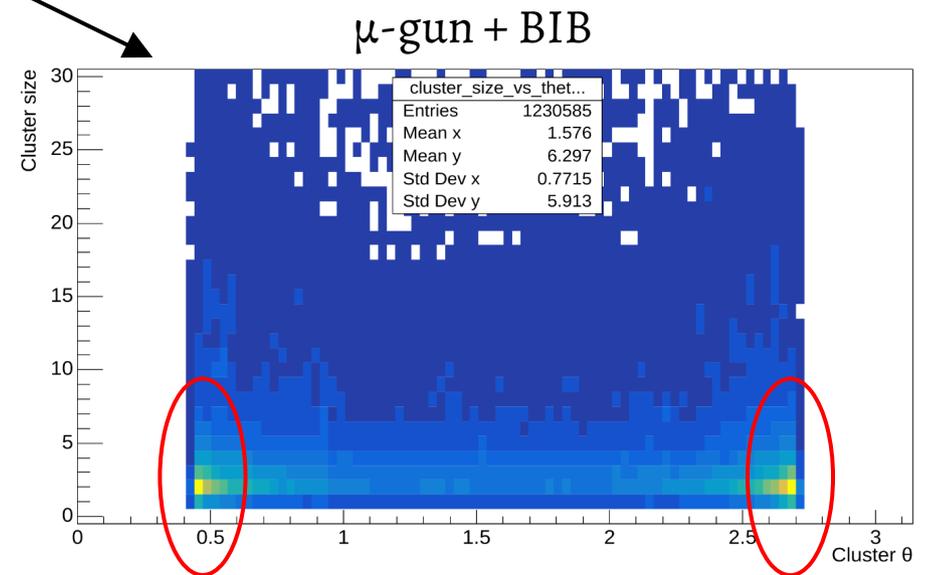
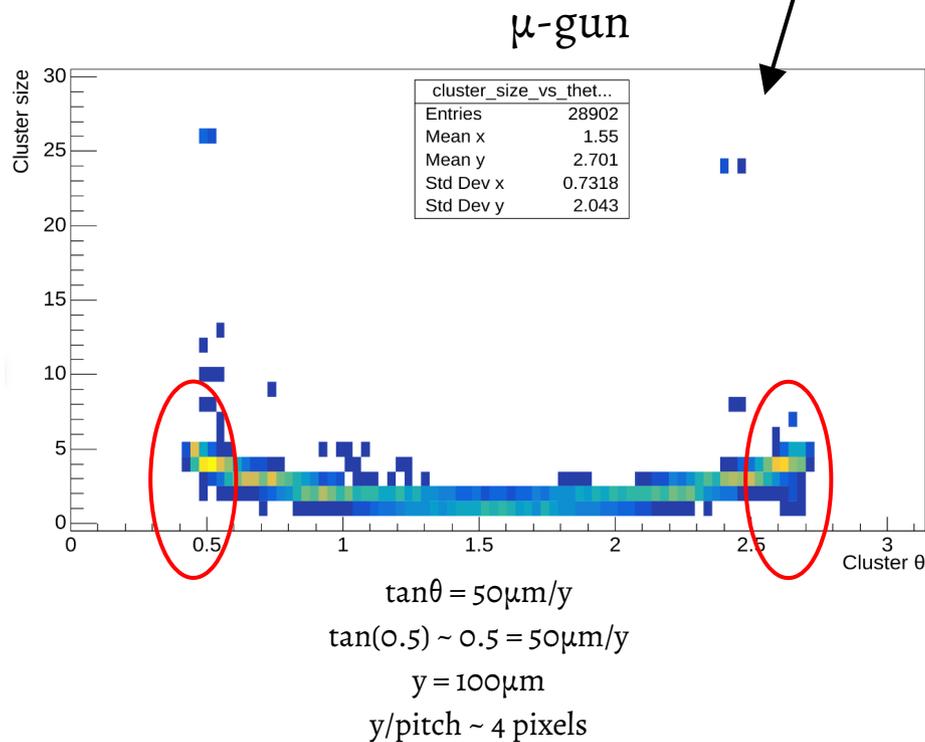
Can leverage this to remove BIB clusters from every BX  $\rightarrow$  less data volume per FE to be readout.

# 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  $\mu\text{m}$ , y-pitch = 25  $\mu\text{m}$

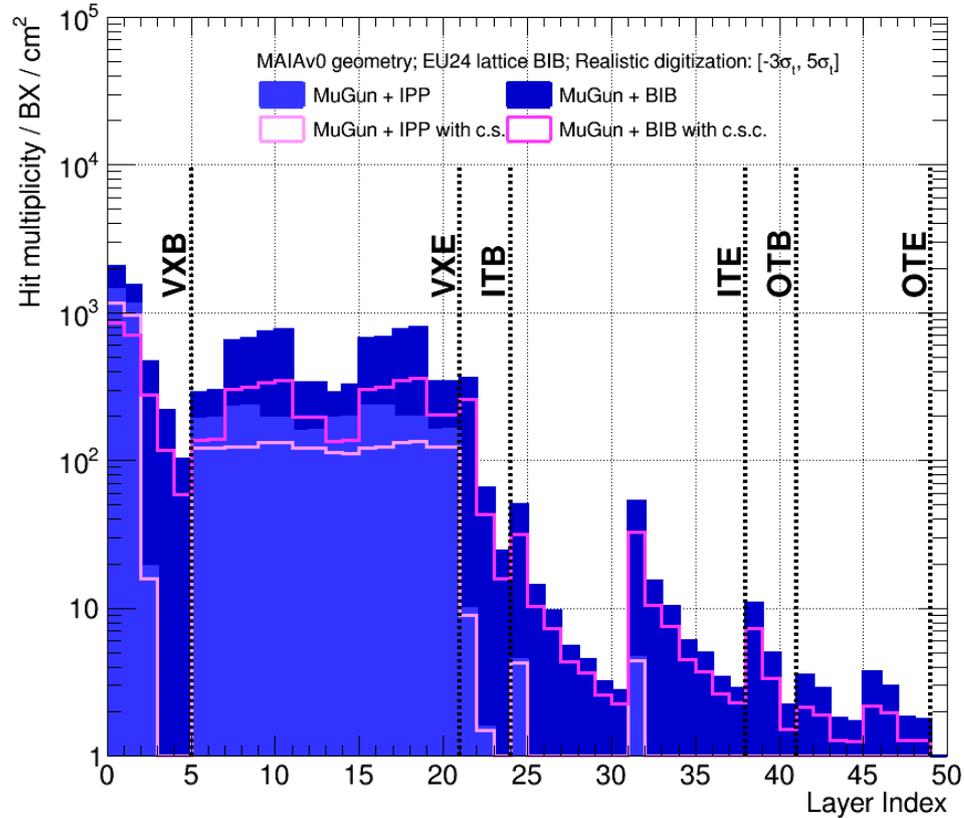


BIB particles either have very short clusters at same angles as signal (due to low energy particles) or excessively long clusters (due to shallow incidences).

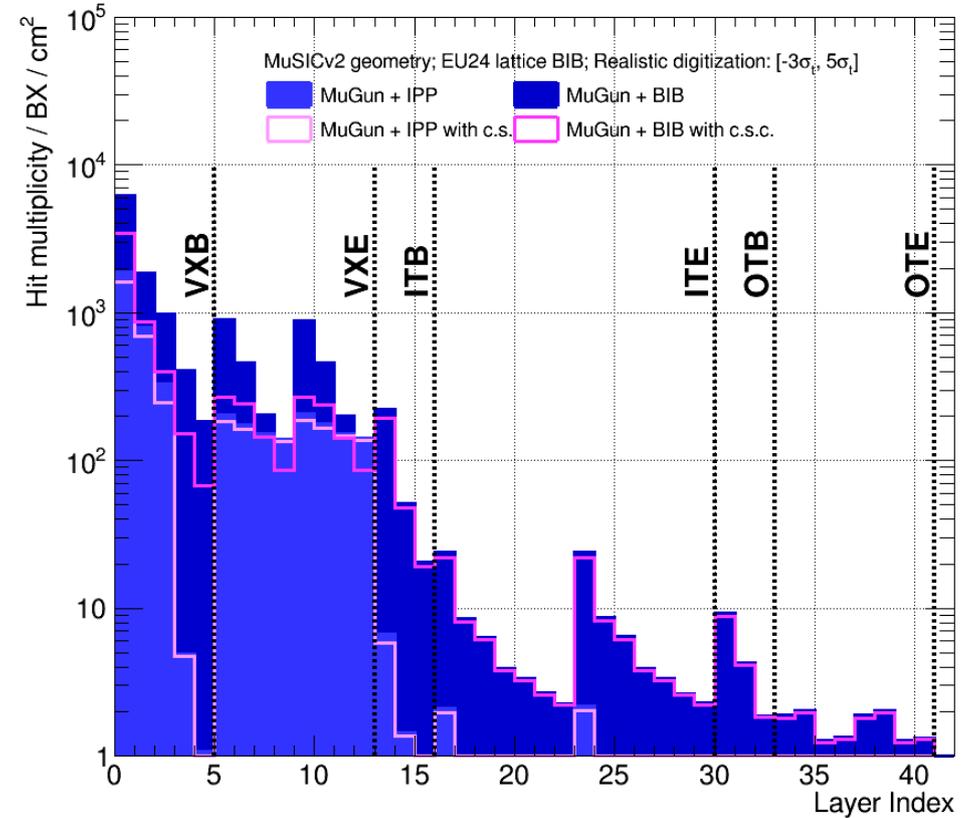
# Results

Removing clusters with larger pixel hits than expected at different incident angles ( $\theta$ ).

## MAIA detector



## MUSIC detector



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

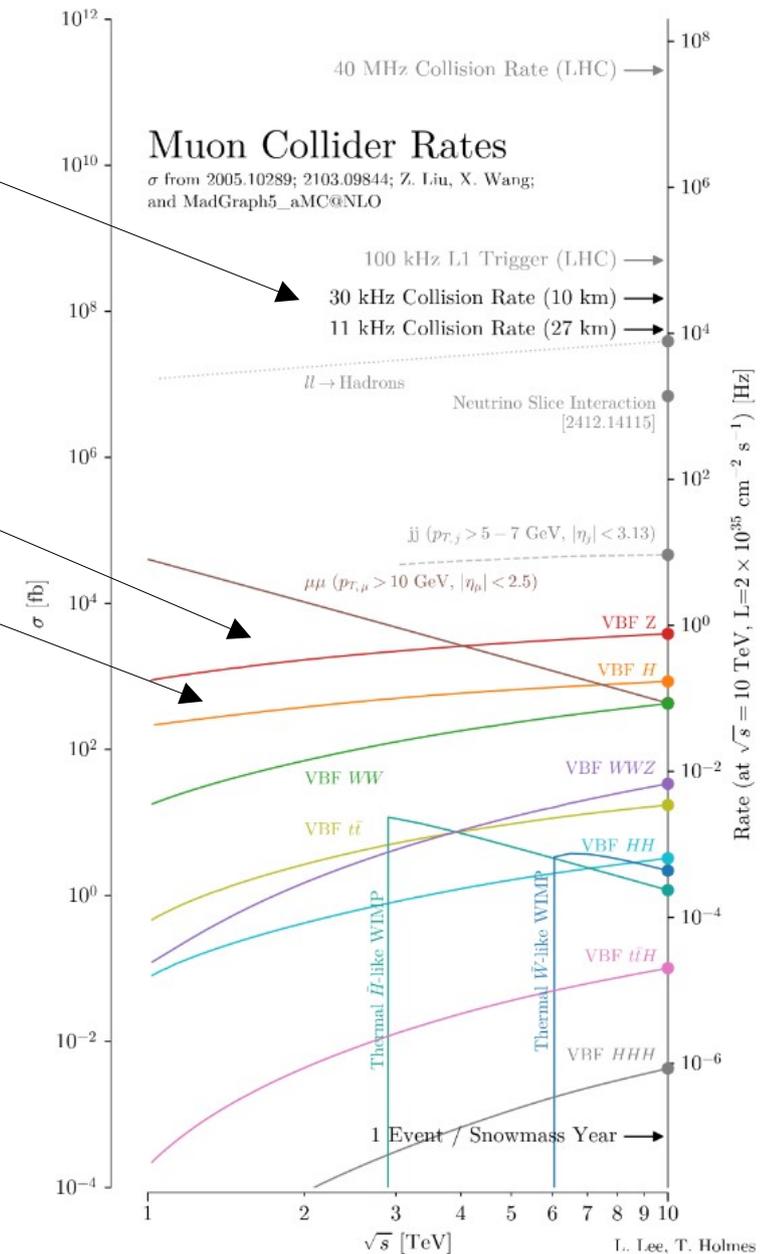
See Smart Pixels [talk](#)

So far assuming trigger-less (or streaming) readout, which is the chosen baseline for all detector subsystems for now...

But, is it an obvious choice ?

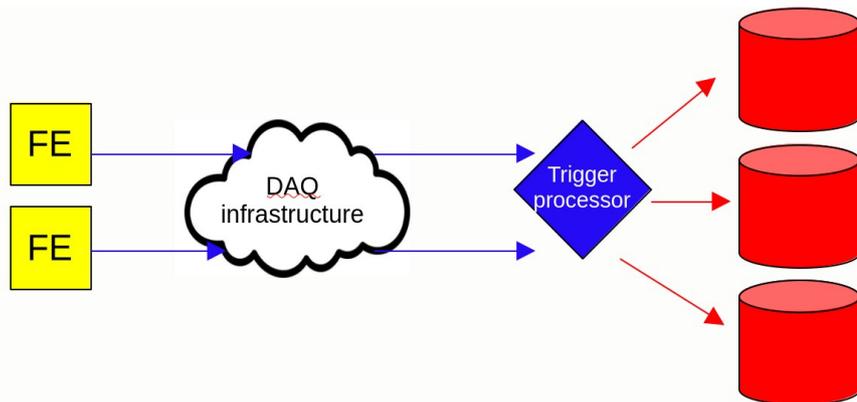
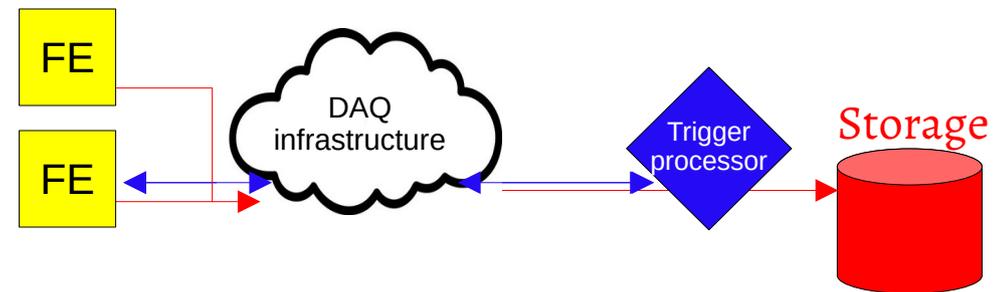
# Event rates of interesting physics

- 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,  $\mu\mu \rightarrow \mu\mu$  ~ 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).



## Trigger-based readout

- Perhaps a very simplified “hardware-level” and highly efficient trigger using calorimeter and muon subsystems or a track trigger for signal events.
- Still need to do on-chip processing if using track-based triggers, to be able to readout all hits per event and run quick track fitting.
- Cons: Need to do cost-benefit analysis for adding all that infrastructure for hardware trigger as well as timing and power budget for detector.

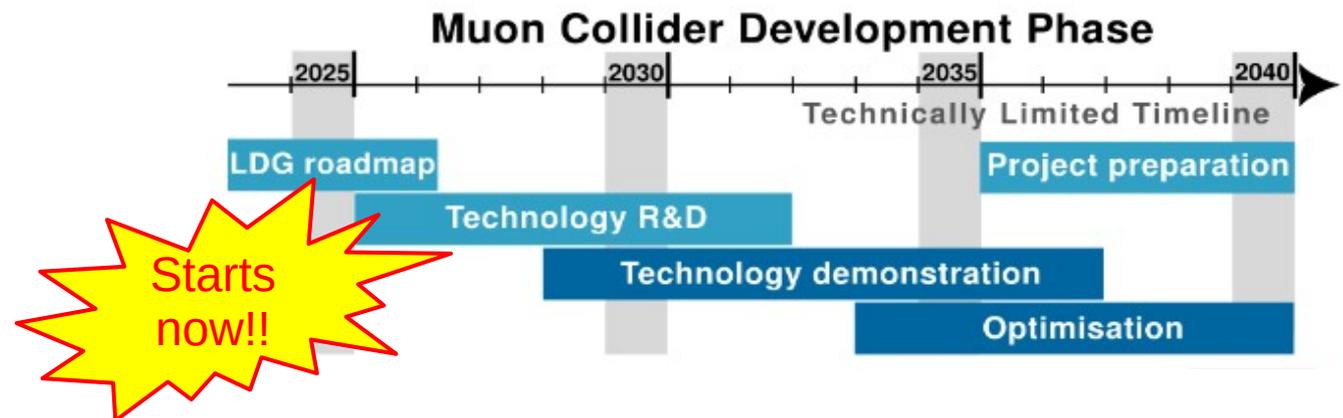


## Trigger-less readout

- 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, especially for the innermost tracker layers.
- Can throw away uninteresting events at the “software-level” to reduce storage requirements.
- Cons: On-chip processing necessary without increasing the time to keep up with BX rate and power constraints of detector.

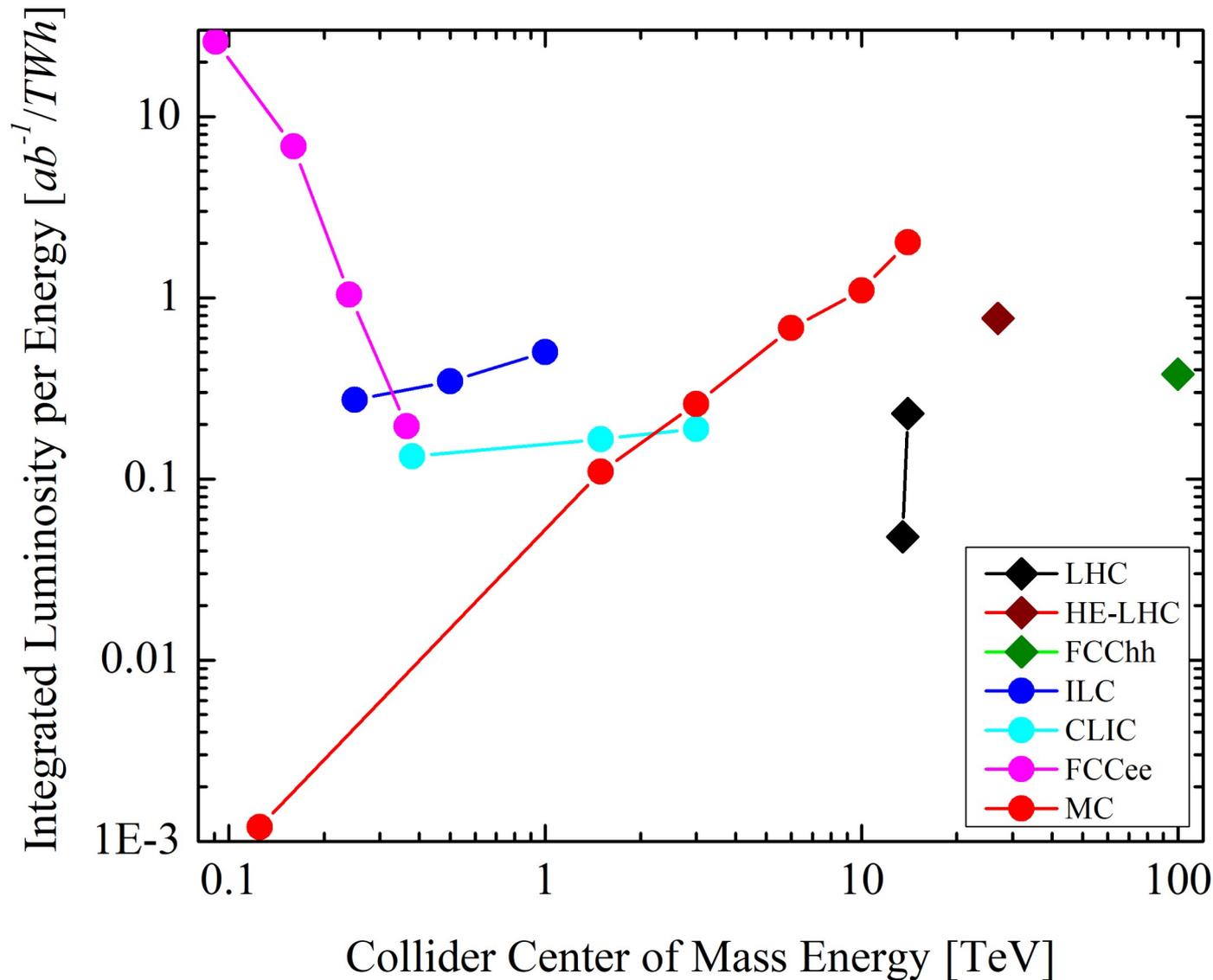
# Conclusion

- Muon collider is a very compelling future collider option, despite all the unique and significant technical challenges.
- Many advantages such as compact footprint, lower power consumption per beam energy and potential synergies with secondary neutrino physics program.
- Drives R&D and innovation for muon production, cooling, acceleration, and detector design; pushing the boundaries of technologies.
- A major detector challenge is handling the beam-induced backgrounds in each event and designing TDAQ system navigating BIB.
- A combination of on-chip processing using hit timing and cluster-shape based rejections can work well with either a trigger-based or a trigger-less readout.
- Need to systematically study the efficiency achievable with a very simplified trigger, timing vs power constraints from on- vs off-detector electronics, and an overall cost-benefit analysis.

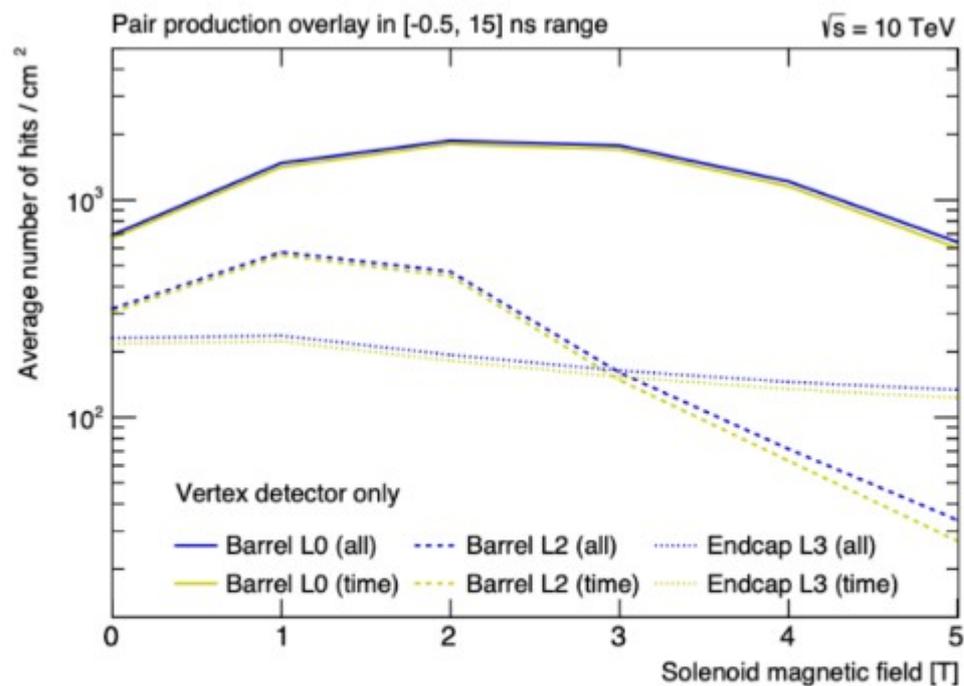


# Extra

# Annual integrated luminosity per electric power consumption



# Cluster multiplicity for IPP



**Figure 3.1.1:** Average hit density per layer, assuming the 3 TeV detector model (MUCOLL\_v1), as a function of the solenoid magnetic field.