

Smart Pixels at a Future Muon Collider

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On behalf of the [Smart Pixels effort](#)

August 27, 2025

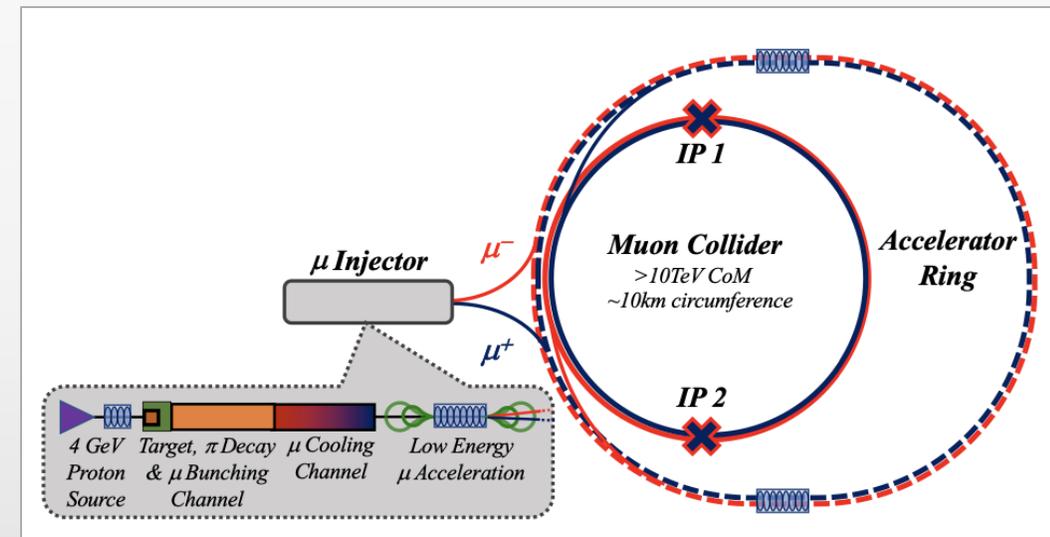


Outline

- A Muon Collider: Motivation and Challenges
- Smart Pixels: Current Prototype and Results for a Hadron Collider
- Applying the Smart Pixels Concept to a Muon Collider

A Muon Collider

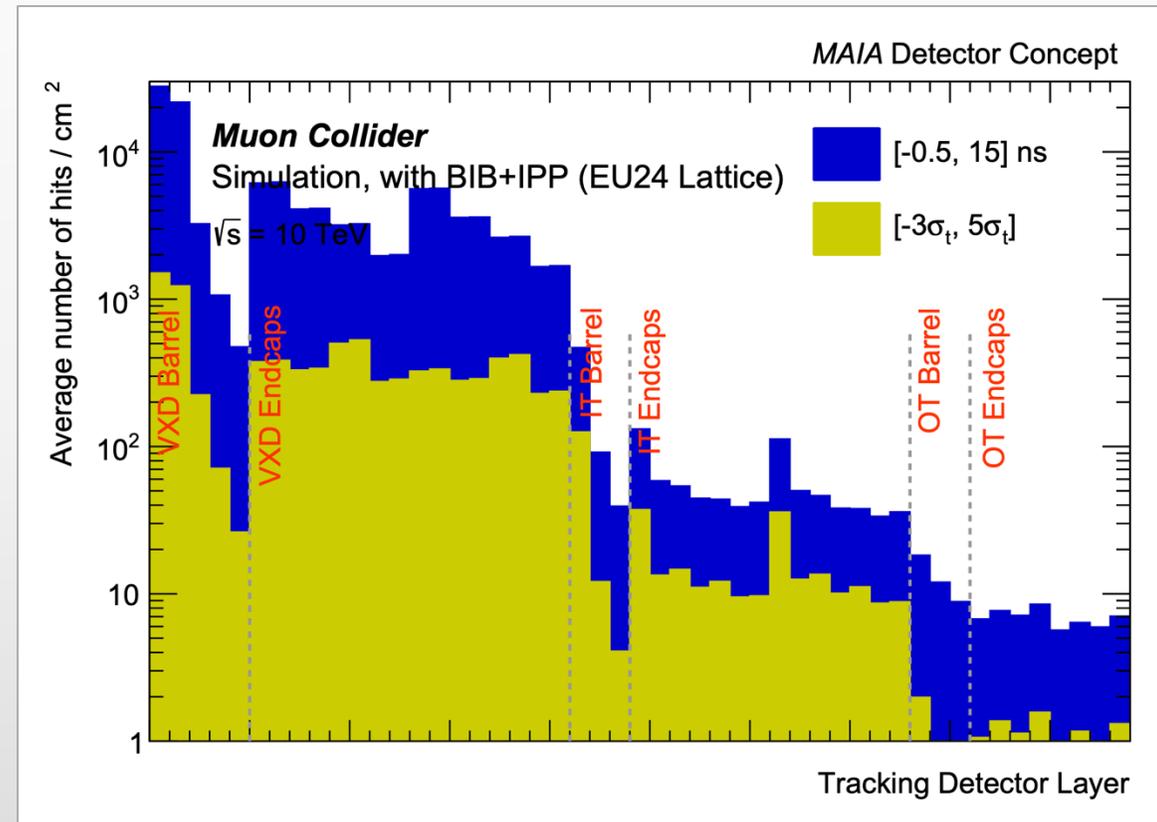
- Breaks the paradigm of e^+e^- and pp colliders:
 - Fundamental particles
 - Negligible synchrotron radiation
 - Compact, power efficient
- Understand the nature of
 - Higgs boson
 - Electroweak symmetry breaking
 - Minimal dark matter



[arxiv:2303.08533v2](https://arxiv.org/abs/2303.08533v2)

Beam Induced Background (BIB)

- High rates of background create significant challenges for:
 - Detector read-out
 - Reconstruction
 - Radiation hardness
- Most challenging for first layer of the vertex detector: $O(10^4)$ per cm^2 per bunch crossing

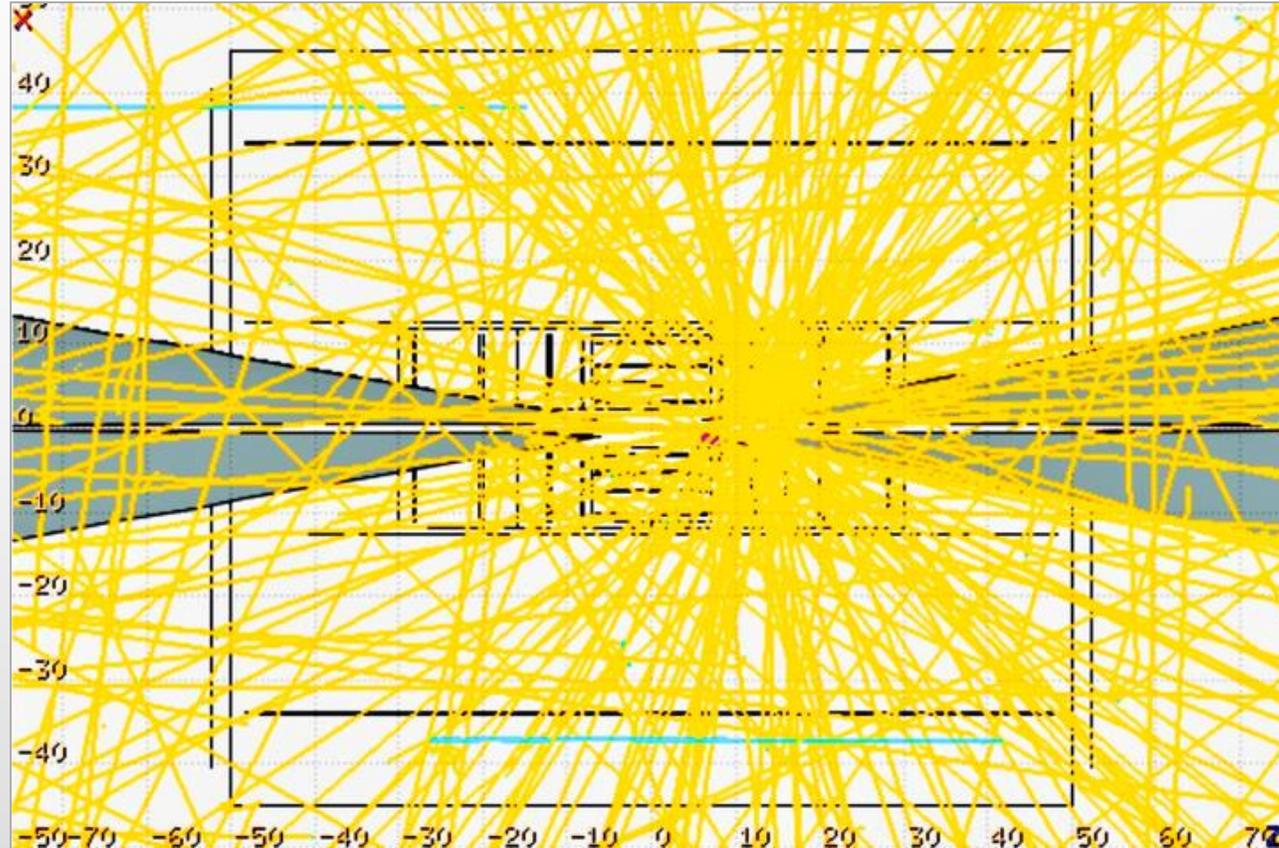


Talk by B. Rosser at USMCC

Beam Induced Background (BIB)

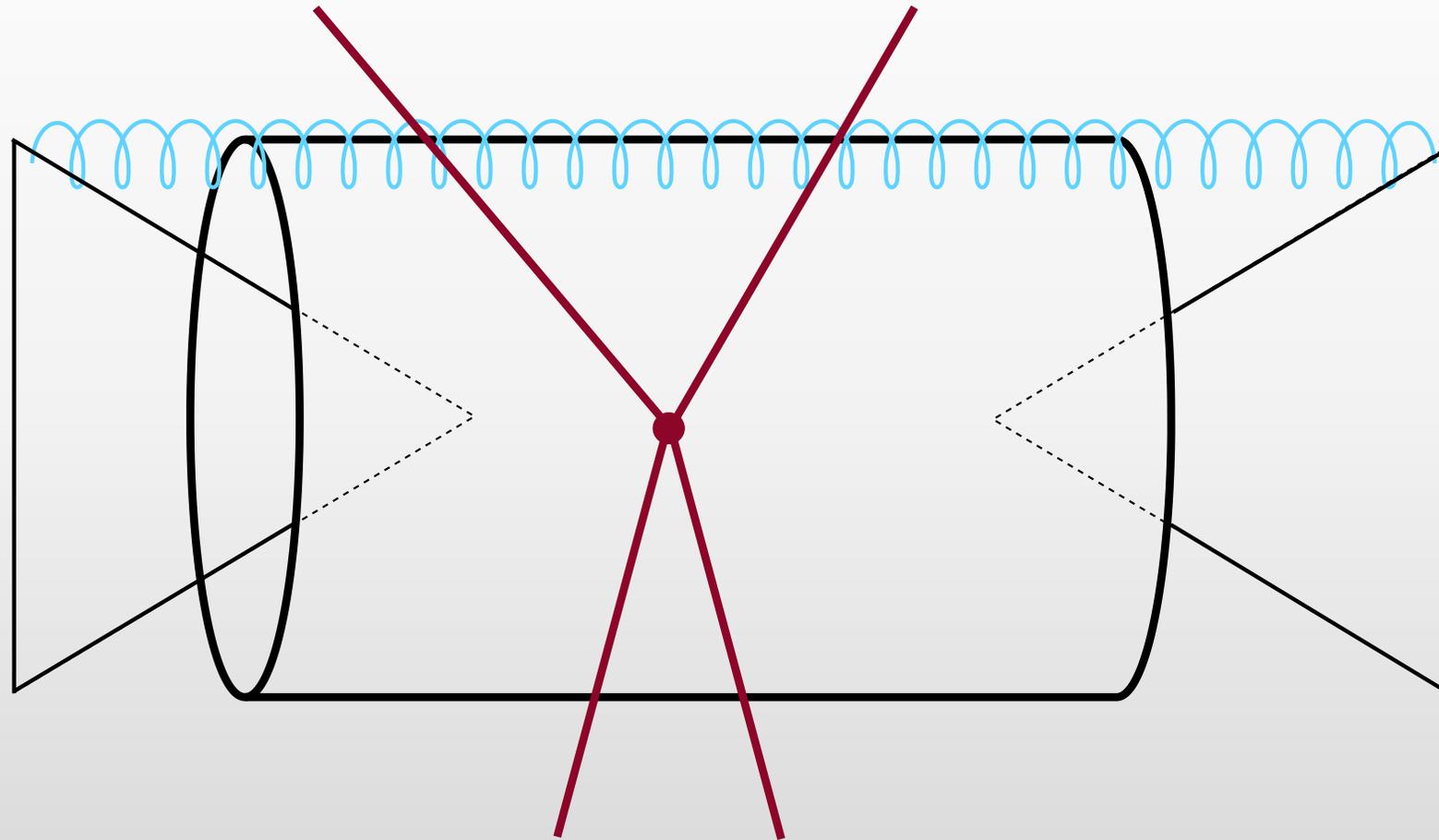
0.0003% of a BIB event

Electrons
Photons



K. Kennedy, CPAD Workshop

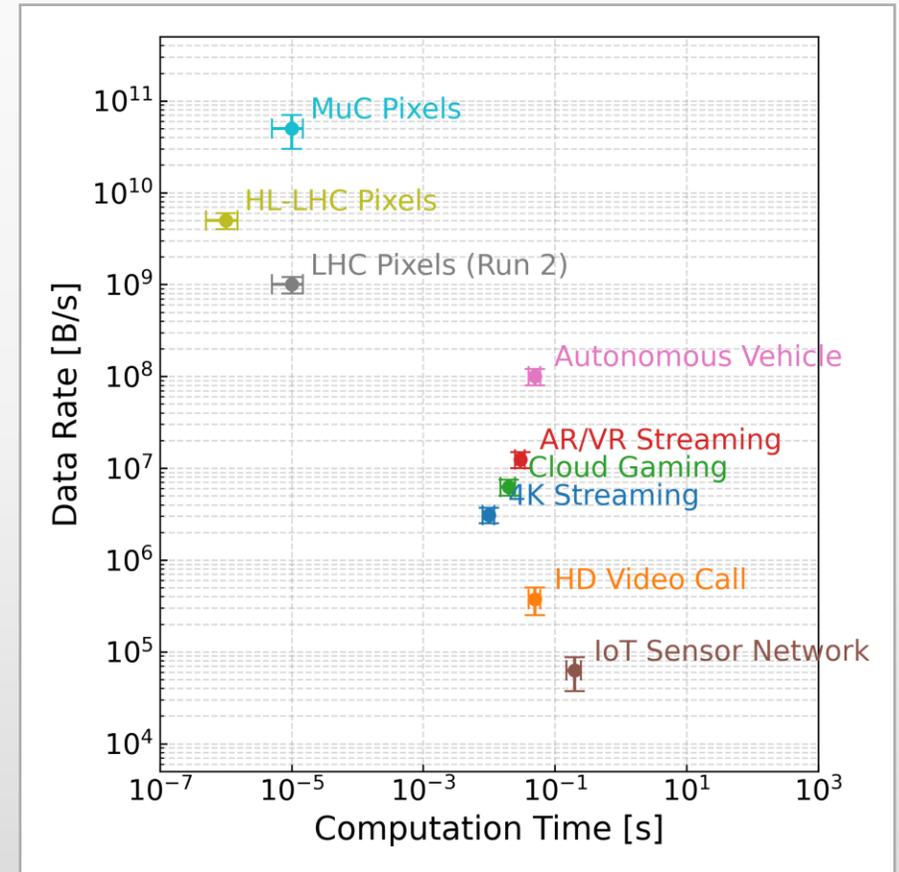
Beam Induced Background (BIB)



Electrons
Signal

Data Rates and Other Challenges

- We want to read out the pixel detector **for every event**
 - Muon Collider: 30 μ s
 - LHC: 25 ns
- We anticipate this exceeding read-out constraints
 - e.g. read-out links: ~ 10 GB/s
- On-detector intelligence
 - Is needed to reduce volume of data being read out per event
 - Can also reduce track reconstruction computation complexity



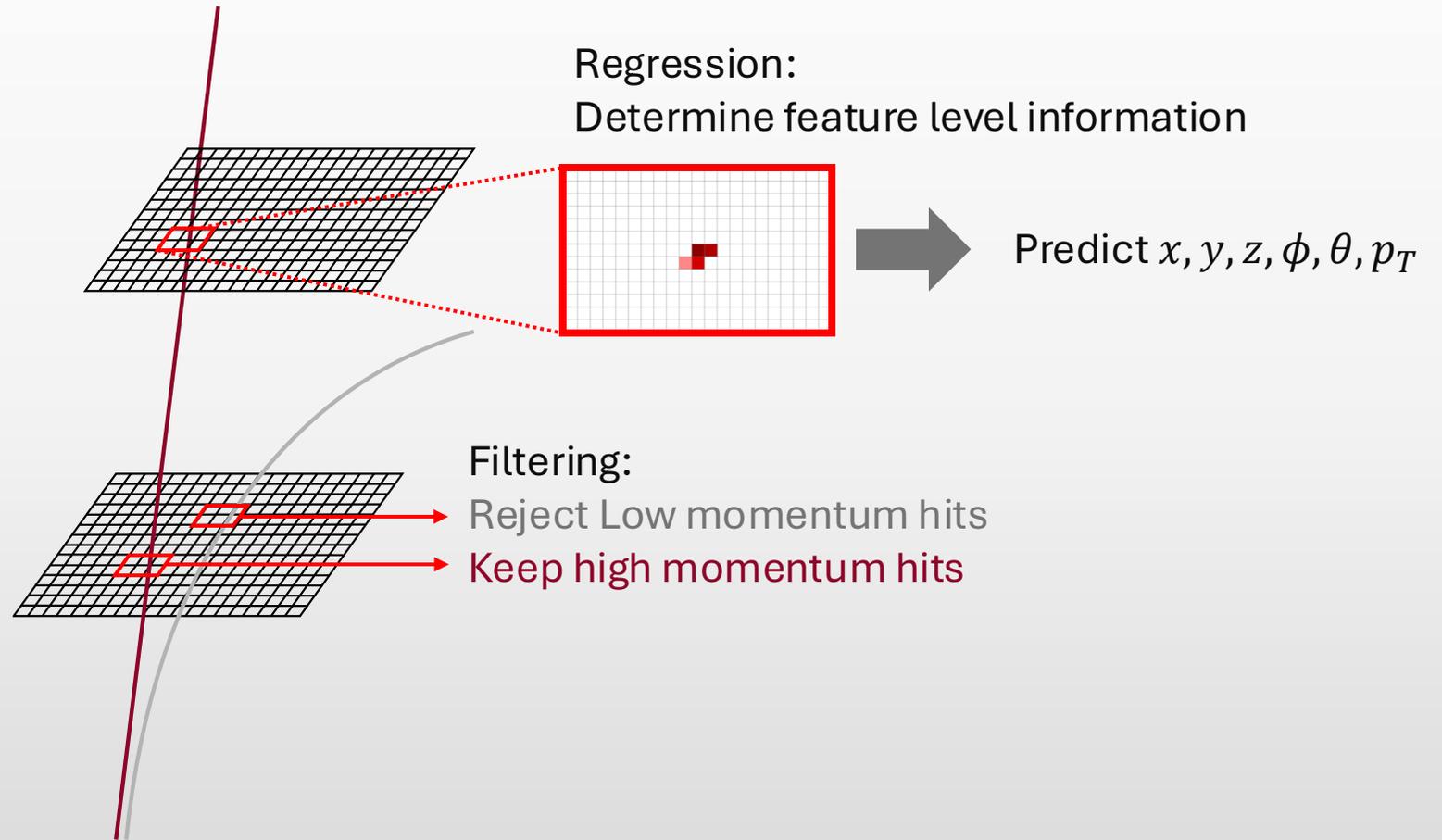
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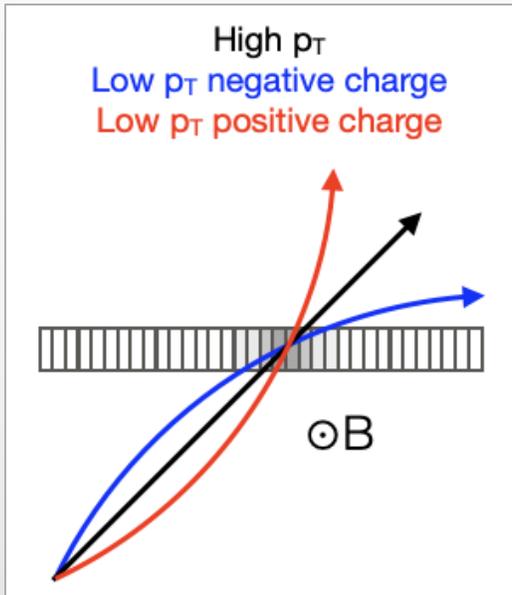
A Potential Solution: Smart Pixels

A neural network on the pixel sensor ASIC would provide intelligent data reduction before data is even read out!

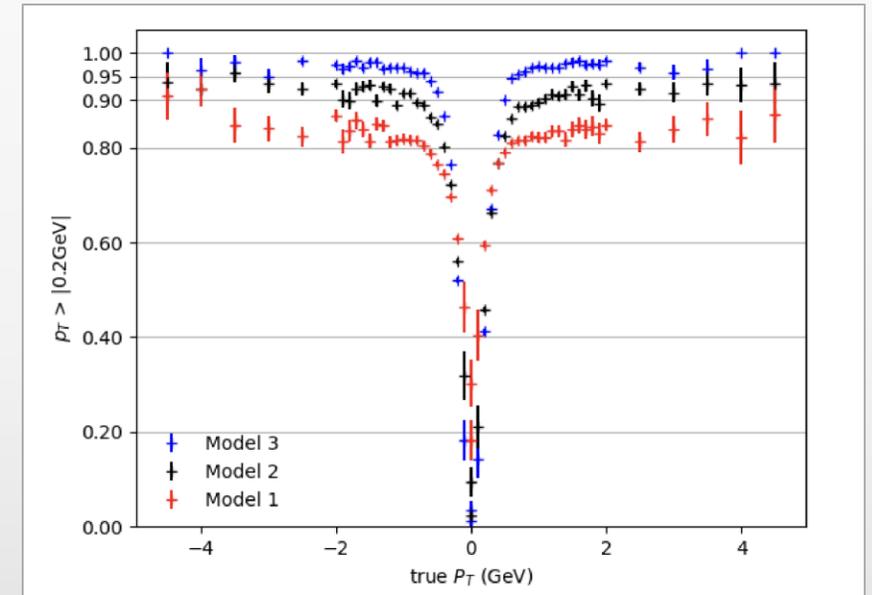
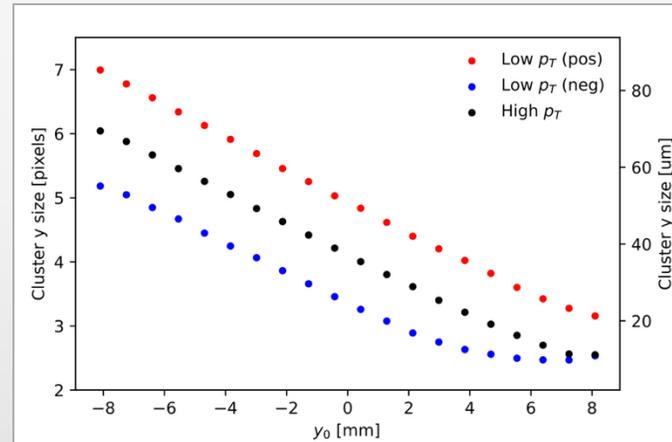
Concepts being explored for pileup rejection for a hadron collider:



Promising Results for a Hadron Collider



Cluster shape is correlated with particle momentum

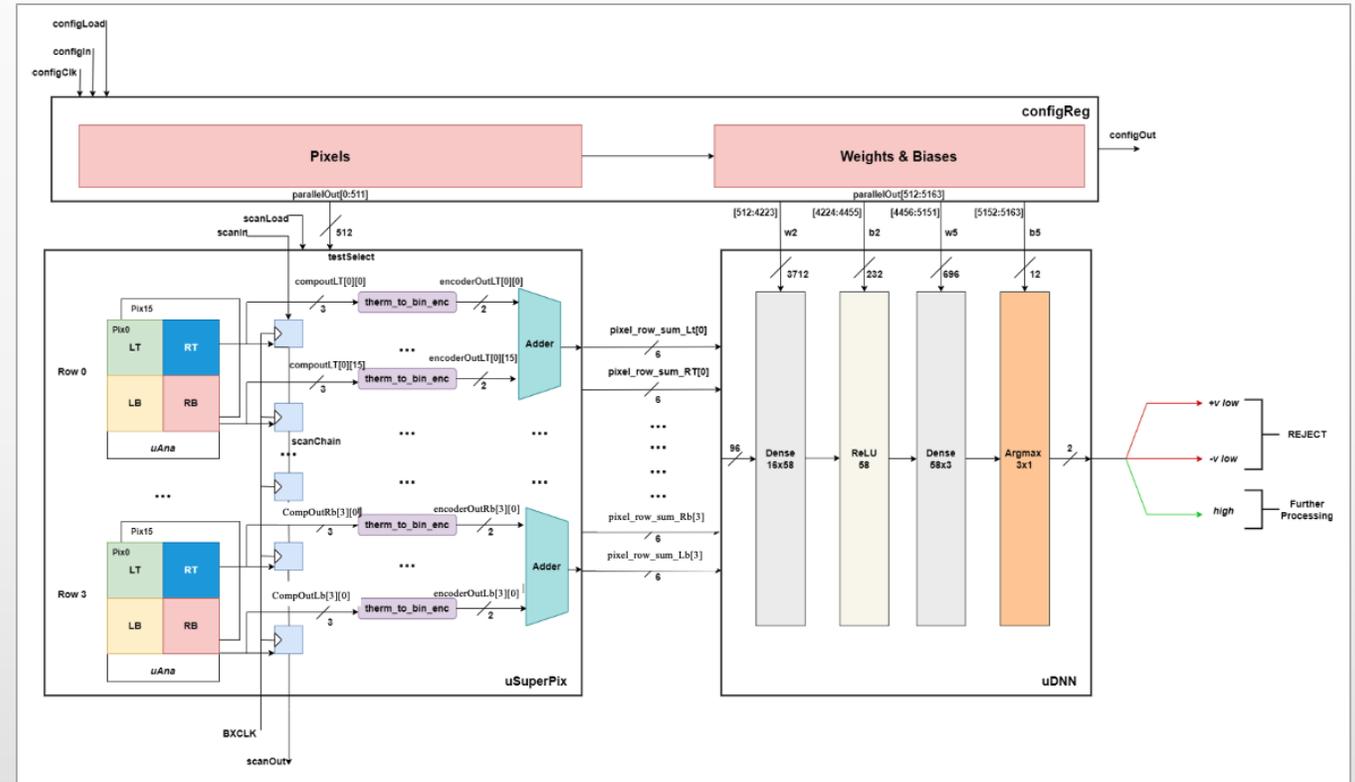


Filtering: [arXiv:2310.02474v1](https://arxiv.org/abs/2310.02474v1)

Regression: [arXiv:2312.11676v1](https://arxiv.org/abs/2312.11676v1)

Promising Results for a Hadron Collider

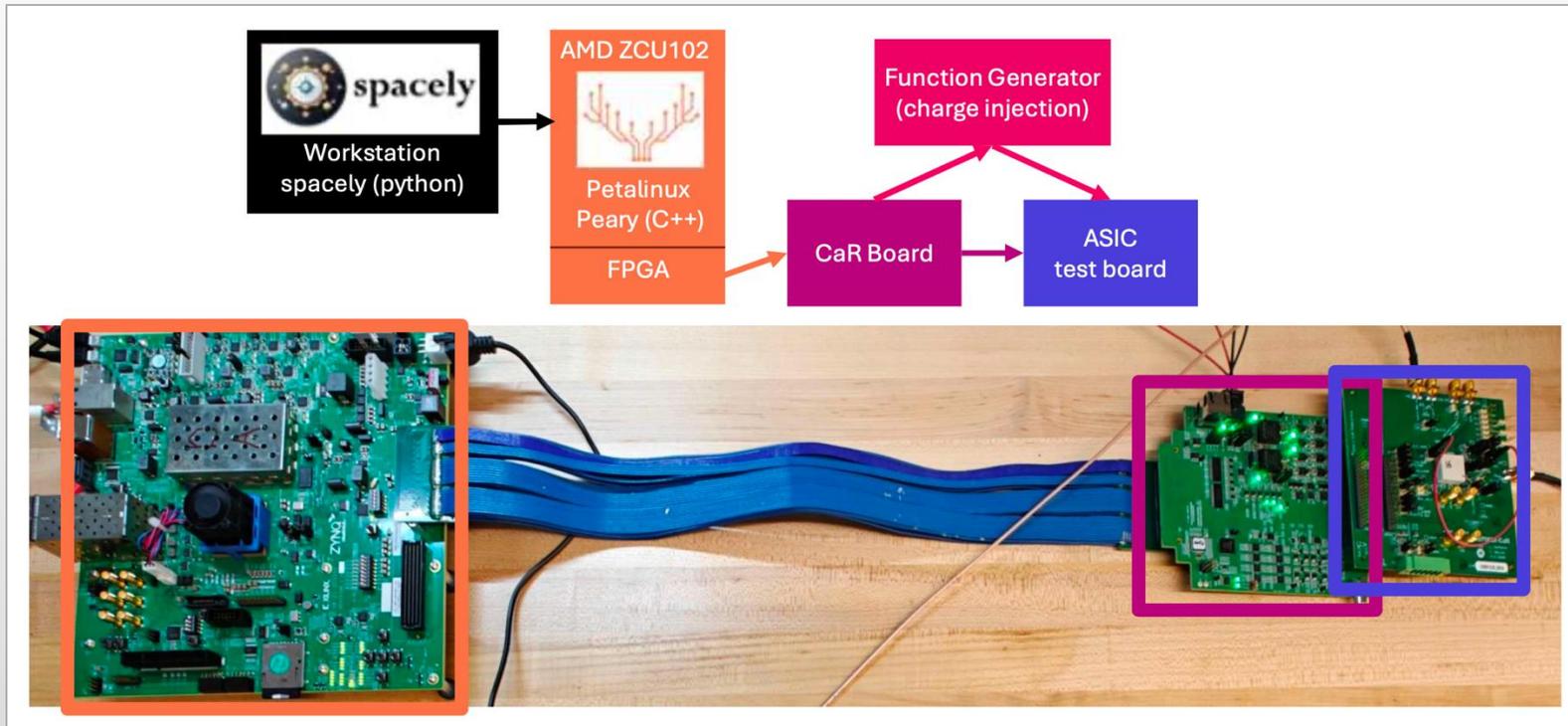
- The Smart Pixels Collaboration has produced a prototype chip in 28 nm CMOS which implements the filtering architecture in digital logic
- Trainable parameters: 1163



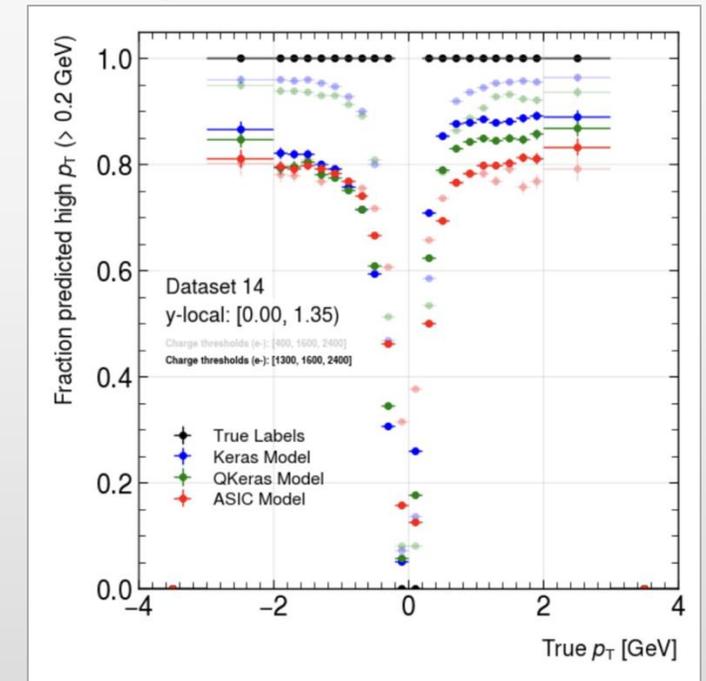
CMS28 Smartpix Test Manual

Promising Results for a Hadron Collider

Smart Pixel ASIC prototype



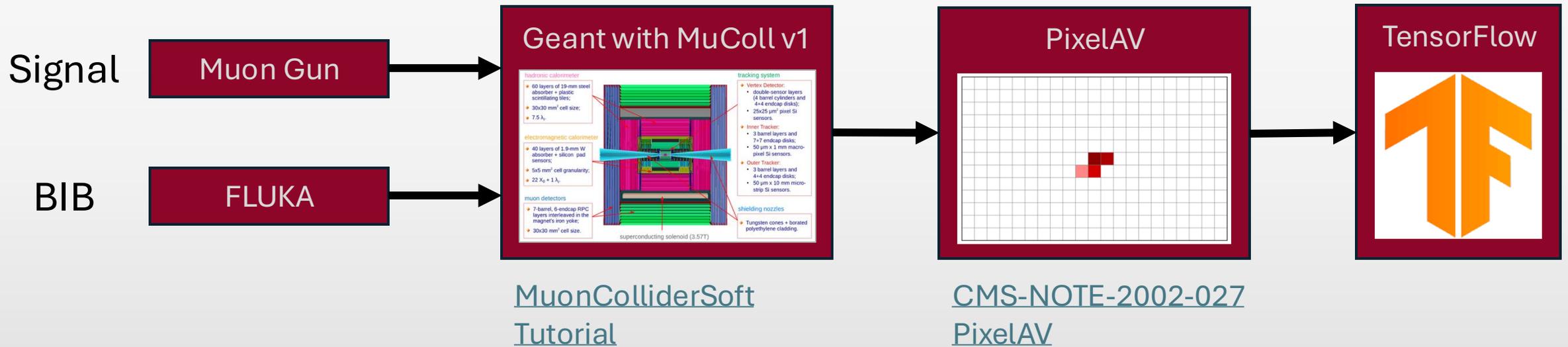
ASIC classification performance



Outline

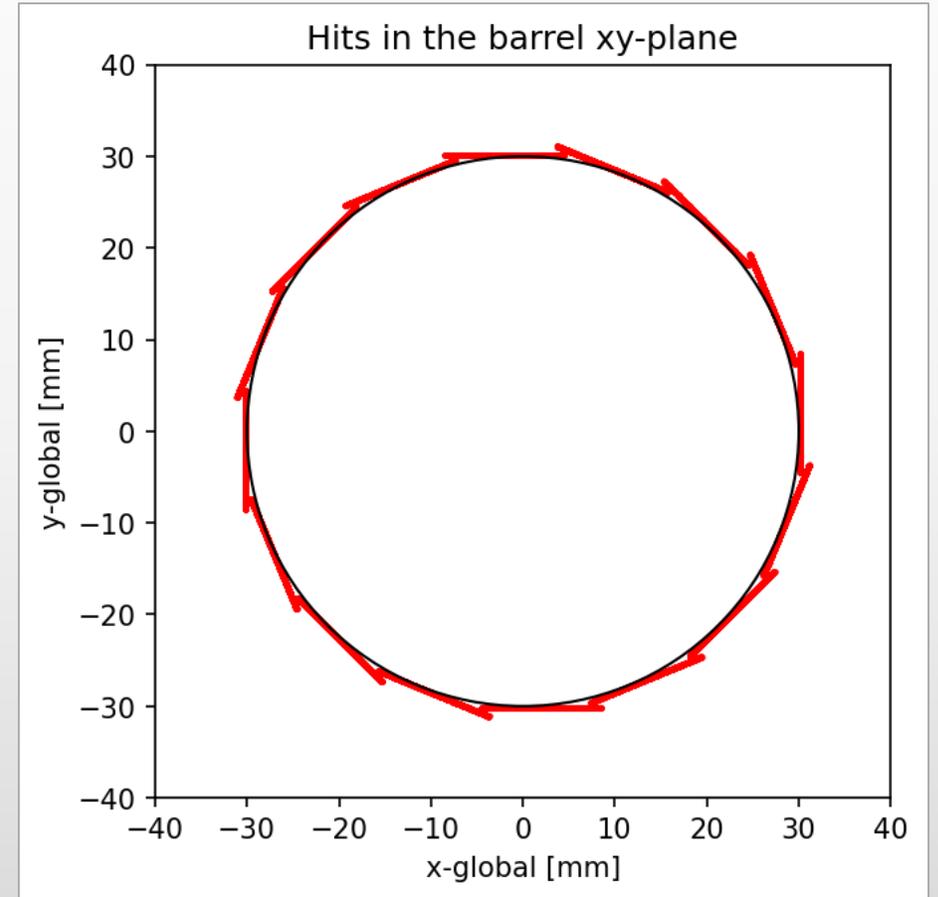
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Data Generation Pipeline



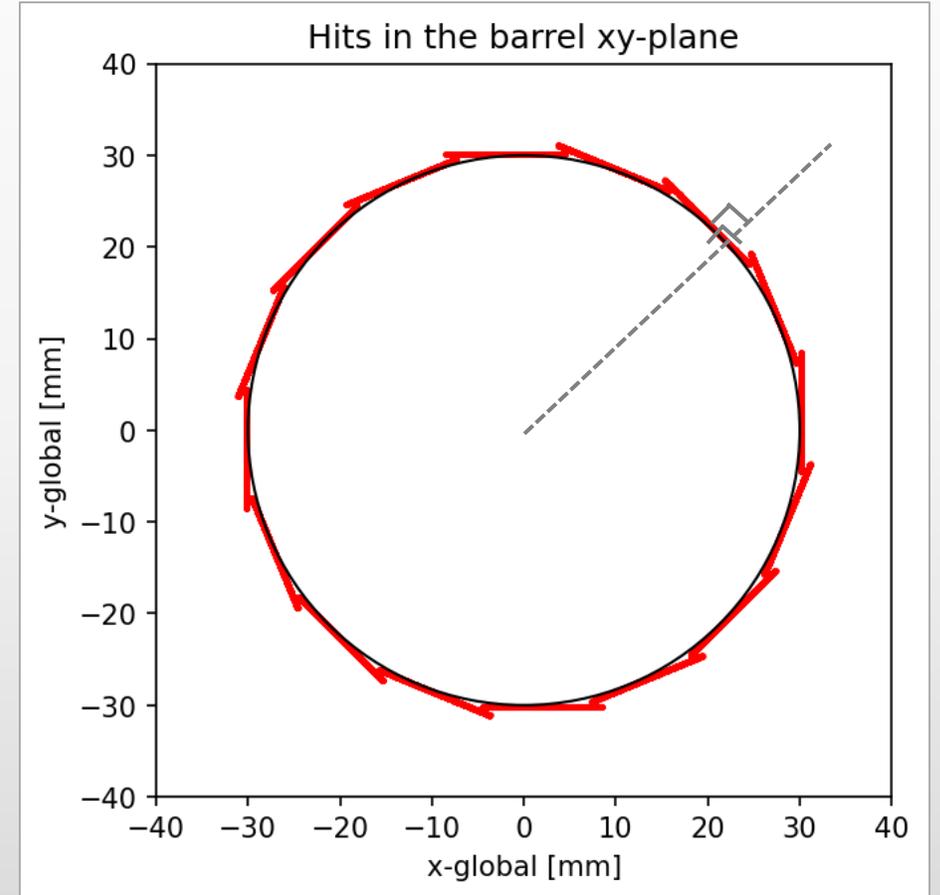
Vertex Detector

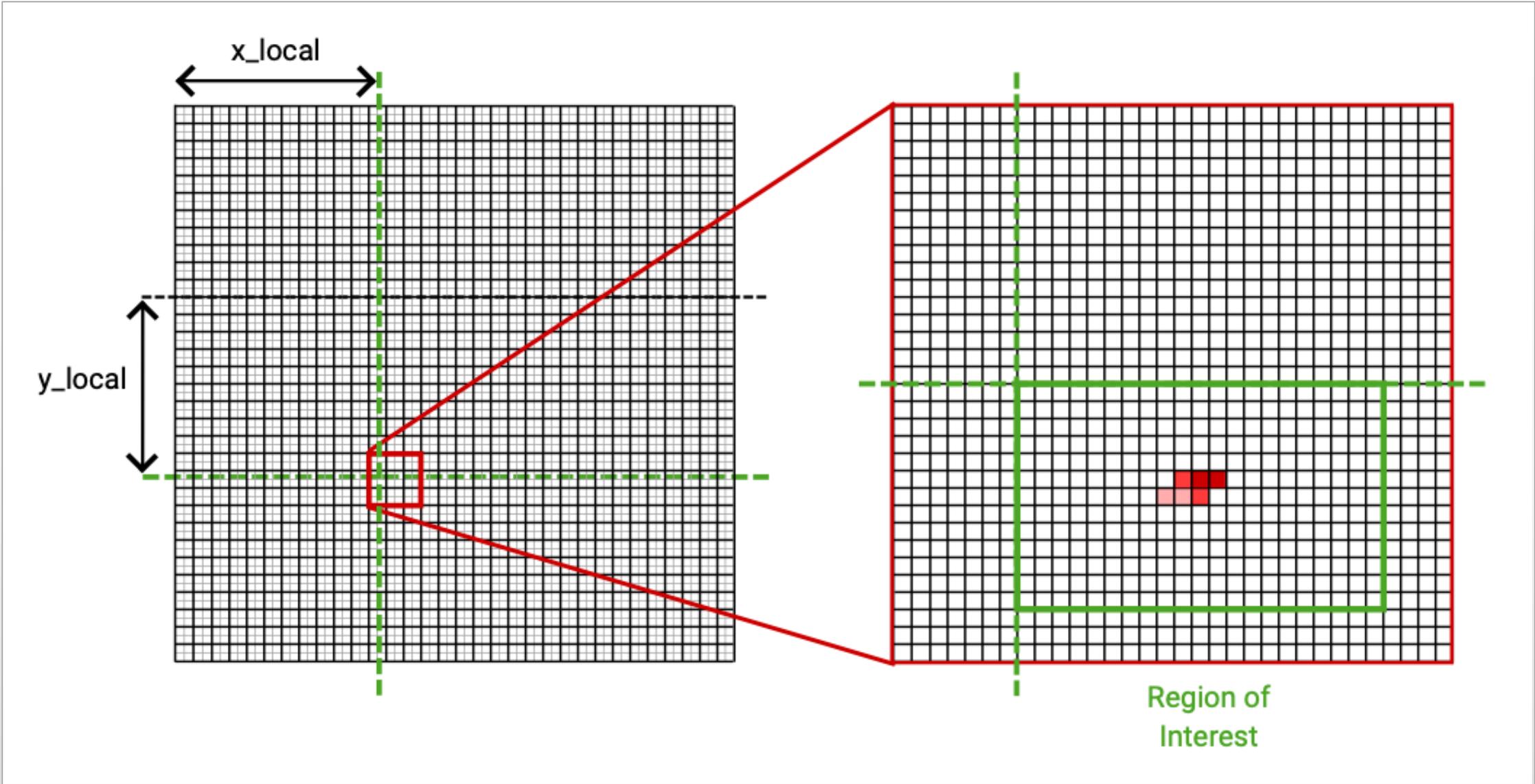
- $25 \times 25 \mu\text{m}^2$ pixel sensors
- 4 double-layer cylindrical shells at radii: 3.0 , 5.1, 7.4, 10.2 cm
- Barrel length: 13.0 cm



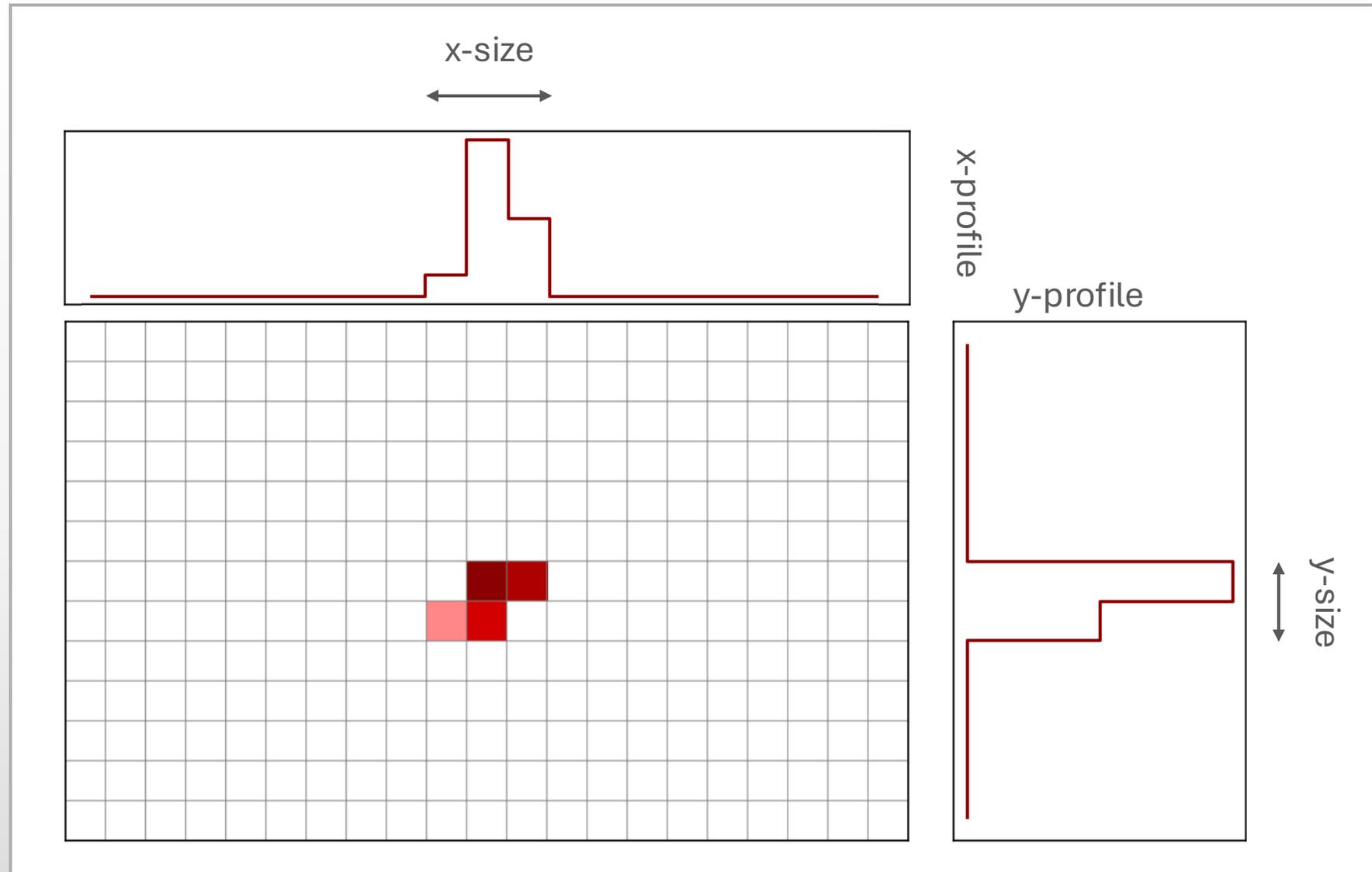
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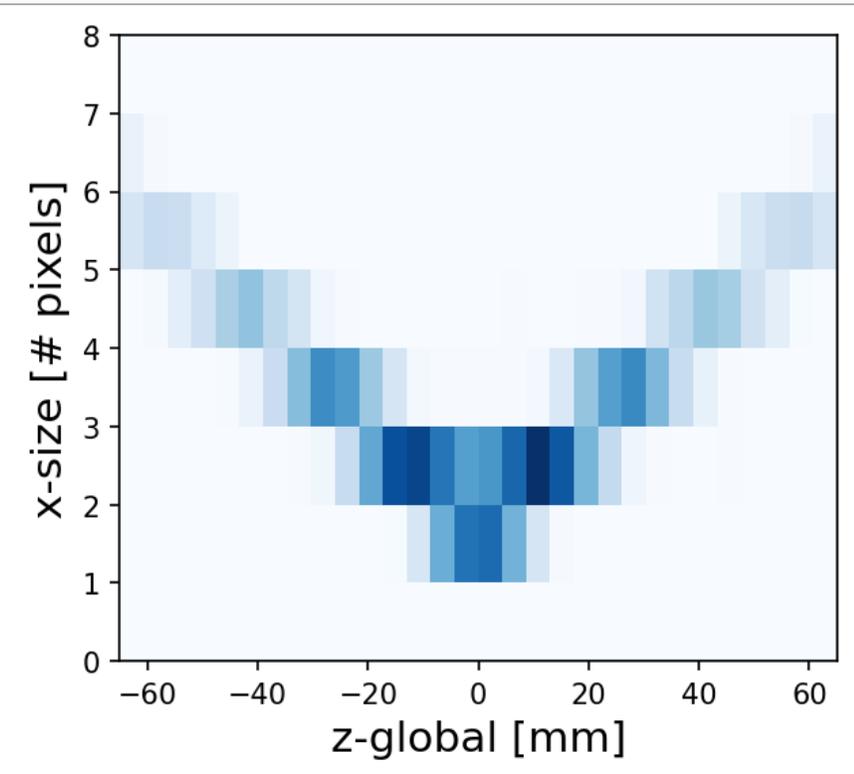
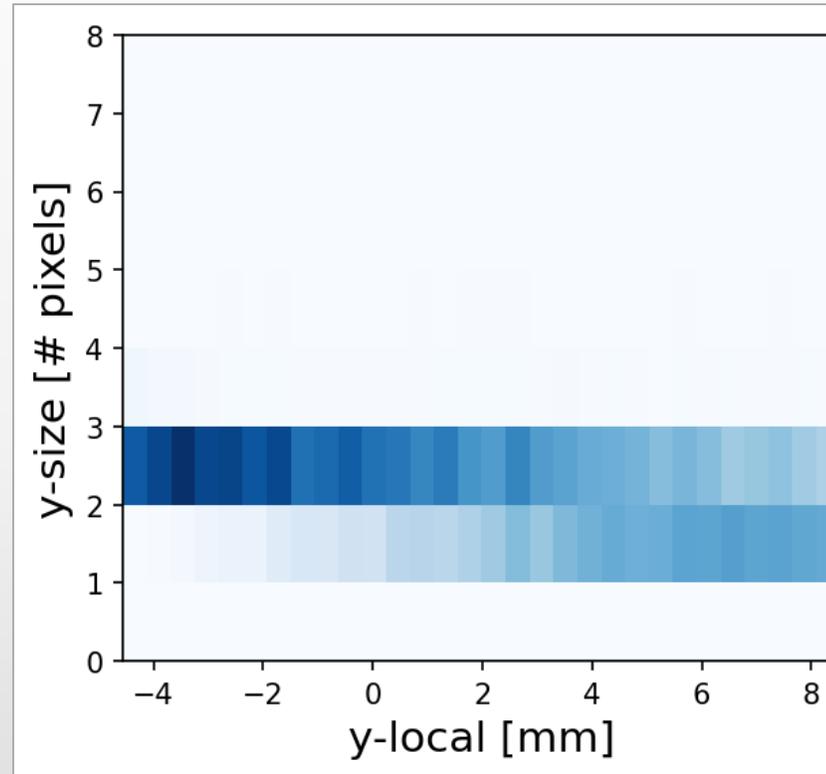


Cluster Features



Key Correlations

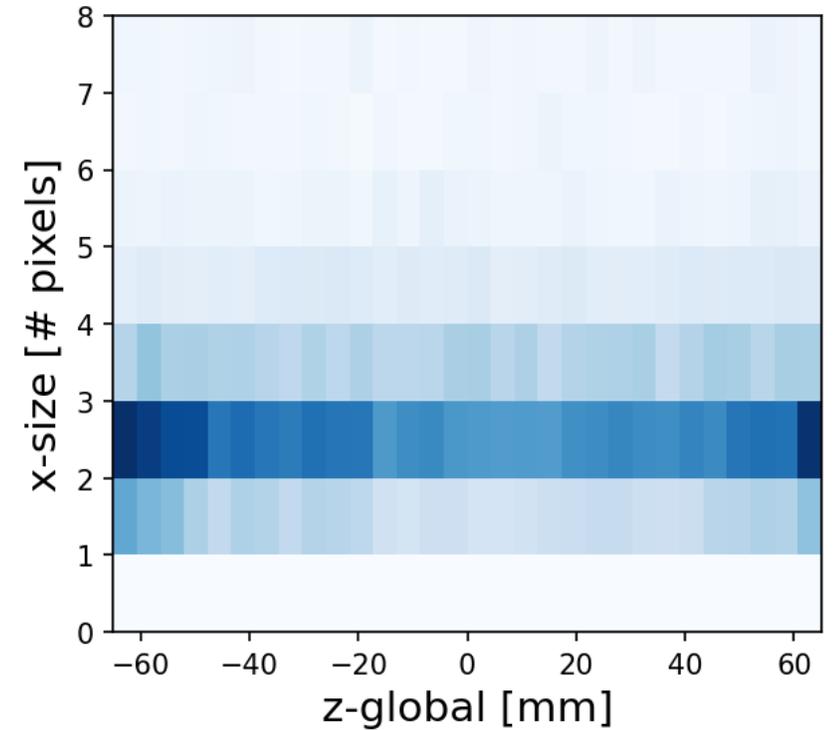
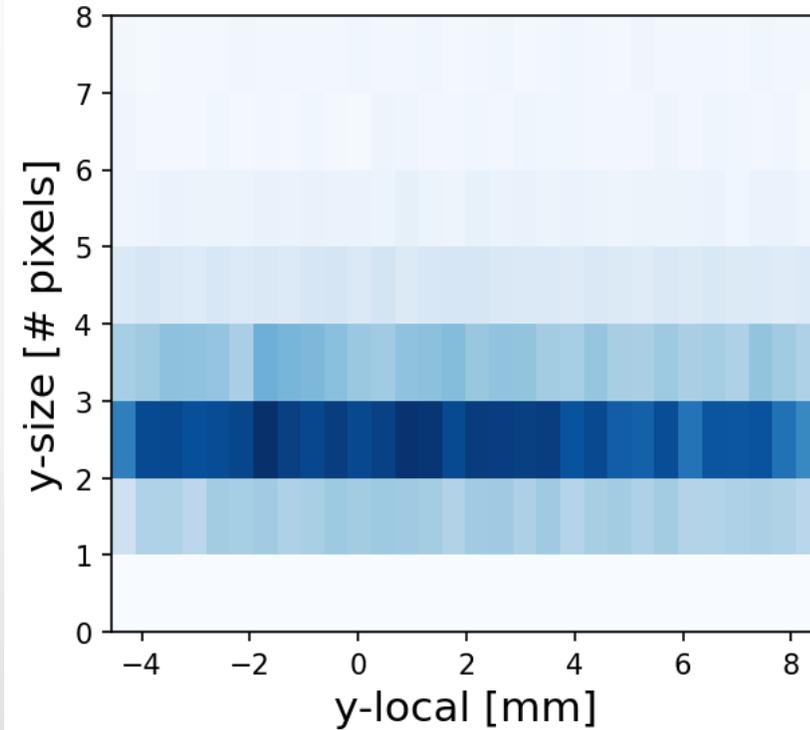
For **signal**, x-size and y-size are correlated with z-global and y-local respectively



Key Correlations

For **BIB**, x-size and y-size are not correlated with z-global and y-local

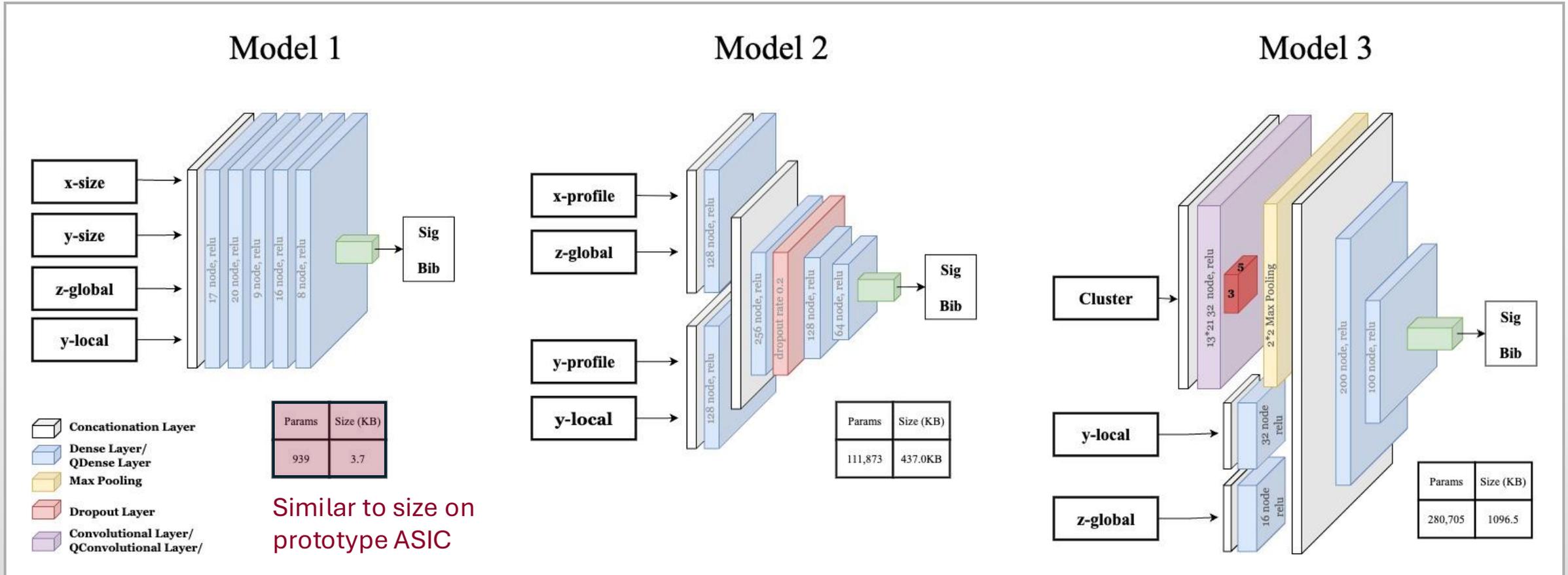
Note: BIB cluster shapes do not significantly change after a timing cut



Neural Network Architectures

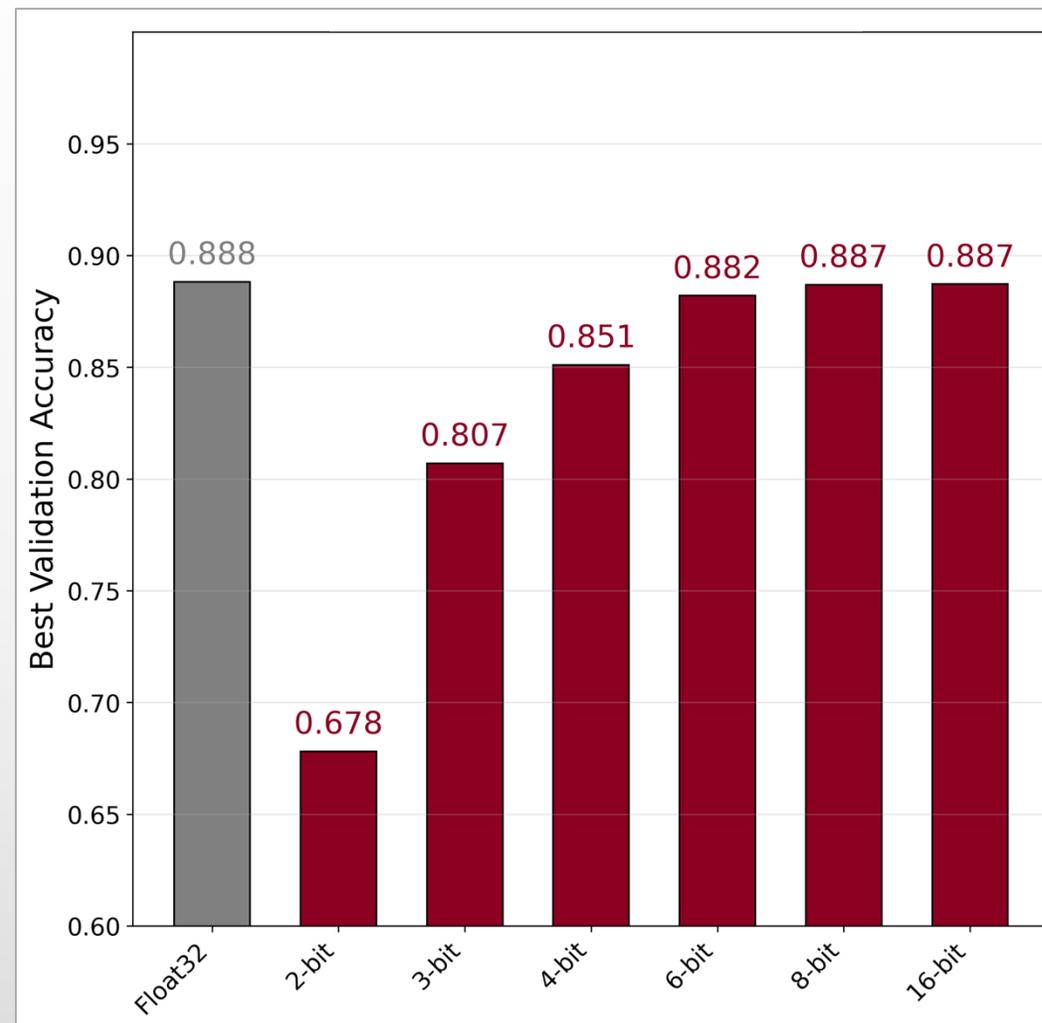
- We need to balance neural network size/complexity with performance
- Current model architectures:
 - Model 1: x-size, y-size, y-local, z-global
 - Model 2: x-profile, y-profile, y-local, z-global
 - Model 3: cluster, y-local, z-global
- Model weights will be constrained by quantization on-chip, so we test 6 levels of precision (2 bit to 16 bit) for model parameters
 - Inputs not yet quantized

Neural Network Architectures



Preliminary Neural Network Results

Model 1



Preliminary Neural Network Results

	Validation Accuracy		
Quantization	Model 1	Model 2	Model 3
Float32	0.888	0.920	0.932
6 bit	0.882	0.901	0.930
4 bit	0.851	0.854	0.929

Preliminary Neural Network Results

	Model 1	± 90 ps Timing Cut	Combined
Signal Efficiency	95.25%	99.61%	94.96%
Background Rejection	81.33%	91.45%	98.95%

In comparison to a cut-based cluster selection [[A. Rasgori @ USMCC](#)]

- Signal Efficiency: ~95%
- Background Rejection: ~58%

For more details & updates see Angira's talk on Thursday

Next Steps

- Determine the constraints we will have for the neural network on the ASIC and modify the neural network accordingly
- Potential avenues for future study
 - Digitize input to NN (pixel charge/hit)
 - Account for electronic noise
 - Different sensor thickness & pixel size
 - Investigate interplay with timing resolution & timing cuts

Summary

- A muon collider is a well-motivated option, but we need to be able to handle BIB
- Smart pixels are currently being developed and applied to hadron colliders with promising results
- Smart pixels have significant potential for mitigating BIB at a muon collider

Acknowledgments

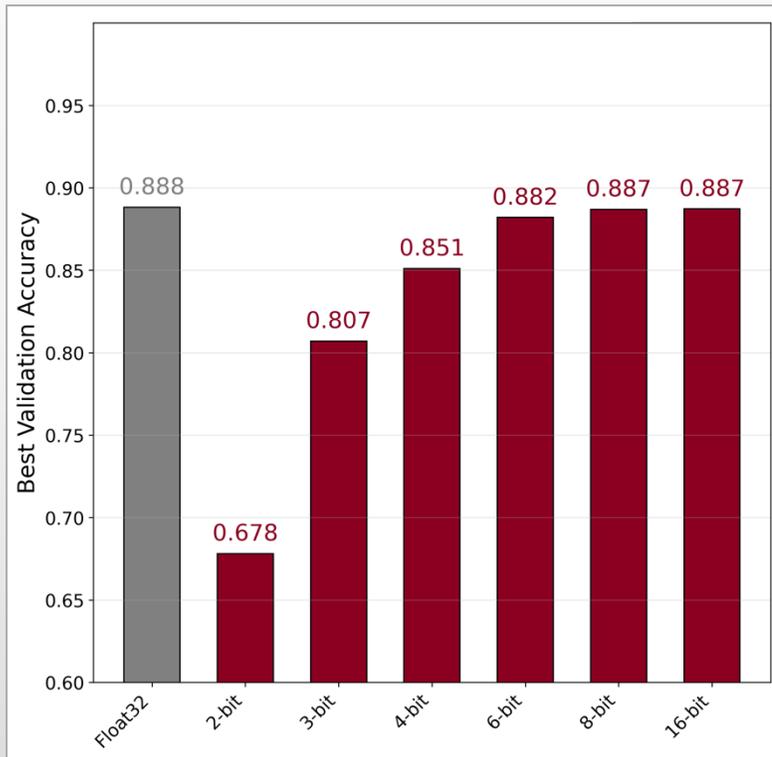
- Karri DiPetrillo
- Eric You
- Daniel Abadjiev
- Ryan Michaud
- Ben Rosser
- The Smart Pixel Collaboration
- International Muon Collider Collaboration

Questions?

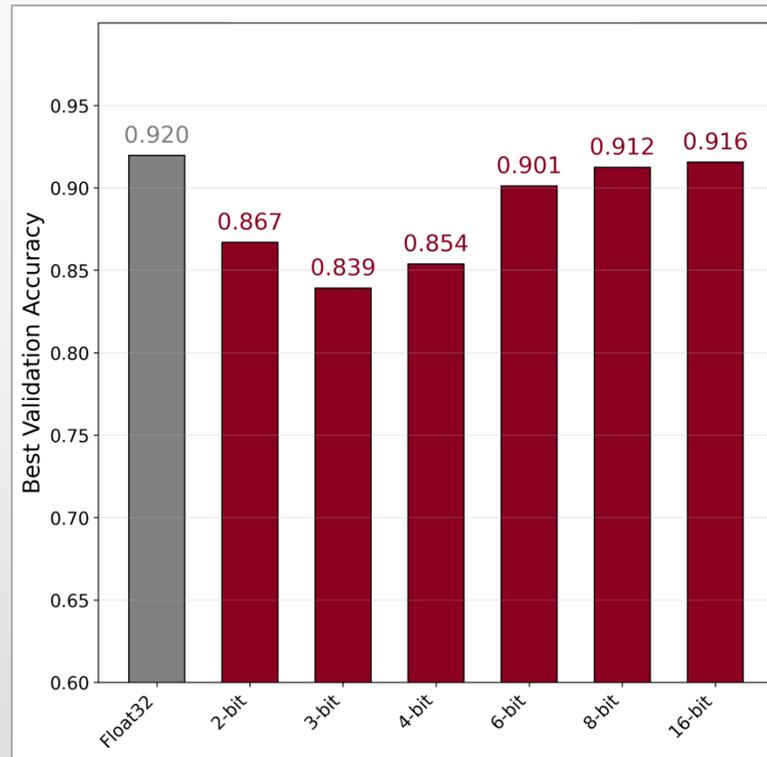
Backup Slides

Preliminary Neural Network Results

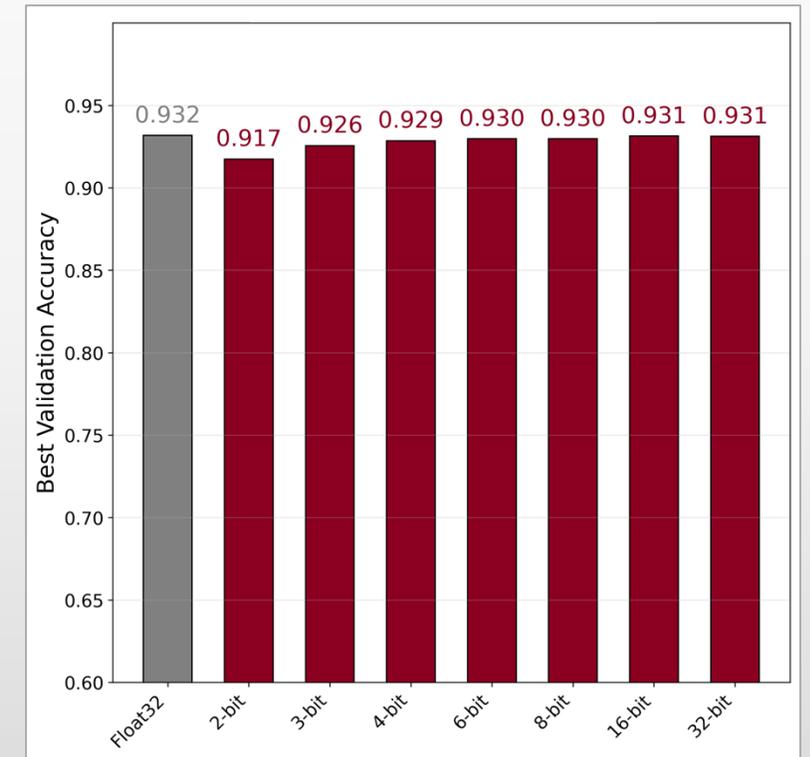
Model 1



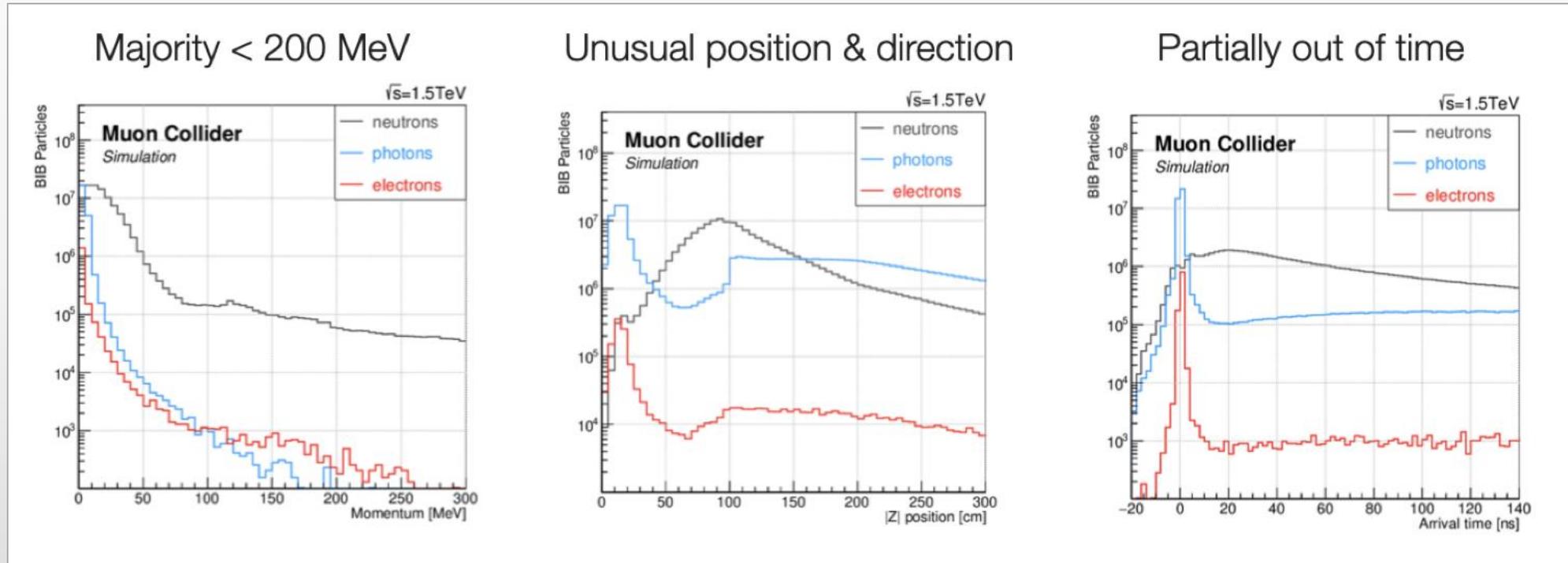
Model 2



Model 3



BIB Properties



PixelAV: Assumptions and Simplifications

- We assume continuous output from each pixel, with no minimum threshold required
- Noise from the electronics is not simulated
- The output for each pixel is the total number of electron-hole pairs collected up to 4 ns in 200 ps increments

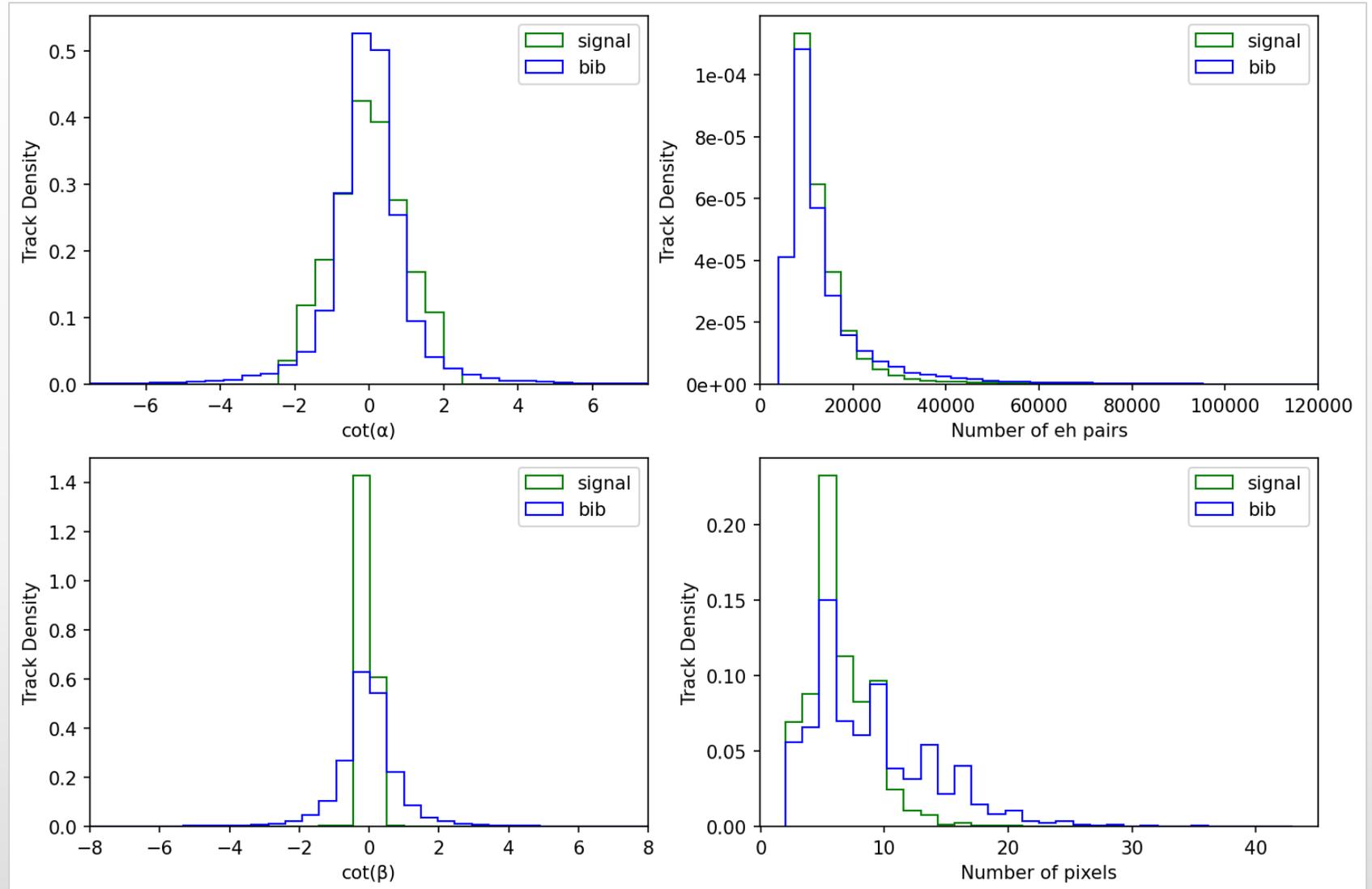
The Particle Gun

- For the purpose of this study, we simplify signal to muons produced at the interaction point
- We assume the interaction point is a gaussian distribution with standard deviations:
 - 1.5 mm in z-global
 - 0.0009 mm in the global xy-plane
- We assume uniform distributions for the following properties:
 - Momentum ranging from 1 to 100 GeV
 - Theta ranging from 10 to 170 degrees

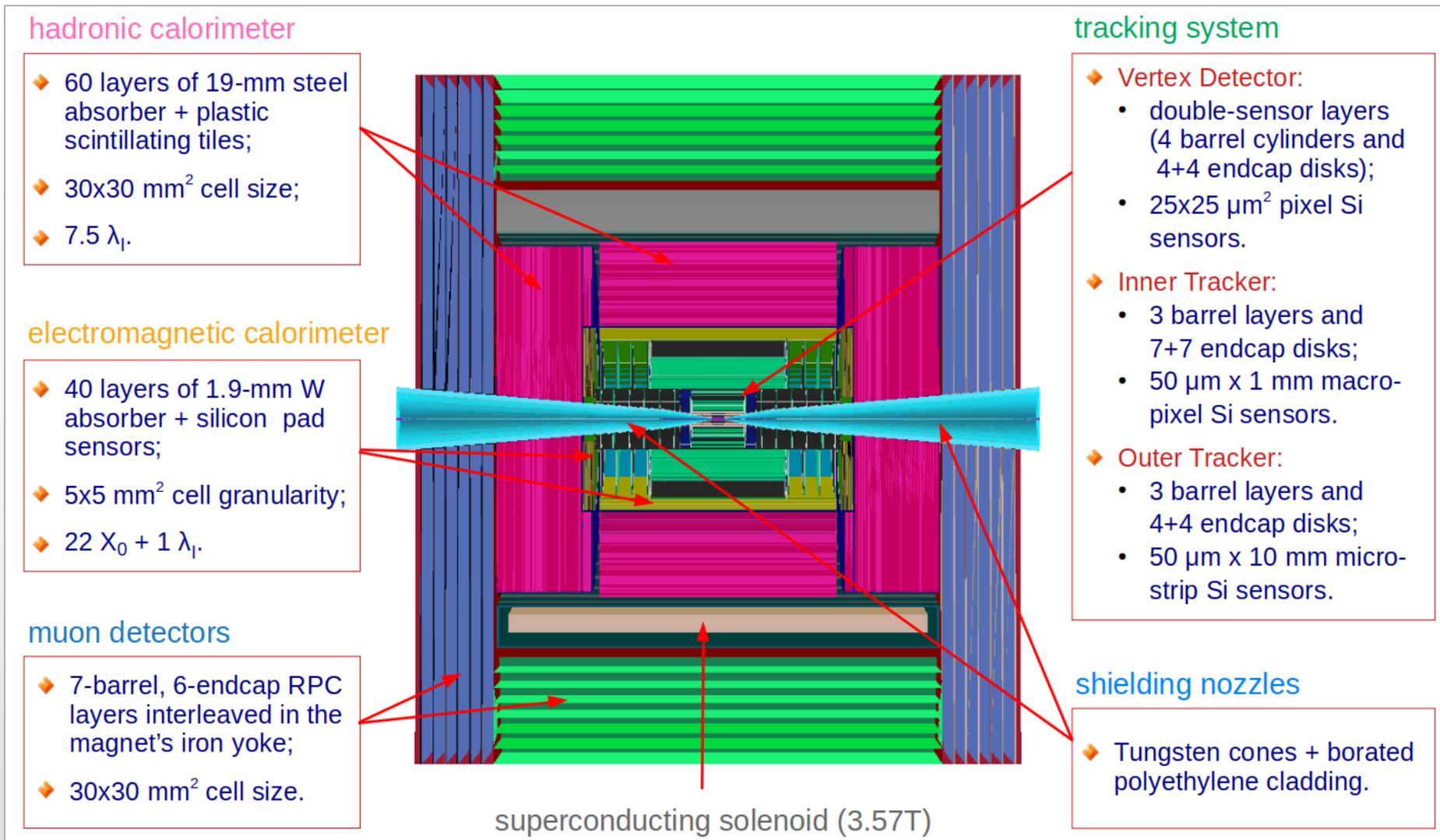
The Data Set

BIB clusters: 37940

Signal clusters: 38475



Muon Collider Geometry

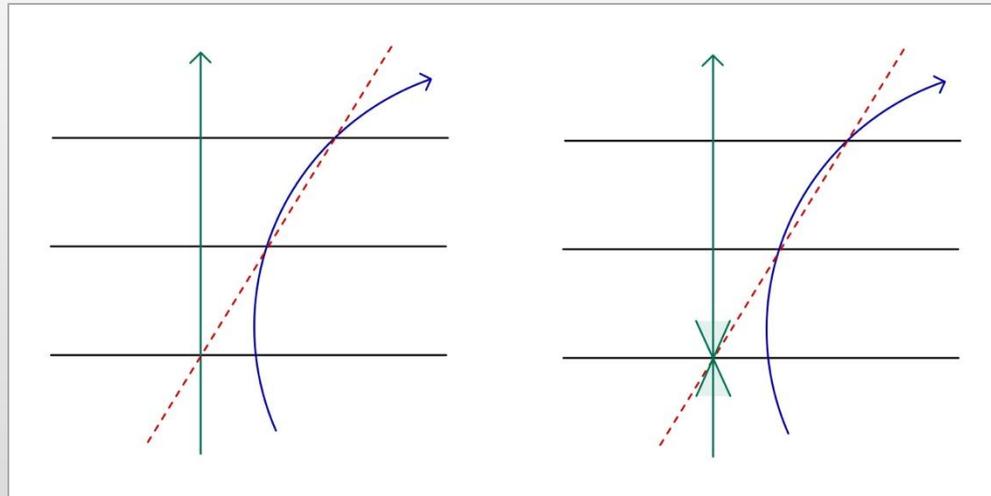


<https://mcd-wiki.web.cern.ch/detector/>

Smart Pixels: Additional Impact

- Reducing the combinatorial fake rate
- Speeding up offline tracking by reducing possible seeding combinations

Without angular information, the fake track seems plausible



With angular information, the fake track is shown to be incorrect