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MAPS ECal for Particle Flow Calorimetry

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Studies coordinated with:

EPICAL-2
DRD Calo
CPAD RDC9

Habib, A., et al., JINST 19 (2024) 04, C04033.

Brau, James E., et al., EPJ Web of Conferences 315, 03005 (2024).



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MAPS offer excellent performance for future collider tracking and calorimetry



Tracking sets the primary requirements for MAPS in future colliders:

- **7 μm resolution, $< \text{ns}$ timing, 1/4 mip threshold;**
- **Power consumption** ($< 10 \text{ mW/cm}^2$) compatible with large area and low material;
- **Fault-tolerant circuit strategies for wafer-scale MAPS;**
- **Stitching** for $\sim 75 \text{ m}^2$ tracking system.

Calorimetry benefits from achieving these tracking motivated detector development goals:

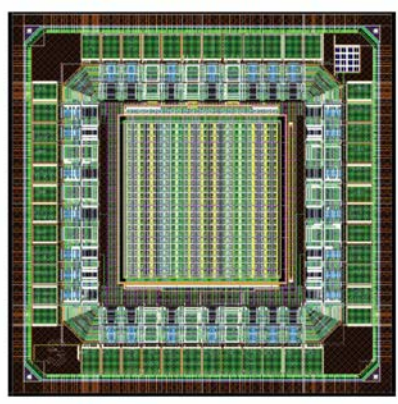
- **Stitching** for $\sim 1200 \text{ m}^2$ calorimeter system;
- **mm scale separation** of shower constituents;
- Detailed **jet reconstruction**, aiding and improving particle flow reconstruction;
- **Energy resolution** performance exceeding energy resolution requirement for electroweak and Higgs physics.

Particle flow calorimetry builds on high precision tracking with high granularity calorimetry to distinguish the source of energy depositions.

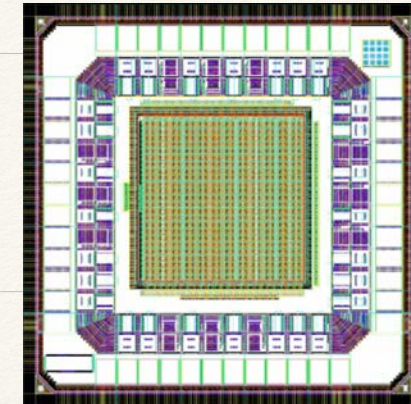
Main specifications for Large Area MAPS development

Parameter	Value	Notes
Min Threshold	140 e ⁻	0.25*MIP with 10 μm thick epi layer
Spatial resolution	7 μm	In bend plane, based on tracker specs
Pixel size	25 x 100 μm ²	Optimized for tracking (or 25x50/25 μm ²)
Chip size	5 x 20 cm ²	Requires stitching on 4 sides
Chip thickness	300 μm	<200 μm for tracker. Could be 300 μm for ECal to improve yield.
Timing resolution (pixel)	~ ns	
Total Ionizing Dose	100 kRads	Total lifetime dose, not a concern
Hits spatial distribution	Clusters	Due to jets
Balcony size	1 mm	Only on one side, where wire-bonding pads will be located.
Power density	20 mW / cm ²	Based on tracker power consumption

L. Rota



MAPS Calorimetry Builds on Tracking Sensor Development



First sensor prototype, NAPA-p1, fabricated in 65 nm CMOS with a 1.5 x1.5 mm² footprint and 25 μ m pitch, achieved promising results.
(as part of a CERN WP1.2 shared run)

Second design, NAPA-p2, developed to reduce power density and achieve good tolerance to ohmic voltage drops across a large column of pixels. (as part of a CERN WP1.2 shared run)

	Specification	Simulated NAPA-p1
Time resolution	1 ns-rms	0.4 ns-rms ✓
Spatial Resolution	7 μ m	7 μ m ✓
Noise	< 30 e-rms	13 e-rms ✓
Minimum Threshold	200 e-	~ 80 e- ✓
Average Power density	< 20 mW/cm ²	0.1 mW/cm ² for 1% duty cycle ✓

Improving time resolution & power trade-off.
Timing resolution designed at system level.
TDC integration
challenging due to
spatial, routing
and power constraints. [\(link\)](#)

Talk by Lorenzo Rota (SLAC), Wednesday, 2:40, Great Room
First laboratory characterization (noise, threshold, timing)
Current performance, operating points, planned improvements

JINST 19 (2024) 04, C04033



SIMULATED ECAL PERFORMANCE

Shower energy & transverse position measurement



EM ENERGY RESOLUTION

single bit digital

HITS

$$16.4 \% / \sqrt{E} \oplus 2.0 \%$$

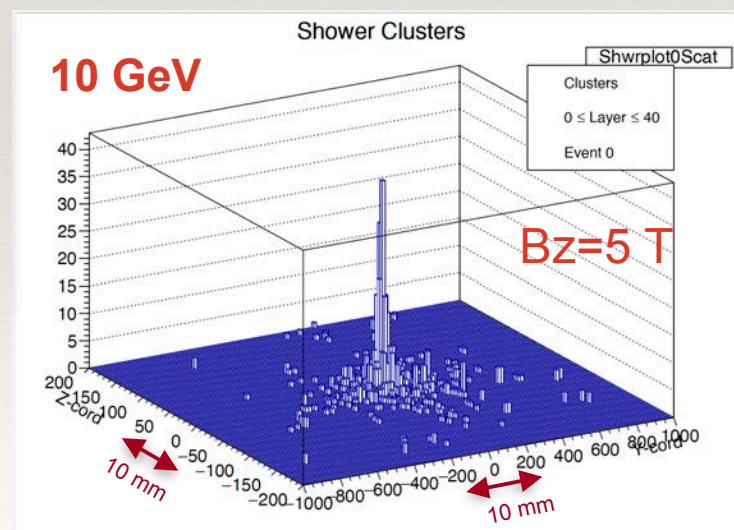
CLUSTERS

$$12.2 \% / \sqrt{E} \oplus 1.4 \%$$

IDEAL - MIPS

$$8.8 \% / \sqrt{E} \oplus 0.2 \%$$

EM resolution goal set by particle flow.
SiD ECal = 27 X_0 (20 thin + 10 thick layers)



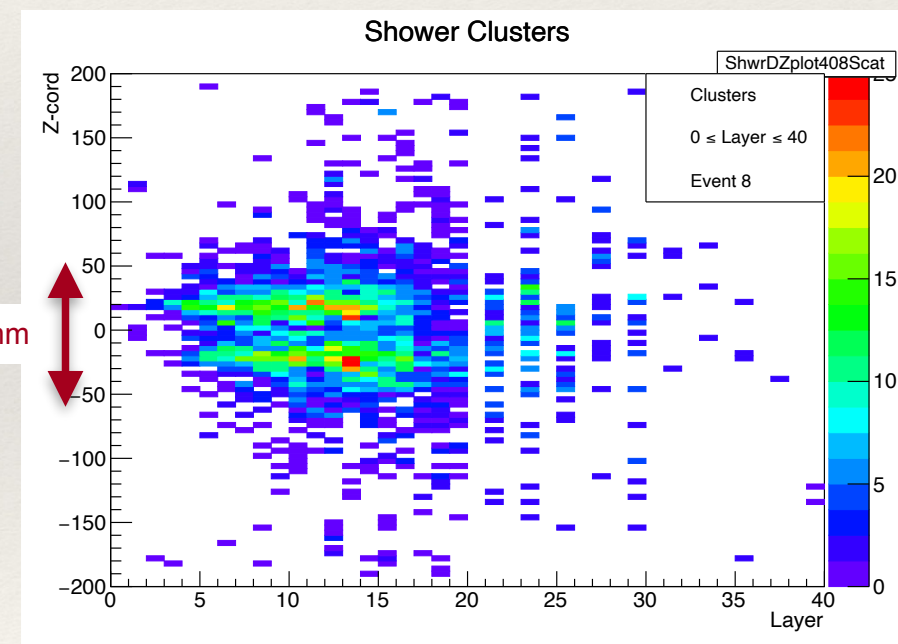
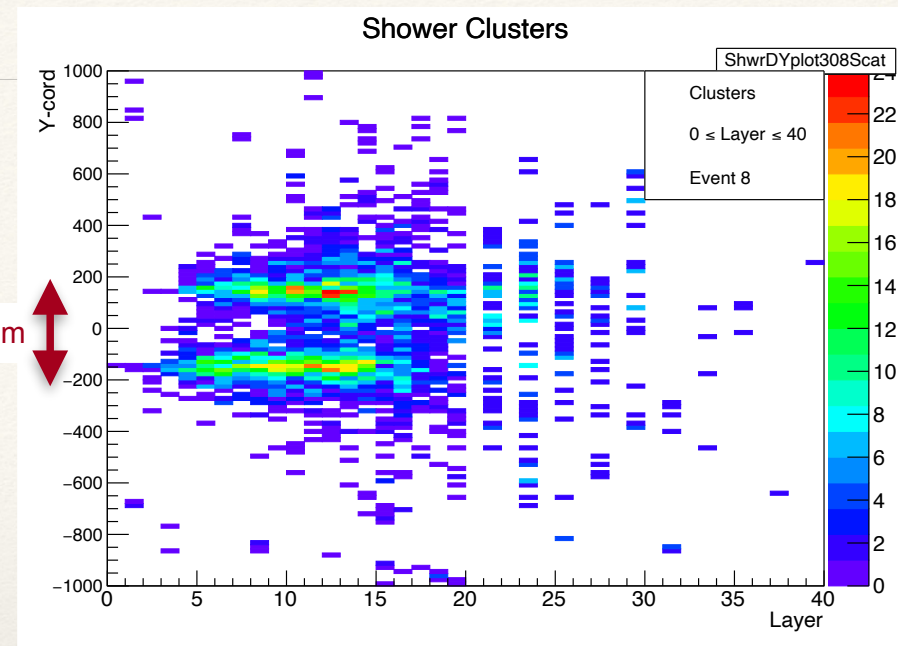
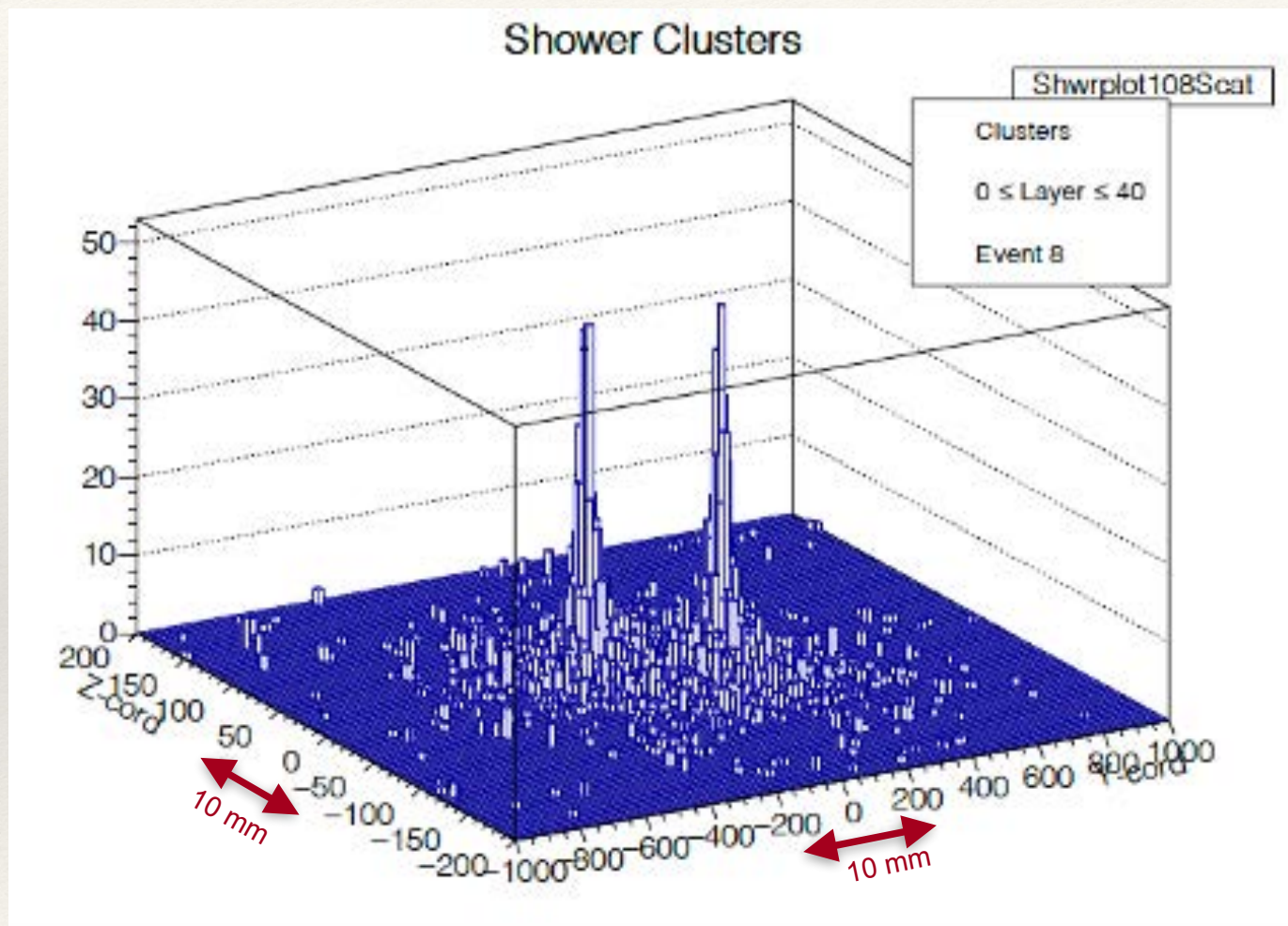
MAPS ECal for Particle Flow Calorimetry

	Shower spread (mm-rms)		Shower position measurement (mm)					
			all clusters		within 4 mm & 1st 20 Layers		within 3 mm & 1st 15 Layers	
E_y (GeV)	Y	Z	δY	δZ	δY	δZ	δY	δZ
1	4.7	4.2	1.19	1.06	0.41	0.40	0.33	0.33
10	4.8	4.3	0.43	0.37	0.14	0.14	0.12	0.11
50	5.1	4.6	0.21	0.19	0.07	0.07	0.06	0.06

- ❖ This precision can be improved:
 - ❖ - naive, simple selections.
- ❖ Important for jet particle flow measurements.



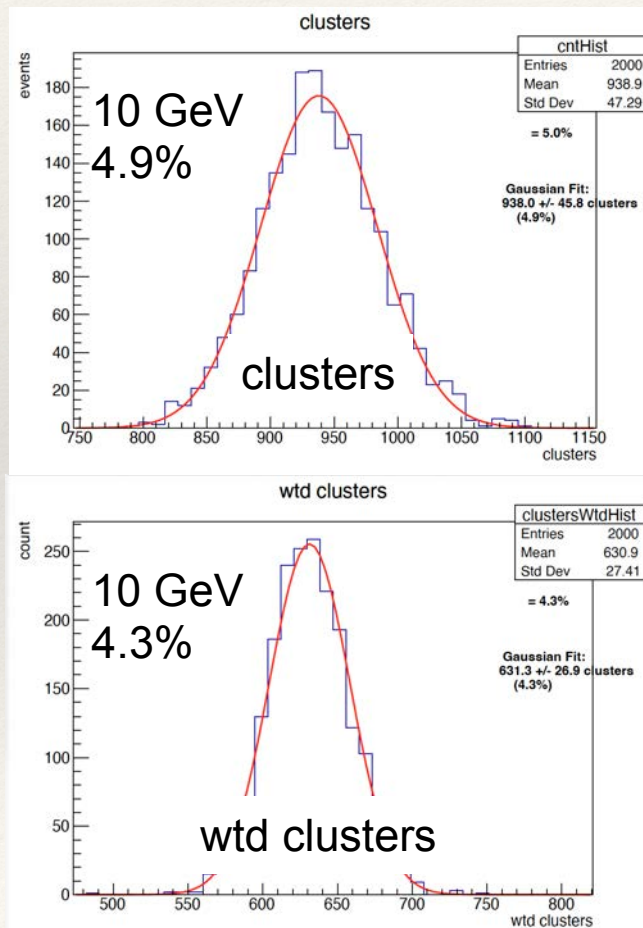
$40 \text{ GeV } \pi^0$
 $\rightarrow$ two $20 \text{ GeV } \gamma$'s



Detailed measurements for particle flow analysis illustrated by π^0 reconstruction

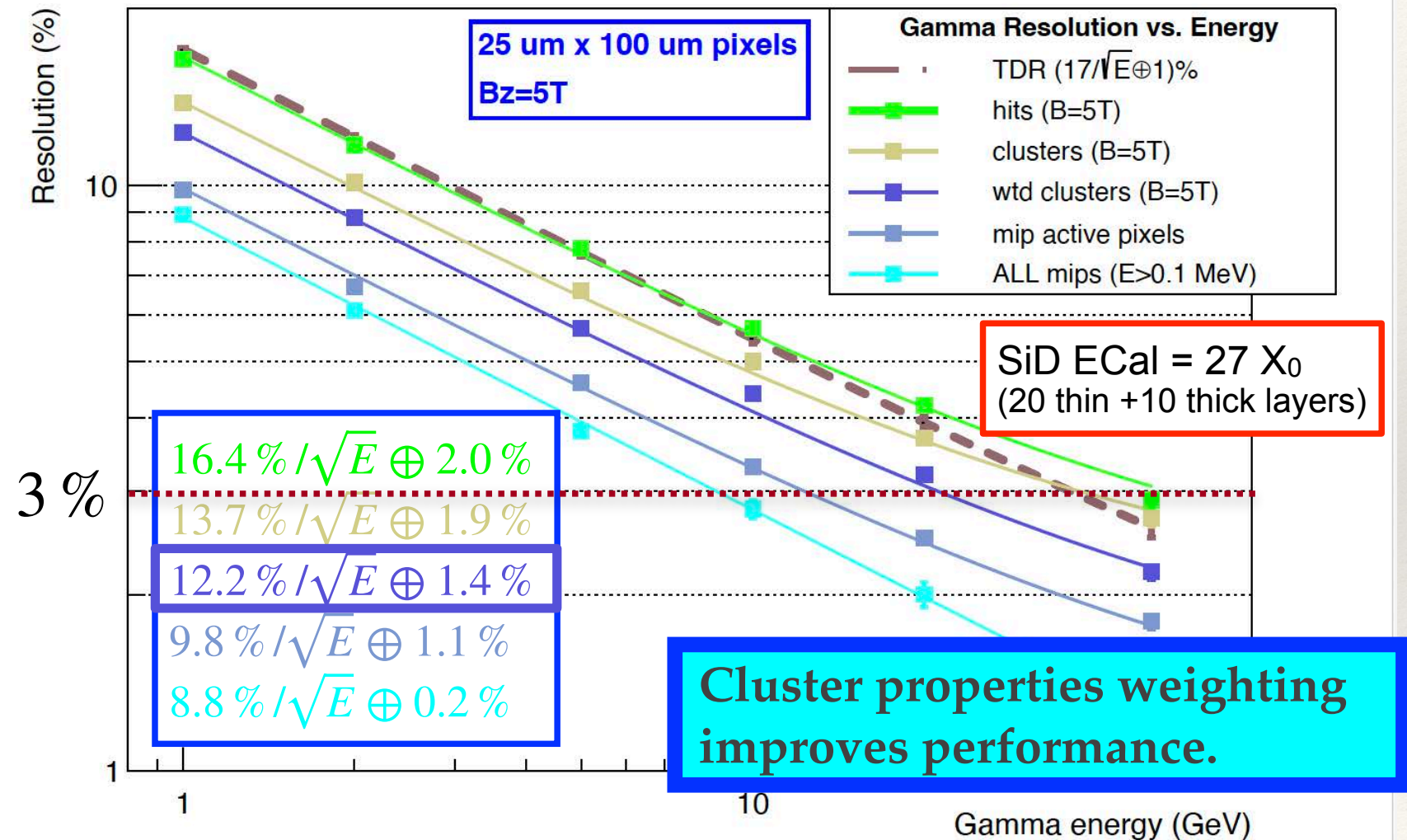
Resolution vs. Energy (hits/clusters/mips)

Resolution vs. Energy
(hits / clusters / mips)
& weighted clusters.

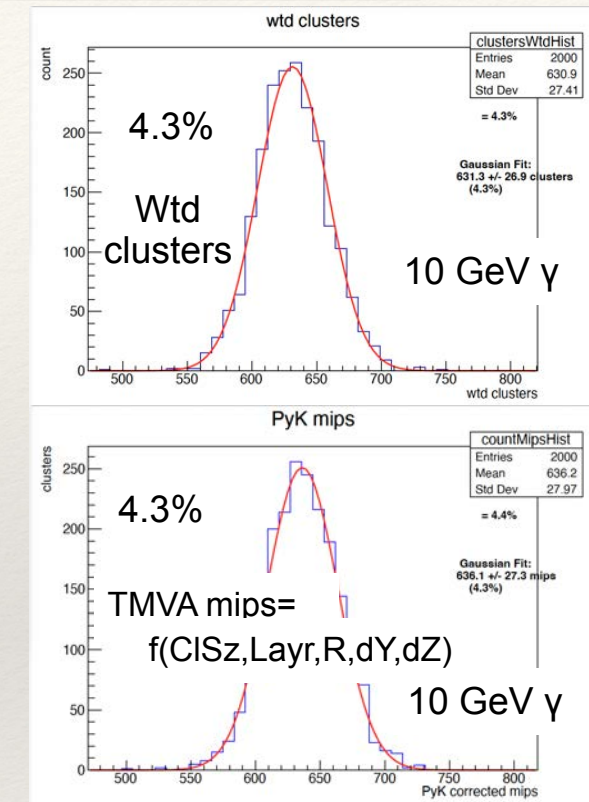


MAPS ECal for Particle Flow Calorimetry

Gamma Resolution vs. Energy (B=5T)



- ❖ Neural net has been applied to isolated MAPS EM shower measurements.
- ❖ Training based on different mix of parameters:
 - ❖ cluster size;
 - ❖ radius from shower axis;
 - ❖ depth in shower;
 - ❖ cluster shape;
 - ❖ pulse height.
- ❖ Neural net optimization of isolated EM shower matches weighted cluster improvements.
- ❖ **Jet reconstruction expected to improve**, using excellent MAPS isolation and detailed measurements for a detailed machine learning approach.

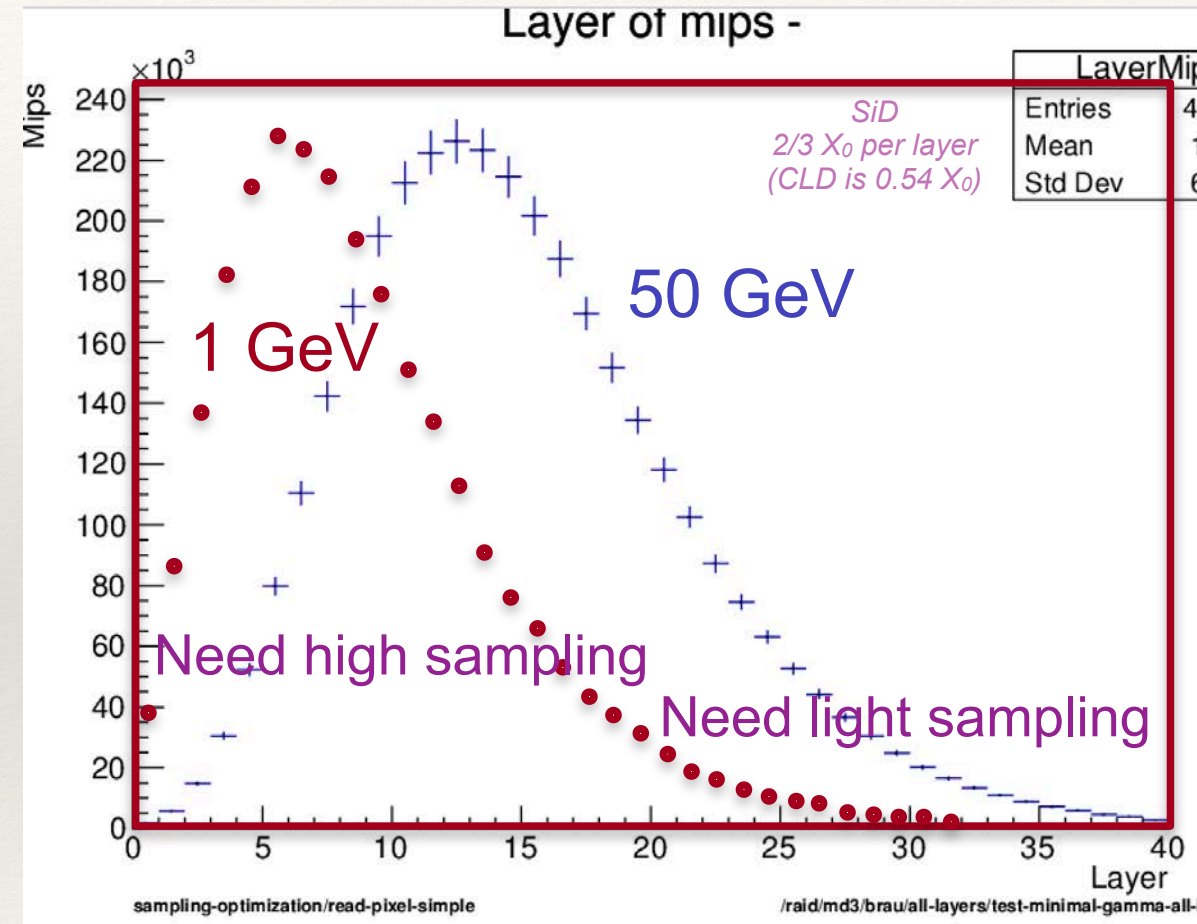




Optimization of ECal Configuration



- ❖ ECal Tungsten configuration
 - ❖ SiD - 20 thin (2.5 mm W) + 10 thick (5 mm W) $\rightarrow 26 X_0$
 - ❖ CLD - 40 (1.9 mm W) $\rightarrow 22 X_0$
- ❖ Studies of pixel size and longitudinal sampling
 - ❖ pixel size: $25 \times 100 \mu\text{m}^2 \rightarrow 1 \times 1 \text{ mm}^2$
 - ❖ longitudinal frequency every $2/3 X_0 \rightarrow$ every $2 X_0$
 - ❖ calorimeter depth: $26 X_0 \rightarrow 20 X_0$



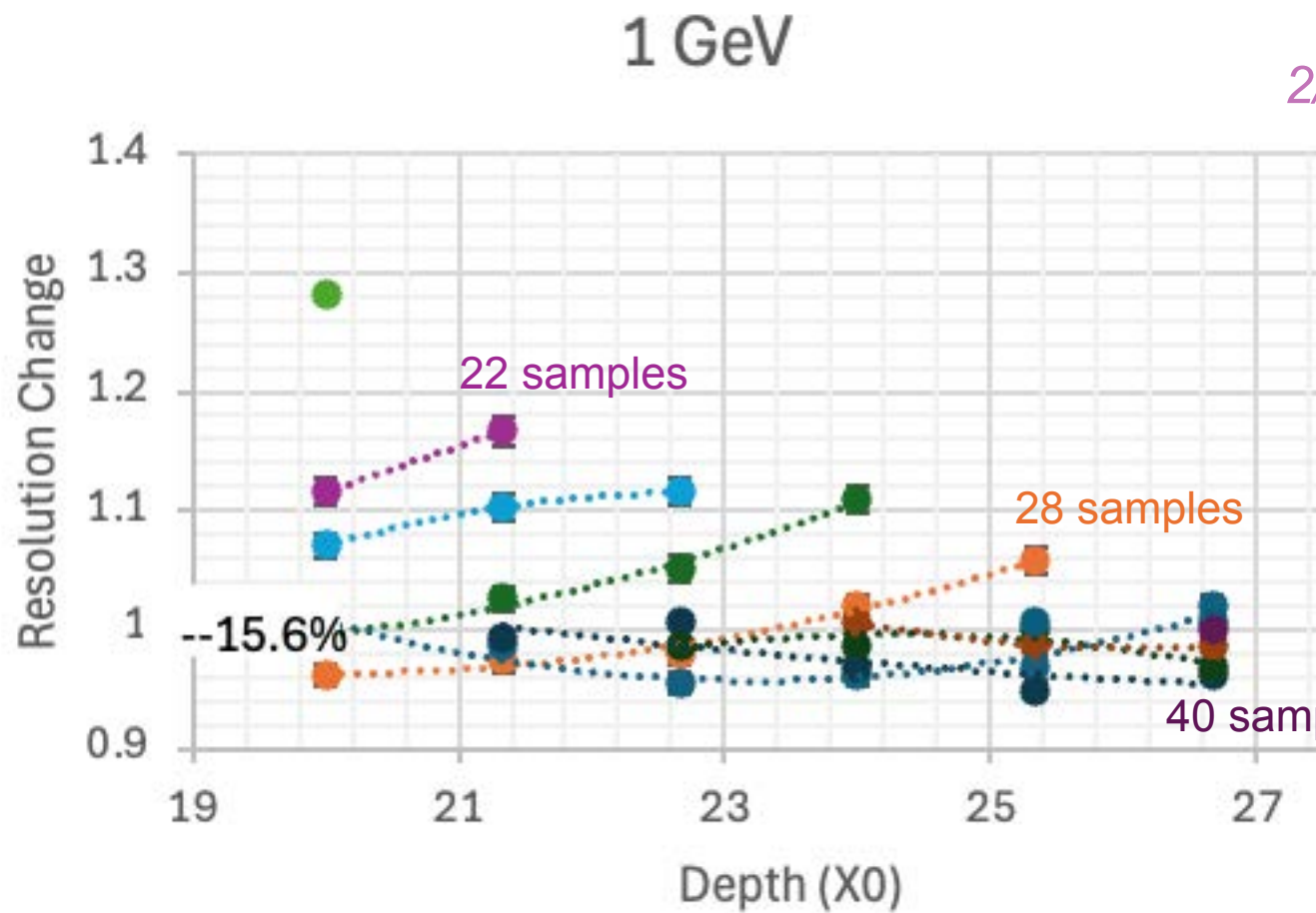


Resolution for ECal Configurations



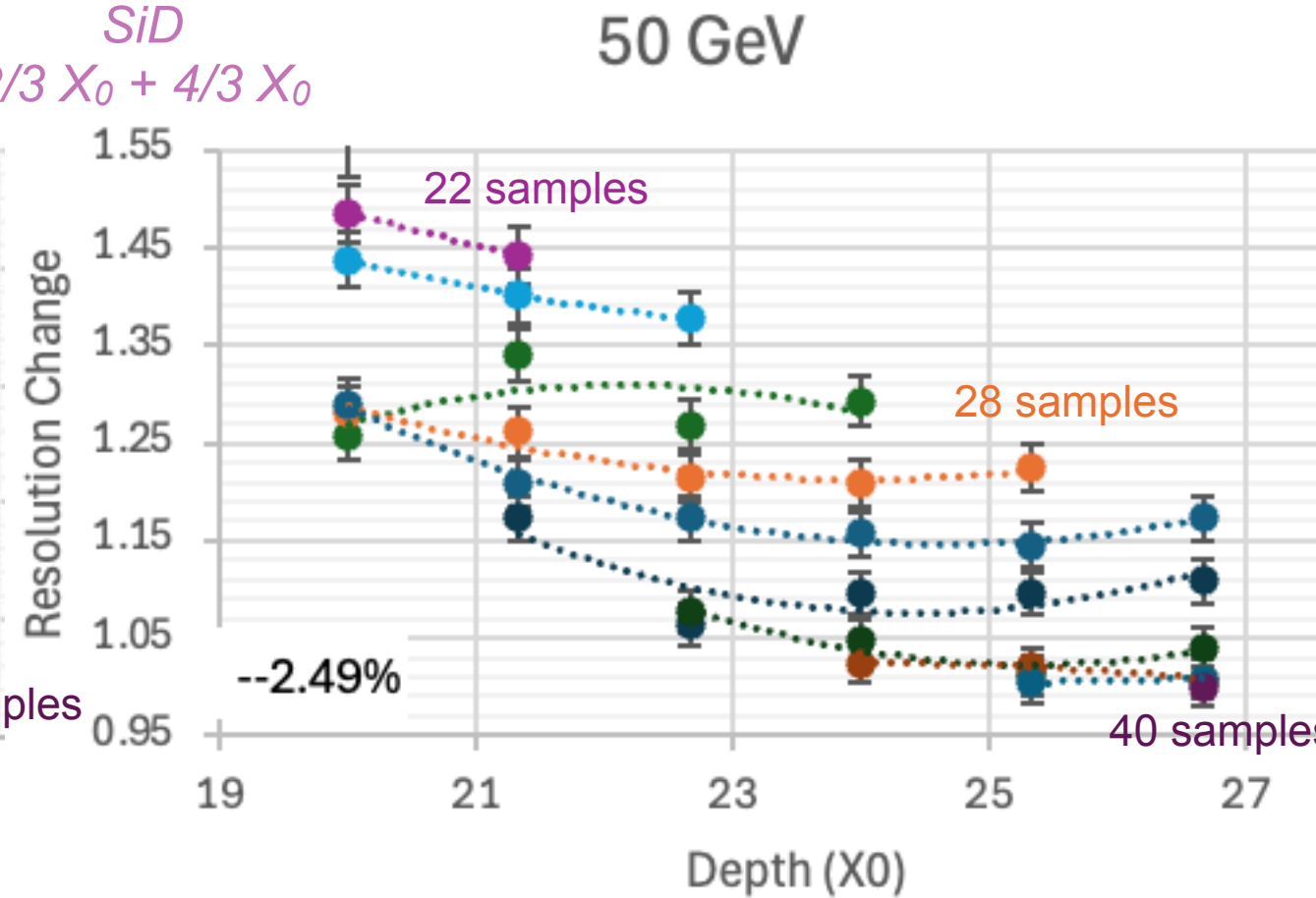
Number of samples = # thin + # thick

Depth = t (# thin + 2 x #thick)



● 20 ● 22 ● 24 ● 26 ● 28 ● 30 ● 32 ● 34 ● 36 ● 38 ● 40

SiD
 $\frac{2}{3} X_0 + \frac{4}{3} X_0$



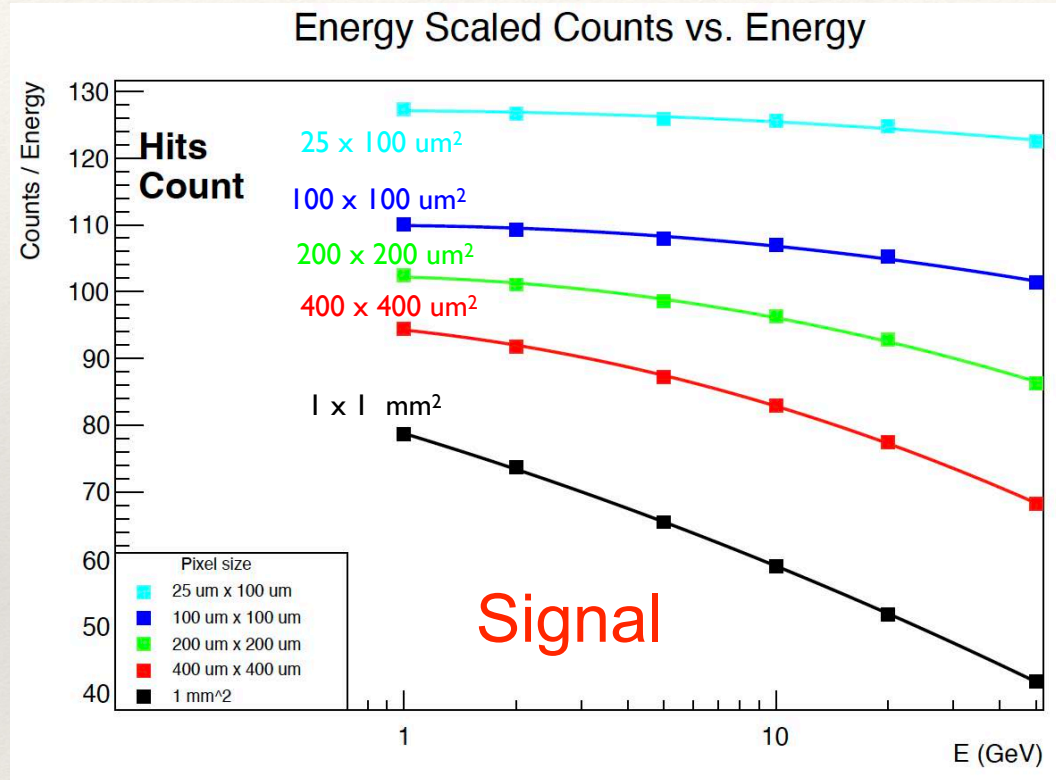
● 20 ● 22 ● 24 ● 26 ● 28 ● 30 ● 32 ● 34 ● 36 ● 38 ● 40



ECal Optimization

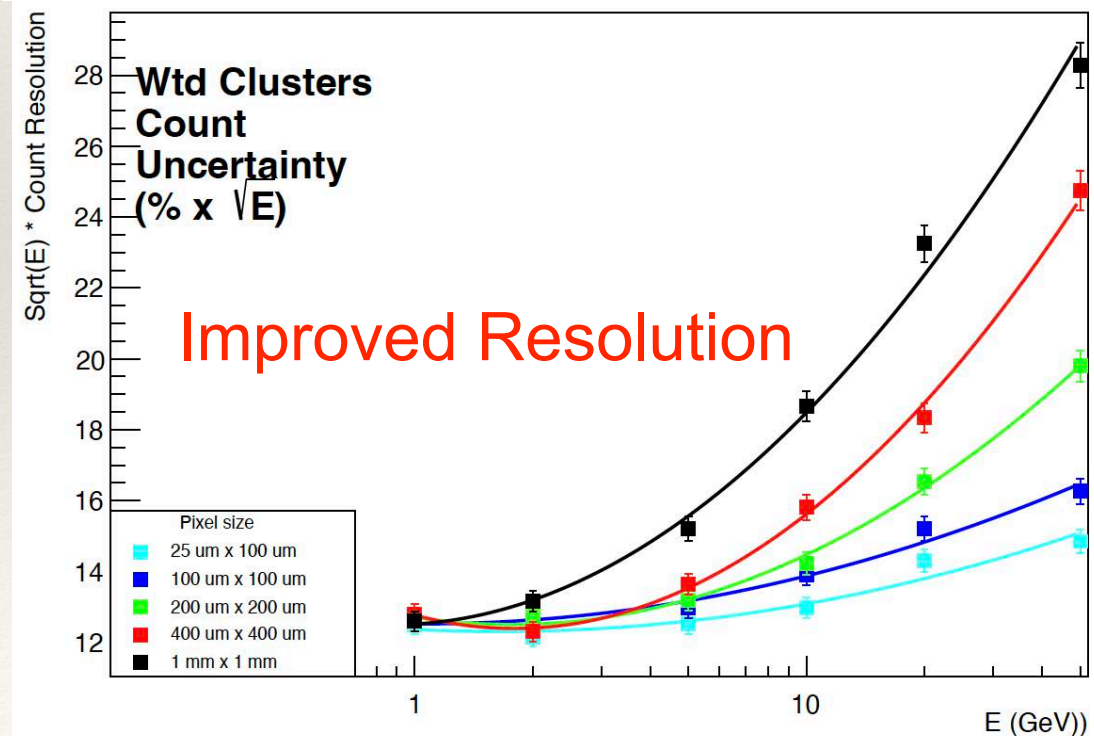
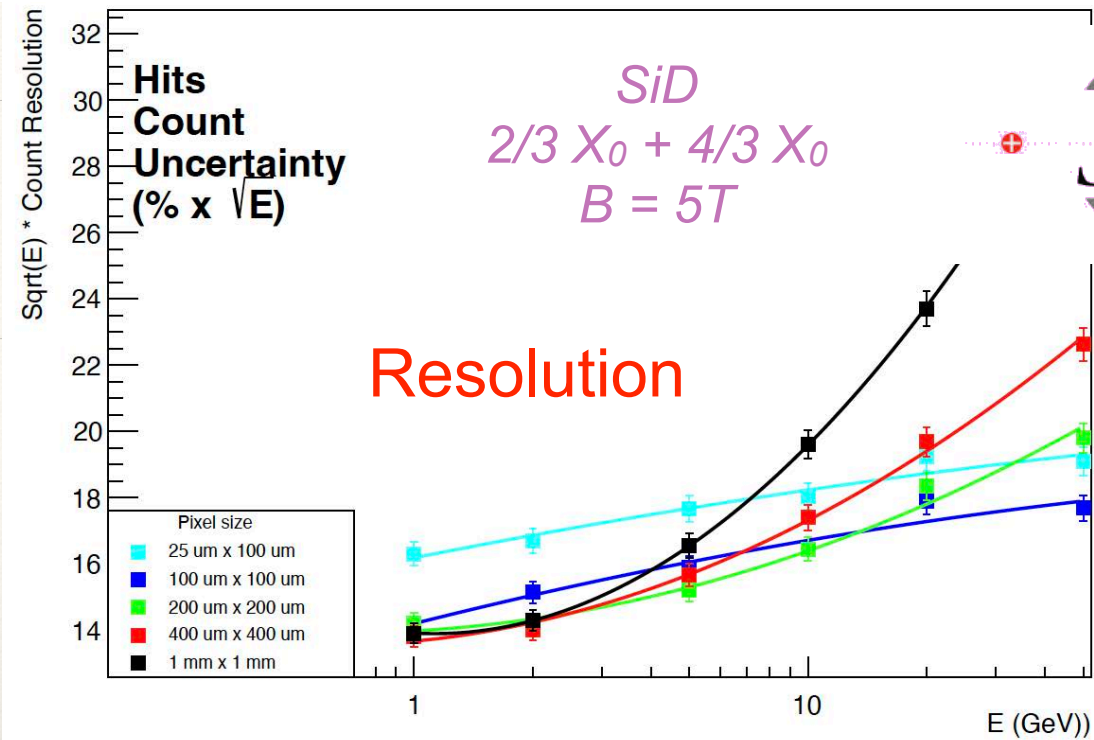
Pixel size variations

.0025 mm² → 1 mm²



100 x 100 um² (dark blue) is nearly as precise as 25 x 100 um² (light blue)

MAPS ECal for Particle Flow Calorimetry



100 x 100 um²
25 x 100 um²



ECal heat management



- ❖ MAPS generates $\sim 1 \mu\text{W}/\text{pixel CW}$
 - ❖ $\sim 0.16 \text{ W}/\text{cm}^2 \text{ CW}$
 - ❖ $\sim 16 \text{ kW}/\text{m}^2 \text{ CW}$
- ❖ **Active cooling** or **power pulsing** is required

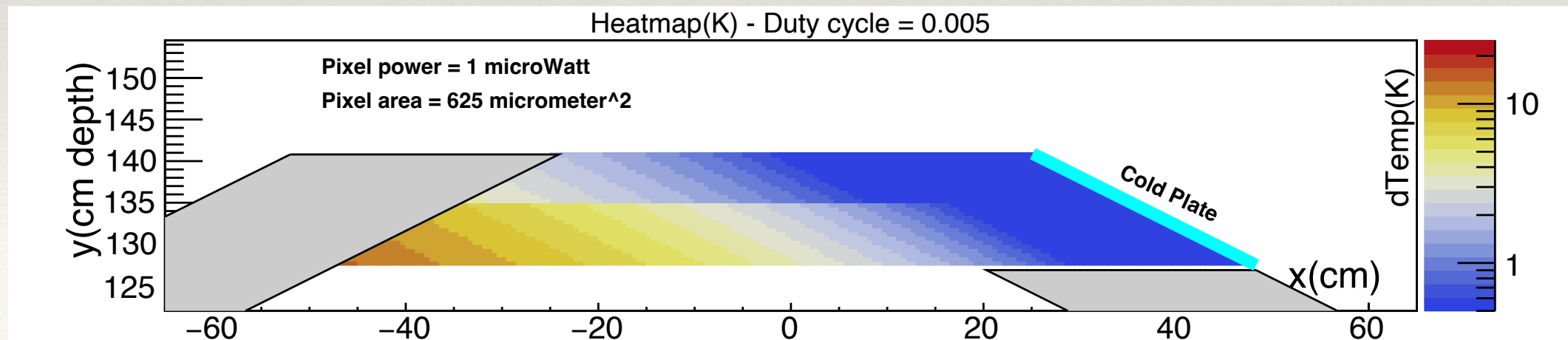
for pixel area
= $625 \mu\text{m}^2$

- ❖ **Active cooling (circular collider):**

- ❖ Material, stretching
- ❖ Minimize degradation

- ❖ **Power pulsing (linear collider)::**

- ❖ Duty cycle - 0.07% (C3/CLIC)
 - $\Delta T \sim 0.5 - 2 \text{ K}$
- ❖ Duty cycle - 0.5% (ILC)
 - $\Delta T \sim 4 - 16 \text{ K}$

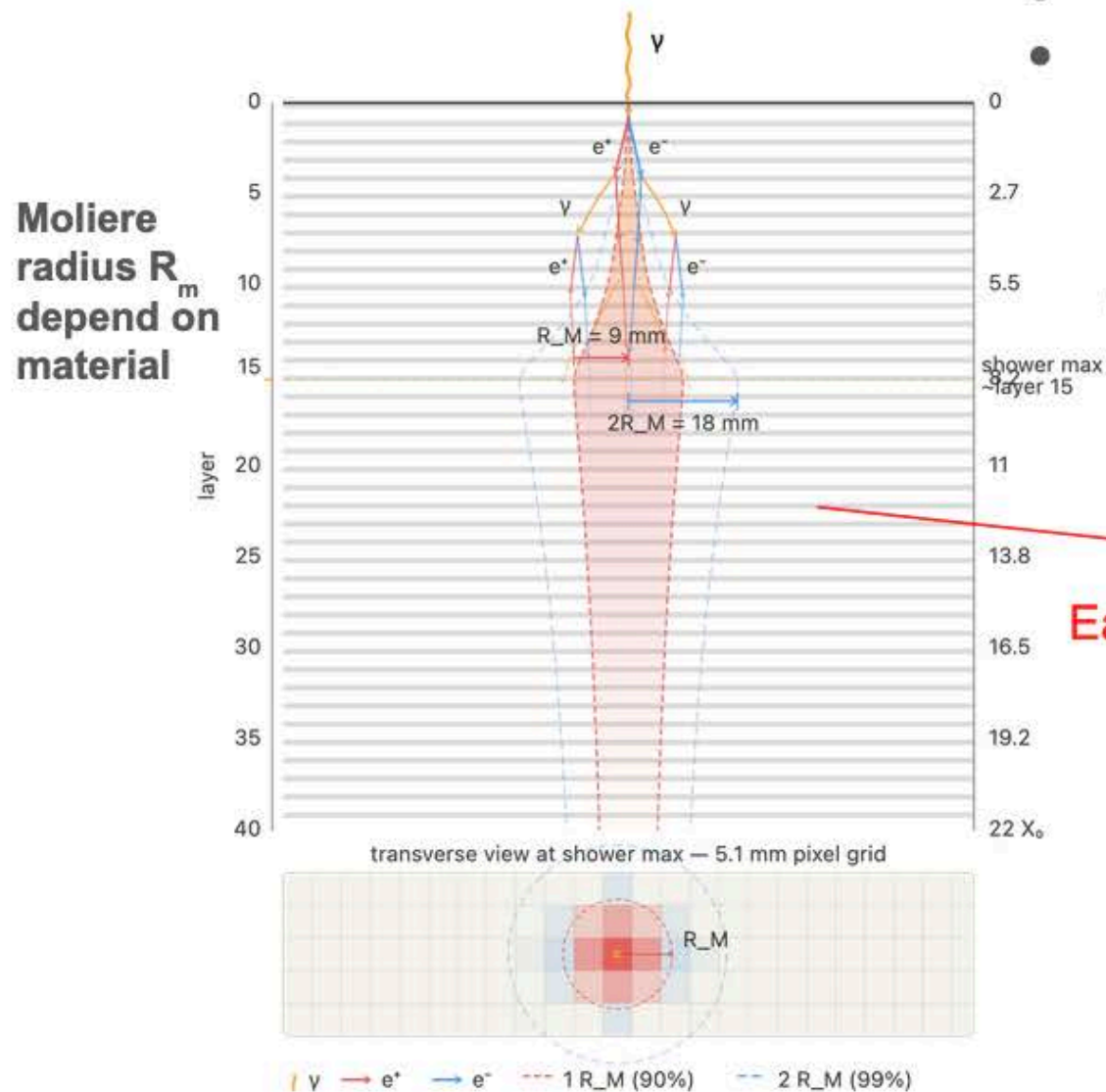


Baseline CLD Calorimetry

Prajita Bhattarai

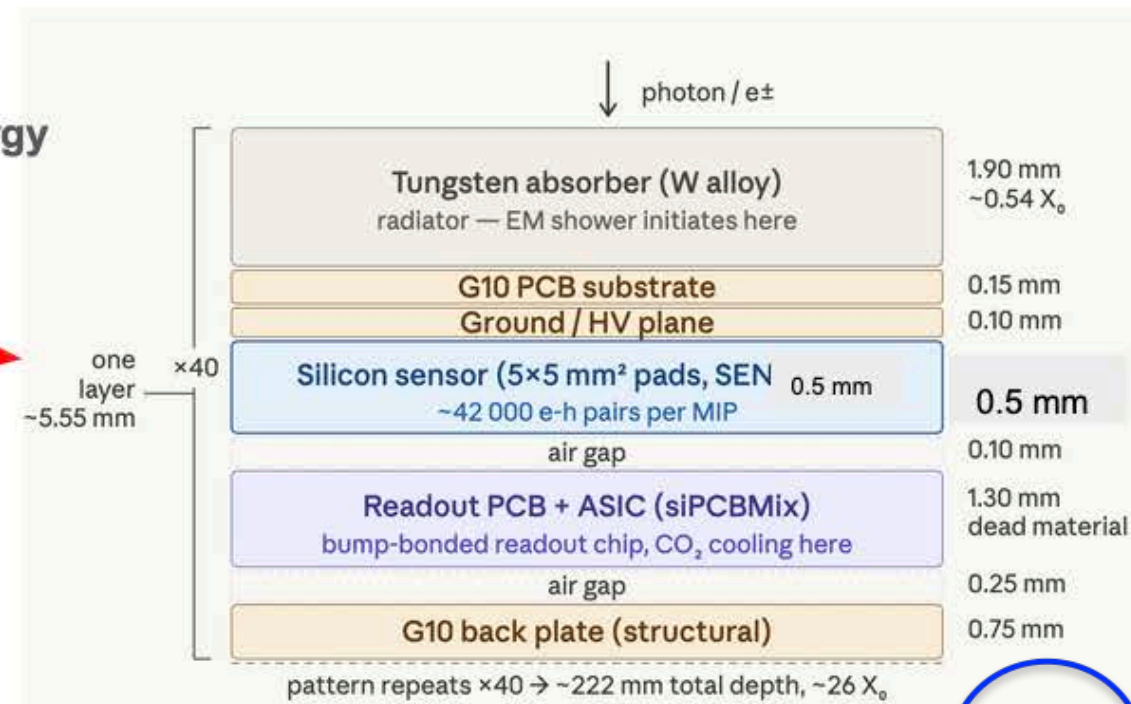
Sampling calorimeter with 5.1mmX5.1mm Si pixel, 40 layers total

- Analog sensors collect all charges above some threshold
- Cooling assumed to be passive, no active cooling for sensors



Shower max
depend on energy

Each layer



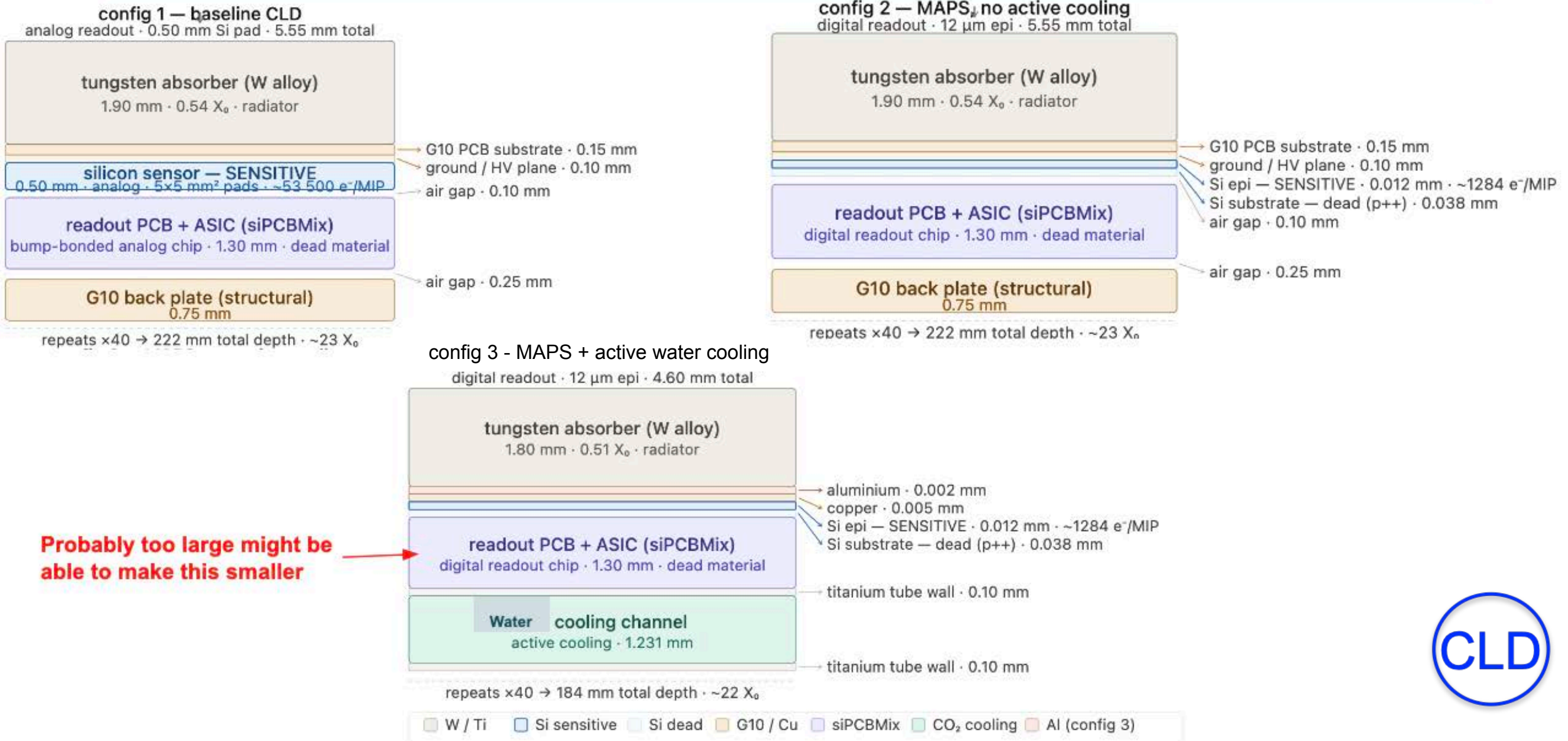
Is MAPS ECal feasible for FCC?
Does this bring any improvement?

CLD

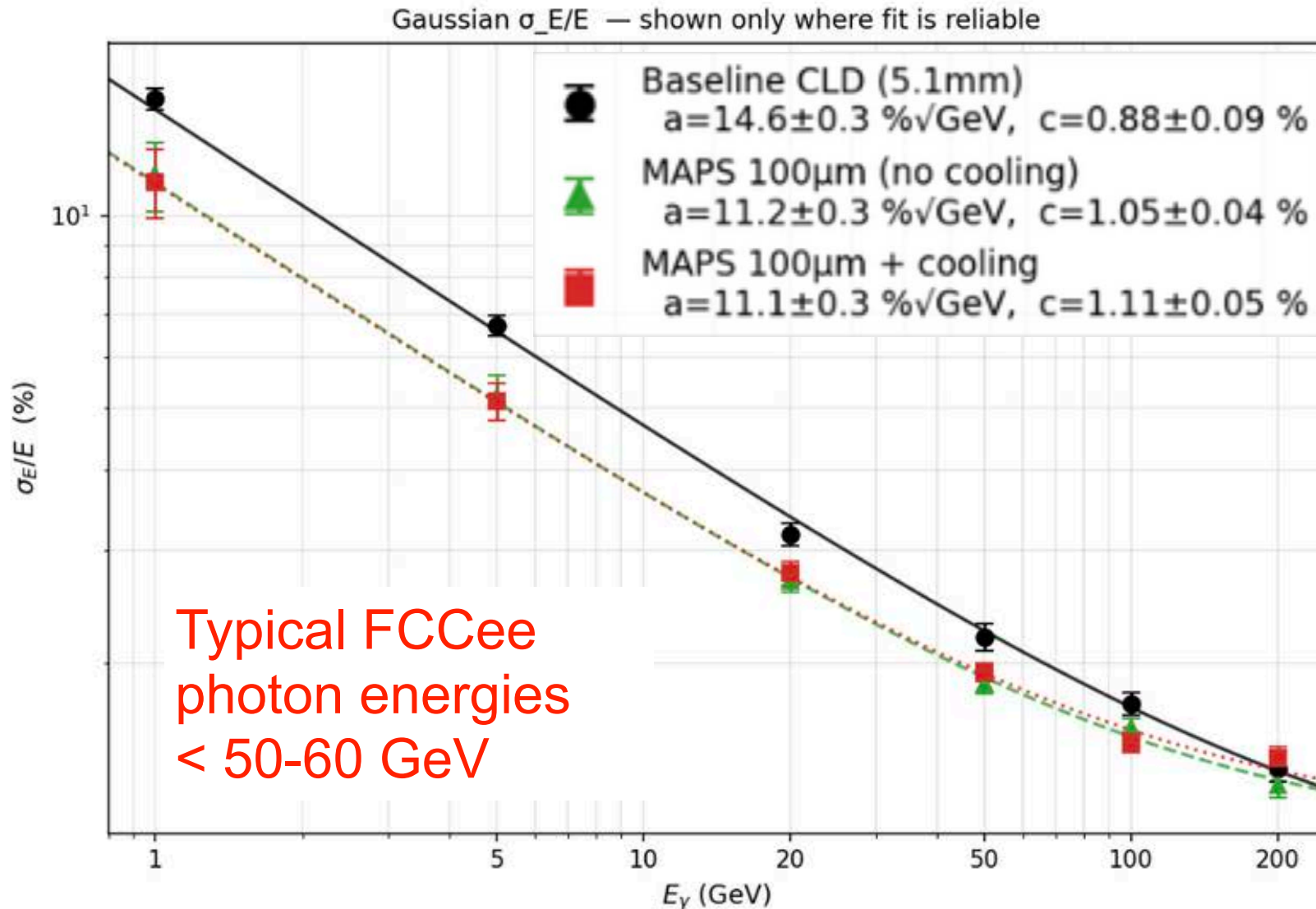
MAPS ECal feasibility under study

Adding Active Cooling

Prajita Bhattarai



Adding Active Cooling



Adding 1.2 mm water cooling reduces ECAL depth by $\sim 1 X_0$ without noticeable changes in resolution throughout all energy ranges, suggesting feasibility of active cooling without physics compromise



Conclusion

MAPS ECal for Particle Flow Calorimetry

- ❖ MAPS offer excellent detector performance for tracking and calorimetry.
- ❖ Excellent performance is simulated for MAPS digital ECal:
 - ❖ EM shower energy measurement;
 - ❖ Particle flow contribution based on transverse energy containment.
- ❖ EM shower structure allows simple algorithmic optimization of energy measurement.
- ❖ Neural nets have been studied to improve energy measurement:
 - ❖ Should improve jet reconstruction.
- ❖ An effort led by SLAC is progressing on the needed MAPS development.
- ❖ CLD-based active cooling study for circular collider looks good.
- ❖ The digital ECal will add valuable future collider performance for particle flow reconstruction.
- ❖ **Critical performance demonstration:**
 - ❖ Coordinated jet reconstruction resolution & efficiency.

Acknowledgements:

- CERN WP 1.2 for the excellent cooperation and support for NAPA-p1 and NAPA-p2 runs
- DRD Calo
- EPICAL-2 Team
- CPAD RDC9

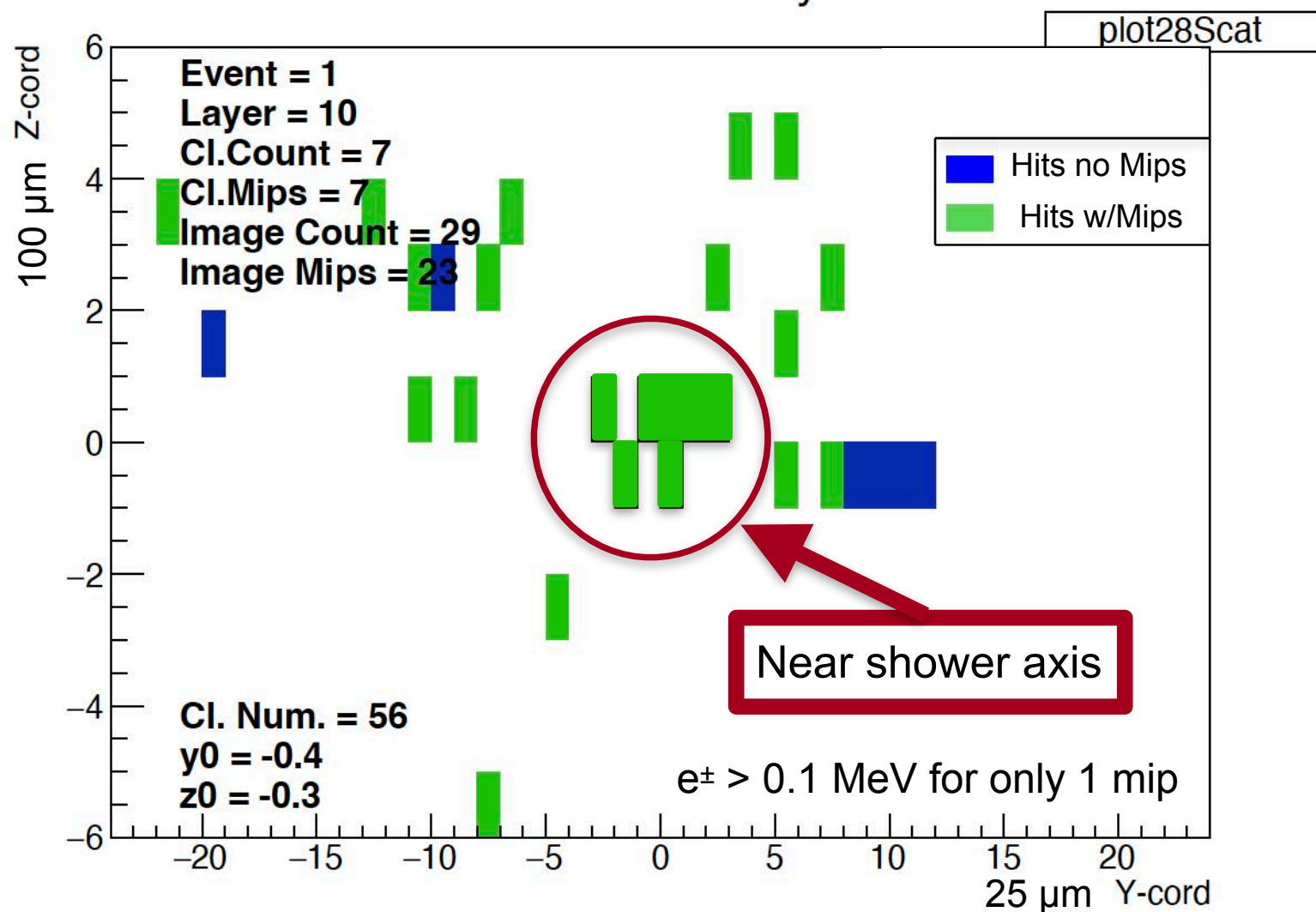
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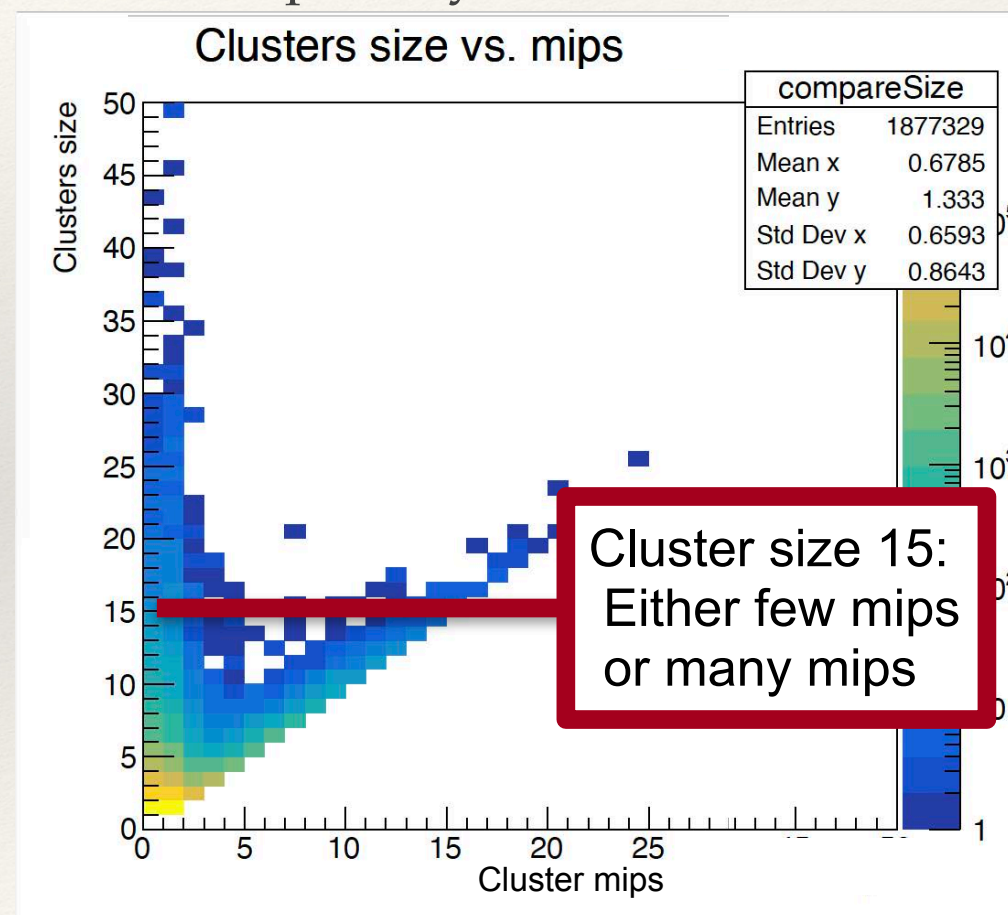
Backup Slides

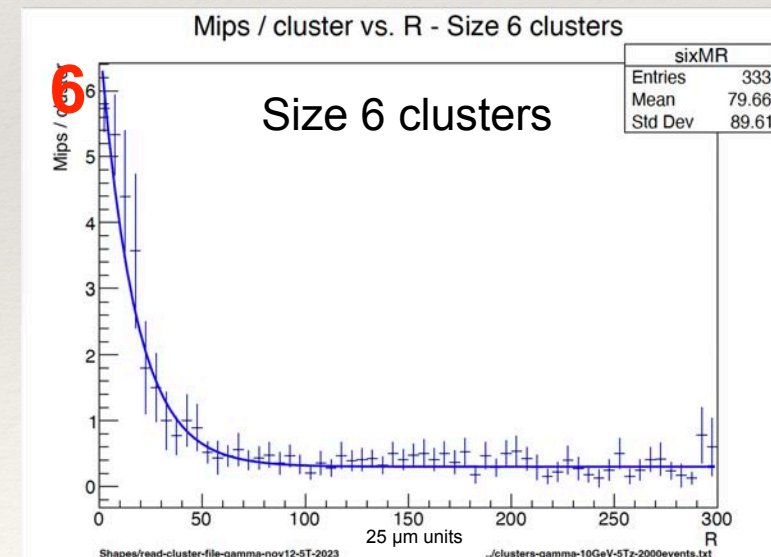
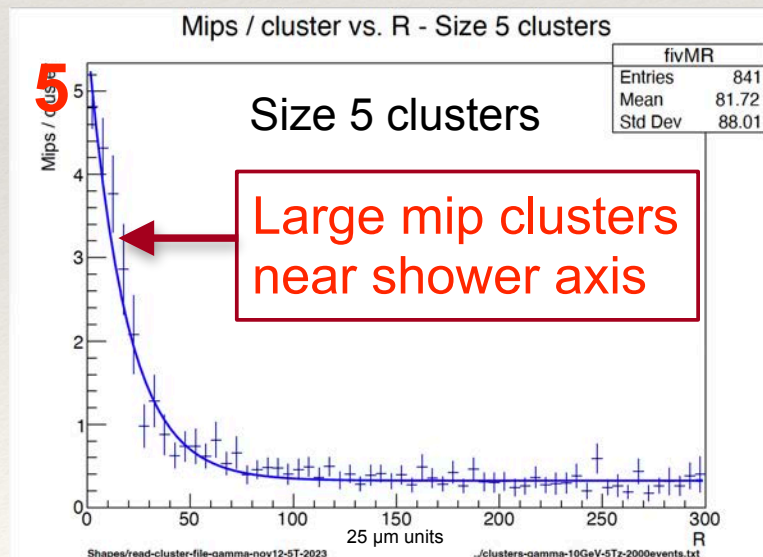
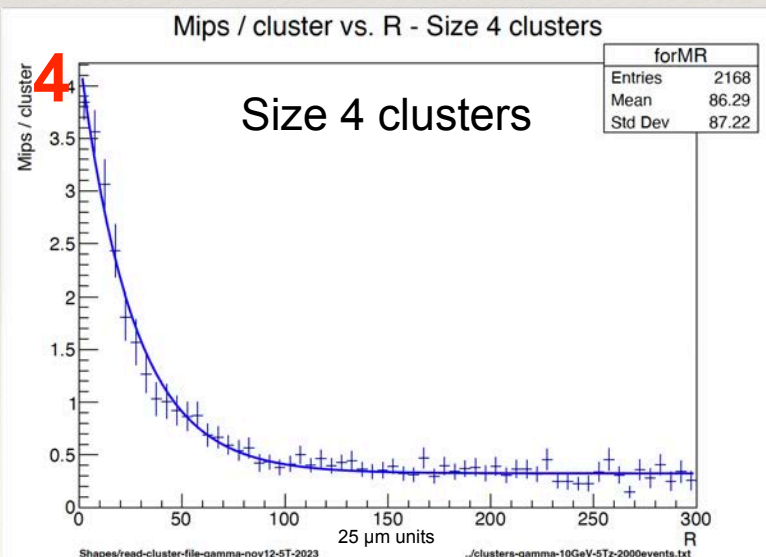
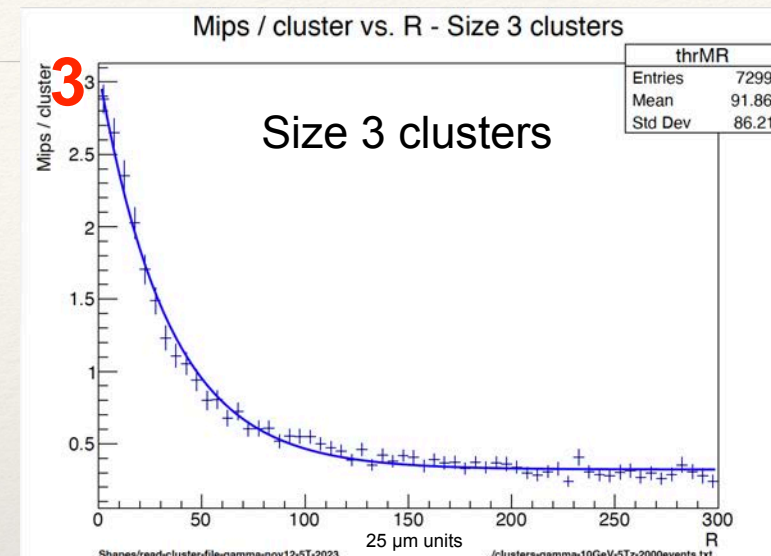
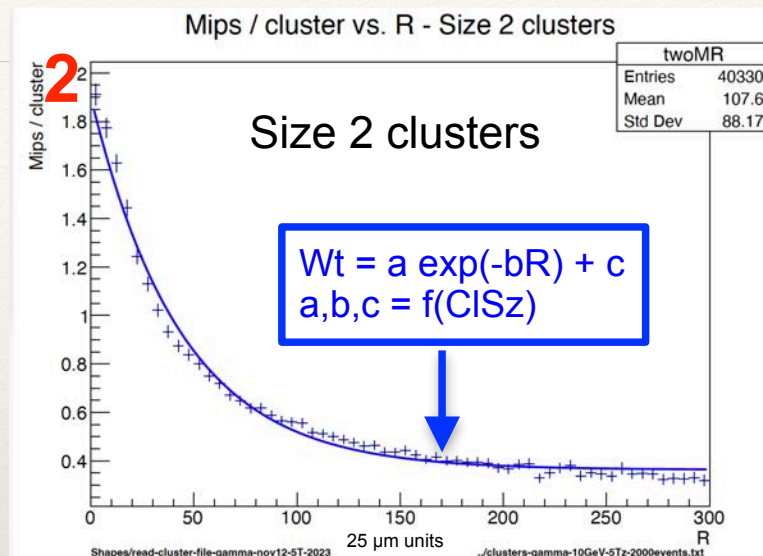
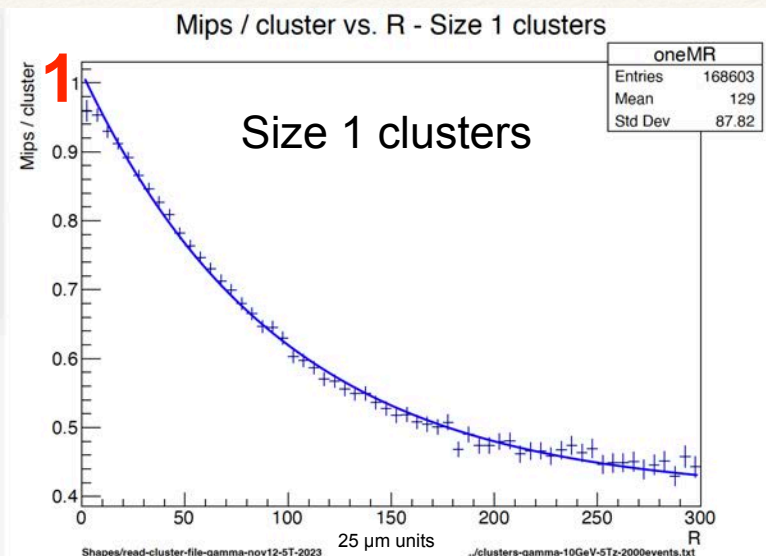
All Clusters are not the same

Cluster and nearby hits

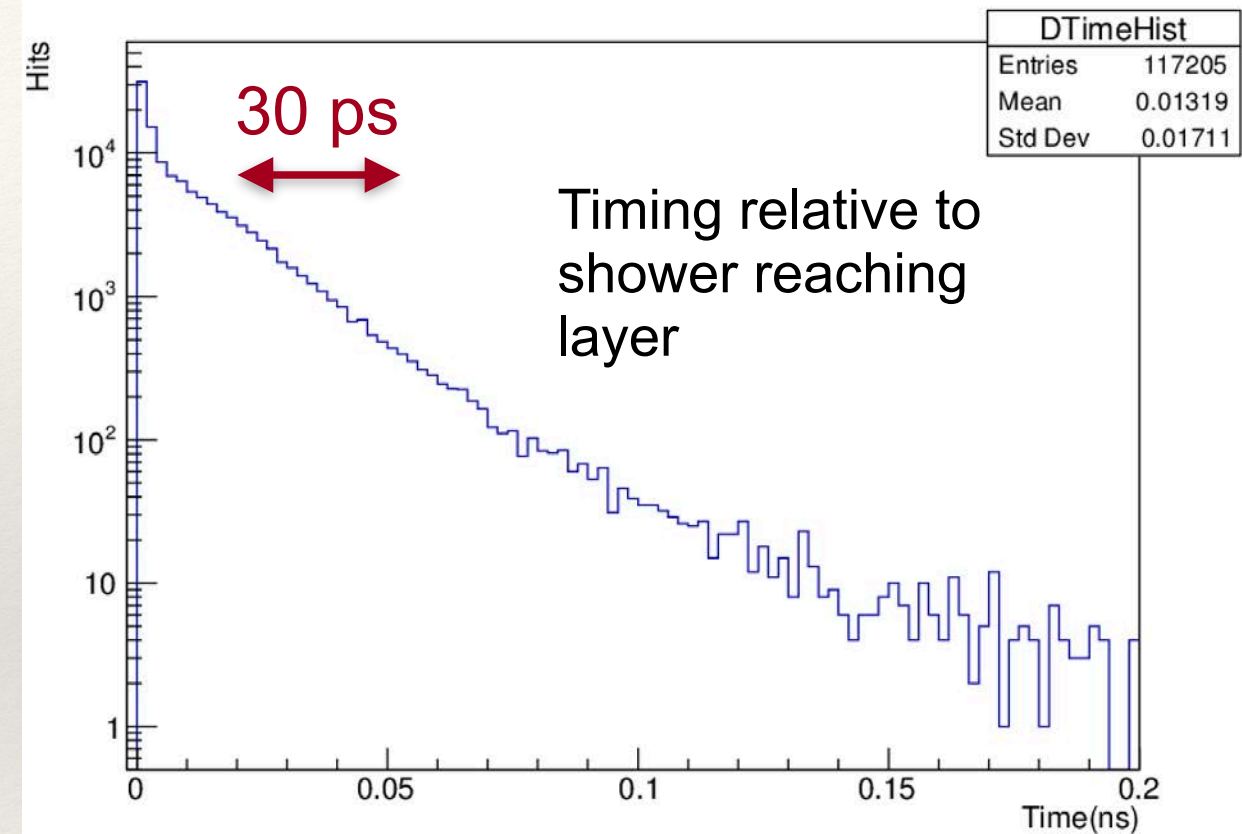
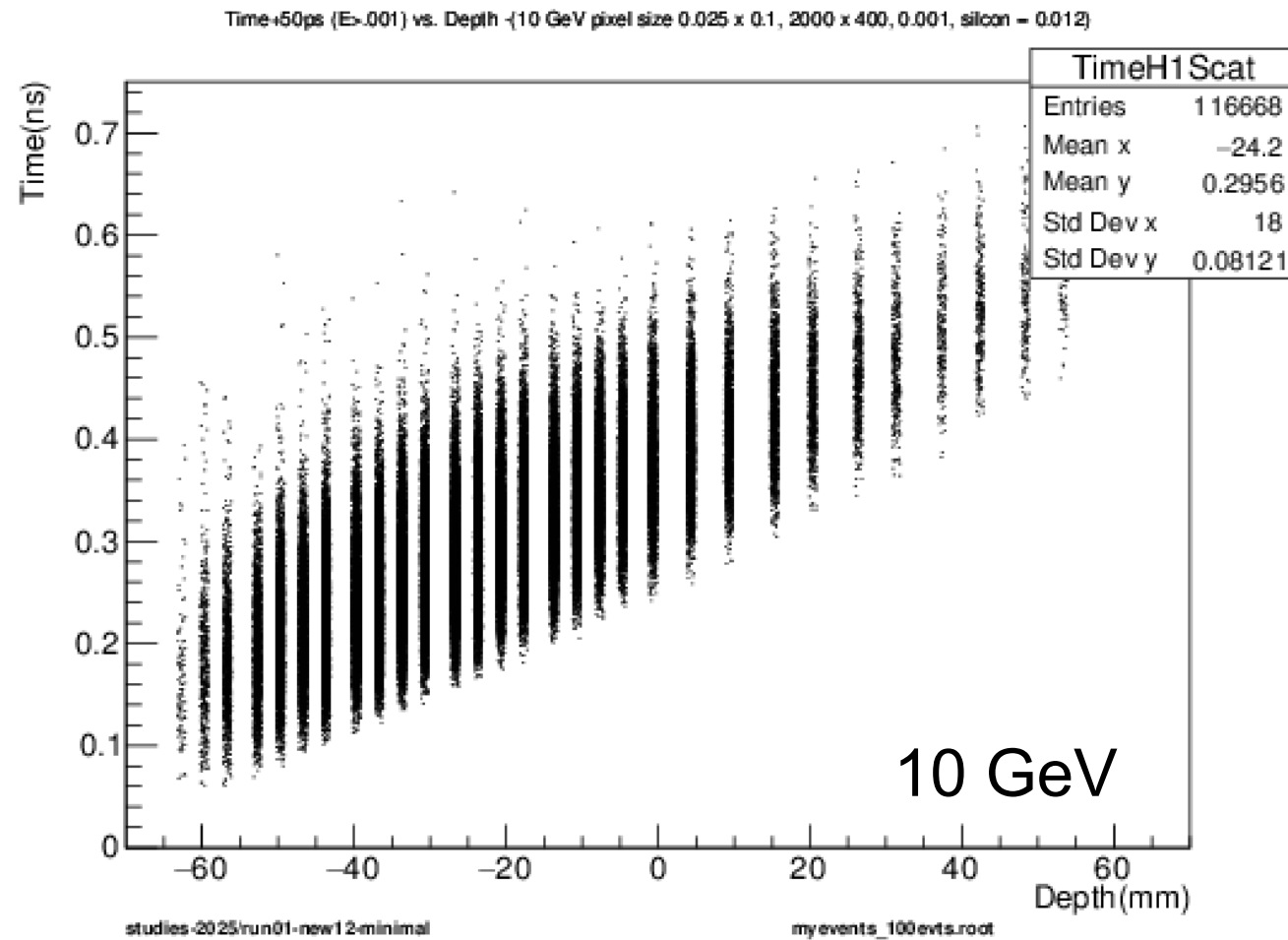


- ❖ Some clusters are numerous mips.
- ❖ especially near shower axis





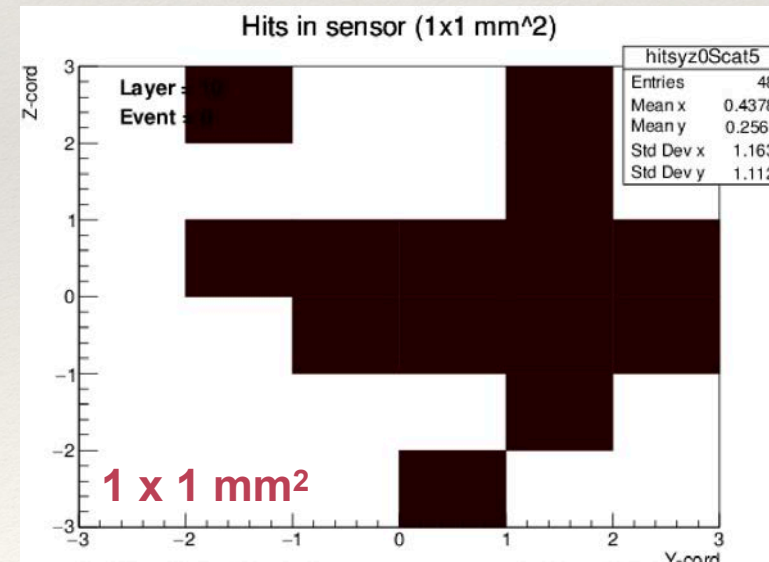
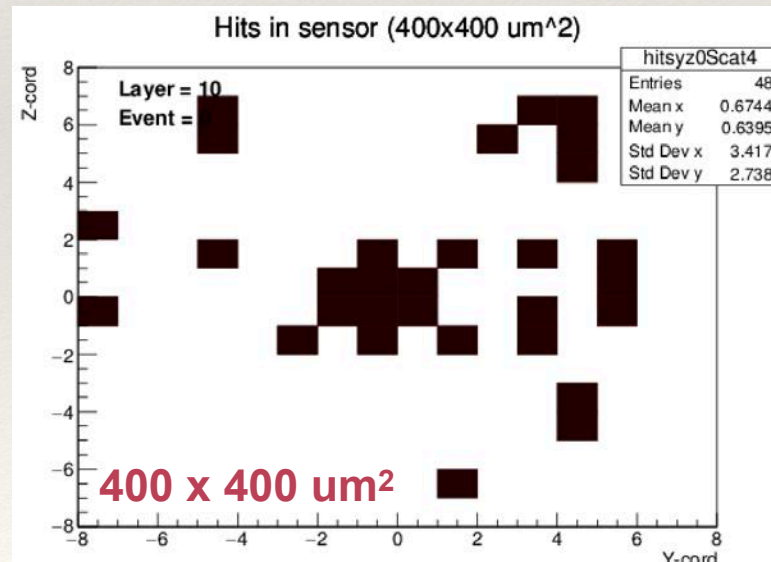
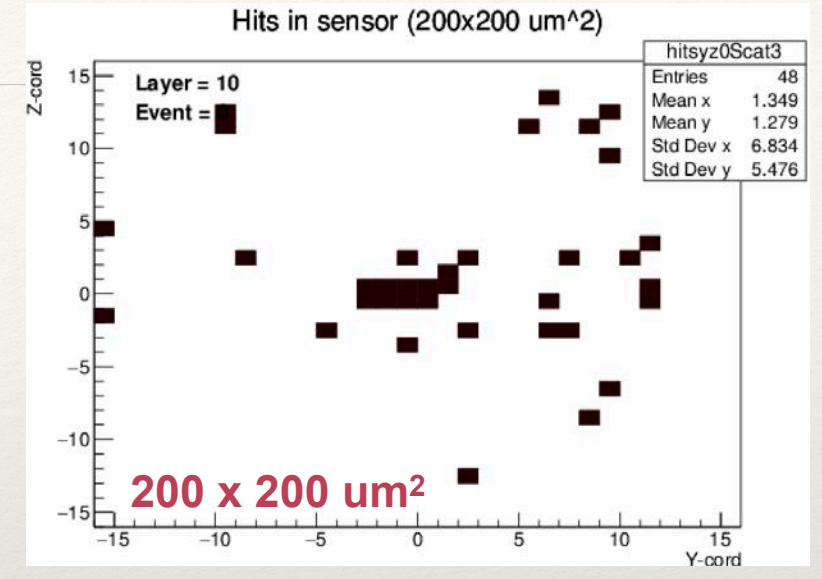
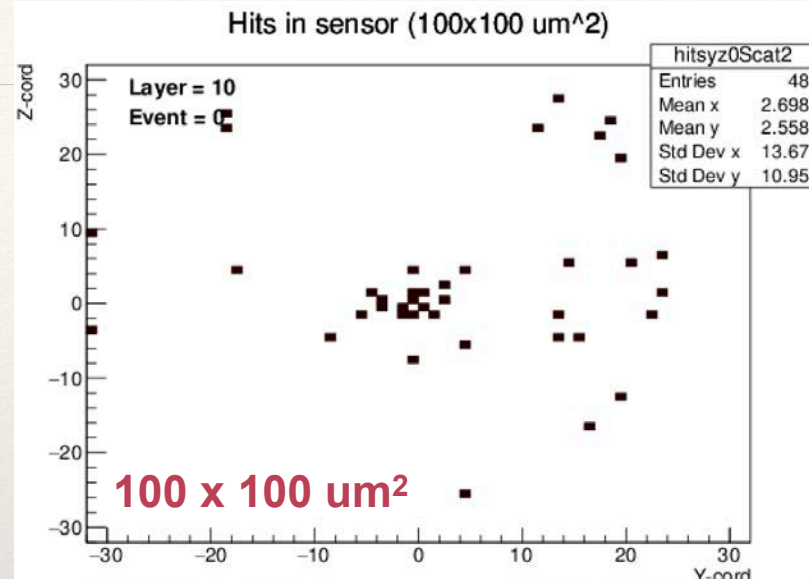
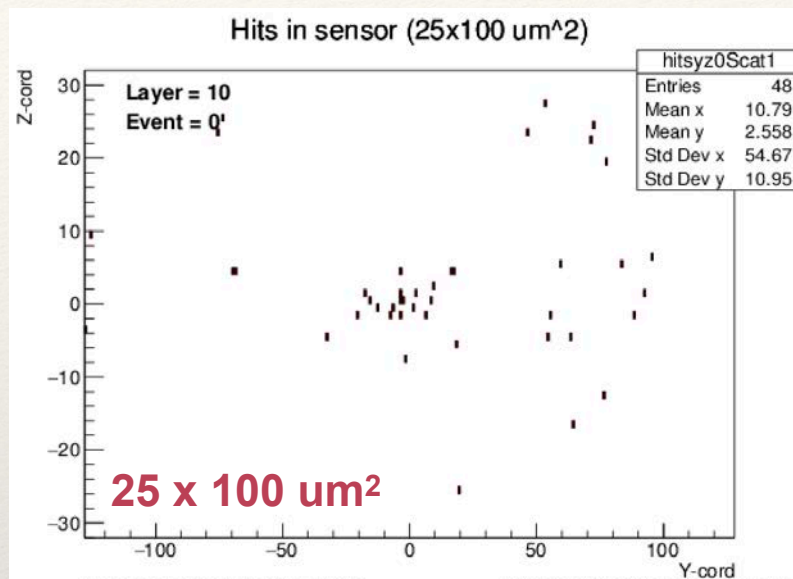
Timing of shower hits



Future study - use of timing



Pixel sizes (same event with each variation)



MAPS ECal efforts

- ❖ **FoCAL - ALICE**
 - ❖ 20 layers of 3.5 mm tungsten
 - ❖ **two MAPS layers** with $30 \times 30 \text{ } \mu\text{m}^2$ pixels
 - ❖ $1002 \times 1008 \text{ mm}^2$ coverage
- ❖ **EPICAL-2 SI-W prototype with beam test**
 - ❖ 24 layers of MAPS - 20 radiation lengths
 - ❖ 3 mm tungsten absorber; $29.24 \times 26.88 \text{ } \mu\text{m}^2$ pixels
 - ❖ ≈ 25 million pixels / active area $\approx 27 \times 30 \text{ mm}^2$
- ❖ **Astropix for ePIC**
 - ❖ 4 imaging layers with $500 \times 550 \text{ } \mu\text{m}^2$ pixels
- ❖ **Higgs factory - expand application**
 - ❖ optimizing sensor, layout and performance

