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The SiD Digital ECal Based on Monolithic Active Pixel Sensors

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on behalf of
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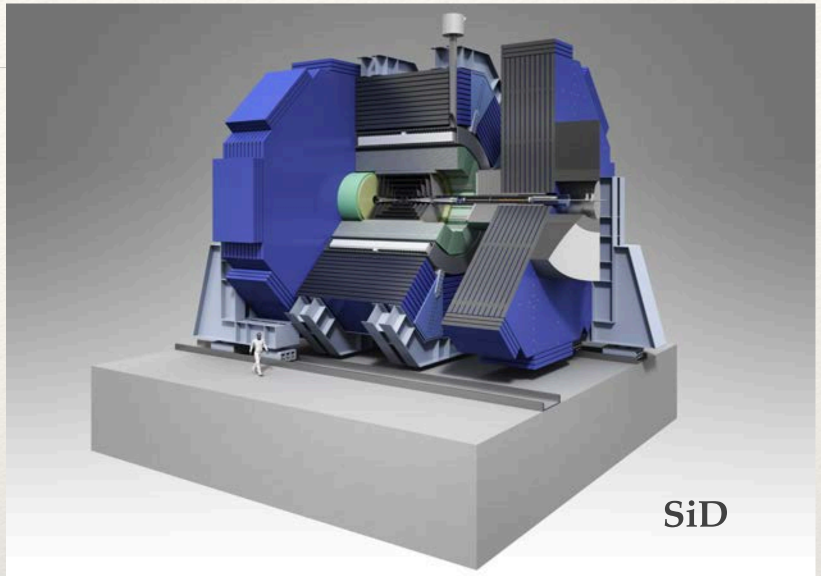
“The SiD Digital ECal Based on Monolithic Active Pixel Sensors",
10.3390/instruments6040051, Instruments, 6, 51 (2022)

SiD Digital ECal Based on MAPS

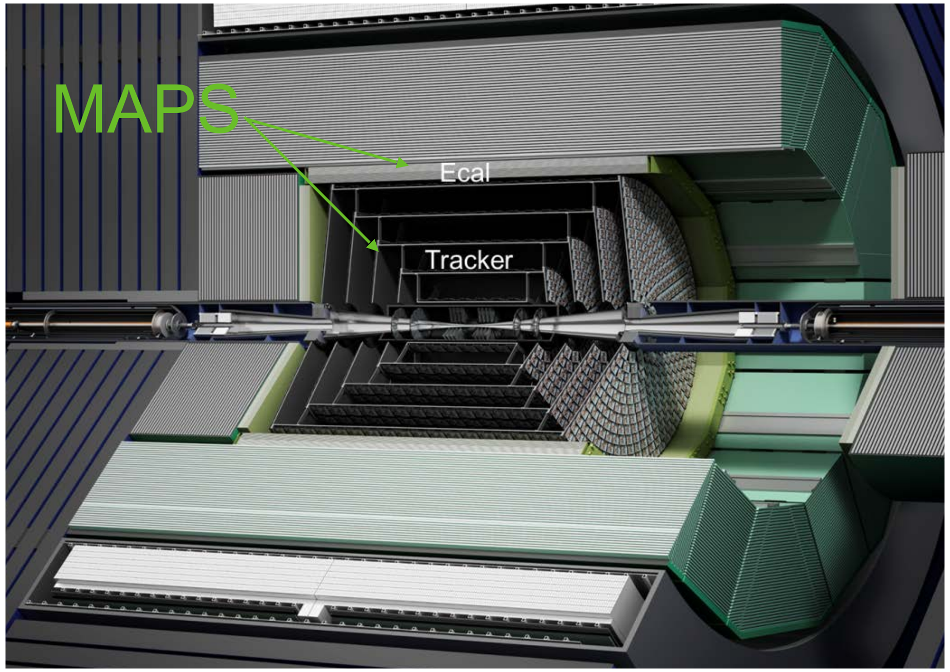


- SiD upgrade now under development with 25 x 100 μm^2 (or 25 x 50/25 μm^2) digital pixels in electromagnetic calorimeter and tracker.
    - Replacing the ILC TDR ECal design based on 13 mm^2 analog pixel sensors.
- Heat management is critical to success.
    - FCC/CEPC solution?
- How well can we measure energy and shower structure with this digital system:
    - Compared to SiD baseline with analog measurements?
    - Can the detailed structural measurements be used to improve measurement?
    - Would a neural net optimization offer an improvement?
- What are the limits of transverse separation and measurement?

Large area MAPS for SiD tracker & ECal

Benefits of large-area MAPS:

- Standard CMOS foundry, low resistivity: **cost ⇩**
- Sensing element and readout electronics on same die
    - In-pixel amplification: **noise ⇩, power ⇩**
    - No need for bump-bonding: **cost ⇩**
- Area > **5x20** cm^2 → enable O(1) m^2 modules



An example of the SiD Tracker and the ECal overall design

Several design challenges:

- Large on-die variations, mismatch
- Yield
- Stitching layout rules
- Distribution of power supply
- Distribution of global control signals/references

Goals of R&D: find solutions and explore novel design techniques

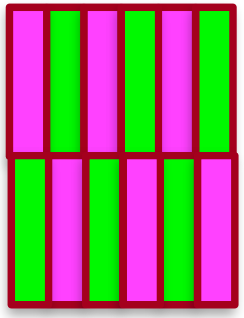
SLAC collaborating with CERN WP1.2 efforts

L. Rota

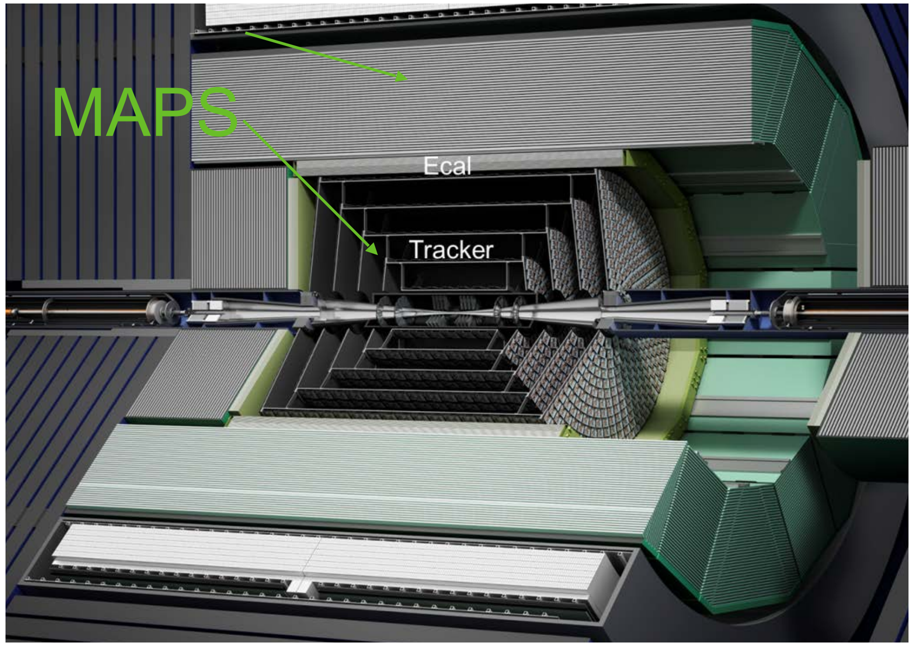
Main specifications for Large Area MAPS development

L. Rota

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 SiD 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 EMCal to improve yield.
Timing resolution (pixel)	~ ns	Bunch spacing: C^3 strictest with 5.3->3.5 ns; ILC is 554 ns
Total Ionizing Dose	100 kRads	Total lifetime dose, not a concern
Hit density / train	1000 hits / cm^2	
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 SiD tracker power consumption: 400W over 67m^2

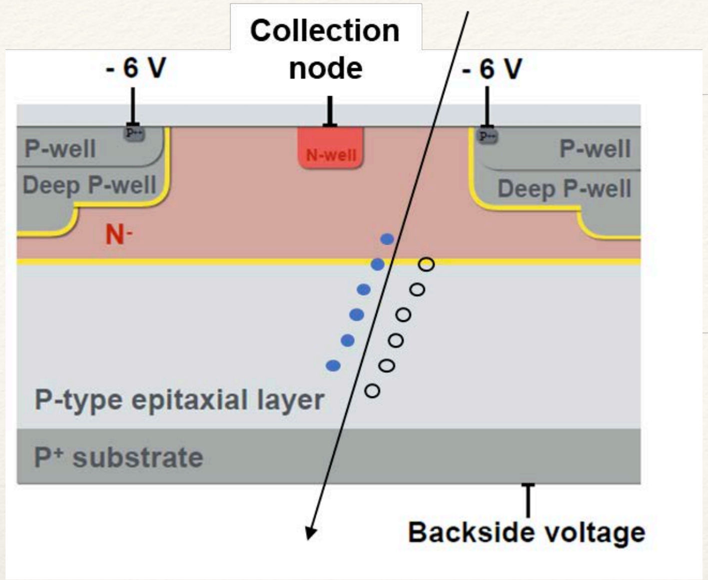


25 x 100 µm^2
ECal performance
same as
50 x 50 µm^2

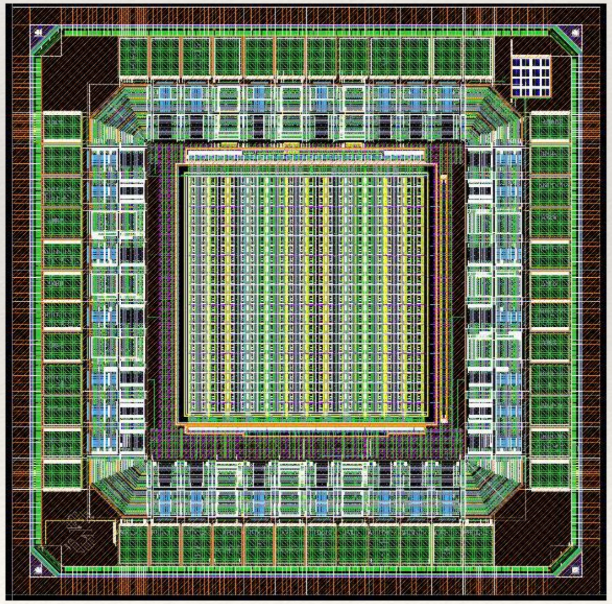


SiD Tracker and the ECal

<1 mW/cm^2
for 1% duty cycle



Current sensor optimization in TJ180/TJ65 nm process
Effort to identify US foundry on going



Layout of SLAC prototype for WP1.2 2022 shared submission on TowerSemi 65nm

Large Area MAPS - Highlights and Next Steps

Approach:

- Focus on long-term R&D, targeting simultaneously:
  - ~ns timing resolution
  - Power consumption compatible with large area and low material budget
  - Fault-tolerant circuit strategies for wafer-scale MAPS

Highlights:

- 1st SLAC prototype on TJ65nm (2023) from CERN WP1.2 shared run
- Performance of 1st SLAC prototype on TJ65nm (2023) evaluated

Next steps:

- New design combining O(ns) timing precision and low-power (2024/2025).
- **Stretch Goals:** design of a wafer-scale ASIC (2025/2026, design only)

Engagement :

- Higgs Factory detector initiative R&D
- DRD 3 silicon sensors
- DRD 7.6 on common issues of power distributions compatible with stitching

A. Habib *et al* 2024 *JINST* **19** C04033
C. Vernieri, MAPS DRD 3.1 talk

SiD Calorimeter Barrel Geometry

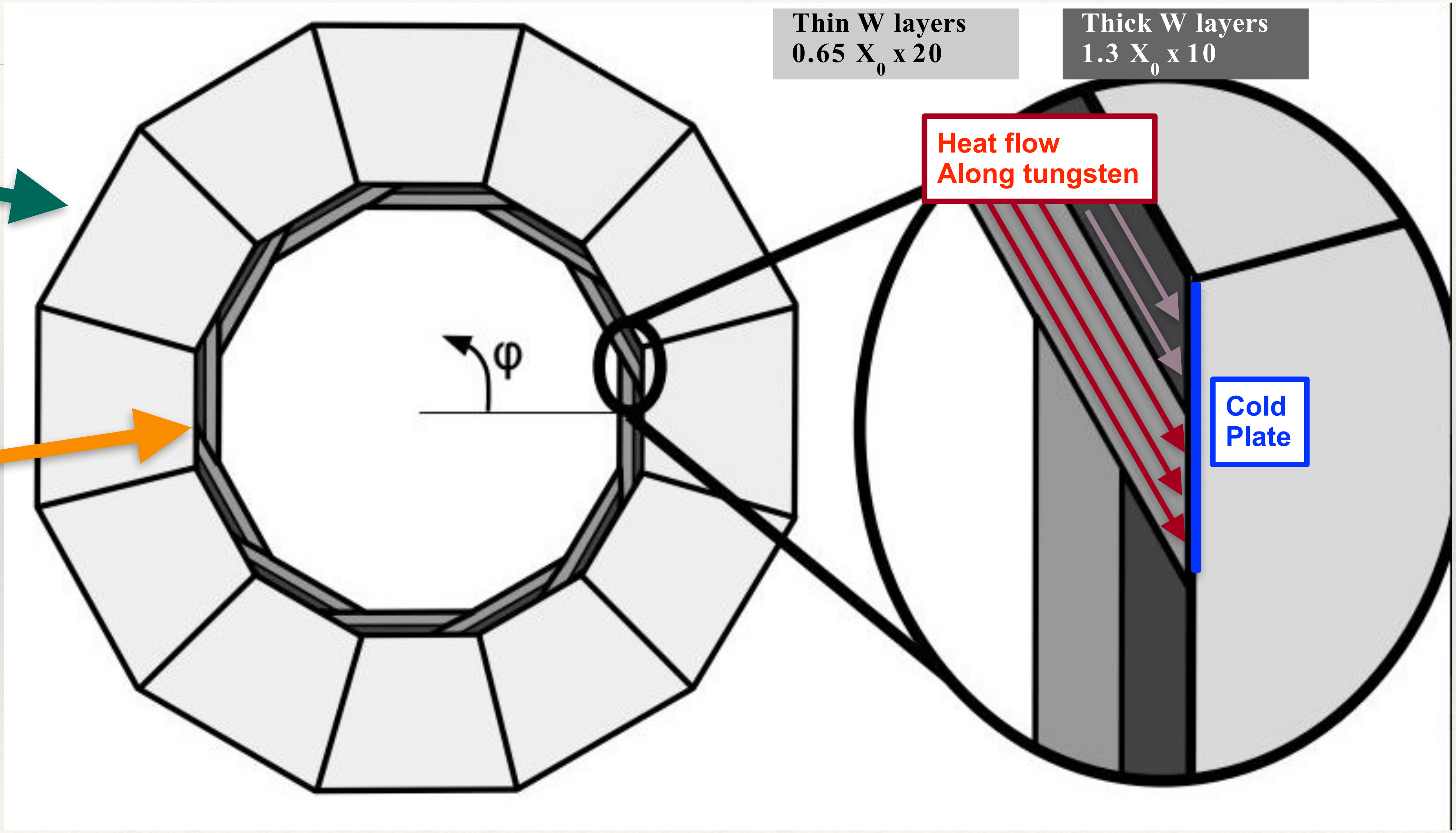
HCal

Scintillator sampling
Steel/polystyrene

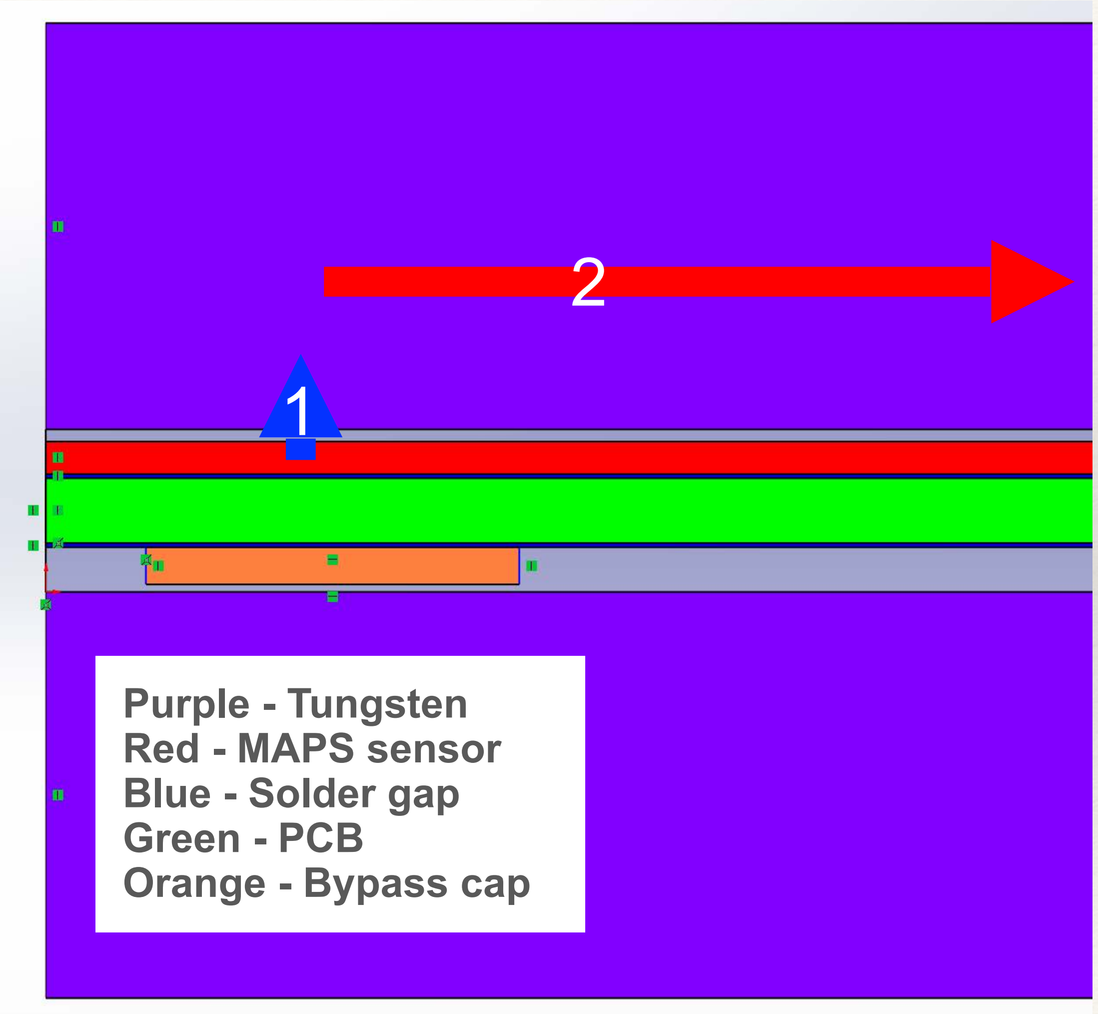
ECal

Solid state sampling
Tungsten alloy/MAPS

Built on first layer of HCal

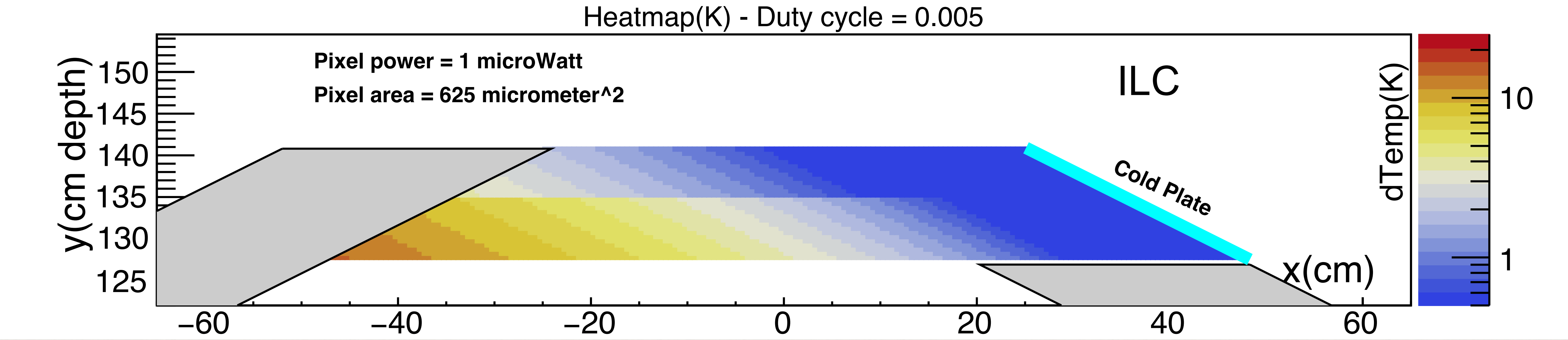


Heat conduction from ECal sensor to cold plate



- MAPS generates ~kW/m² (each sensor is 100 cm²)
- First heat flows through 300 μm N_2 to tungsten
  - $\Delta T << 1$ K
- Then heat flows thru tungsten to cold plate
  - Tungsten absorber lengths 0.5-1.0 m
  - Temperature rise is length dependent
- Duty cycle - 0.07% (C3/CLIC) - $\Delta T \sim 0.5 - 2$ K
- Duty cycle - 0.5% (ILC) - $\Delta T \sim 4 - 16$ K
  - Without power pulsing temperature blows up and needs active cooling

Heat conduction from ECal sensor to cold plate

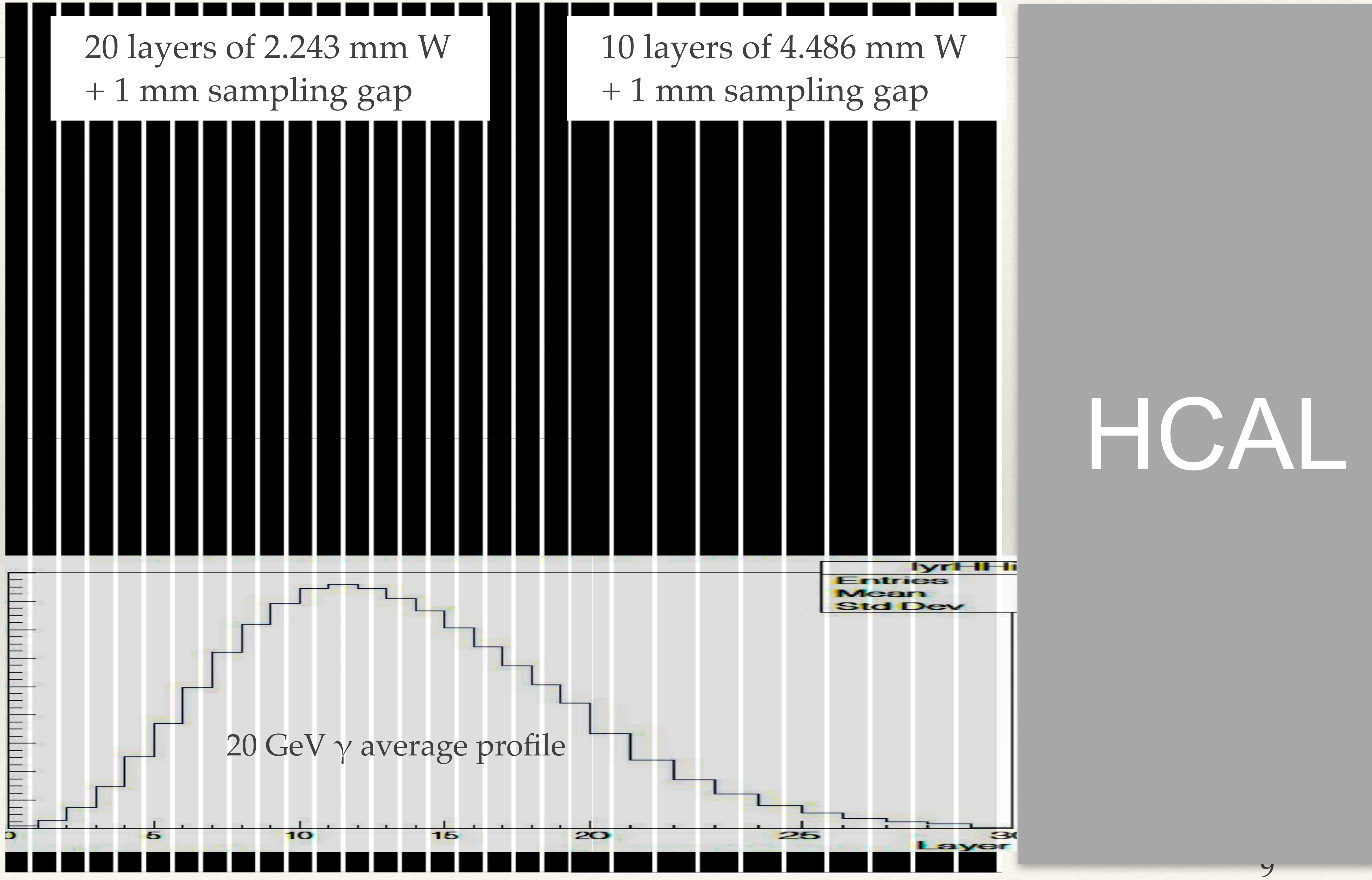


- **Duty cycle - 0.07% (C3/CLIC) - ΔT ~ 0.5 - 2 K**
- **Duty cycle - 0.5% (ILC) - ΔT ~ 4 - 16 K**
    - **Without power pulsing temperature blows up and needs active cooling**
        - **such as for FCC/CEPC**

Model of longitudinal structure of SiD ECal

Total = 27 X_O

Incident Particle



20 layers of 2.243 mm W
+ 1 mm sampling gap

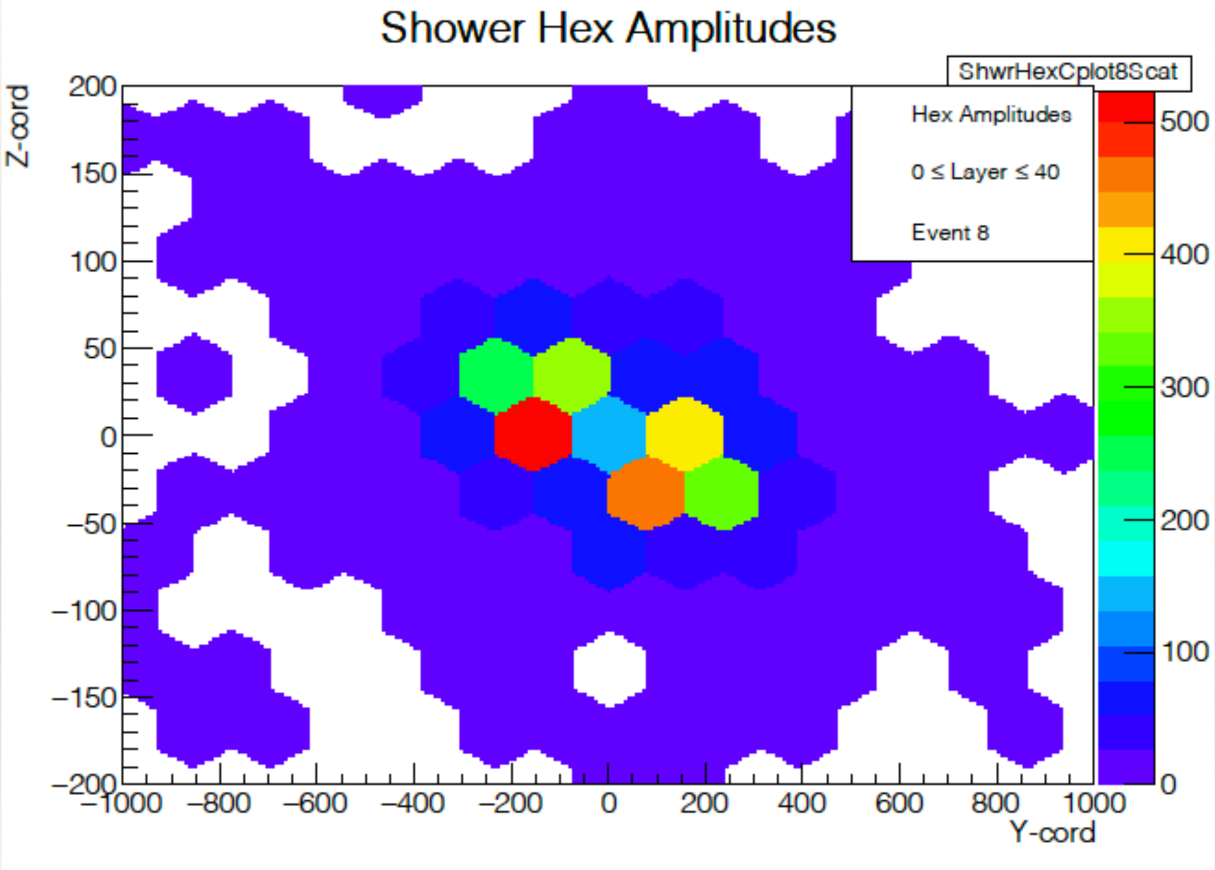
10 layers of 4.486 mm W
+ 1 mm sampling gap

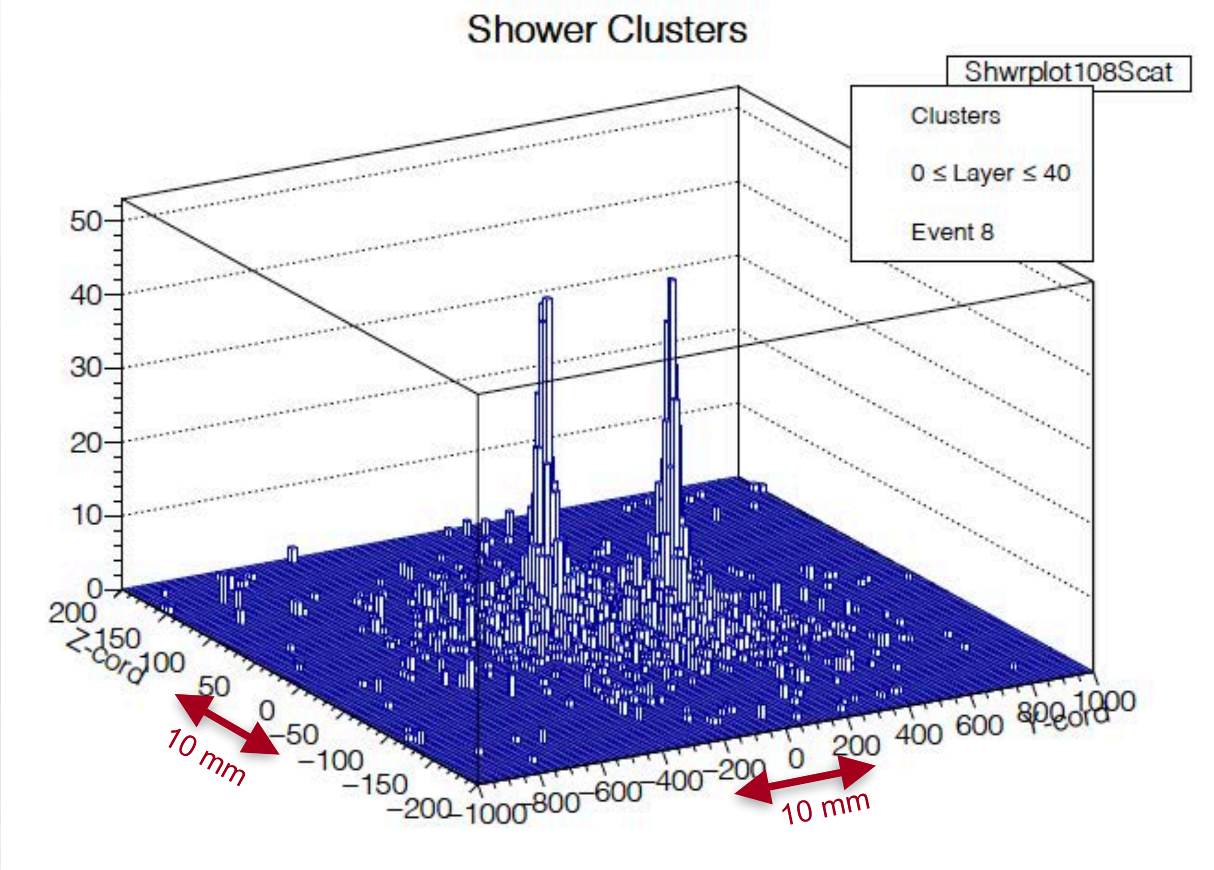
20 GeV γ average profile

Minimize sampling gap to achieve optimal Moliere radius (14 mm) & shower separation

Multi-shower of SiD MAPS compared to SiD TDR

40 GeV $\pi^0 \rightarrow$ two 20 GeV γ's





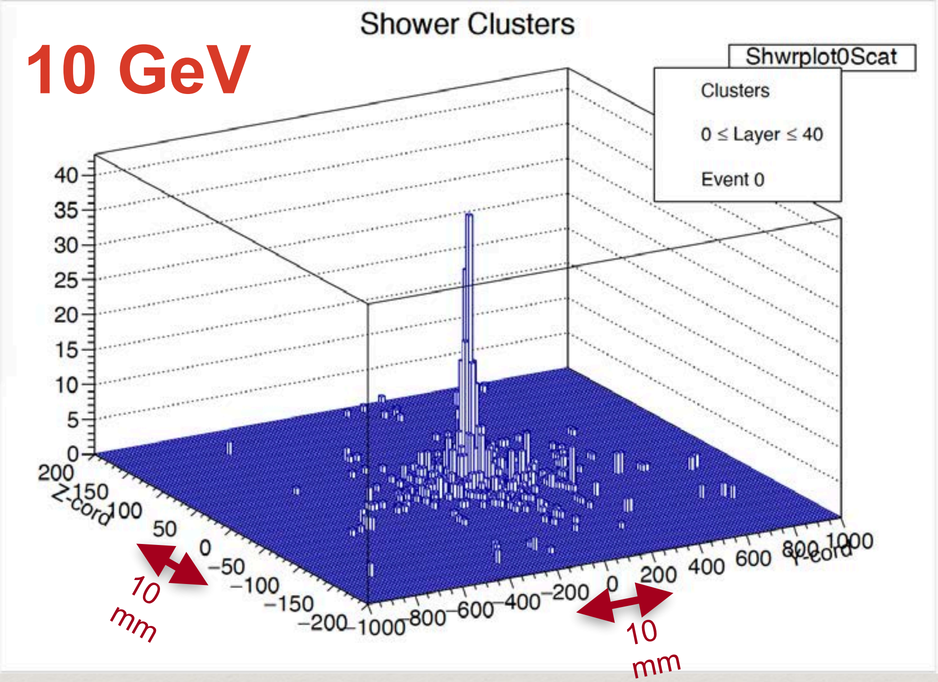
SiD TDR hexagonal sensors
13 mm² pixels

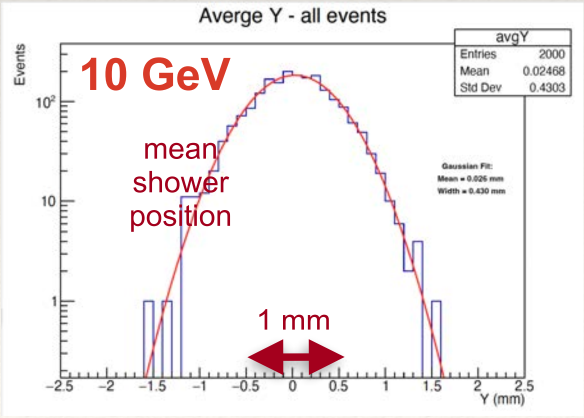
Illustrates PFA
Potential

New SiD fine pixel sensors
25 µm x 100 µm pixels

Shower transverse position measurement

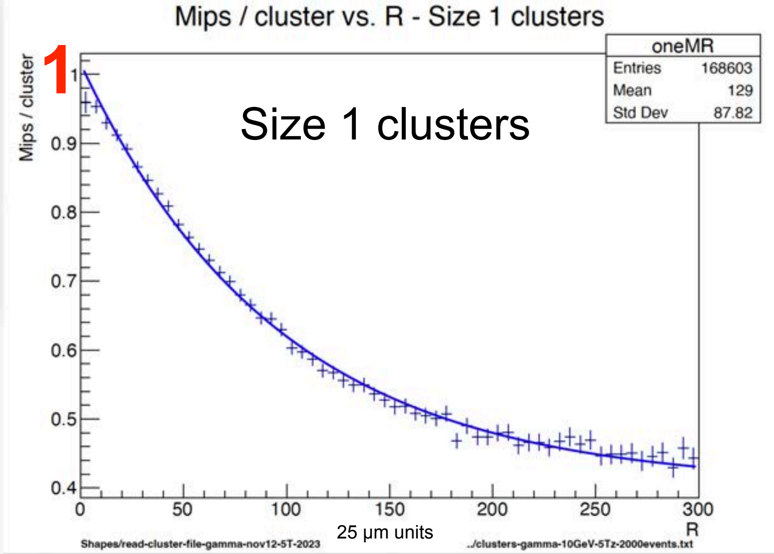
	Simulated measurements			
	Y-spread (rms)	Z-spread (rms)	δY	δZ
1 GeV	4.7 mm	4.2 mm	**1.17 mm**	**1.04 mm**
10 GeV	4.8 mm	4.3 mm	**0.43 mm**	**0.37 mm**
50 GeV	5.1 mm	4.6 mm	**0.21 mm**	**0.20 mm**





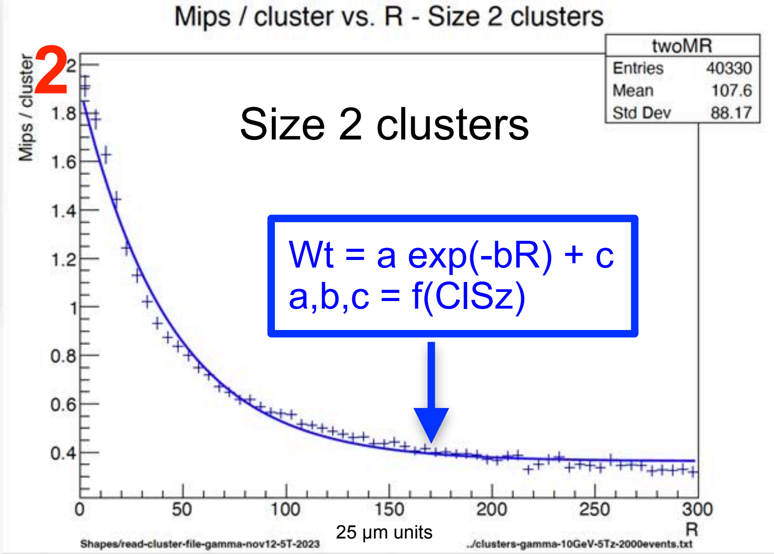
- This precision can be improved - naive, simple average used
- Important for jet particle flow measurements

Mips/cluster vs. showerR 10 GeV γs - 2000 showers



1

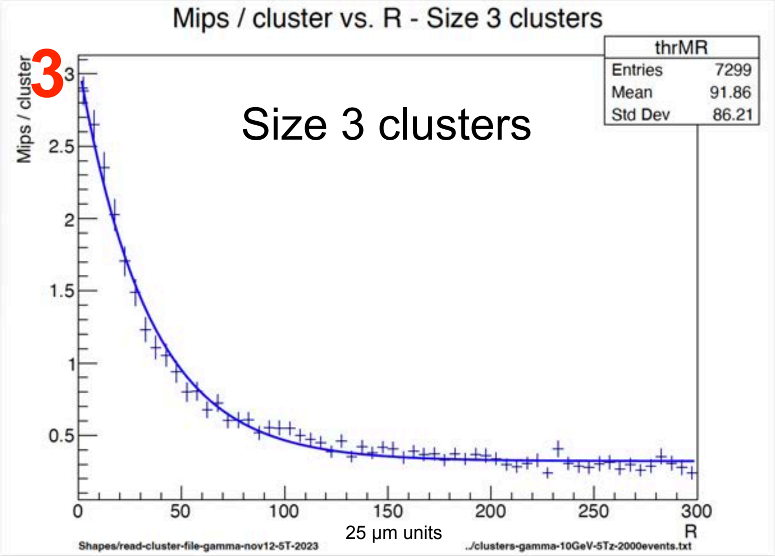
Size 1 clusters



2

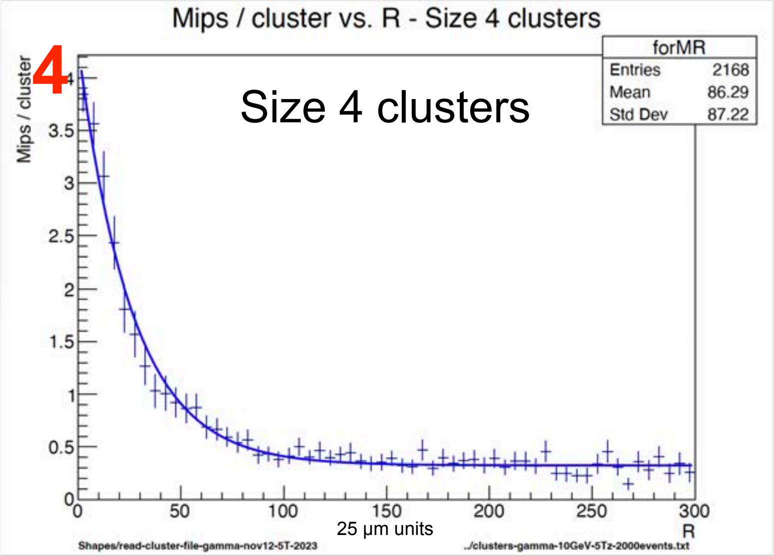
Size 2 clusters

Wt = a exp(-bR) + c
a,b,c = f(ClSz)



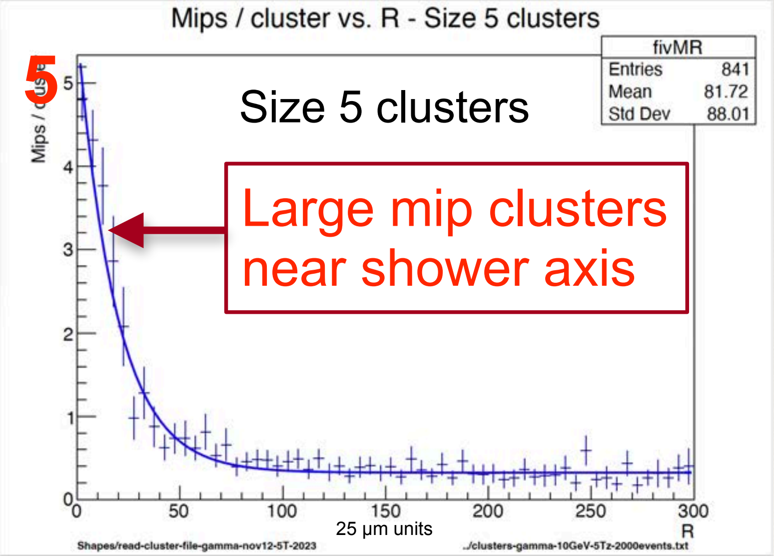
3

Size 3 clusters



4

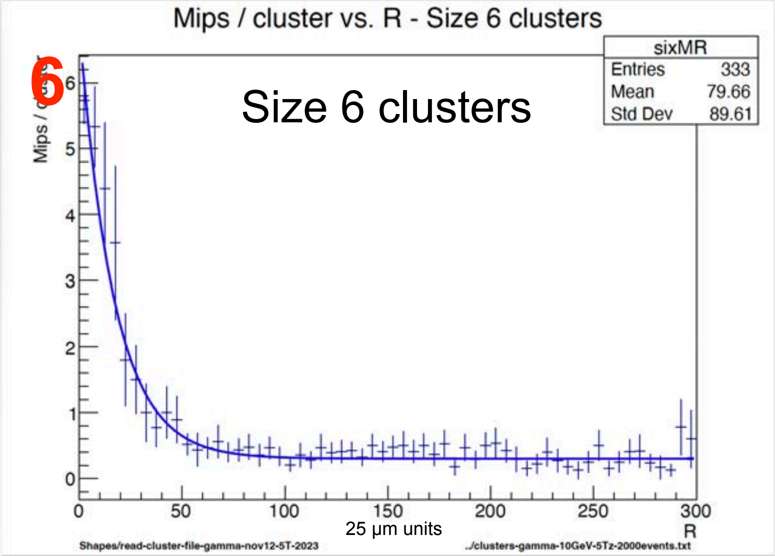
Size 4 clusters



5

Size 5 clusters

Large mip clusters
near shower axis

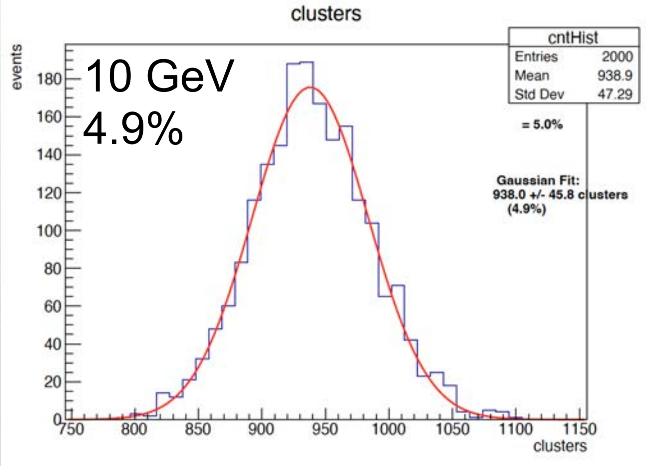


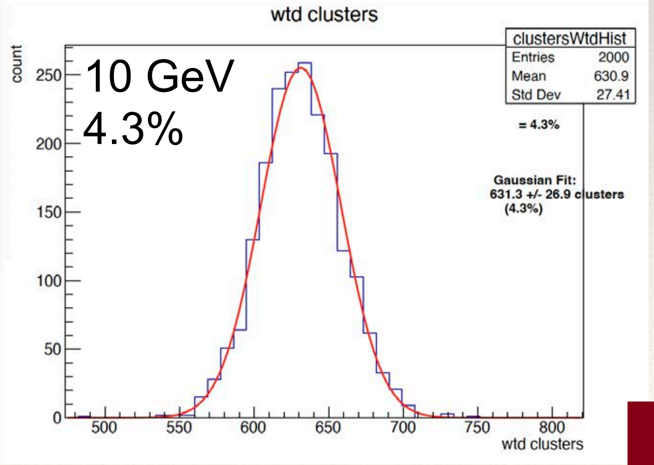
6

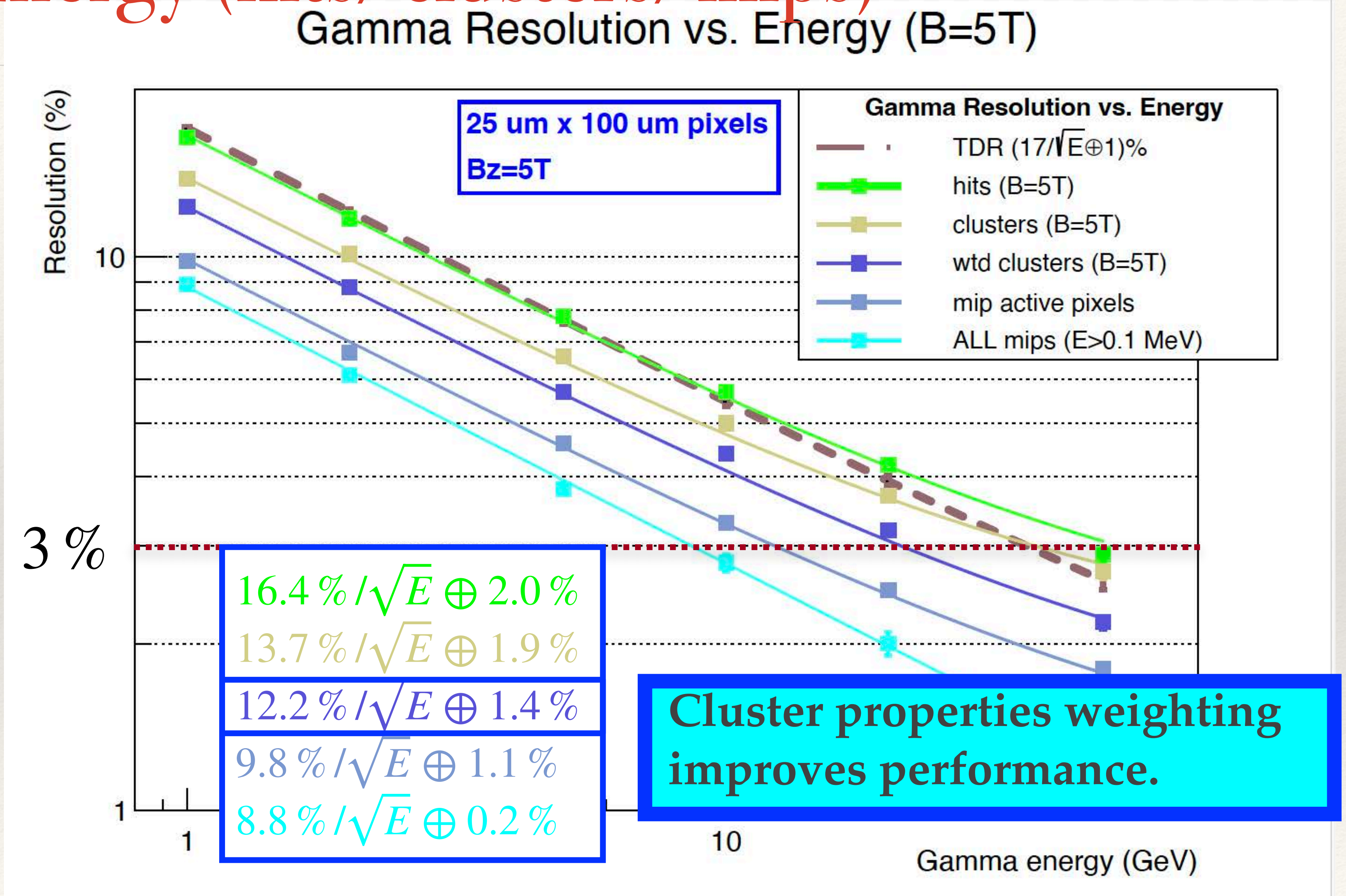
Size 6 clusters

Resolution vs. Energy (hits/clusters/mips)

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







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

$13.7\,\%/\sqrt{E} \oplus 1.9\,\%$

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

$9.8\,\%/\sqrt{E} \oplus 1.1\,\%$

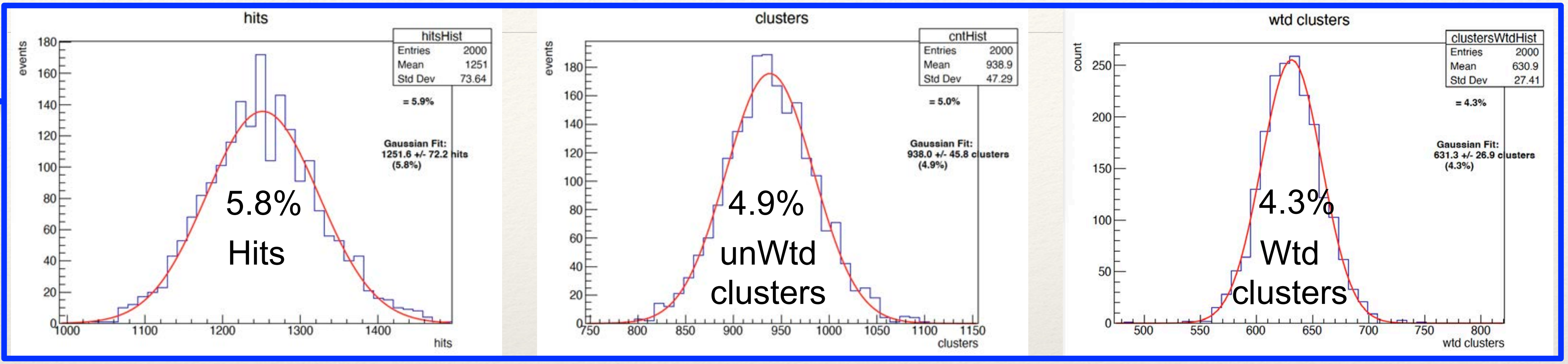
$8.8\,\%/\sqrt{E} \oplus 0.2\,\%$

Cluster properties weighting improves performance.

Can a Neural Net Improve Performance?

Weighted function vs. TMVA neural net (10 GeV γs)

Weighted Clusters Analysis

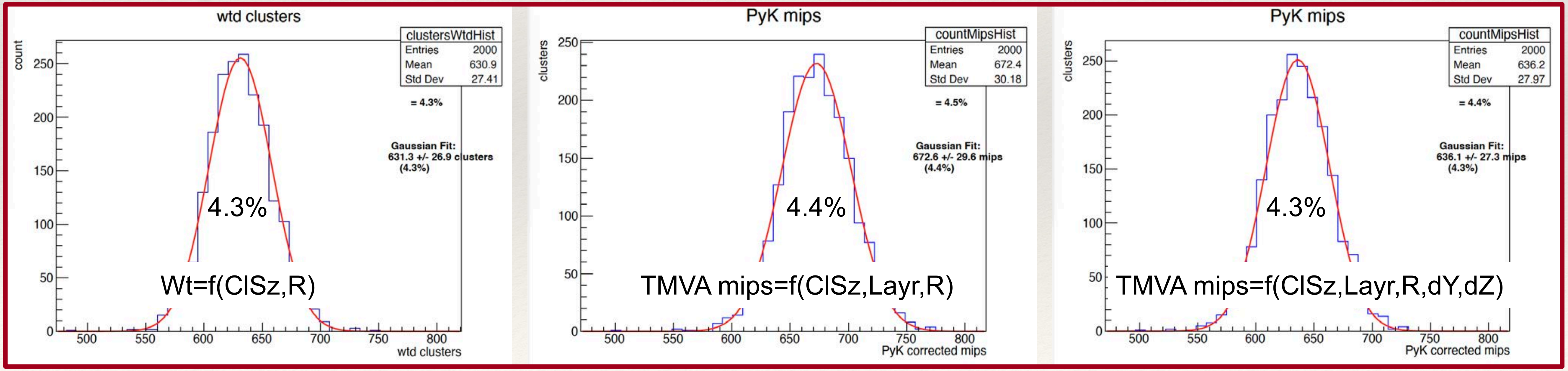


5.8%
Hits

4.9%
unWtd
clusters

4.3%
Wtd
clusters

Neural Net Analysis



4.3%

Wt=f(ClSz,R)

4.4%

TMVA mips=f(ClSz,Layr,R)

4.3%

TMVA mips=f(ClSz,Layr,R,dY,dZ)

Results: Energy Resolution

Energy	1	2	5	10	20	50
clusters	13.8%	10.1%	6.6%	4.9%	3.7%	2.7%
wtd clusters	12.3%	8.8%	5.7%	4.4%	3.2%	2.2%
3 par TMVA	12.6%	9.5%	6.2%	4.4%	3.4%	2.2%
5 par TMVA	12.8%	9.4%	5.9%	4.3%	3.1%	2.2%

- **Weight fits for 2, 10, 50 GeV; extrapolated for 1, 5, 20 GeV.**
- **NN optimized for each energy**
- **3 par = cluster size, layer, radius**
- **5 par = cluster size, layer, radius, dY, dZ**

Weighted clusters already achieve performance of this neural net.

Conclusion

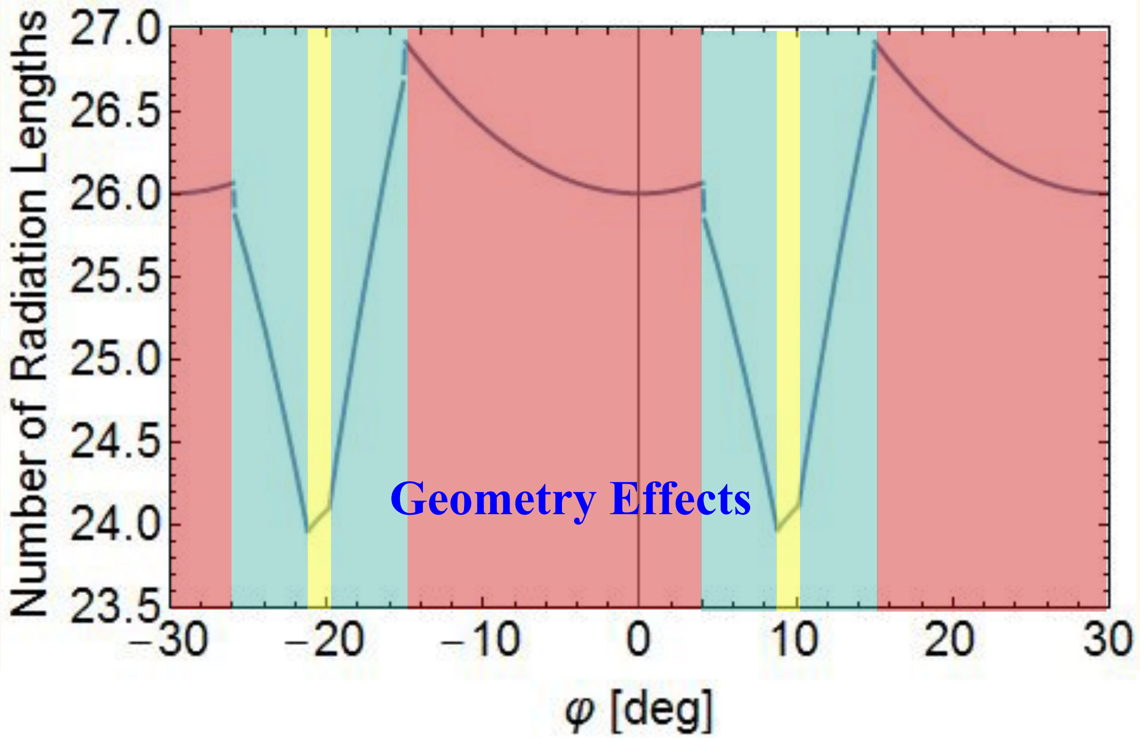
- Application of monolithic active pixel sensors (MAPS) to SiD digital ECal offers excellent performance:
    - Energy measurement
    - Transverse energy containment & particle flow separation
- Well defined EM shower structure allows simple algorithmic optimization of energy measurement.
- An effort led by SLAC is progressing on the needed MAPS development.
- Neural nets have been studied to improve energy measurement:
    - They have not yet provided improvement over the "informed" algorithm.

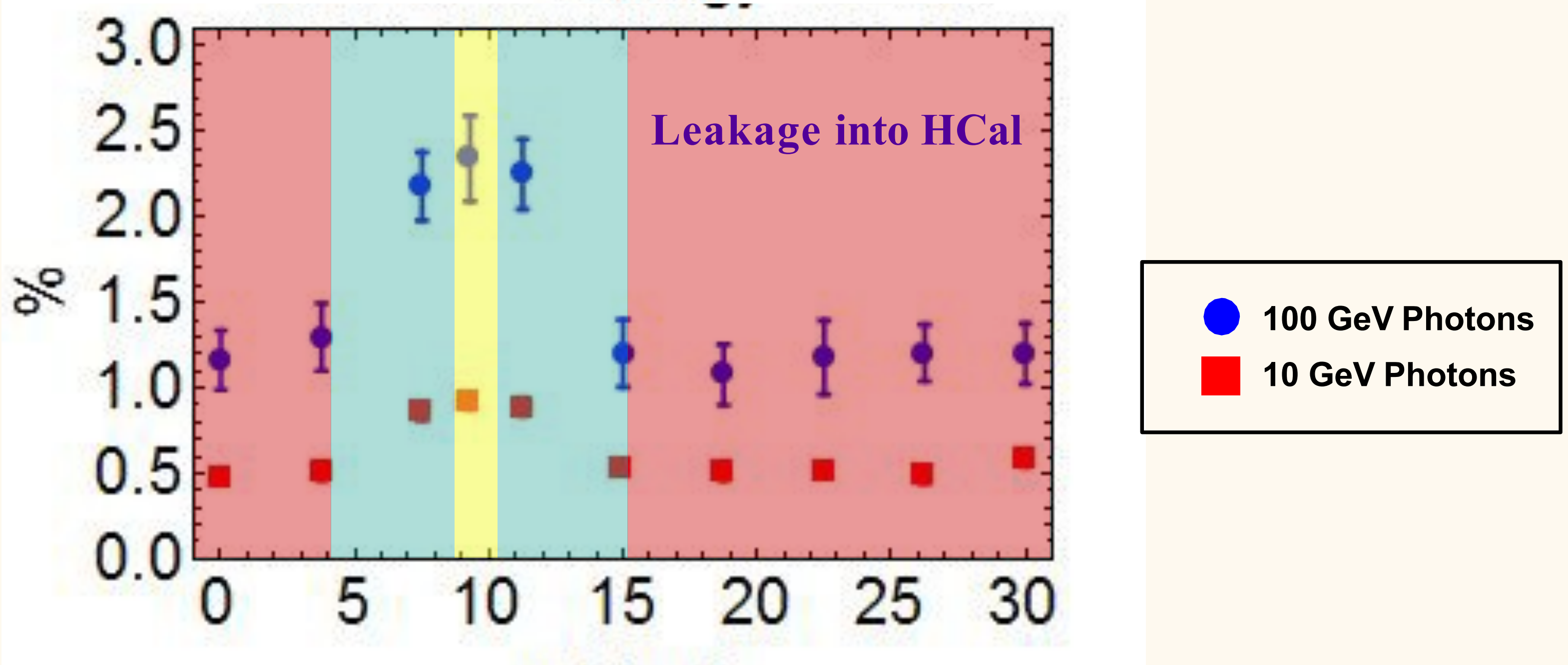
- Passive heat management works for linear colliders given the very low duty cycle.
    - FCC/CEPC solution?

- The digital ECal will add valuable performance for particle flow reconstruction.

- Future - simulation of full SiD detector with high granularity of MAPS ECal.

Extras





A. Steinhebel