July 10, 2024

The SiD Digital ECal Based on Monolithic Active Pixel Sensors

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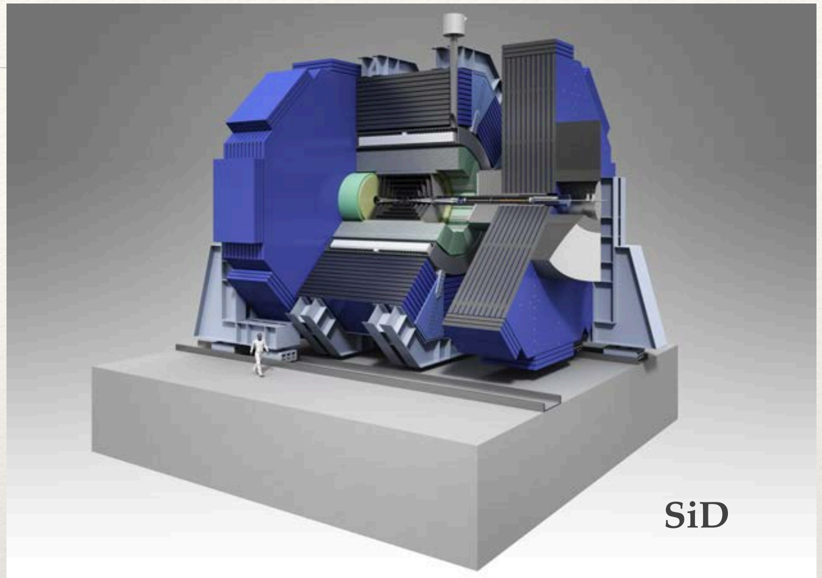
“The SiD Digital ECal Based on Monolithic Active Pixel Sensors",
10.3390/instruments6040051, Instruments, 6, 51 (2022)

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 using 13 mm^2 analog pixel sensors.

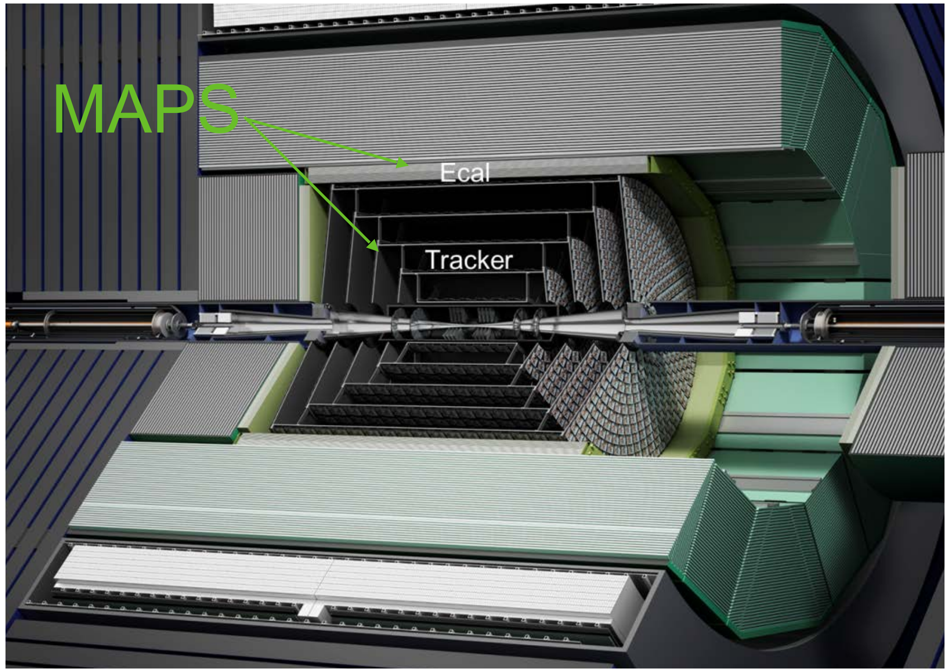


- Heat management is critical to success.
- How well can we measure energy and shower structure with this digital system:
  - Compared to SiD baseline with analog measurements?
  - Can the detailed structural measurements be used to improve measurement?
  - Would a neural net optimization offer an improvement?
- 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

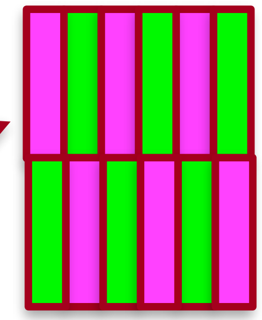
Main specifications for Large Area MAPS development

TID-AIR SLAC

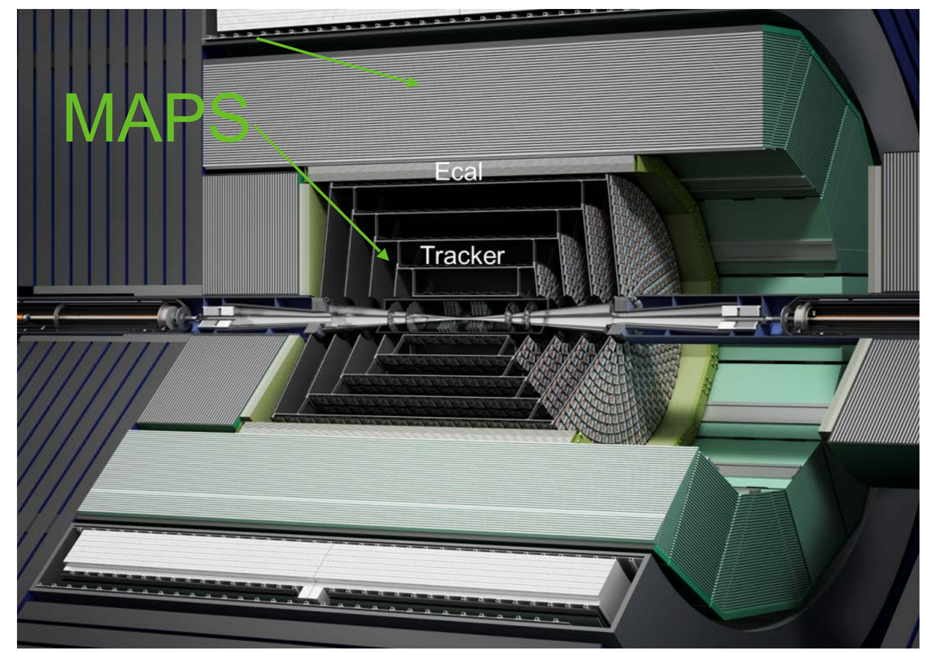
L. Rota

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 $67 m^2$

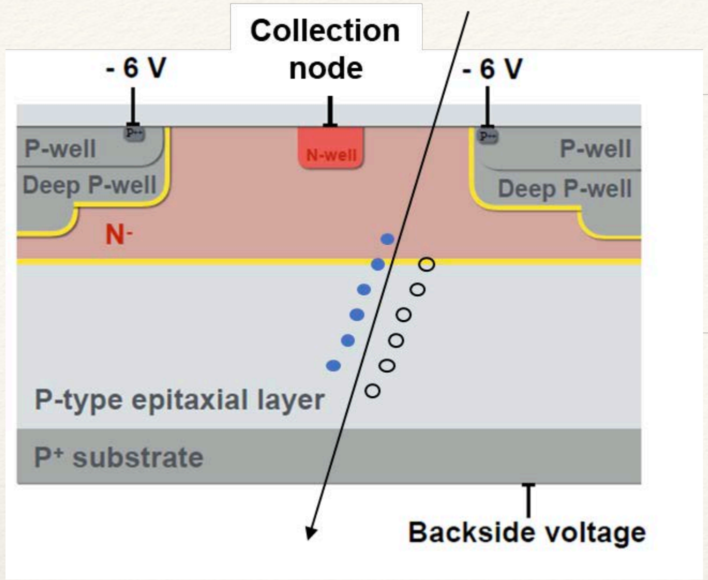
<1 mW/cm^2 for 1% duty cycle



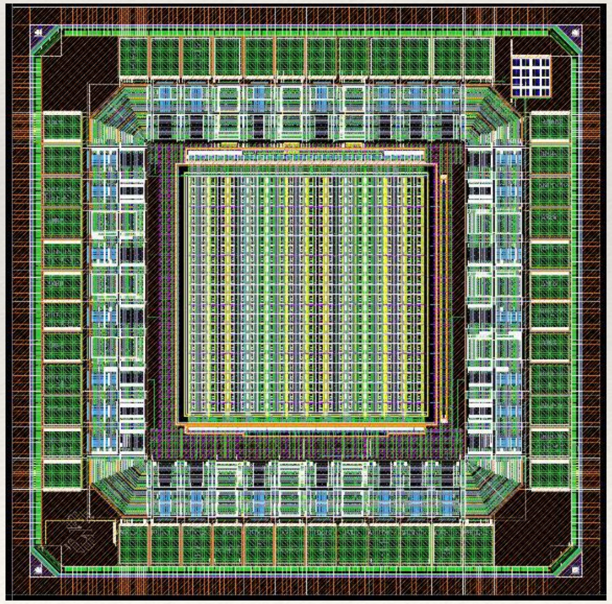
25 x 100 μm^2 ECal performance same as 50 x 50 μm^2



SiD Tracker and the ECal



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:
- Engaged with the scientific community to share know-how
- 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

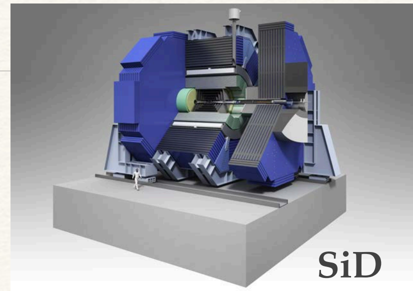
Highlights:
- Designed pixel architecture with binary readout optimized for linear colliders
- Submitted a small pixel matrix for fabrication on CERN WP1.2 shared run
- Architecture will allow us to evaluate technology in terms of defects and RTS

Next steps:
- Evaluate performance of 1st SLAC prototype on TJ65nm (2023).
- New design combining O(ns) timing precision and low-power (2024/2025).
- **Stretch Goals:** design of a wafer-scale ASIC (2025/2026, design only)

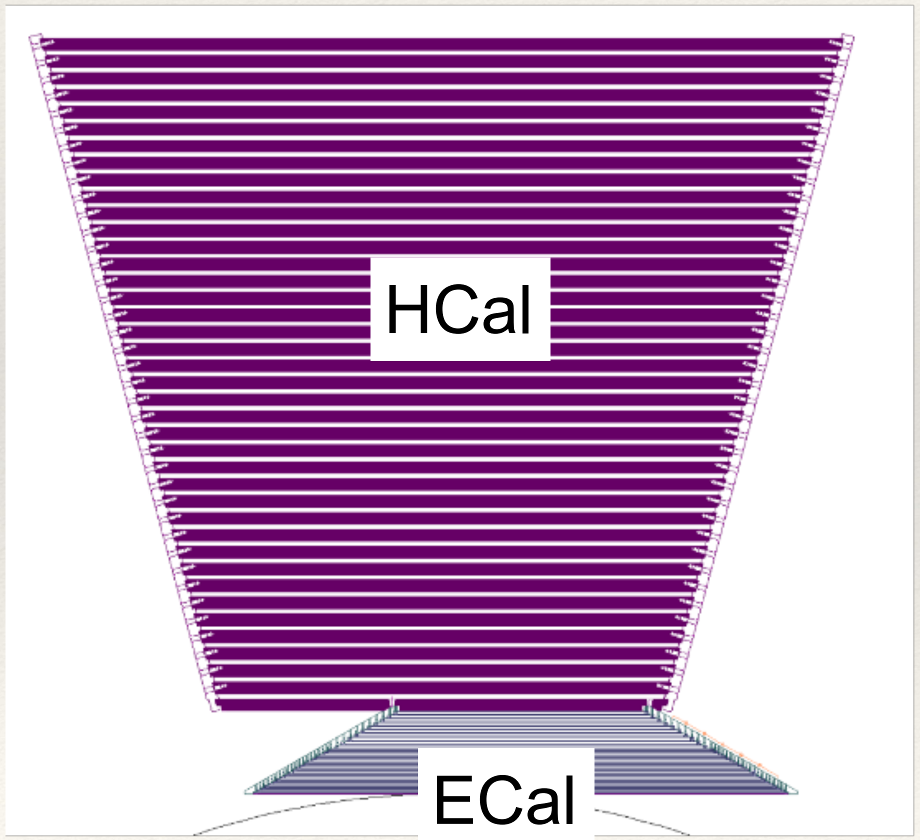
Engagement :
- Higgs Factory detector initiative R&D
- DRD 7.6 on common issues of power distributions compatible with stitching

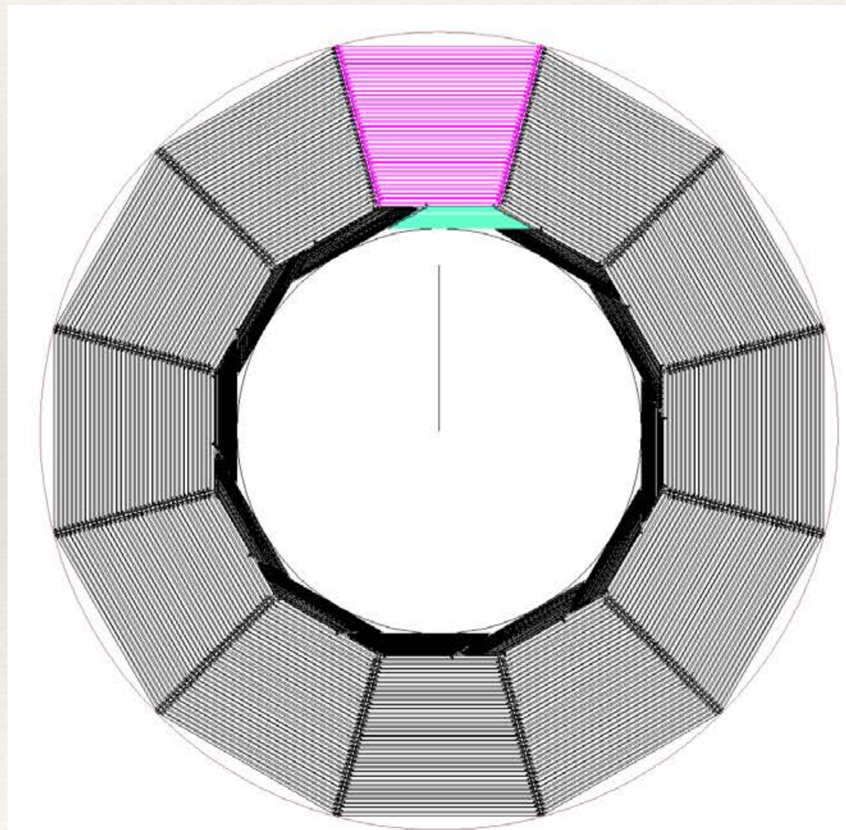
MAPS status @ LCWS 2024 - Tuesday, 11am, Caterina Vernieri

A. Habib *et al* 2024 *JINST* **19** C04033



SiD Mechanical Design





- ECal module is built on first layer of HCal
- HCal module supports ECal module
- Note module overlap: No gaps; service cables at ends.

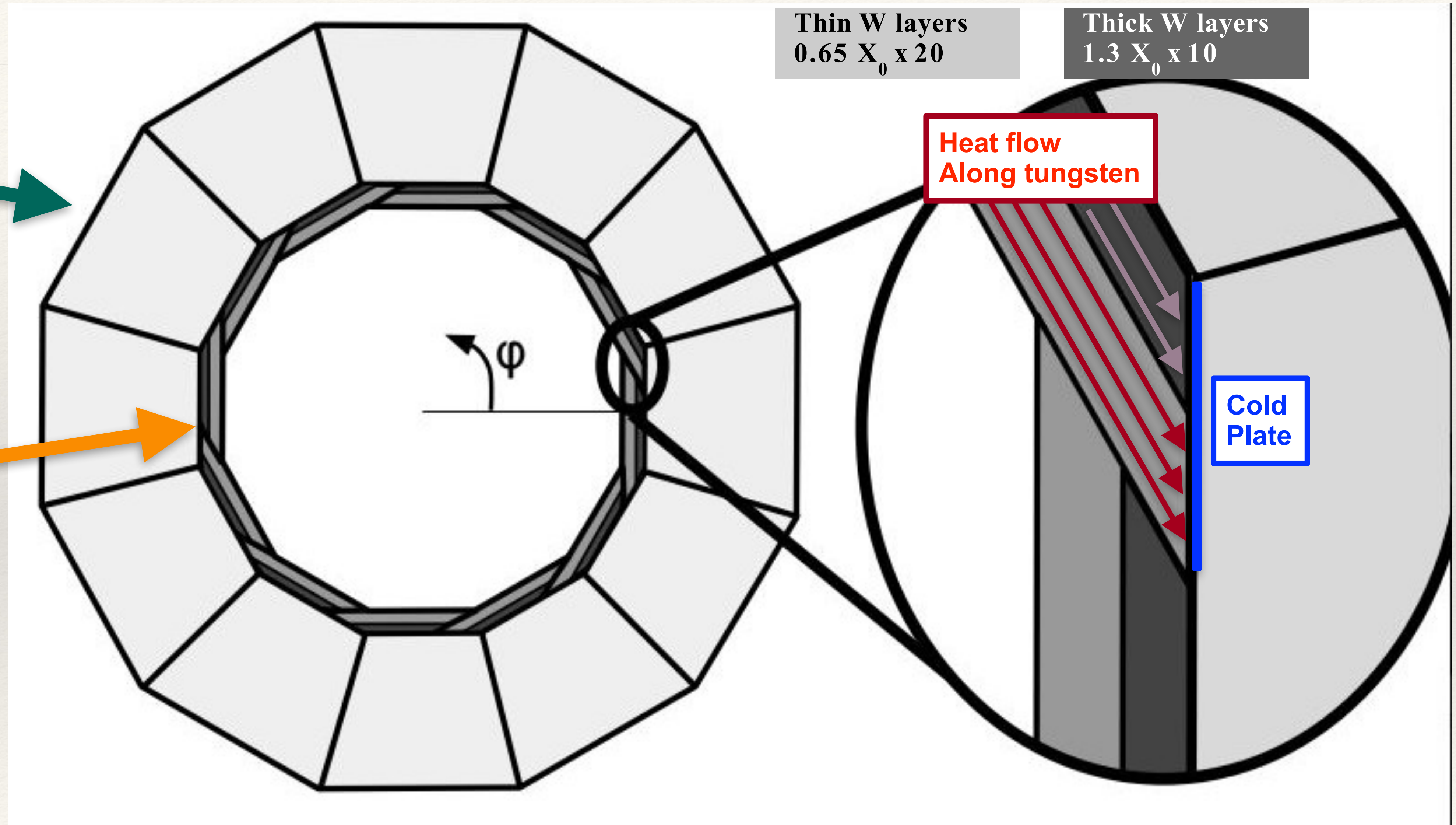
SiD Calorimeter Geometry

HCal

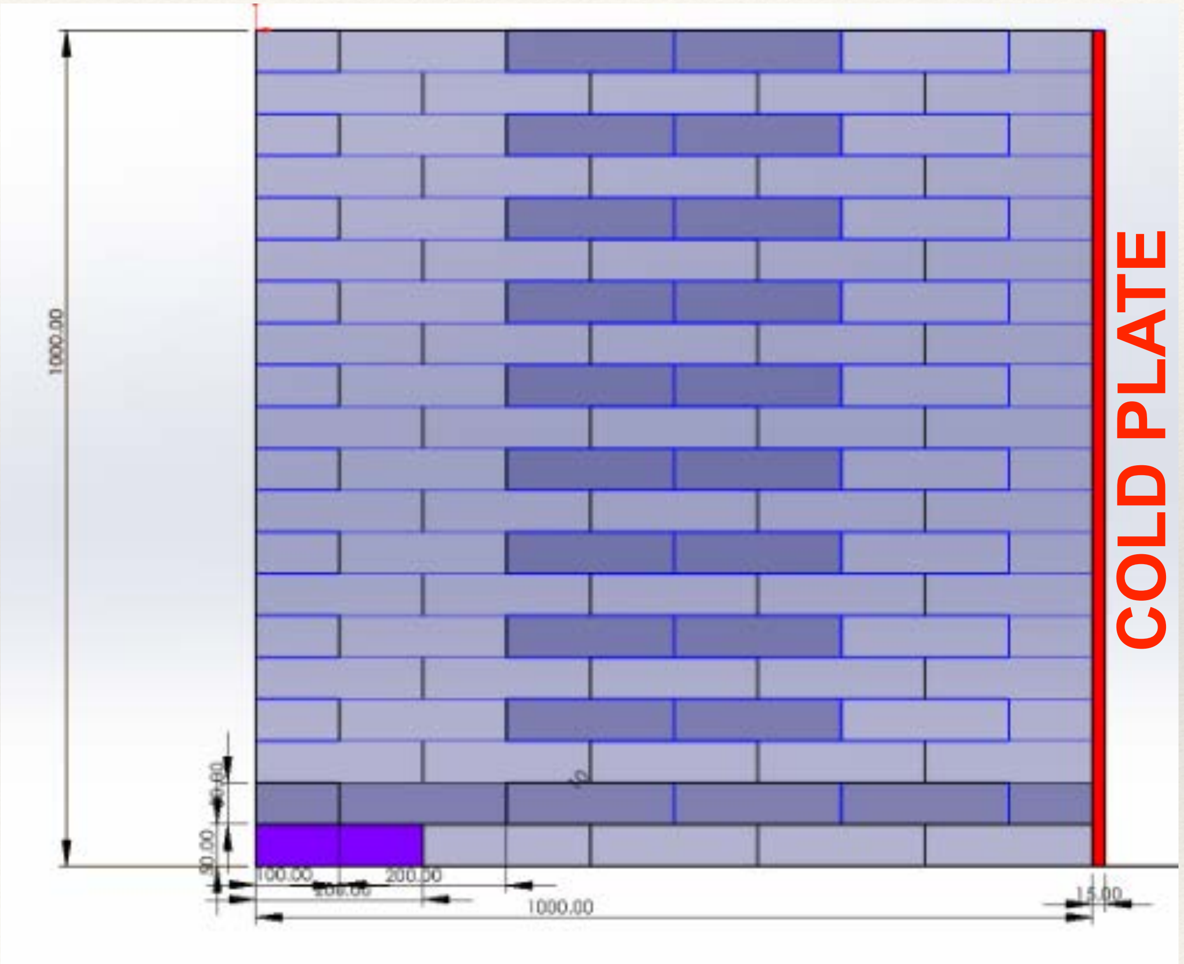
Scintillator sampling
Steel/polystyrene

ECal

Solid state sampling
Tungsten alloy/MAPS



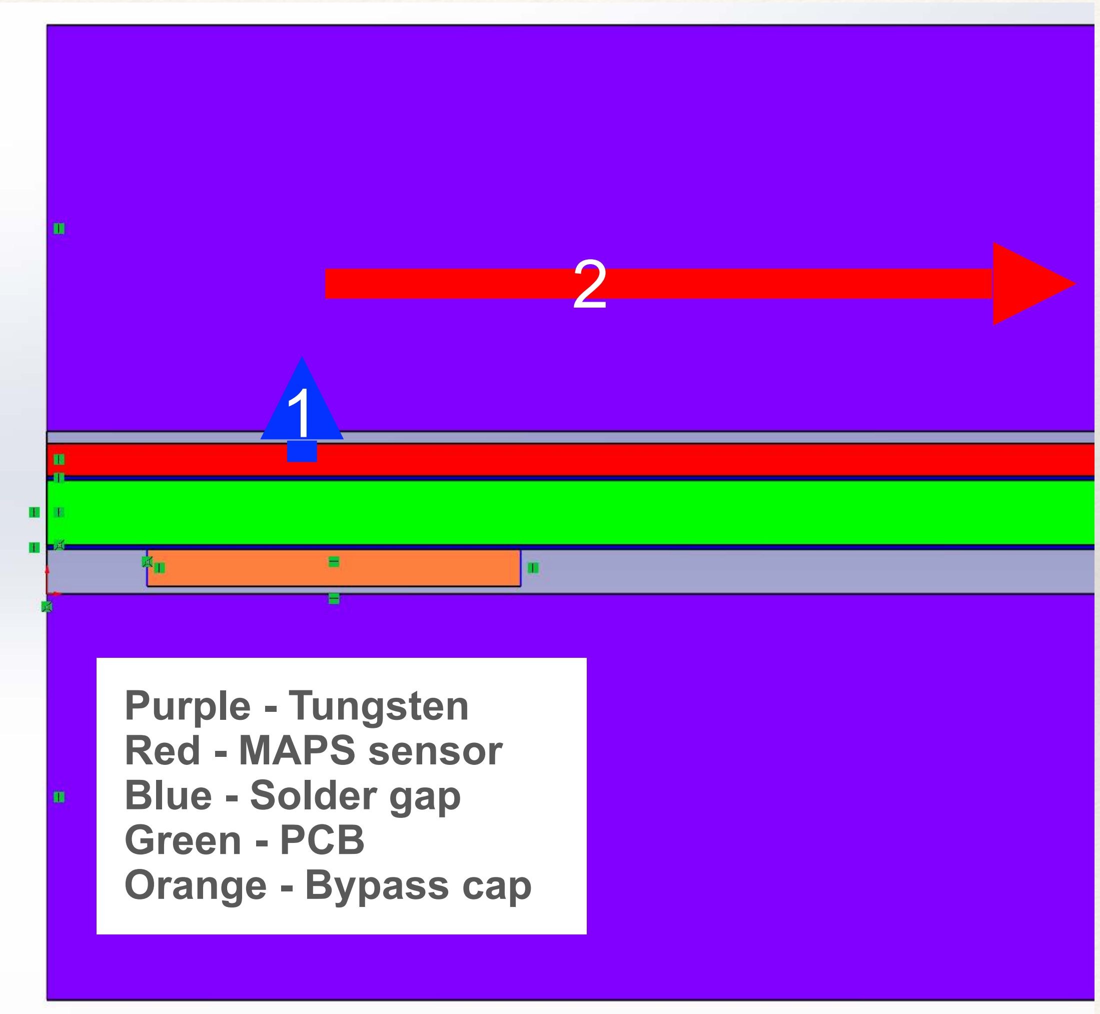
Thermal Model for Heat Removal from SiD ECal



1 layer of 5 x 20 cm^2 MAPS sensors

- MAPS generates 1 μW/pixel CW.
  - ~kW/m^2 (each sensor is 100 cm^2)
- **Power pulsing** critical for heat management
  - ILC duty cycle ~0.5% (<10 W/m^2)
  - CLIC/C^3 <0.01% (<1 W/m^2)
- What is **temperature rise** (ΔT) on end opposite the cold plate?

Heat conduction from ECal sensor to cold plate



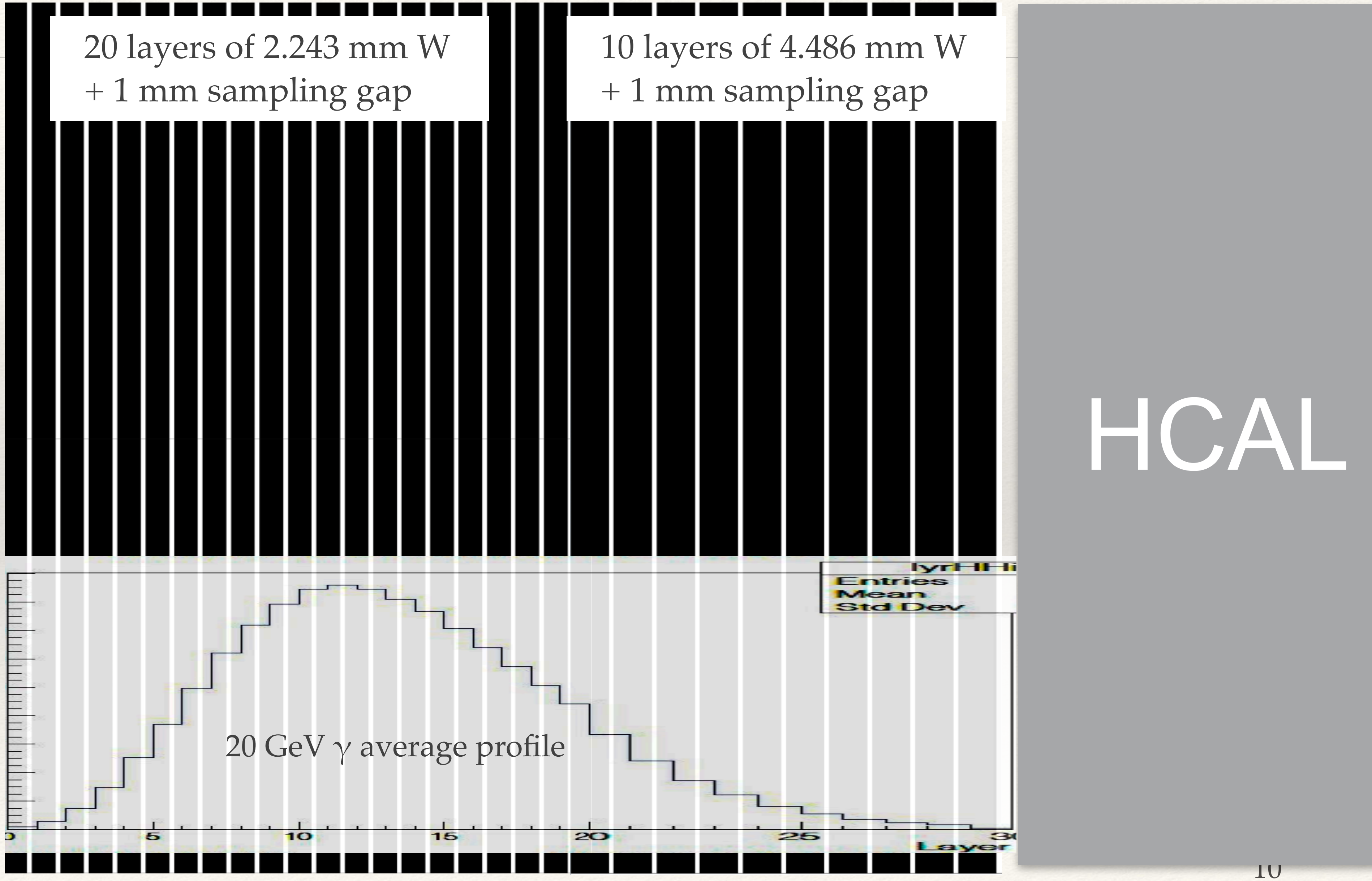
- First heat flows through 300 μm N_2 to tungsten
  - ΔT << 1 K
- Then heat flows thru tungsten to cold plate
  - Tungsten absorber lengths 0.5-1.0 m
  - Temperature rise is length dependent
- Duty cycle - .0007% (C3/CLIC) - ΔT ~ 0.5 - 2 K
- Duty cycle - .005% (ILC) - ΔT ~ 4 - 16 K
  - Without power pulsing temperature blows up and needs active cooling

Model of longitudinal structure of SiD ECal

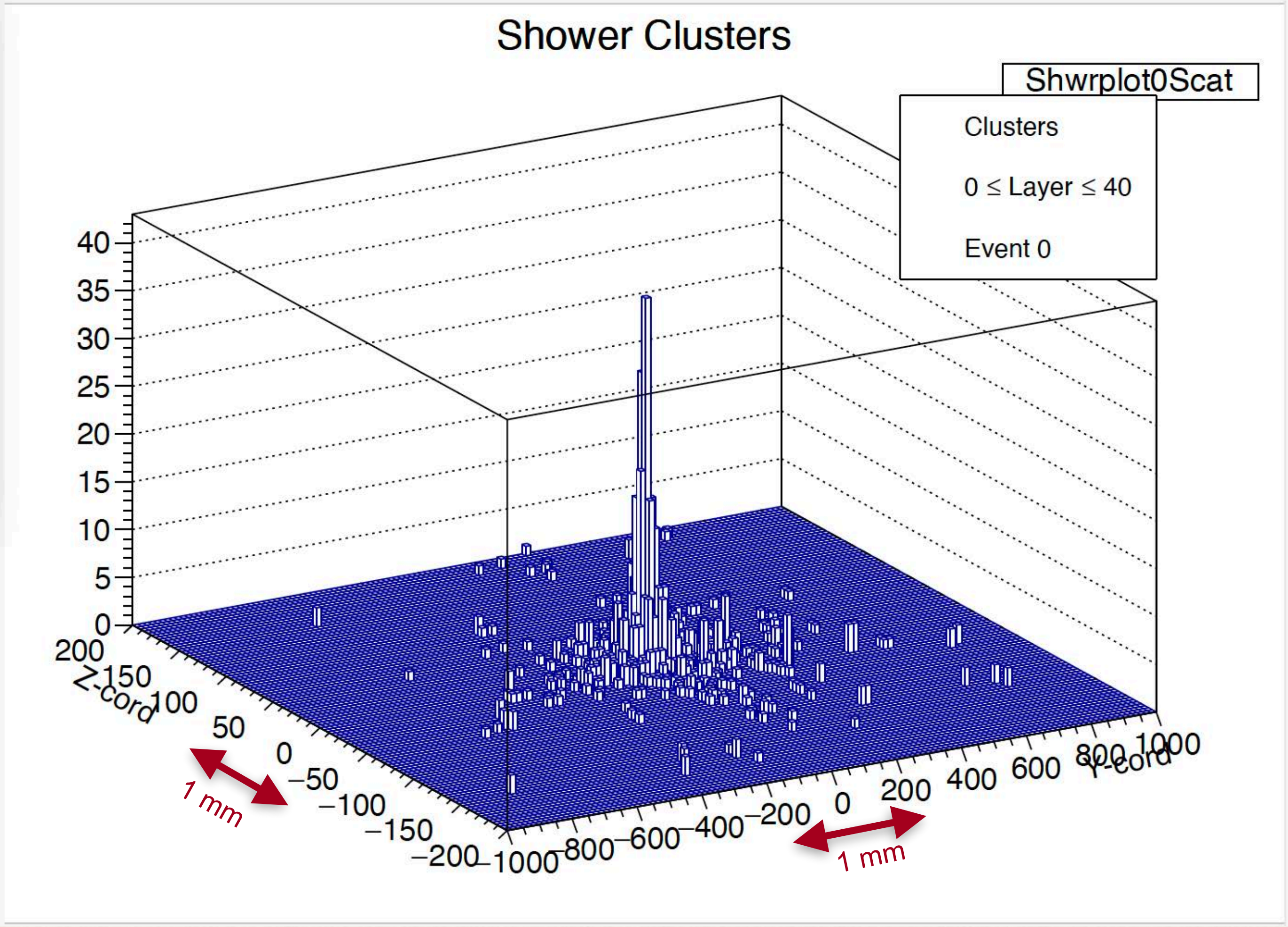
Total = 27 X_O

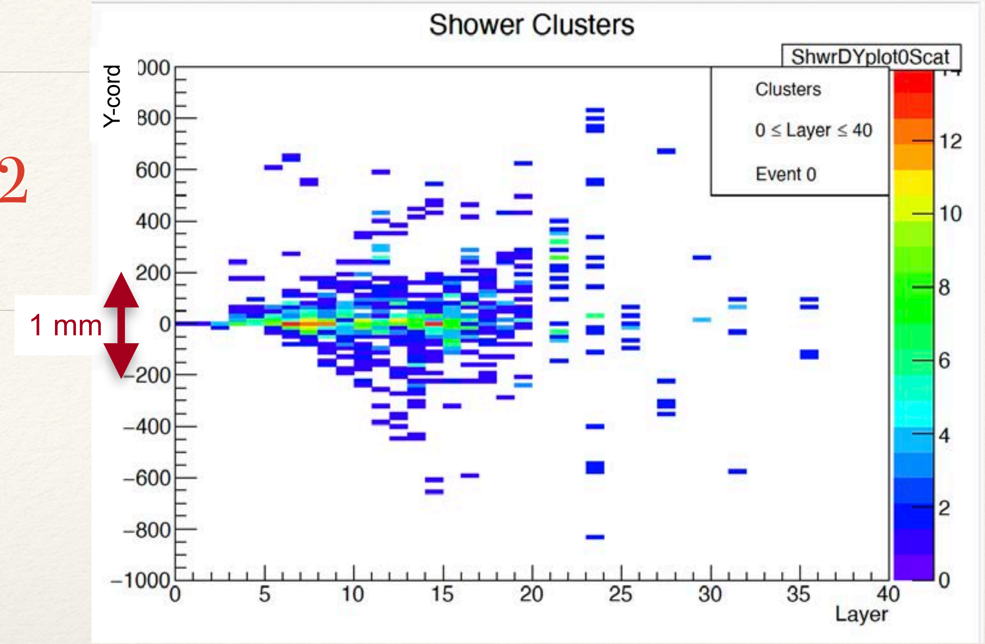
Incident Particle

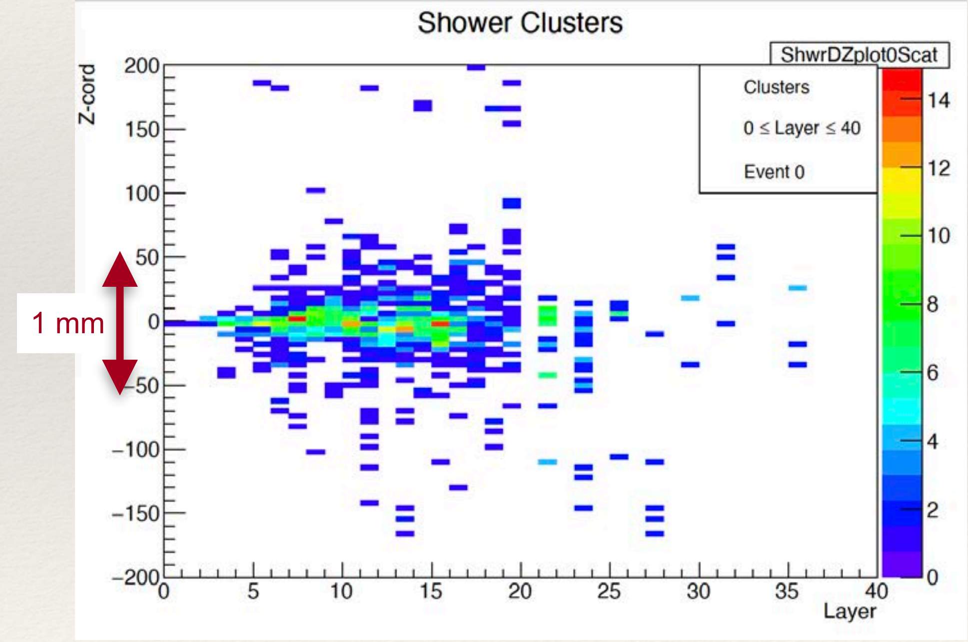
Minimize sampling gap to achieve optimal Moliere radius (14 mm) & shower separation



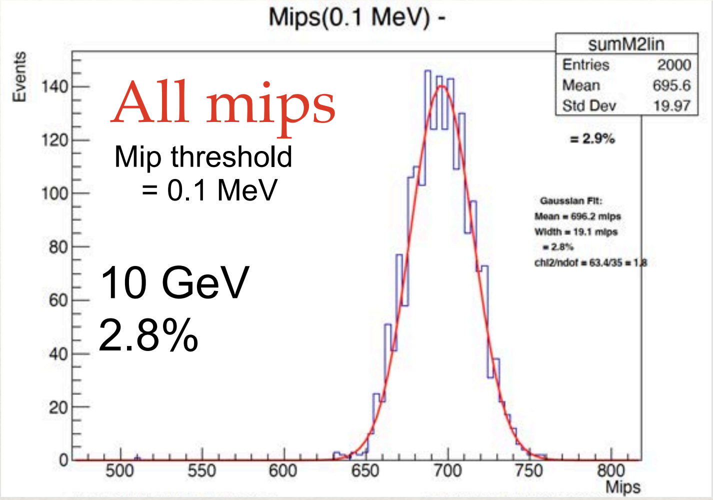
10 GeV Shower in 25 x 100 μm²

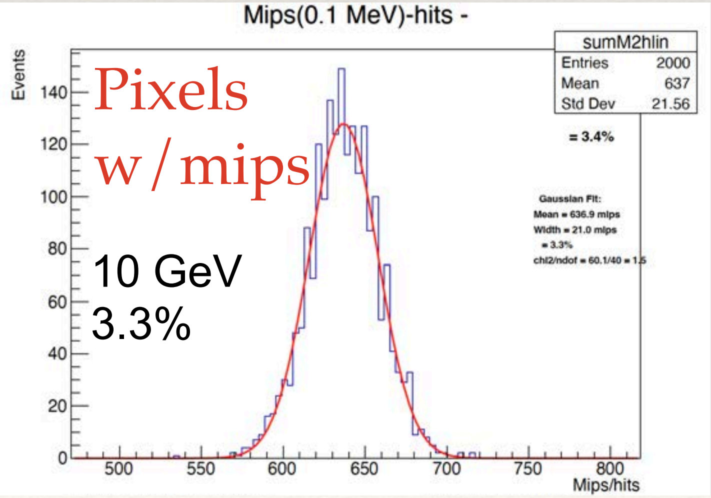




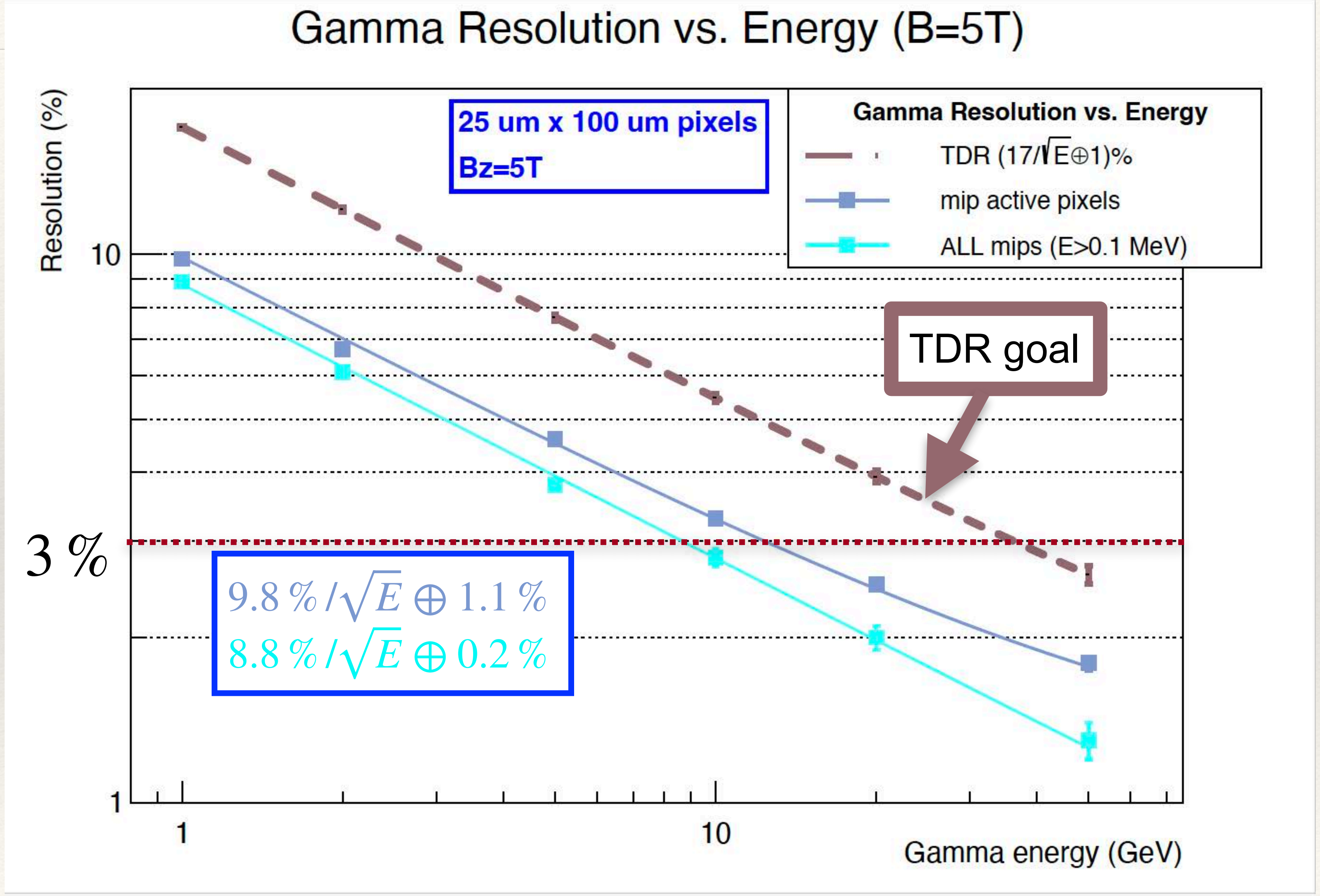


Ultimate Resolution (mips)



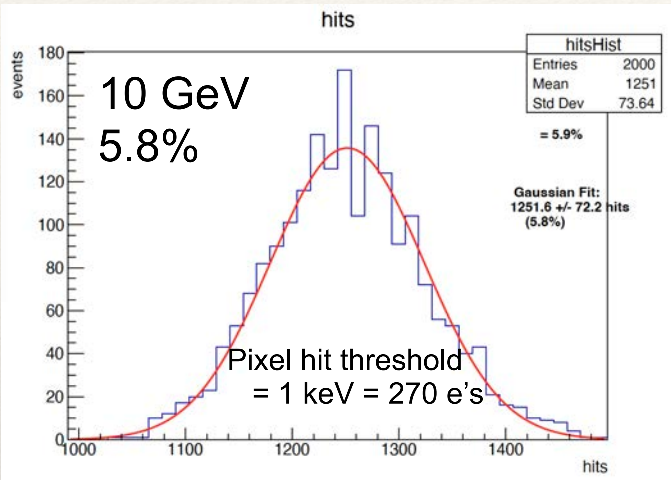


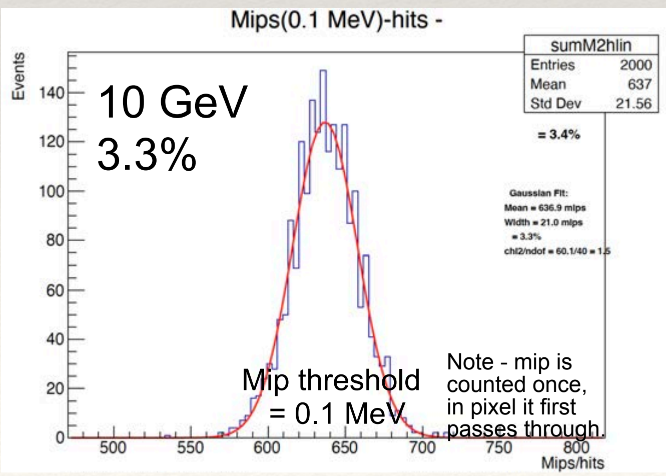
mip counted once in a layer,
when it enters sensor.

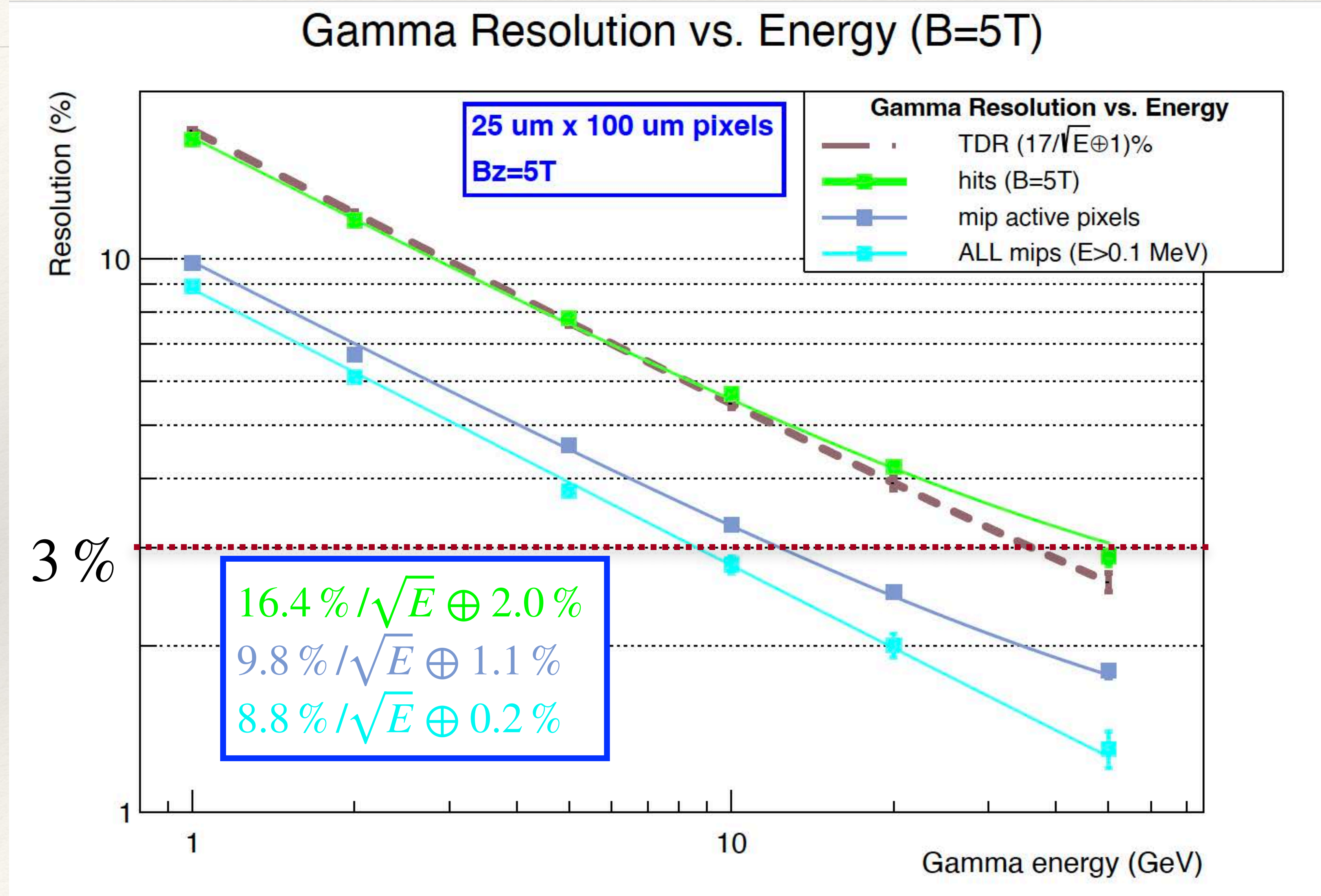


Resolution vs. Energy (hits & mips)

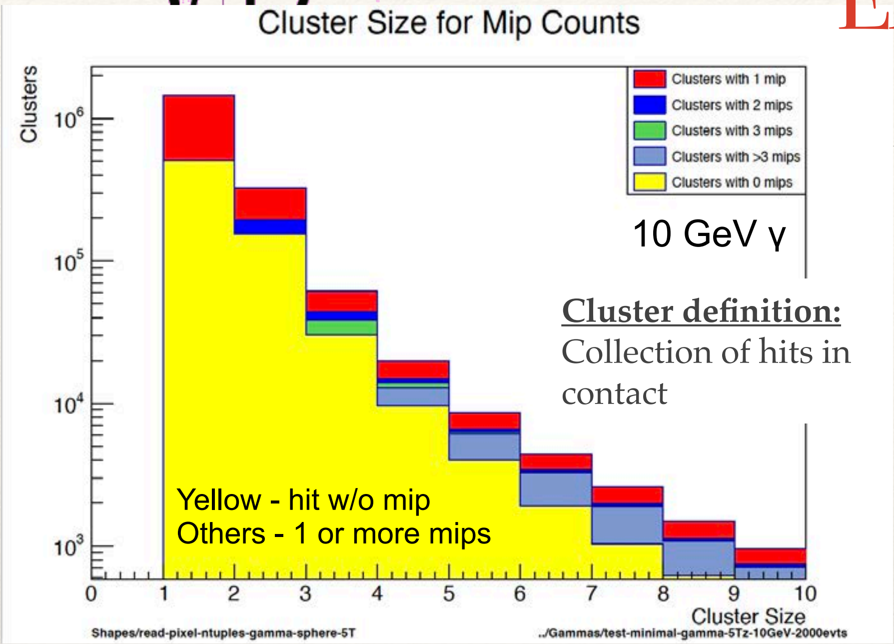
Resolution vs. Energy (hits & mips)

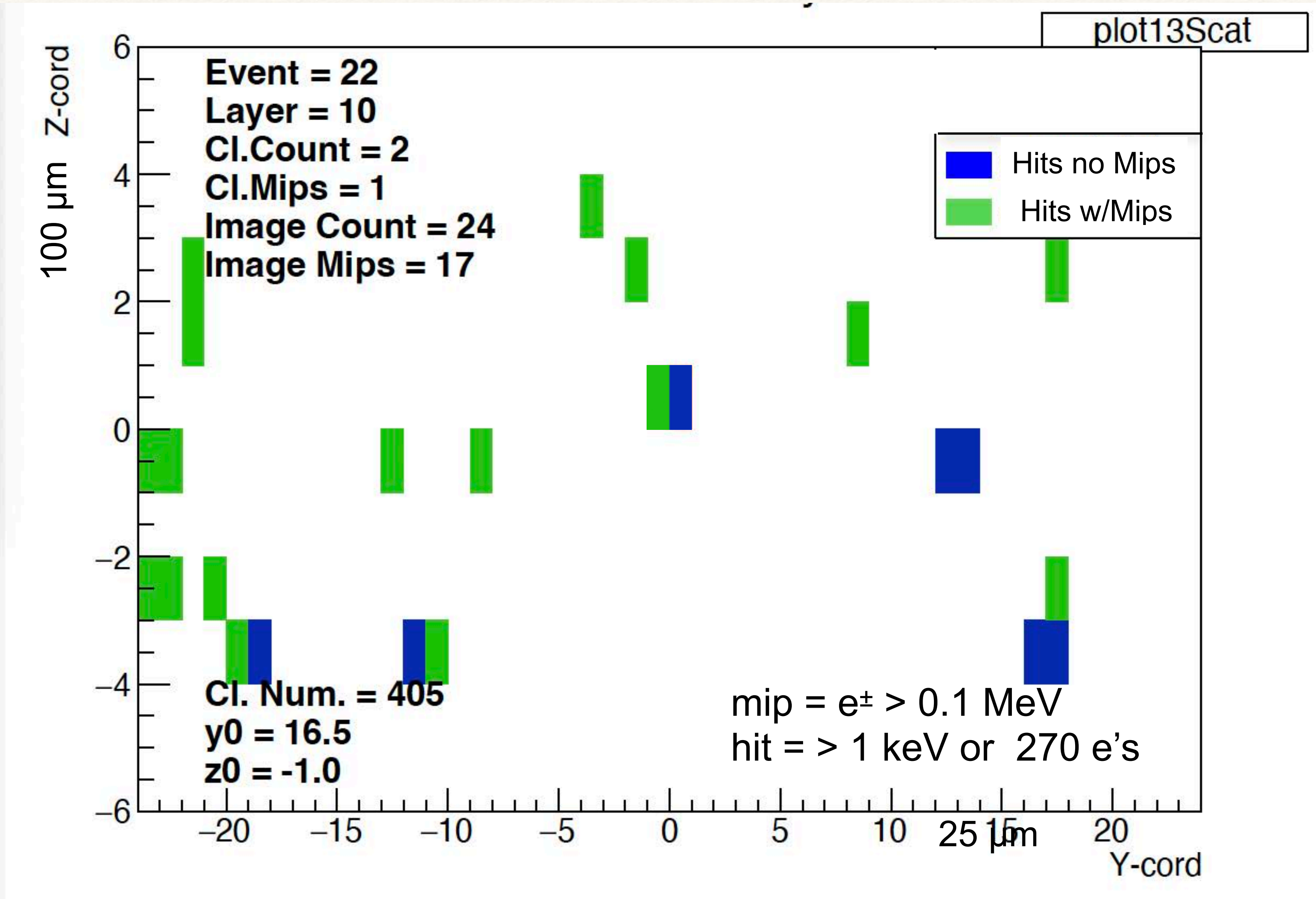






Example of hit distribution in a MAPS

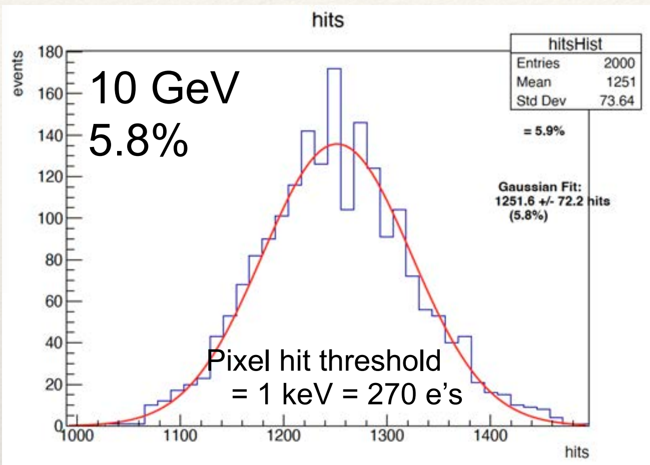


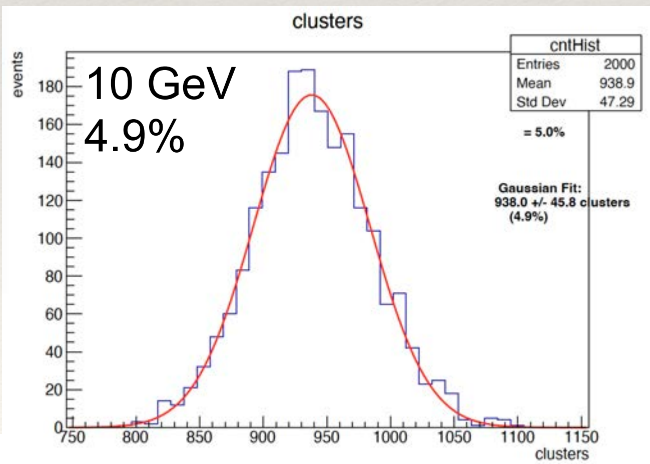


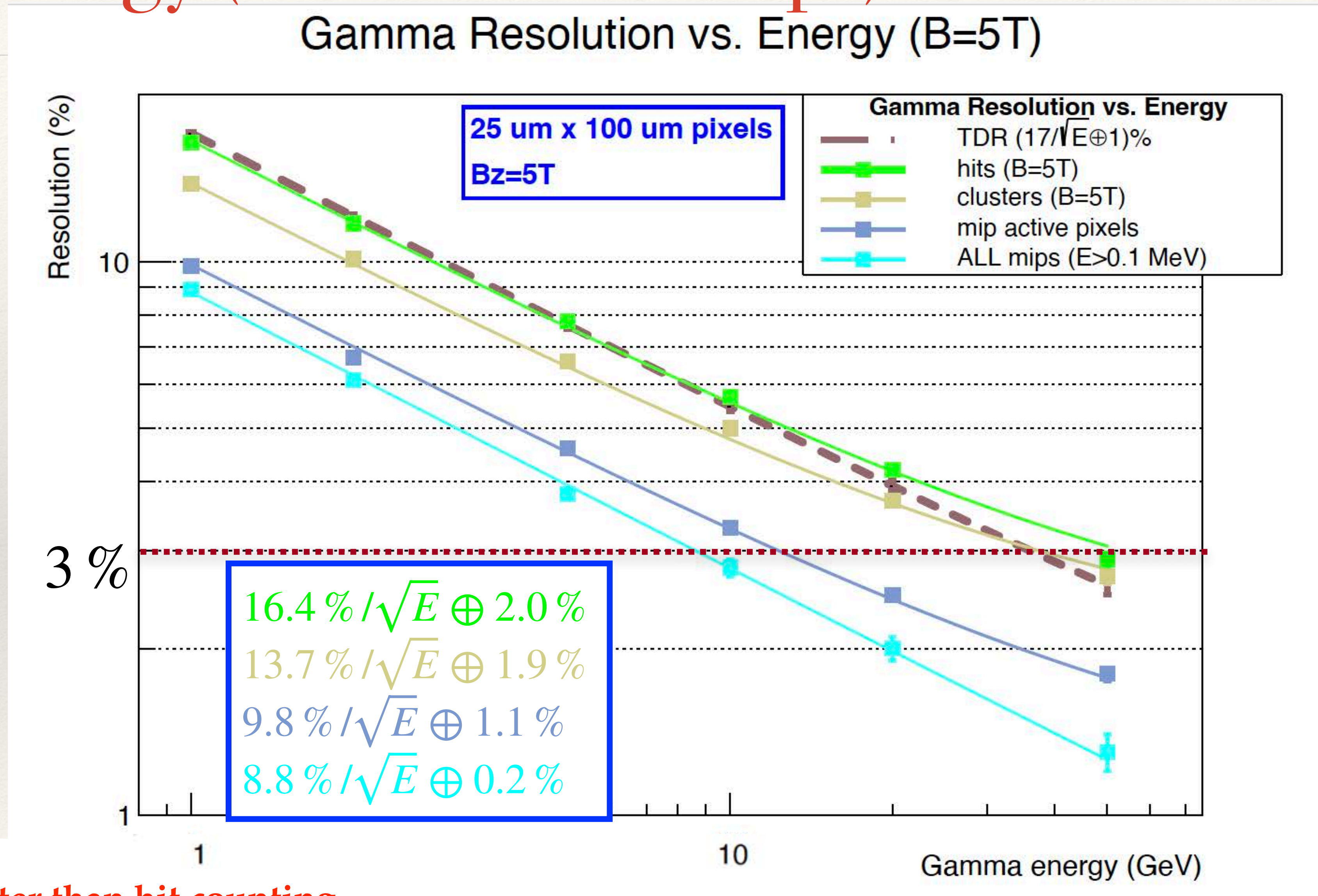
- Most hits isolated
  - Single hit cluster
- Multiple hit clusters
  - Often single mip,
  - Or no mip
- Counting clusters should reduce hit fluctuations

Resolution vs. Energy (hits/clusters/mips)

Resolution vs. Energy (hits/clusters/mips)

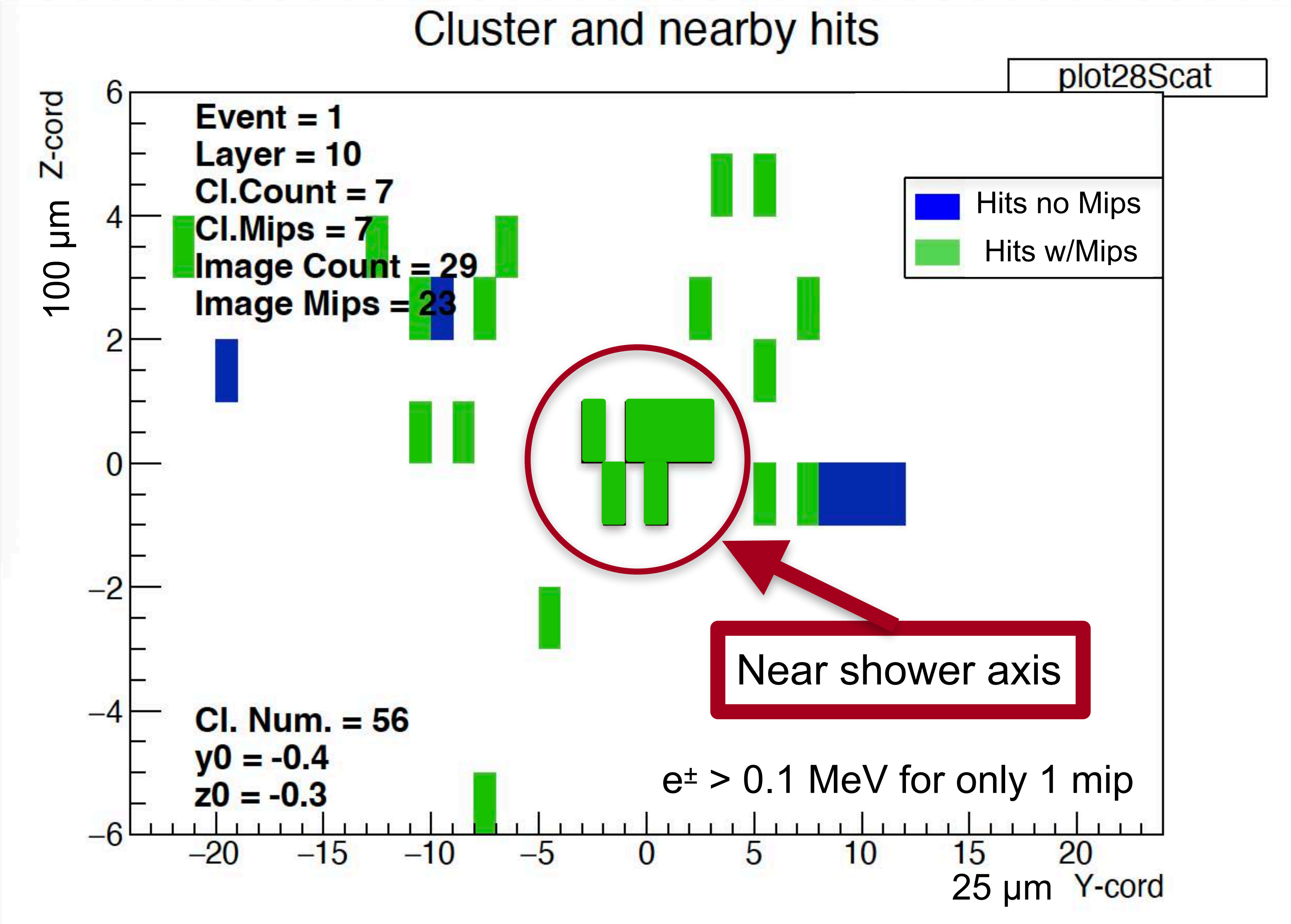




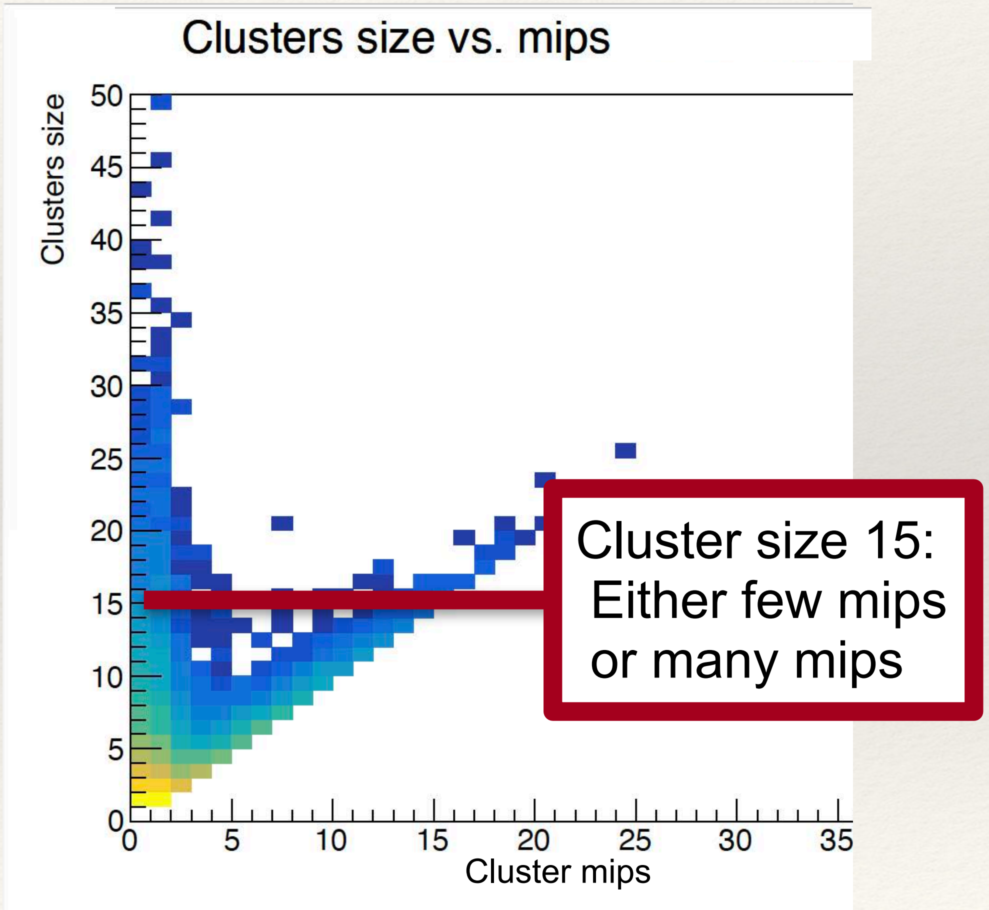


Simple cluster performance is better than hit counting.
We can do better!

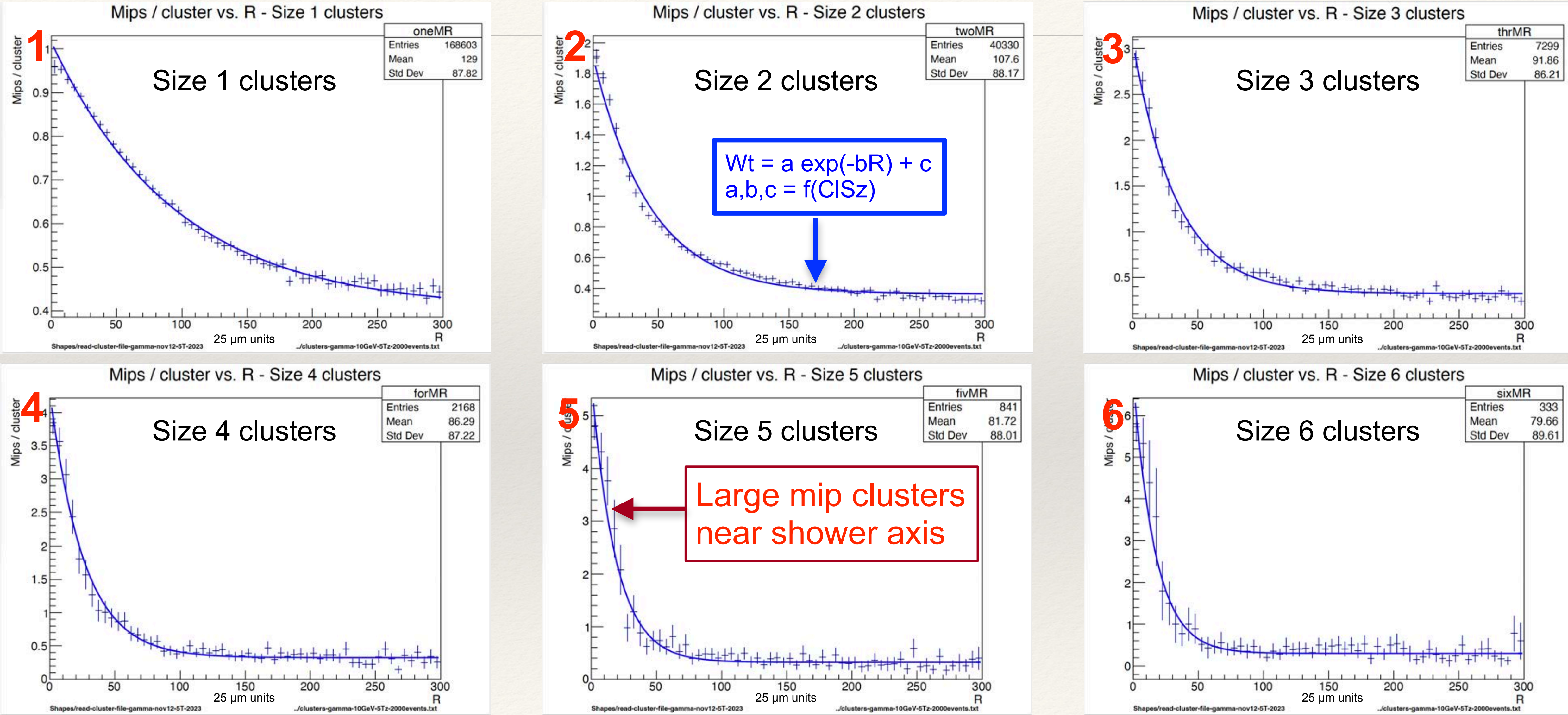
All Clusters are not the same



- Some clusters are numerous mips.



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

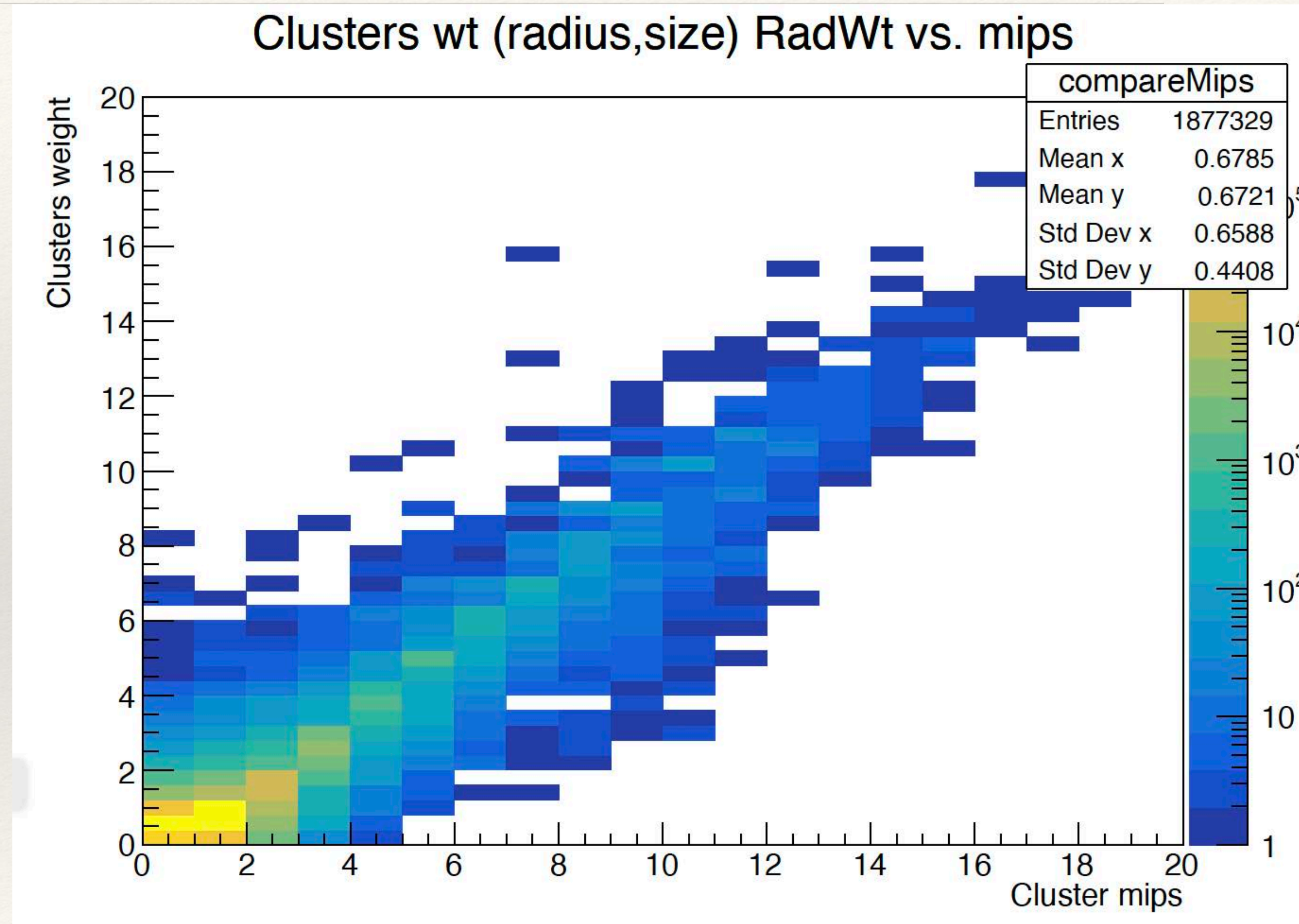


10 GeV γs - 2000 showers

Apply weight to clusters:

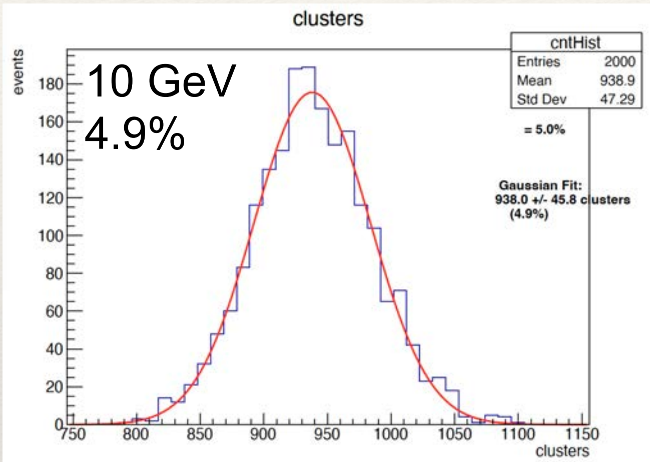
RadWt = a exp(-bR) + c

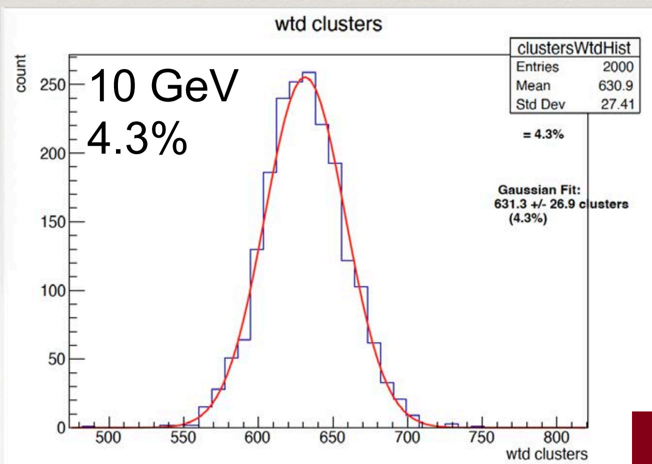
a,b,c = f(ClSz)

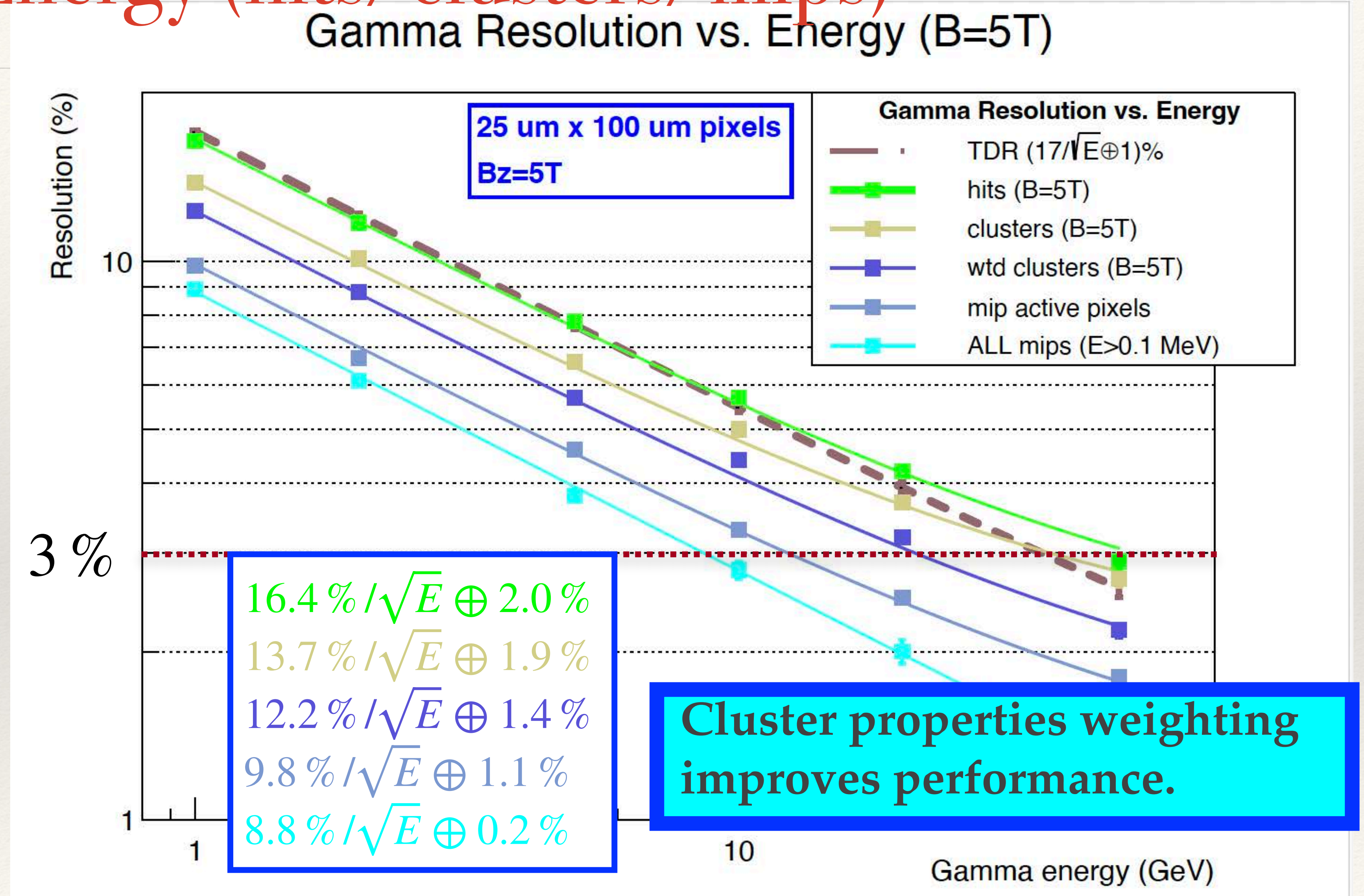


Resolution vs. Energy (hits/clusters/mips)

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







Can a Neural Net Improve Performance?

TMVA Neural Net

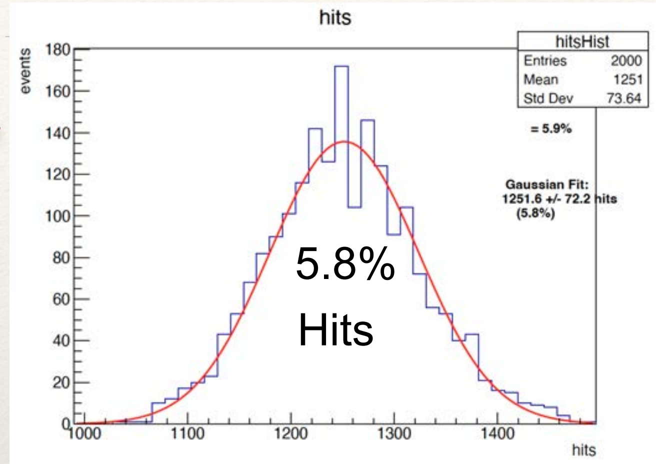
TRAINING - 10 GeV
- 2000 events
- 2,502,000 hits
- 1,878,999 clusters

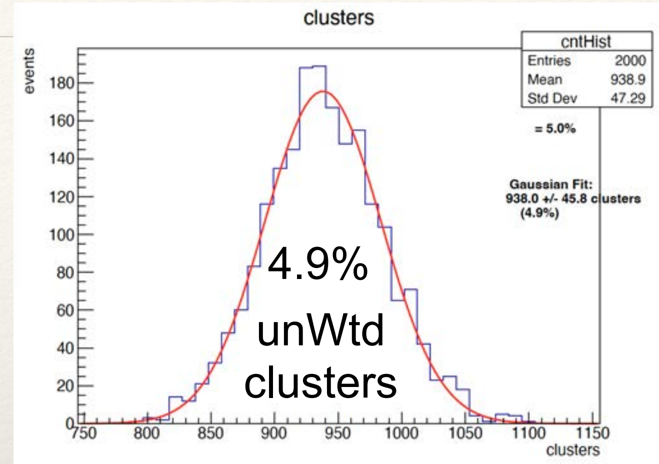
Neural net cluster weighting based on
1. Three input parameters =
   Cluster size,layer num,shower radius
2. Five input parameters =
   Add cluster length in Y and Z

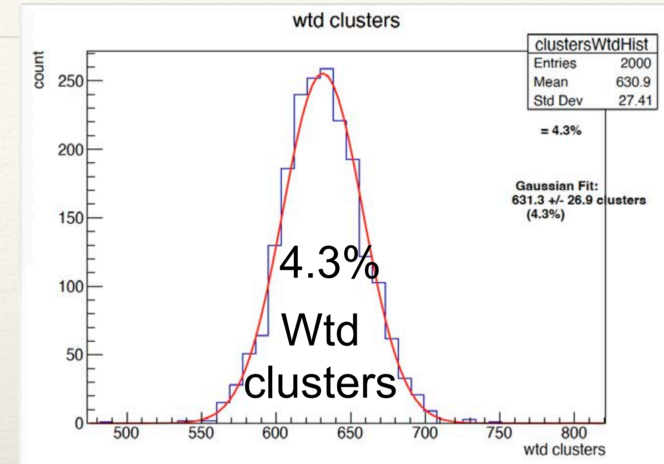
```
# Store model to file
model.save('modelRegression%s.h5'%Efact)
model.summary()

# Book methods
factory.BookMethod(dataloader, TMVA.Types.kPyKeras, 'PyKeras',
        'H:!
V:VarTransform=D,G:FilenameModel=modelRegression%s.h5:FilenameTrainedModel=
trainedModelRegression%s.h5:NumEpochs=20:BatchSize=32'%(Efact,Efact))
```

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

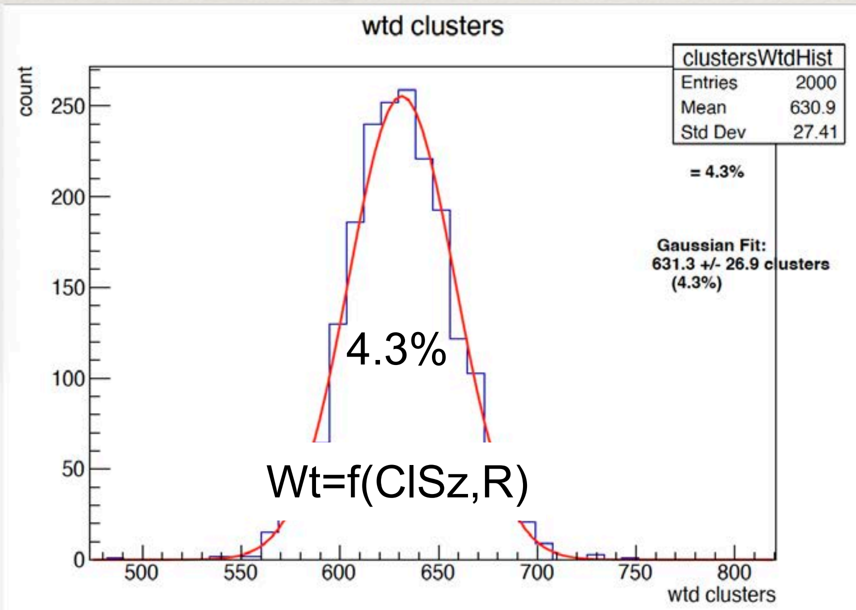
Weighted Clusters Analysis

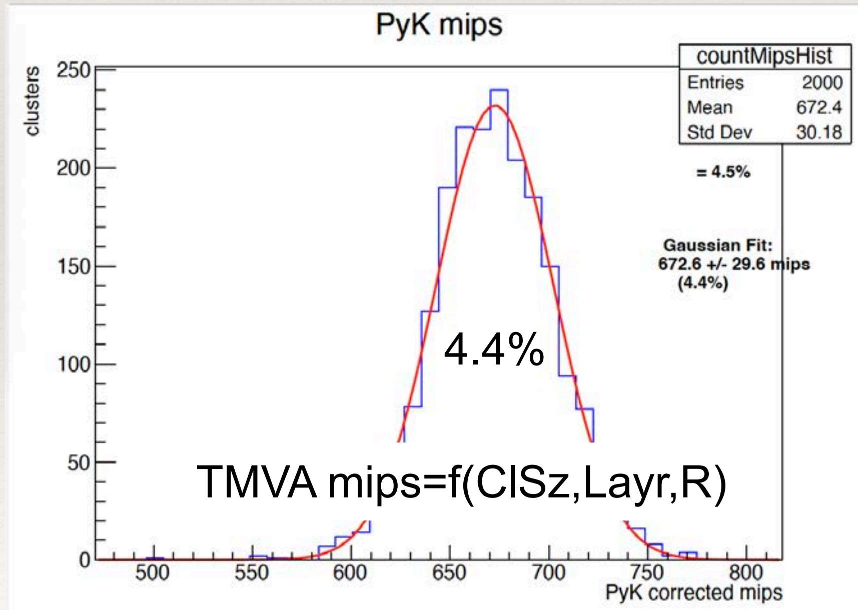


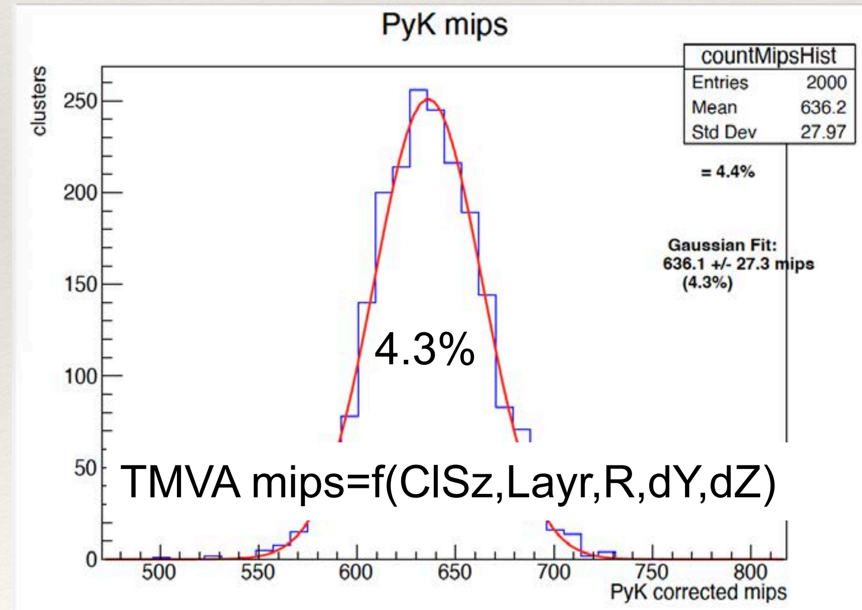




Neural Net Analysis







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%

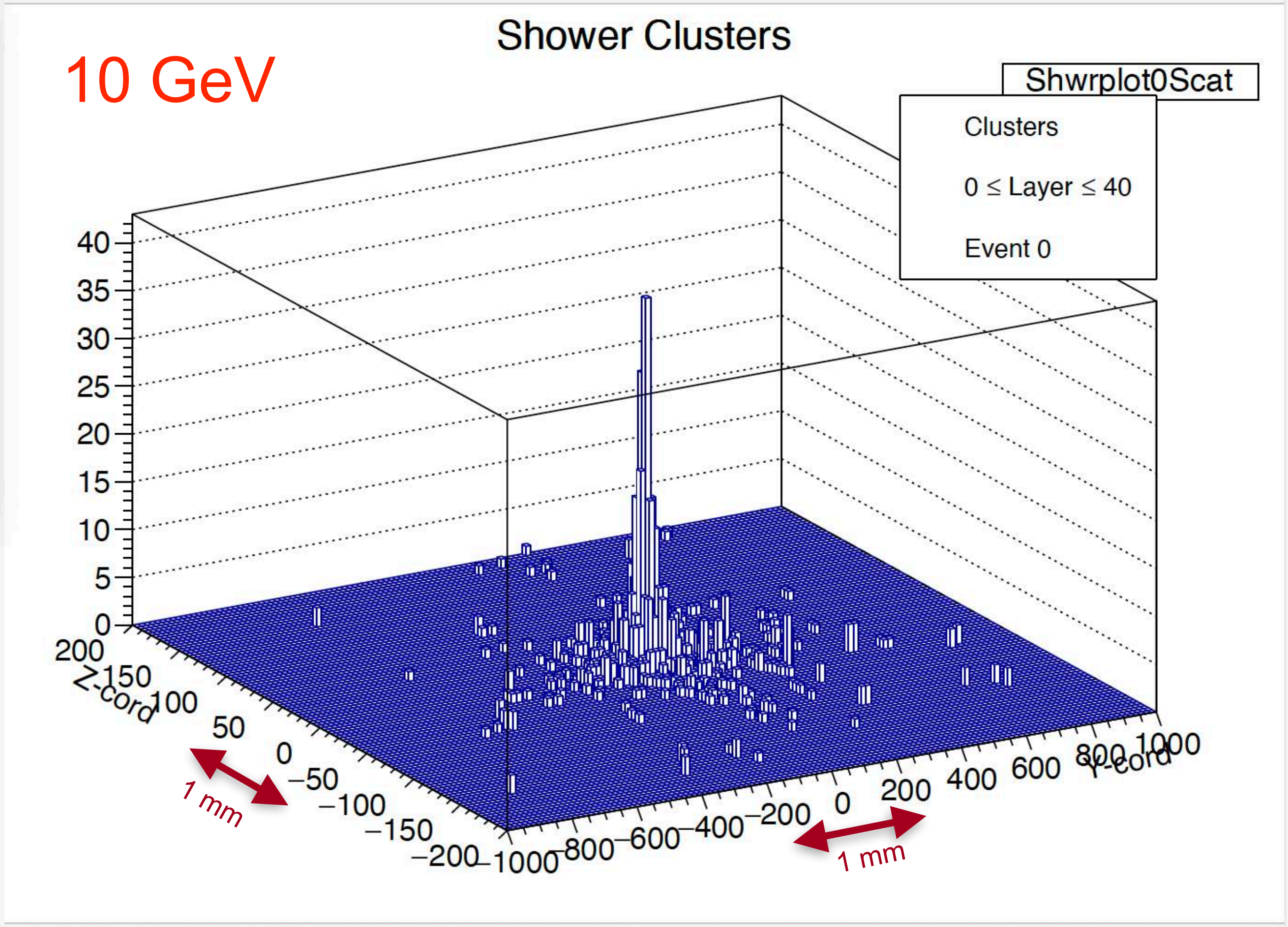
- Weight fits for 2, 10, 50 GeV; extrapolated for 1, 5, 20 GeV.
- NN optimized for each energy
- 3 par = cluster size, layer, radius
- 5 par = cluster size, layer, radius, dY, dZ

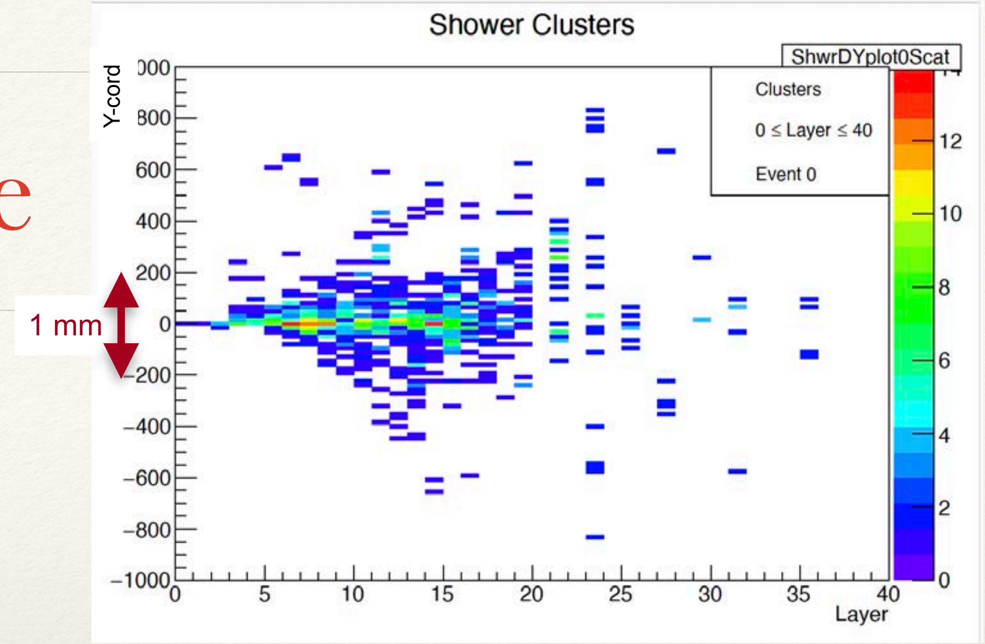
Weighted clusters already achieve performance of this neural net.

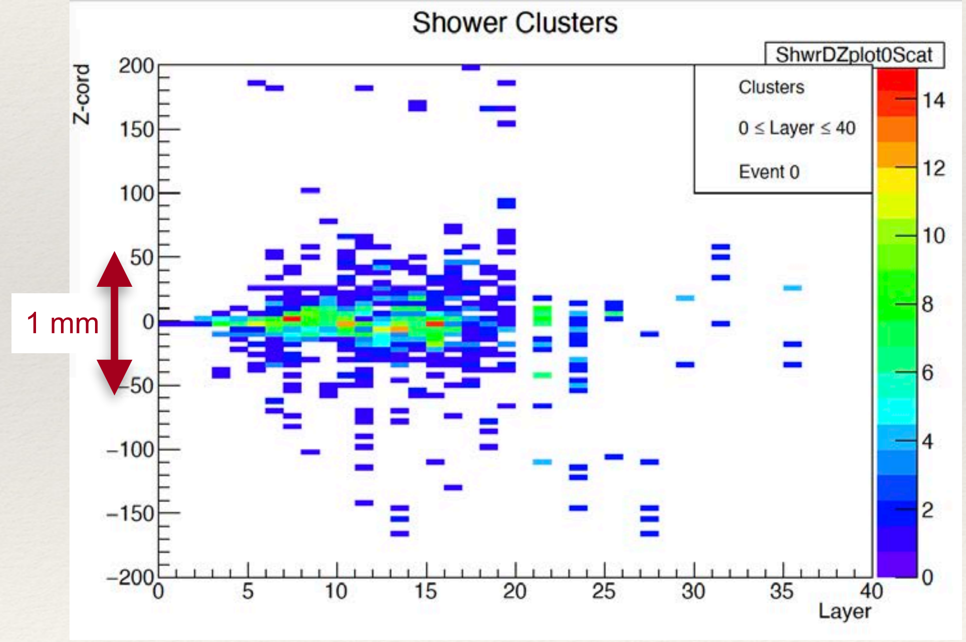
Another topic:

Potential impact of high granularity on particle flow measurements

Transverse Shower Structure

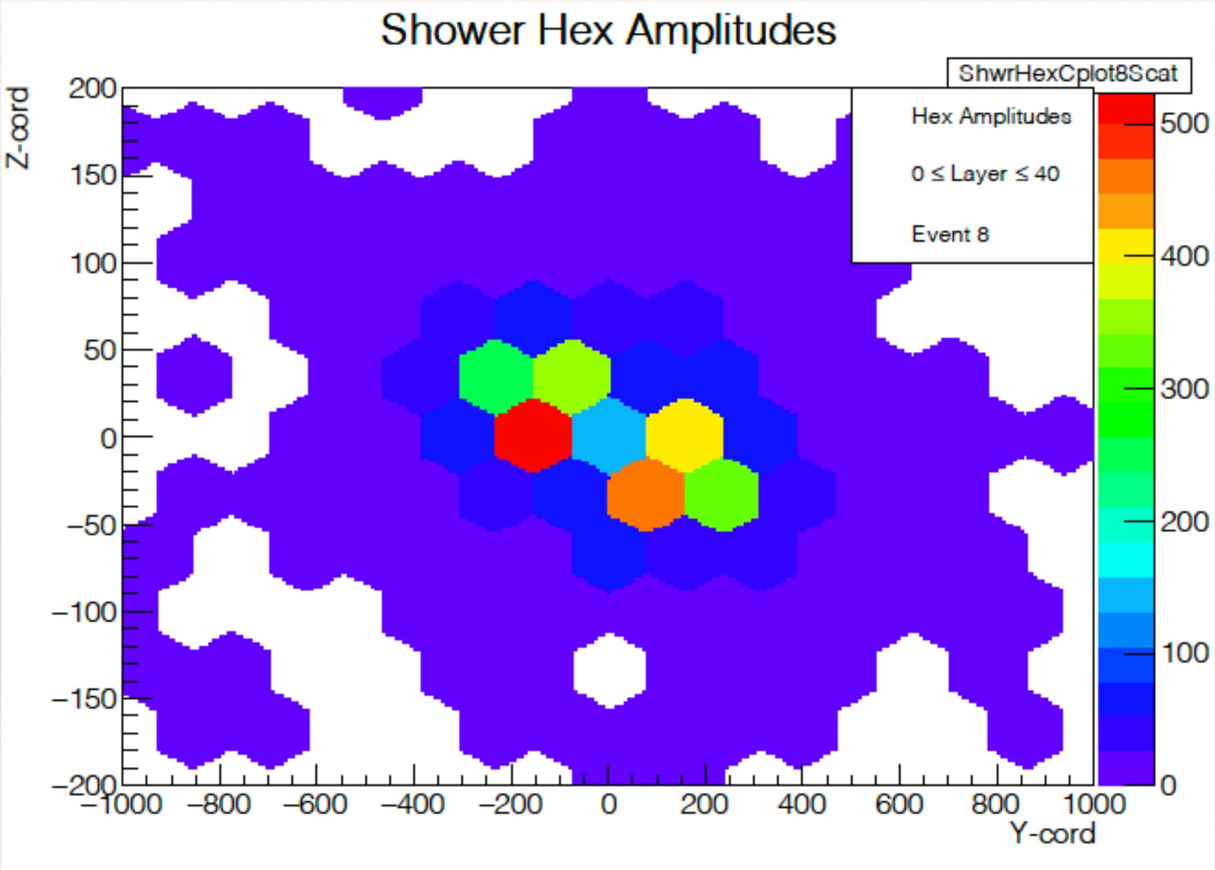




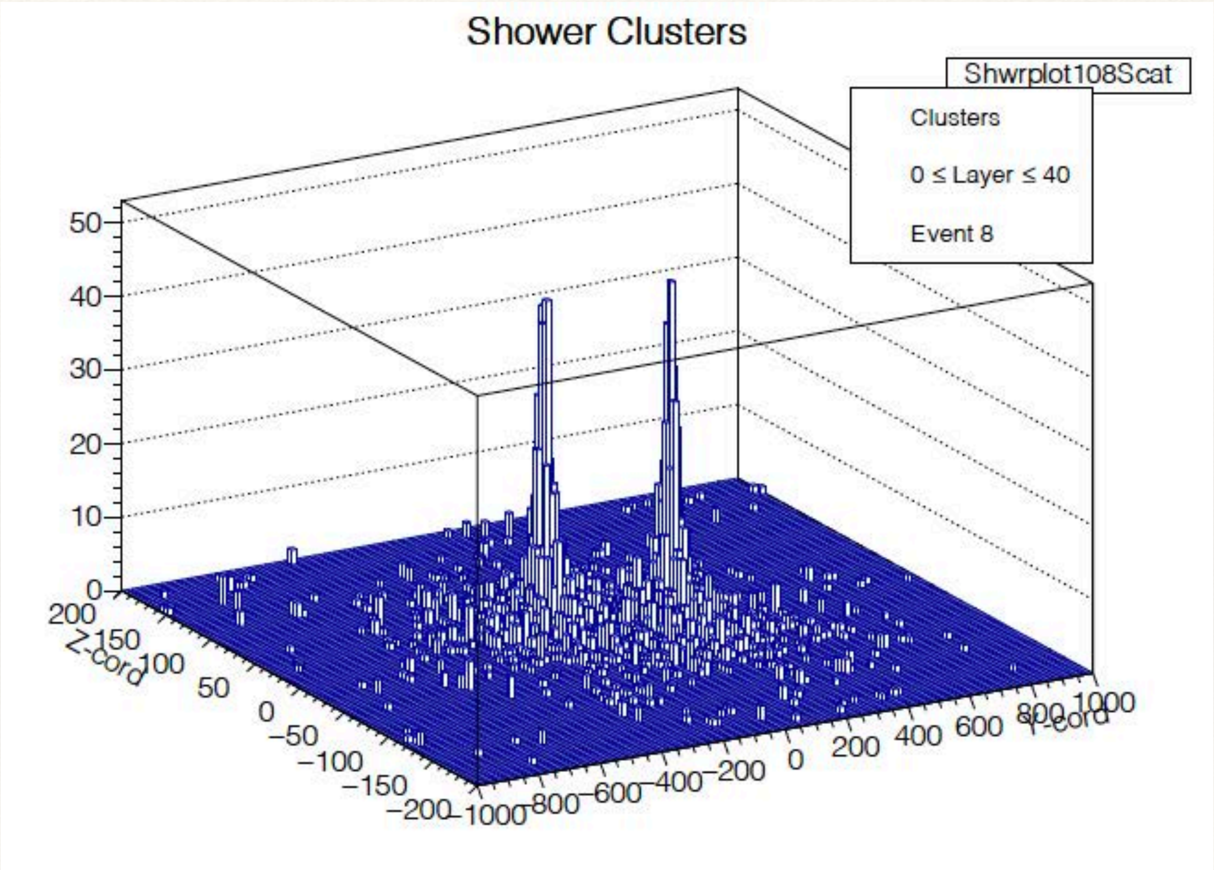


Multi-shower of SiD MAPS compared to SiD TDR

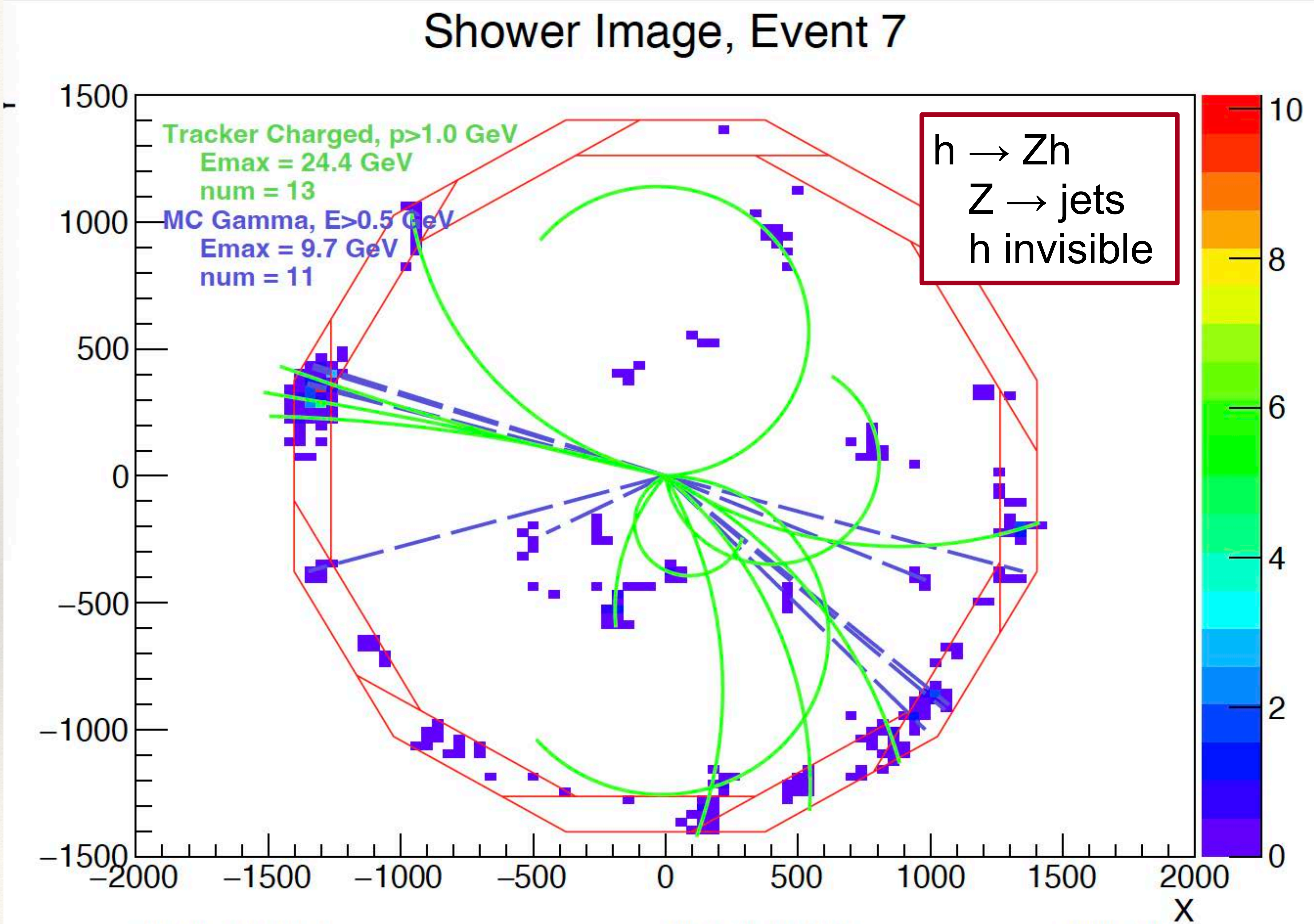
40 GeV $\pi^0 \rightarrow$ two 20 GeV γ's



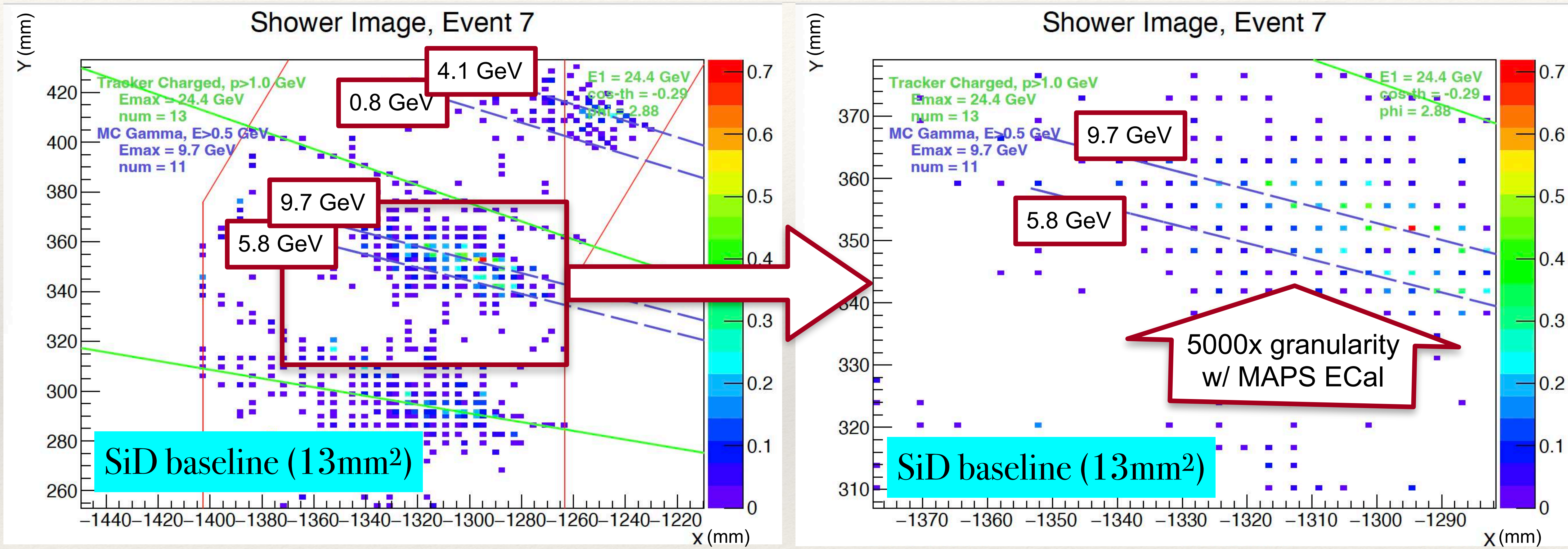
SiD TDR hexagonal sensors
13 mm² pixels



New SiD fine pixel sensors
25 µm x 100 µm pixels


Shower Image, Event 7
Tracker Charged, p>1.0 GeV
Emax = 24.4 GeV
num = 13
MC Gamma, E>0.5 GeV
Emax = 9.7 GeV
num = 11
h → Zh
Z → jets
h invisible
1500
1000
500
0
−500
−1000
−1500
−2000
−1500
−1000
−500
0
500
1000
1500
2000
X
10
8
6
4
2
0

γ's in jet / SiD baseline ECal (13mm² pixels)

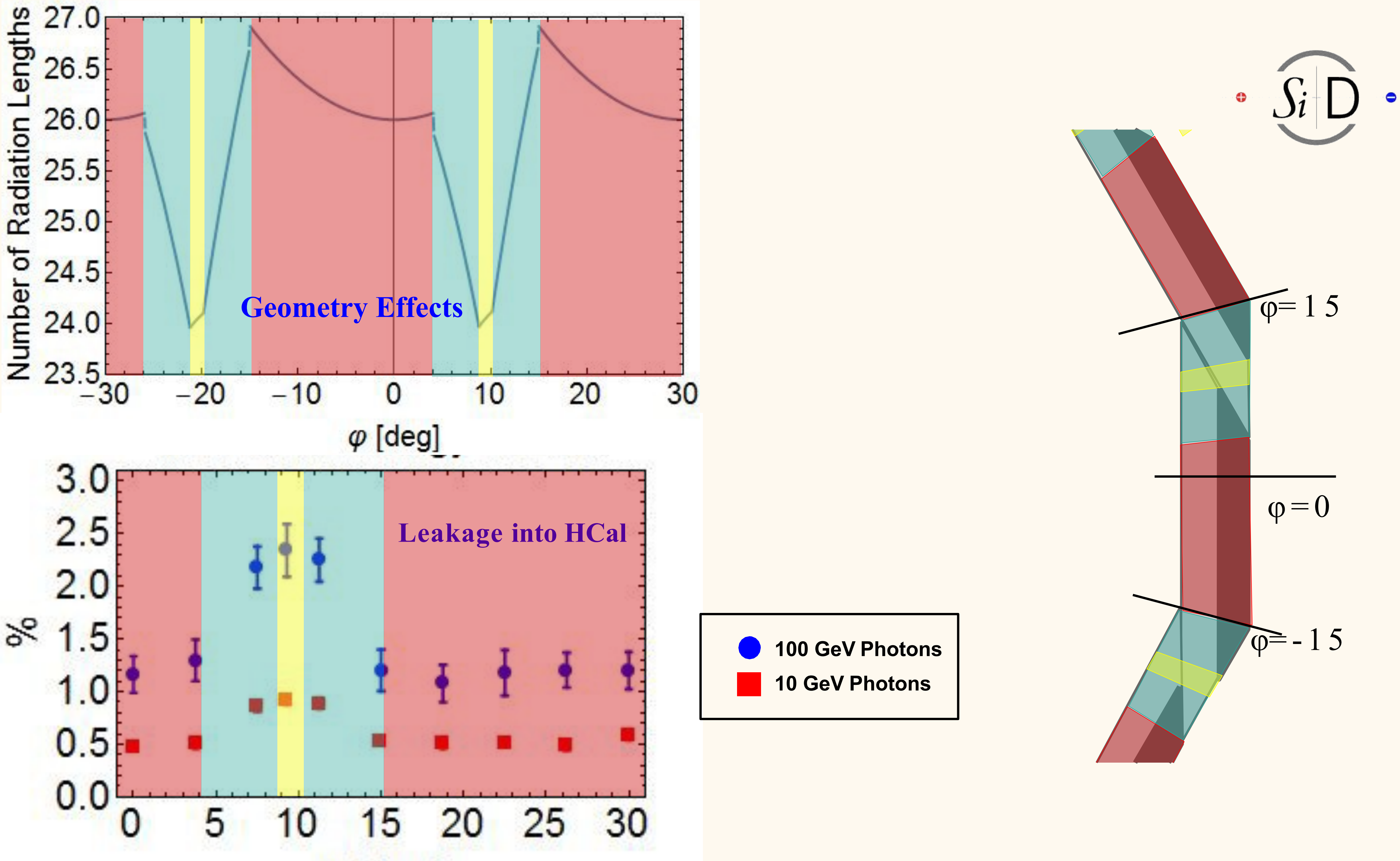


- 13 mm² pixels of analog SiD ECal
- **5000x granularity** with digital MAPS ECal
- Future MAPS integration into full SiD simulation will define scale of improvement?

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.
- 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