May 17, 2022

The SiD Digital ECal based on Monolithic Active Pixel Sensors

Jim Brau,
University of Oregon

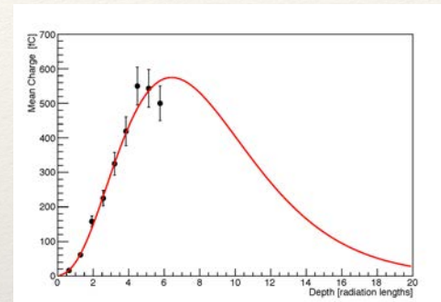
on behalf of
the SiD MAPS Collaboration
(M. Breidenbach, L. Rota,
C.Vernieri et al.)

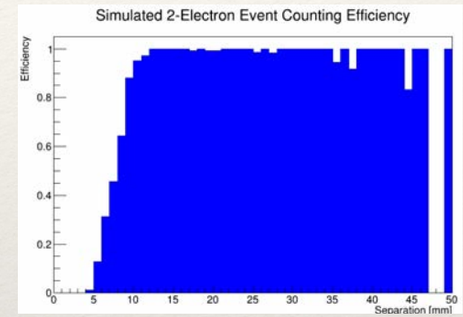
Research partially supported
by the U.S. Department of Energy

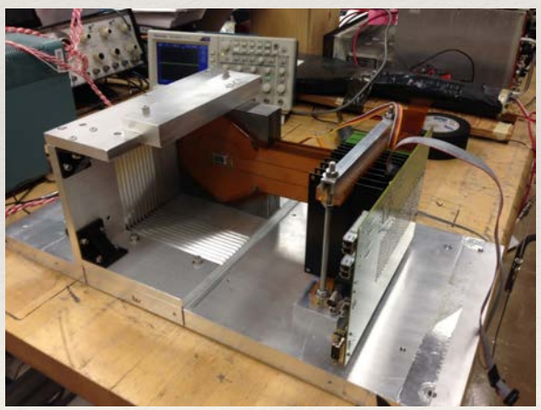
Reference: arXiv:2203.07626 [physics.ins-det]

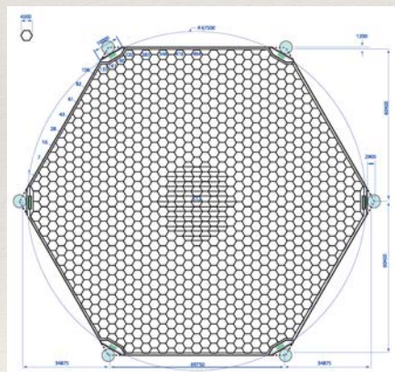
SiD TDR Design Based on Analog Silicon Pixels

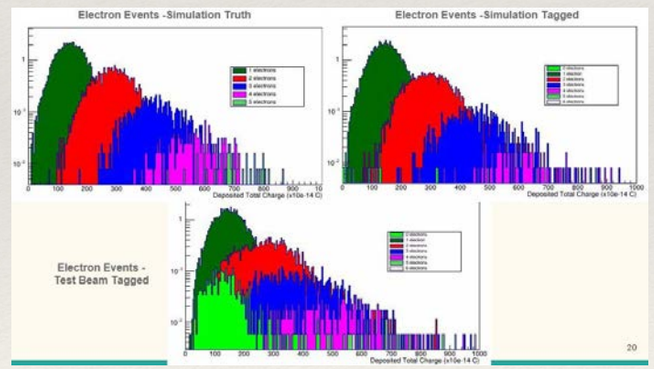
- **SiD ILC TDR ECal** design successfully tested in 9 layer SLAC beam test.
  - **13 mm²** pixels on 6 inch wafers
  - 1024 pixels per wafer
  - KPiX readout bump-bonded to sensor

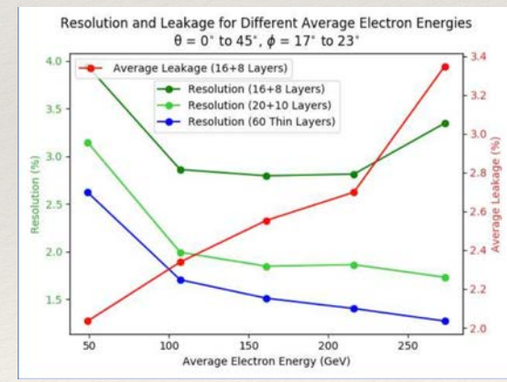




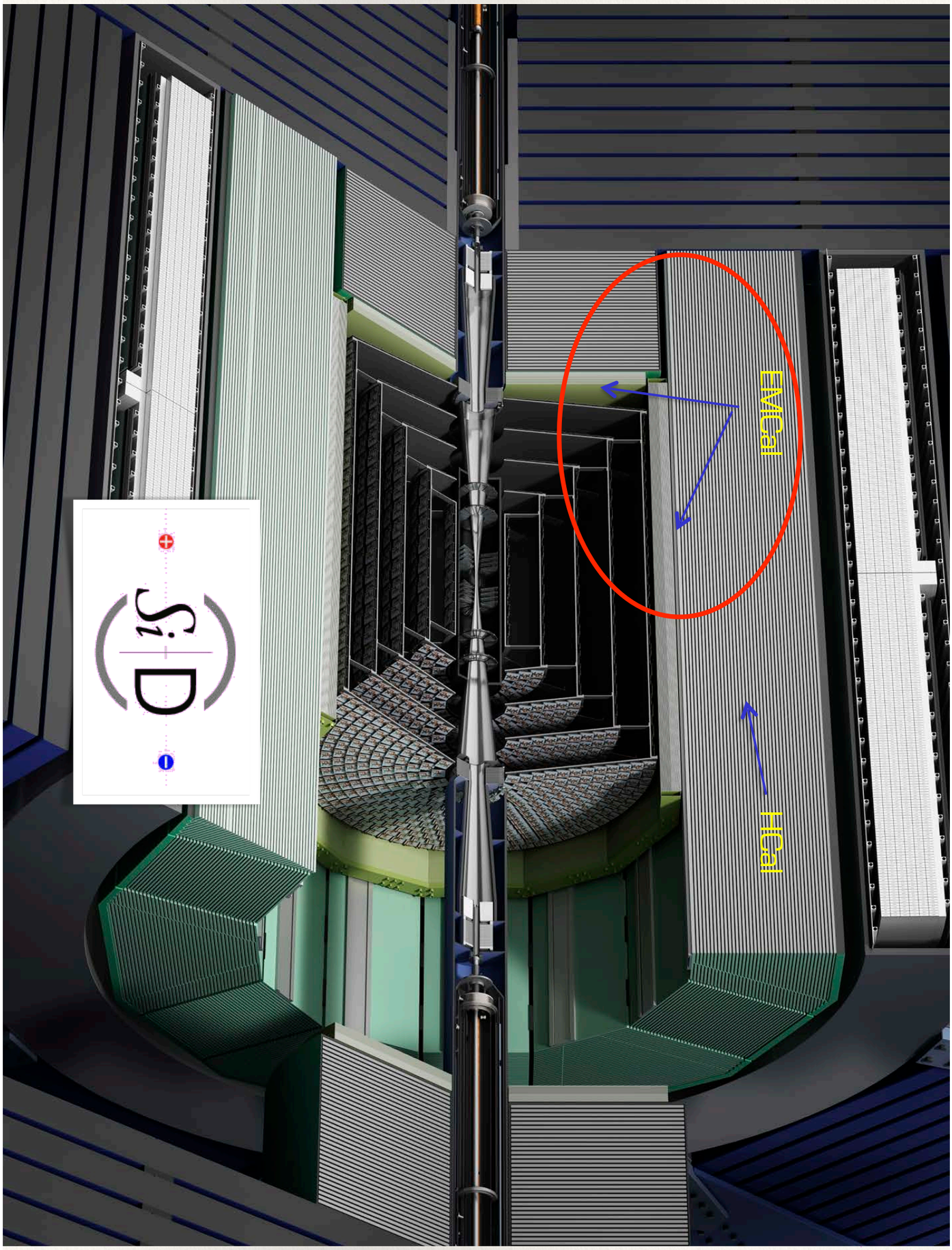








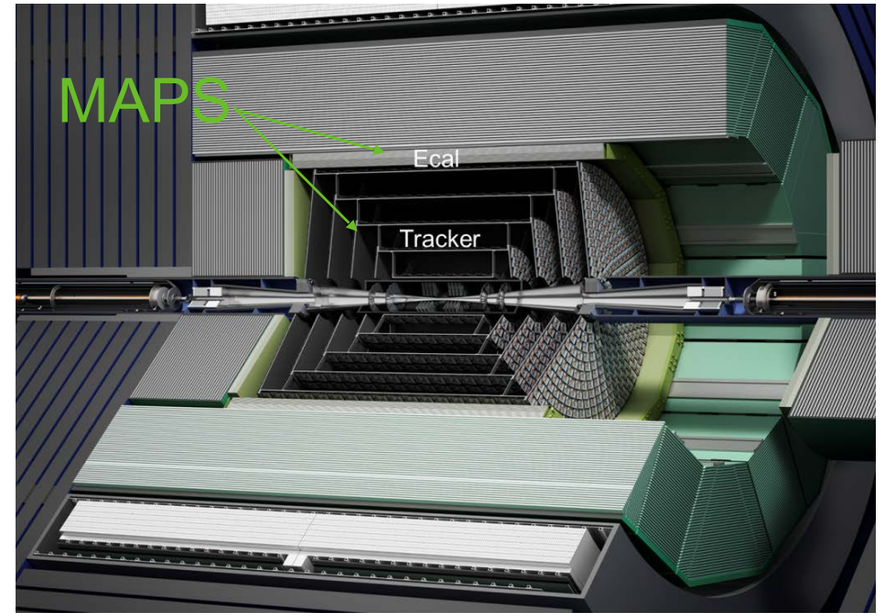
New development to improve design based on 25 μm x 100 μm digital **MAPS.**
Calorimetry application largely emphasizing Particle Flow Analysis.


EMCal
HCal

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 > 10x10 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

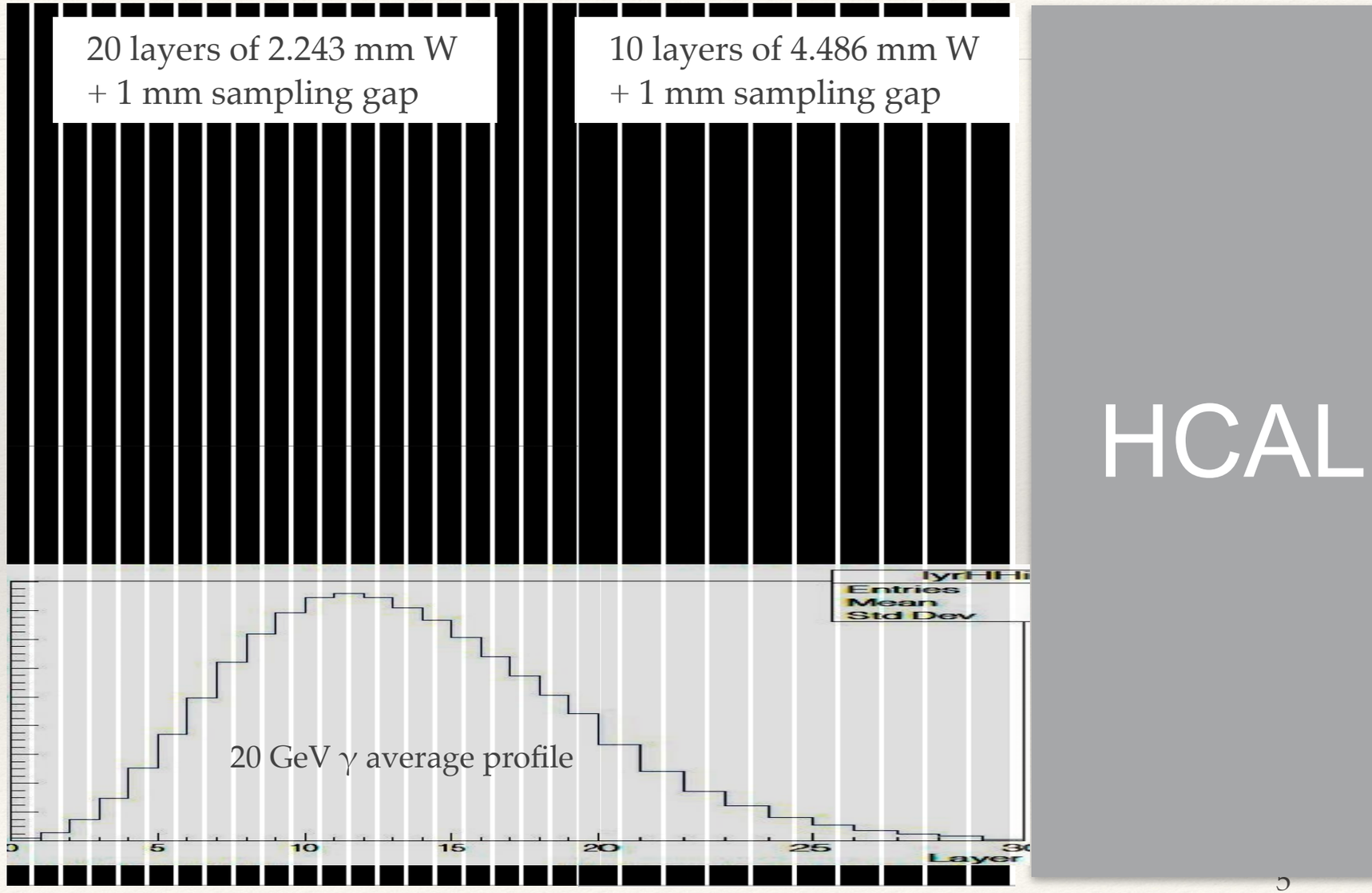
L. Rota

Model of longitudinal structure of SiD ECal

Total = 27 X_O

Incident Particle

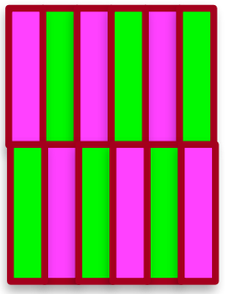
Minimize sampling gap to achieve optimal Moliere radius and shower separation



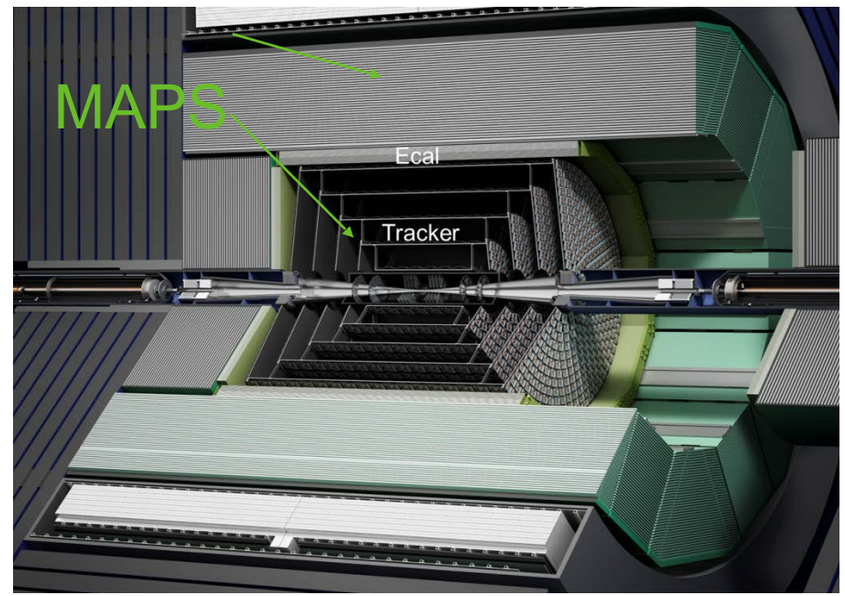
Main specifications for Large Area MAPS development

TID-AIR SLAC

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
Chip size	10 x 10 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



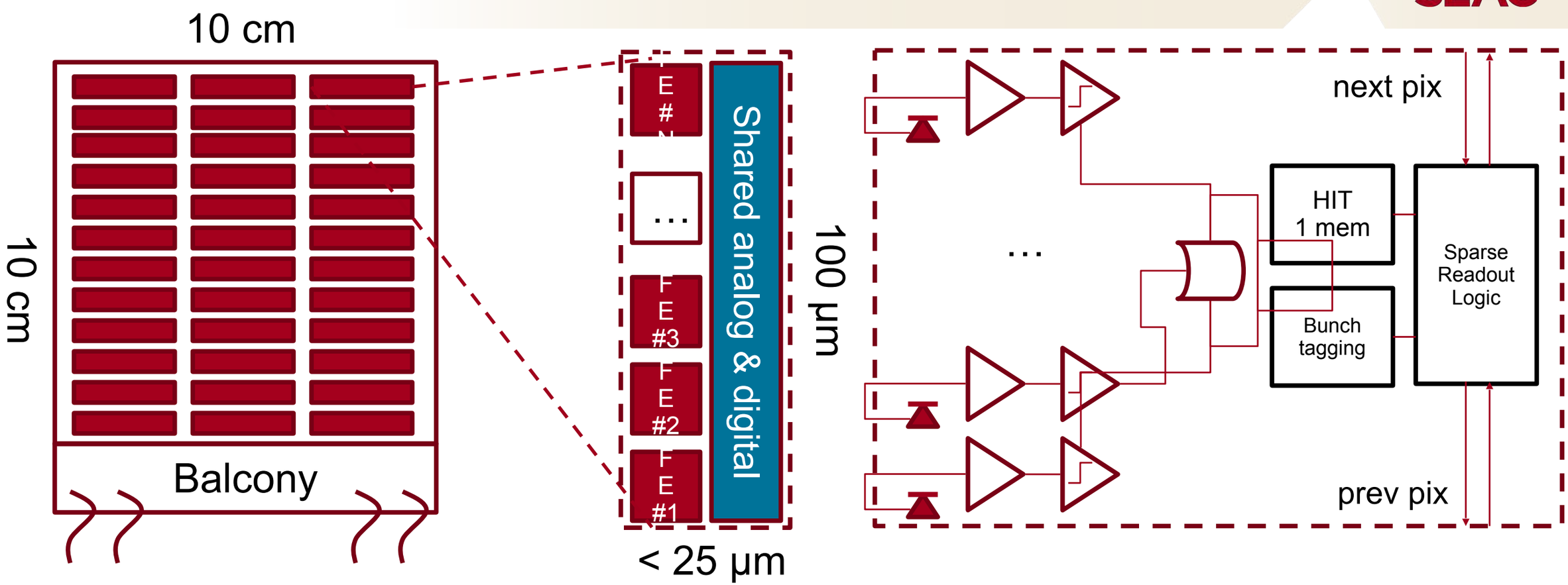
25 x 100 μm^2
ECal performance same as
50 x 50 μm^2



SiD Tracker and the ECal

L. Rota

Overall architecture



- Expected 1 hit/pixel/bunch train → integrate charge through whole bunch train → store 1 hit/pixel
- Segmentation of pixel front-end connected to common digital logic. *See also CLICTD [1]*
- Optimal segmentation of pixel front-ends will depend on sensor performance

L. Rota

[1] https://cds.cern.ch/record/2643766/files/CLICdp-Conf-2018-008.pdf

Power during integration phase

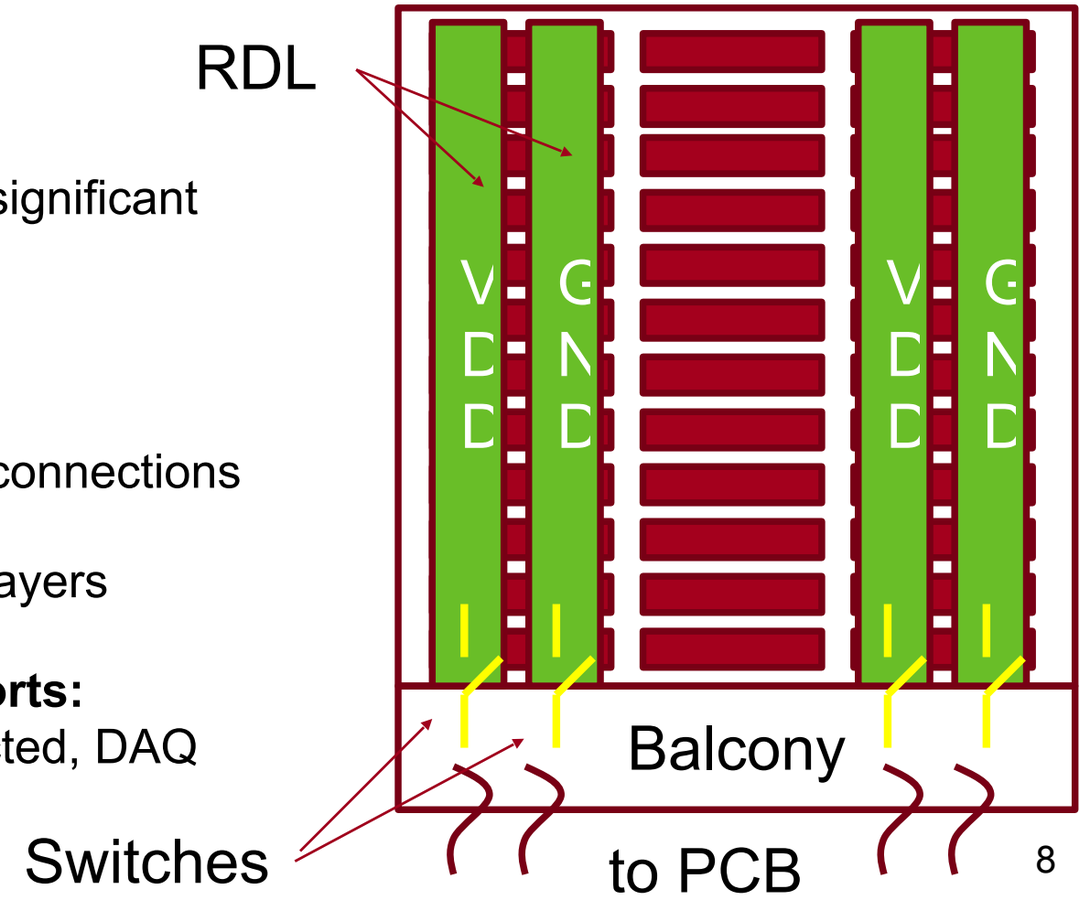
Phase:

- Avg power consumption reduced by power-cycling
  … but **peak** current draw is not!
- Assuming 1μA/pixel, current draw is ~16 A
- Resistance of metal lines not negligible over 10 cm → significant voltage drop

Possible strategies:

- Bypass caps distributed over sensor
- EMCal flat cable distributes power to all reticule bump connections
- Re-distribution layer with thick metal deposited on-top
- Discuss with foundry about having more/thicker metal layers

Need to investigate strategies on how to cope with shorts:
Add "switches" for each column/cluster → if a short detected, DAQ disables the column during initial power-up sequence



L. Rota

Power during readout phase

Phase:

Design an **asynchronous** readout logic with **zero-suppression:**

- Only pixels with HIT information are read-out by balcony
- Need to transmit data from pixel to balcony over ~10 cm lines, with large interconnection RC → minimize bit transitions → **power ⇩**
- Remove clock → **power ⇩**
- Handshaking between pixel and balcony ensures proper data transmission even with large on-die variations
- First simulations done, data throughput meets specs: ~200 ns to transmit one "hit" from pixel to balcony

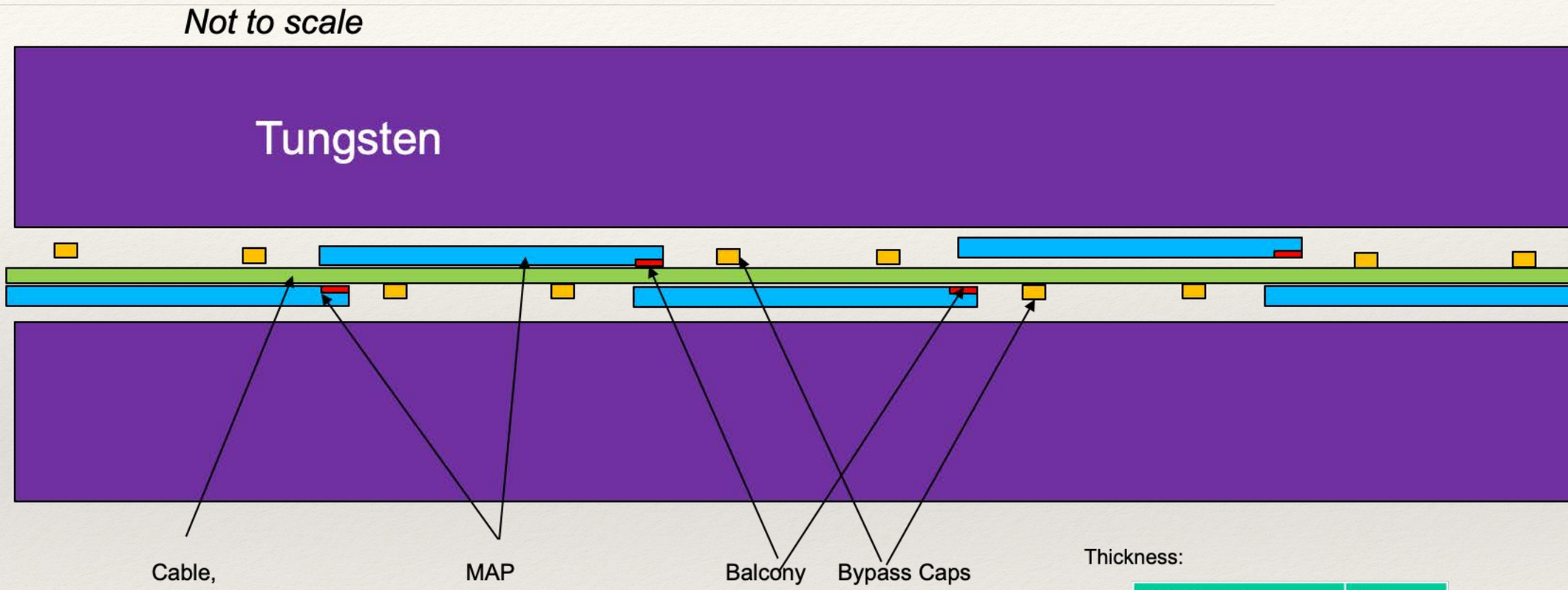
L. Rota

Large area MAPS: next steps

- SLAC working in WP1.2 collaboration at CERN
  - ALICE ITS3 upgrade main driver
- Design 1.5x1.5 mm^2 prototype with few pixels to test sensor + front-end
- Submission of first prototype in 2022
  - Small-scale prototype in late 2022
- Study sensor performance on TowerSemi 65 nm process
  - TCAD simulations to optimize sensor design
  - Feedback from WP 1.2 measurements done at CERN
- Study bunch-tagging strategy (linear collider specific)
  - Analog-based: ramp, with low-res ADC in balcony (~8 bits)
  - Digital-based: local DLL for Time-to-Digital Conversion

L. Rota

Gap Structure with MAPS



Thickness:

Middle Cable	400 μ
Top Sensor	200
Bottom Sensor	200
Bottom Cable	0
Total	800
Clearance with 1 mm gap	200

ONE CABLE IN GAP DESIGN

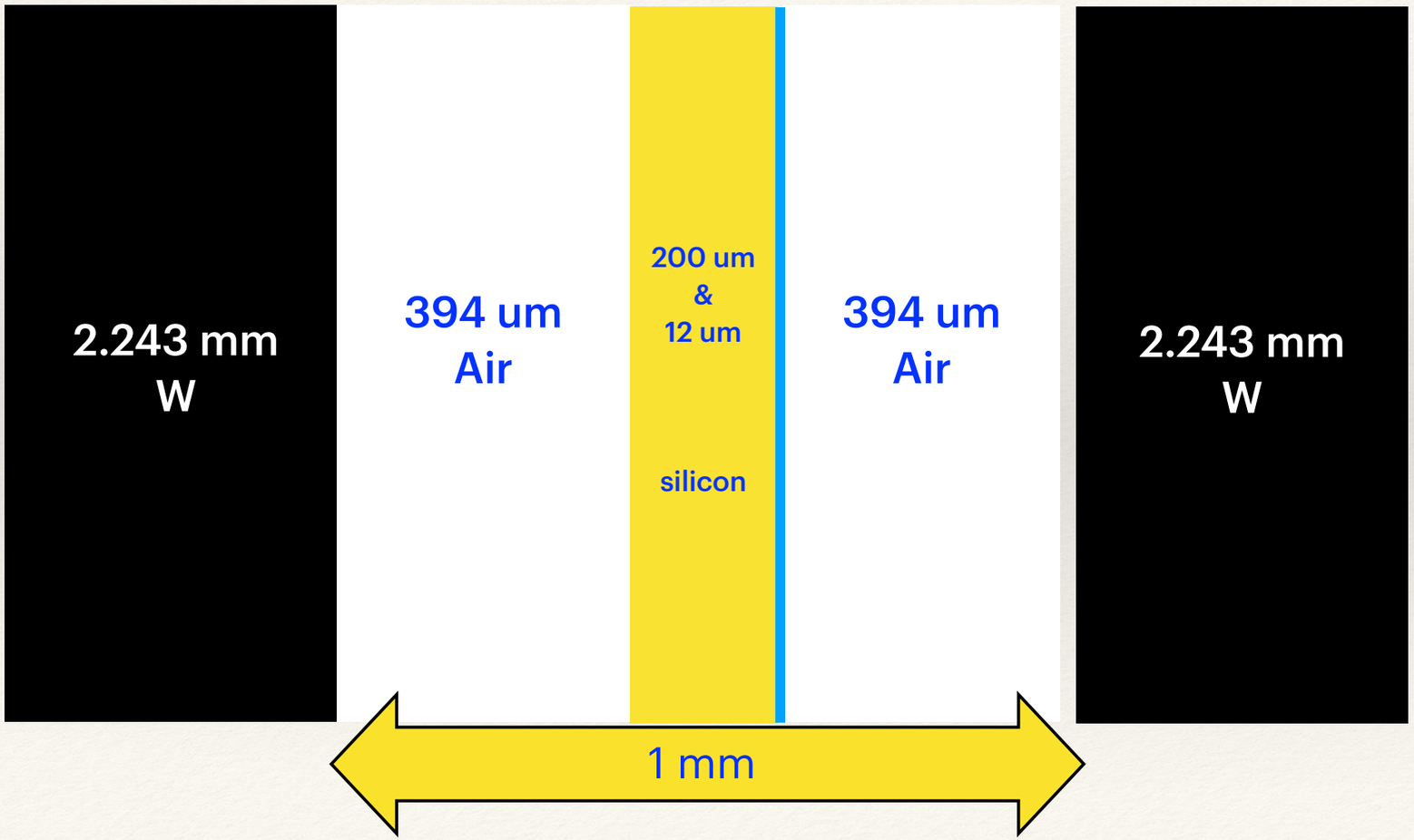
Gap structure with MAPs on one cable (or pcb). Requires bump bonding

This may well need adjustment following more cable design

M. Breidenbach

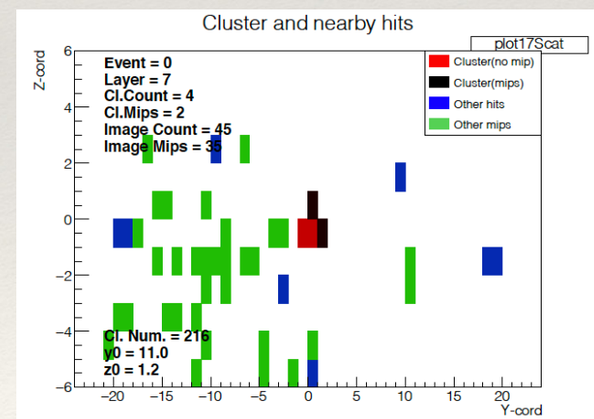
Sampling Gap Simulation - SiD MAPS Digital ECal

Geant4 simulated silicon gap structures



Assumption:
Pixel threshold =
1 keV ≈ 270 e's

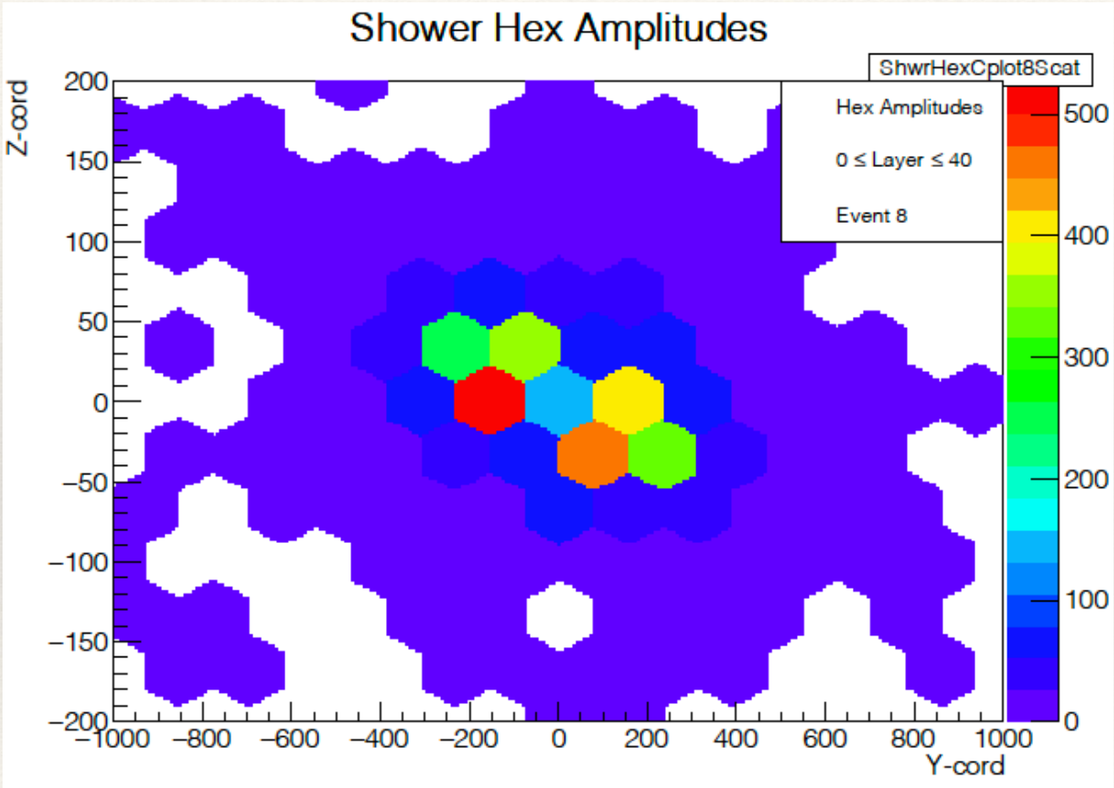
Future:
More detailed
gap model



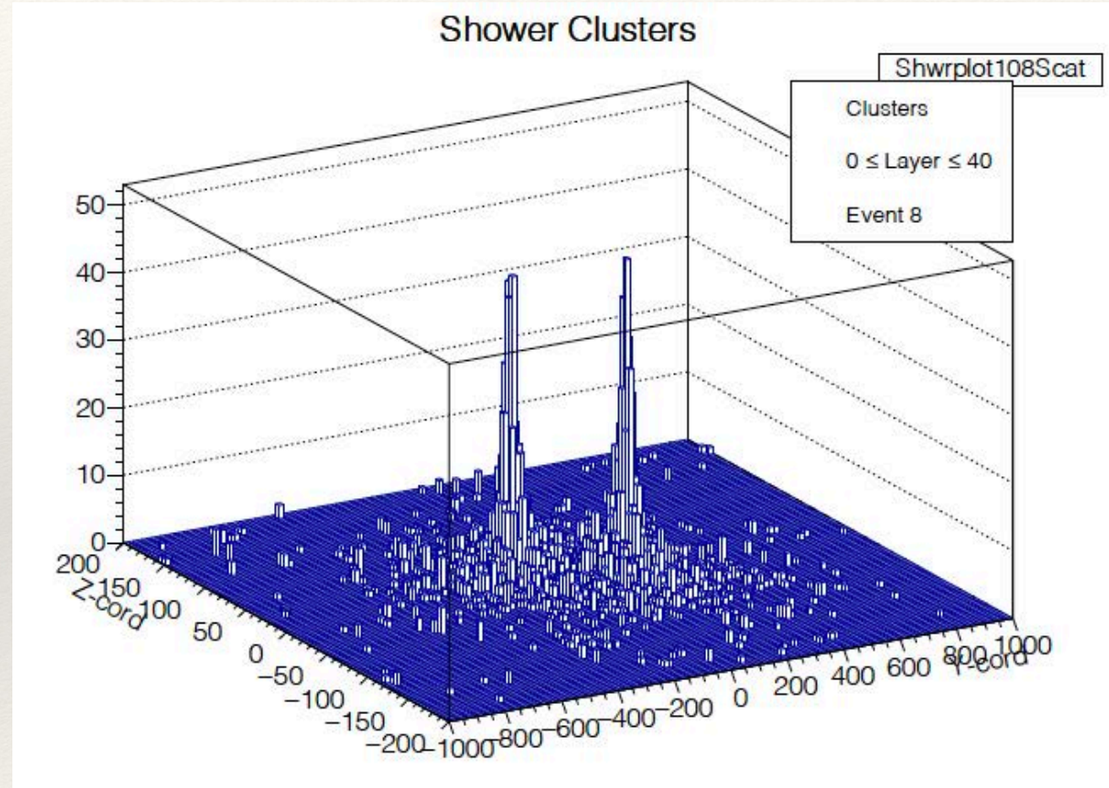
Typical hits distribution

Multi-shower of SiD MAPS compared to SiD TDR

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



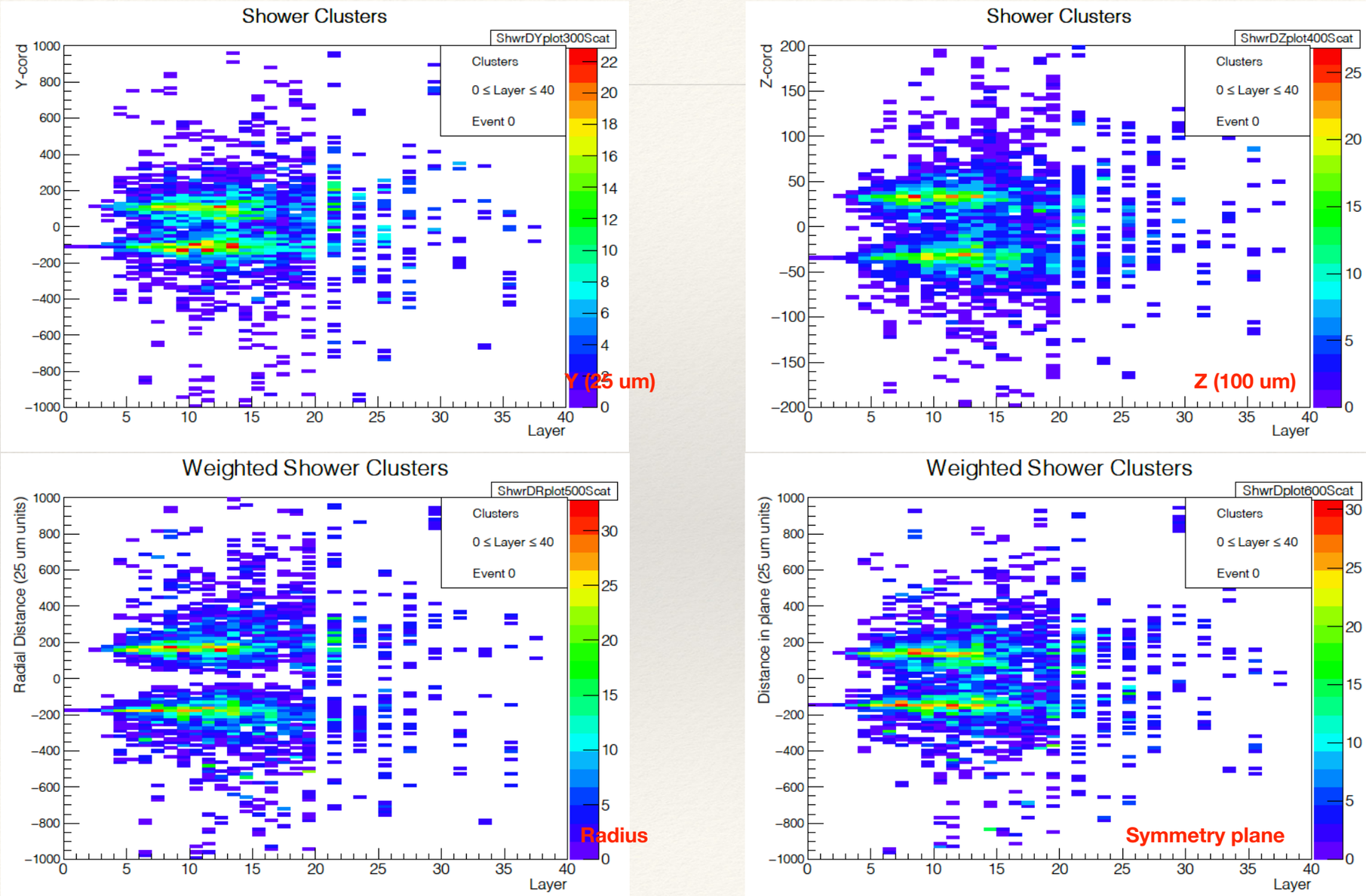
SiD TDR hexagonal sensors
13 mm² pixels



New SiD fine pixel sensors
25 μm x 100 μm pixels

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

Vertical bin
400 um



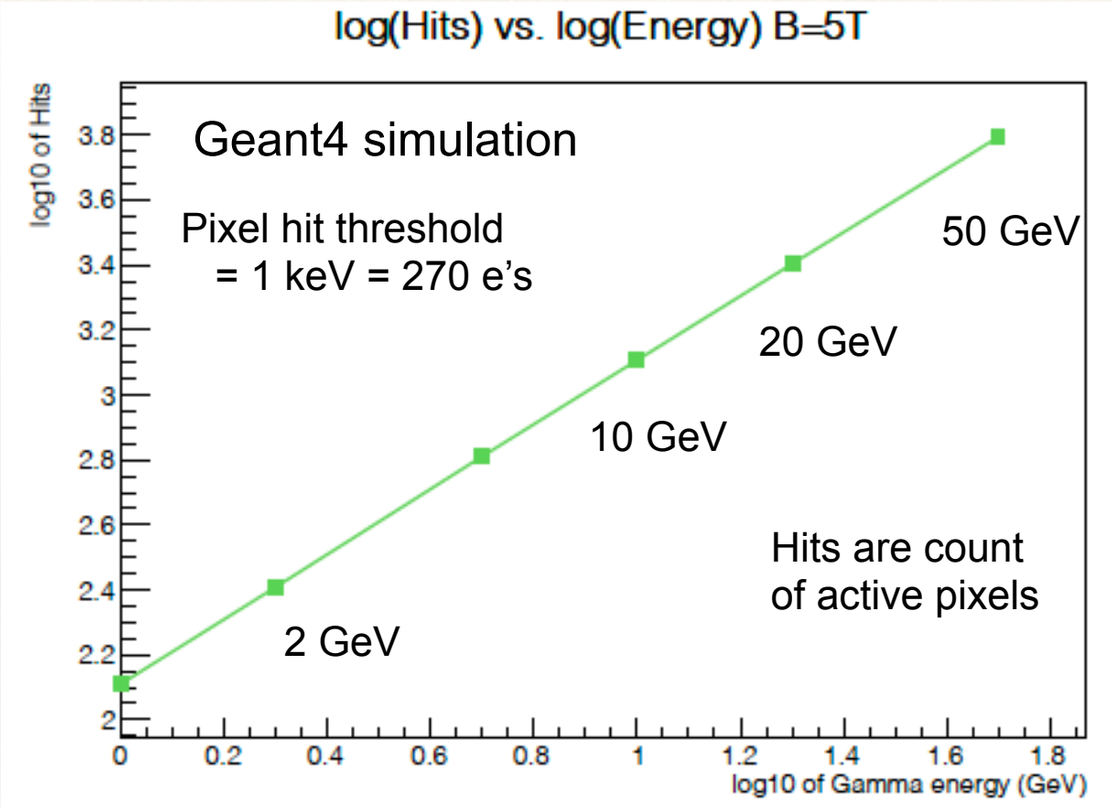
Performance simulation - Overview

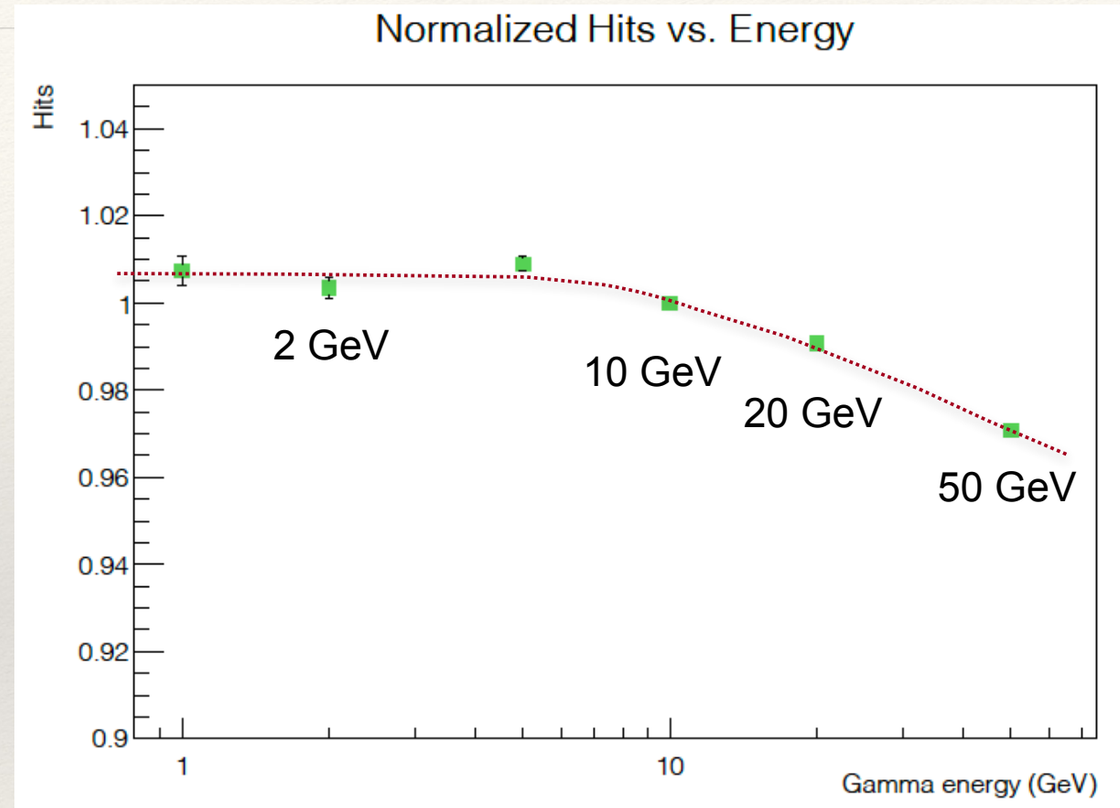
Geant4

- Linearity
- Energy resolution
  - Ideal - count mips - sets unreachable goal
  - Simplest approximation to mips - count digitized hits
  - Improvement - count clusters of hits - reduce fluctuations
  - Optimized - apply weights cluster counts from cluster properties
- Localization
  - Multiple shower separation

- Note - SiD's 5 T B field degrades resolution ~5%

Linearity of response (counting hits in γ showers)

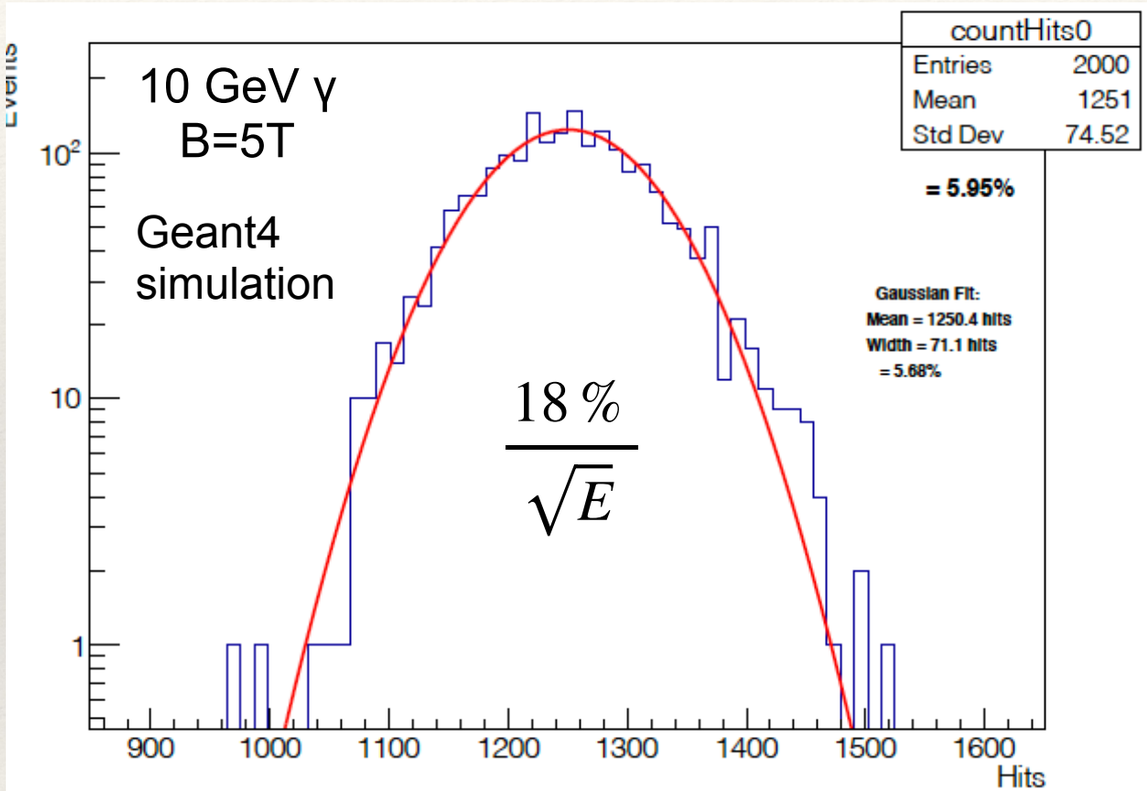


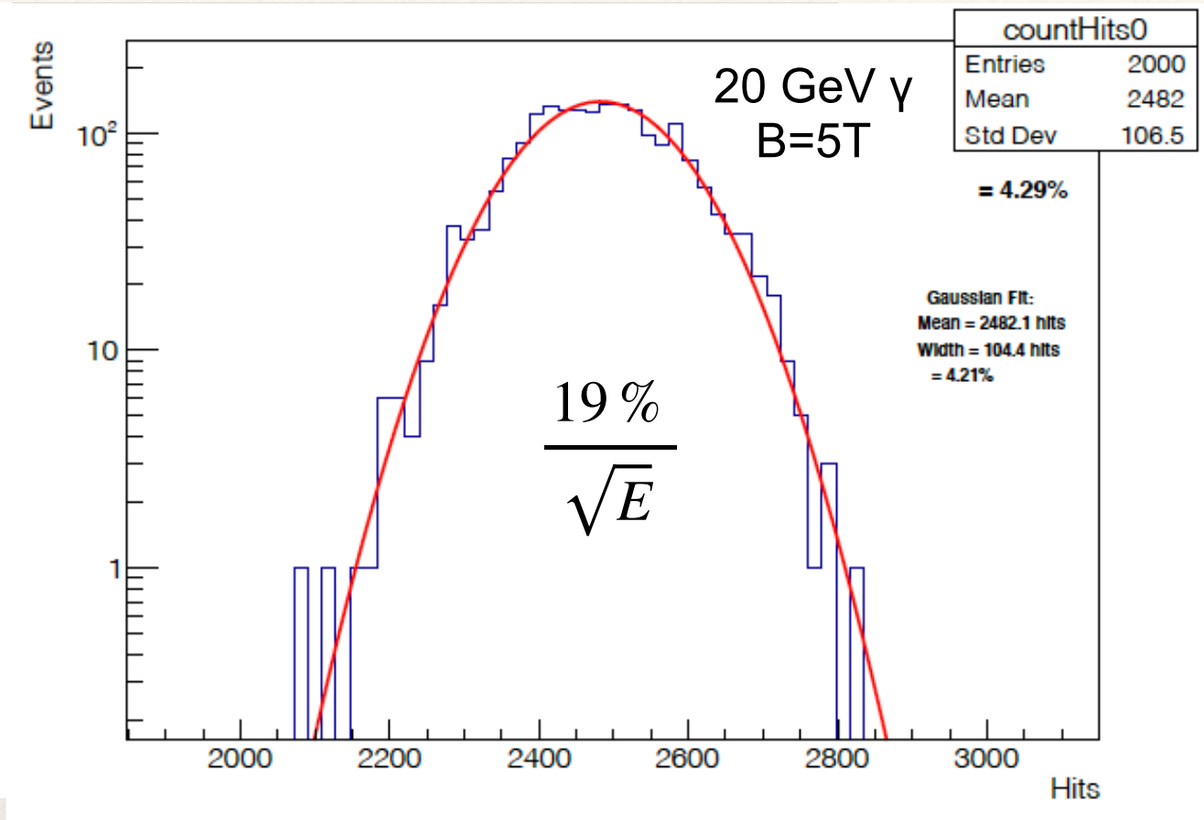


Non-linearity due to differing response and counting in thin (0.7 X_0) and thick (1.4 X_0) layers (and uncorrected leakage).

Hits resolution - count active pixels

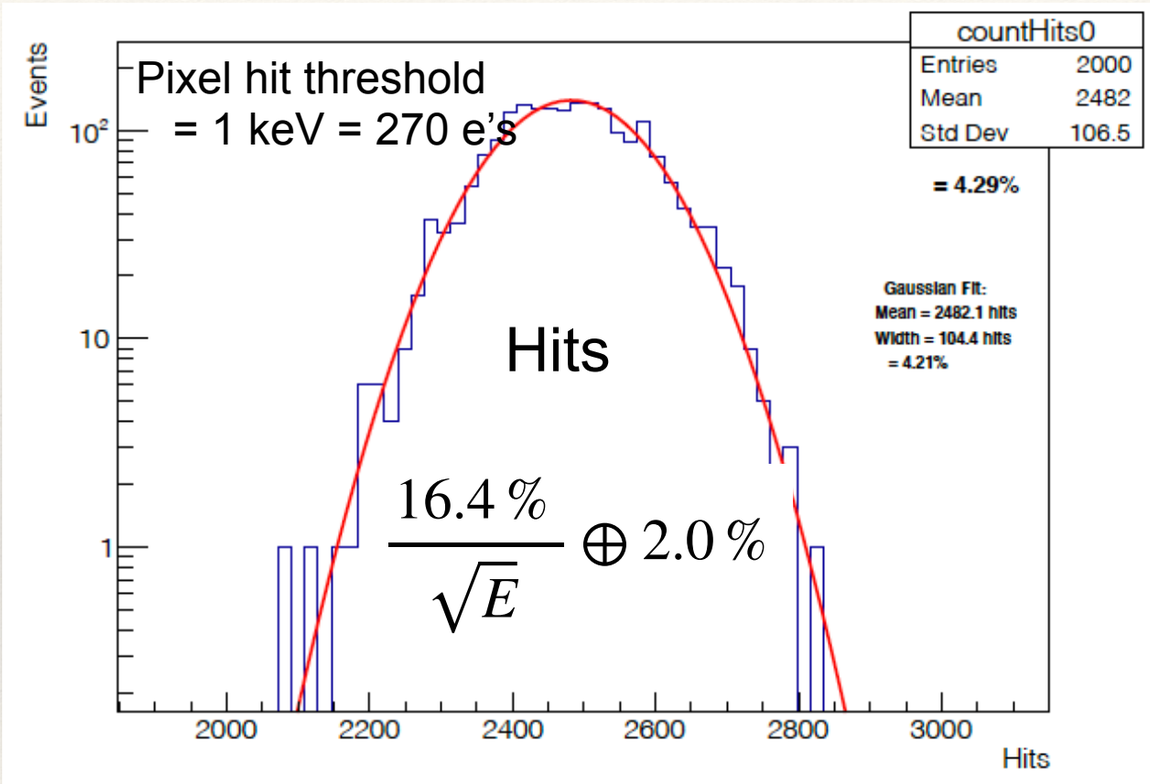
Pixel hit threshold
= 1 keV = 270 e's

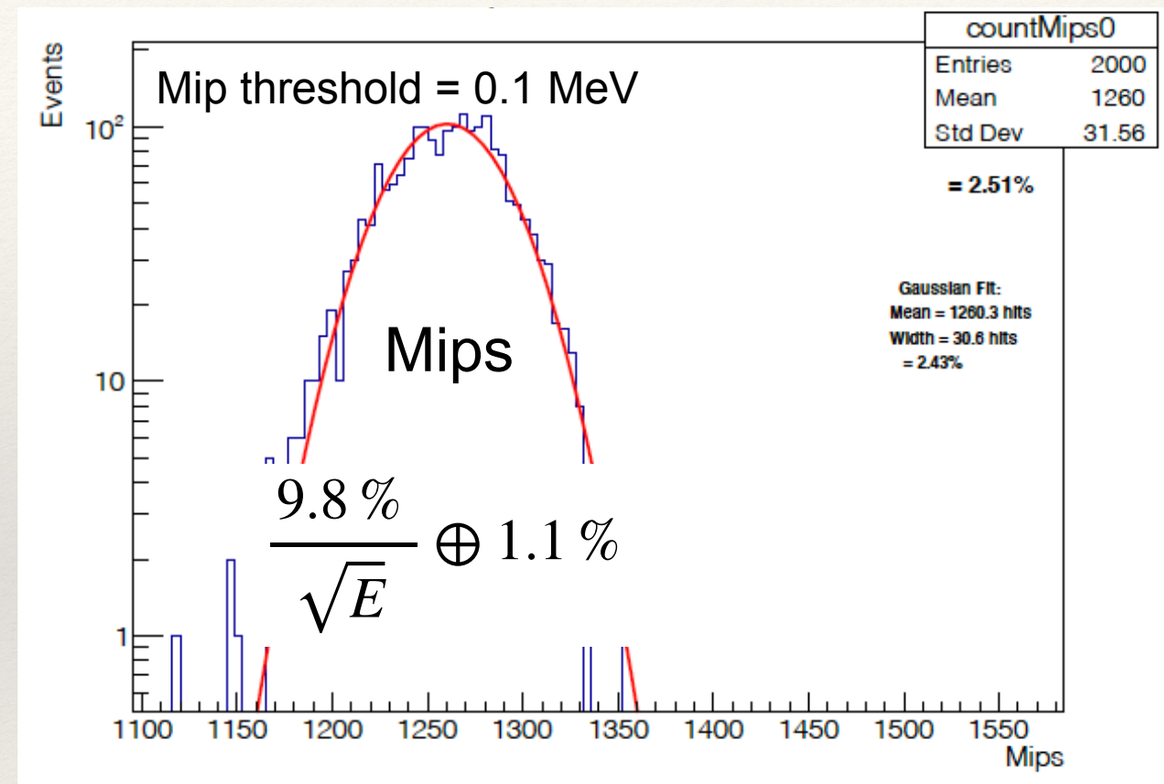




ILC TDR anticipates $\frac{17\,\%}{\sqrt{E}} \oplus 1\,\%$ for the SiD SiW ECal; **<u>but we can do better.</u>**

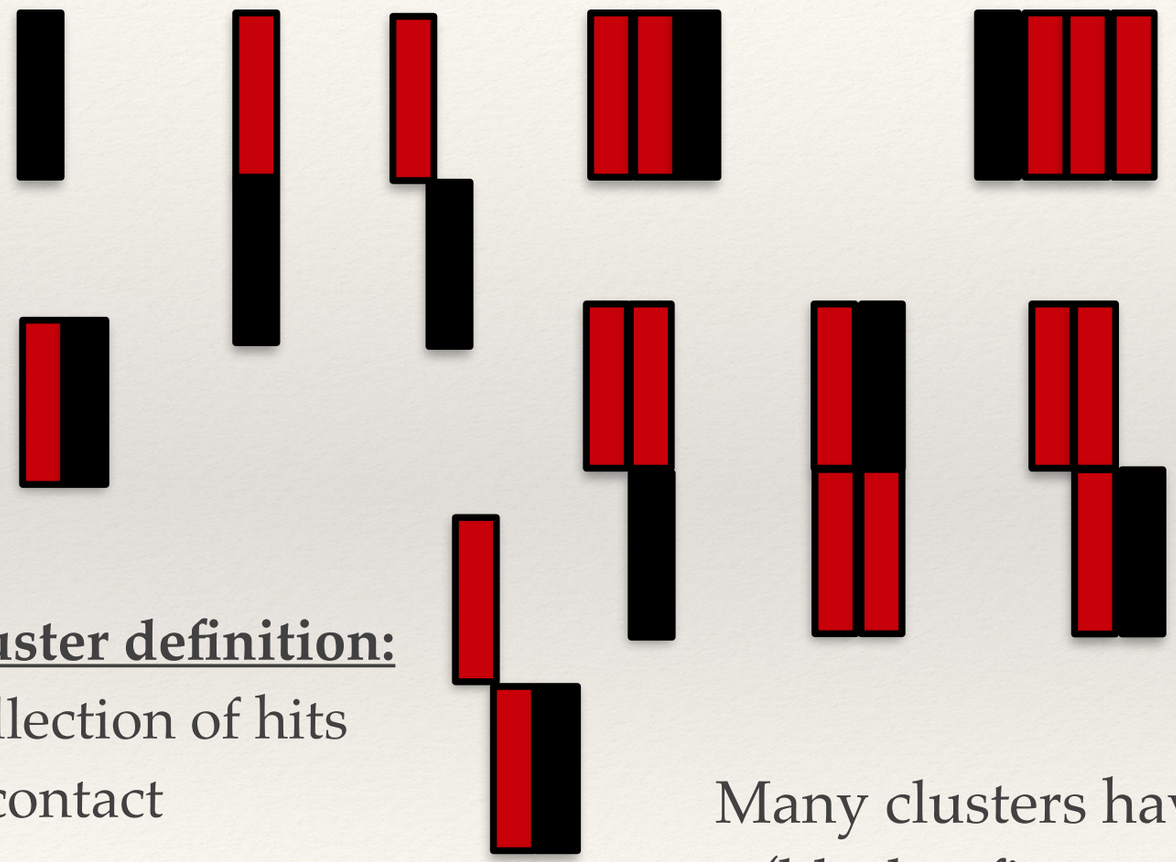
Pixel counts (hits & mips) - 20 GeV γ (B=5T)

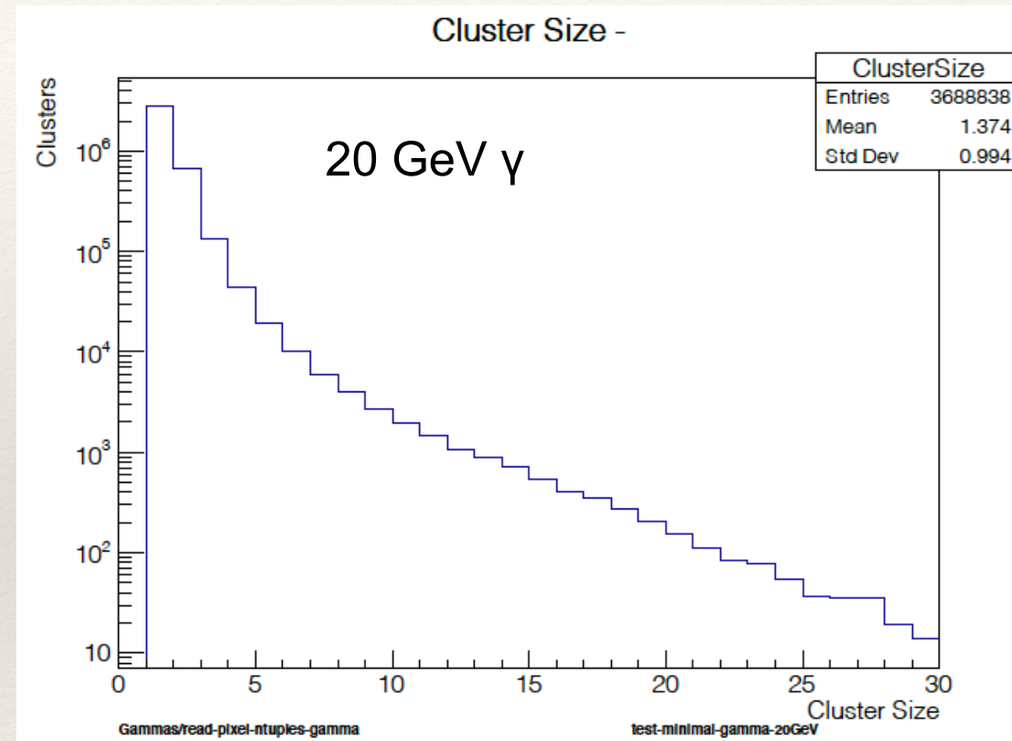




Ultimate goal is to count mips based on hit distribution.
Potential to improve resolution compared to hit count.

Hits appear in clusters (size 1, 2, 3,...)

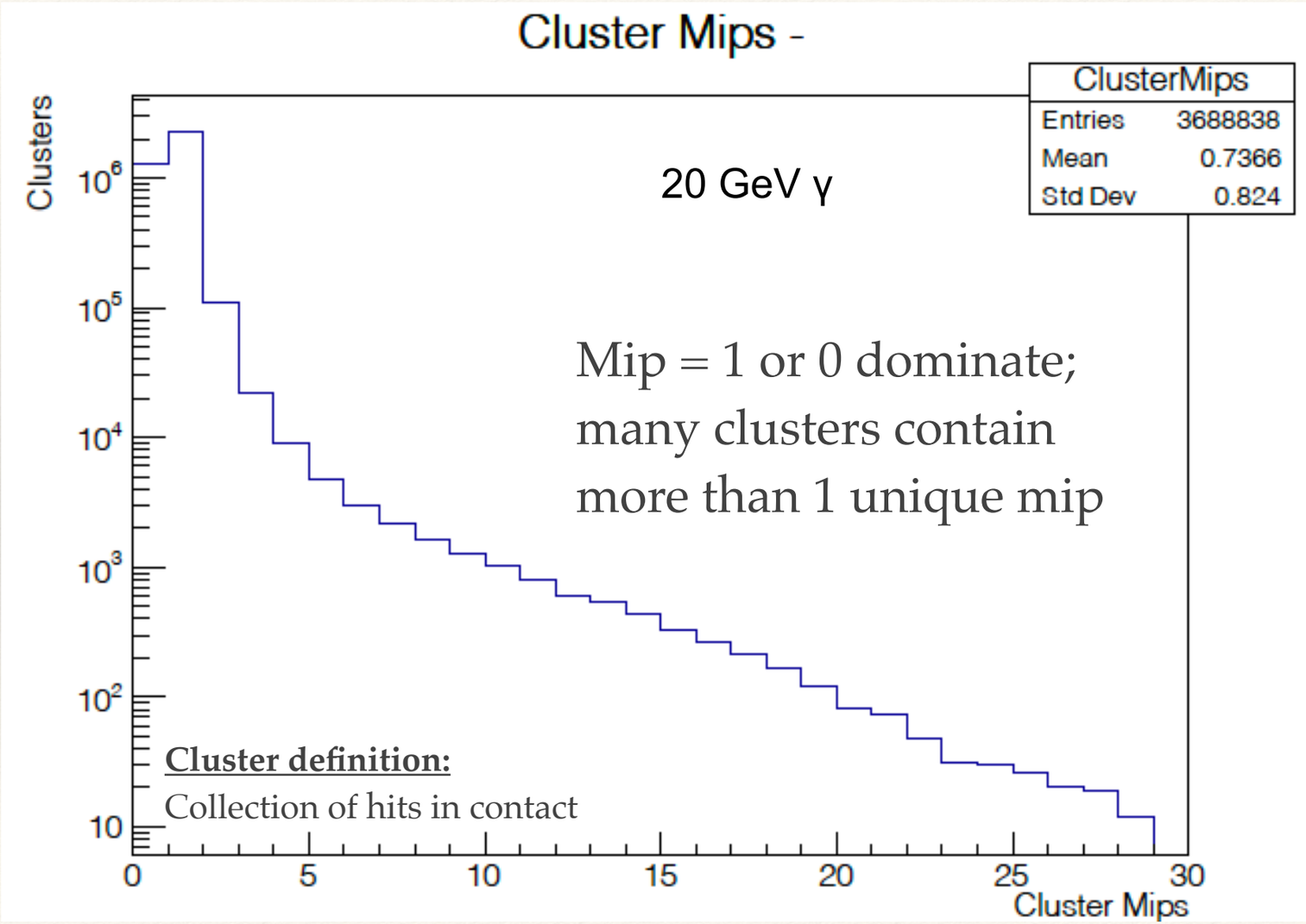


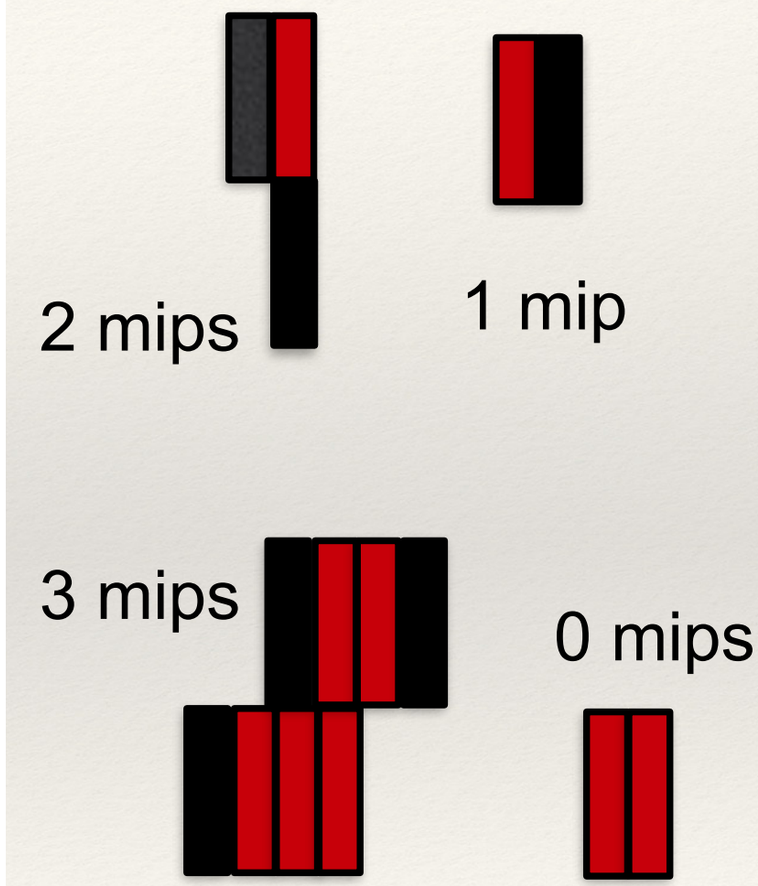


Cluster definition:
Collection of hits
in contact

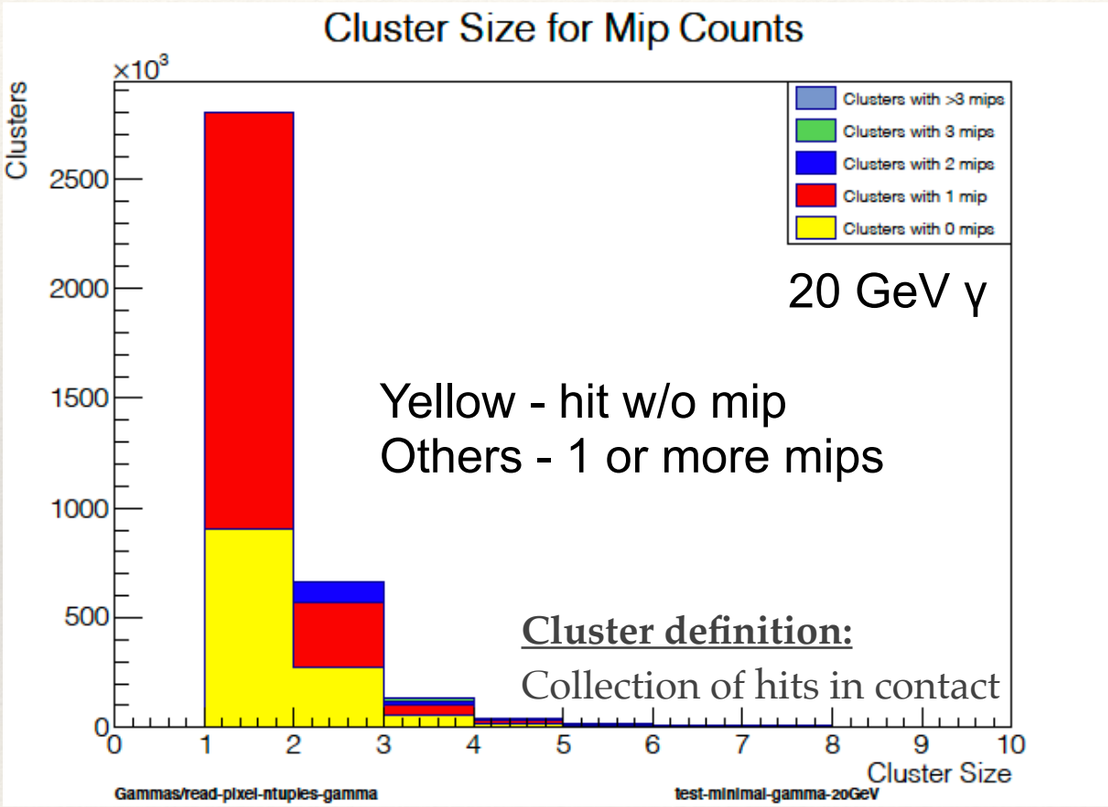
Many clusters have 1 mip
(black - first appearance of mip)

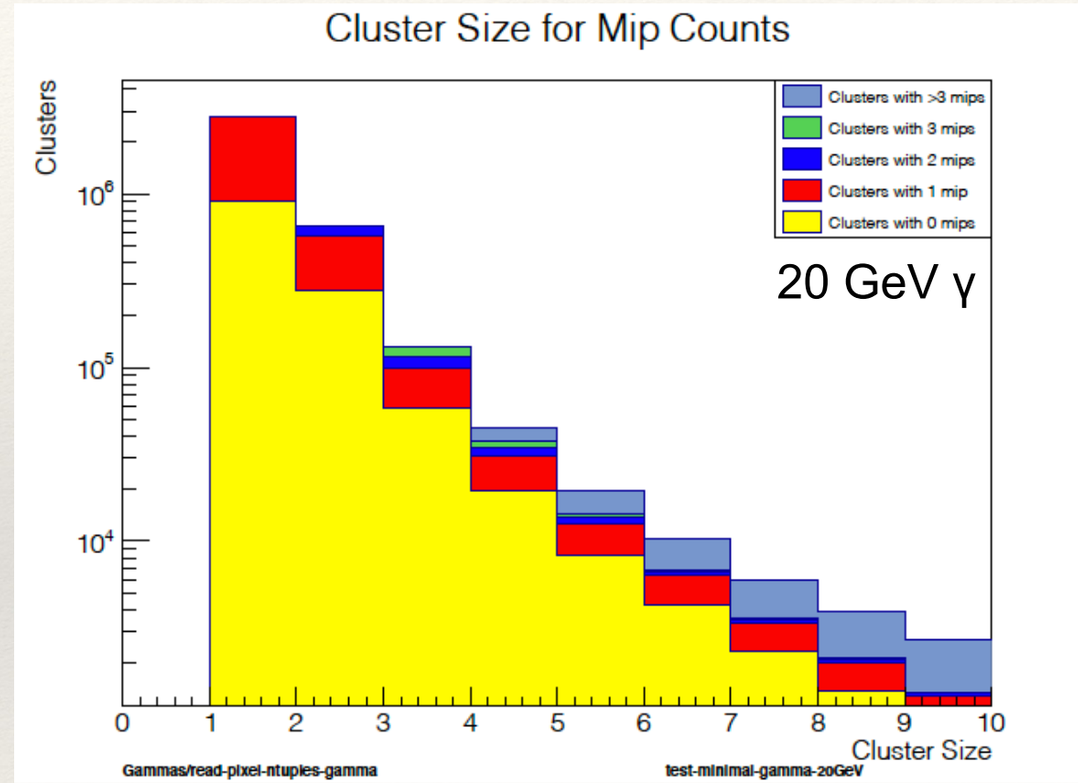
Mips per cluster





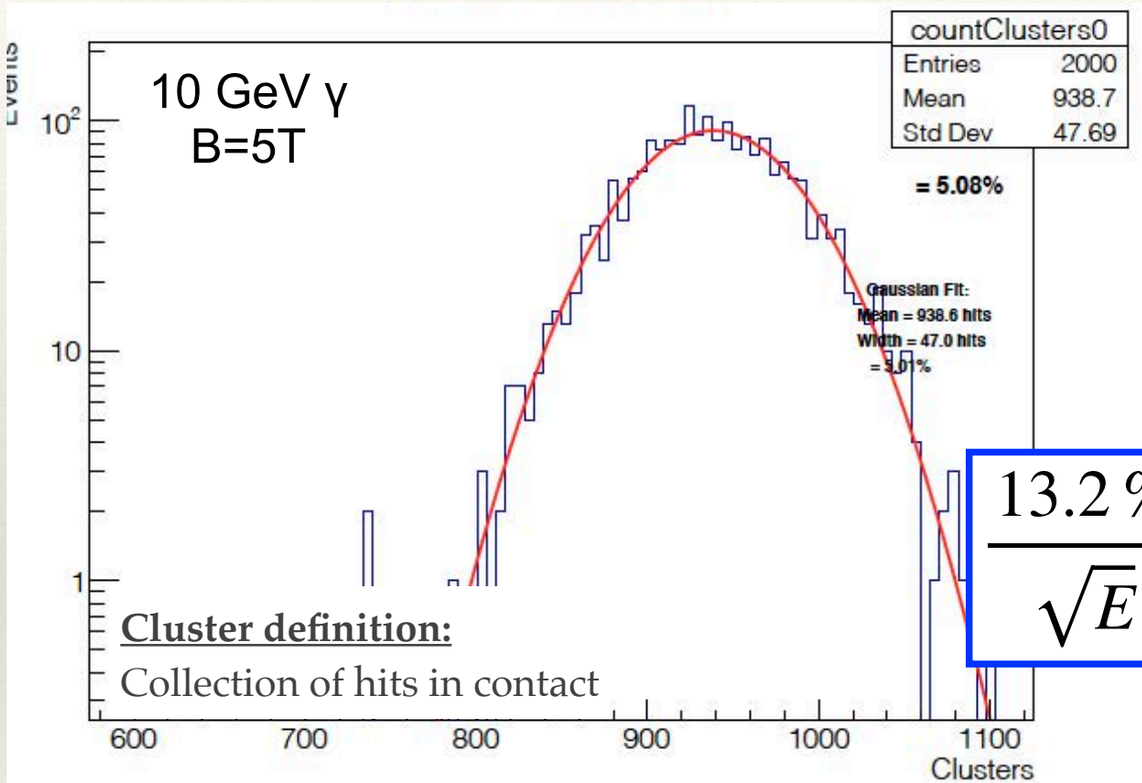
Cluster summary (20 GeV γ)

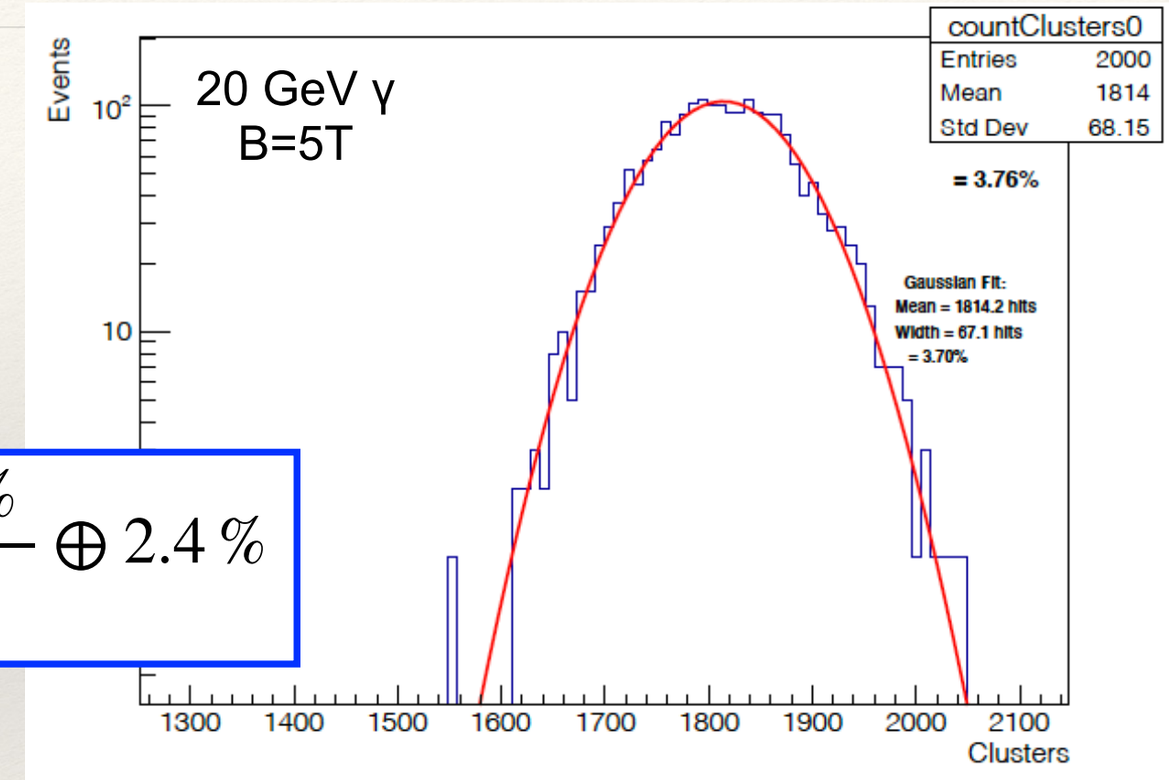




Cluster count is closer to mip count, reducing fluctuations from multiple hits.

Energy resolution from counting clusters





$$\frac{13.2\,\%}{\sqrt{E}} \oplus 2.4\,\%$$

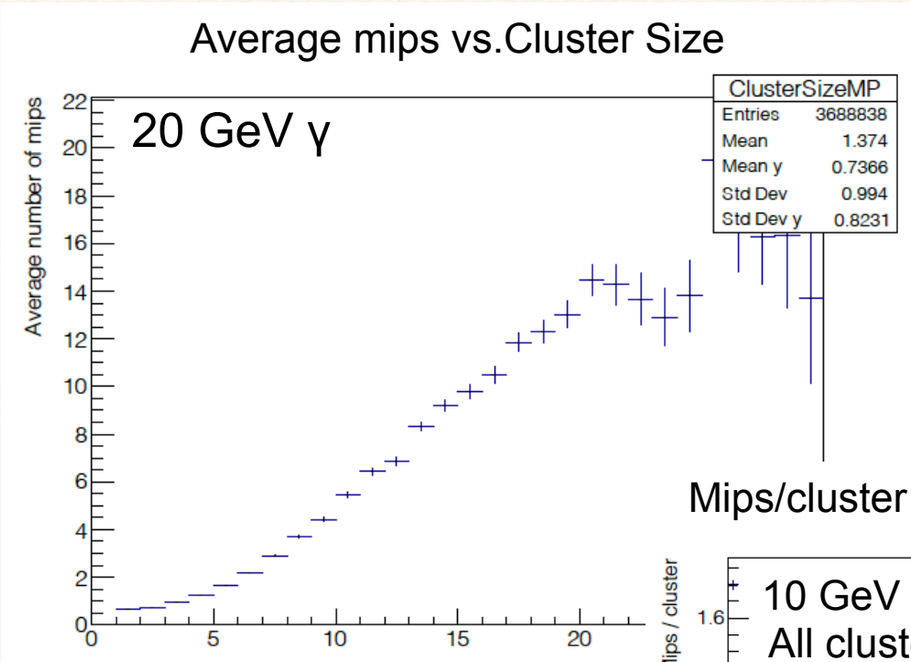
Cluster definition:
Collection of hits in contact

Improved compared to hit resolutions:

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

But, cluster properties can improve more.

Mips/cluster and shower radius dependence

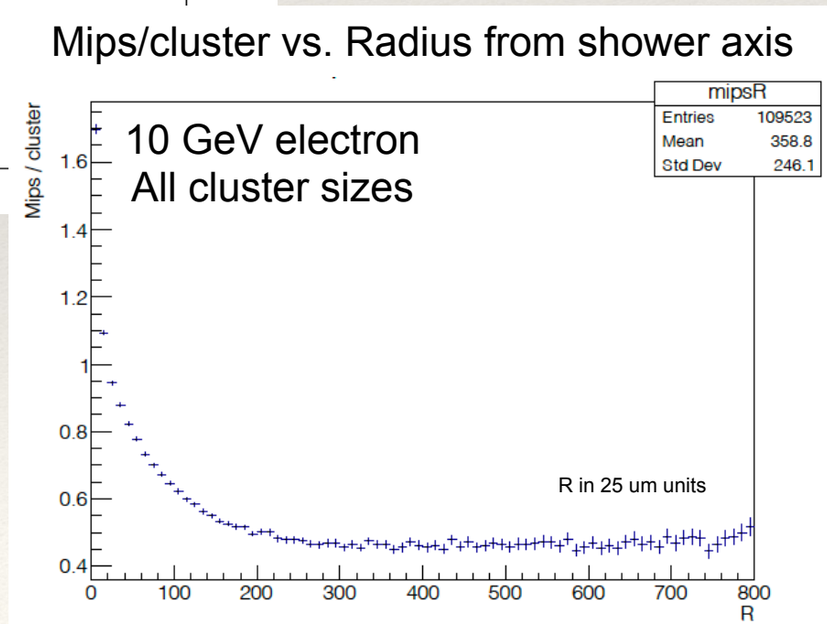


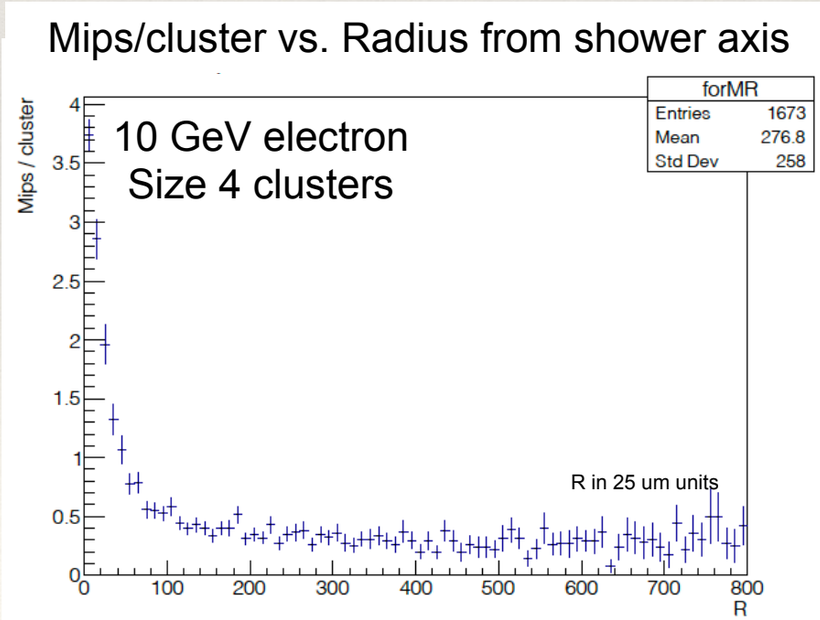
Cluster details "sense" number of mips:

Postion (radius from shower axis);

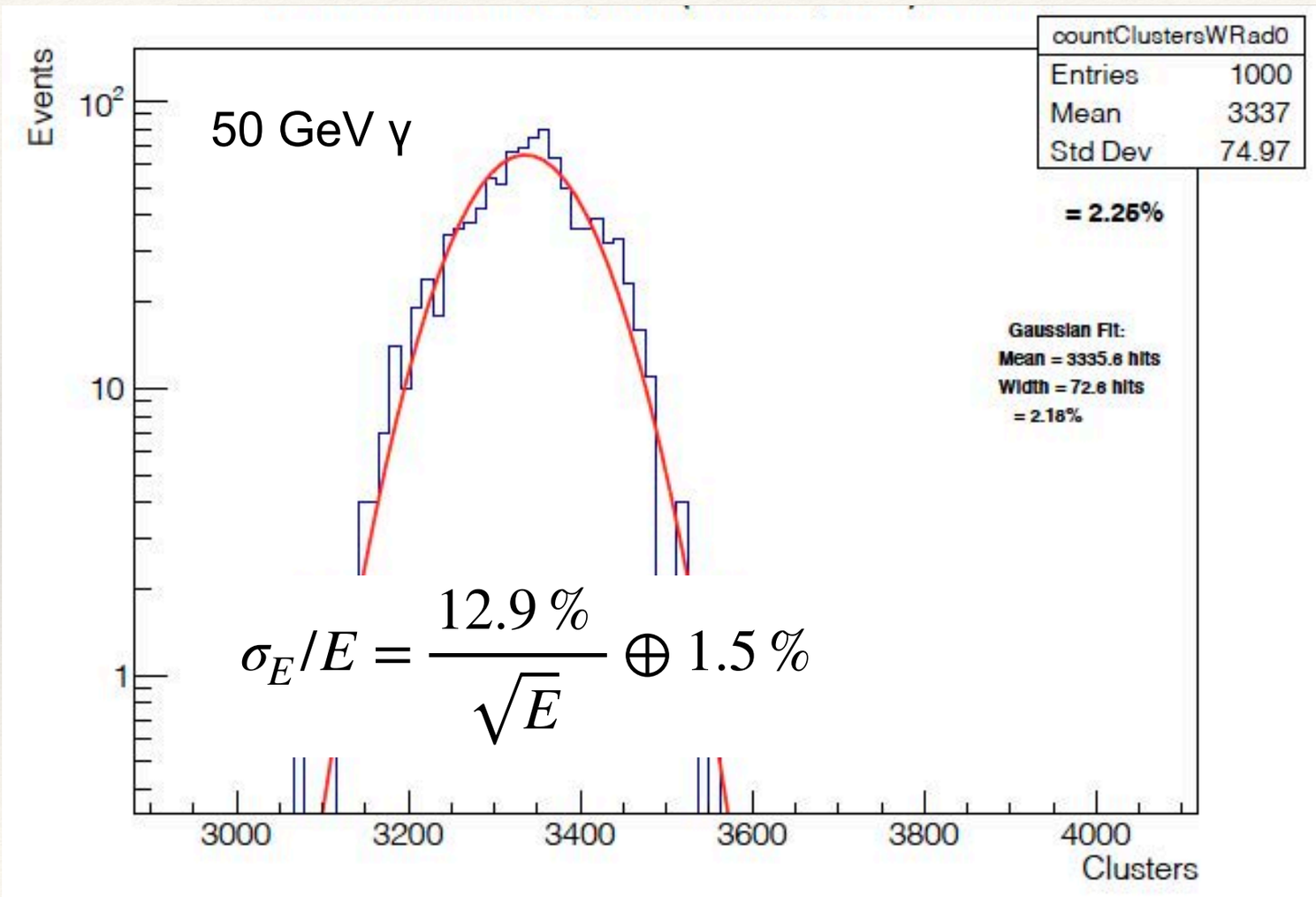
Cluster size.

Analysis using these parameters improves cluster resolution in our studies.





Clusters weighted by radius & size

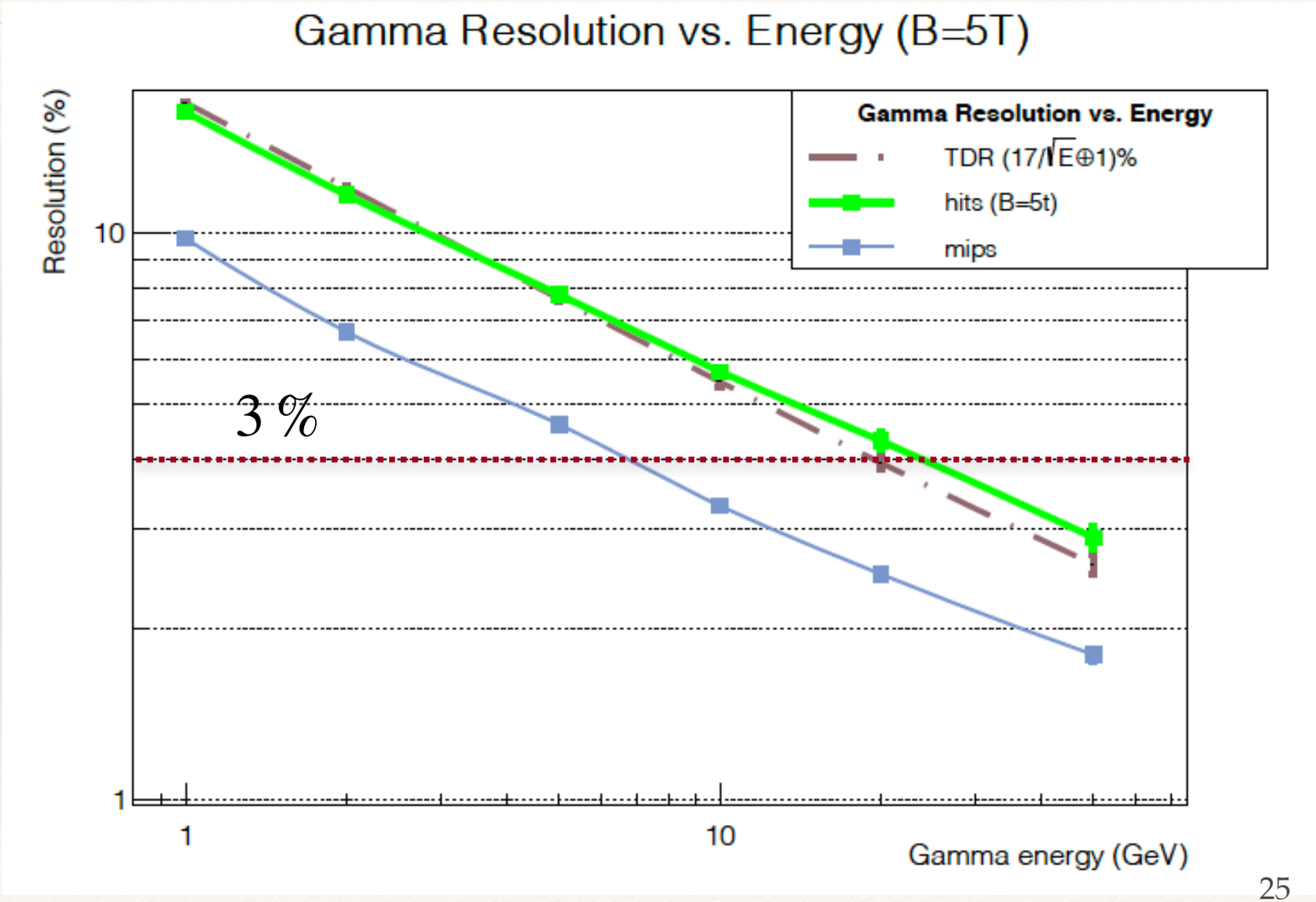


$$\sigma_E/E = \frac{12.9\,\%}{\sqrt{E}} \oplus 1.5\,\%$$

When cluster properties are taken into account with weighting, performance improves.

Resolution vs. Energy (hits/clusters/mips)

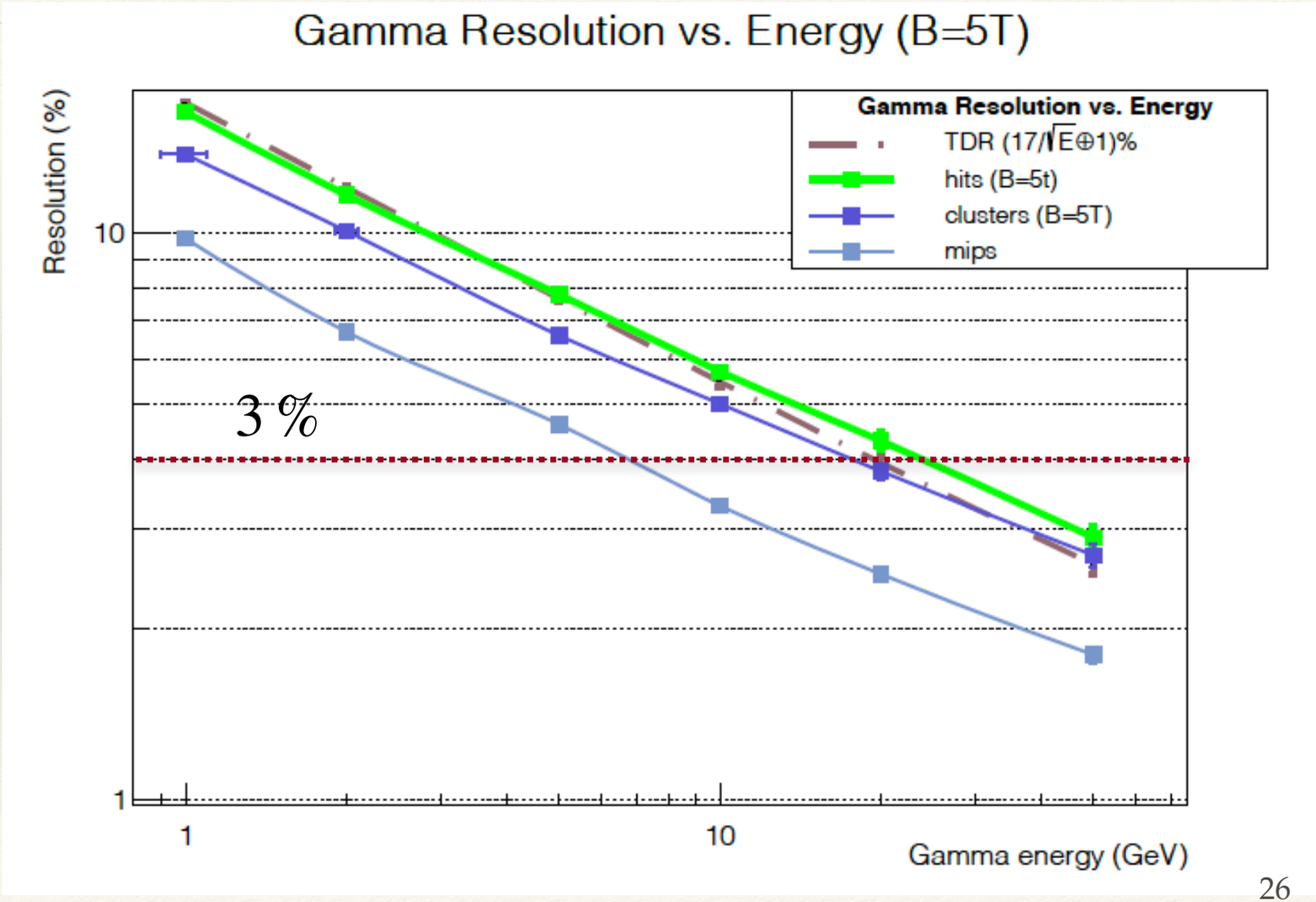
Resolution vs. Energy (hits and mips)



Resolution vs. Energy (hits/clusters/mips)

Resolution vs. Energy (hits/clusters/mips)

Simple cluster performance is better than hit counting.

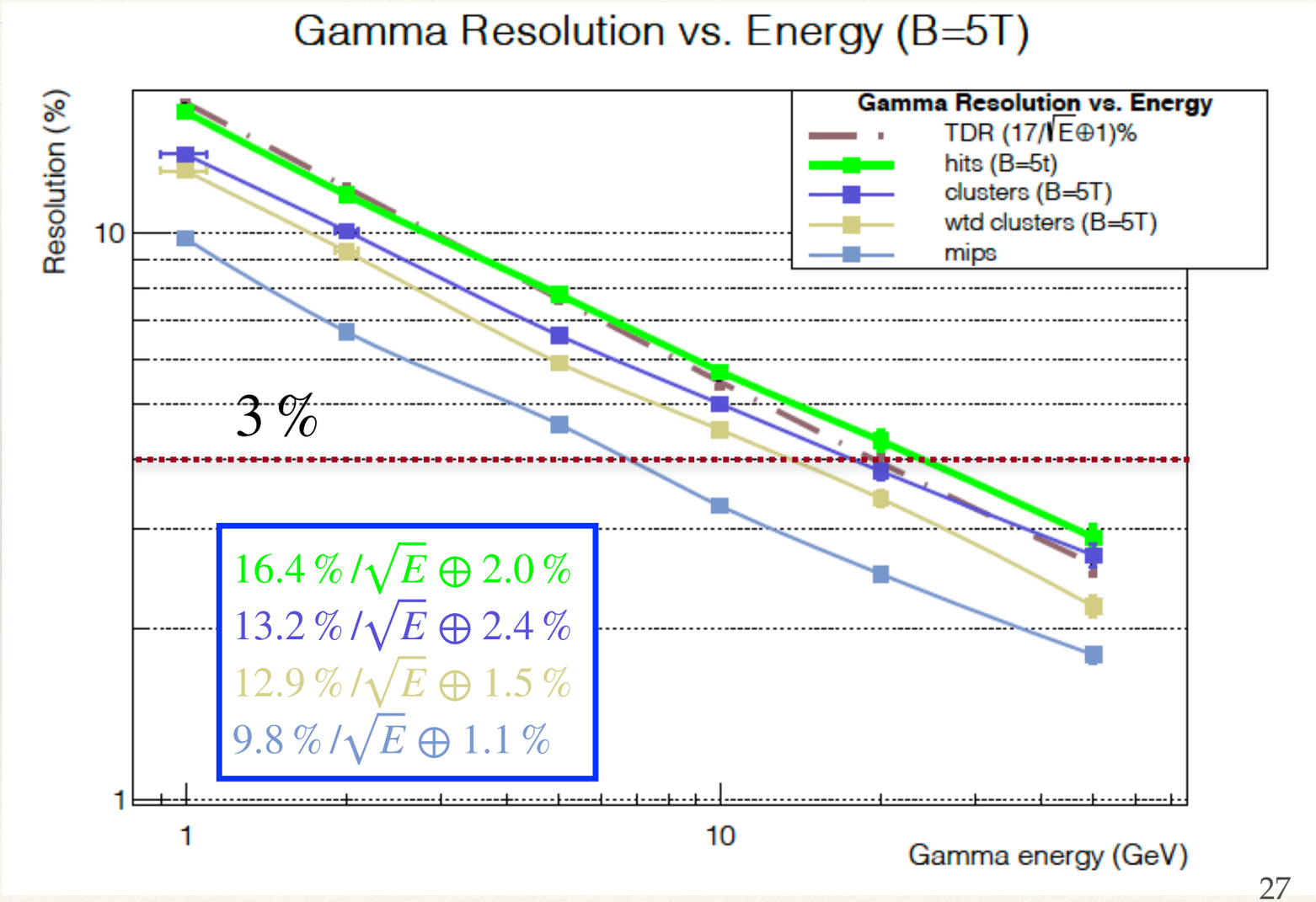


Resolution vs. Energy (hits/clusters/mips)

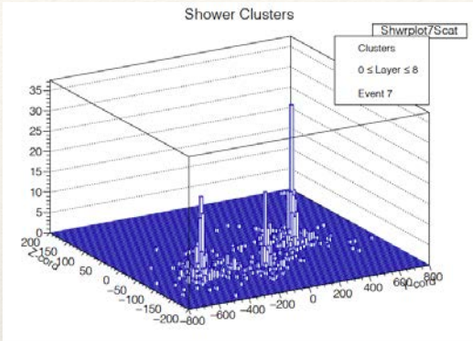
Resolution vs. Energy (hits/clusters/mips) & weighted clusters.

Simple cluster performance is better than hit counting.

When cluster properties are taken into account with weighting, performance improves.



Other performance offered by MAPS and demonstrated in Geant4 studies



- Precise location of EM showers
- Multiple shower separation.
  - Two nearby showers - excellent separation to few mm.
  - Multiple nearby showers or showers/tracks
    - excellent counting and measurement.
- Pi0 reconstruction in busy environment.

MAPS for SiD Tracking

- Size similar to that described for SiD in the ILC TDR, 10×10 cm^2 devices. Constructed by stitching 2 cm x 2 cm reticles.
- Exceptional granularity of 25 μm by 100 μm pixels, with 25μm in bend direction resolution of 25μm/√12 ≈ 7 μm without charge sharing.
- The 25μm pixel matches KPiX-readout, silicon-strip width of the SiD TDR design recently assembled, tested, and shown to achieve 7μm resolution†.
- The depleted 10μm thick epi layer charge collection of the MAPS allows a minimum threshold of 1/4 MIP, ensuring high efficiency.
- The pixel nature provides vastly improved pattern recognition for track finding over the strip devices.
- For the endcaps, such a sensor would eliminate the need for two sensors in a small-angle-stereo configuration, reducing both the material budget and cost.

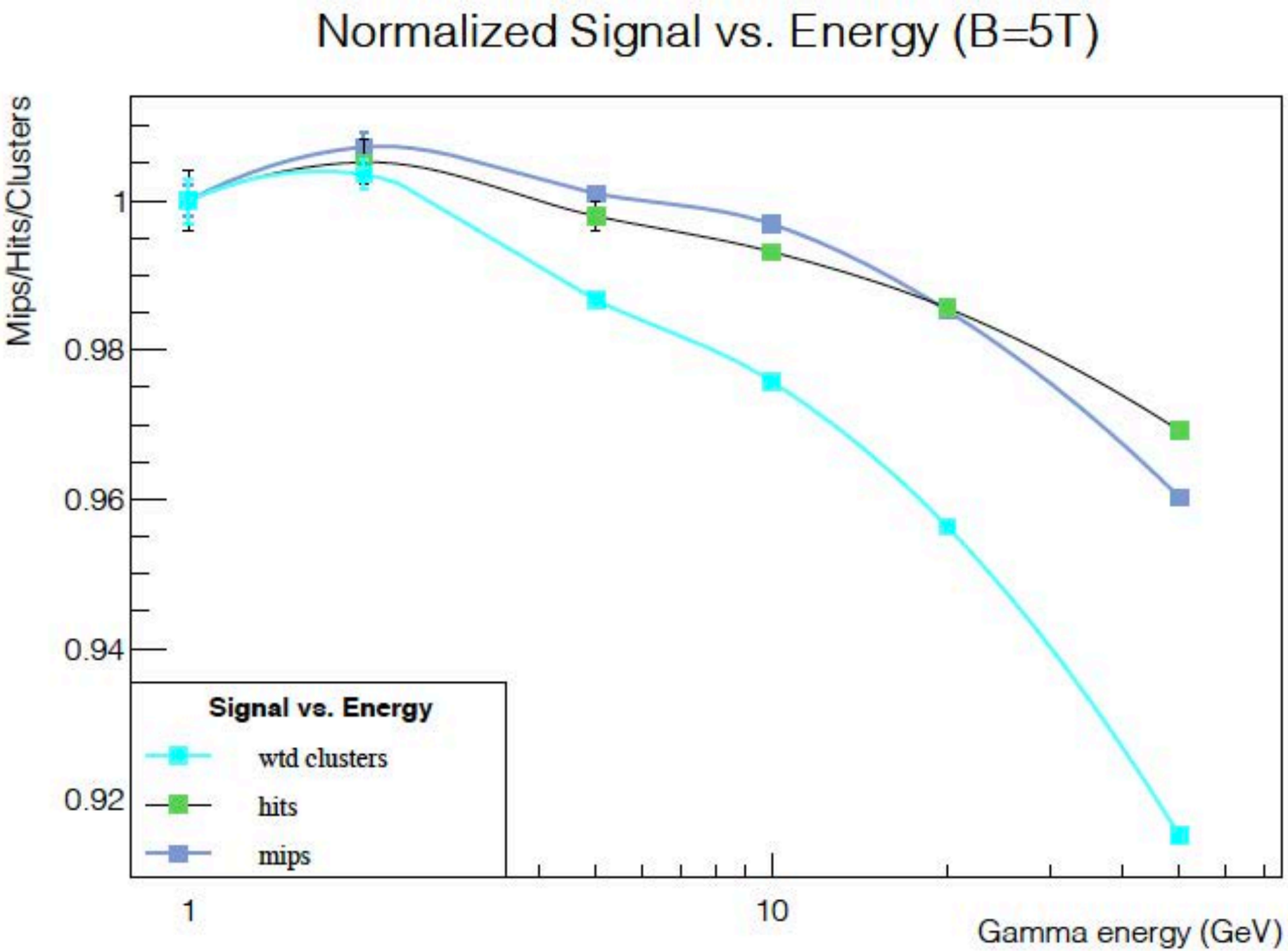
† J. Brau et al., "Lycoris – a large-area, high resolution beam telescope," 2021 JINST 16 P10023, arXiv:2012.11495 [physics.ins-det]

Ongoing effort
Sensor development and shower analysis

- Sensor development progressing.
  - Anticipating first small-scale devices later in 2022.
- Shower performance studies advancing:
  - Various cluster features "sense" mip count in "large" clusters.
  - Cluster features improve performance:
    - Based on radial position in shower;
    - Based on longitudinal position in shower;
    - Based on shape of cluster.
  - Simulated energy resolution exceeds TDR performance.

Reference: arXiv:2203.07626 [physics.ins-det]

Extra


Normalized Signal vs. Energy (B=5T)
Mips/Hits/Clusters
1
0.98
0.96
0.94
0.92
Signal vs. Energy
wtd clusters
hits
mips
1
10
Gamma energy (GeV)