



June 22, 2022 - UO Quarknet

The SiD Digital ECal Based on Monolithic Active Pixel Sensors

Jim Brau,
University of
Oregon

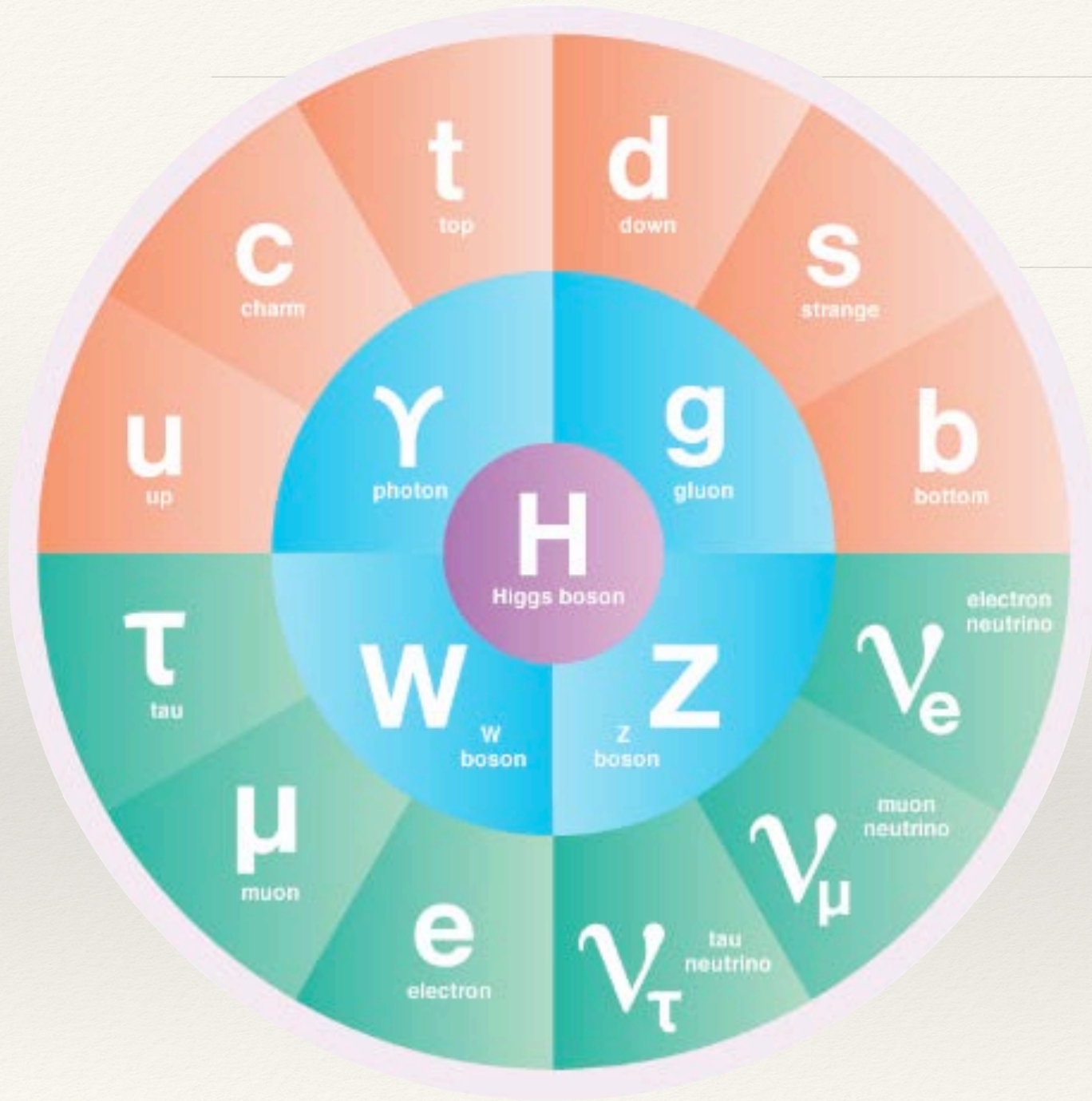
A New Technology for HEP Detectors



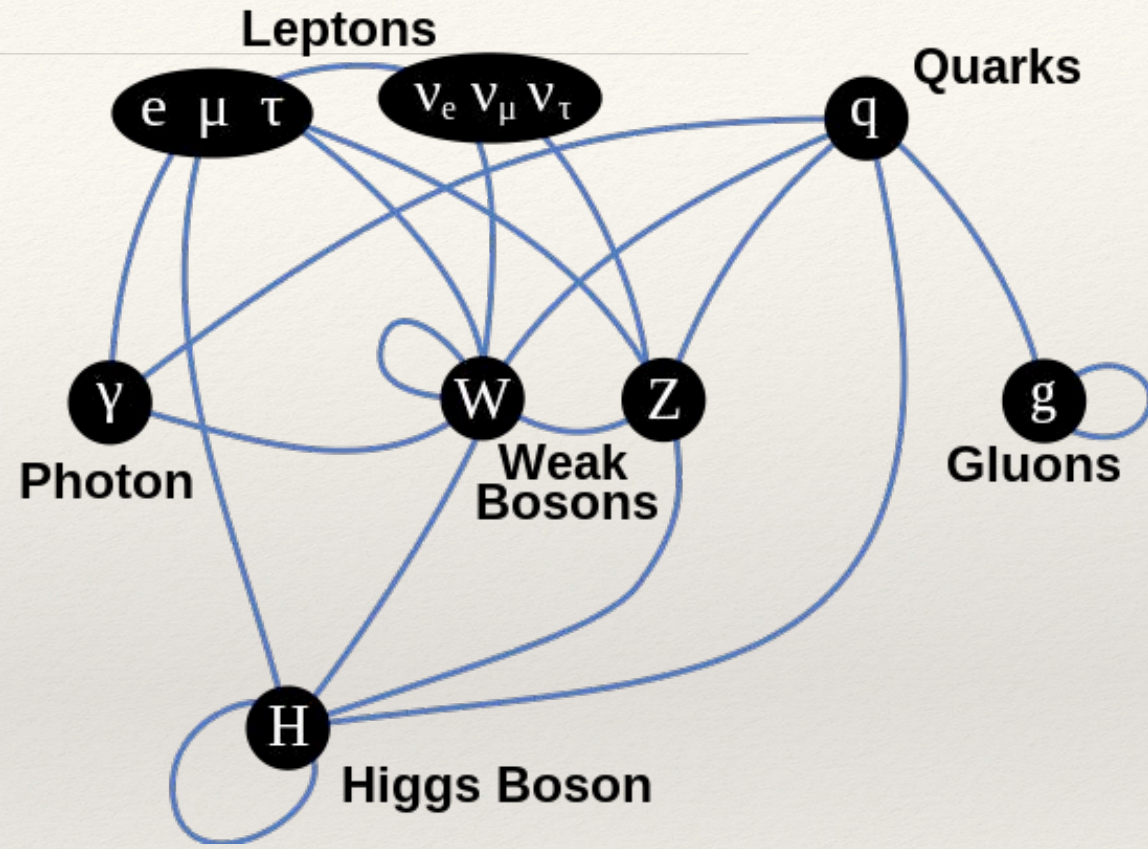
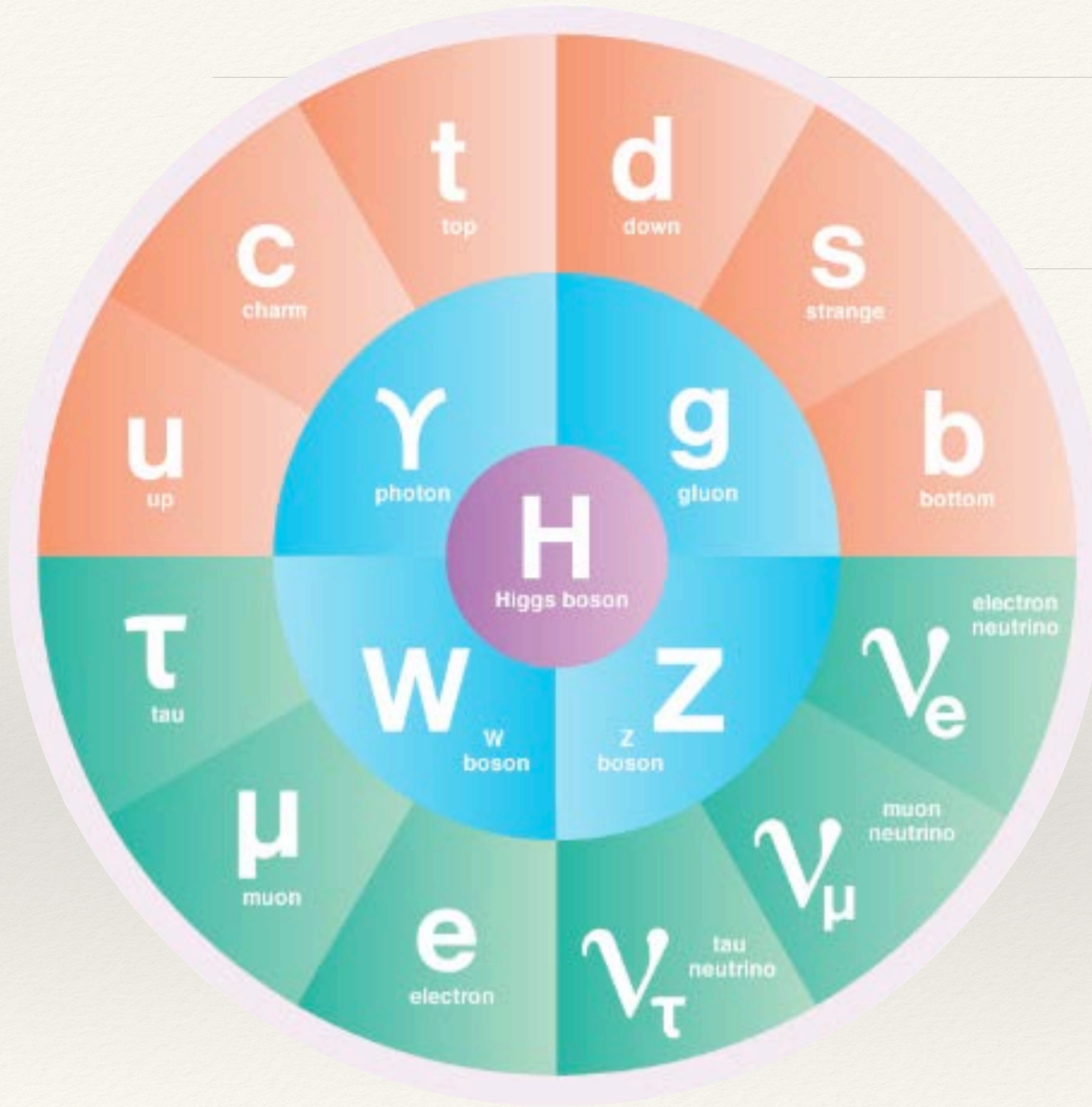
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OREGON

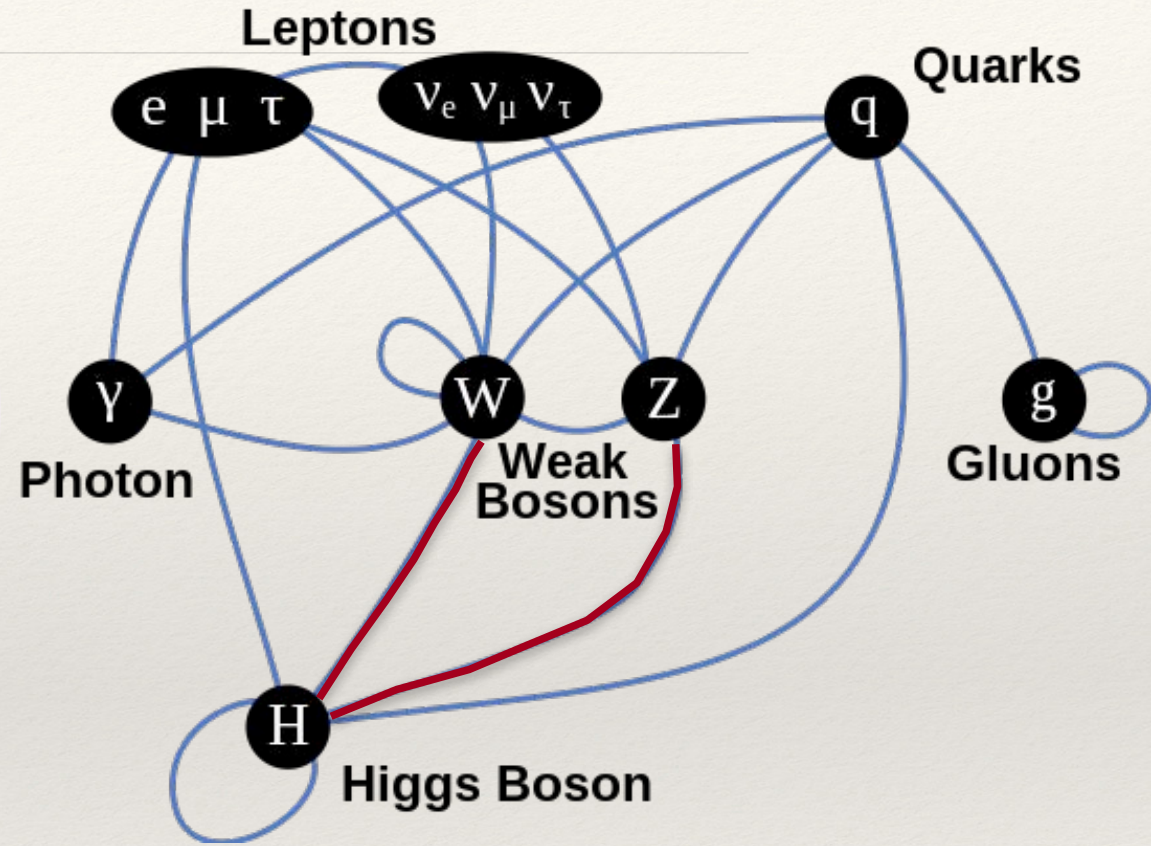
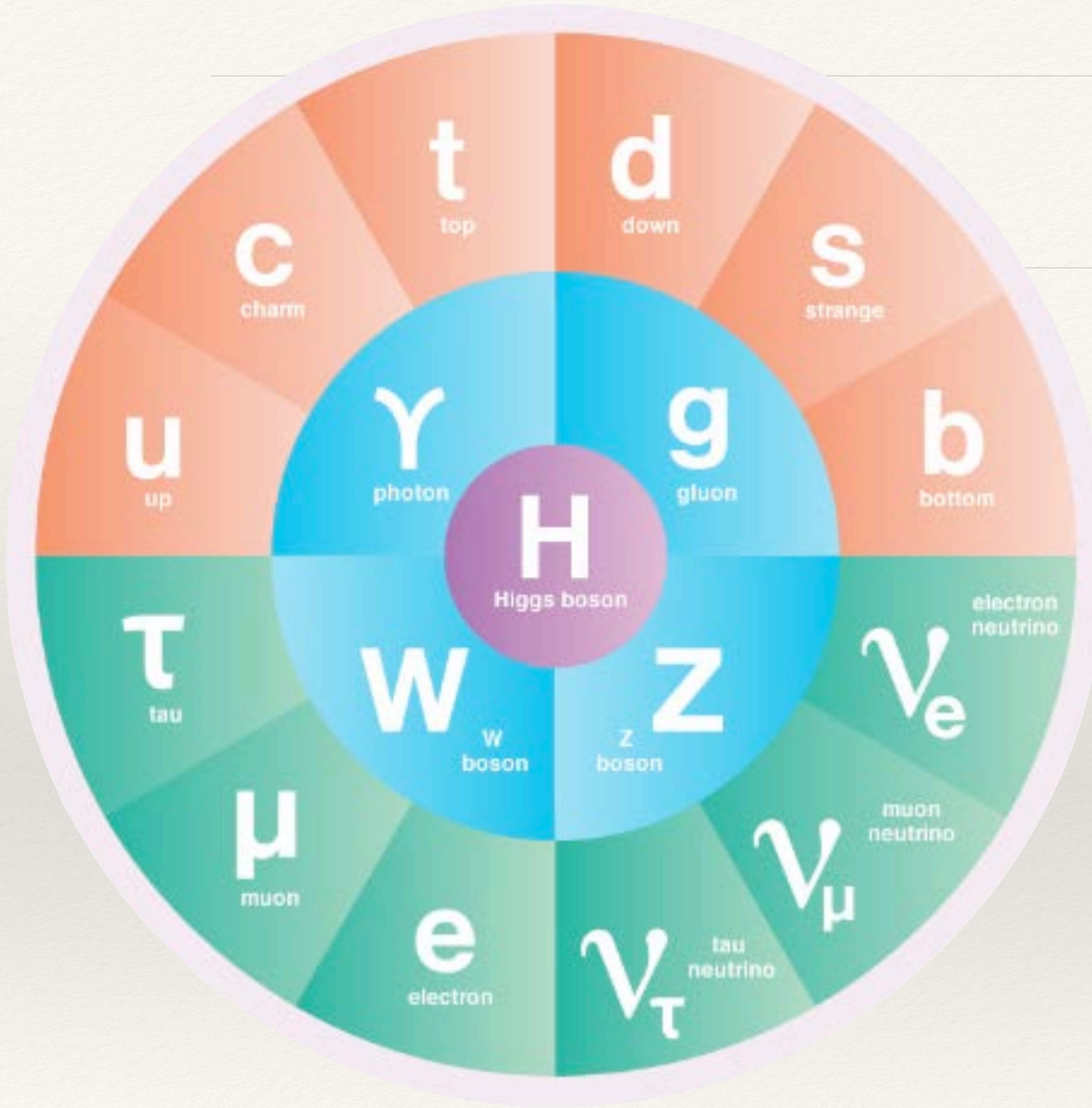
Research partially supported
by the U.S. Department of Energy

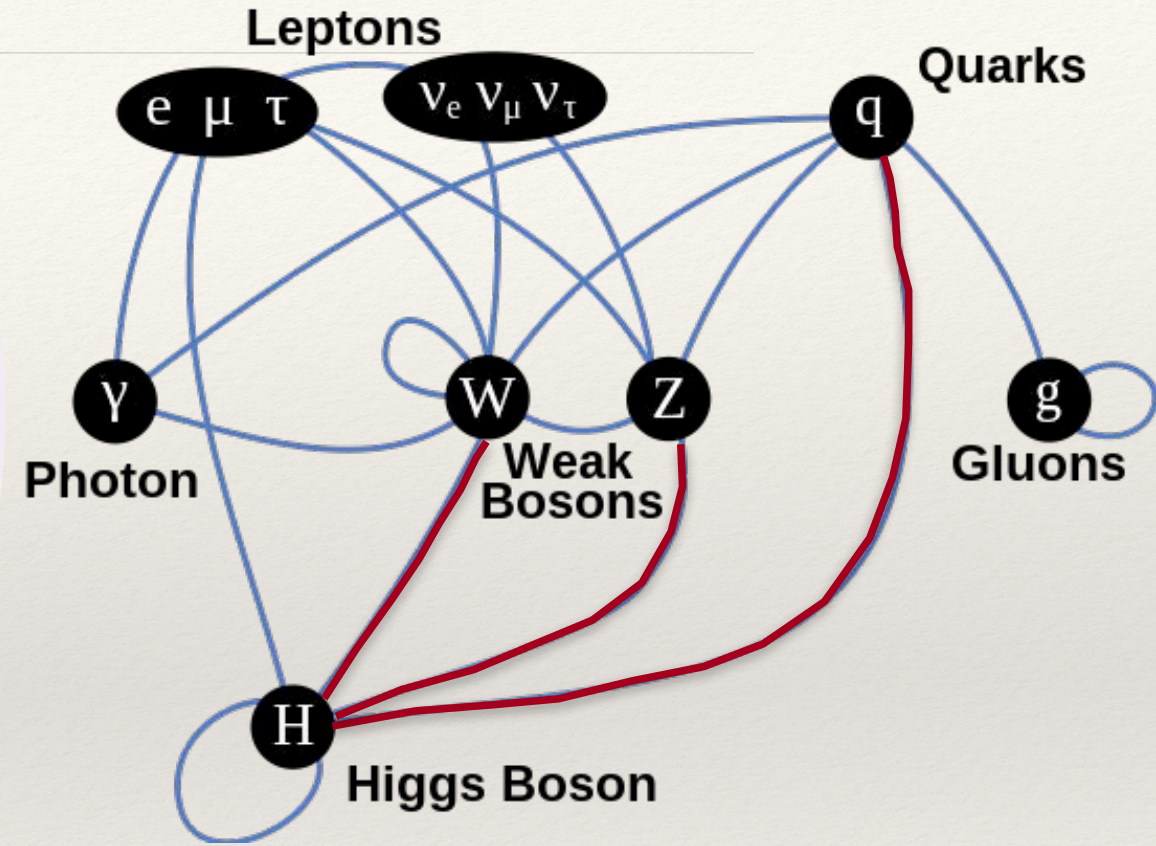
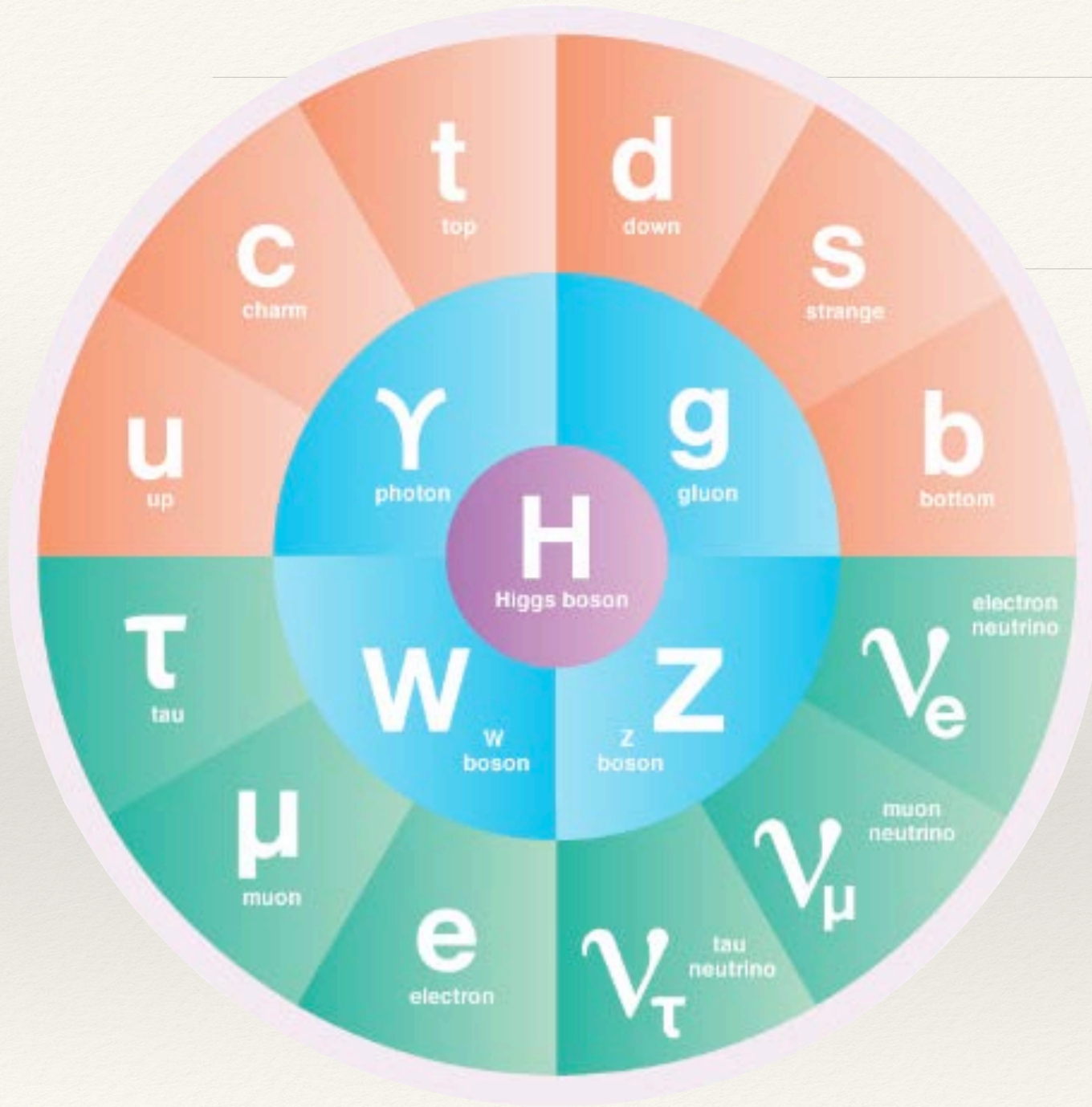
Reference: [arXiv:2203.07626](https://arxiv.org/abs/2203.07626) [physics.ins-det]

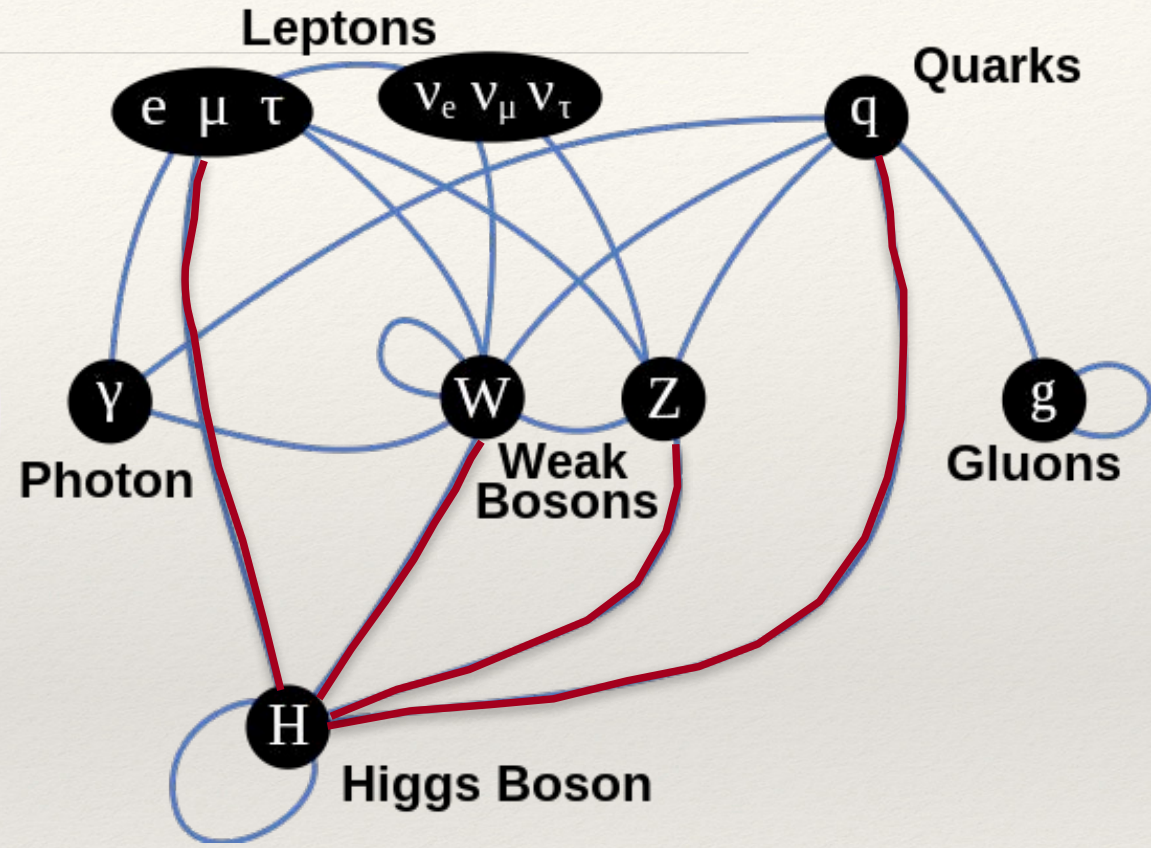
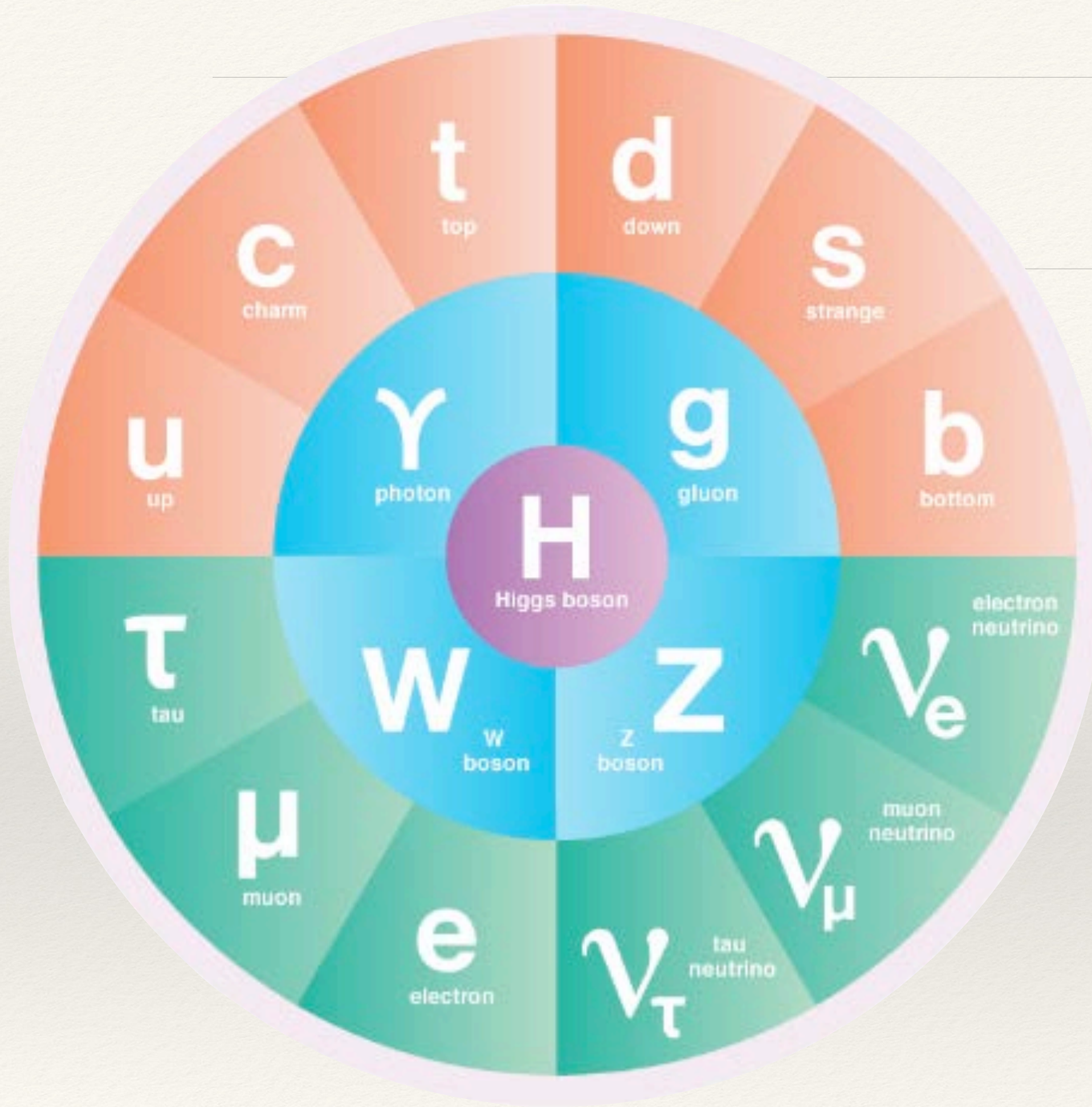


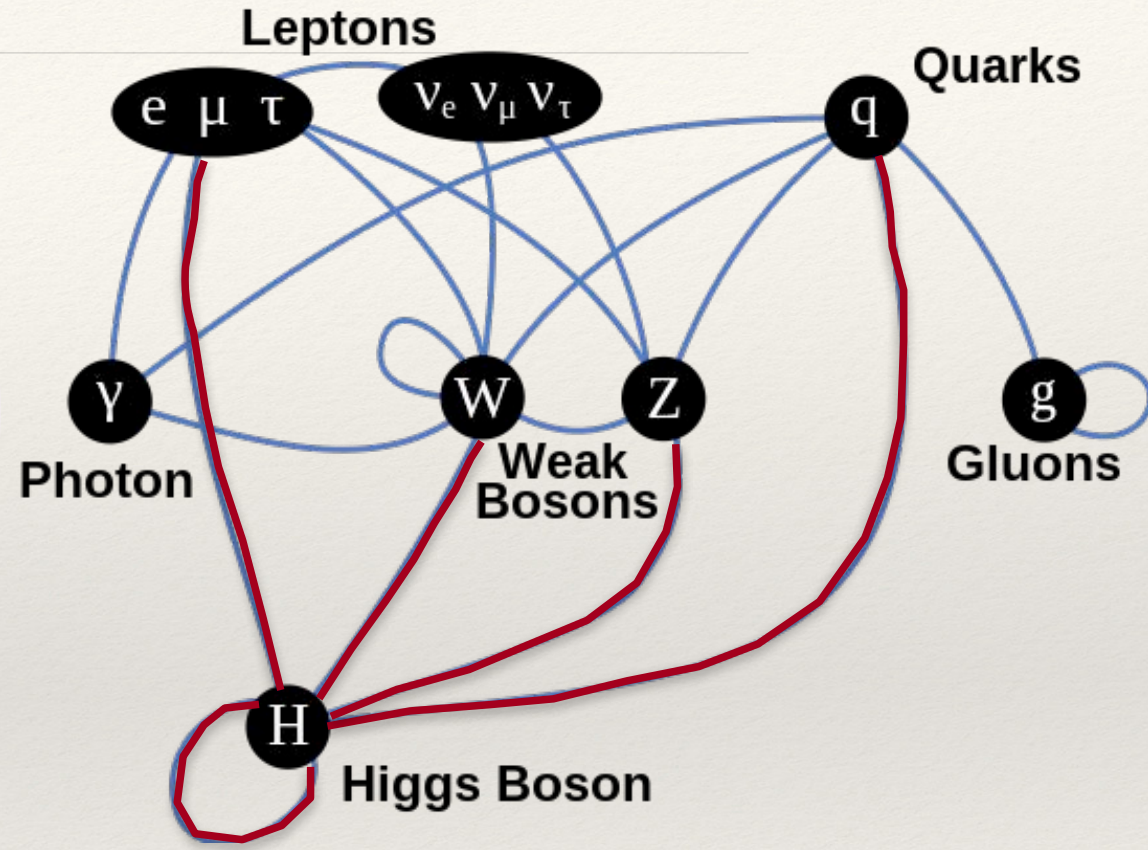
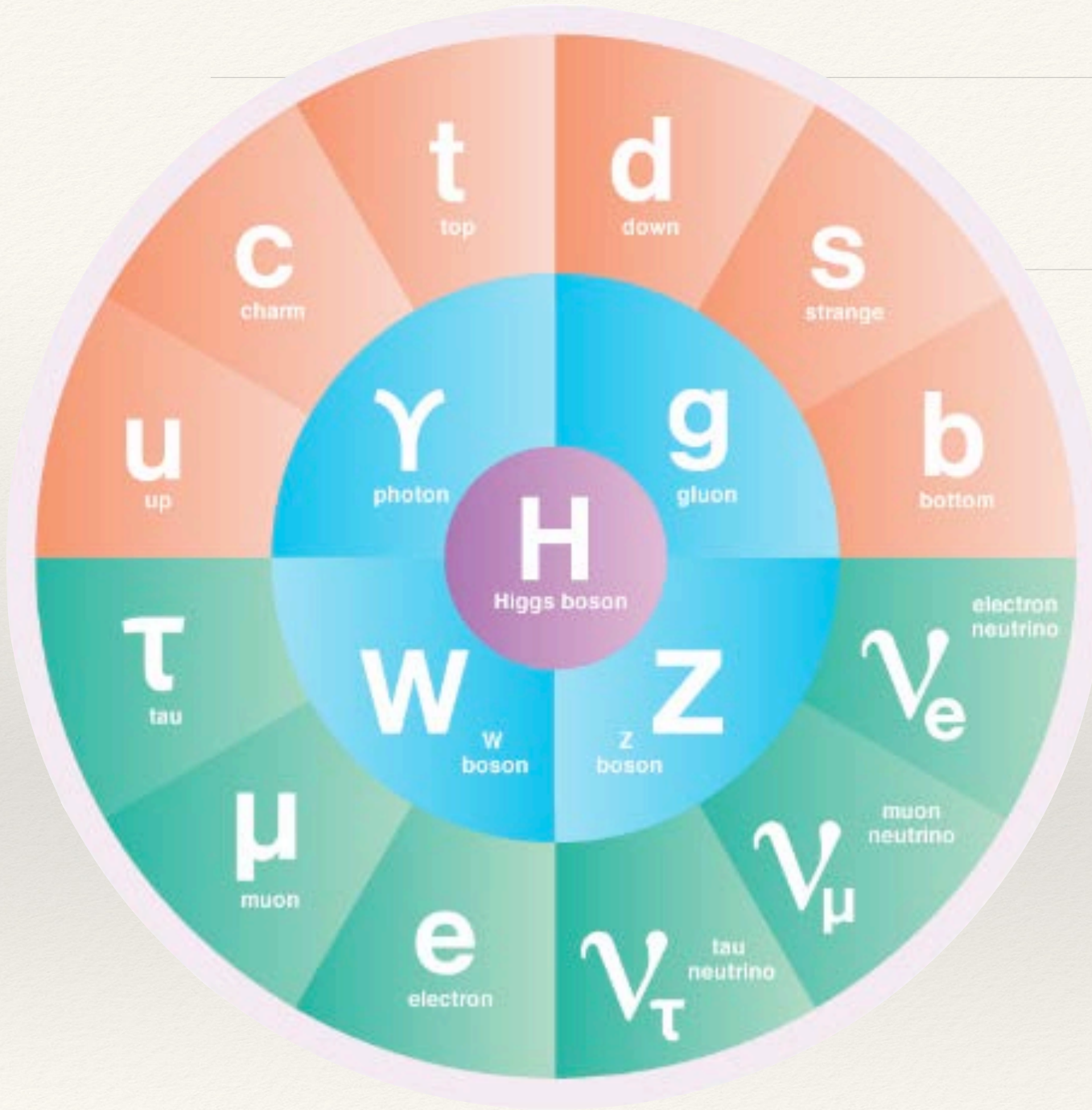
● QUARKS ● LEPTONS ● BOSONS ● HIGGS BOSON

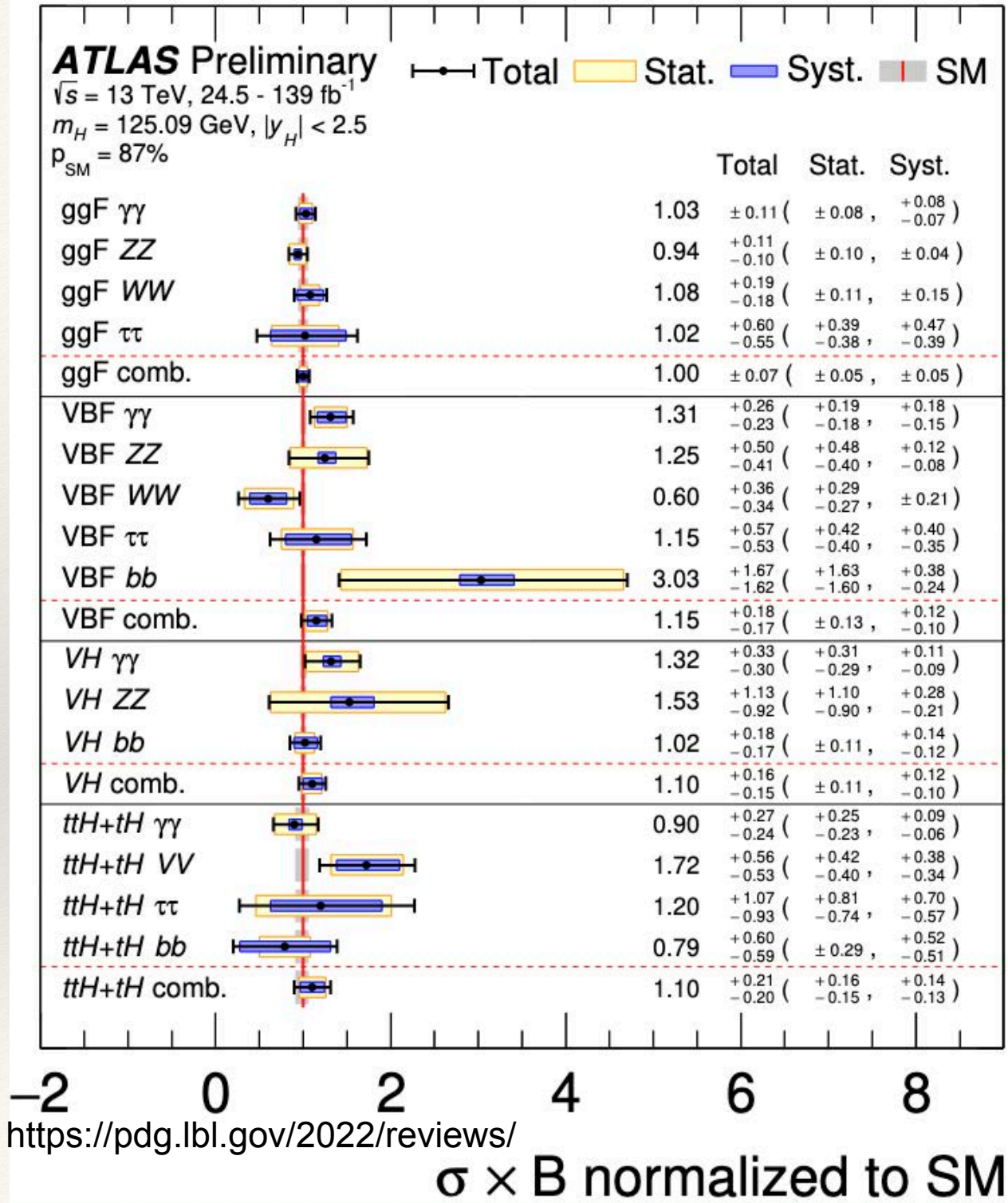










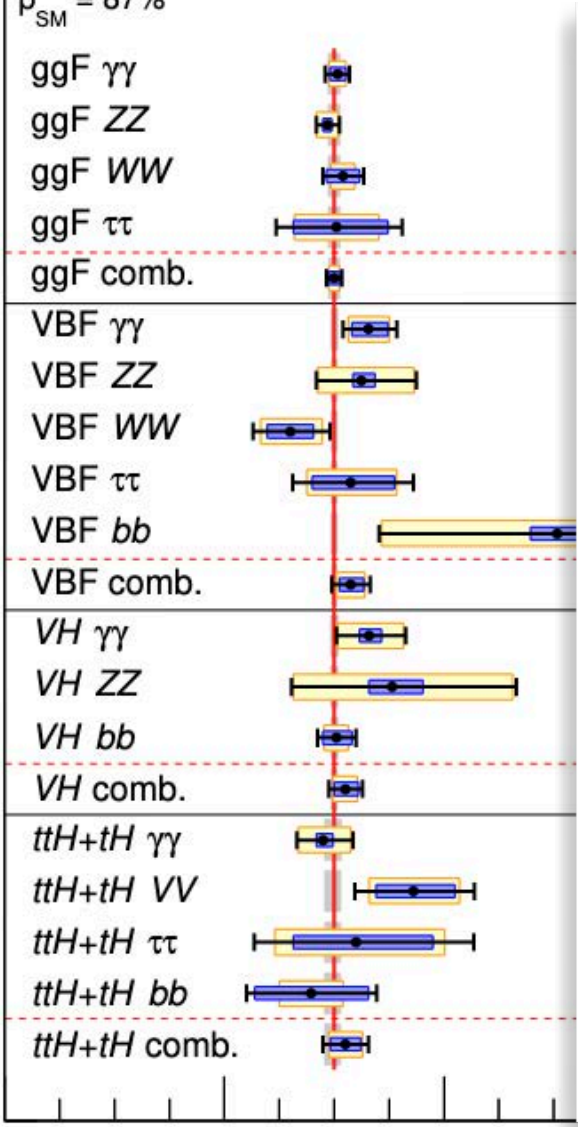


<https://pdg.lbl.gov/2022/reviews/>

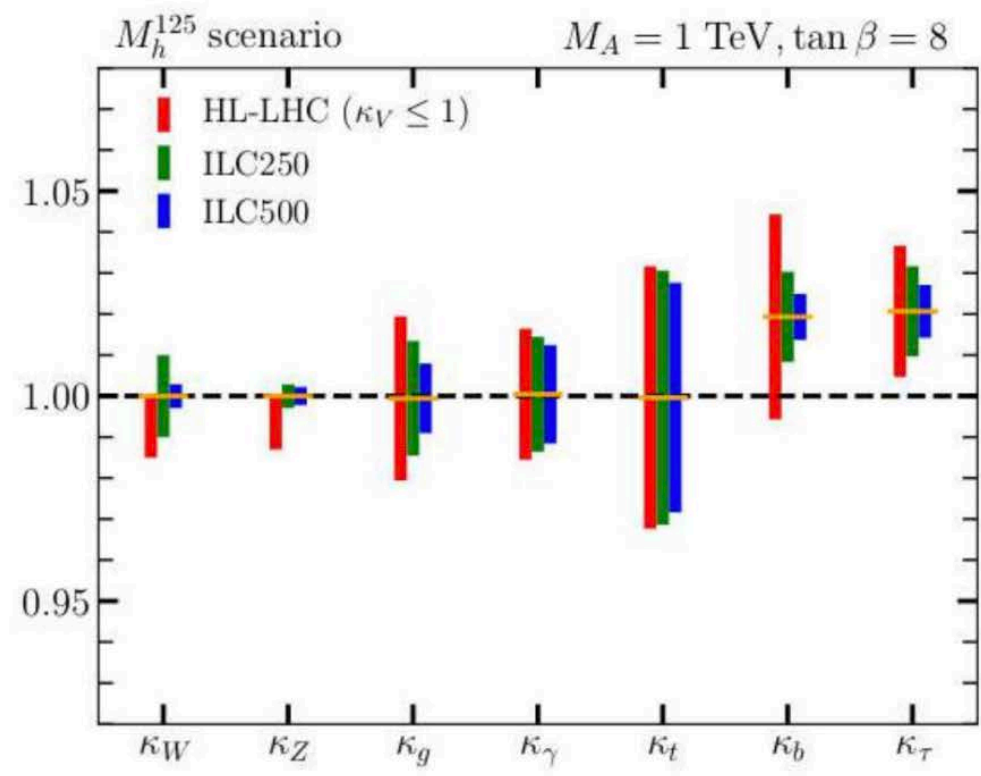


ATLAS Preliminary $\sqrt{s} = 13 \text{ TeV}, 24.5 - 139 \text{ fb}^{-1}$
 $m_H = 125.09 \text{ GeV}, |y_H| < 2.5$
 $p_{\text{SM}} = 87\%$

—•— Total Stat. Syst. SM



⇒ couplings to bosons in the **per mille** range
 ⇒ couplings to fermions in the **per cent** range



Composite Higgs example:

$$\kappa_V \approx 1 - 3\% \left(\frac{1 \text{ TeV}}{f} \right)^2$$

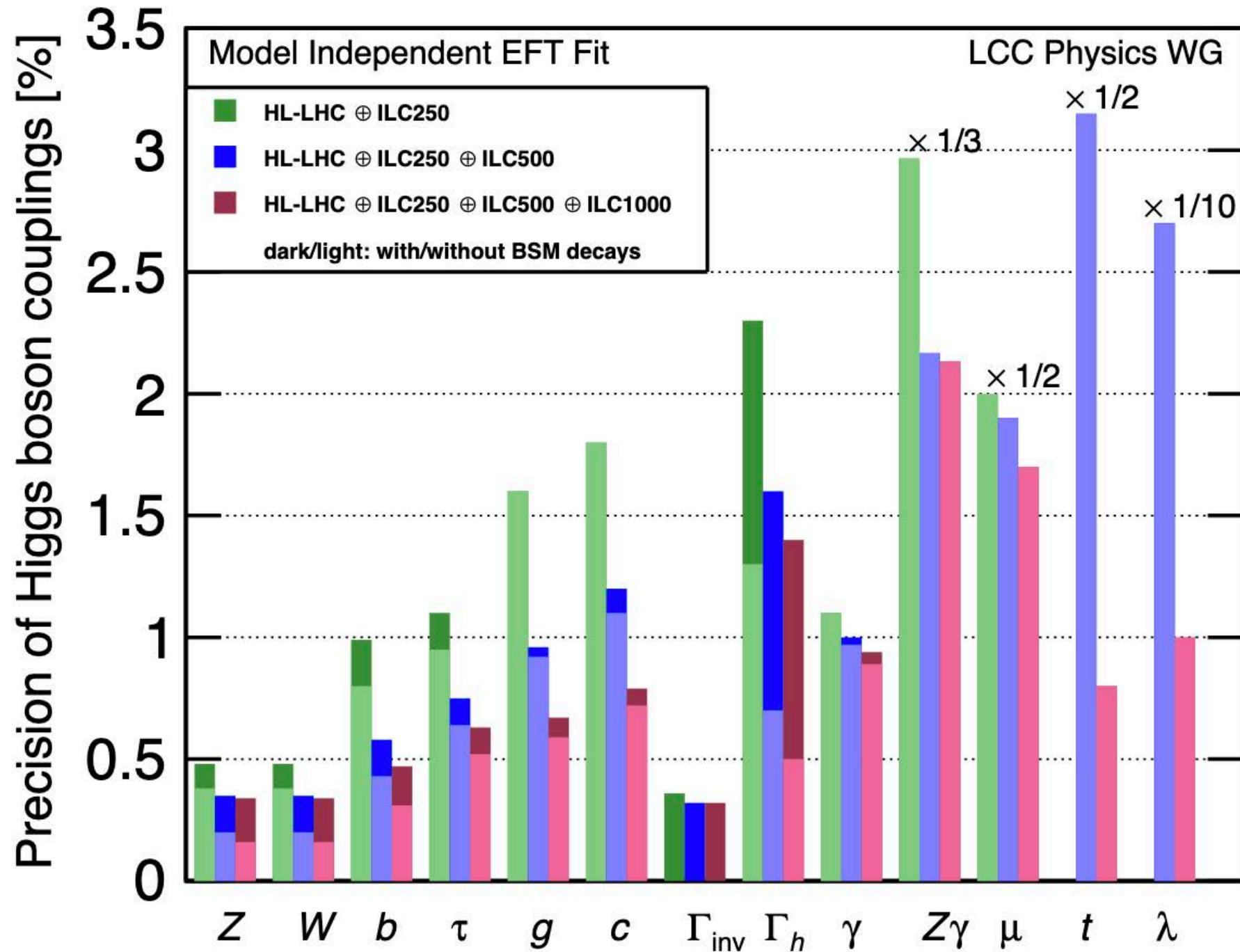
$$\kappa_F \approx 1 - (3 - 9)\% \left(\frac{1 \text{ TeV}}{f} \right)^2$$

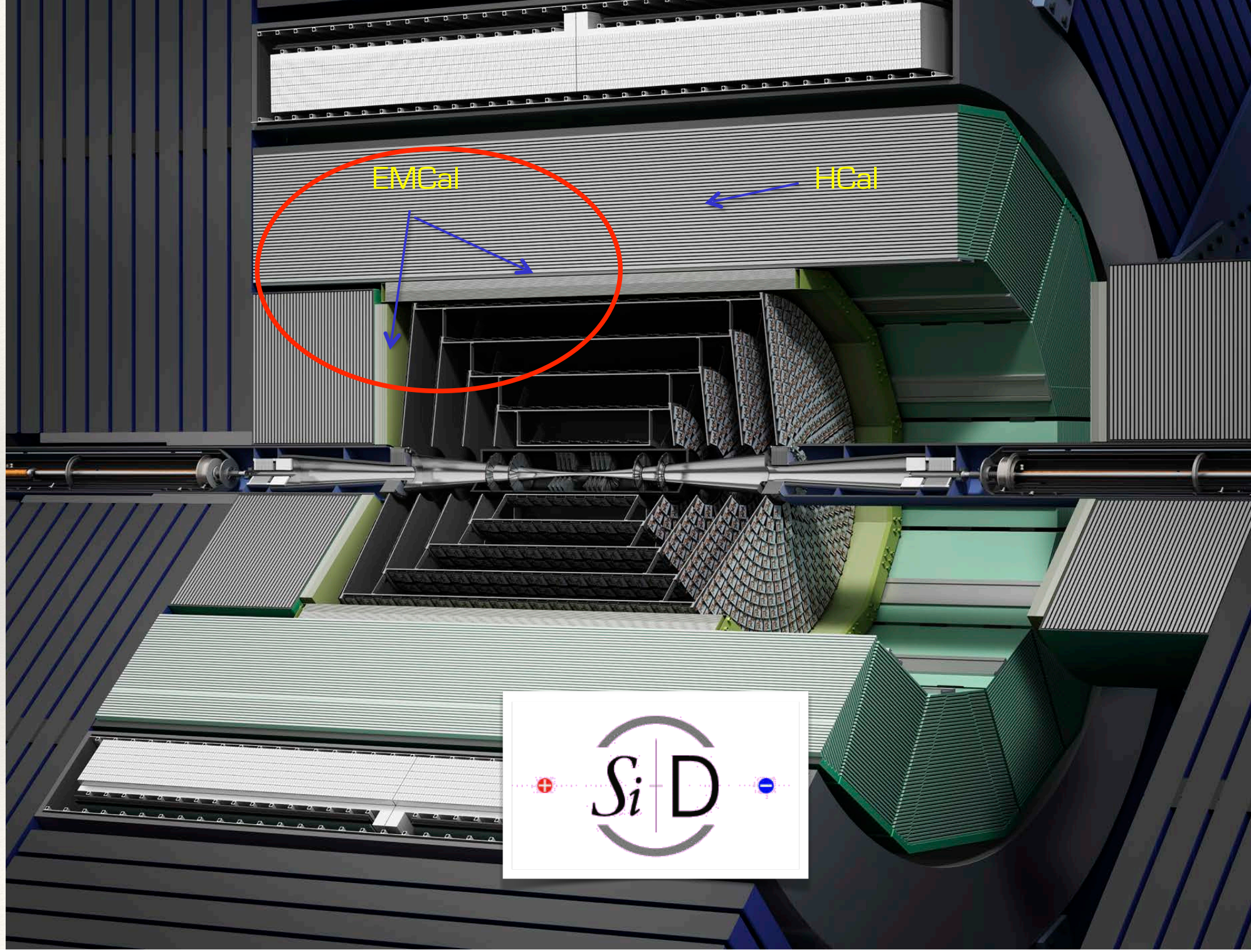
Sven Heinemeyer,
 ILC-IDT-WG3 BSM workshop,
 28.02.2022

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<https://pdg.lbl.gov/2022/reviews/>

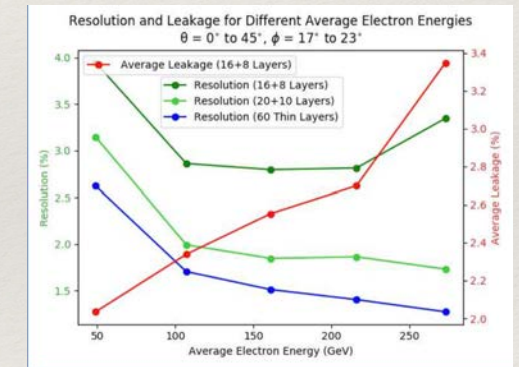
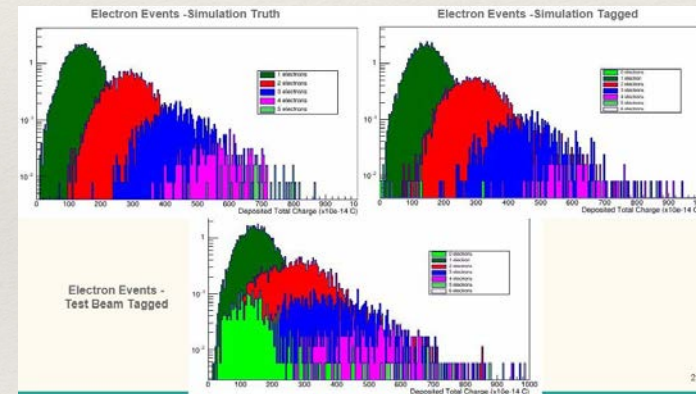
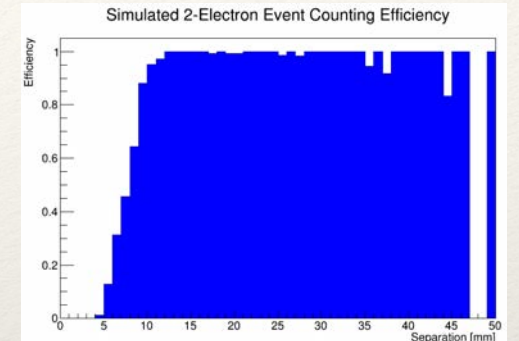
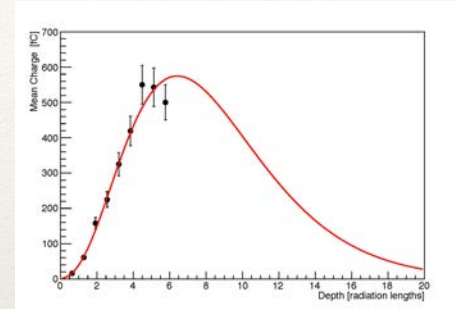
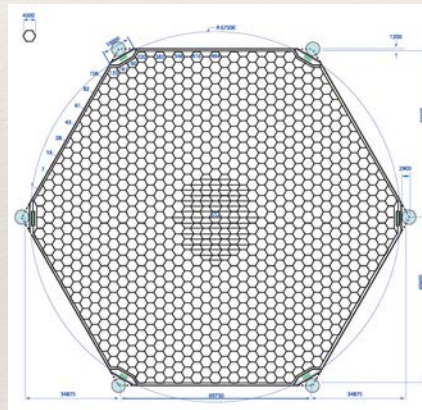
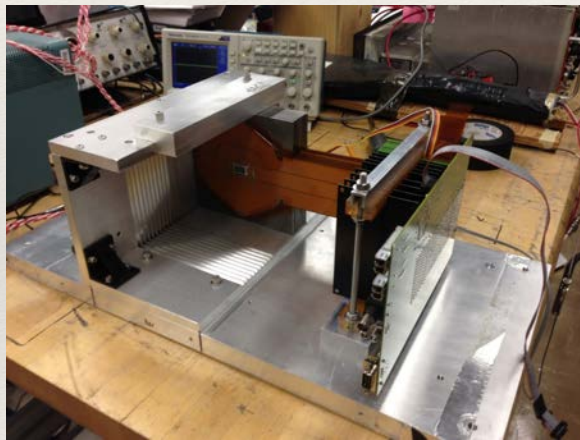
$\sigma \times B$ normalized to SM





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



J Barkeloo *et al* 2019 *J. Phys.: Conf. Ser.* **1162** 012016

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

13 mm² \rightarrow 0.0025 mm² \sim 5,000 times finer

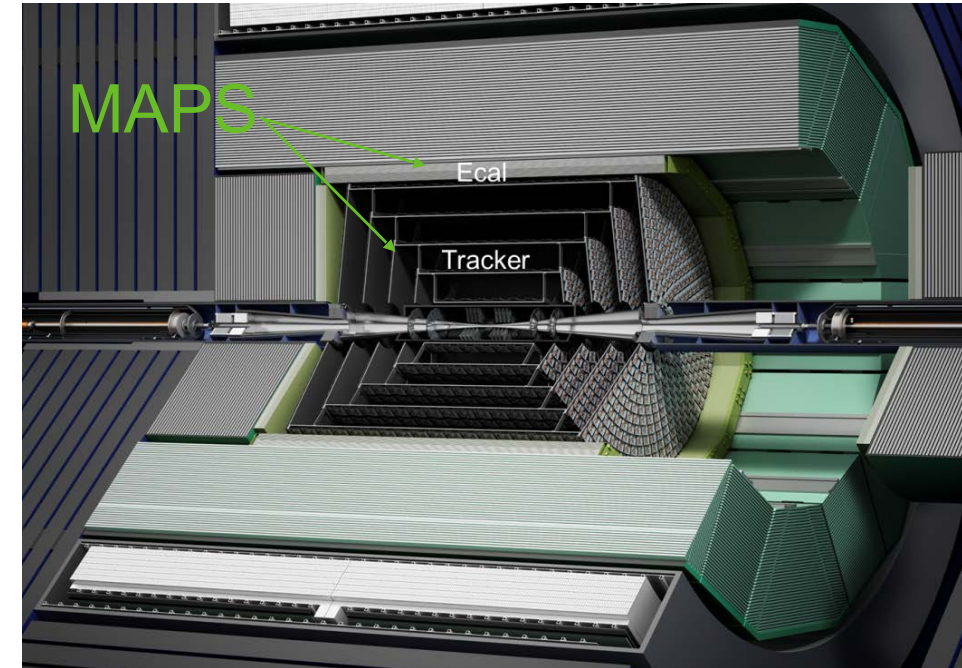
Large area MAPS for SiD tracker & ECal

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 cm² → enable O(1) m² modules

Several design challenges:

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



An example of the SiD Tracker and the ECal overall design

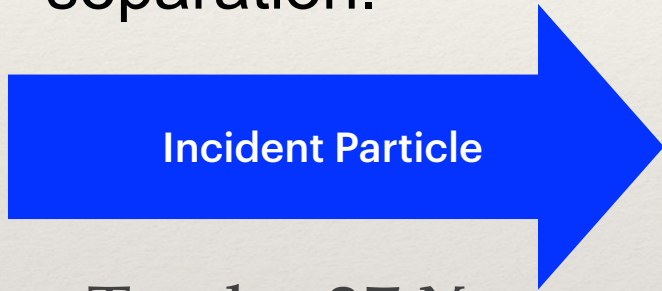
Goals of R&D: find solutions and explore novel design techniques

Sensor design has been submitted for fabrication

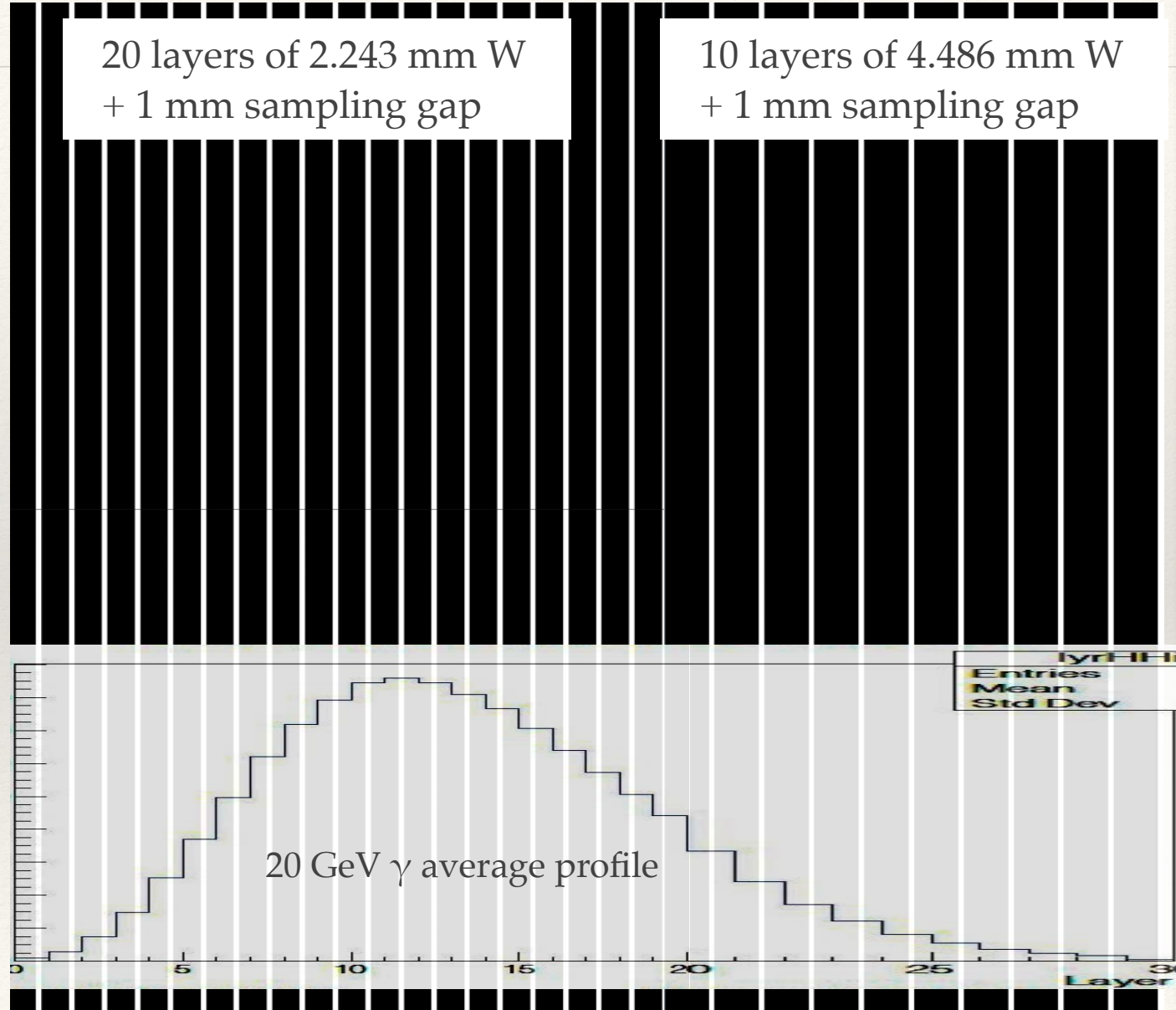
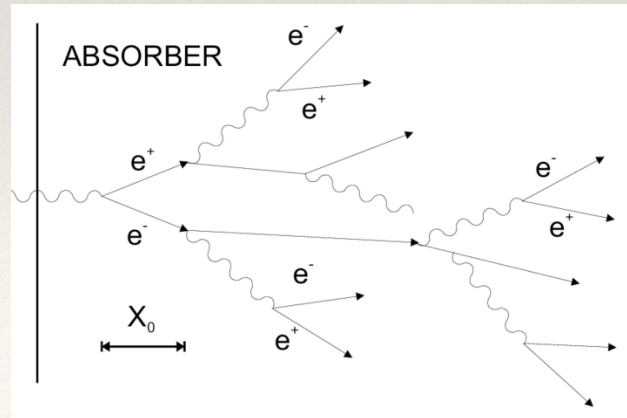


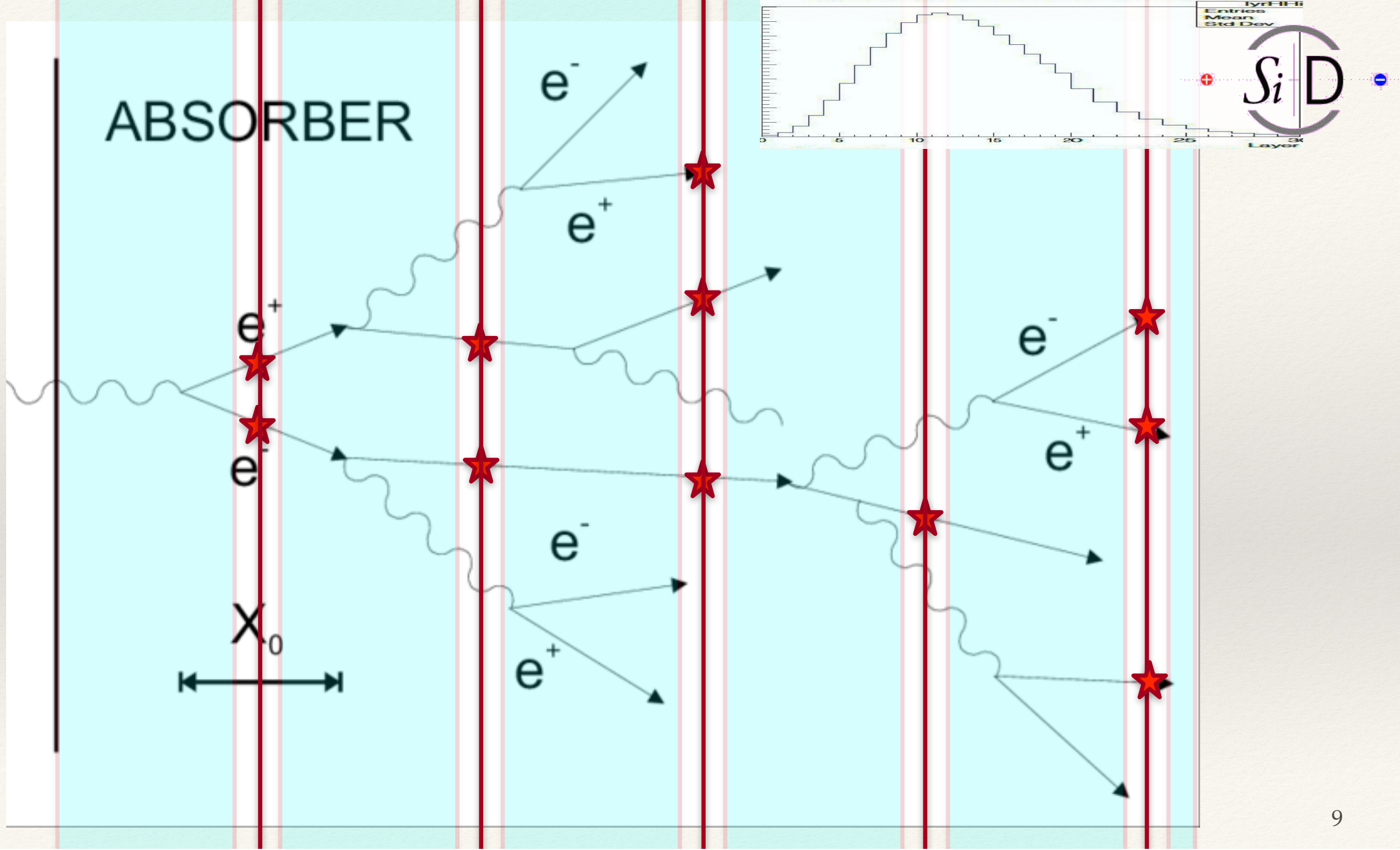
Model of longitudinal structure of SiD ECal

Minimize sampling gap to achieve optimal Moliere radius and shower separation.



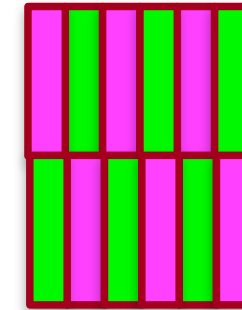
Total = $27 X_0$



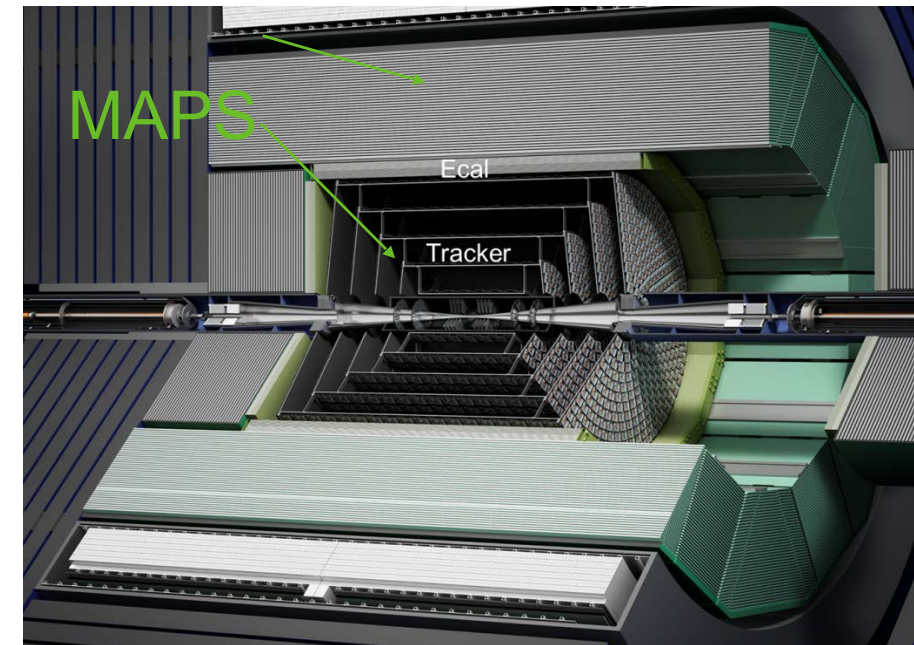


Main specifications for Large Area MAPS development

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 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 ECal 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



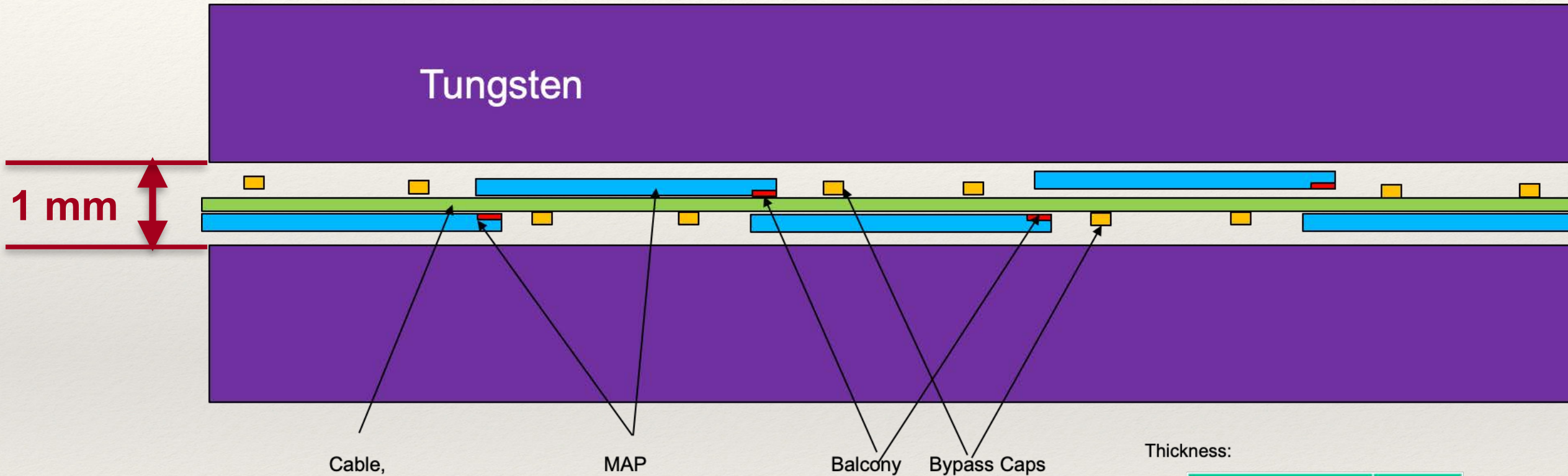
25 x 100 μm²
ECal performance same as 50 x 50 μm²



SiD Tracker and the ECal

Gap Structure with MAPS

Not to scale



ONE CABLE IN GAP DESIGN

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

Thickness:

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

This may well need adjustment following more cable design

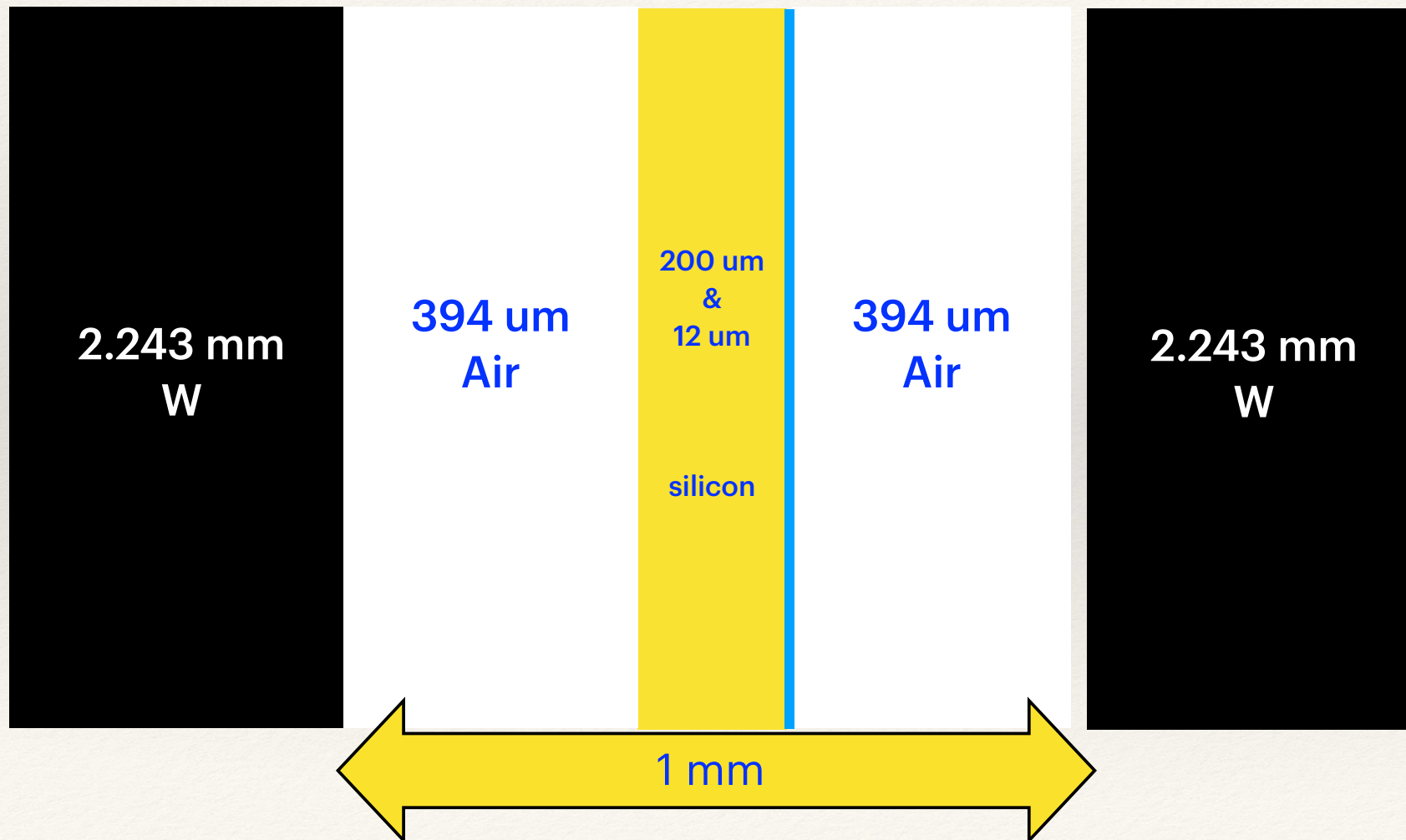
M. Breidenbach

Sampling Gap Simulation - SiD MAPS Digital ECal

J. Brau - 22 June 2022

SiD Digital ECal based on Silicon MAPS

Geant4 simulated silicon gap structures

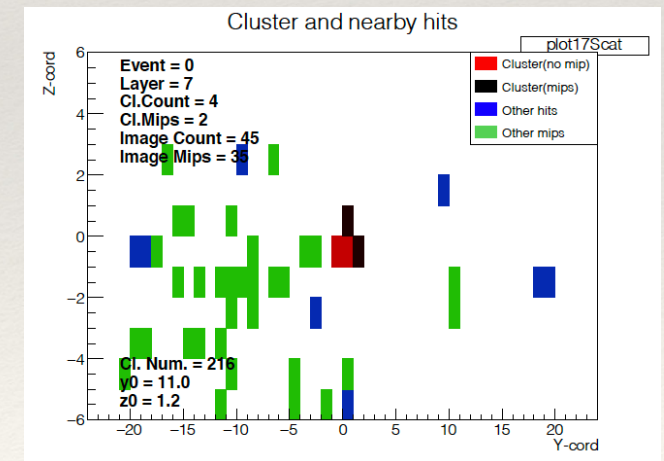


Assumption:

Pixel threshold =
1 keV \approx 270 e's

Future:

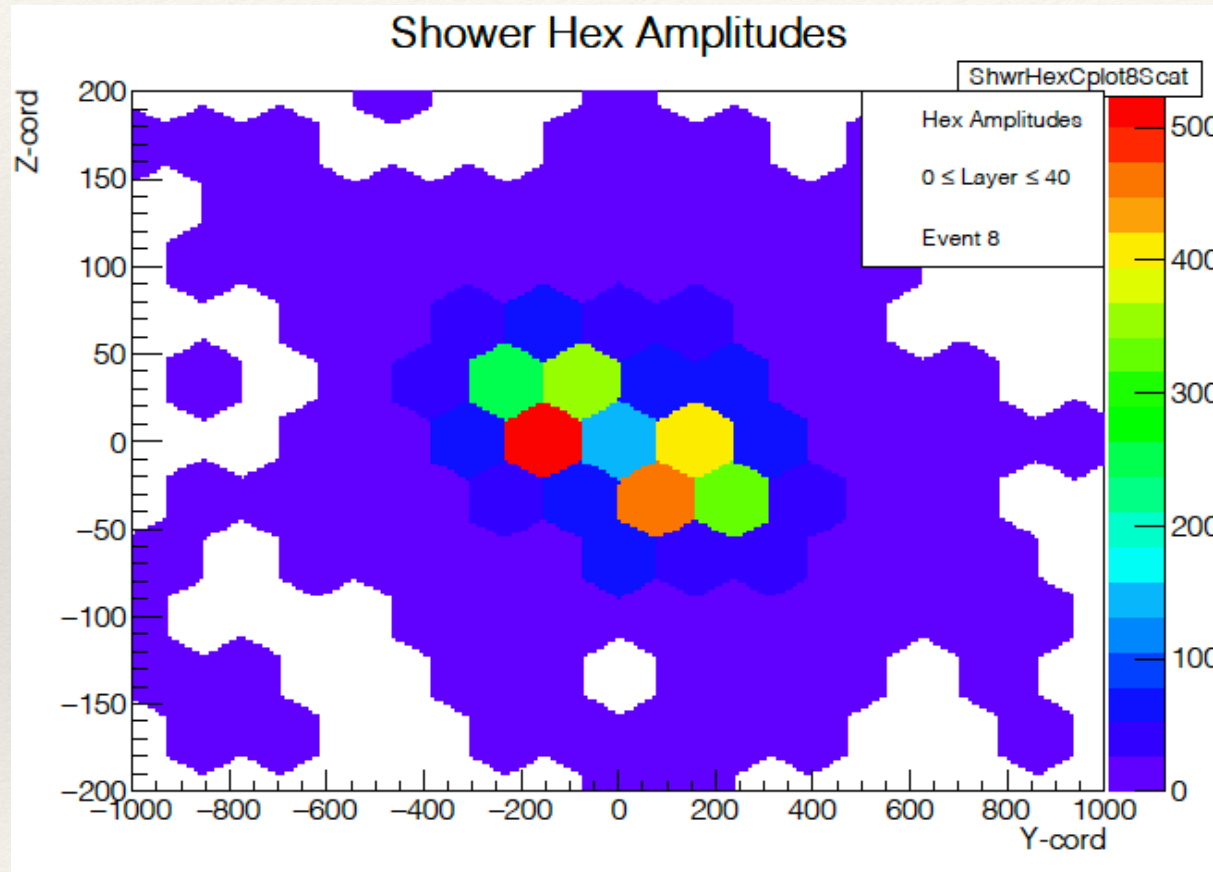
More detailed
gap model



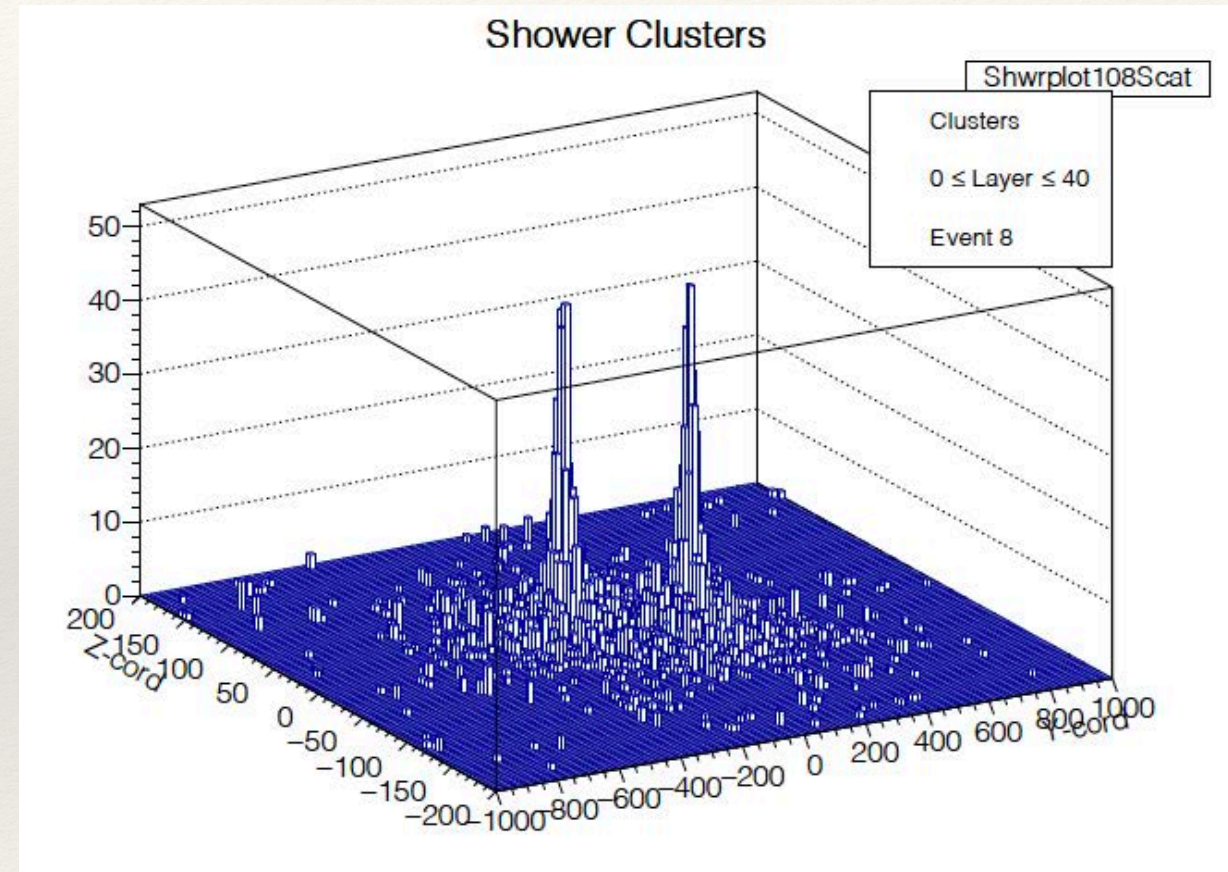
Typical hits distribution

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 μ m x 100 μ m pixels

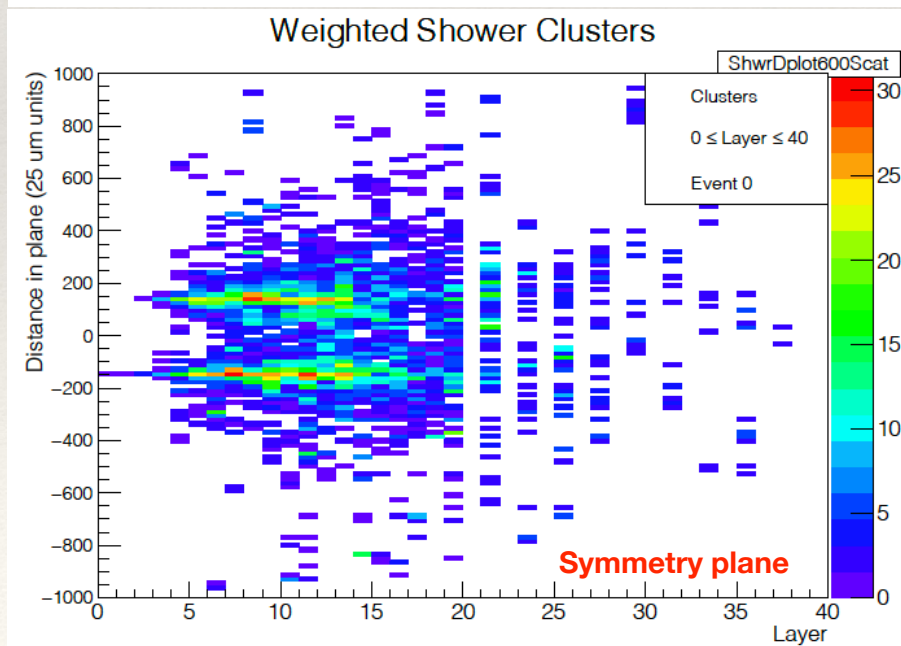
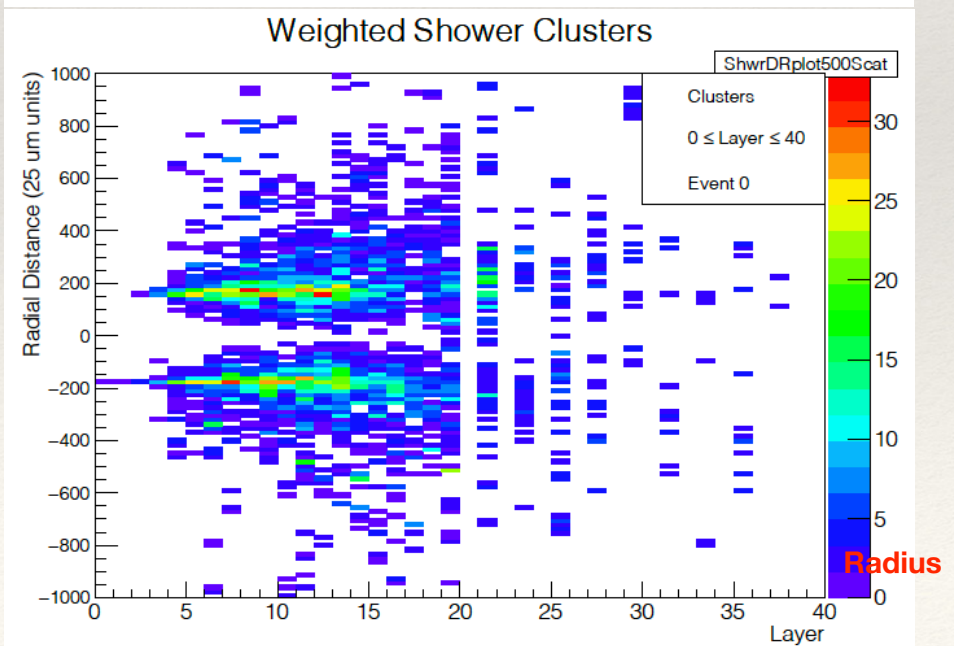
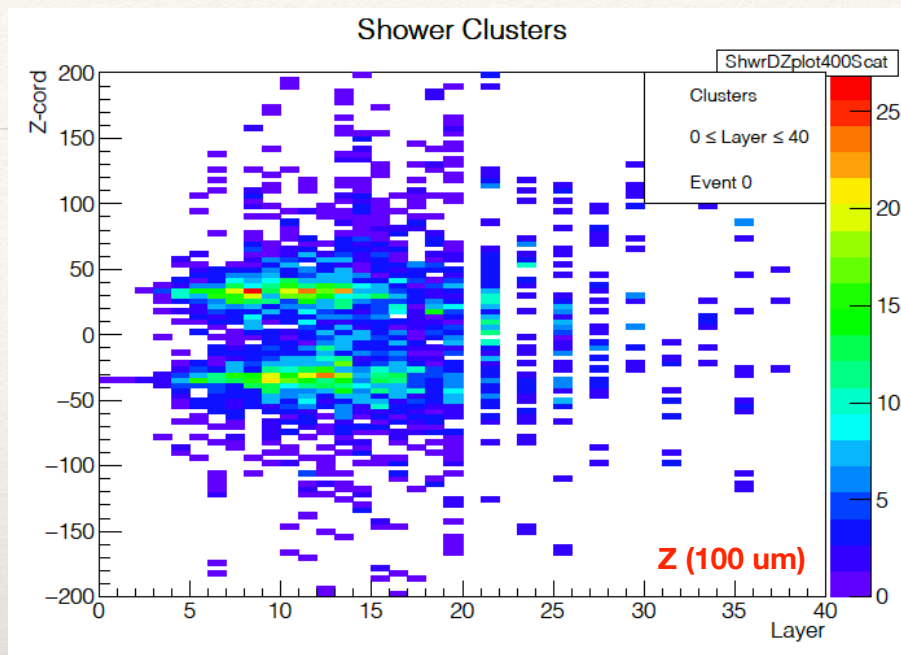
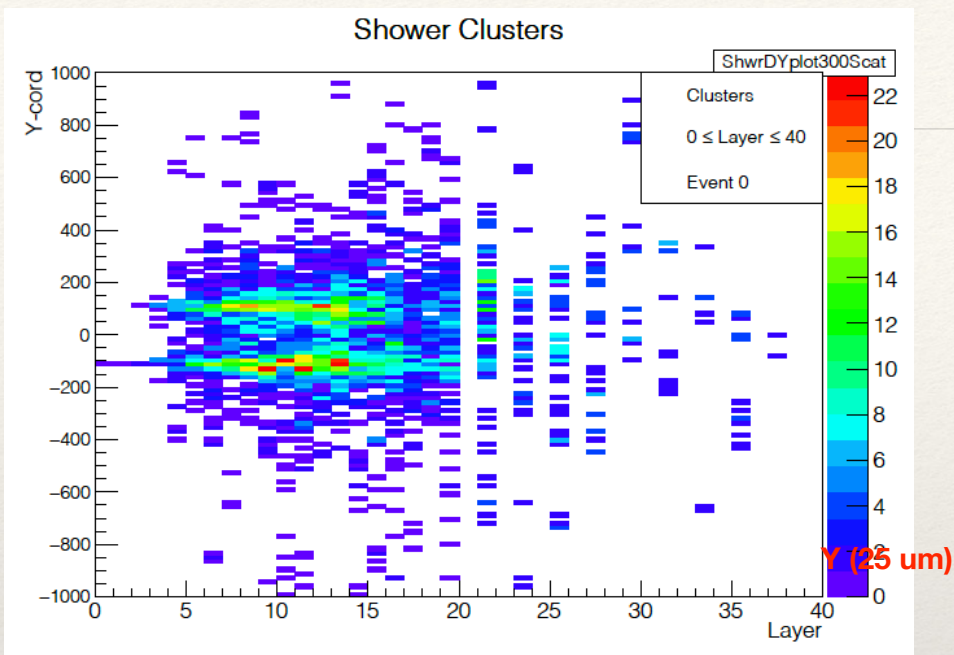
40 GeV $\pi^0 \rightarrow$ two 20 GeV γ 's

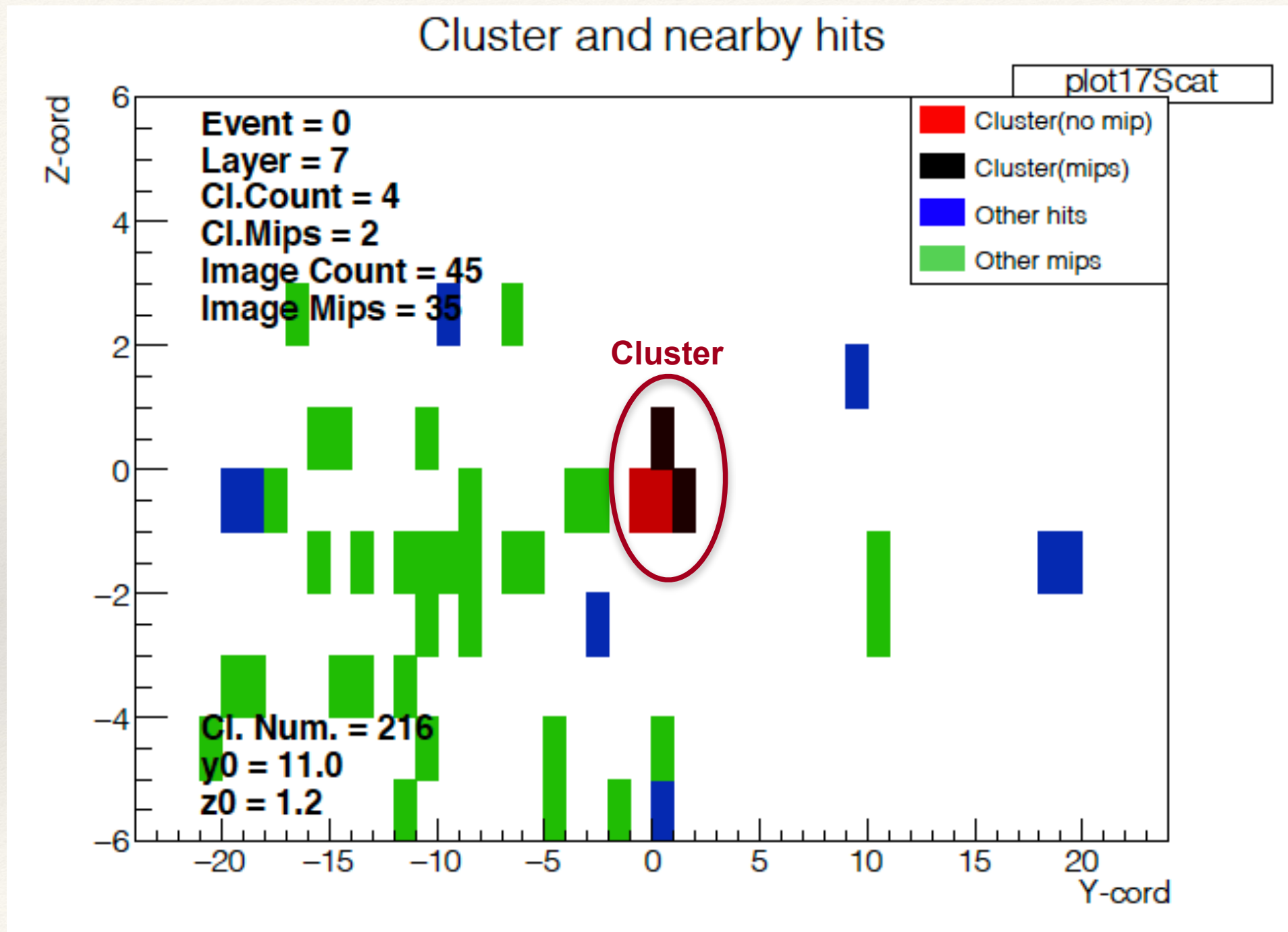


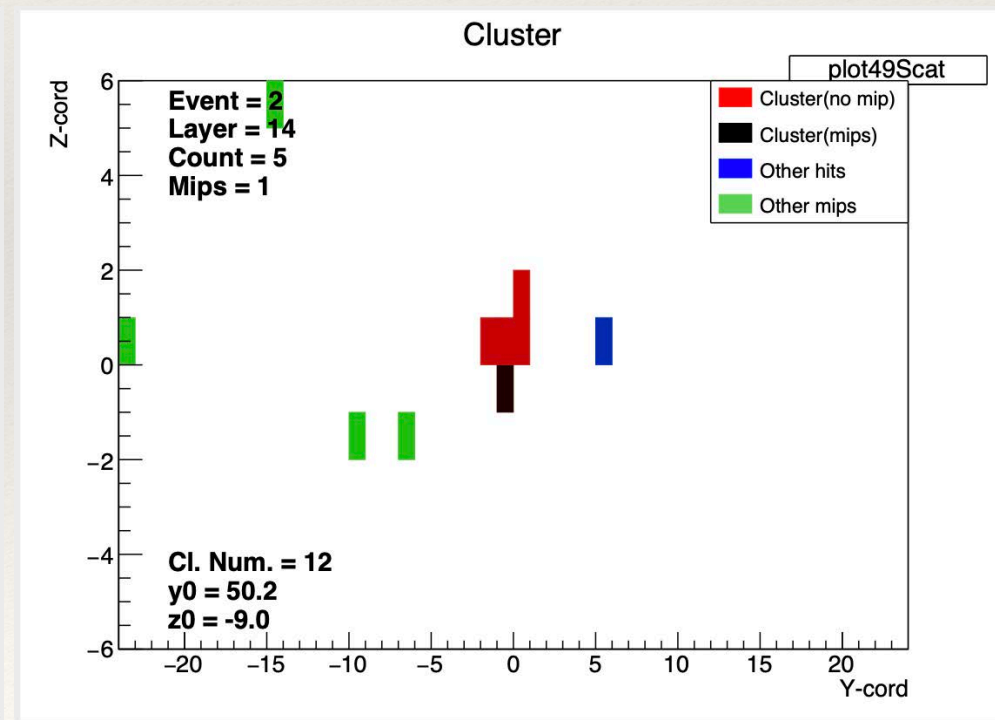
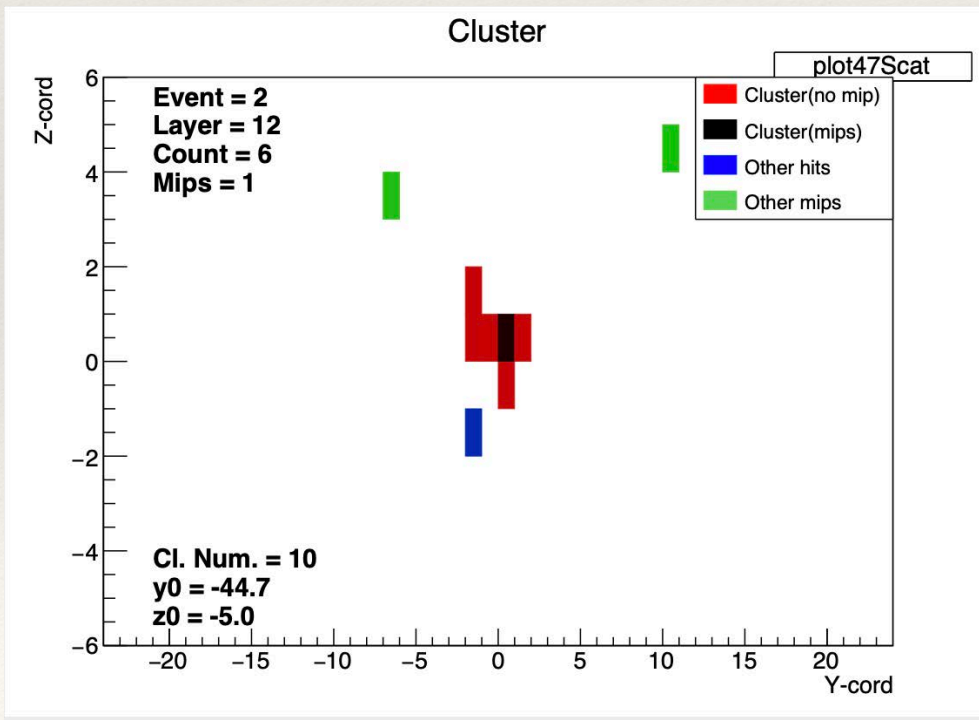
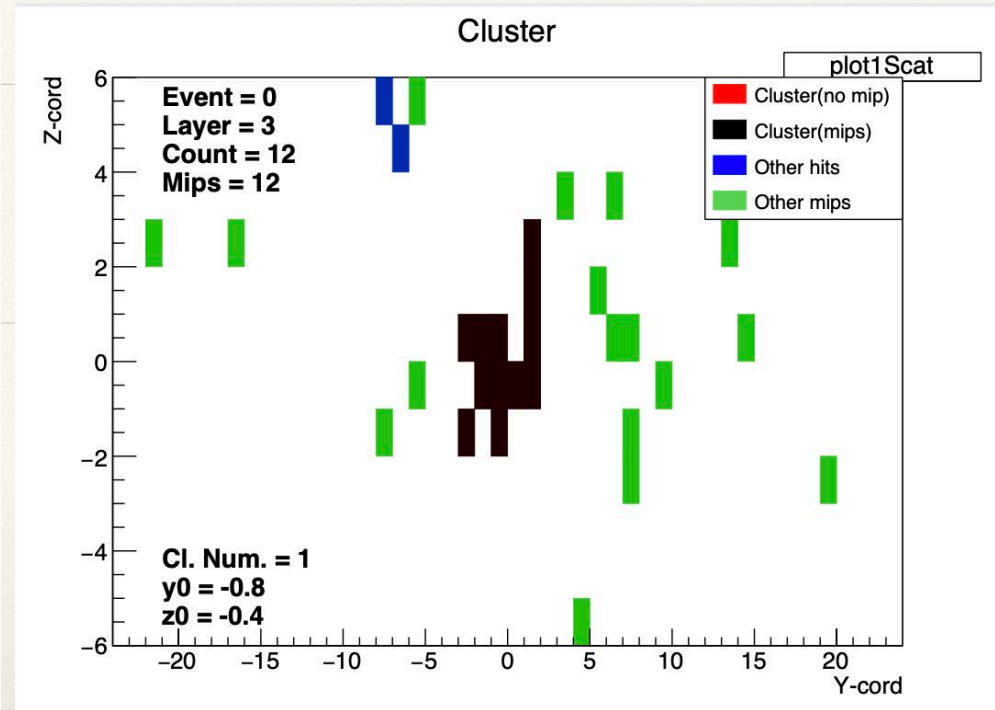
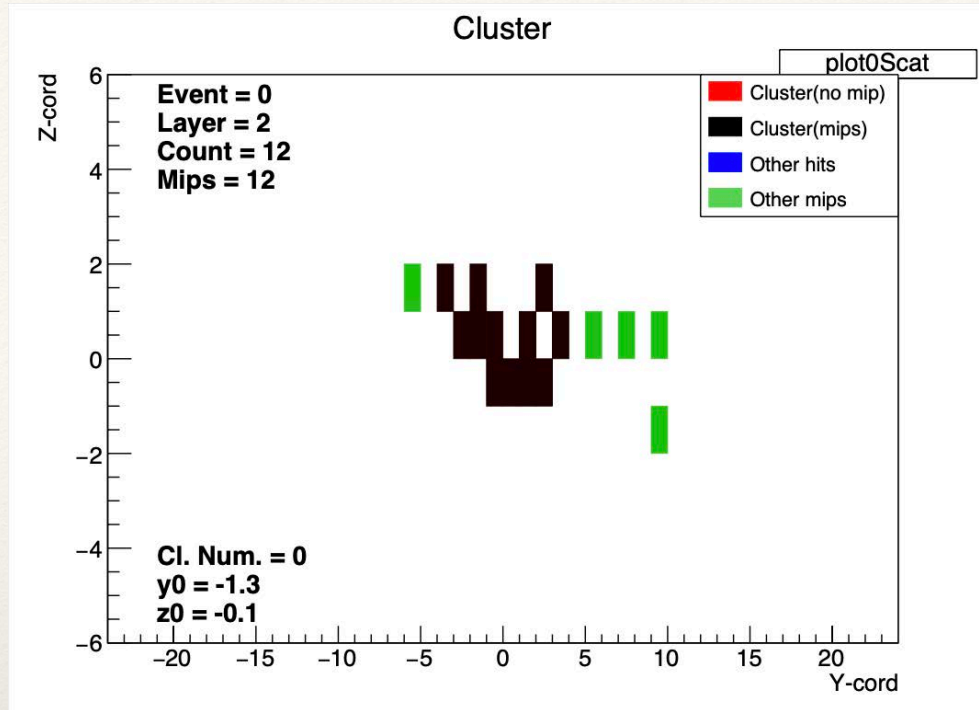
Vertical bin
400 μm

J. Brau - 22 June 2022

SiD Digital ECal based on Silicon MAPS







Performance simulation - Overview

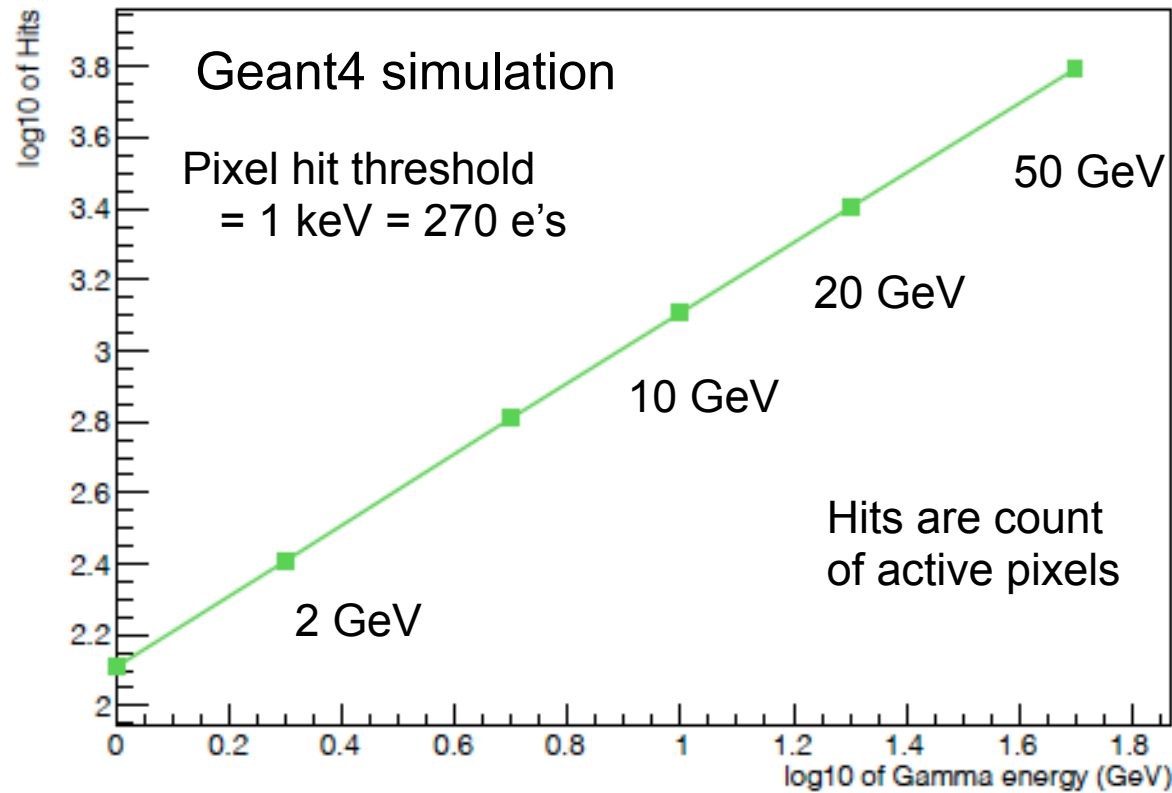


Geant4

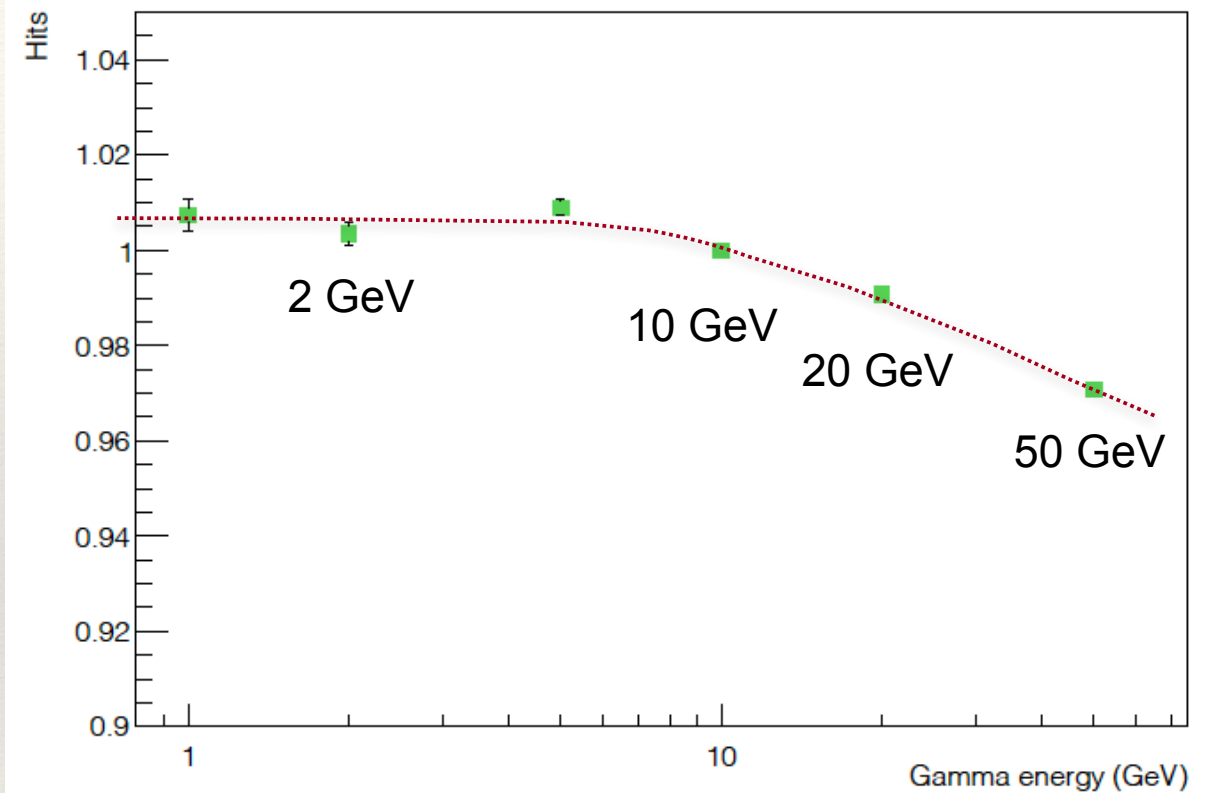
- ❖ Linearity
- ❖ Energy resolution
 - ❖ Ideal - count mips - sets unreachable goal
 - ❖ Simplest approximation to mips - count digitized hits
 - ❖ Improvement - count clusters of hits - reduce fluctuations
 - ❖ Optimized - apply weights cluster counts from cluster properties
- ❖ Localization
 - ❖ Multiple shower separation
- ❖ Note - SiD's 5 T B field degrades resolution ~5%

Linearity of response (counting hits in γ showers)

log(Hits) vs. log(Energy) B=5T



Normalized Hits vs. Energy

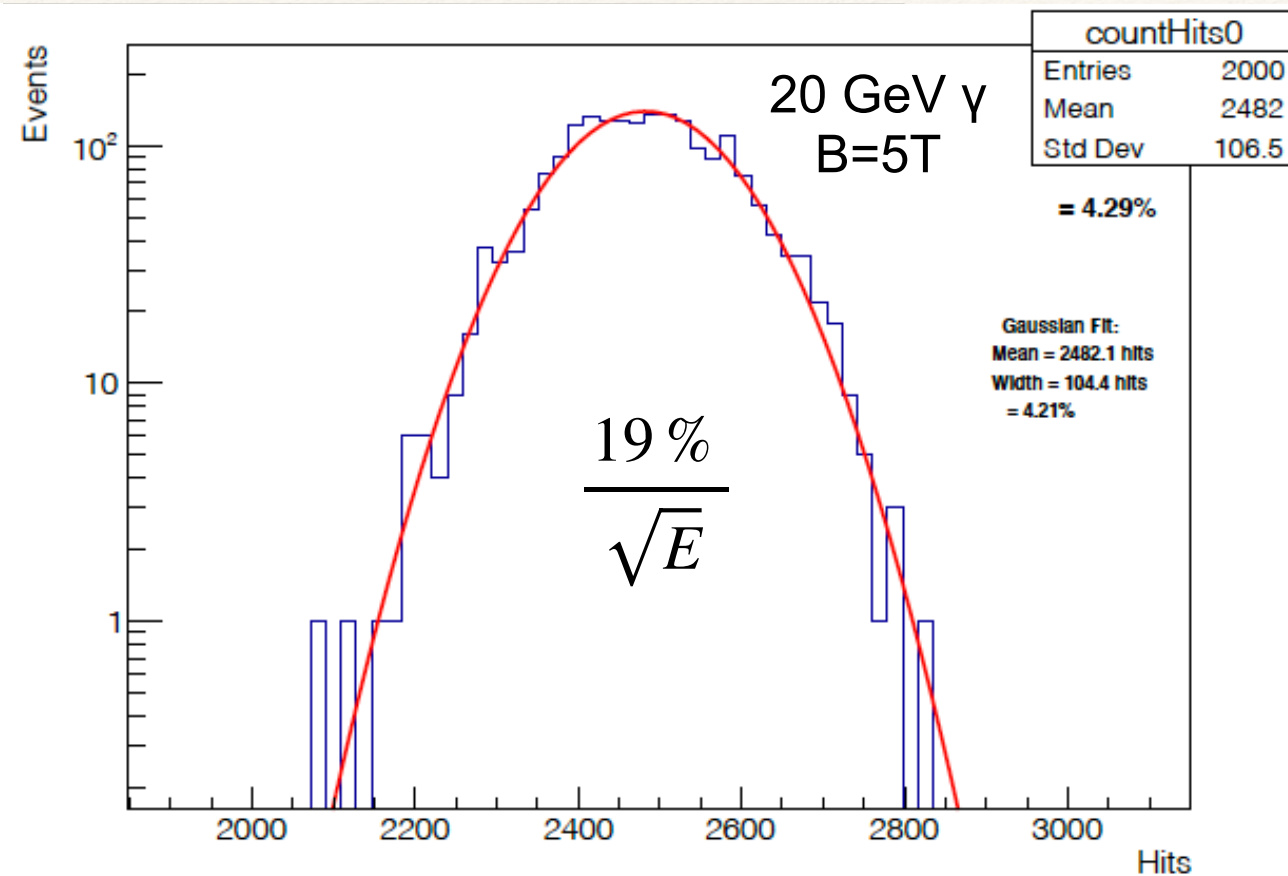
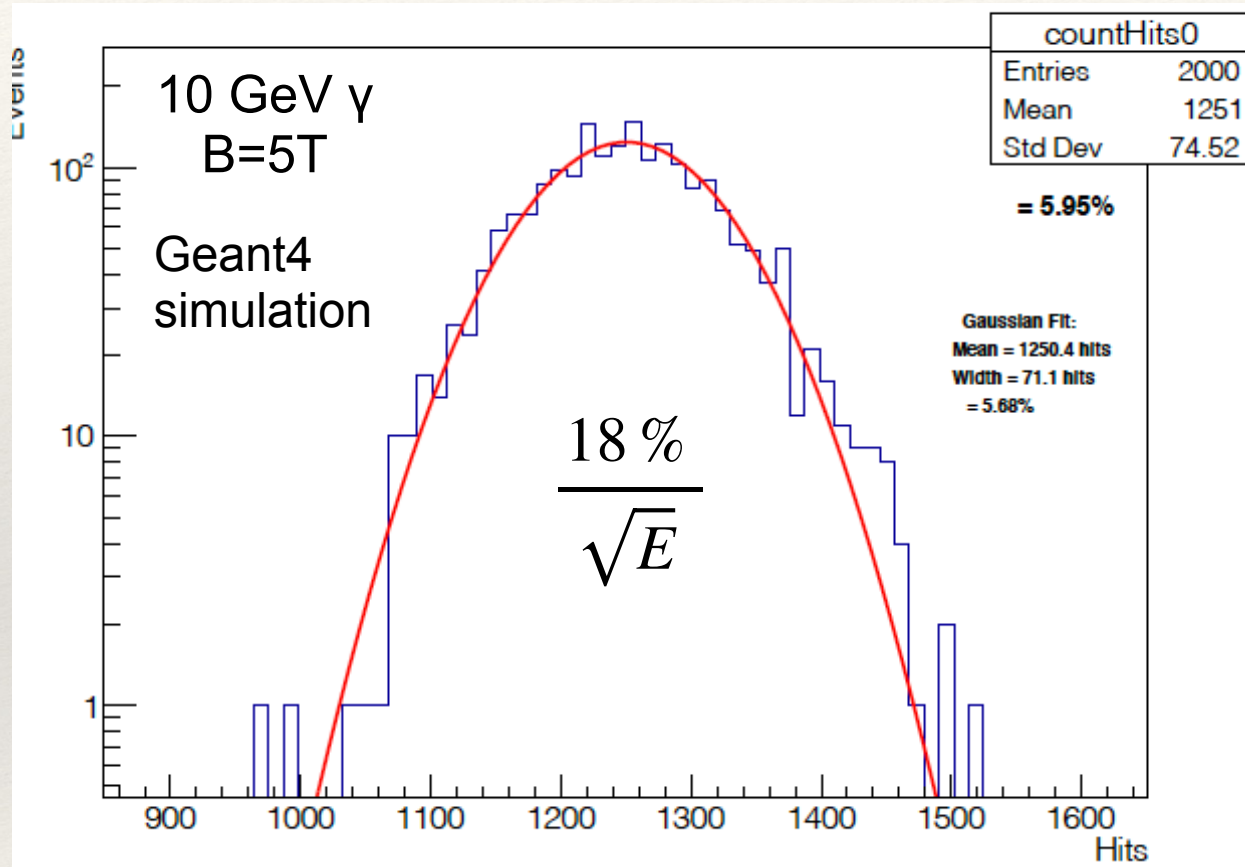


Few percent non-linearity due to differing response and counting in thin ($0.7 X_0$) and thick ($1.4 X_0$) layers (and uncorrected leakage).



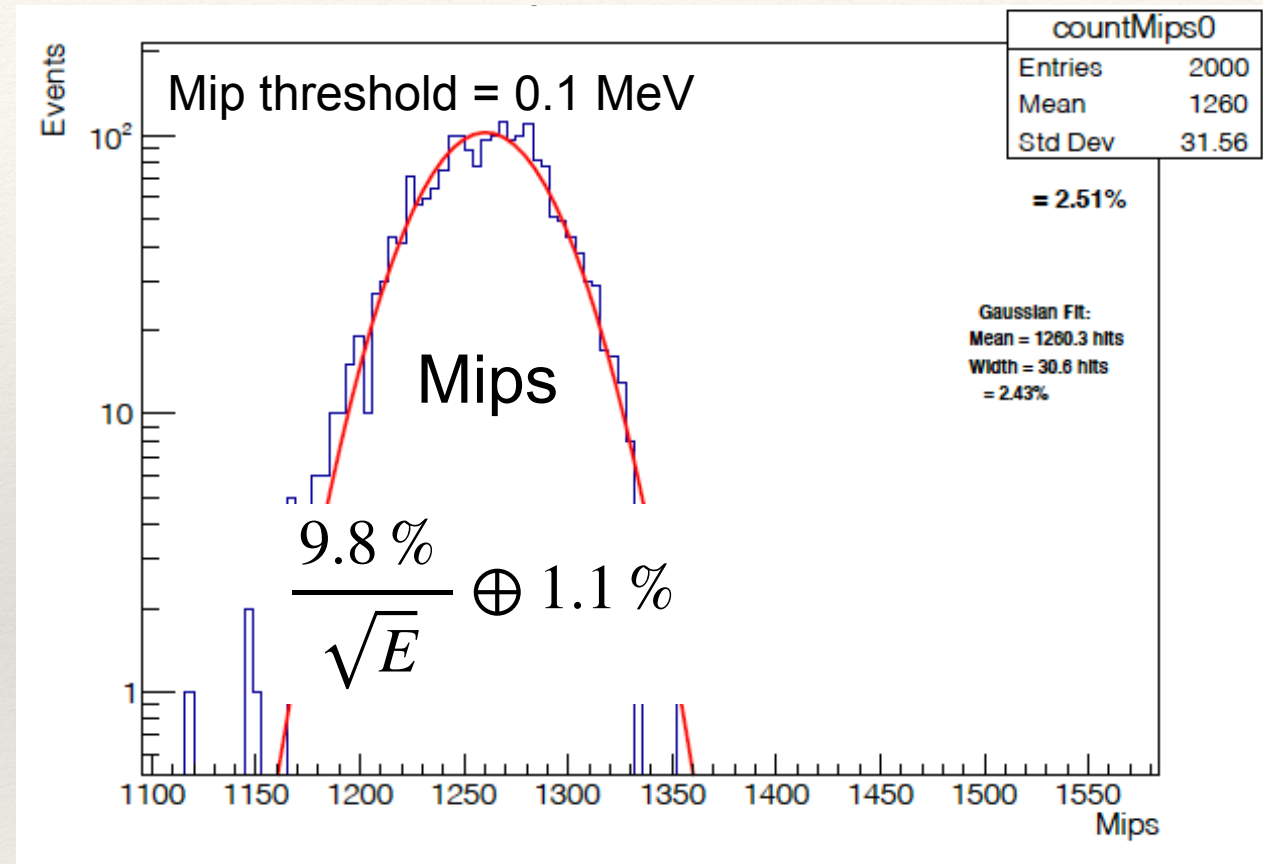
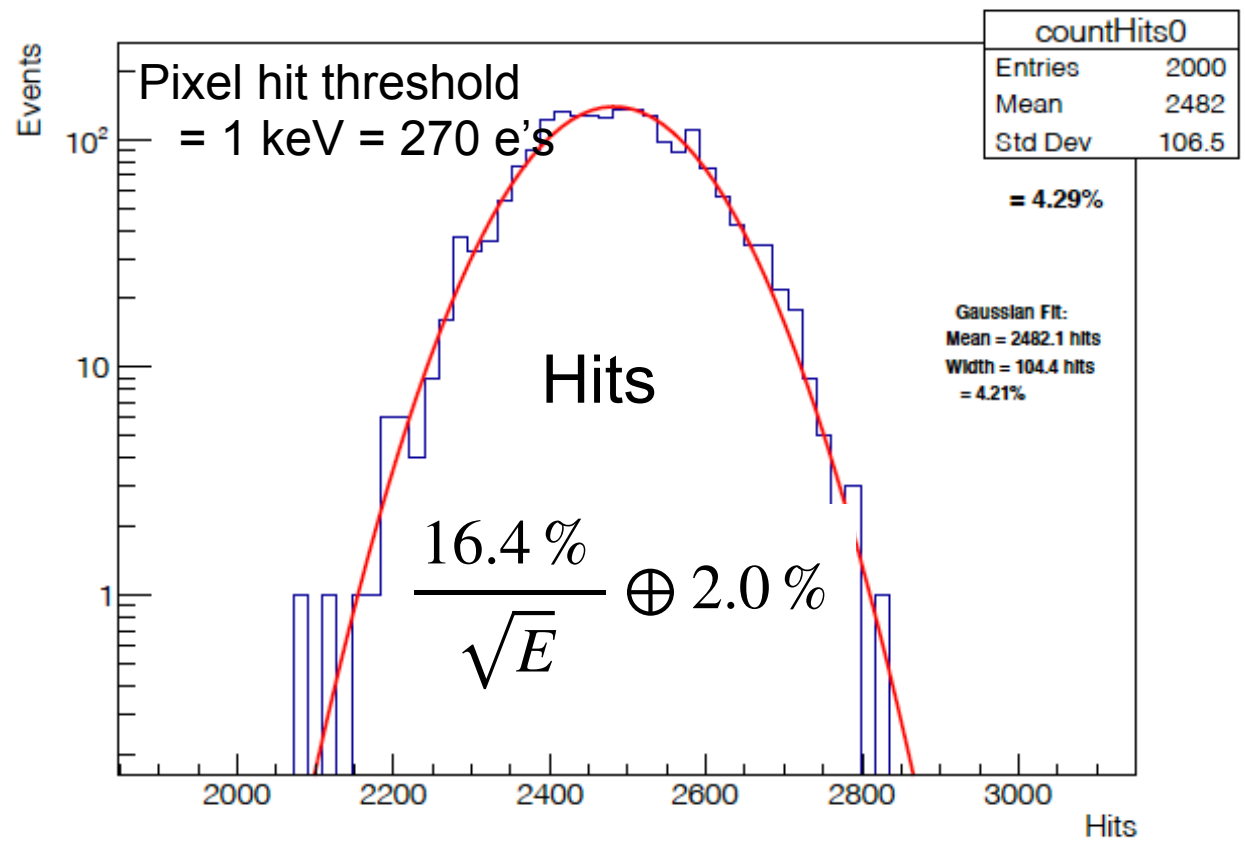
Pixel hit threshold
= 1 keV = 270 e's

Hits resolution - count active pixels



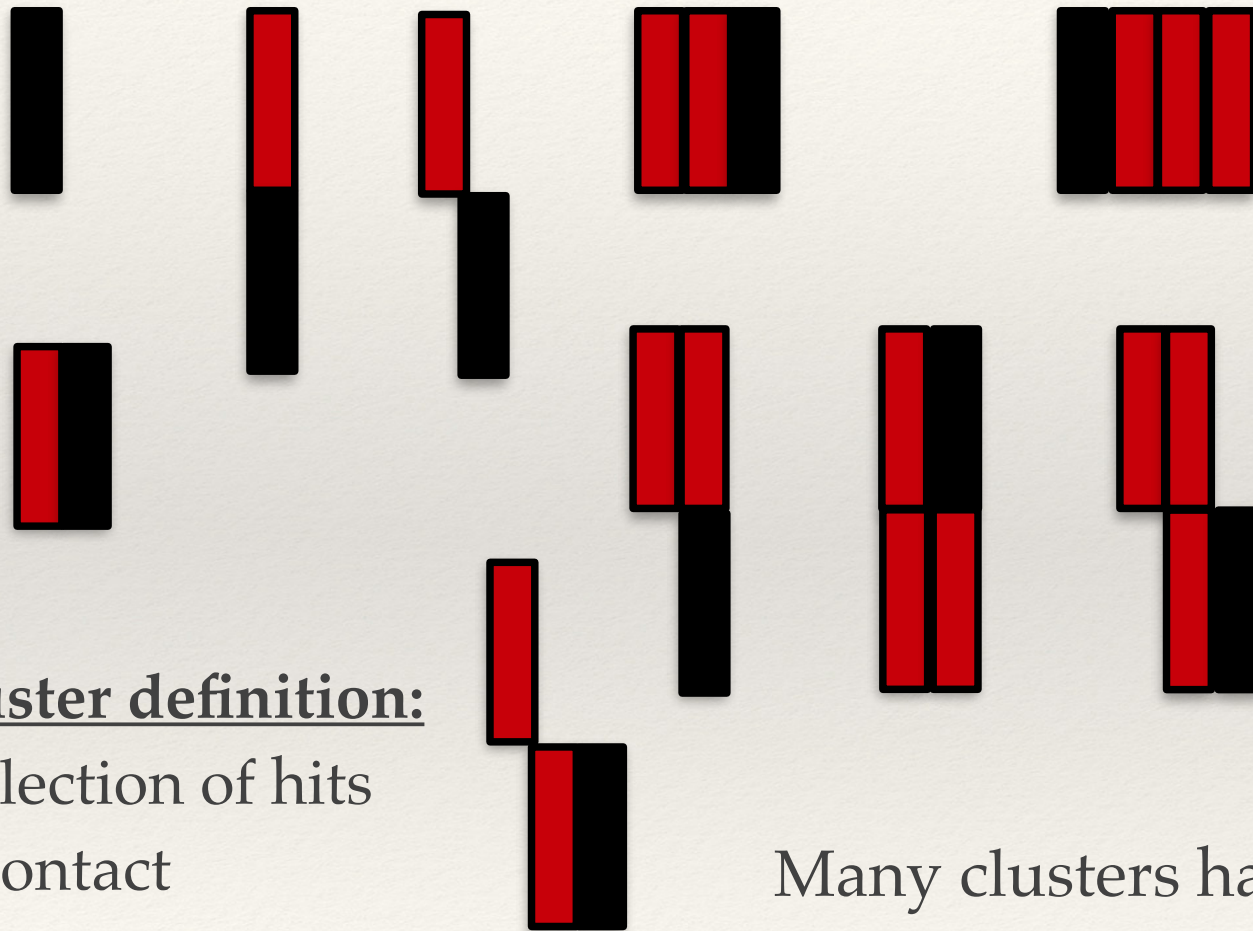
ILC TDR anticipates $\frac{17\%}{\sqrt{E}} \oplus 1\%$ for the SiD SiW ECal; but we can do better.

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.

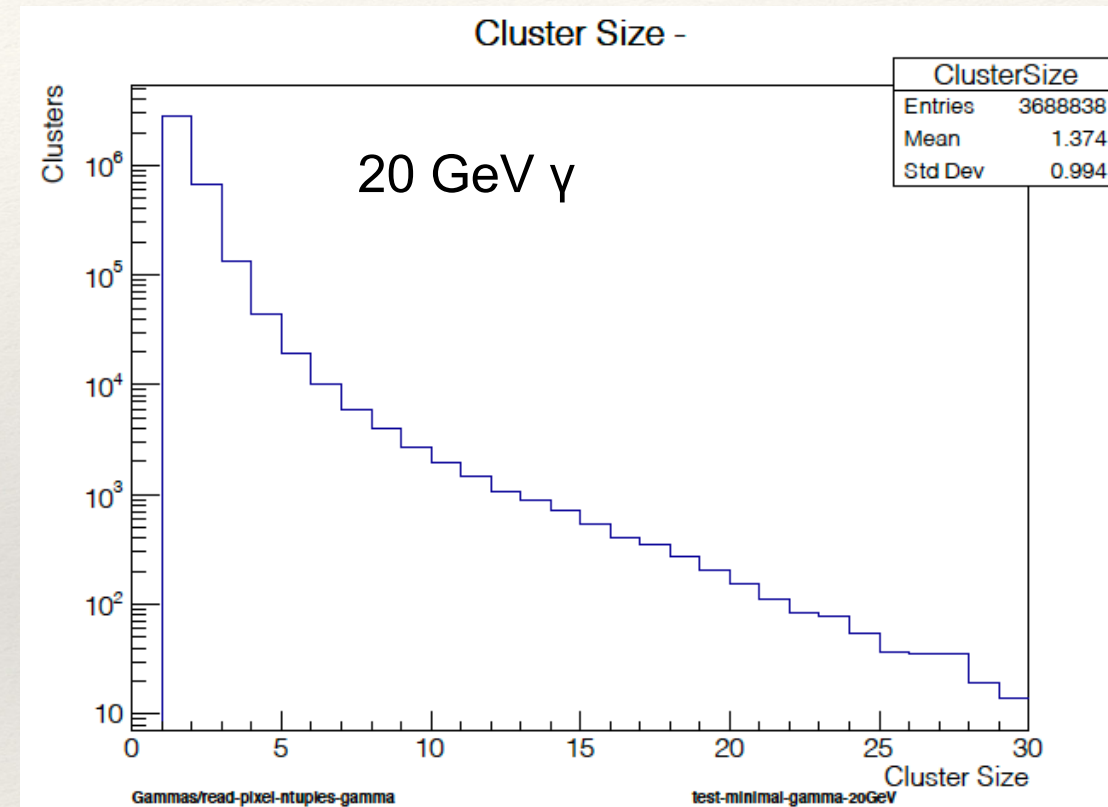
Hits appear in clusters (size 1, 2, 3,...)



Cluster definition:

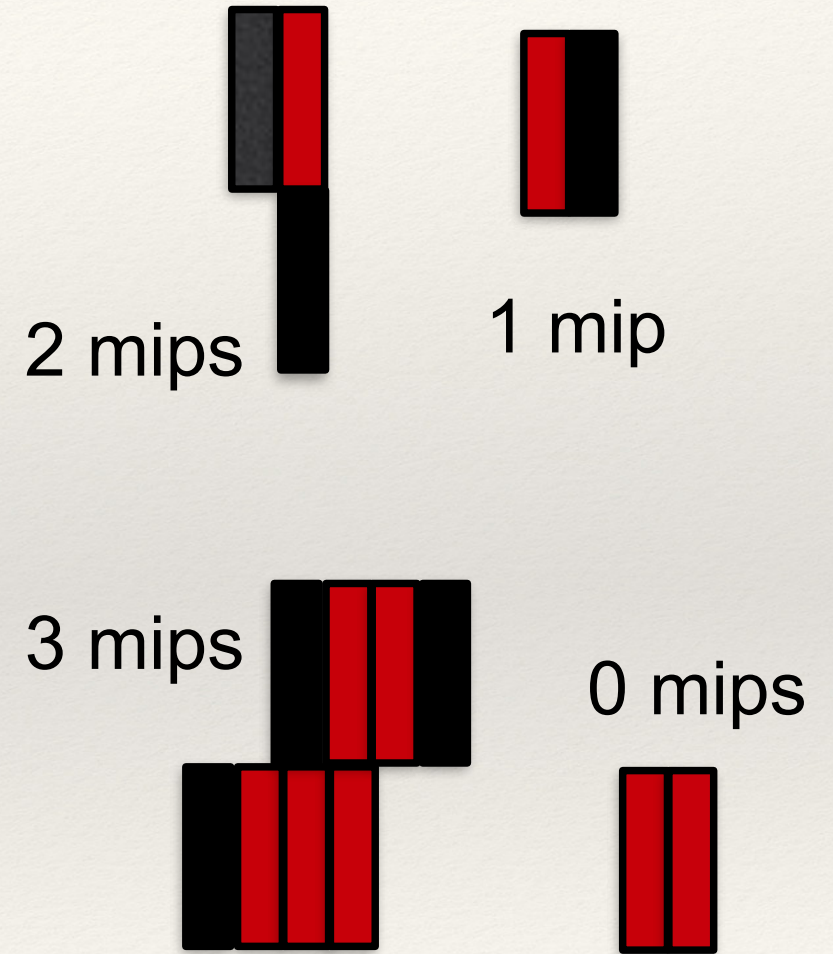
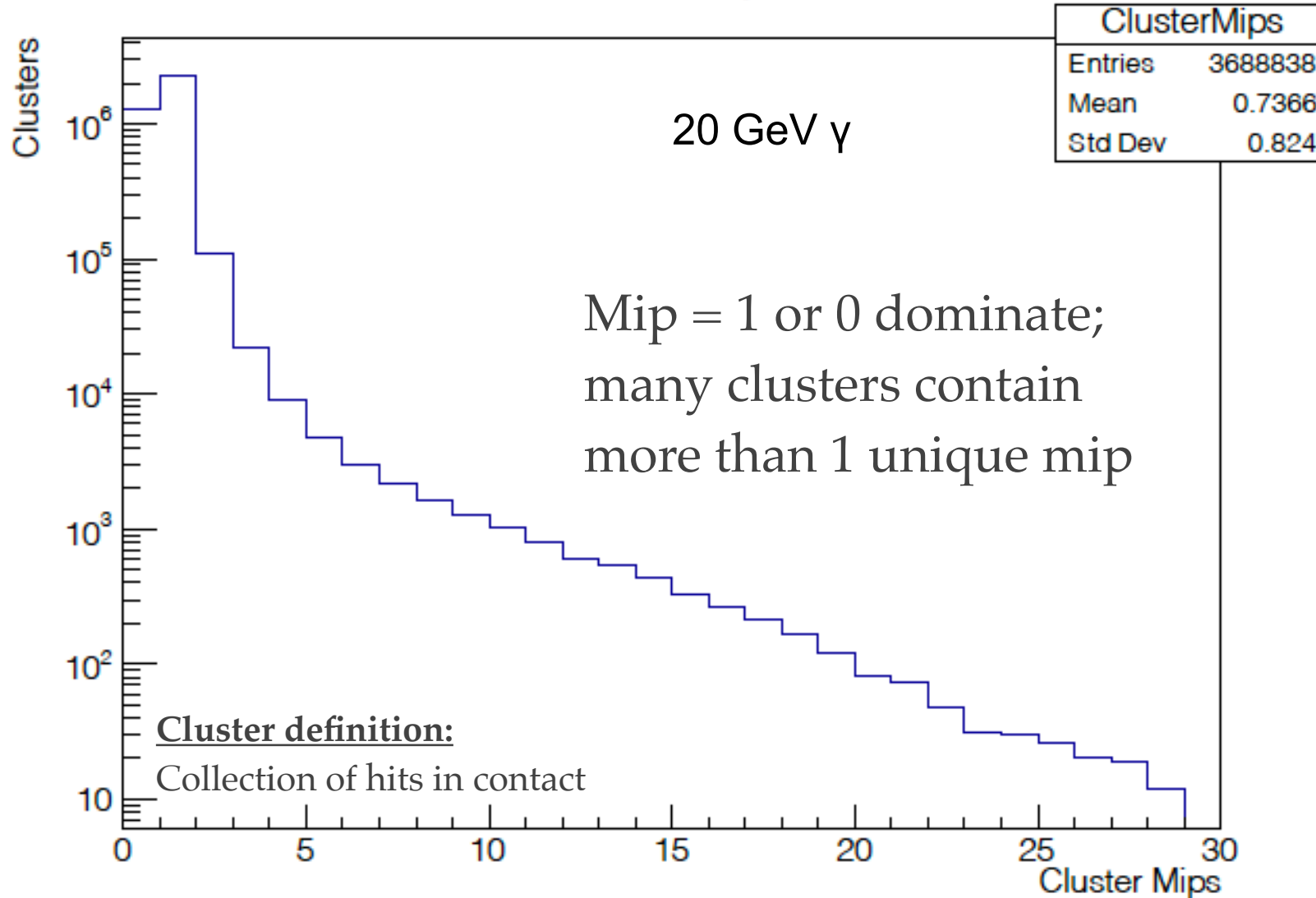
Collection of hits
in contact

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

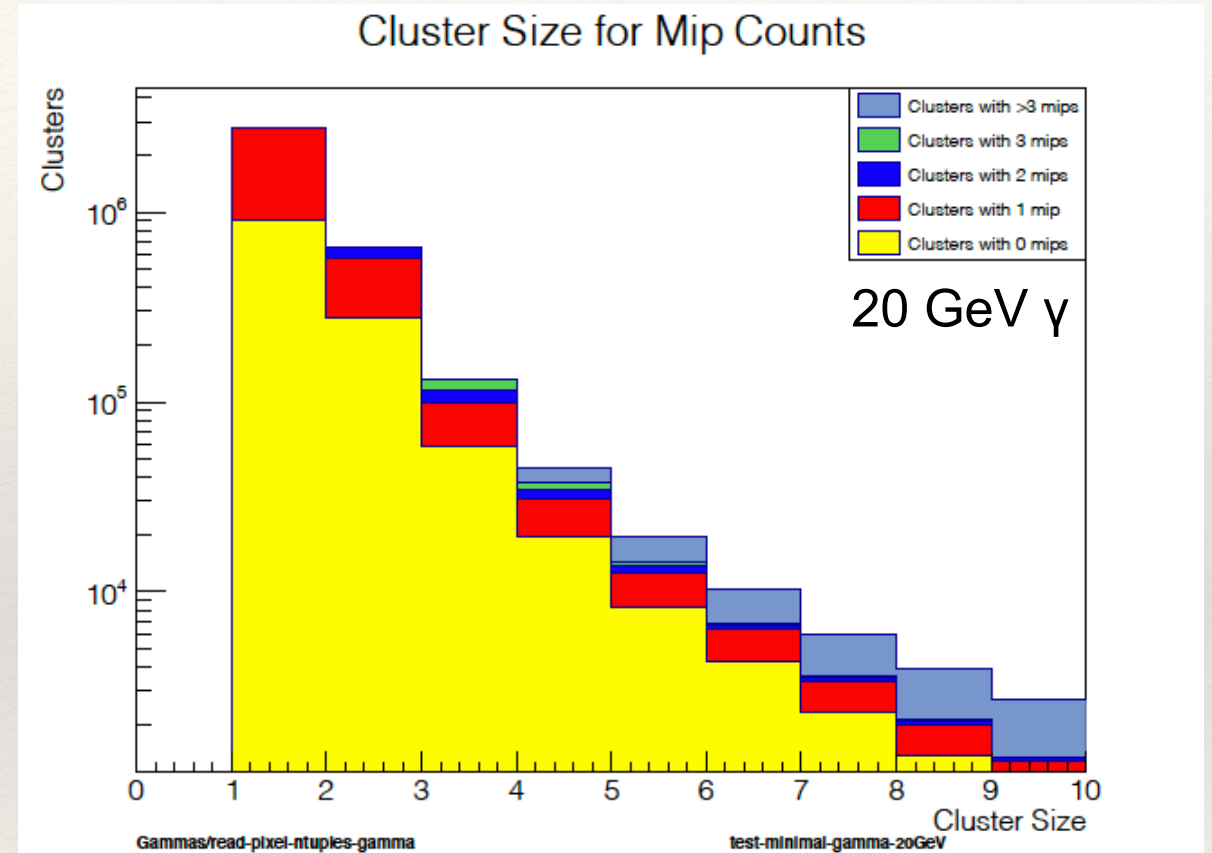
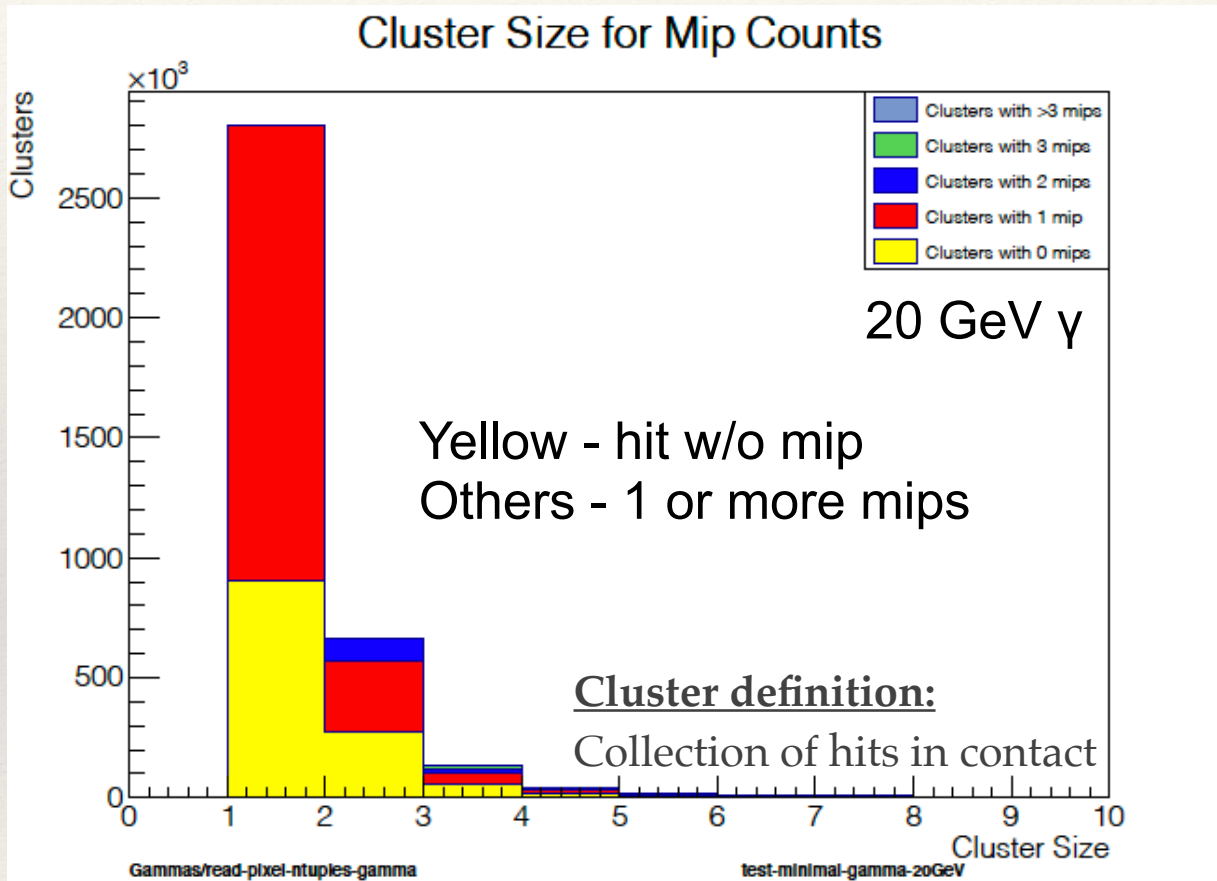


Mips per cluster

Cluster Mips -

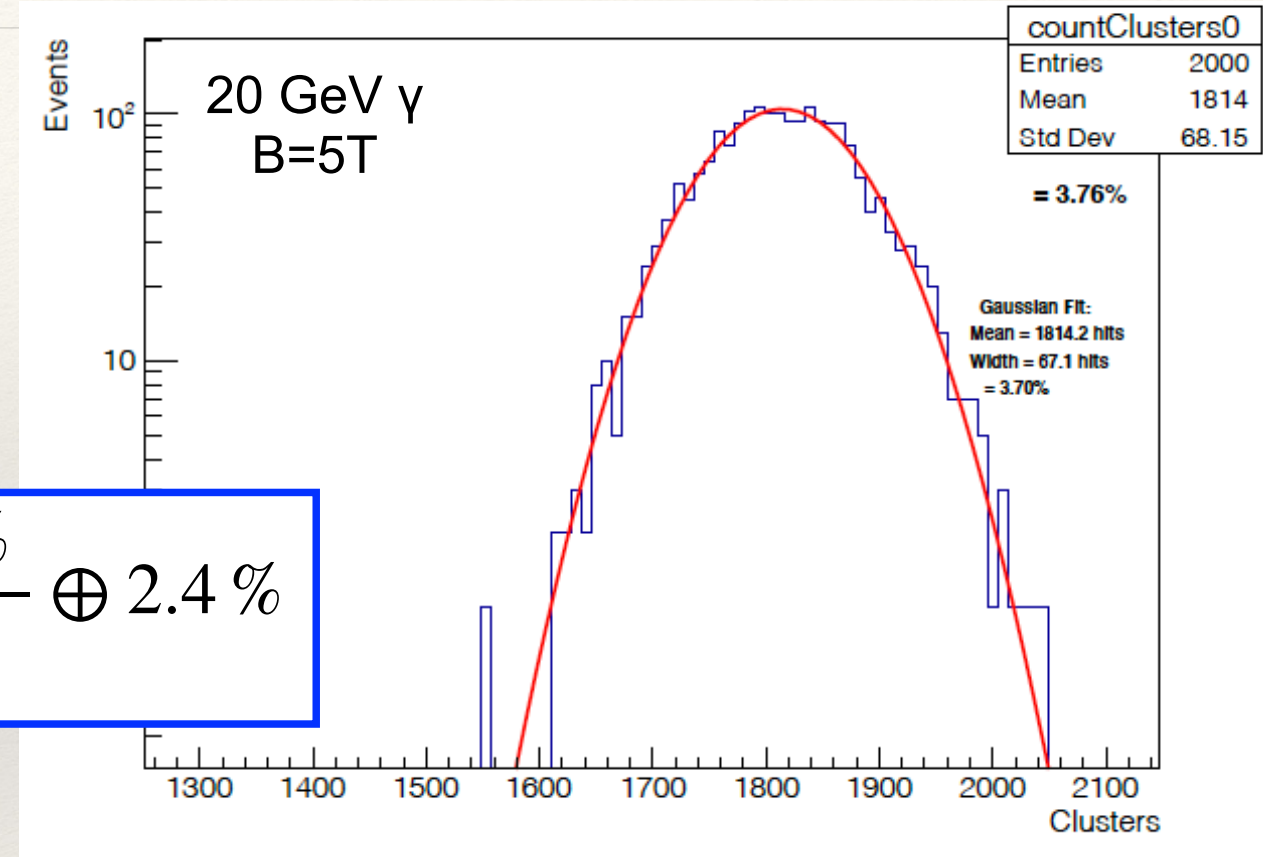
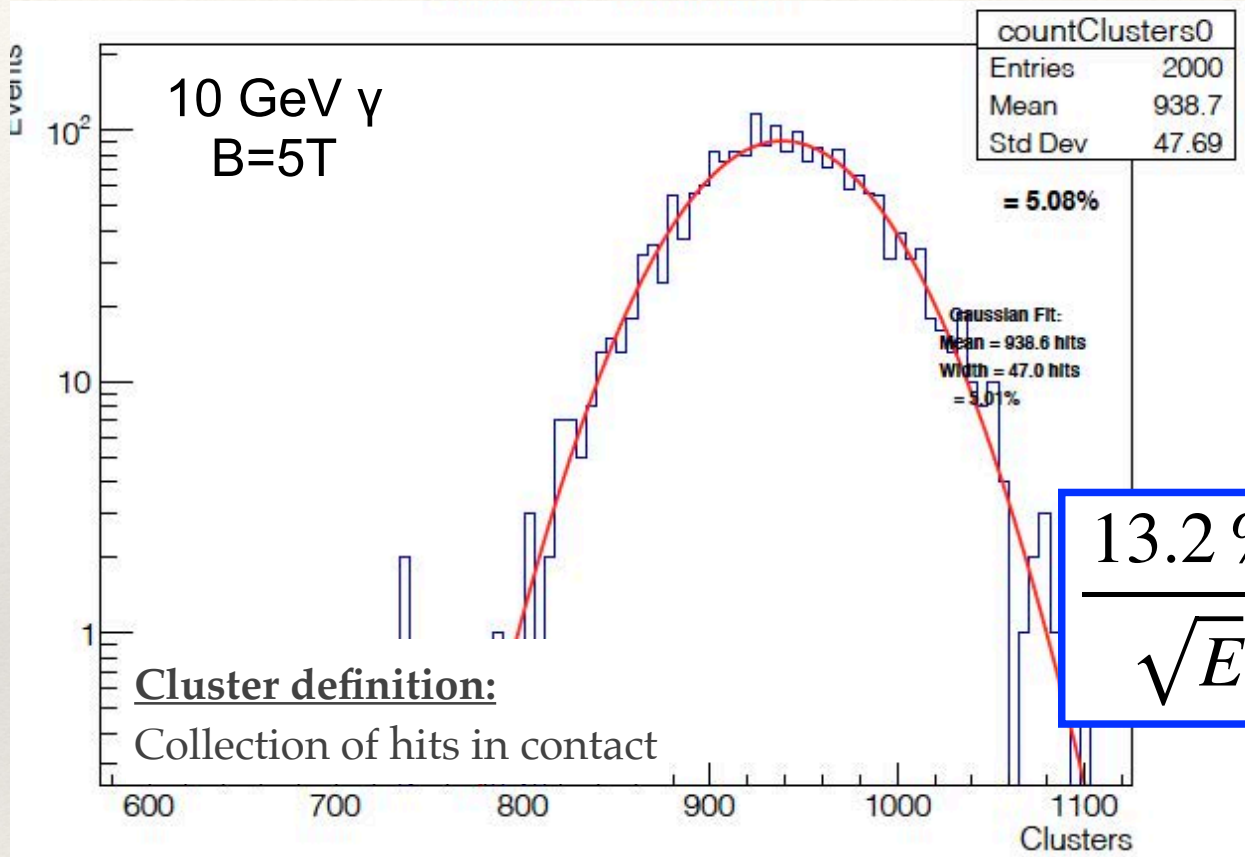


Cluster summary (20 GeV γ)



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

Energy resolution from counting clusters



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

Improved compared to hit resolutions:

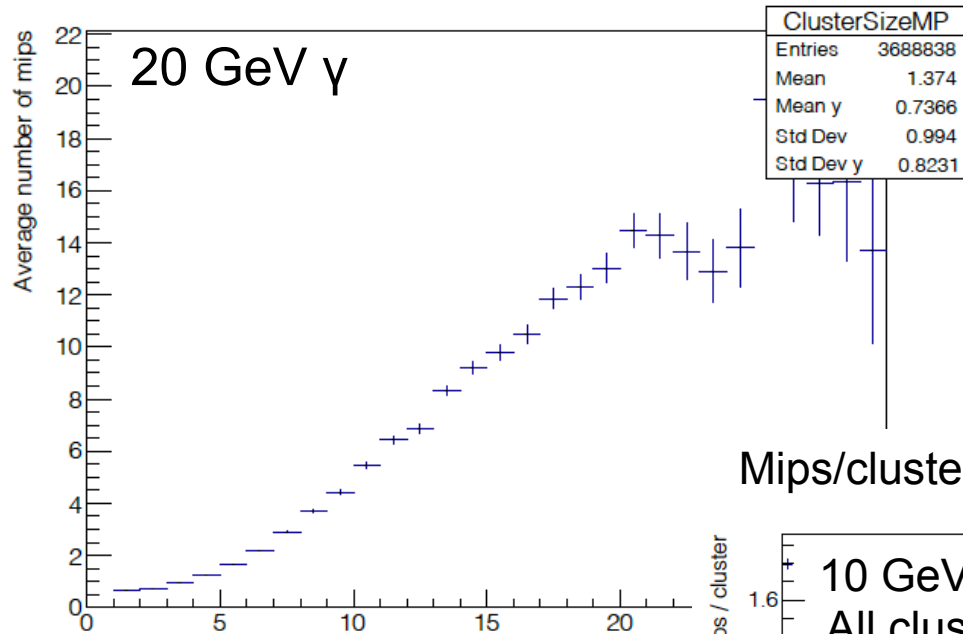
$$\frac{16.4\%}{\sqrt{E}} \oplus 2.0\%$$

But, cluster properties can improve more.



Mips/cluster and shower radius dependence

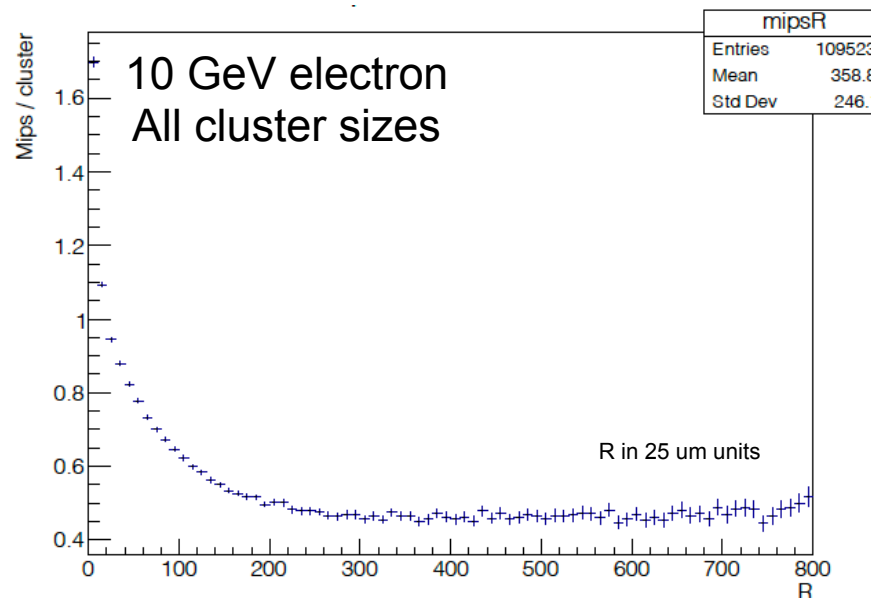
Average mips vs.Cluster Size



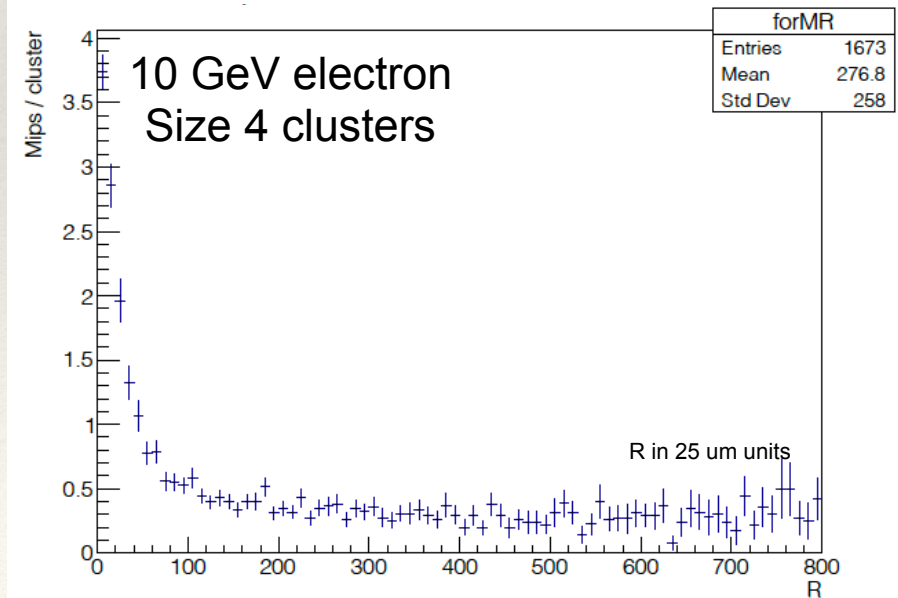
Cluster details “sense” number of mips:
Position (radius from shower axis);
Cluster size.

Analysis using these parameters improves
cluster resolution in our studies.

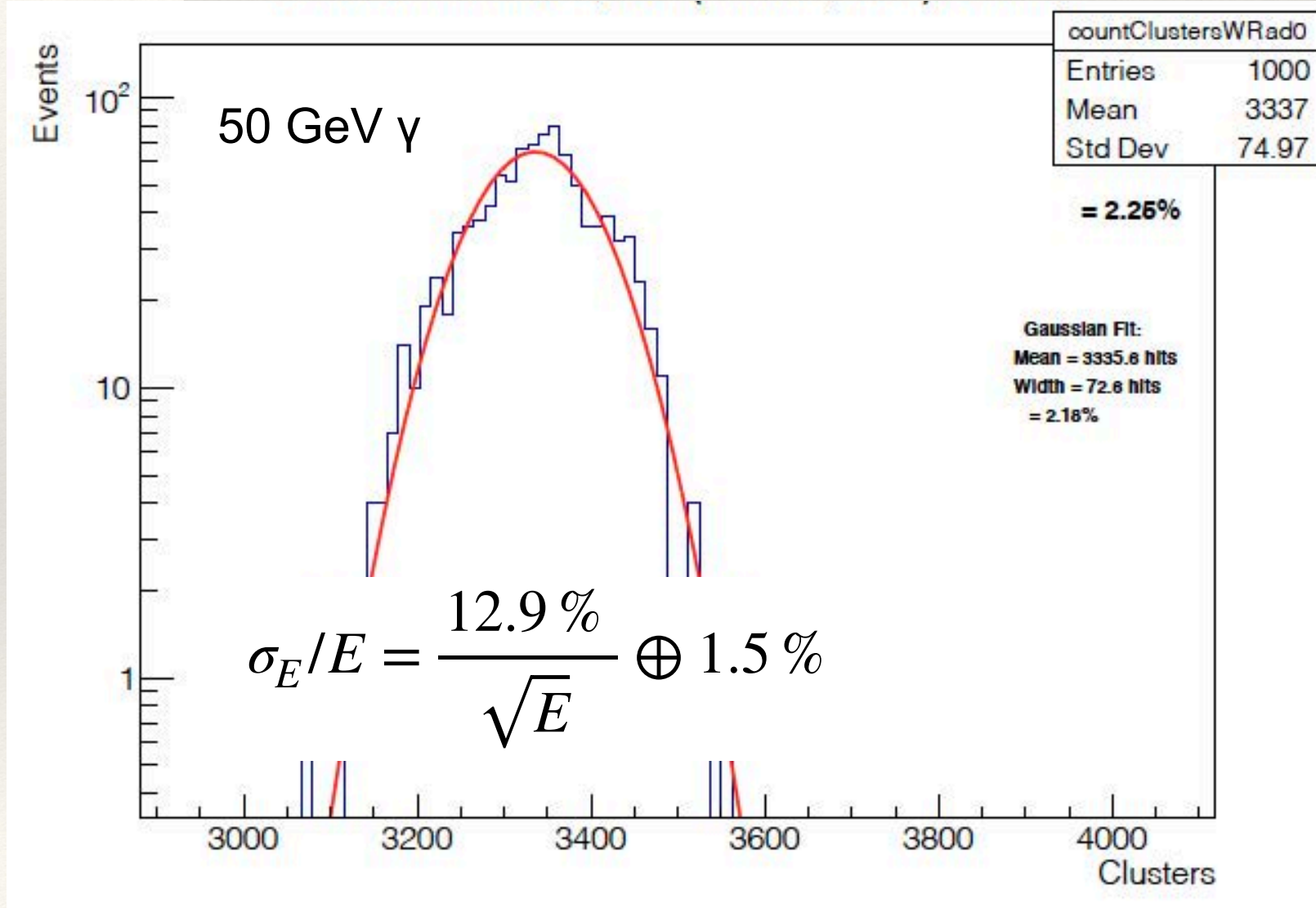
Mips/cluster vs. Radius from shower axis



Mips/cluster vs. Radius from shower axis



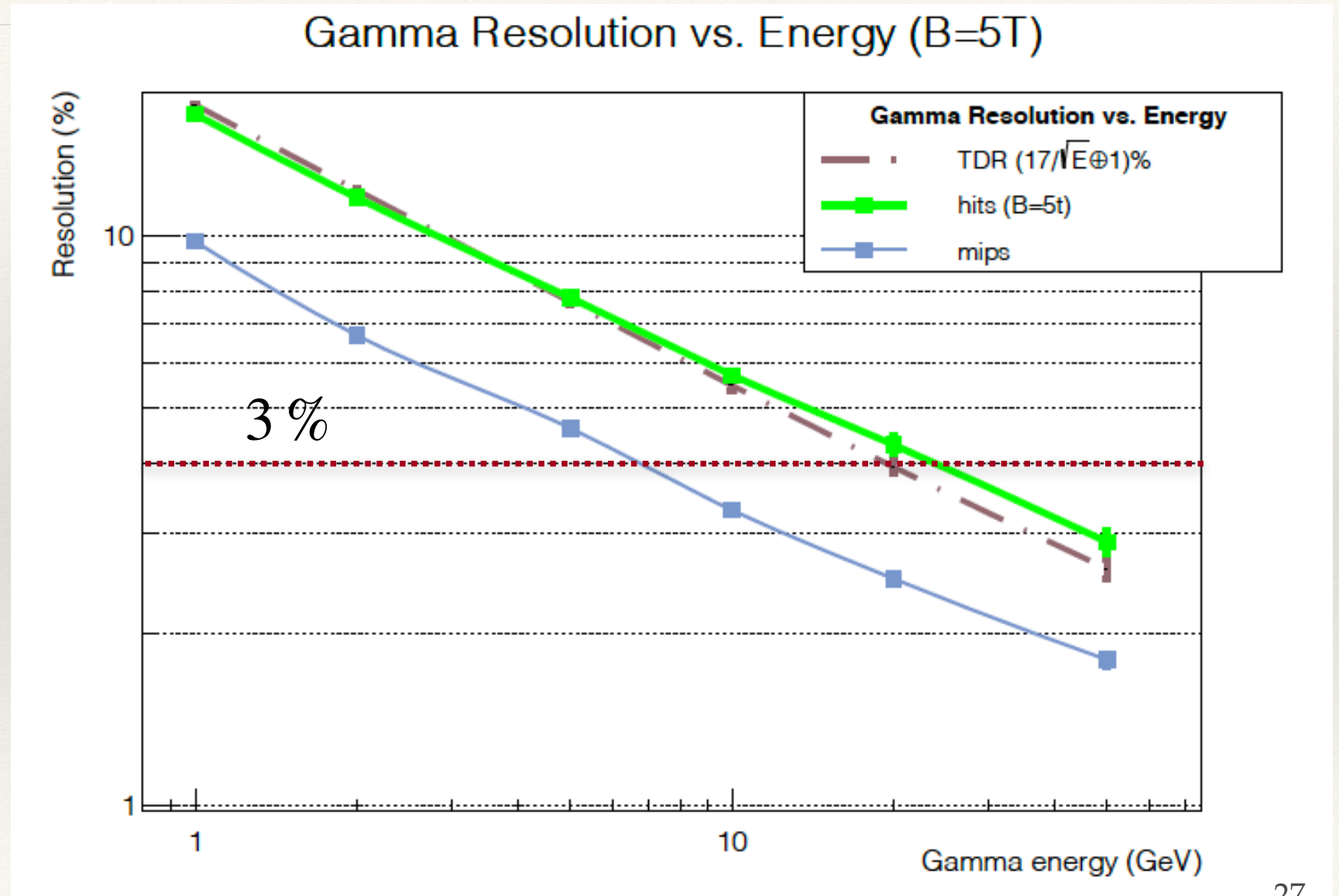
Clusters weighted by radius & size



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

Resolution vs. Energy (hits/clusters/mips)

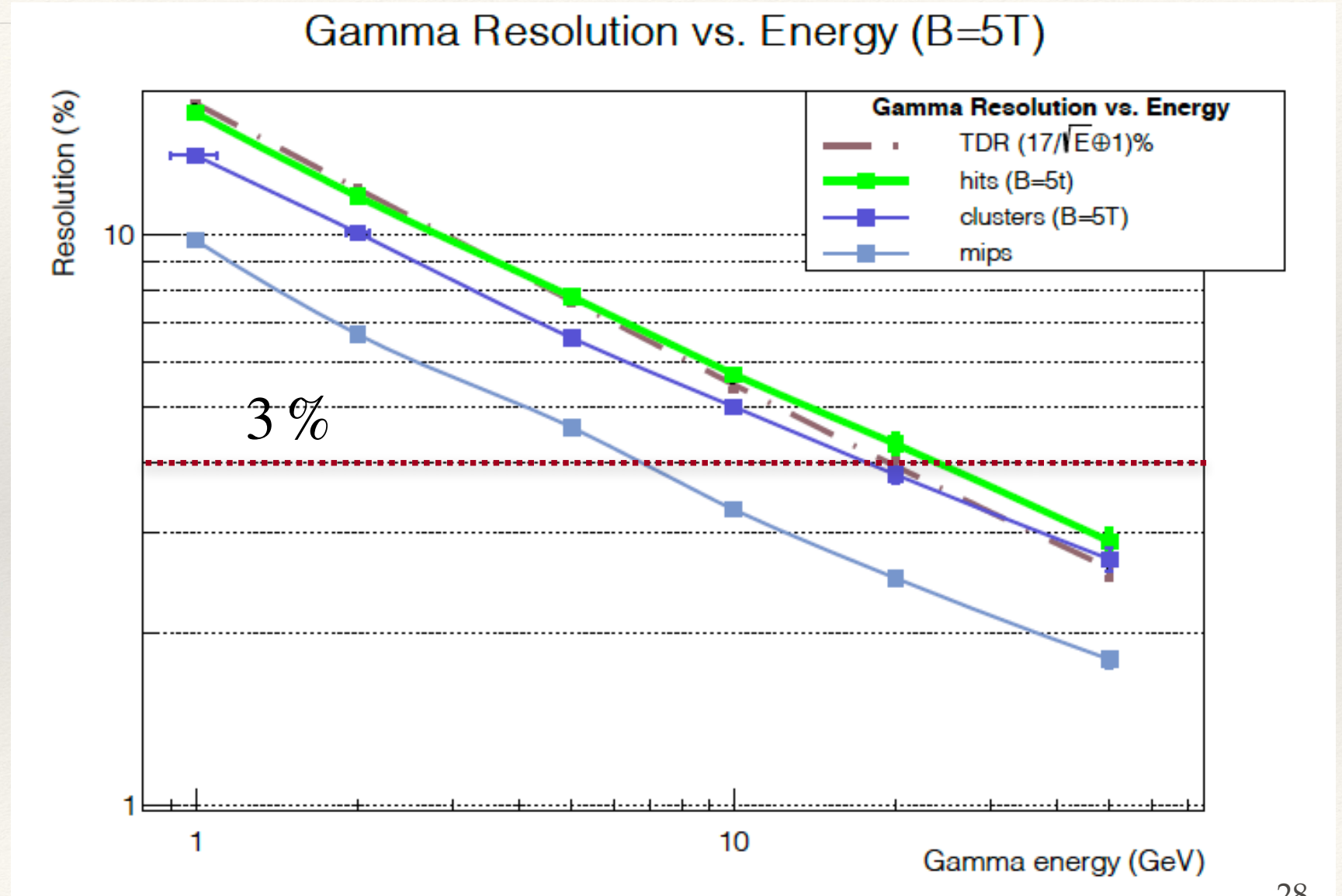
Resolution vs. Energy
(hits and mips)



Resolution vs. Energy (hits/clusters/mips)

Resolution vs. Energy
(hits / clusters / mips)

Simple cluster
performance is better
than hit counting.



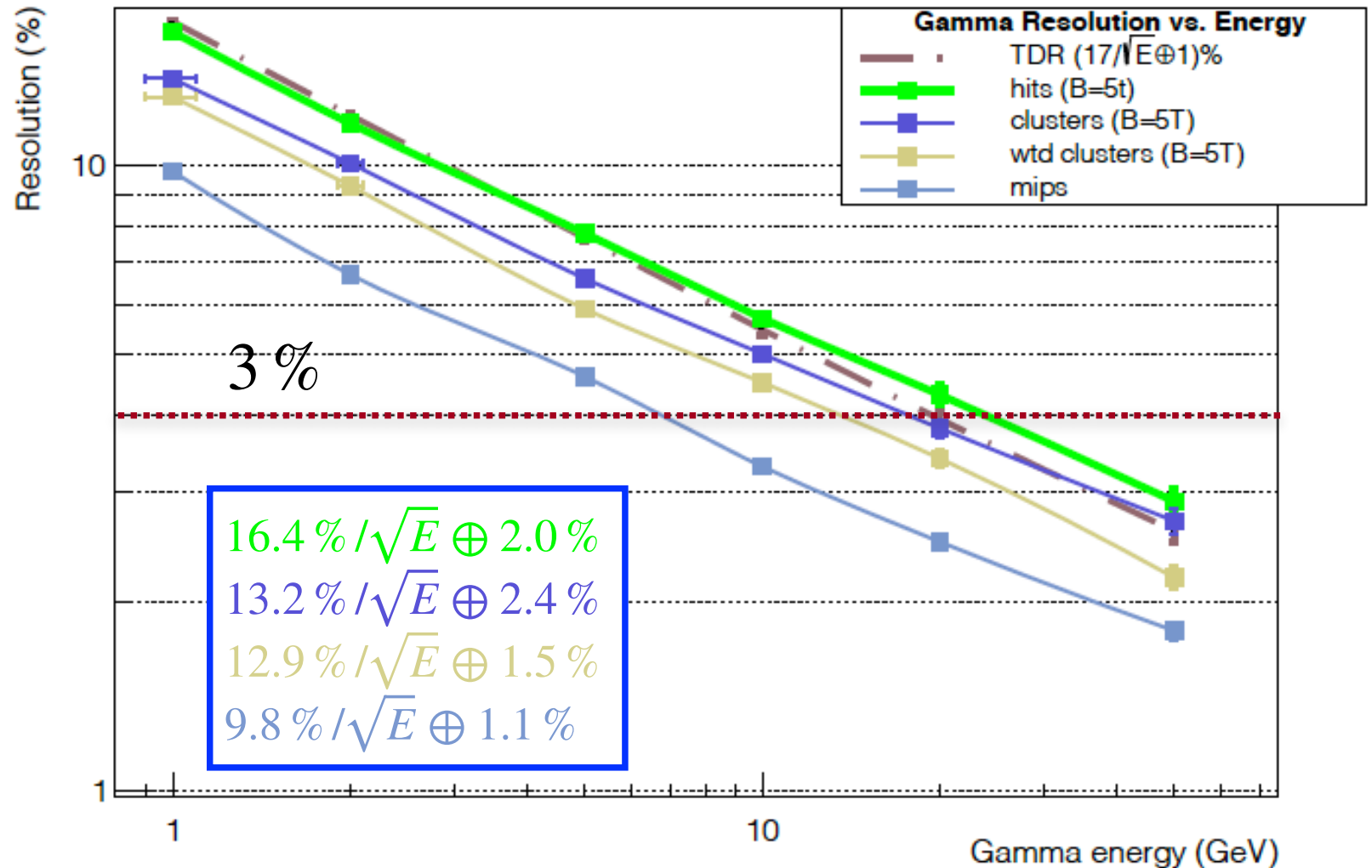
Resolution vs. Energy (hits/clusters/mips)

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.

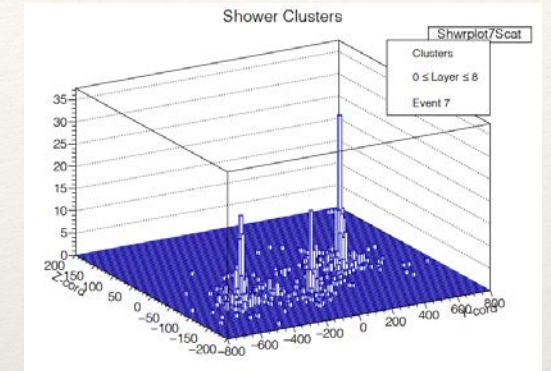
Gamma Resolution vs. Energy (B=5T)





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.
- ❖ $\text{Pi}0$ reconstruction in busy environment.



MAPS for SiD Tracking



- ◆ Size similar to that described for SiD in the ILC TDR, 10×10 cm² devices. Constructed by stitching 2 cm x 2 cm reticles.
- ◆ Exceptional granularity of 25 μ m by 100 μ m pixels, with 25 μ m in bend direction resolution of $25\mu\text{m} / \sqrt{12} \approx 7 \mu\text{m}$ without charge sharing.
- ◆ The 25 μ m pixel matches KPiX-readout, silicon-strip width of the SiD TDR design recently assembled, tested, and shown to achieve 7 μ m resolution[†].
- ◆ The depleted 10 μ m 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](https://arxiv.org/abs/2203.07626) [physics.ins-det]