UNIVERSITY OF BIRMINGHAM | SCHOOL OF PHYSICS AND ASTRONOMY

Digital Electromagnetic Calorimetry at the FCC-hh

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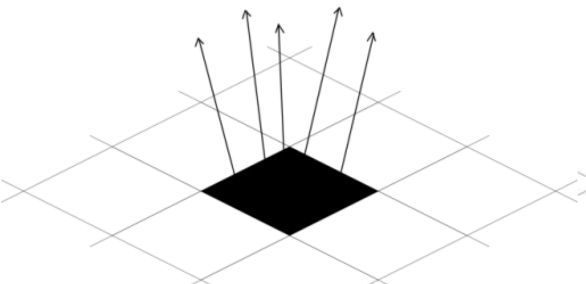
Contents

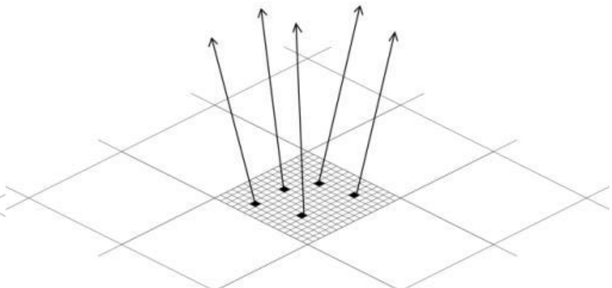
- Digital Calorimetry concept
- Previous experimental work
- Simulations within FCCSW
- Geometric effects
- Future Outlooks

Digital Calorimetry: The Concept

- Dates back to c.2005 work within CALICE
- Make a pixelated calorimeter to count the number of particles in each sampling layer
- Was designed to reduce uncertainties due to Landau fluctuations of energy deposits
- Ensure that the pixels are small enough to avoid multiple particles passing through it to avoid undercounting and non-linear response in high particle density environments
- Proposed ILD ECAL has a silicon area of ~2400m^2 .
- Digital variant would require 10^{12} pixels

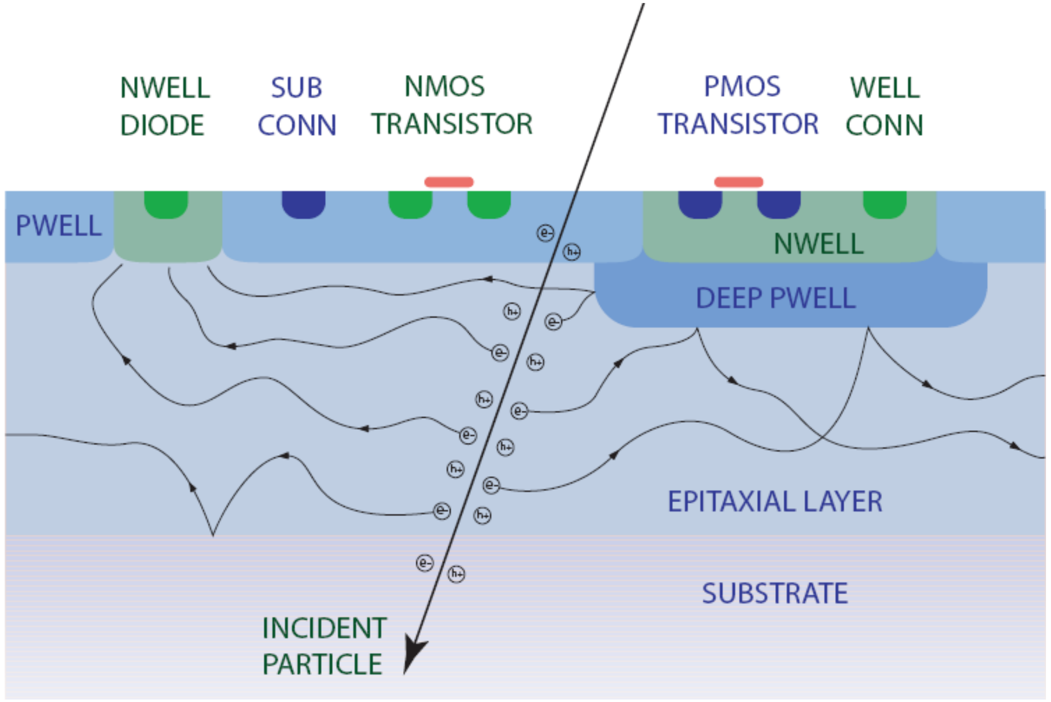


Analogue: 5mm pitch



Digital: 50um pitch

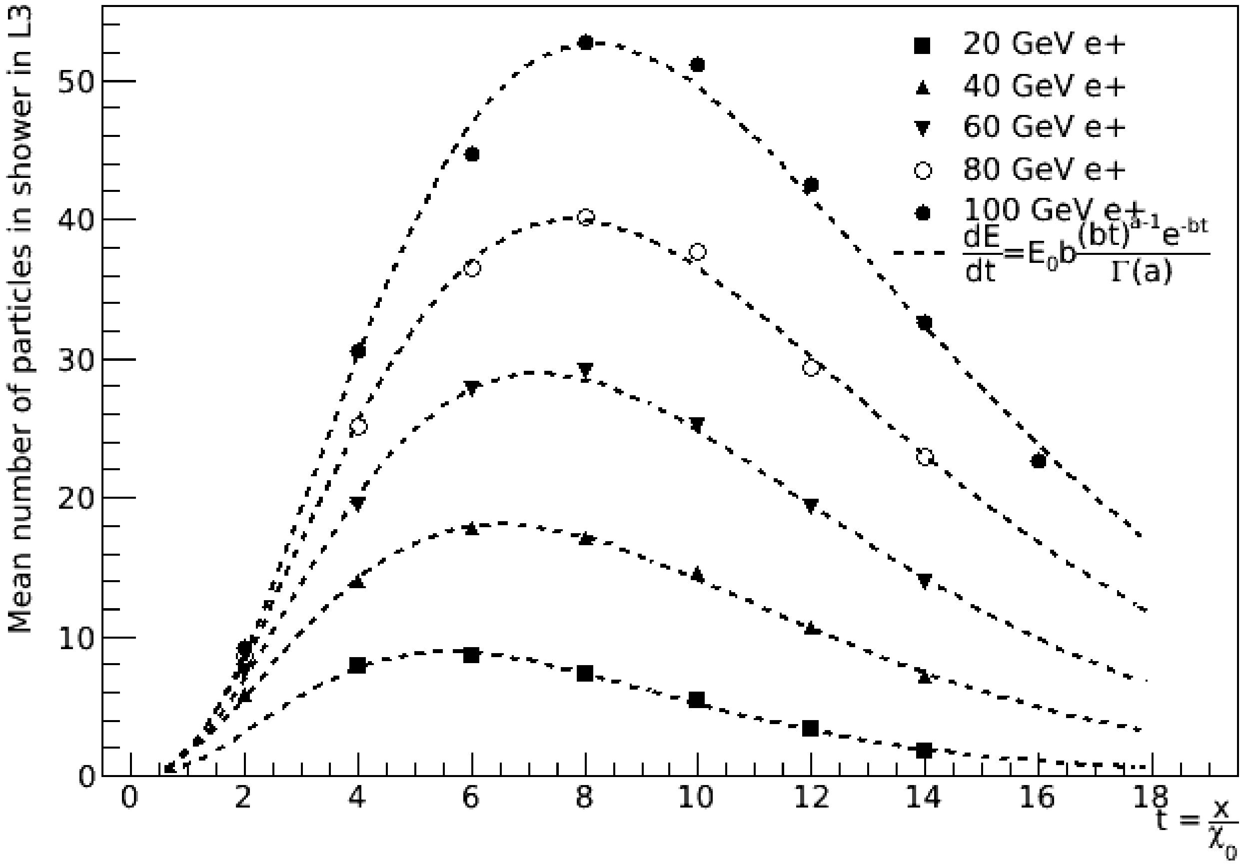
CMOS MAPS



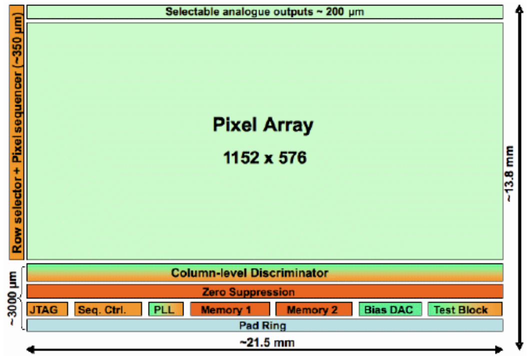
- Can achieve the ultra high granularity with the use of CMOS Monolithic Active Pixel Sensors
- Thin sensitive region, usually 12-25um
- Low noise
- Deep wells shield parasitic charge collection so can use full CMOS
- Readout on the sensor so no need for separate chip
- Developments in HV/HR CMOS to deplete the sensor improve charge collection speed and radiation hardness

CERN TB September 2010: Shower Multiplicity in EUTelescope

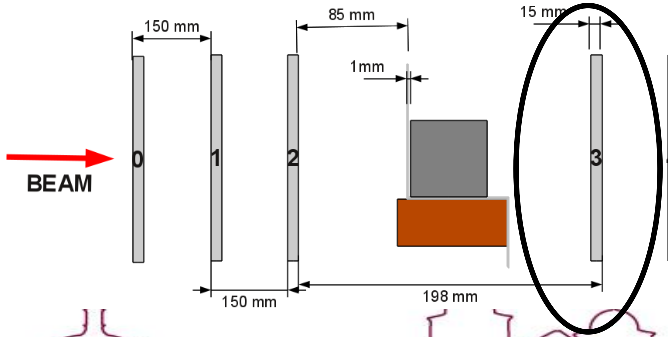
SPiDeR



Mimosa-26
1152x576 matrix
18.4µm Pitch
21.5x10.6 mm area



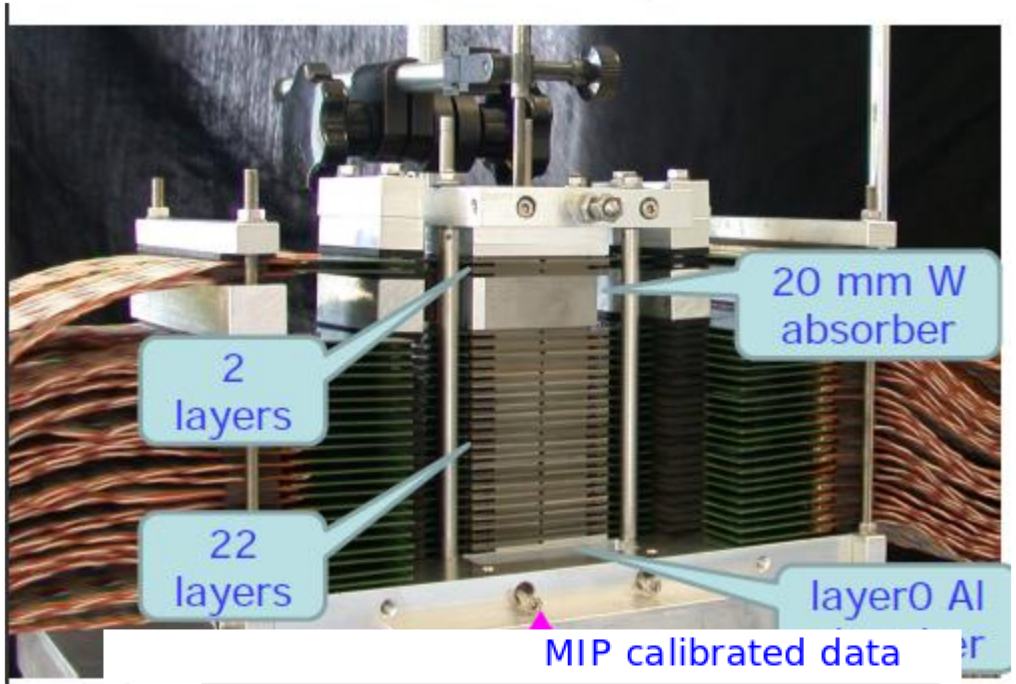
- Form tracks in first 3 layers
- Shower induced in W
- Measure core in 4th layer 15cm from W

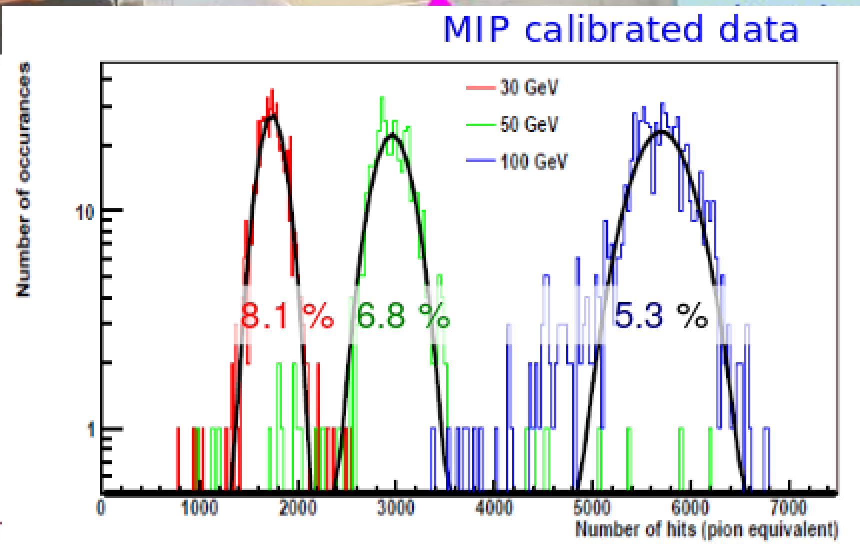


DECAL pixel counting shows correct shower development behaviour

ALICE FoCal: Test beams

- ALICE Forward Calorimeter (FoCal) require highly granular to separate showers
- Mixture of MAPS and pad sensors proposed
- Prototype used 24 plane
- Each plane consisted 4 Mimosa-23 (30μm Pitch) interweaved with W
- Tested at DESY and SPS in 2012
- Details can be found here https://agenda.linearcollider.org/event/7454/contributions/38742/attachments/31355/47159/CaliceParisNooren.pdf
- https://agenda.linearcollider.org/event/7454/contributions/38724/attachments/31383/47207/focal-analysis-calice.pdf





DECAL implementation within FCCSW

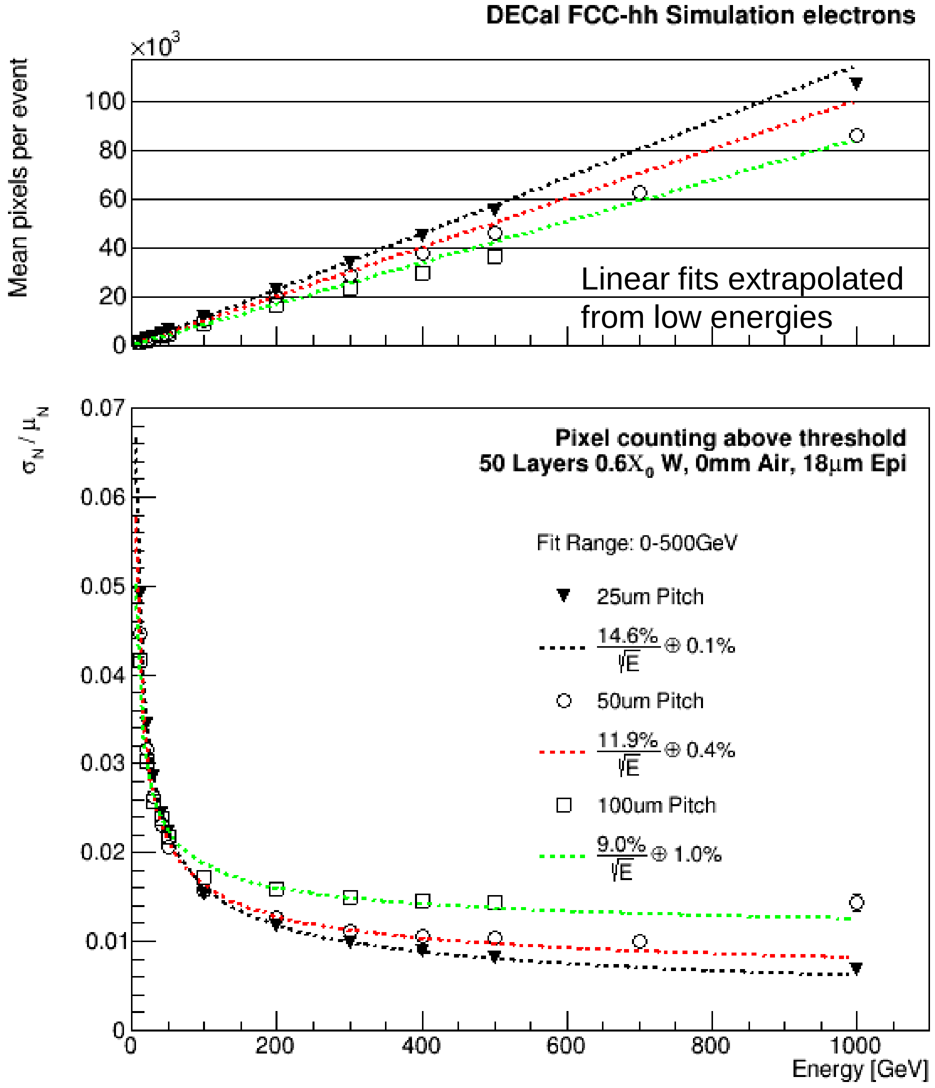
- Previously all work in Birmingham on DECAL has been in the context of ILD within iLCSoft. Modified the current ECAL driver for our needs.
- DECAL for hadron collider will have additional complexities such as pile-up, much higher energy jets, higher radiation environment. FCCSW will allow us to simulate these directly
- DECAL implementation at the early stages of FCCSW development also means that we can optimise layout
- Currently simple model used of concentric cylinders repeating
  - Epitaxial layer (sensitive) 18um thick
  - 50um Pixel Pitch (default)
  - Substrate 450um thick Si
  - Absorber material (W/Pb, different thicknesses)
  - Air gaps as required

```
// STANDARD CONFIGURATION WITH PADDING (air) >= 0 mm
// |    MODULE 1     |     MODULE 2     |  ...  |    MODULE N     |
// |   |   |   |   |   |   |   |   |  ...  |   |   |   |   |
// | E | S | A | A | E | S | A | A |  ...  | E | S | A | A |
// | P | U | B | I | P | U | B | I |  ...  | P | U | B | I |
// | I | B | S | R | I | B | S | R |  ...  | I | B | S | R |
// |   |   |   |   |   |   |   |   |  ...  |   |   |   |   |
```

- Digital SD class implemented which sums energy per pixel in an event, applies threshold, and counts pixels above threshold.

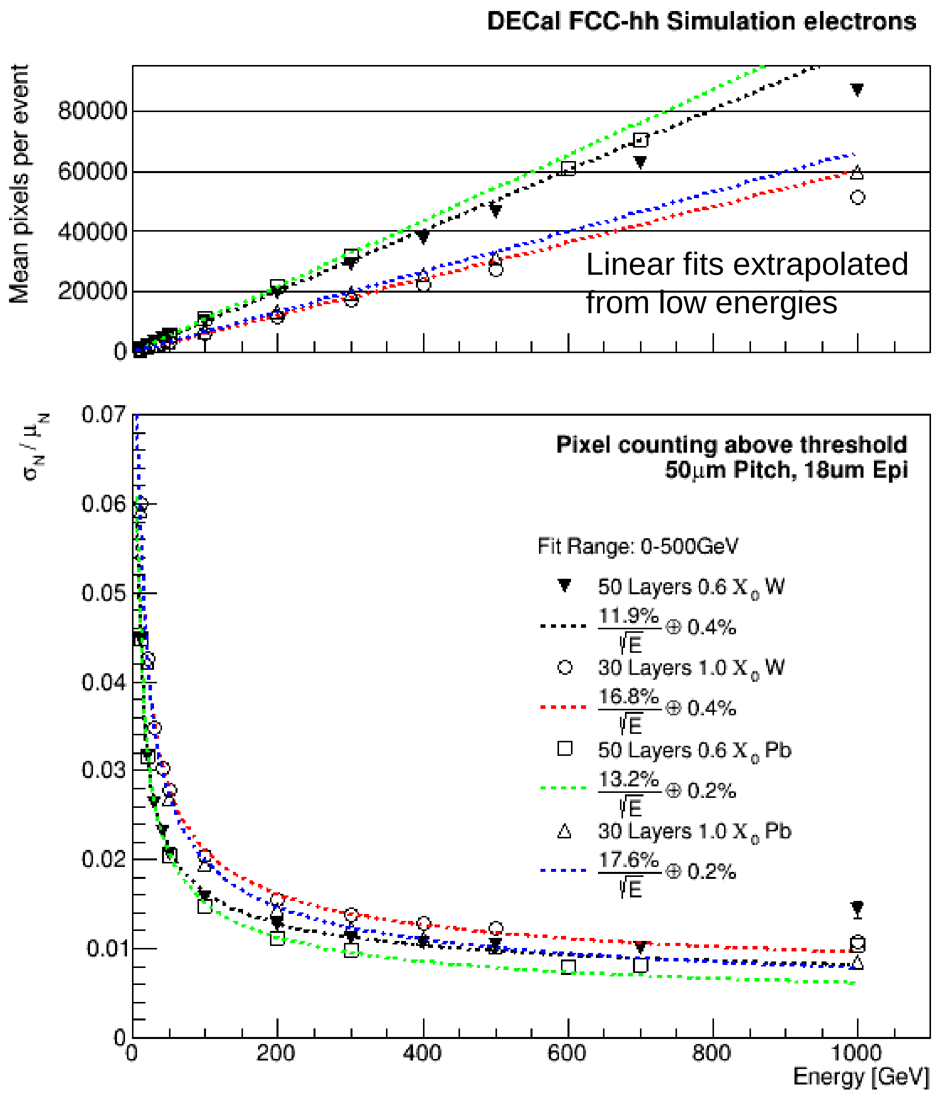
Effect of Cell Size

- Impact on multiple particles hitting the same pixel studied: pitches of 25um, 50um, 100um
- Previous studies mainly up to 100 GeV
- Work for ILC demonstrates optimal pitch:thickness parameters of 50:18um
- Energy resolution comes from just counting pixels (at this stage)
- For 100um pitch the detector becomes very non linear very quickly
- 25um pitch suffers from particles hitting multiple pixels in a layer and increasing the number of hits / particle. -> **Clustering underway to solve this**
- Studies in this talk focus on 50um pixels to optimise linearity



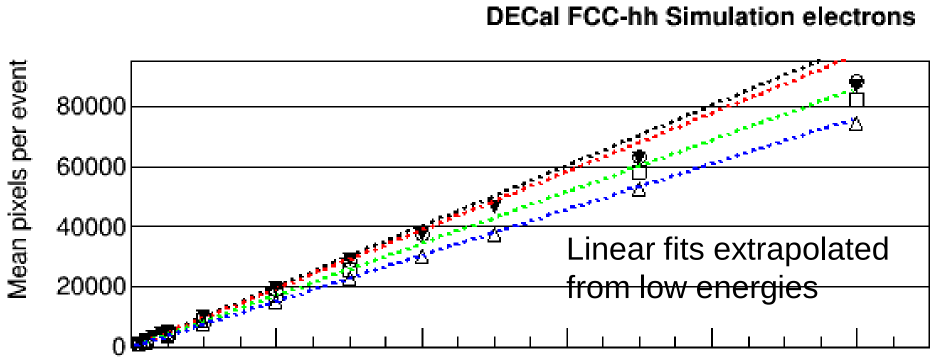
Effect of Layer Geometry

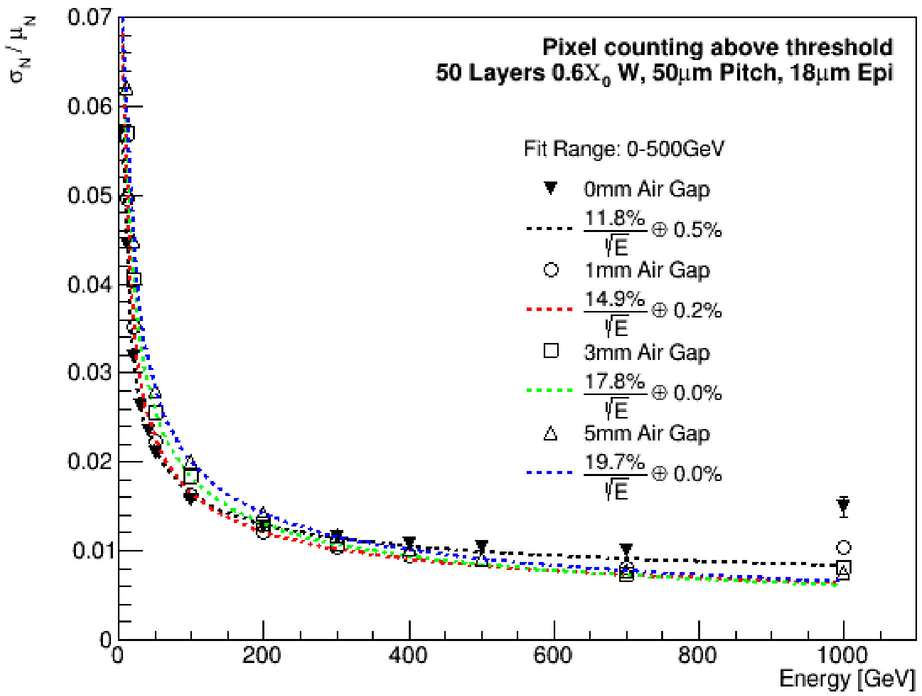
- Detector Configuration
  - 30 layers of $1.0\chi_0$ W
  - 30 layers of $1.0\chi_0$ Pb
  - 50 layers of $0.6\chi_0$ W
  - 50 layers of $0.6\chi_0$ Pb
- Increased number of layers (sampling fraction) improves resolution for both materials
- Material choice has minimal effect on energy resolution
- **Pb improves linearity and 50 layers achieves energy resolution of 13%/√E (but thicker)**

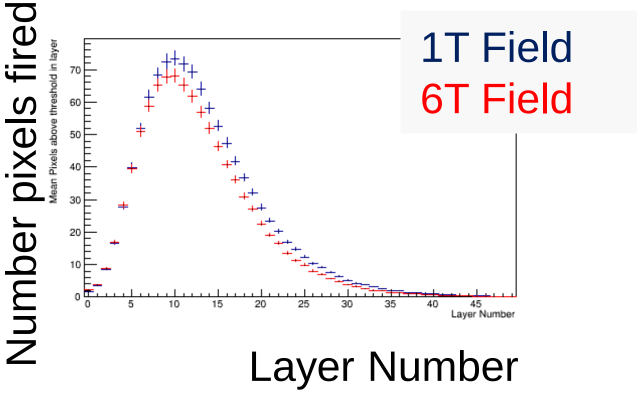


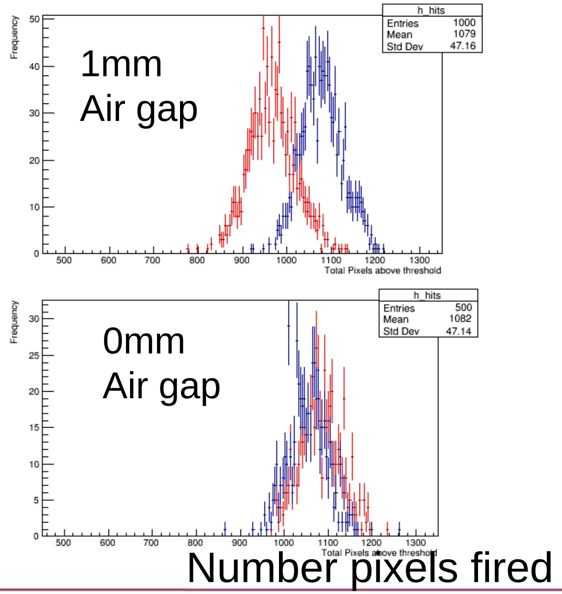
Air Gap

- Air gap varied between layers to access impact
- Linearity improves with air gap as shower has more range to spread which reduces the number of pixels with multiple particles
- However, the resolution decreases
- The counts are reduced due to magnetic field effects where low energy particles exit the W but are bent in the air and do not reach the sensitive layer









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- However, the resolution decreases
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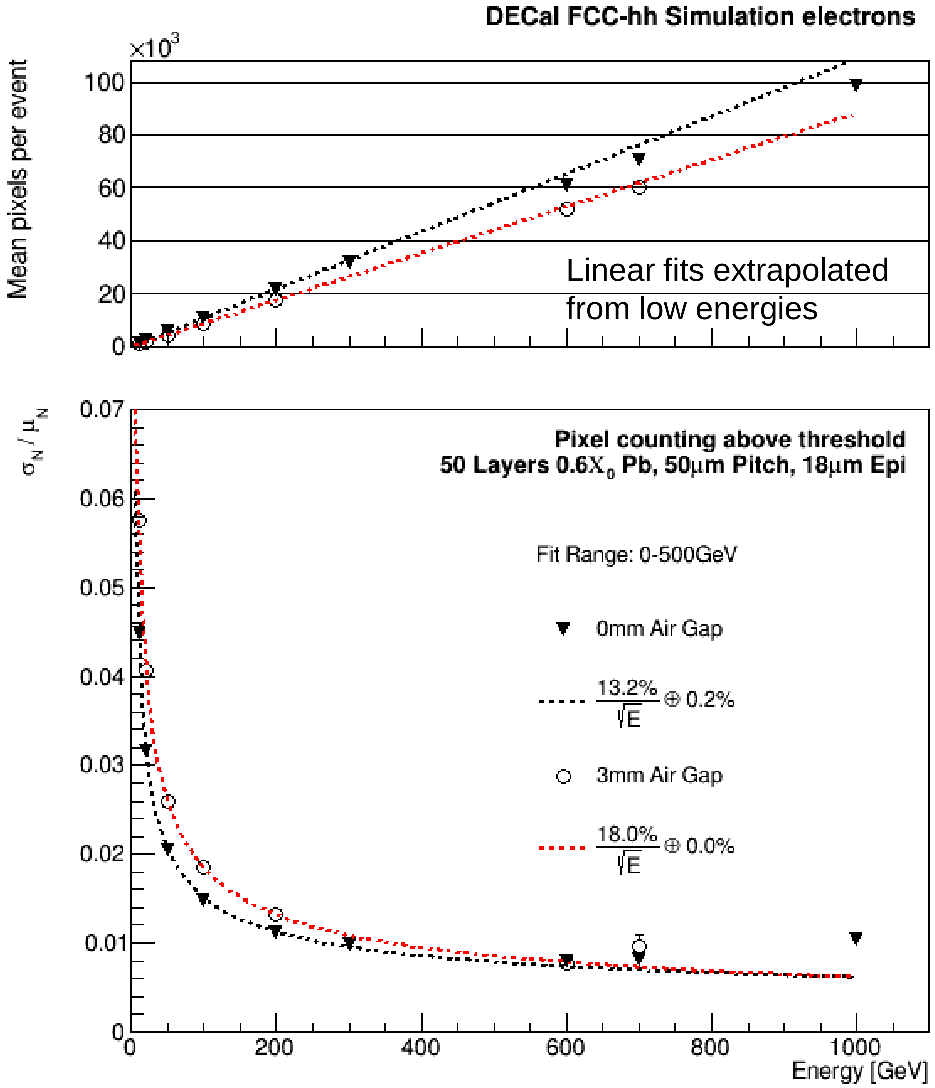
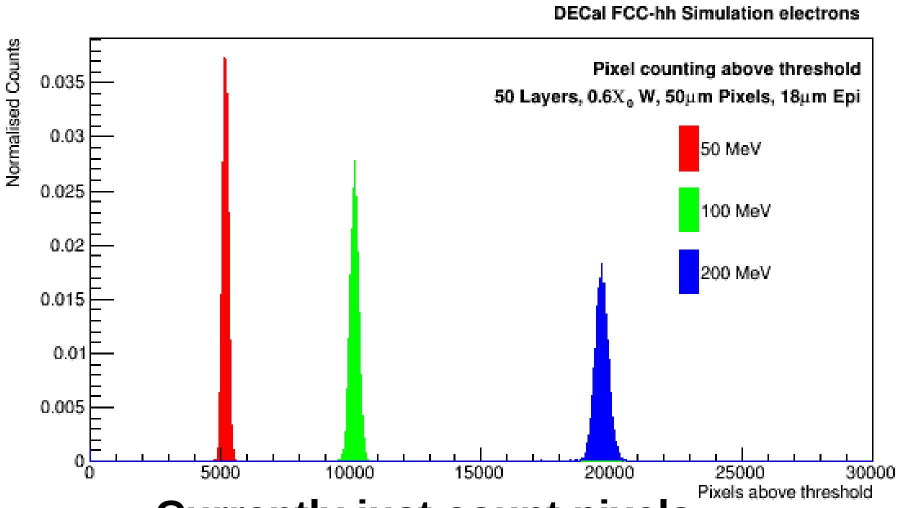
- Linearity improves for Pb with 3mm air gap up to 700 GeV

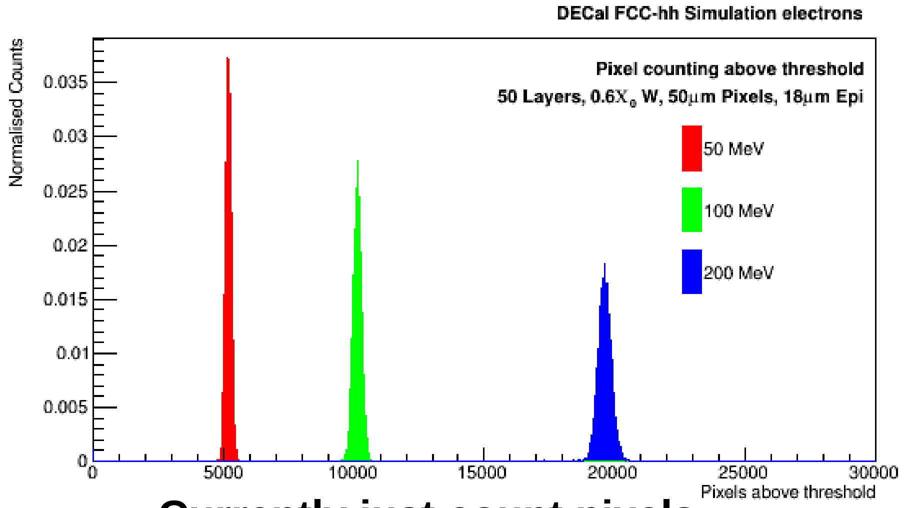


Further considerations: Using shower properties

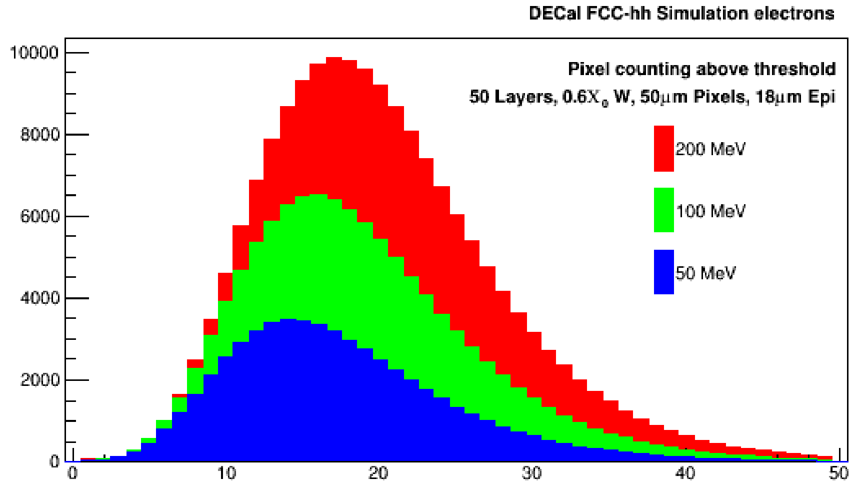


Currently just count pixels

Further considerations: Using shower properties



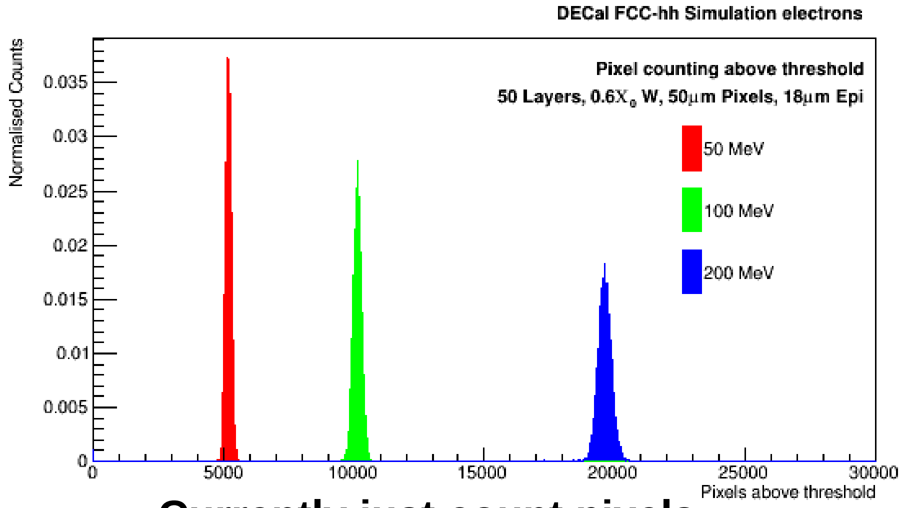
Currently just count pixels

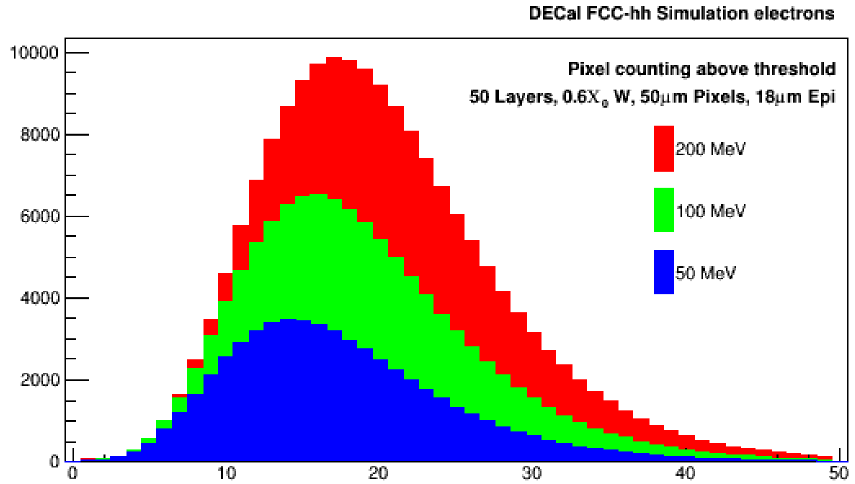


Longitudinal shower profiles

- **Peak position**
- **Rising / falling edge profiles**
- **FWHM**
- **Ratio of hits in layers**

Further considerations: Using shower properties





Currently just count pixels

Longitudinal shower profiles

- **Peak position**
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Channel Counts

Layers	Material	Pixel Pitch [um]	Air Gap [mm]	Total ECAL thickness [mm]	Number of Pixels *^	Number of pads *^#	Area of Silicon *^ [m^2]
30	Tungsten	50	0	119	2.24e12	2.24e8	5500
50	Tungsten	50	0	129	3.75e12	3.75e8	9400
50	Tungsten	50	3	278	3.89e12	3.89e8	9700
50	Pb	50	0	193	3.81e12	3.81e8	9500
50	Pb	25	3	343	1.52e13	3.96e8	9900

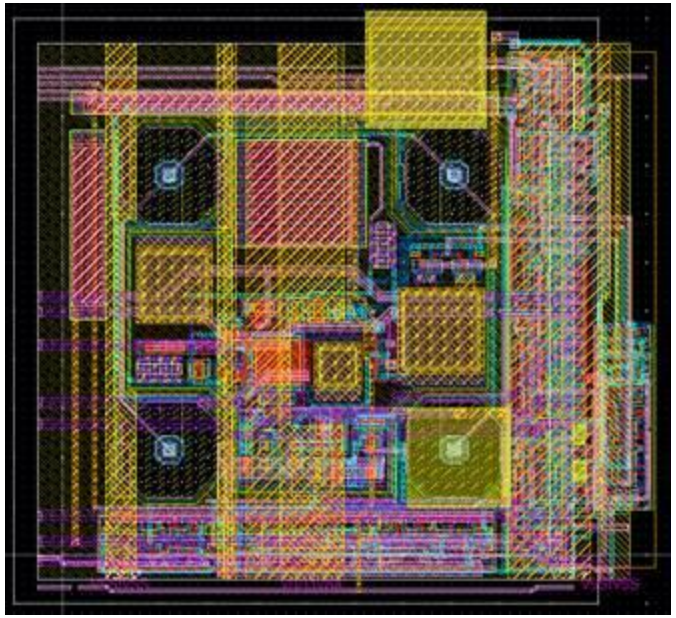
* 1800mm inner radius
# Pixels read out in 5x5mm^2 pads
^ Length of barrel = 16m

Further Considerations

- Radiation Hardness
  - Forward region of FCC-hh detectors Si probably not an option
  - Depleted CMOS currently under development (HV/HR) with results to 10^{15} n_{eq}/cm^2 and beyond presented recently by other groups so feasible for Barrel region
- Cost
  - Cost of CMOS imaging sensors needs to decrease to make affordable but over 20 years this is expected to fall dramatically.
  - A cost of 30 cents / cm^2 would mean an ECAL with ~$30M for Silicon.
  - Much more compact ECAL could also reduce size and costs of other systems
- Pile Up
  - Average occupancies look low compared to shower density but needs to be evaluated
- Deployment
  - Complimentary technology as a pre-shower / outer tracker
  - Seamless transition from outer tracker to ECAL possible with same technology

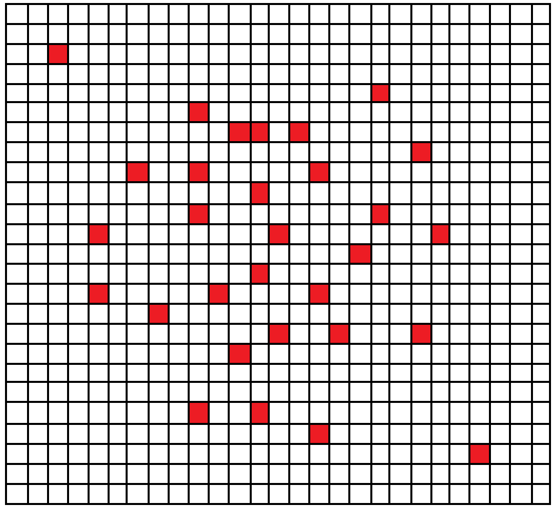
DECAL Chip for higher radiation environments

- Currently developing radiation hard, reconfigurable CMOS MAPS devices for future experiments
- Applications for tracking, calorimetry and medical applications
- Architecture designed for high rate (25ns BX), also relevant to other applications (hadron therapy at cyclotrons)
- Prototyping with same foundry as used for ALICE ALPIDE sensor
- Recent results from CERN (ALICE/ATLAS) have shown TJ modified process can deliver excellent radiation hardness https://indico.cern.ch/event/587631/contributions/2467389/attachments/1415291/2166554/CMOS-TJ-Trento-Pernegger.pdf
- Cannot read out every hit pixel address in 25ns so reduce data rates by reconfiguring the sensor
- FCCSW has been used to influence key design choices such as the maximum number of allowed hits per column and dead time.



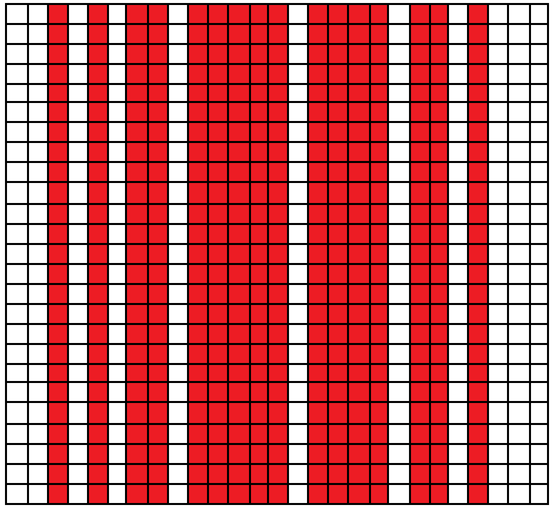
Reconfigurability

- Reconfiguring the pixel matrix to read out hit column addresses (effectively 5mmx50um strixel with applications in outer tracking and possibly pre-shower)
- Sum the number of hit pixels in a 5x5mm^2 pad and readout this value (calorimetry)
- Sums performed using digital logic in columns to avoid moving data



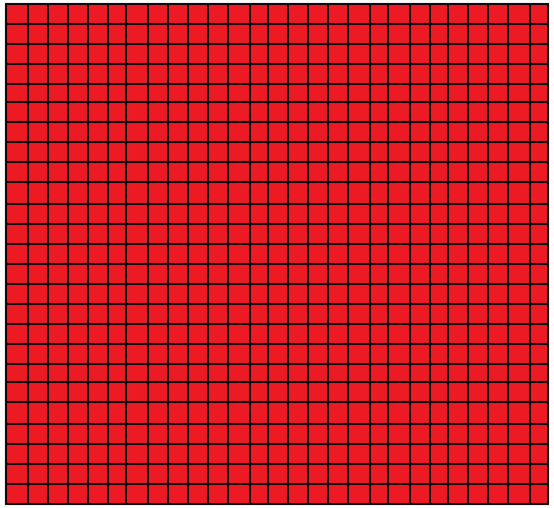
Pixel Mode

N pixels fired
N positions read out



Strixel Mode

hit column IDs read out



Pad Mode

Sum hits in all columns
hits and Pad ID read out

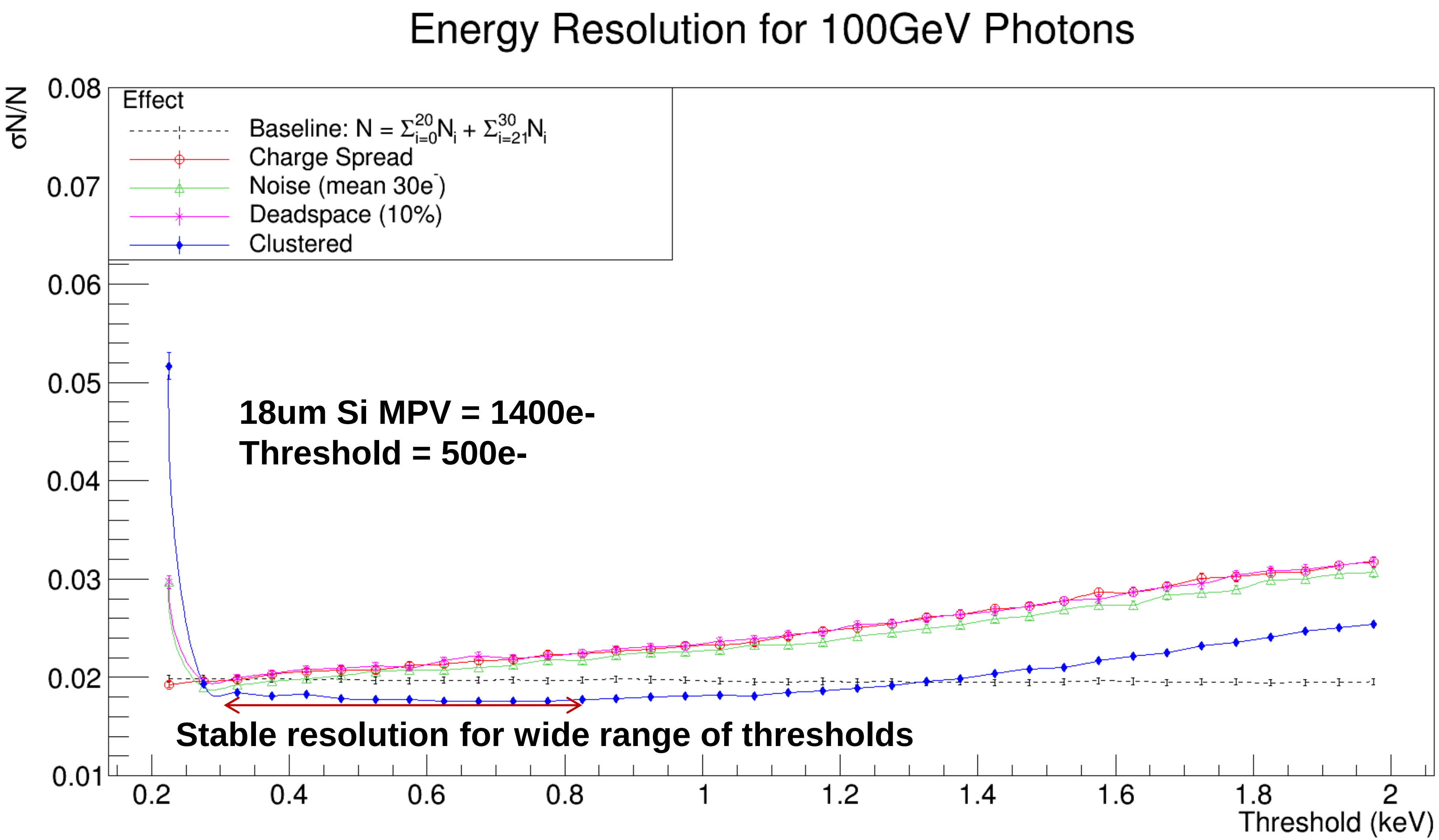
Conclusions

- Digital calorimetry is under development in CALICE for ILD and in ALICE for the FoCal with results looking promising
- DECAL geometry now included within FCCSW to allow studies at FCC-hh
- Lead for the absorber yields improved linearity
- A greater number of layers improves the energy resolution
- Added realism such as air gaps degrade the resolution but improve linearity
- The compact nature of the DECAL will reduce the overall detector size and have cost benefits
- Total of 10^{12} pixels in the FCC-hh ECAL barrel but can be read out using 10^{8} pads
- A study into shower shapes to improve resolution is underway
- DECAL chip has been submitted to foundry and will be tested later this year.
- This concept offers the opportunity to use the same technology for outer tracking, pre-shower, and calorimetry

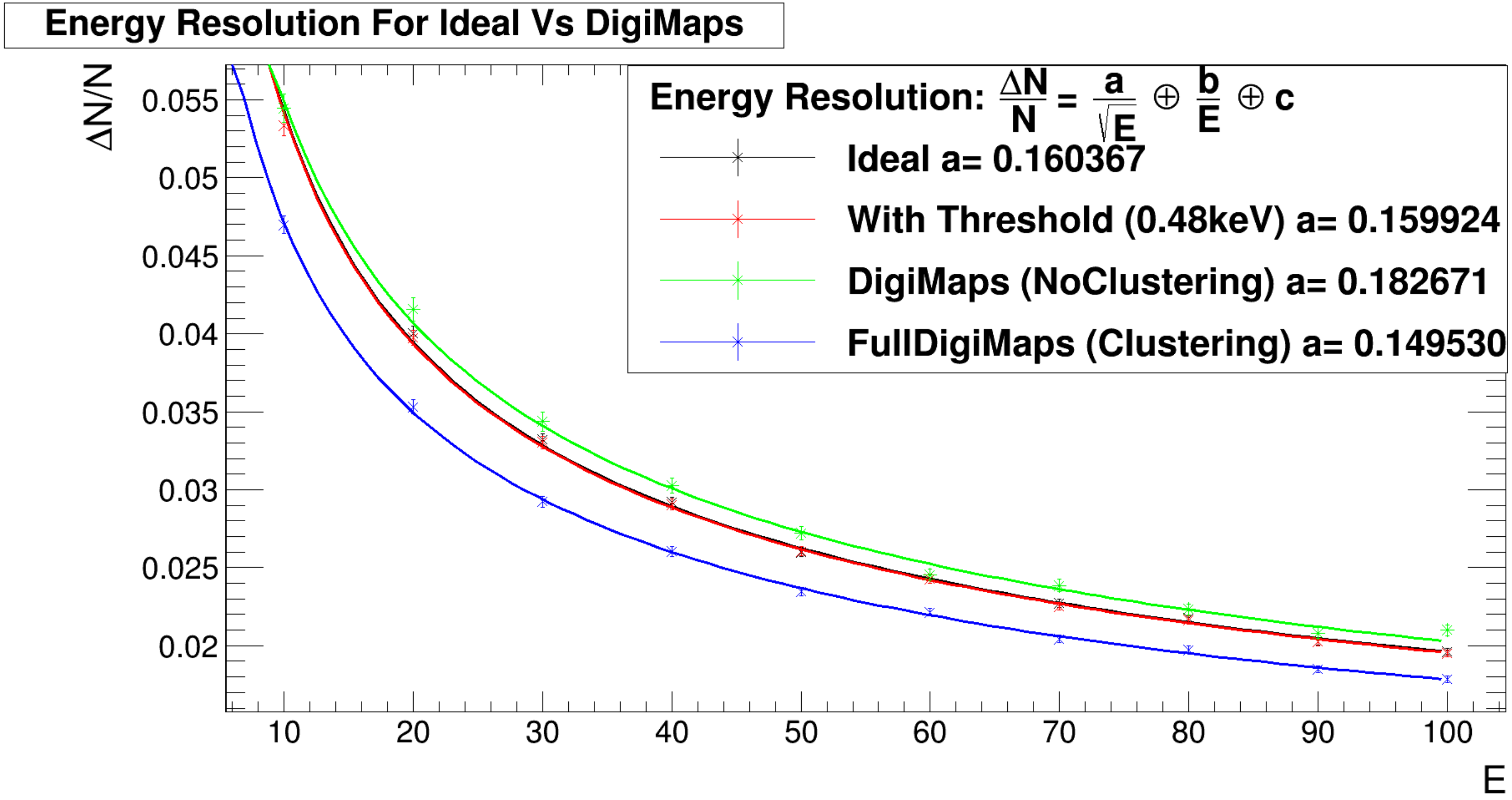
DigiMAPS Package

- Tool for adding additional levels of realism to simulations performed within iLCSoft for ILD.
- Developed for CALICE in 2008 by Anne-Marie Magnan (Imperial,CMS)
- Resurrected and adapted by Alasdair Winter (PhD UoB)
- Accounts for numerous effects not dealt with by Mokka:
  - Charge spread
  - Dead space
  - Clustering
  - Noise
  - Threshold spread

DigiMAPS Package

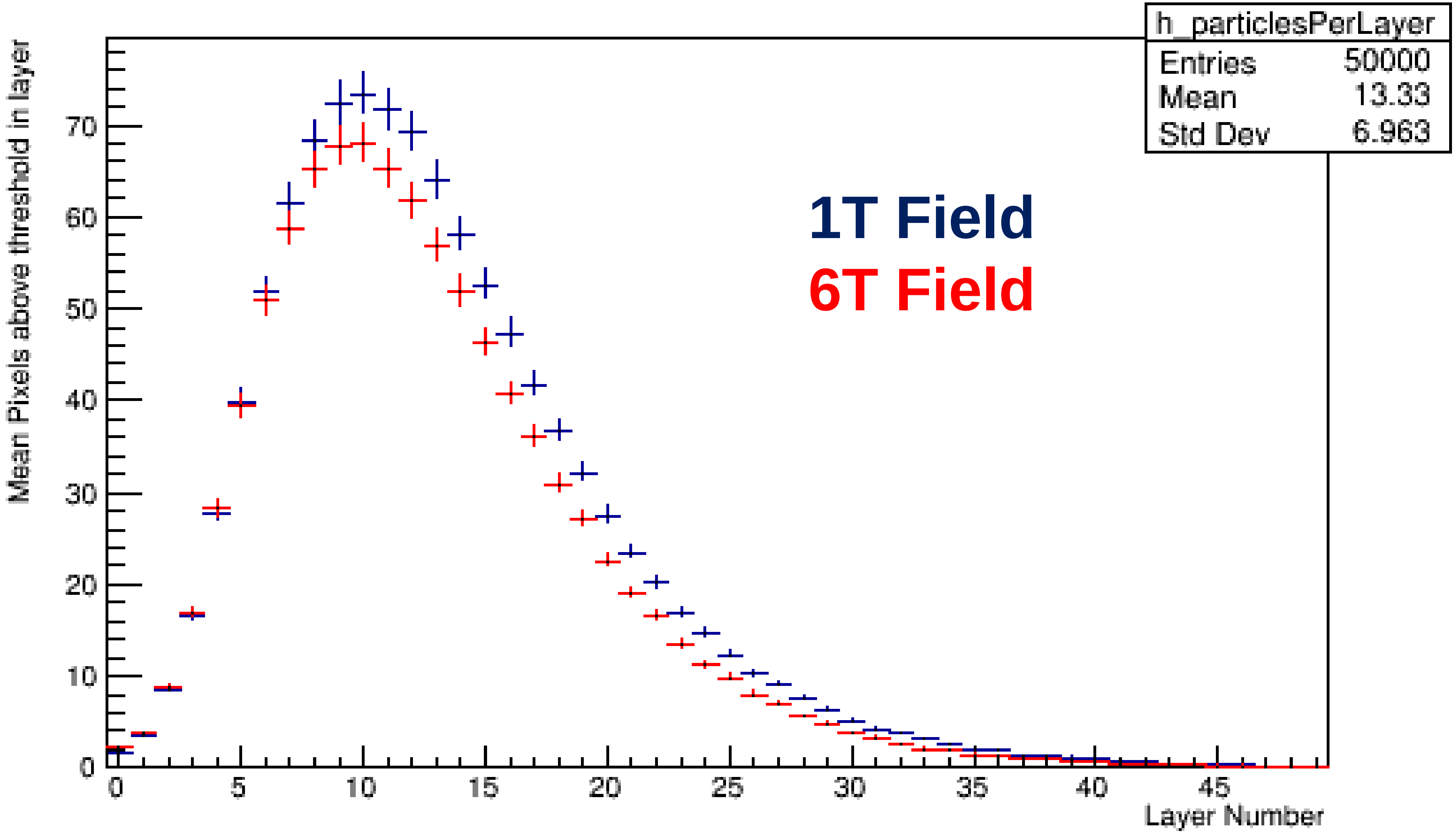


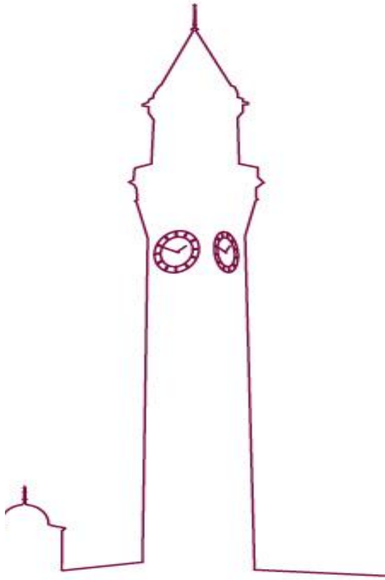
Impact of realism



Effect of Magnetic Field

50 Layers, 2.1mm W, 18um epi,
450um substrate, 1mm Air Gap
100 GeV e-





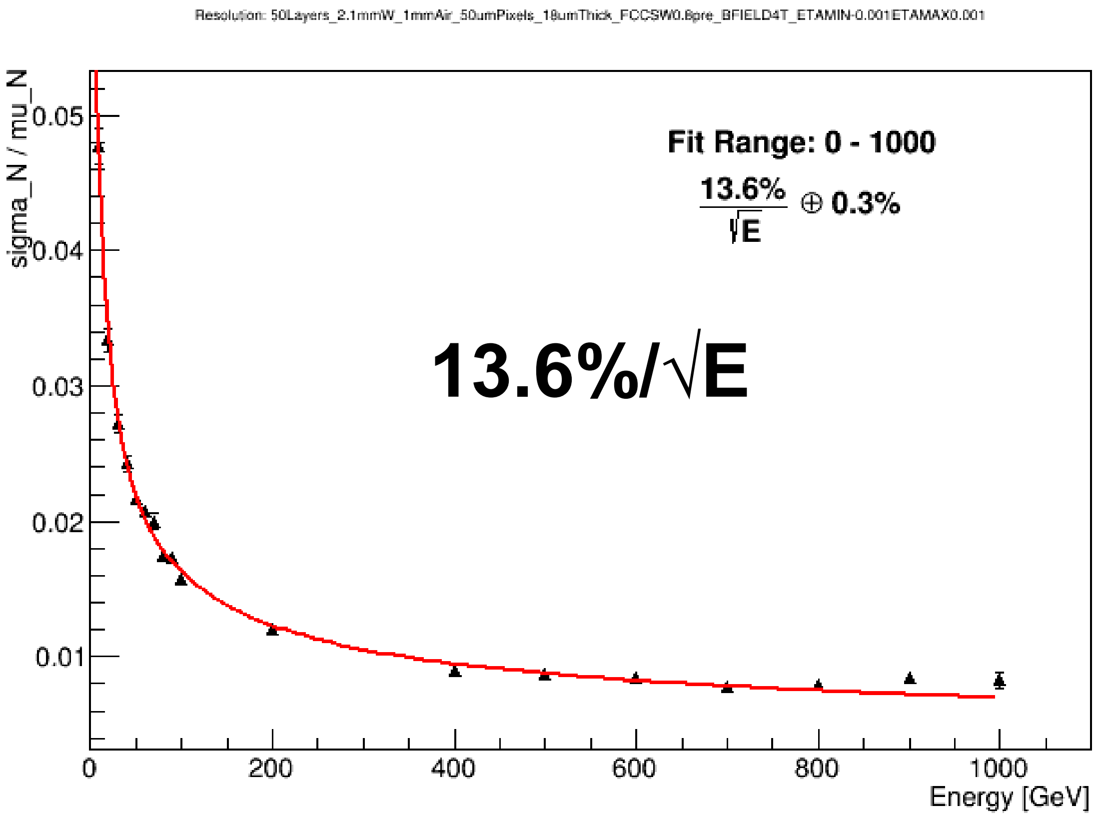
10 GeV electrons

- Previous results are all Si-W-Air-Si ….. W-Air-Si
- What happens if we swap to order to Si-Air-W-Si ….Air-W-Si?
- As we increase the B-Field we see an increase in counts for Si-Air-W-Si and a decrease for Si-W-Air-Si
- This points towards low energy particles curling up in the B-Field and either not reaching the Si (for Si-W-Air-Si) or being double counted in the Si (for Si-Air-W-Si)

B-Field (T)	Si-W-Air-Si counts	Si-Air_W-Si counts
1	107.8	104.1
2	100.8	N/A
3	88.7	109.8
4	86.5	115.6

Energy Resolution. 4T 10-1000GeV electrons, 1mm Air gap

- Si-W-Air-Si …. W-Air



- Si-Air-W-Si .. Air-W