UNIVERSITY OF BIRMINGHAM | SCHOOL OF PHYSICS AND ASTRONOMY

Digital Electromagnetic Calorimetry at the FCC-hh

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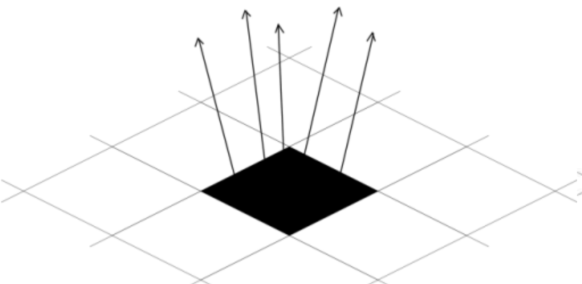
1st June 2017

Contents

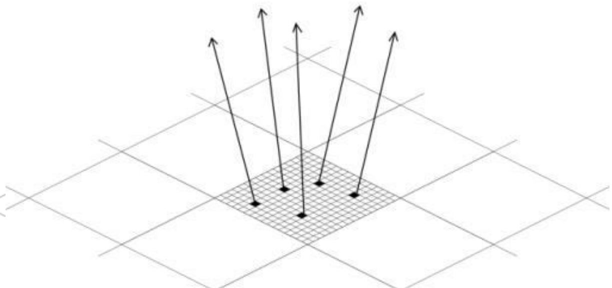
- Digital Calorimetry concept
- Previous experimental work
- Simulations within FCCSW
  - Geometric effects
- Future Plans
- DECAL Chip

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

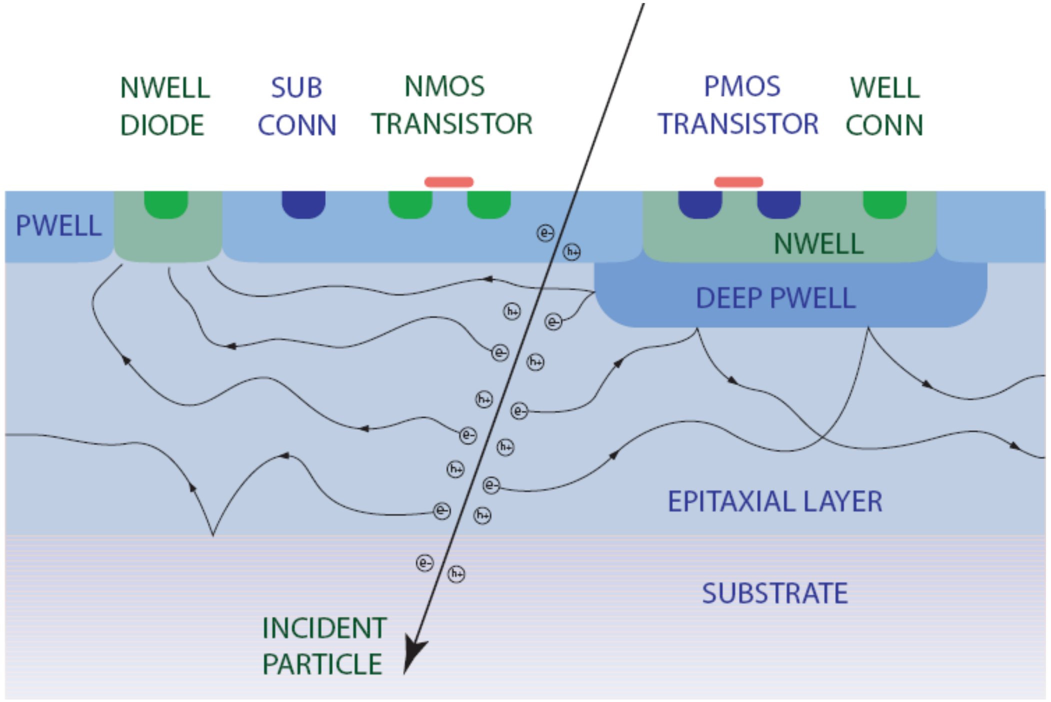


Analogue: 5mm pitch



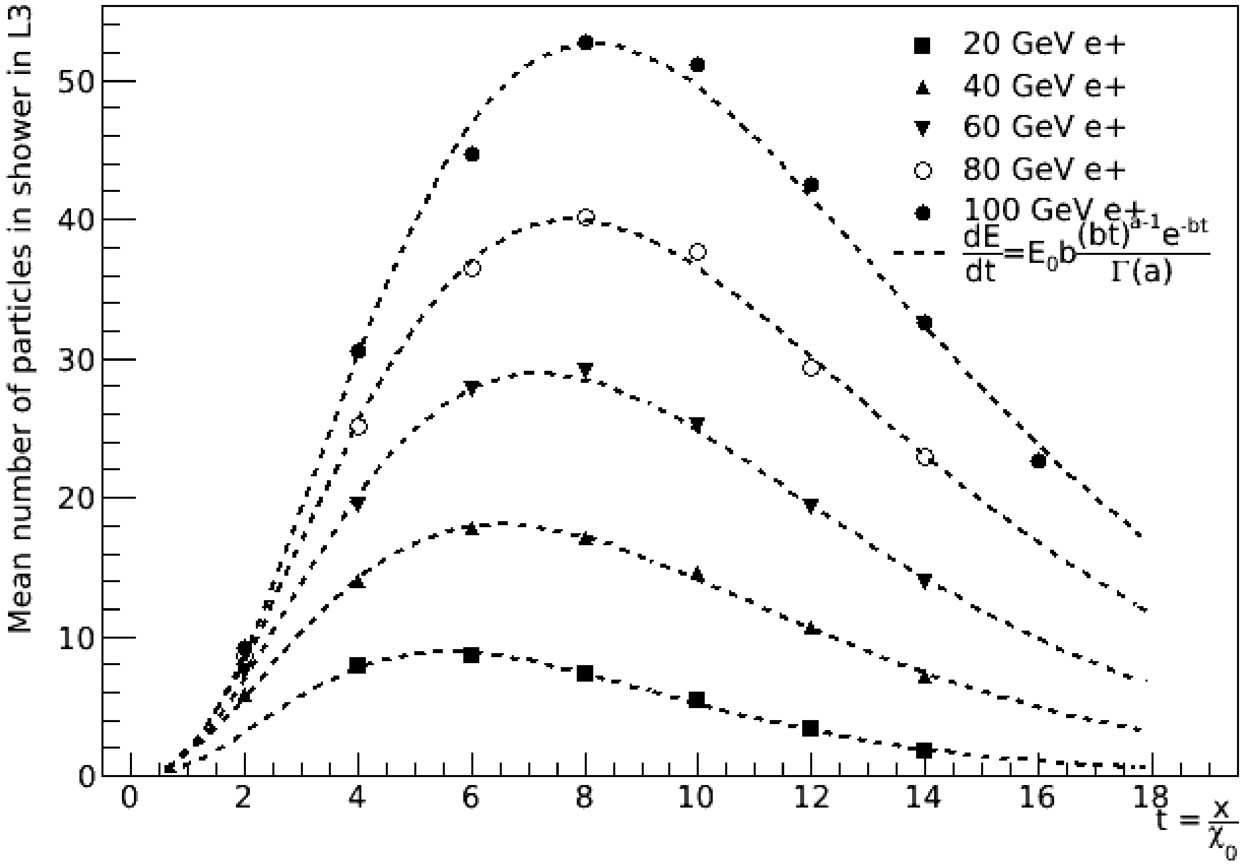
Digital: 50um pitch

CMOS MAPS



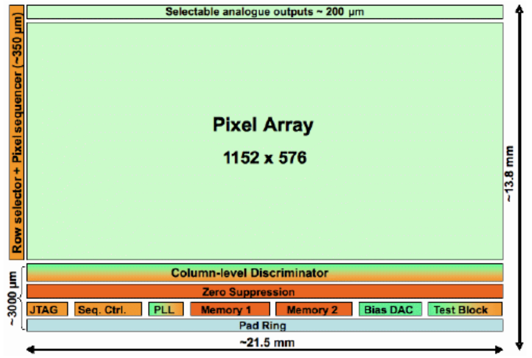
- Can achieve the ultra high granularity with the use of CMOS Monolithic Active Pixel Sensors
- Thin sensitive region, usually 12-25um
- Low noise
- Deep wells shield parasitic charge collection so can use full CMOS
- Readout on the sensor so no need for separate chip
- Developments in HV/HR CMOS to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

CERN TB September 2010: Shower Multiplicity in EUTelescope

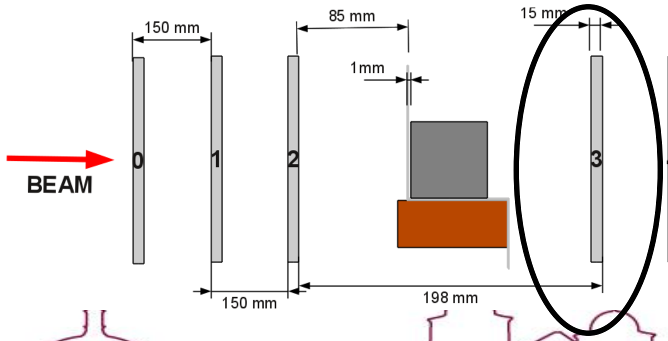


DECAL pixel counting shows correct shower development behaviour

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

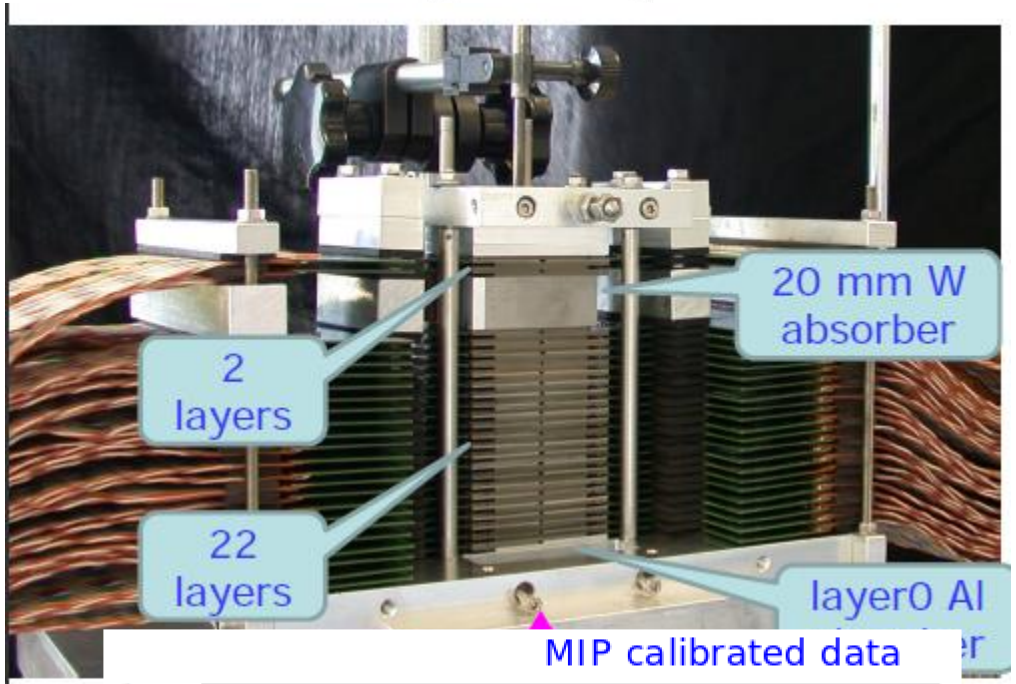


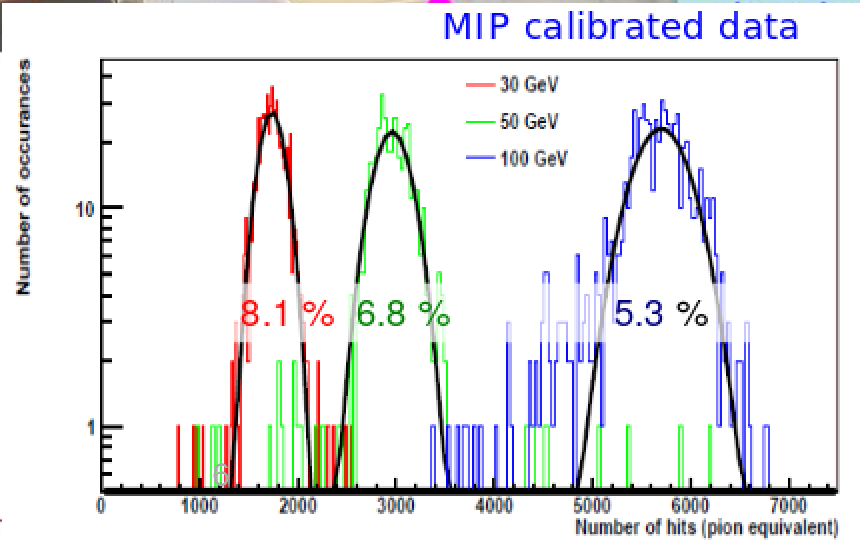
- Form tracks in first 3 layers
- Shower induced in W
- Measure core in 4th layer 15cm from W



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

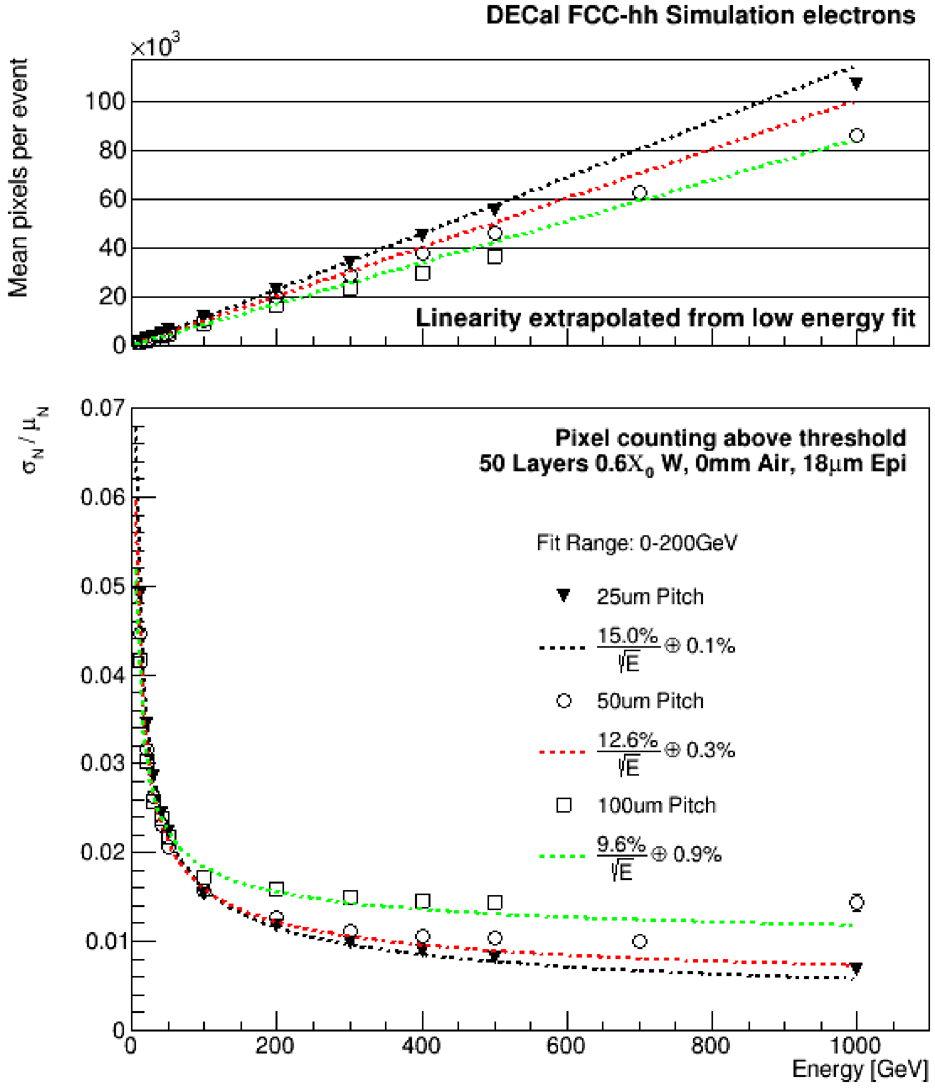
- Previously all work in Birmingham on DECAL has been in the context of ILD within iLCSoft. Modified the current ECAL driver for our needs.
- DECAL for hadron collider will have additional complexities such as pile-up, much higher energy jets, higher radiation environment. FCCSW will allow us to simulate 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.

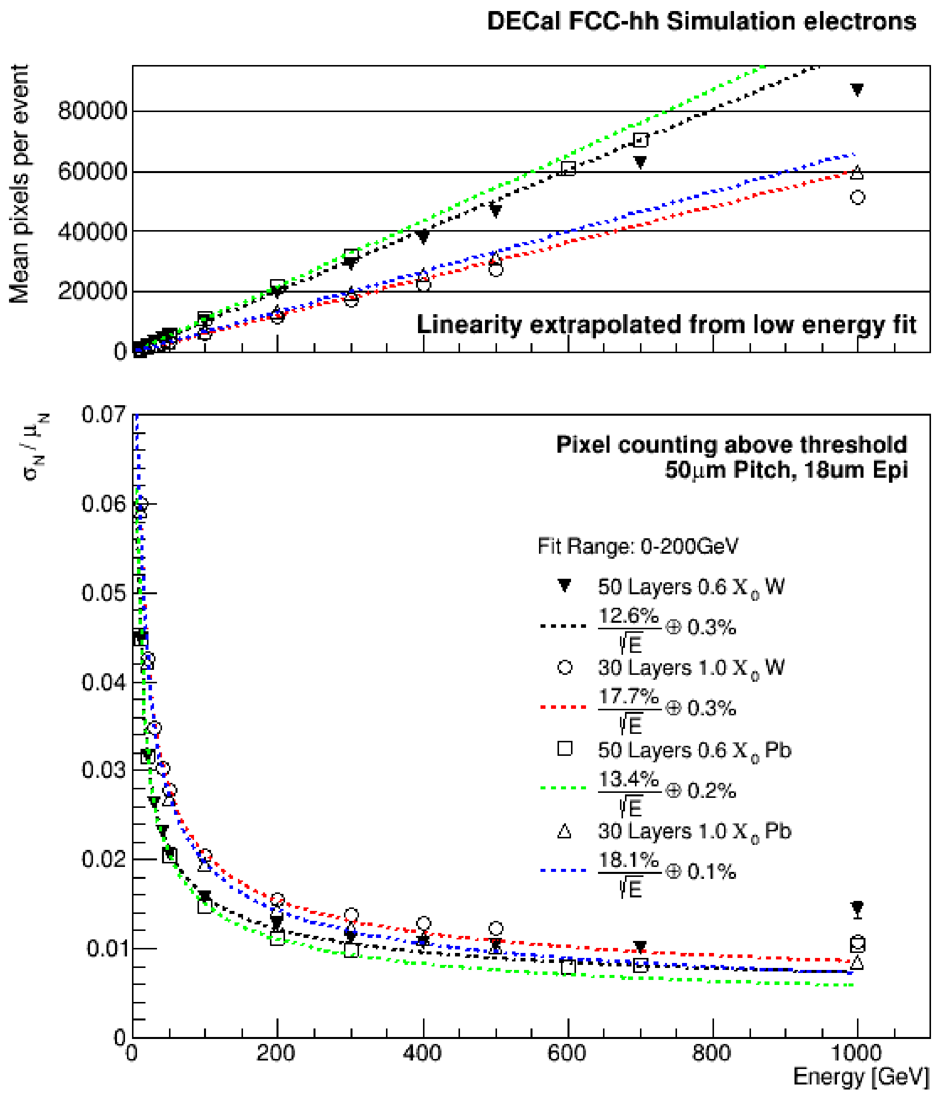
Effect of Pixel Size

- 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



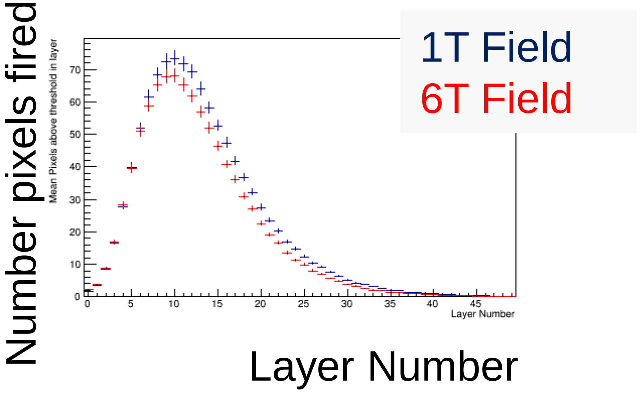
Effect of Layer Geometry

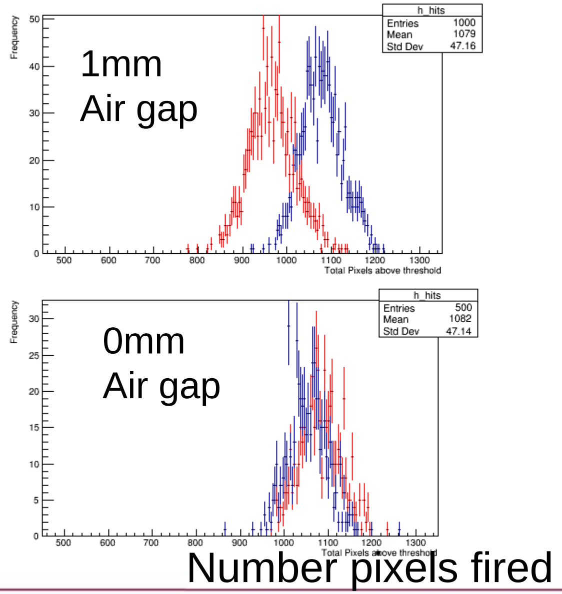
- Detector Configuration
  - 30 layers of $1.0\chi_0$ W
  - 30 layers of $1.0\chi_0$ Pb
  - 50 layers of $0.6\chi_0$ W
  - 50 layers of $0.6\chi_0$ Pb
- Increased number of layers (sampling fraction) improves resolution for both materials
- Material choice has minimal effect on energy resolution
- **Pb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

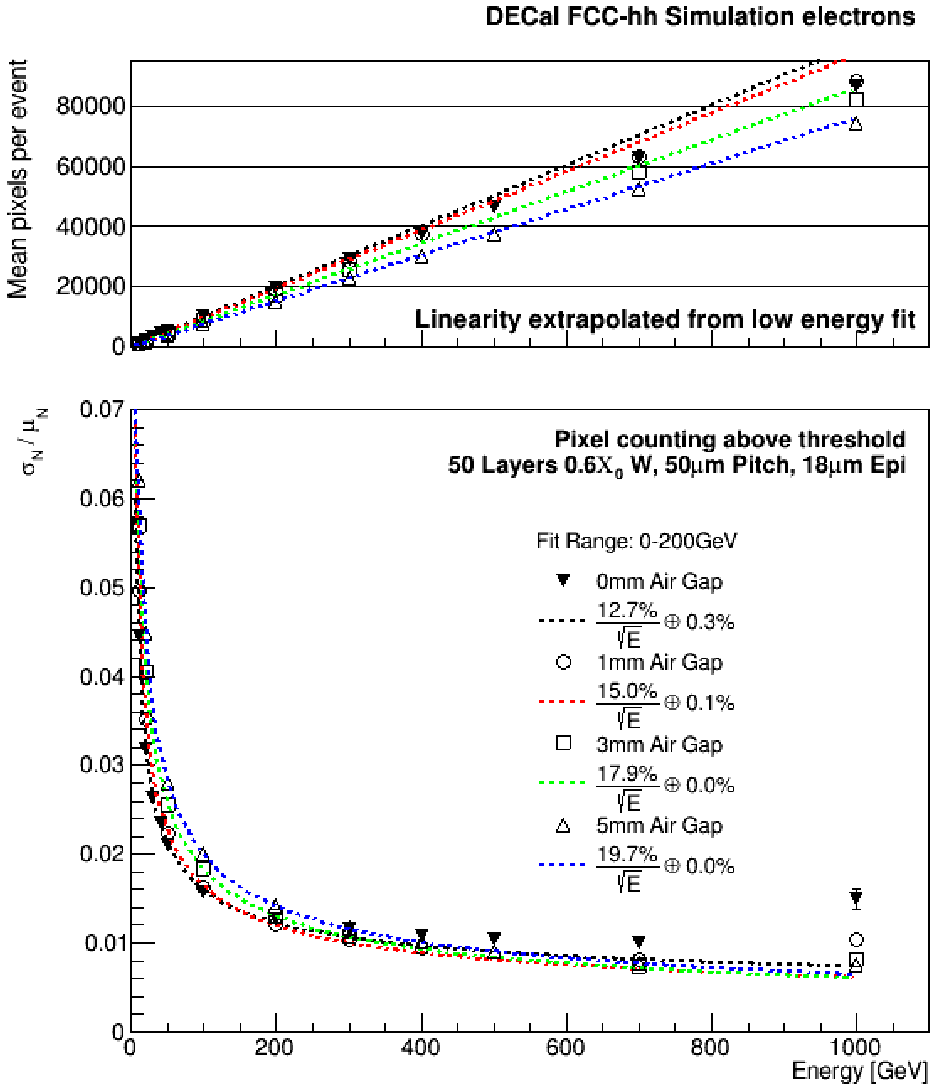


Air Gap

- 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







Air Gap

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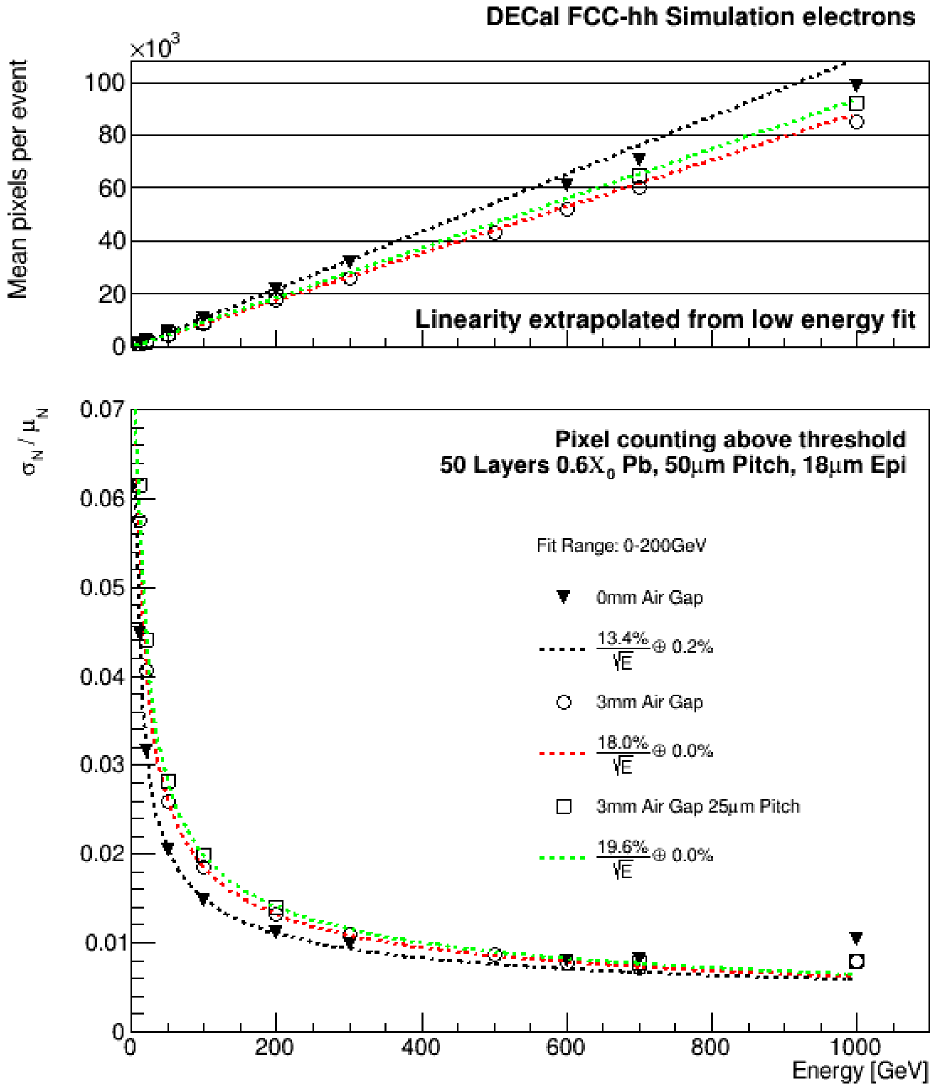
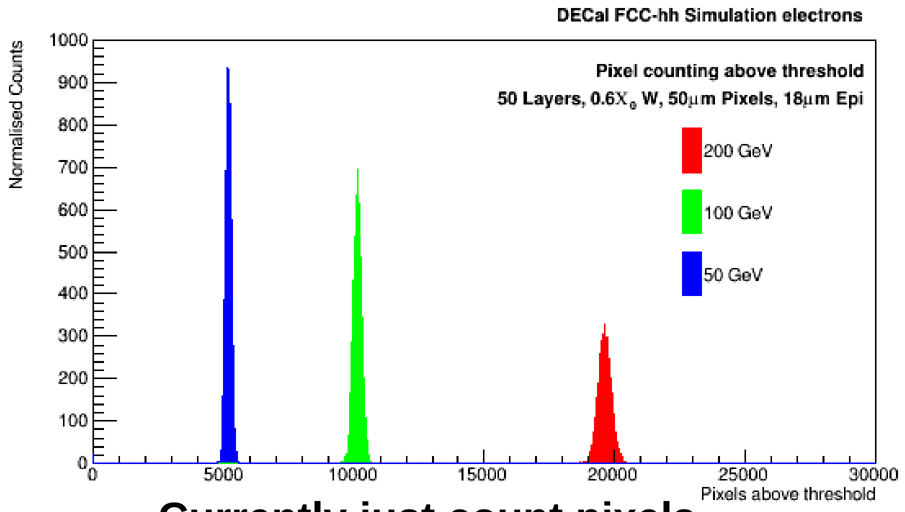
- However, the resolution decreases
- The counts are reduced due to magnetic field effects where low energy particles exit the W but are bent in the air and do not reach the sensitive layer
- Linearity improves for Pb with 3mm air gap up to 1 TeV

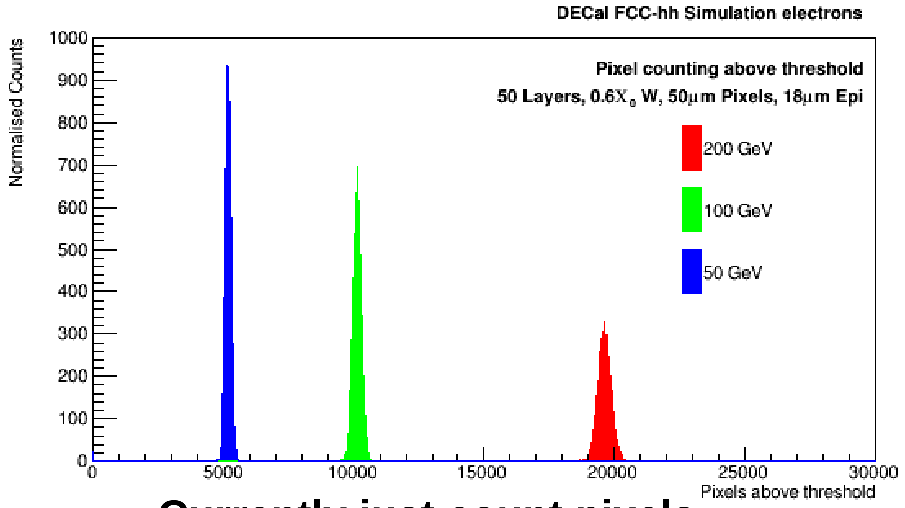


Further considerations: Using shower properties

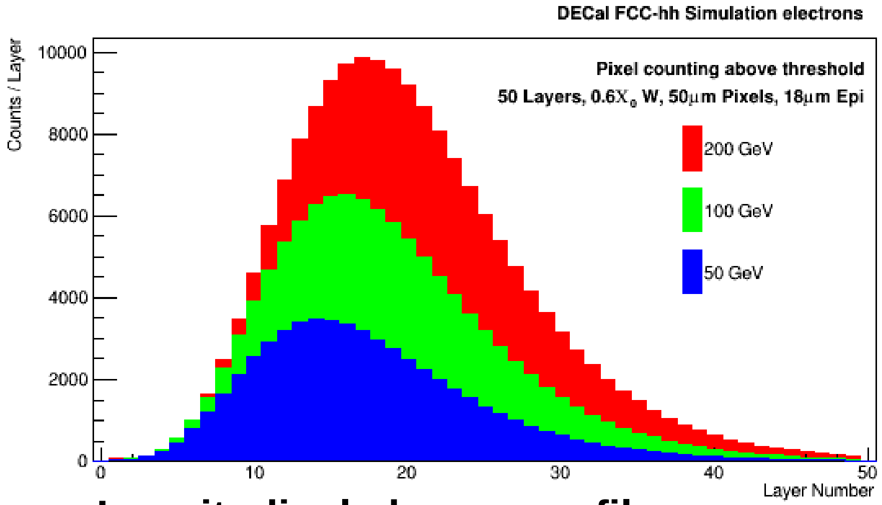


Currently just count pixels

Further considerations: Using shower properties



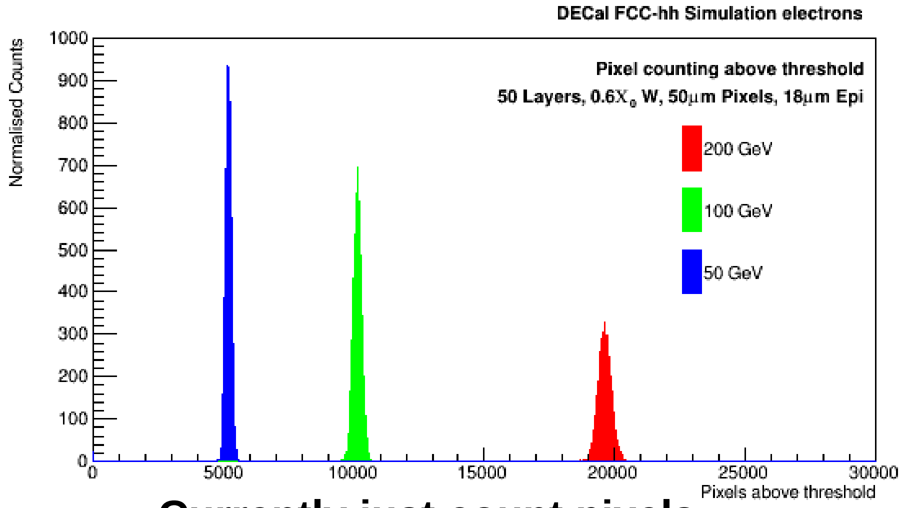
Currently just count pixels



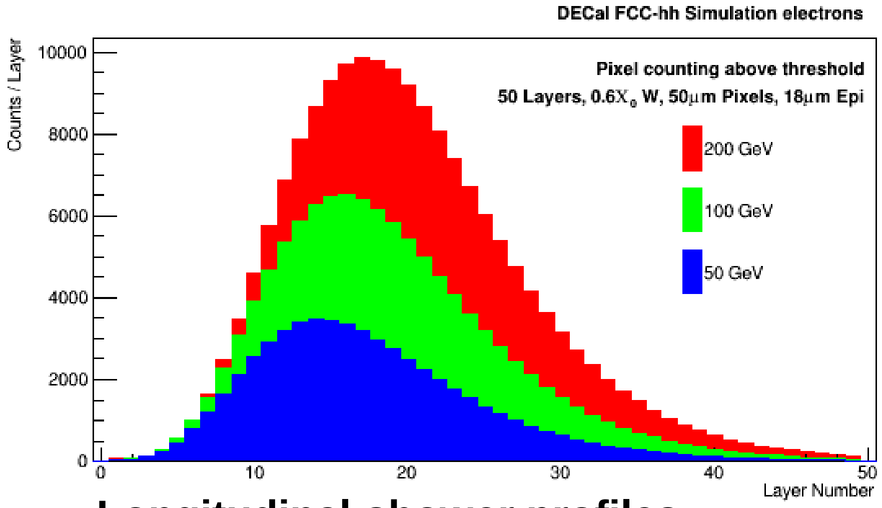
Longitudinal shower profiles

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

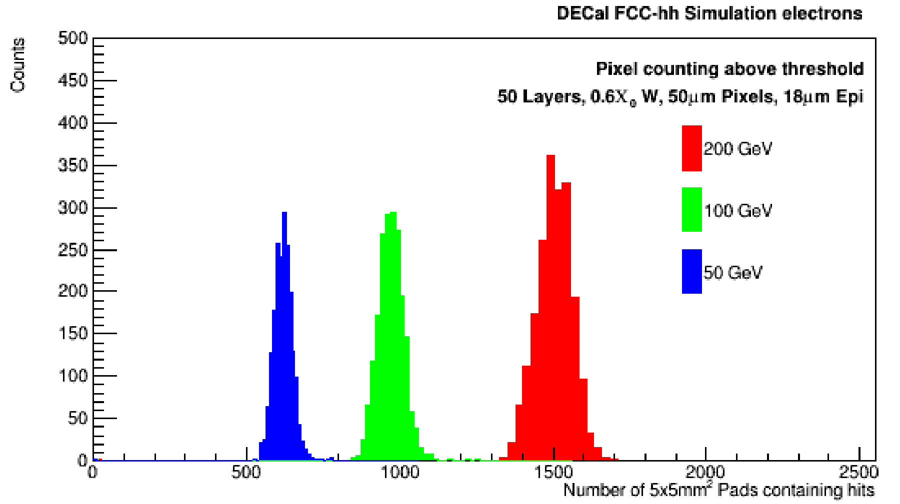
Further considerations: Using shower properties



Currently just count pixels

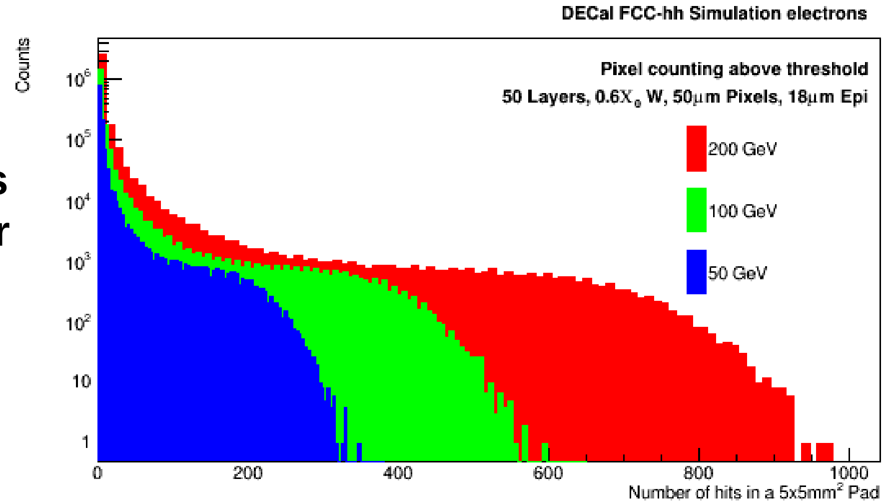


Longitudinal shower profiles



Pad readout possible

- **Count pads**
- **Pads / layer**
- **Hits / pad**



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	1.40e12	1.40e8	3400
50	Tungsten	50	0	129	2.34e12	2.34e8	5900
50	Tungsten	50	3	278	2.43e12	2.43e8	6000
50	Pb	50	0	193	2.38e12	2.38e8	5900
50	Pb	25	3	343	9.50e12	2.48e8	6200

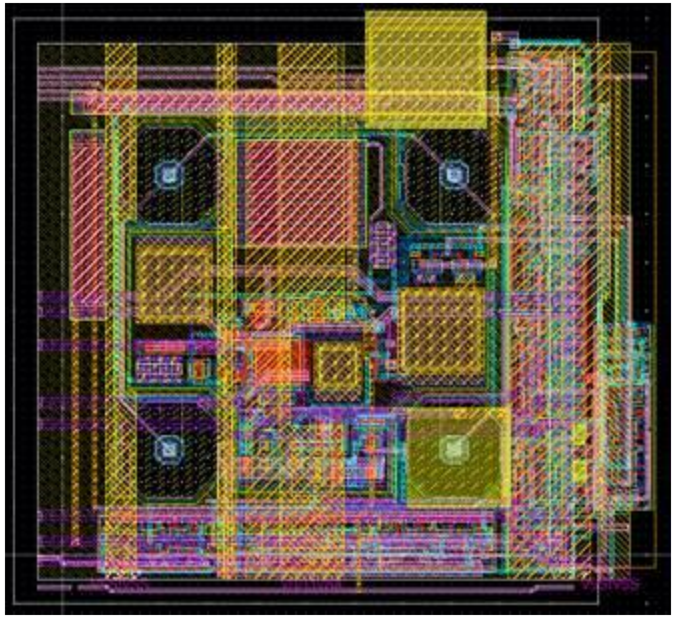
* 1800mm inner radius
# Pixels read out in 5x5mm^2 pads
^ Length of barrel = 10m

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

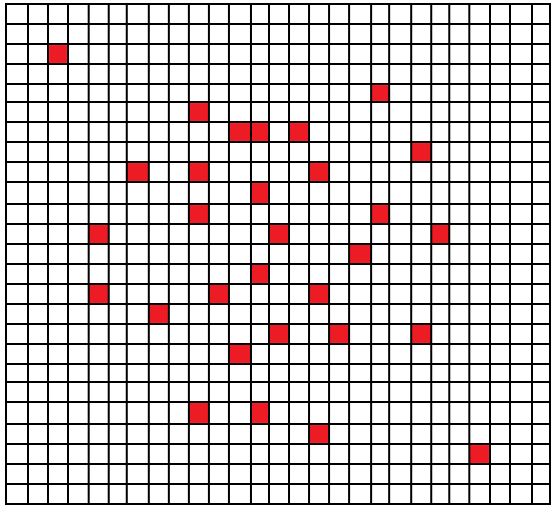
DECAL Chip for higher radiation environments

- 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
- Reduce data rate by not reading every hit pixel address in 25ns but combining information in each 5x5mm^2 pad using fast logic
- FCCSW has been used to influence key design choices such as the maximum number of allowed hits per column and dead time.



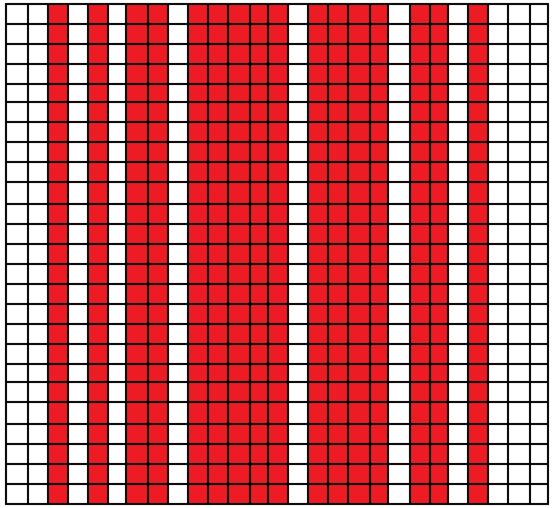
Reconfigurability

- 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



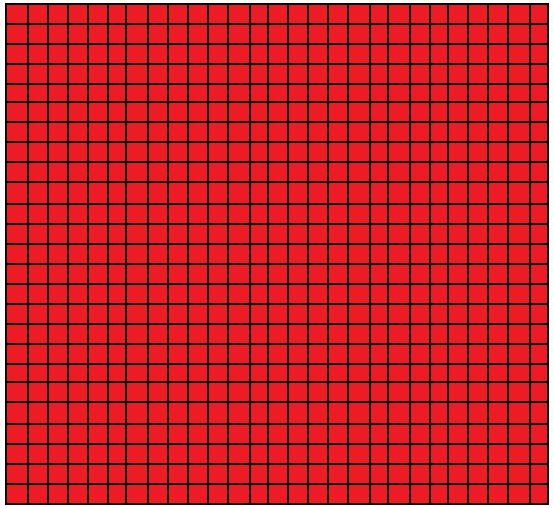
Pixel Mode

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

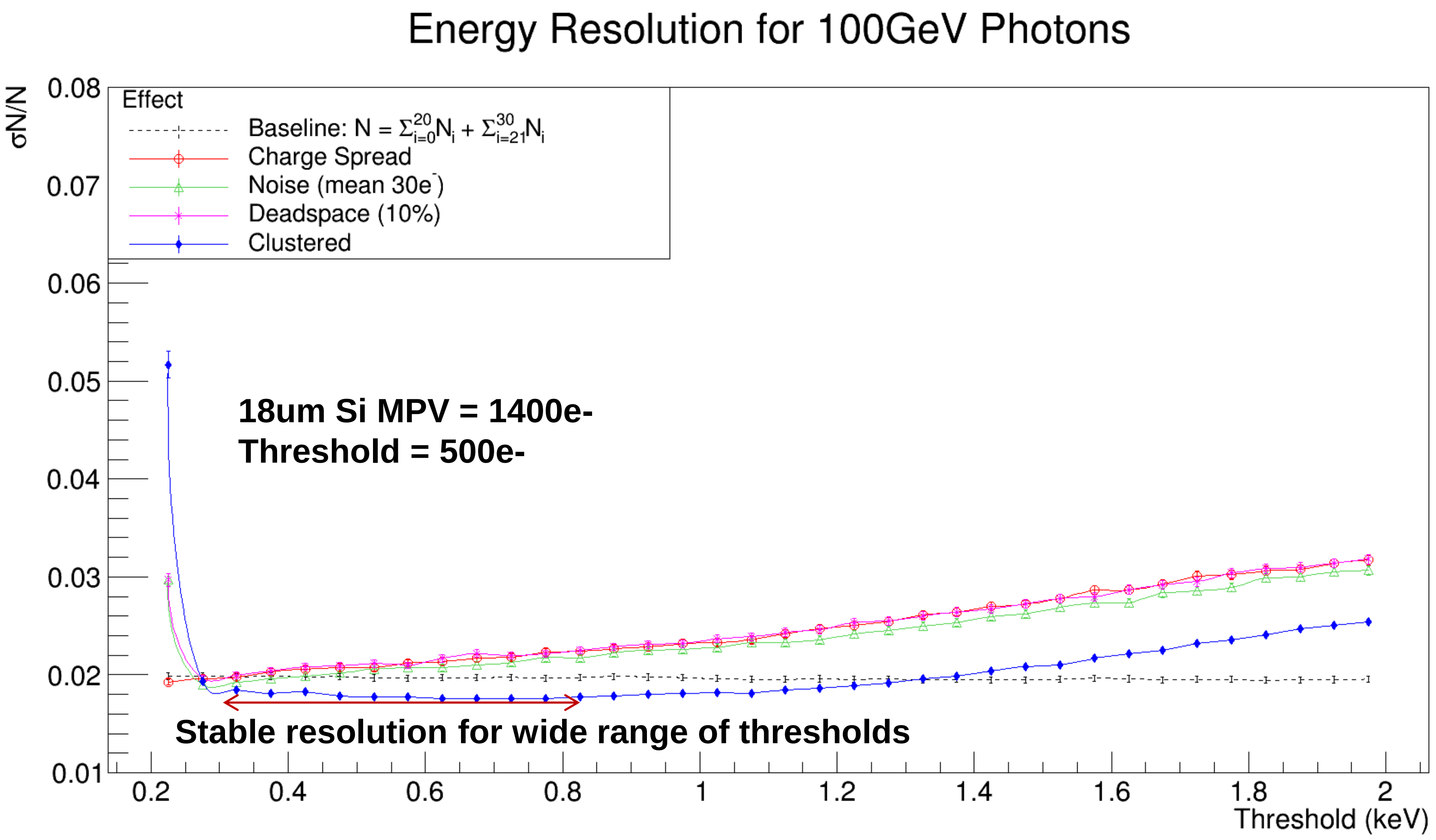
Conclusions

- 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 absorber improves linearity
- A greater number of layers (sampling fraction) 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 costs
- 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
- Technologies available offering full epitaxial layer depletion after irradiation promise excellent S/N and good timing resolution (further help with pile-up?)

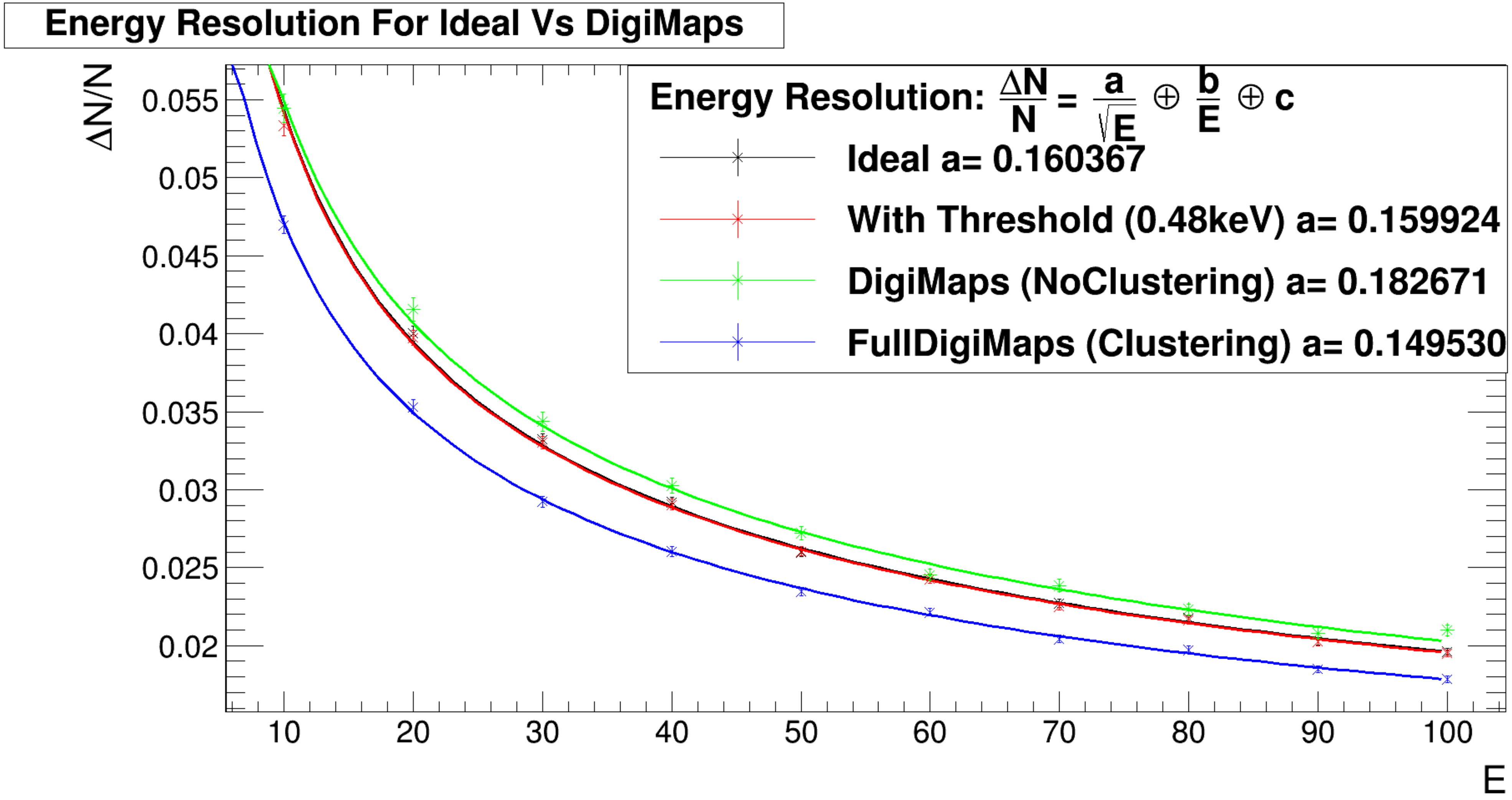
DigiMAPS Package

- 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

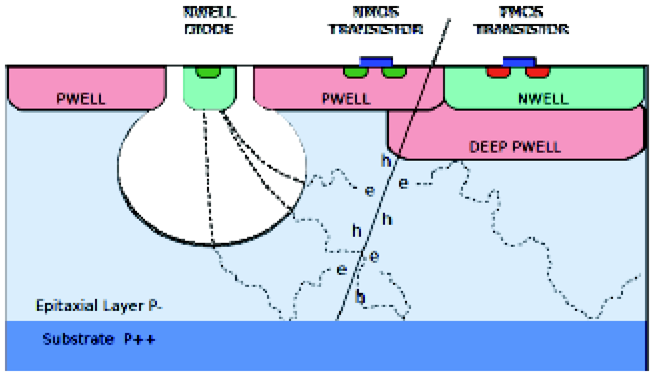


10 GeV electrons

- 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

Modified TowerJazz Process

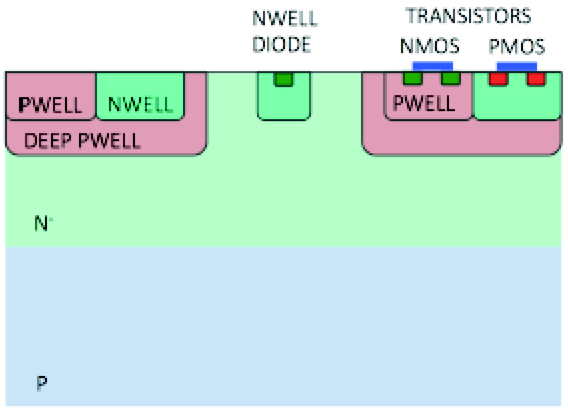


Schematic cross-section of CMOS pixel sensor
(*ALICE ITS Upgrade TDR*)

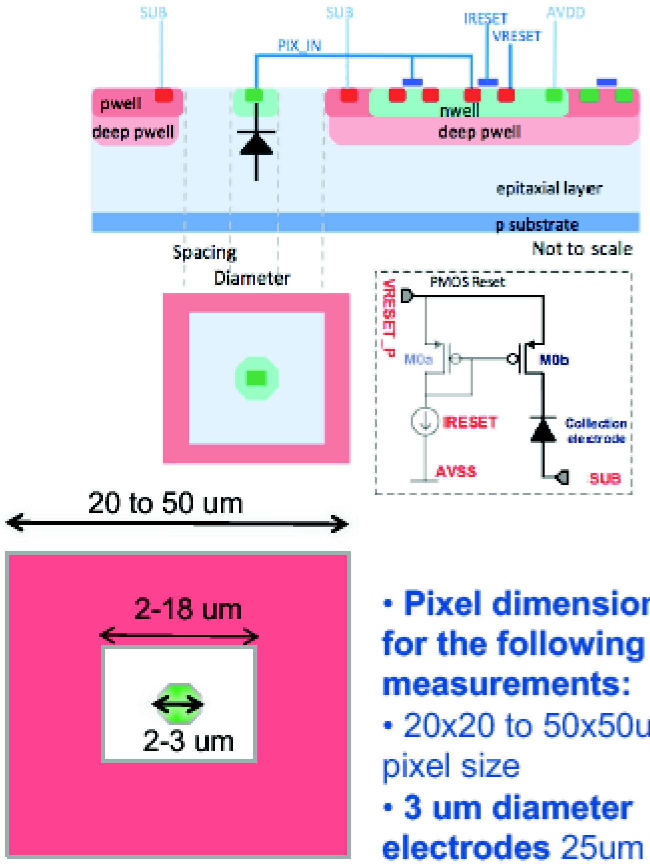
- **Small collection electrodes**
  - Higher gain and faster response due to smaller capacitance (~5fF) and higher Q/C
  - Potentially lower power consumption
  - Signal collection under DPW after irradiation more difficult on edges

- **Modified Process**
  - Add planar n-type layer
  - Significantly improves depletion under p-well with deep junction
  - Does not require significant circuit or layout changes

L. Musa, ECFA High Luminosity LHC Experiments Workshop - 2016



TowerJazz 180nm Investigator



- **Pixel dimensions for the following measurements:**
  - 20x20 to 50x50um^2 pixel size
  - **3 um diameter electrodes** 25um EPI layer

Designed as part of the ALPIDE development for the ALICE ITS upgrade

Emphasis on small fill factor and small capacitance enables low analog power designs (and material reduction in consequence)

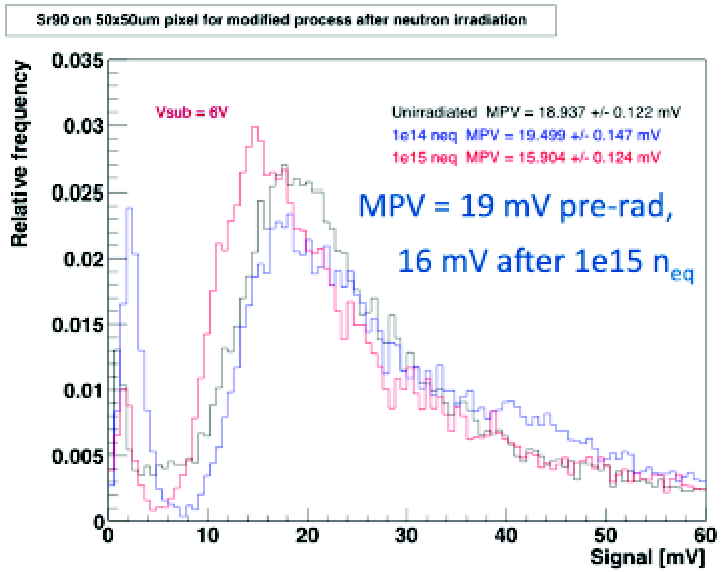
C. Gao et al., NIM A (2016) 831
http://www.sciencedirect.com/science/article/pii/S0168900216300985

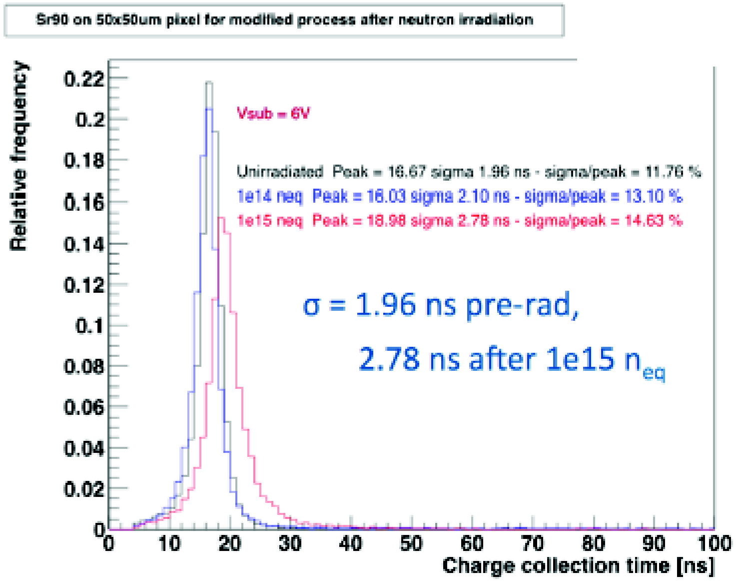
J. Van Hoorne, proceedings of NSS2016
http://2016.nss-mic.org/nss.php

Produced in TowerJazz 180nm on 25-30um thick epi layer in the modified process

Design: C. Gao, P. Yang, C. Marin Tobon, J. Rousset, T. Kugathasan and W. Snoeys

After 10^{15} n_{eq}/cm^2 and 1Mrad TID





Very little signal loss after 10^{15}, also very encouraging results on detection efficiency.
Signal well separated from noise.
Measurements on samples irradiated to 10^{16} n_{eq}/cm^2 ongoing.

H. Pernegger, Terascale Detector Workshop, DESY, April 2017