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# The UK MAPS/DECAL Project

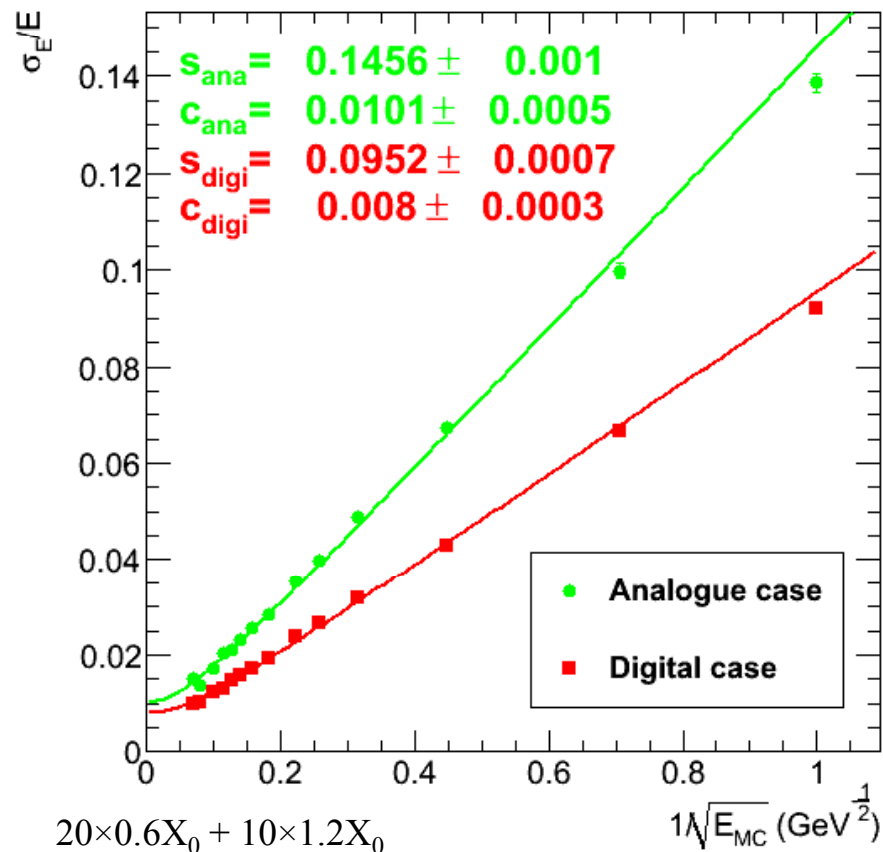
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for the CALICE-UK MAPS group

# Motivation

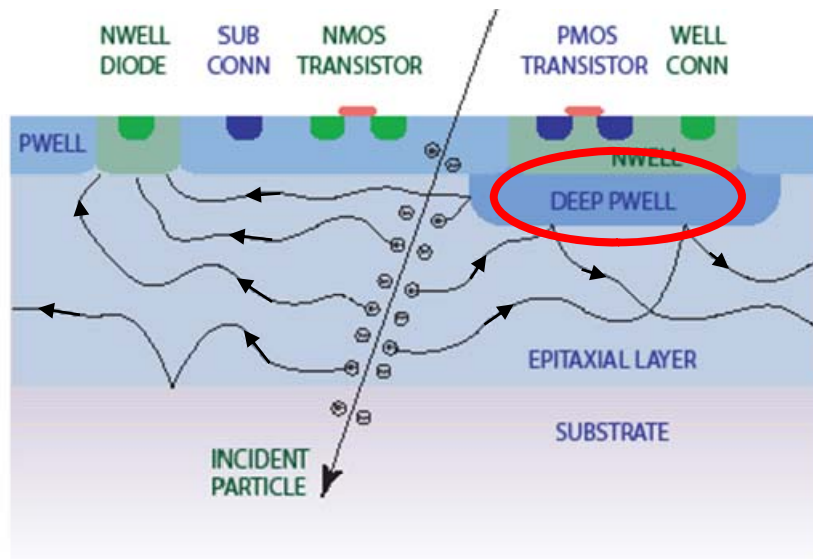
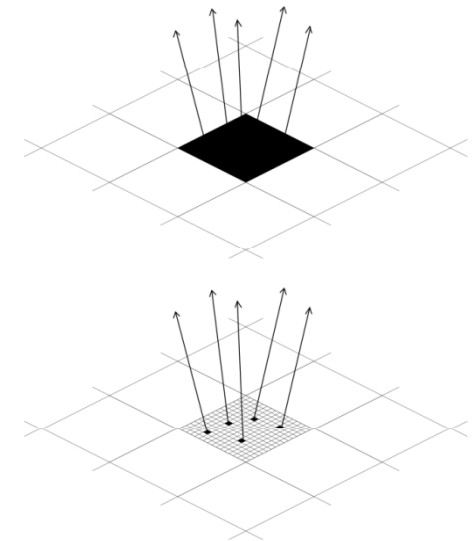
- Average number of **charged particles** in an EM shower  $\propto$  **incident energy**
  - Fluctuations around the average occur due to statistical nature of the shower
- Average **energy deposited** in the sensitive layers  $\propto$  number of **charged particles**
  - Fluctuations around the average occur due to angle of incidence, velocity and Landau spread



- Number of charged particles is an **intrinsically better measure** than the energy deposited
  - Energy deposited (“analogue” ECAL) resolution  $\sim 50\%$  worse than number of particles (“digital” ECAL) resolution
- Can we measure the number of charged particles **directly**?
  - It is possible to get close to the analogue ideal resolution with low noise electronics
  - Can we get anywhere near the **ideal resolution** for the digital case?

# Digital ECAL concept

- Make **pixellated detector** with small pixels
  - Probability of more than one charged particle per pixel must be small
  - Allows **binary** readout = hit/no hit
- EM shower density  $\sim 100/\text{mm}^2$  in core so need pixels  $\sim 50\mu\text{m}$ 
  - Results in huge number of pixels in a real ECAL  $\sim 10^{12}$  pixels

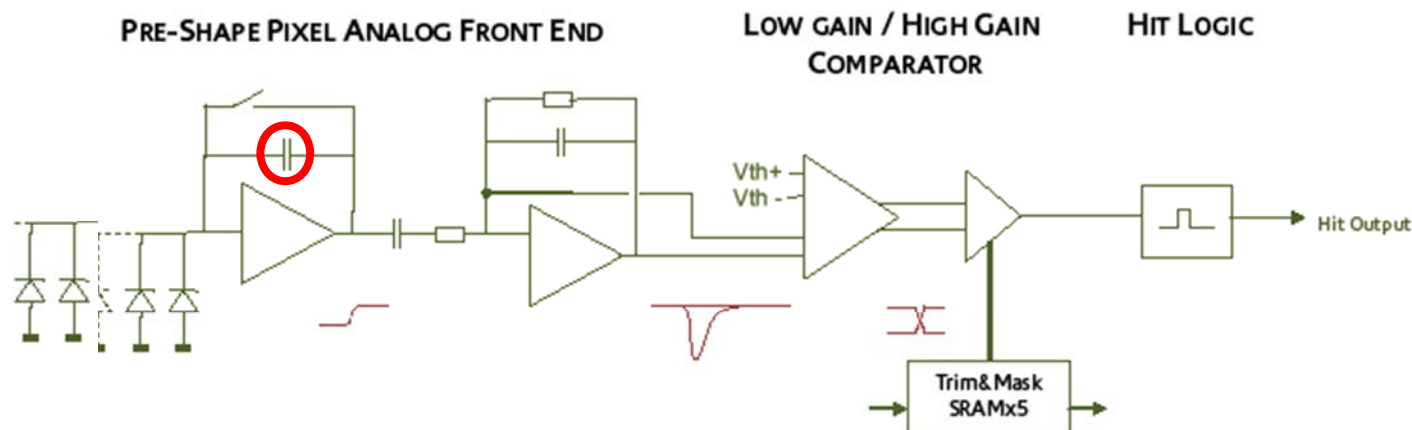
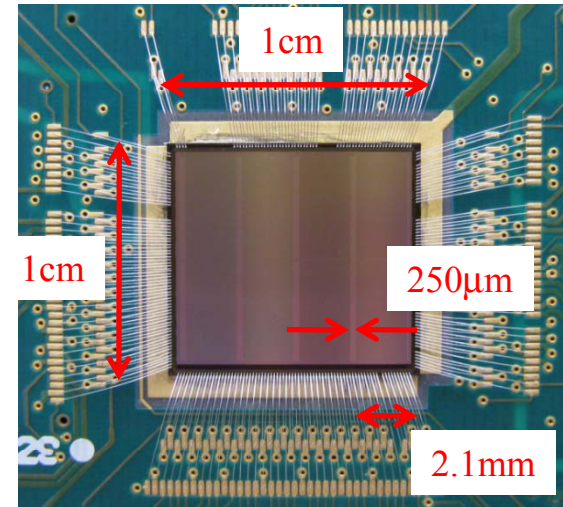


- Cannot afford to have external electronics with individual connections to so many channels
  - Need readout integrated into pixel
  - Implement as **CMOS MAPS sensor**
  - Includes **deep p-well** process to shield PMOS circuit transistors

- Very high granularity should help with PFA too
  - Requires major systematic study; here concentrate on **EM resolution**

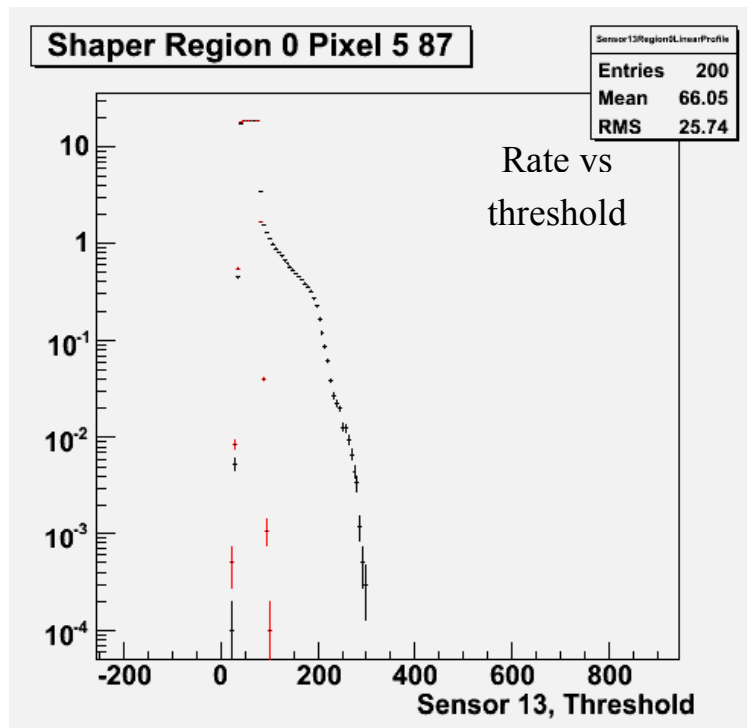
# TPAC1.0 sensor

- **168×168** pixels = 28k total, each  $50\times 50\mu\text{m}^2$ 
  - 0.18 $\mu\text{m}$  CMOS process
- Two major pixel variants, each in two capacitor combinations
  - Only one major variant worked well; “preShaper”
  - Both minor variants (Quad0 and Quad1) worked
  - All results shown are from this type
- Every pixel has 4 diodes, Q-preamp, mask and 4-bit pedestal trim, asynchronous comparator and monostable to give hit/no hit response
- Pixel hits stored with 13-bit timestamp on-sensor until end of bunch train
- Memory for data storage inactive; **11% dead area** in four columns

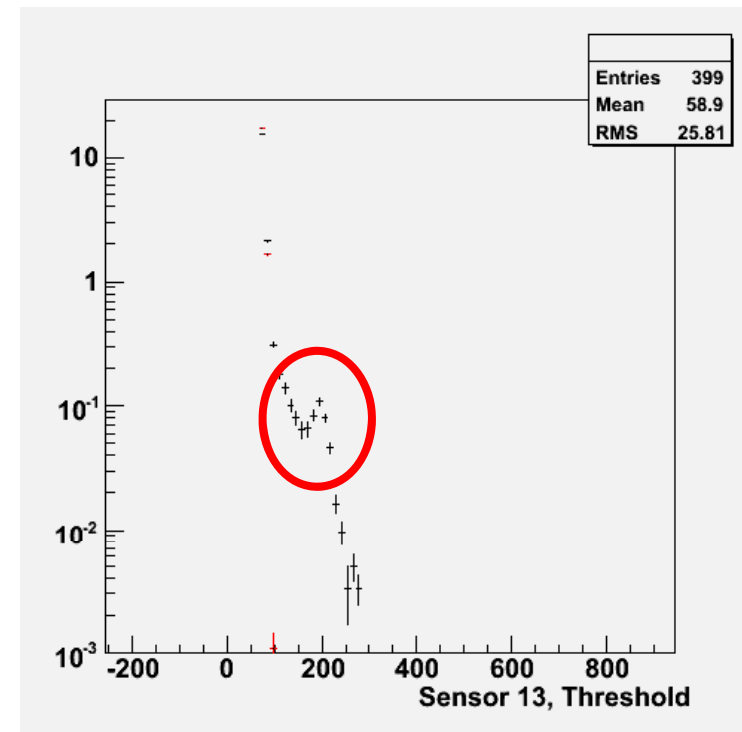


# Calibration using $^{55}\text{Fe}$

- $^{55}\text{Fe}$  gives **5.9keV** photon
  - Deposits all energy in  $\sim 1\mu\text{m}^3$  volume in silicon;  $1640e^-$
  - If within diode, then all charge registered in single pixel with no diffusion
- Binary readout mean measurement need **threshold scan**
  - Need to differentiate distribution to get signal peak in threshold units (TU)



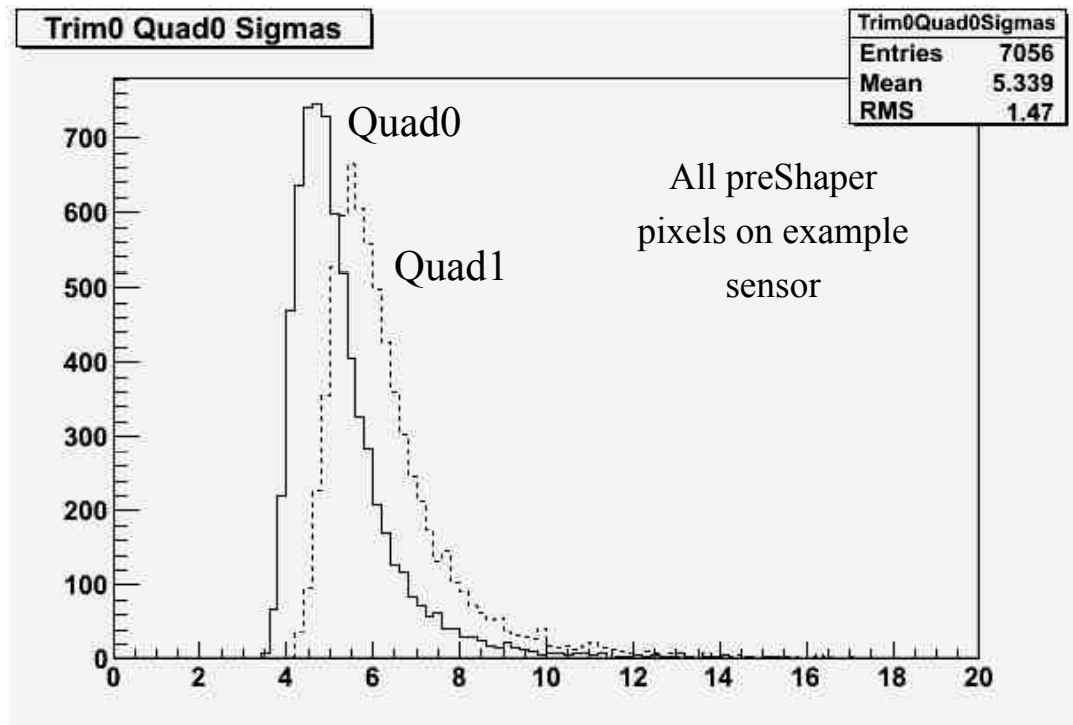
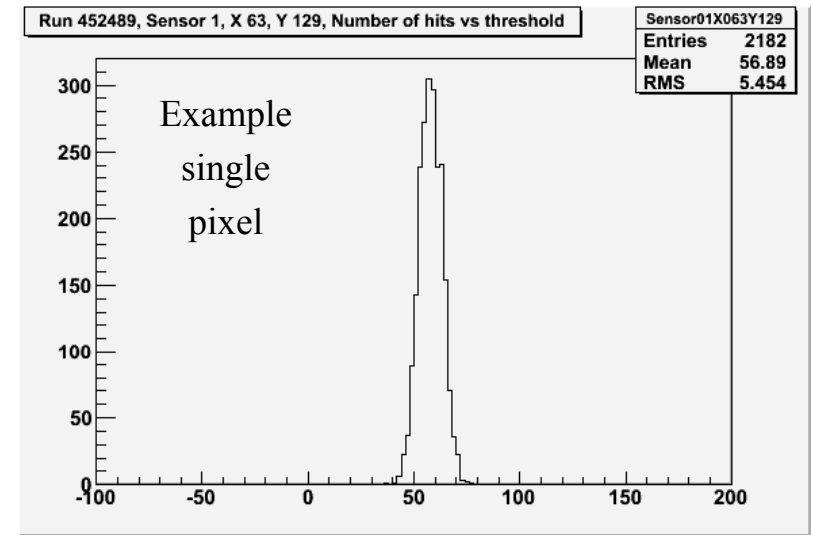
Derivative  
approximated  
using previous  
bin subtraction



- Signal peak  $\sim 200\text{TU}$  above pedestal;  $1\text{TU} \sim 8e^- \sim 30\text{eV}$  deposited

# Single pixel noise performance

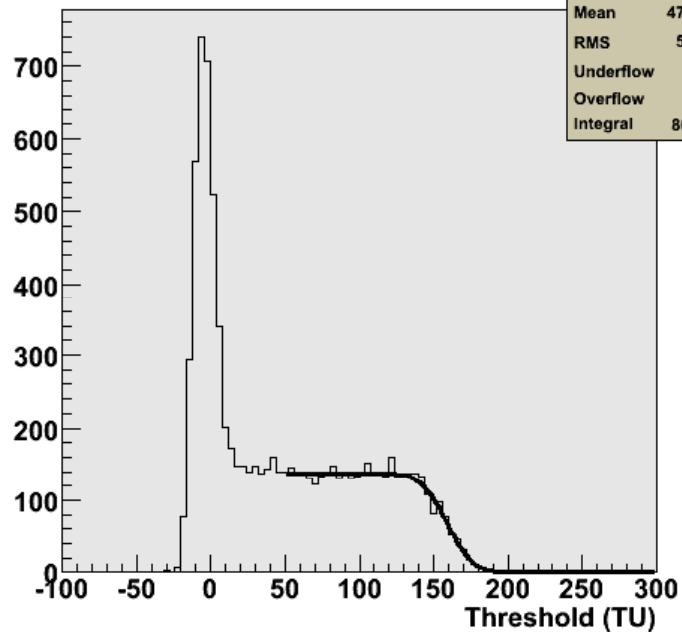
- Also need threshold scan to see **pedestal and noise**
  - Comparator fires on signal going high across threshold level
  - No hits when far above or below threshold
  - Width of distribution equivalent to noise



- RMS  $\sim 5.5\text{TU} \sim 44e^- \sim 170\text{eV}$  on average
  - Minimum is  $\sim 4\text{TU} \sim 32e^- \sim 120\text{eV}$
  - Target level was  $\sim 90\text{eV}$
  - No correlation with position on sensor
  - Spread not fully understood
  - Quad1  $\sim 20\%$  larger than Quad0

# Single pixel relative gain

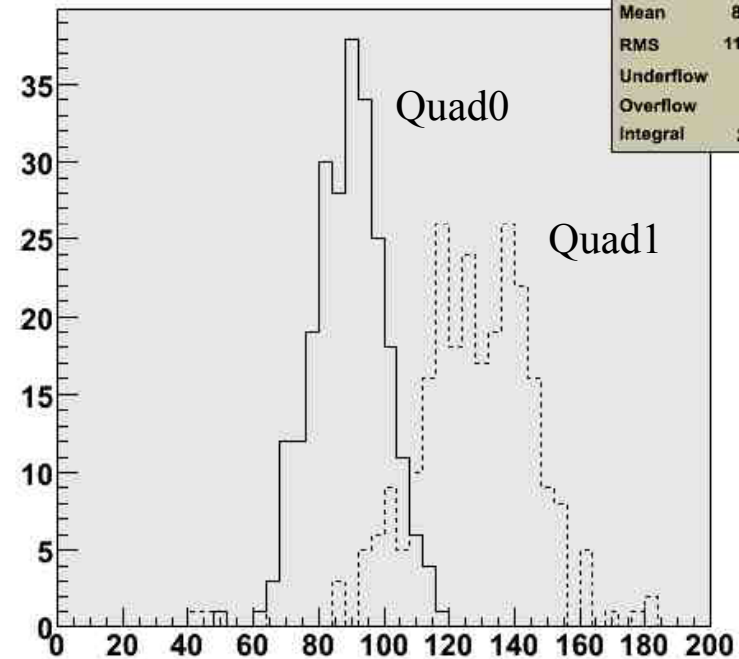
Run 470853, X 21, Y 126 vs Threshold (TU)



- Measured using **laser**
  - Silicon transparent to **1064nm** light so illuminate from back side of sensor
  - Focus on epitaxial layer
  - Again need to do threshold scan and find edge to measure laser signal

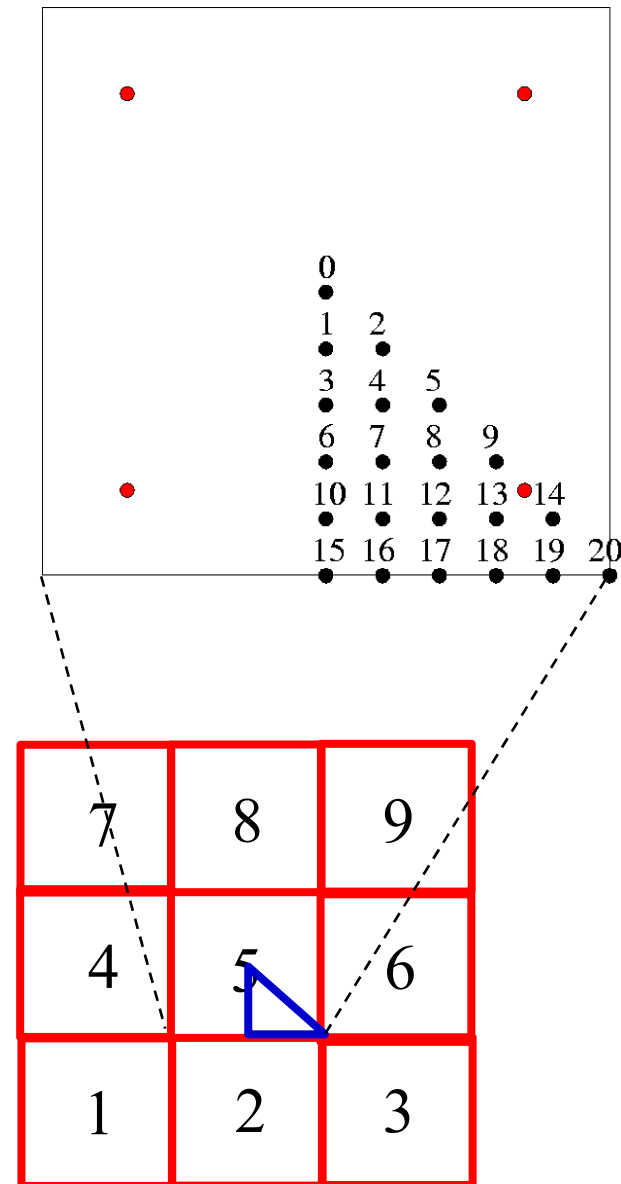
- Fixed laser intensity gives **relative gain** for individual pixels
  - Can do hundreds of pixels automatically
  - Gain uniform to 12%
  - Quad1 ~40% more gain than Quad0
  - **Quad1 ~20% better S/N than Quad0**

Signal Quad0



# Charge diffusion

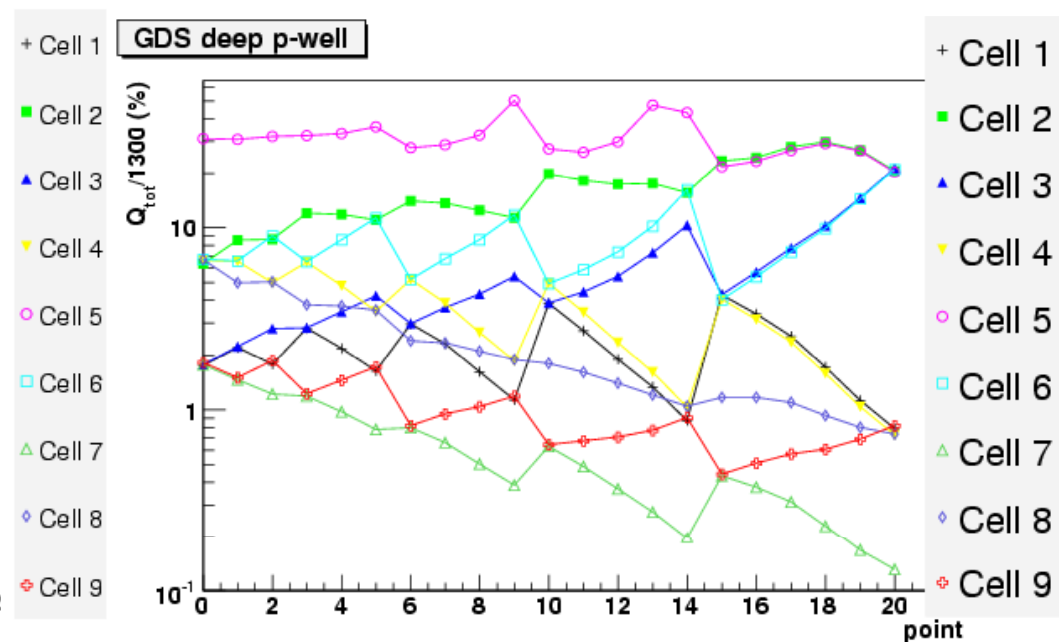
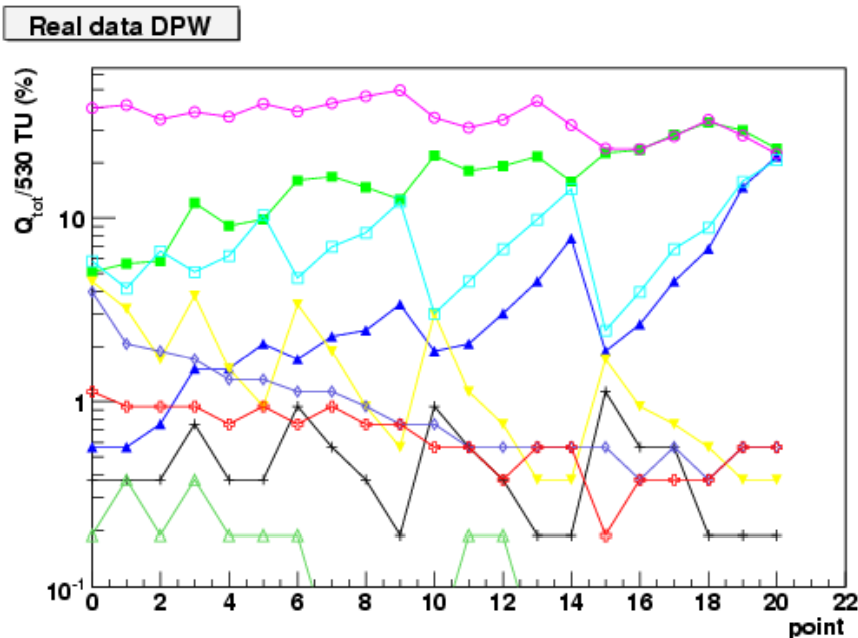
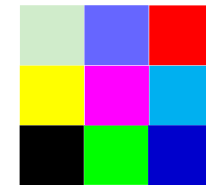
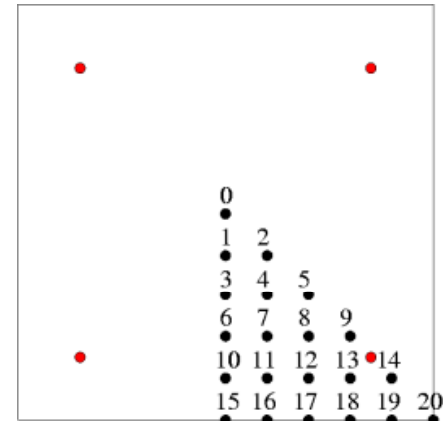
- Charge **diffuses** to neighbouring pixels
  - Reduces signal in “hit” pixel
  - Causes hits in neighbouring pixels
  - Need to make sure this is correctly **modelled**
- Simulation using Sentaurus package
  - Full **3D finite element** model
  - 3×3 pixel array = 150×150µm<sup>2</sup> area
  - Thickness of silicon to 32µm depth; covers epitaxial layer of 12µm plus some of substrate
- Use laser to fire at **21 points** within pixel
  - Laser spot size < 2µm, step size 1µm
  - Points numbered 0-20, **5µm apart**
  - Symmetry means these cover whole pixel surface
- Measure signal using **threshold scan** in centre pixel and all eight neighbours
  - Numbered “Cell 1” to “Cell 9”





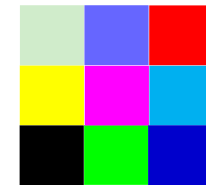
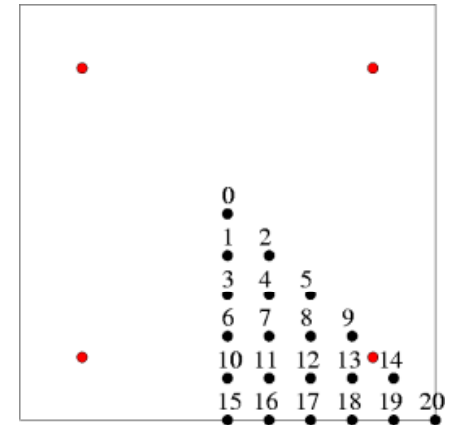
# Charge diffusion results

- Simulation **reasonably** reproduces the spatial dependence
  - Small differences near diodes (points 9,13,14)
- Average signal over whole pixel  $\sim 35\%$  of deposited signal
  - Total charge is  $1300e^-$  so average  $\sim 450e^-$
  - Average signal/noise  $\sim 10$
- **Worst case** signal in central pixel is when hitting corner
  - Gives  $\sim 24\%$  of total charge so  $\sim 300e^-$  and S/N  $\sim 7$

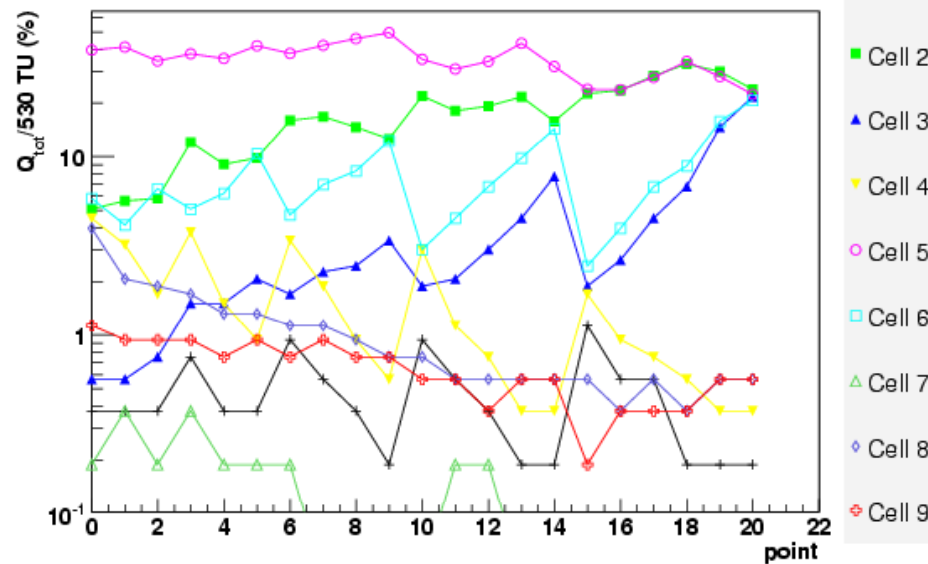


# Effect of deep p-well

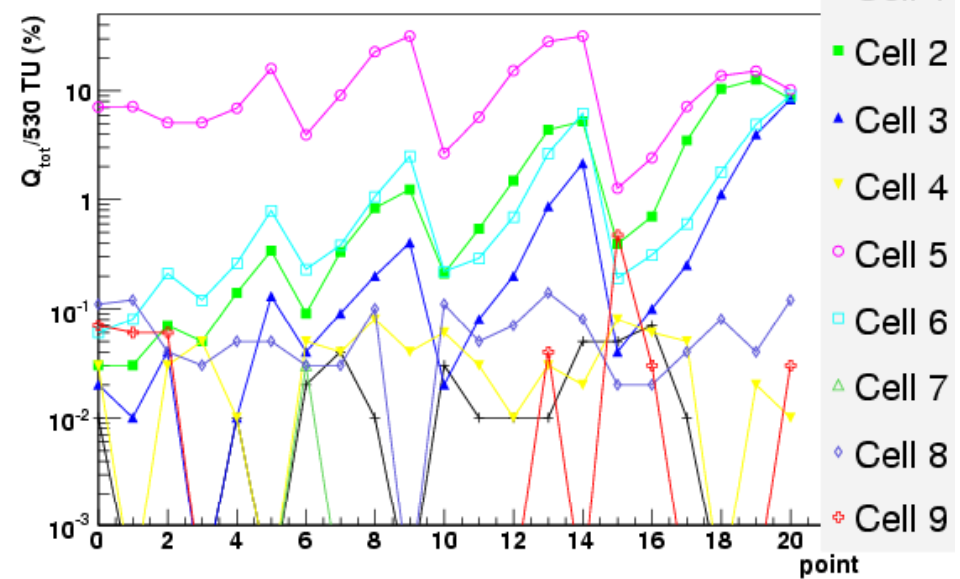
- Development included **modification** to foundry CMOS process
  - Deep p-well “INMAPS” processing
  - **Blocks** signal charge from being absorbed in pixel amplifier, etc
- Deep p-well **essential** for usable sensor
  - Average signal without deep p-well  $\sim 10\% \sim 130e^-$
  - Worst case  $\sim 1\% \sim 13e^-$



Real data DPW

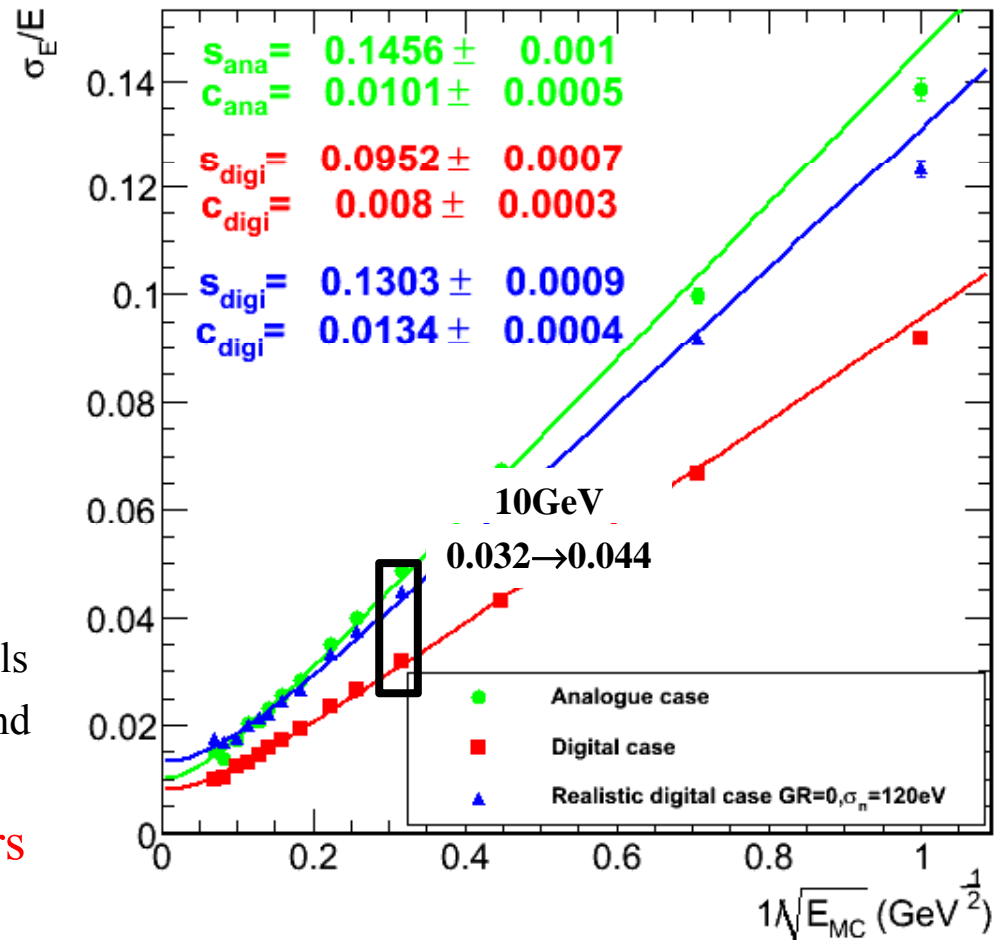


Real data NDPW



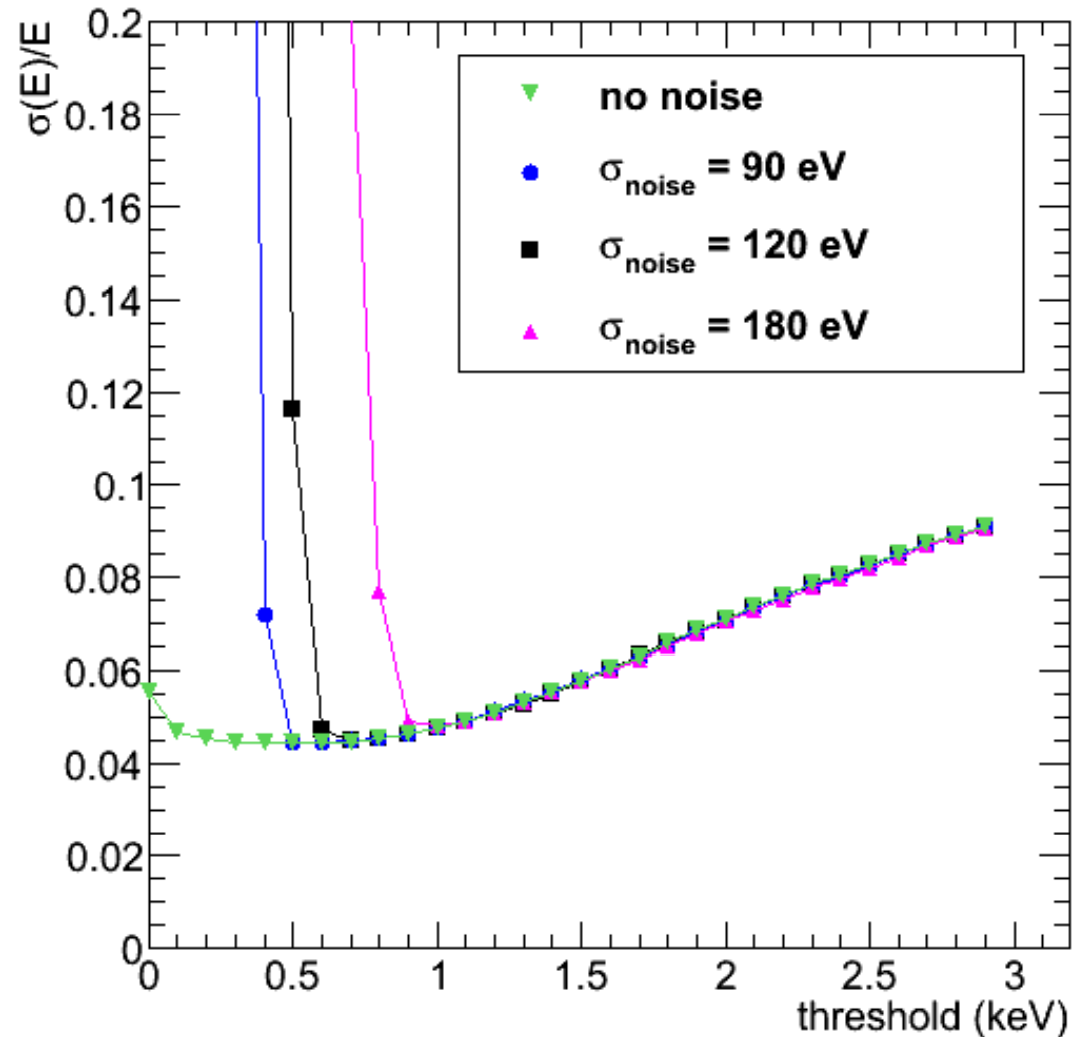
# Simulation expectation

- Shown at LCWS07 but with no **verification** of assumptions
  - Now have concrete noise values and measured charge diffusion
- Current extrapolation to “real” detector shows **significant degradation** of ideal DECAL resolution
  - 35% increase in error
  - Number of pixels hit not trivially related to number of charged tracks
- Degradation arises from
  - Noise hits
  - Dead area
  - Charge diffusion to neighbouring pixels
  - Particles crossing pixels boundaries and sharing pixels
- Importance of various effects **differs**



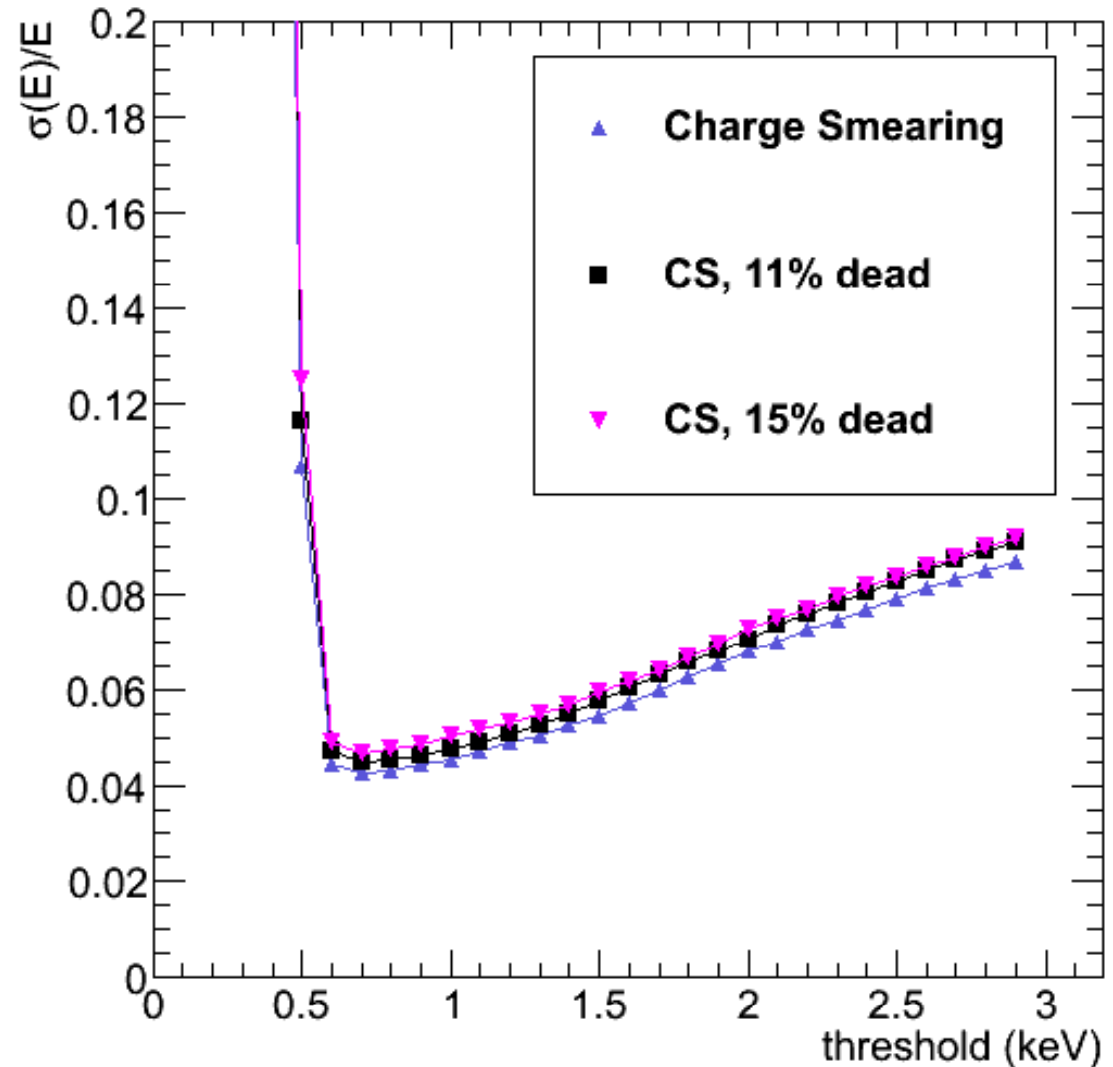
# Effect of noise

- Noise adds hits to showers so increases  $\sqrt{N}$ 
  - Depends very strongly on threshold
- Need to increase **threshold** above noise “wall”
  - Noise has **no effect** for higher thresholds
  - Gain spread  $\sim 12\%$  is equivalent to threshold spread here so small effect
- Resolution degradation  $\sim 5\%$ 
  - If S/N can be improved, then get a **plateau** so noise has no effect on resolution

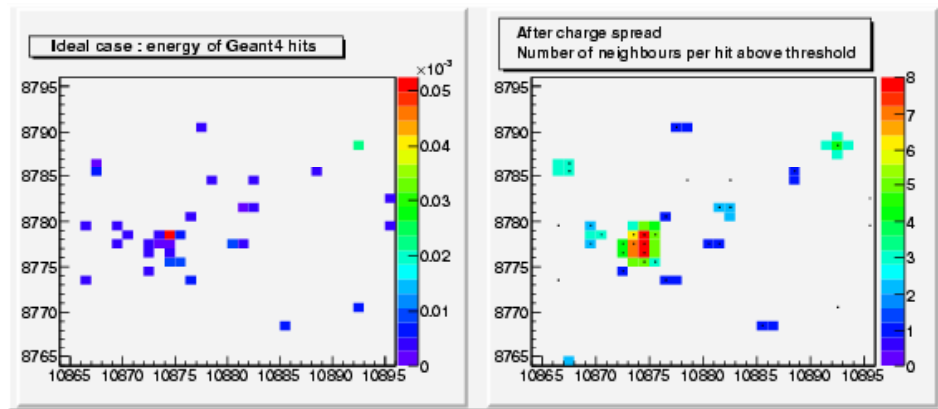


# Effect of dead area

- Sensor has **11% dead region** due to on-pixel memory
  - Bands of 250 $\mu$ m wide spaced every 2.4mm
- Shower width  $\sim$  **1cm** so every shower sees several dead bands
  - Always loses 11% of hits with small fluctuations
- Since  $\sigma_E/E \propto 1/\sqrt{N}$ , impact is not large
  - Gives  $1/\sqrt{(0.89)} \sim 1.06$  effect
  - Hence  $\sim$  **6%** degradation
- Assumes sensor large enough that **edge effects** are negligible
  - May add  $\sim$  4% more dead area in reality so  $\sim$  **2%** more to resolution

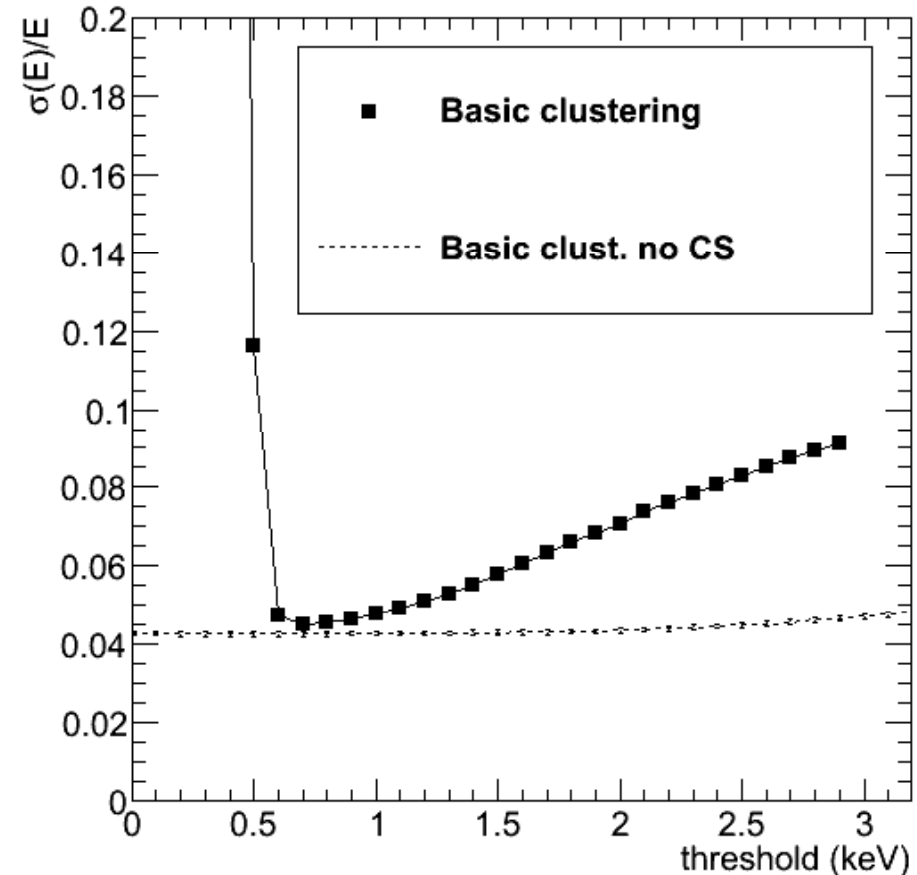


# Effect of charge diffusion



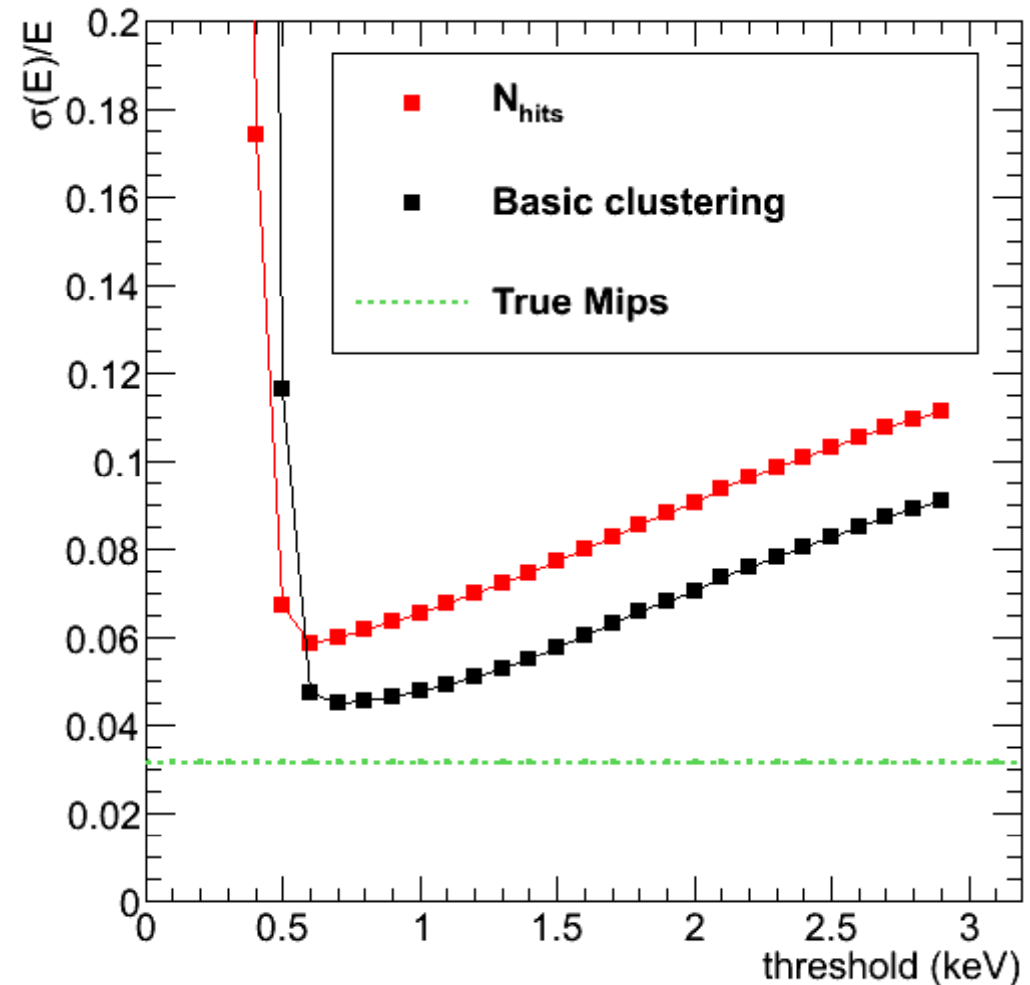
Hits in a layer before and after charge diffusion

- Need to do neighbouring hit “**clustering**” to convert hits to particle count
  - Following clustering, the effect of charge diffusion on the EM resolution is  $\sim 5\%$



# Effect of hit confusion

- Basic property of an **EM shower**
  - How **dense** are hits in the core?
  - GEANT4 not verified at this granularity
- Clustering helps but it is not clear where the **limit** is
  - Which algorithm to use depends on effects which may not be **modelled** well
- Currently gives remaining  $\sim 20\%$  degradation to resolution so this is the dominant effect
  - Major study of **clustering algorithms** still to be done
  - **Essential** to get experimental data on fine structure of showers to know realistic resolution



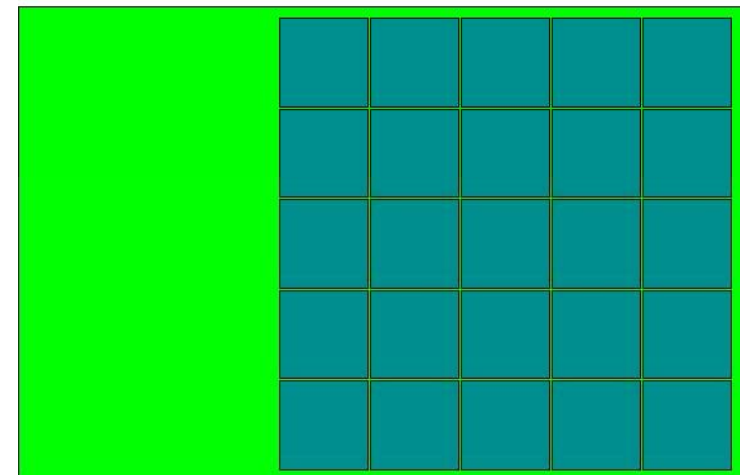
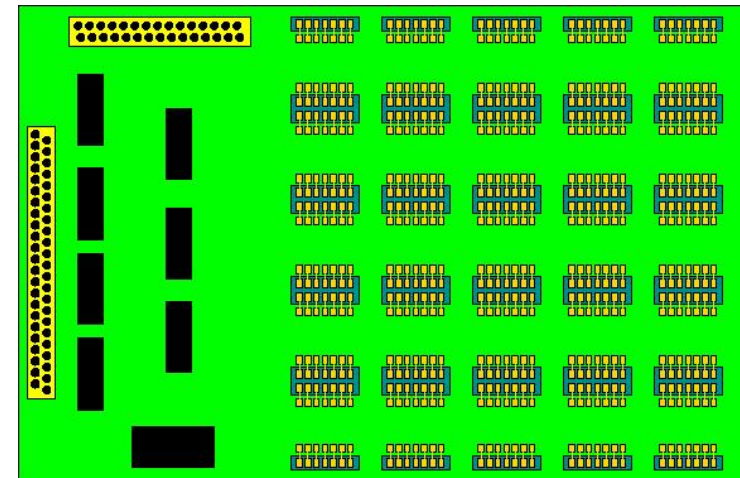
# Short term future plans

- “Debugged” version, **TPAC1.1** due back on Sept 23
  - All pixels uniform; **Quad1 preShaper** variant
  - Decoupled power mesh, thought to cause pickup between pixels
  - Adjusted pixel circuit layout to improve gain and S/N
  - Trim setting has six not four bits to allow finer trim adjustment
  - Other small fixes, e.g. fix low level of memory corruption <1%
- **Pin-compatible** with existing PCB
  - Can **reuse** all readout hardware and firmware
  - Very minor changes to software; only for six trim bits
- Will check sensor performance fully over **next year**
  - Including **beam test at DESY early in 2009**
- Beam test will have at most **four layers**, each with a single sensor
  - Will see **real data samples** of showers at various depths in tungsten
  - Compare with simulation at 50 $\mu$ m granularity
  - Check critical issues of **charged particle separation** and **keV photon flux**
  - But only 1 $\times$ 1cm<sup>2</sup> sensor; will not be able to verify true performance of a DECAL...



# Long term future plans

- Submitted a proposal last week for **large sensor TPAC2**
  - **450×450** pixels and  $2.5 \times 2.5 \text{cm}^2$ ; a factor ten in area; otherwise a scaled-up TPAC1.1
  - Bid includes funding for **16-layer** Si-W DECAL stack;  $5 \times 5$  sensors =  $12.5 \times 12.5 \text{cm}^2$  per layer
  - Sufficient for proof-of-principle
- To pack sensors in the plane, will **wirebond** through slots in PCB
  - Aim for pixel-pixel gap between sensors to be only  $500 \mu\text{m}$  ~ 4% extra dead area
  - “Real” detector would **bump-bond** but we need to minimise engineering effort for this programme
- A rough **schedule**
  - Sensor design in **2009**
  - Stack assembly and system tests in **2010**
  - Beam test of stack in **2011**
- BUT... **not cheap**, UK funding still very difficult
  - External collaborators **very much welcome**



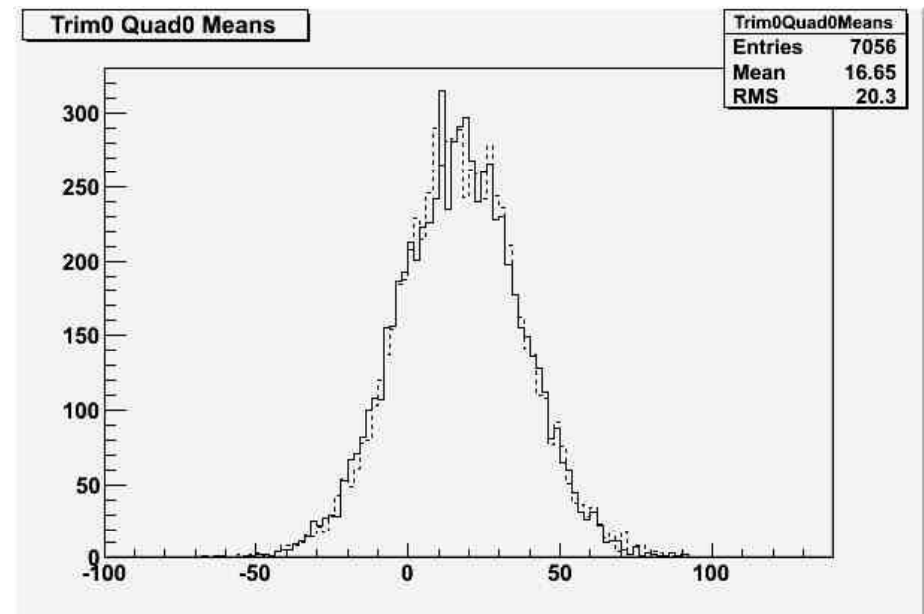
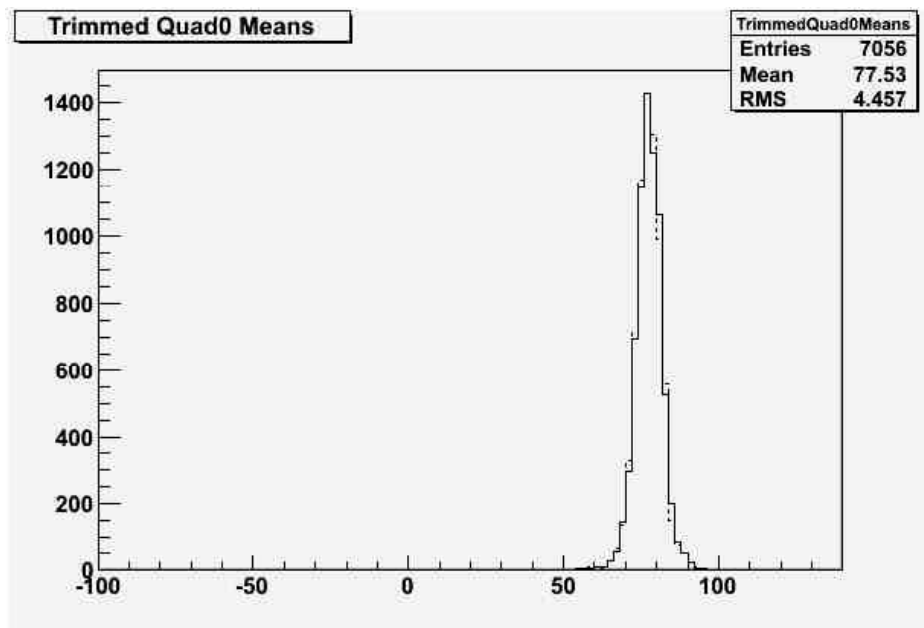
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## Conclusions

- A **DECAL** still seems possible in principle
- Actual **EM resolution** which would be obtained depends heavily on details of showers and on the algorithm for clustering
- The **simulation** has not been verified at small granularities
- Essential to get **real data** to compare
- Will have first look at **showers** early in 2009
- May have first look at **EM resolution** in 2011

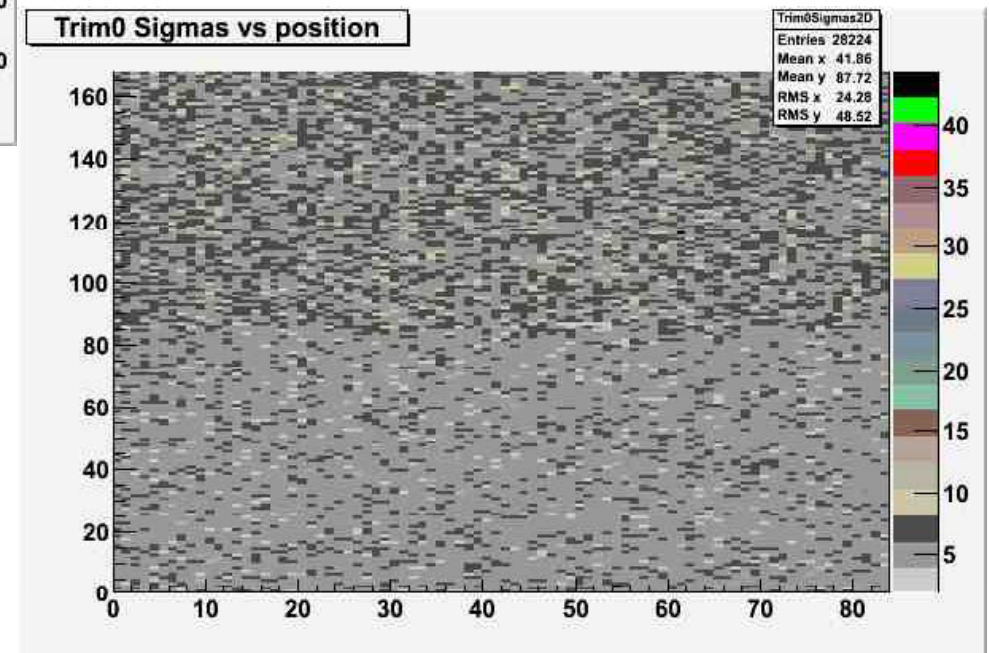
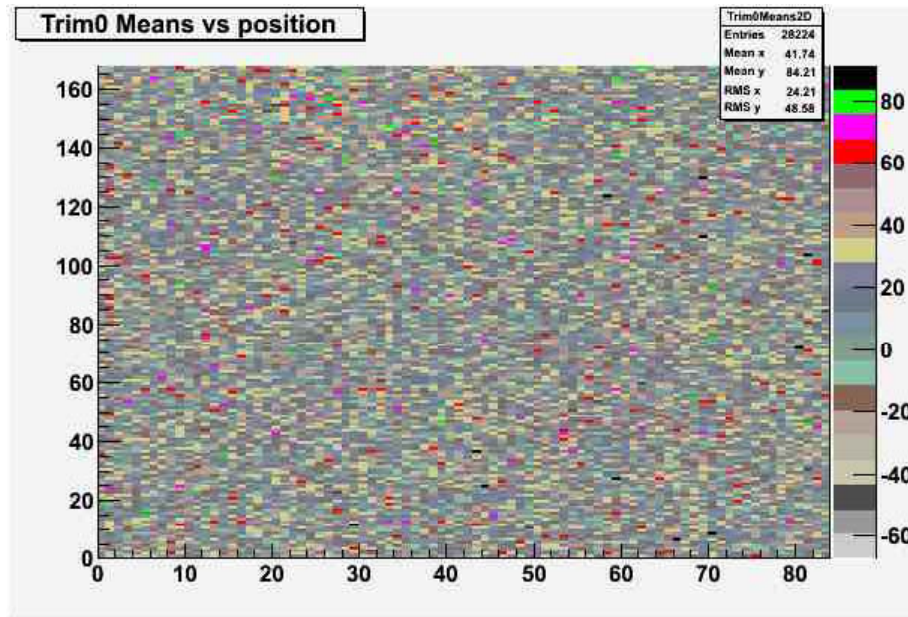
# Backup: Single pixel pedestals

- Pedestal given by mean of threshold scan
  - Pedestal spread is  $\sim 4$  times noise



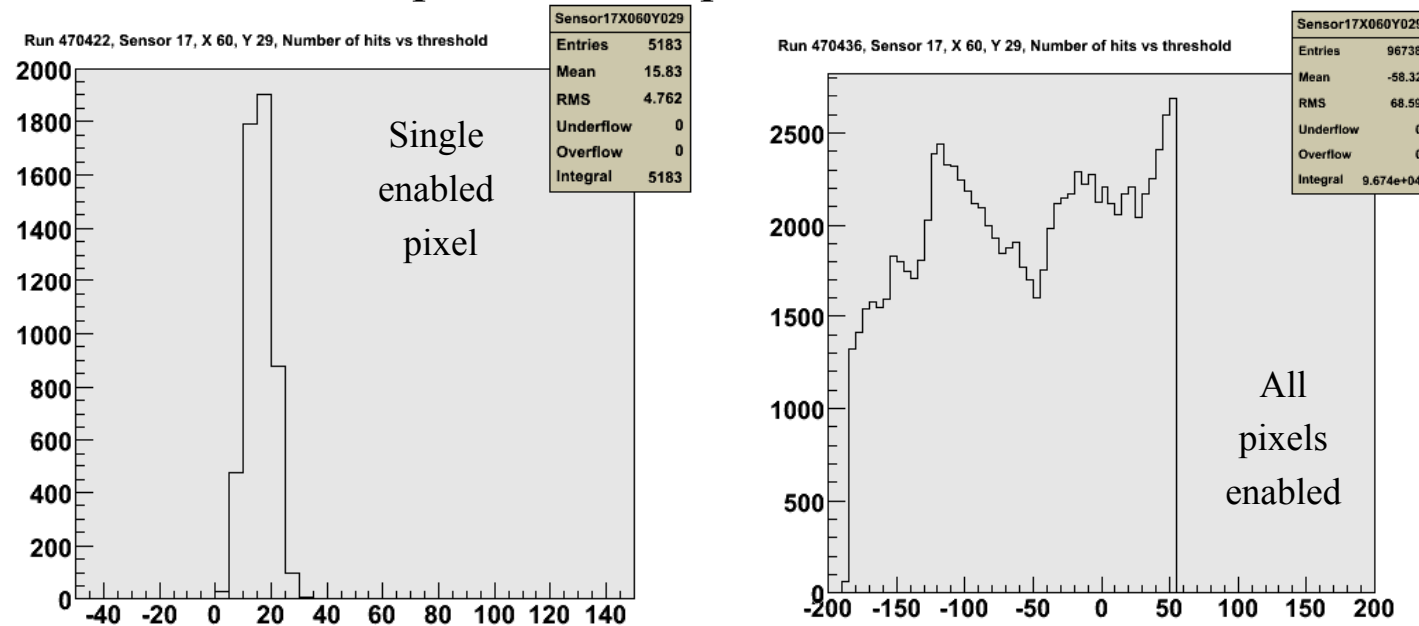
- Must correct using trims to get sensible data
  - Trimming works reasonably well; down to RMS of  $\sim 4.5$  TU
  - Still not completely below noise level so more trim bits would help

# Backup: Pedestal and noise over sensor



# Backup: pixel hit pickup

- Find different results for pixel if other pixels enabled



- Prevented pedestals from being determined until effect understood
  - Plots shown previously had most pixels masked
  - Not found before Dec 2007 beam test so data had bad trims; probably unusable
- Probably due to shared power mesh for comparators and monostables
  - If  $> \sim 100$  pixels fire comparators at same time, power droops and fires other monostables
  - Not an major issue for normal use (once understood)

# Backup: DECAL 16-layer stack

- Should give definitive answer to whether DECAL concept is viable
- 16 layers gives degraded resolution by factor  $\sim 2$
- Funding not available for more layers
- Hopefully extrapolate to realistic calorimeter sampling using simulation

