# The UK MAPS/DECAL Project

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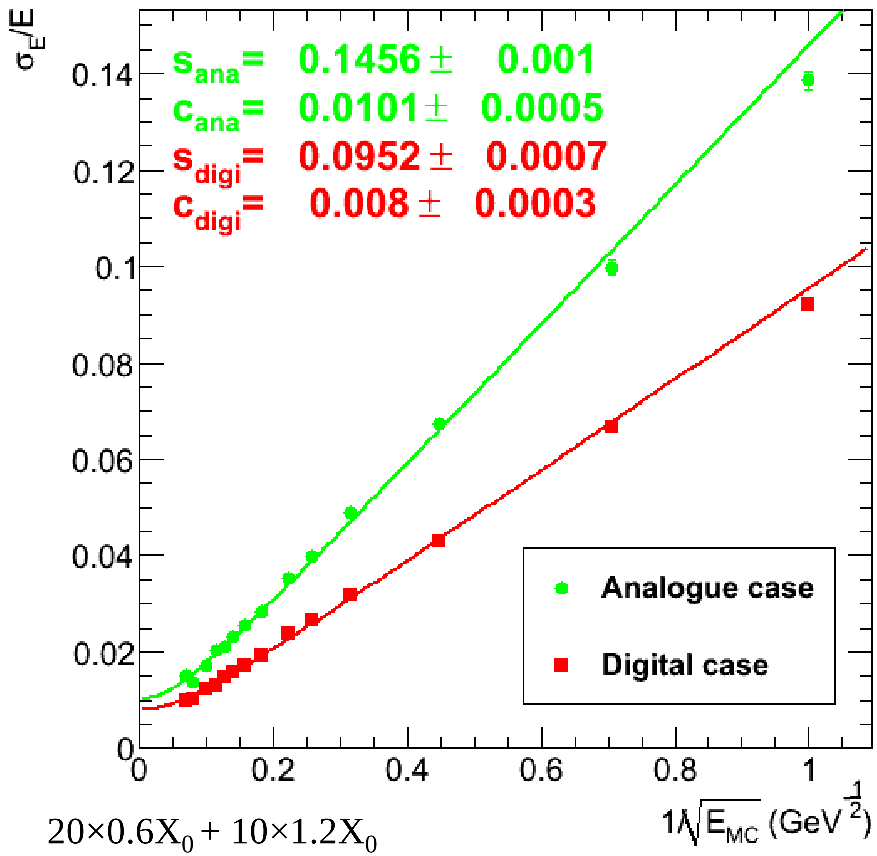
for the CALICE-UK MAPS group

# Motivation

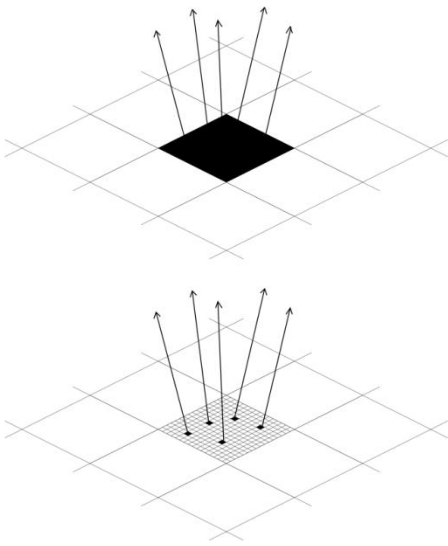
- Average number of charged particles in an EM shower ∝ incident energy
  - Fluctuations around the average occur due to statistical nature of the shower
- Average energy deposited in the sensitive layers ∝ number of charged particles
  - Fluctuations around the average occur due to angle of incidence,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



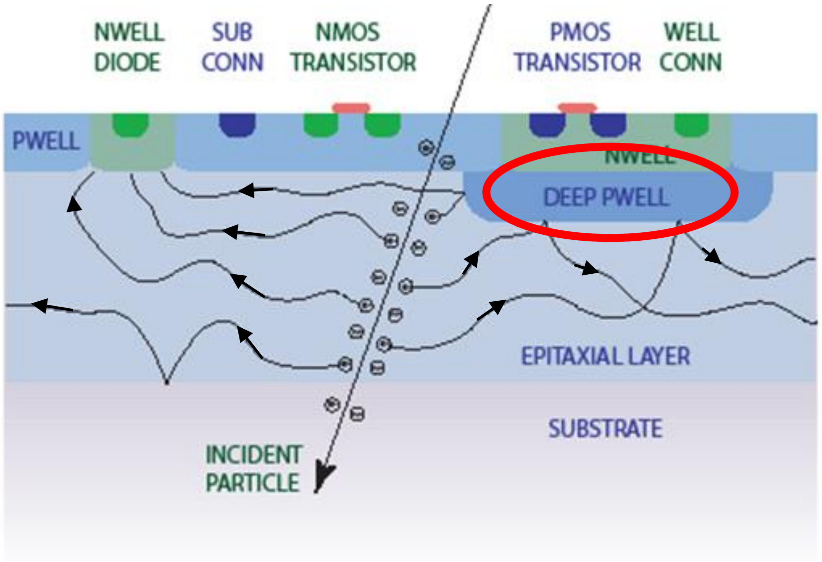

$20\times0.6X_0 + 10\times1.2X_0$

- Number of charged particles is an intrinsically better measure than the energy deposited
  - Energy deposited ("analogue" ECAL) resolution ~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



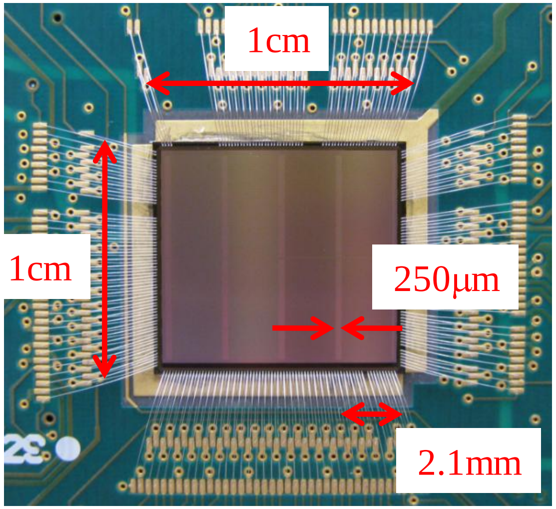
- Make pixellated detector with small pixels
  - Probability of more than one charged particle per pixel must be small
  - Allows binary readout = hit/no hit
- EM shower density ~100/mm$^2$ in core so need pixels ~ 50µm
  - Results in huge number of pixels in a real ECAL ~ $10^{12}$ pixels



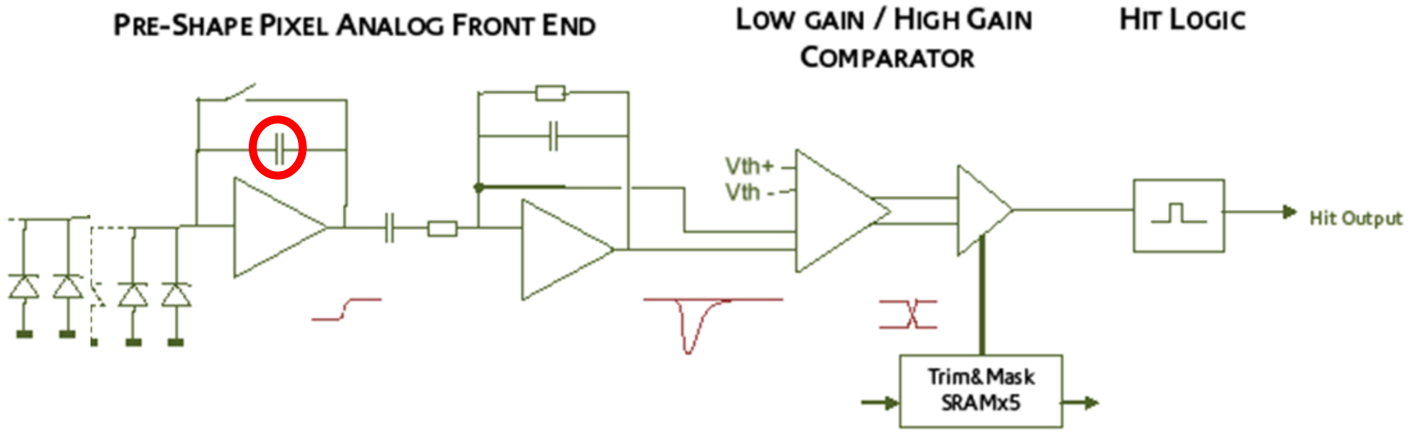

- Cannot afford to have external electronics with individual connections to so many channels
  - Need readout integrated into pixel
  - Implement as CMOS MAPS sensor
  - Includes deep p-well process to shield PMOS circuit transistors

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

# TPAC1.0 sensor

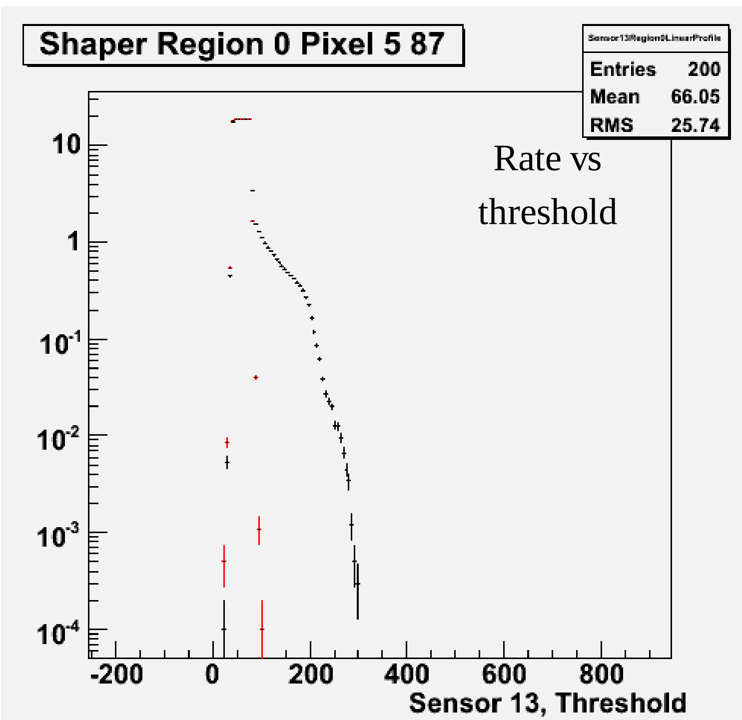



- 168×168 pixels = 28k total, each 50×50μm²
  - 0.18μm CMOS process
- Two major pixel variants, each in two capacitor combinations
  - Only one major variant worked well; "preShaper"
  - Both minor variants (Quad0 and Quad1) worked
  - All results shown are from this type
- Every pixel has 4 diodes, 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

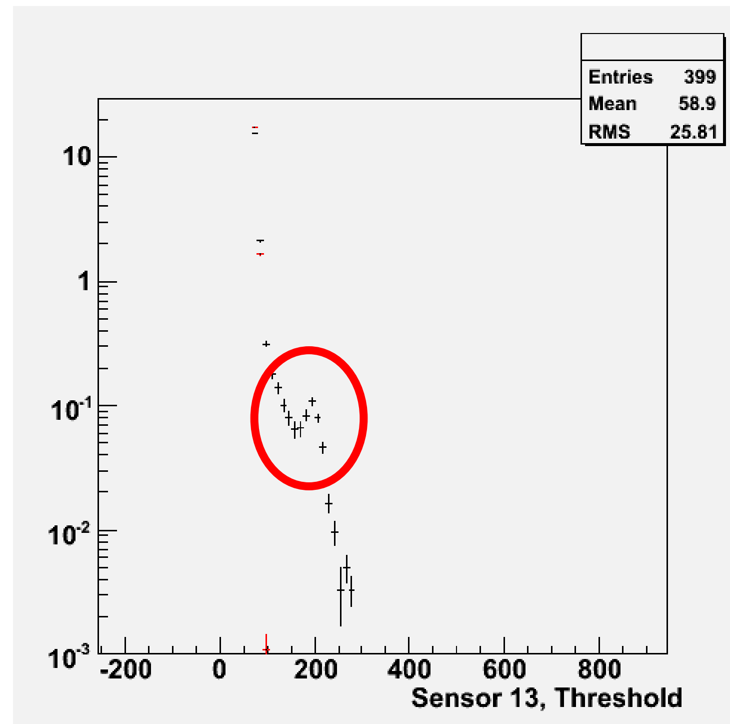


# Calibration using $^{55}Fe$

- $^{55}Fe$ gives 5.9keV photon
  - Deposits all energy in ~1μm$^3$ 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)



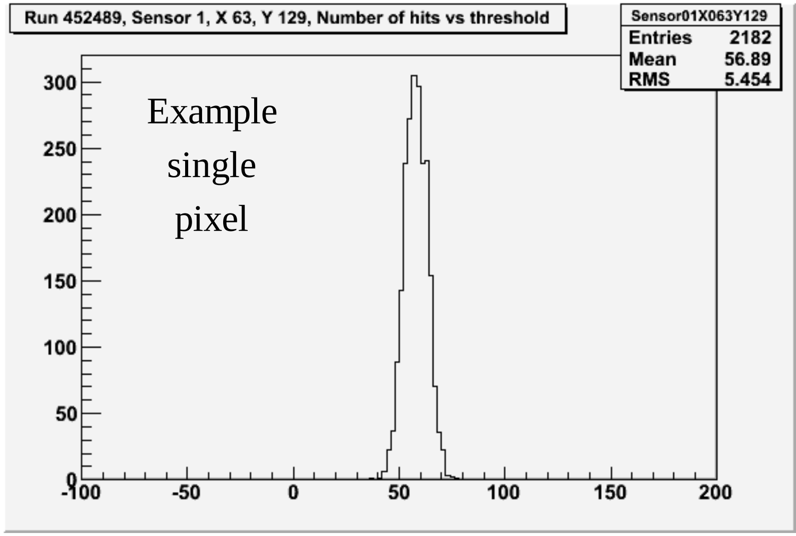

Derivative approximated using previous bin subtraction

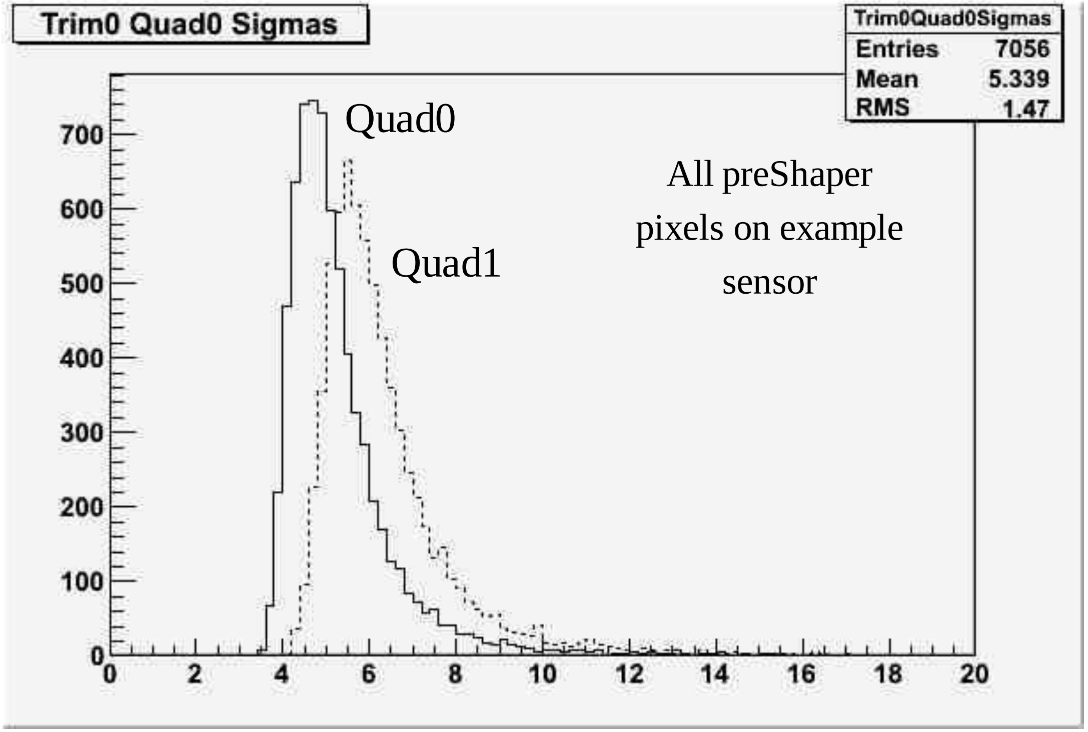



- Signal peak ~200TU above pedestal; 1TU ~ 8e$^-$ ~ 30eV deposited

# Single pixel noise performance

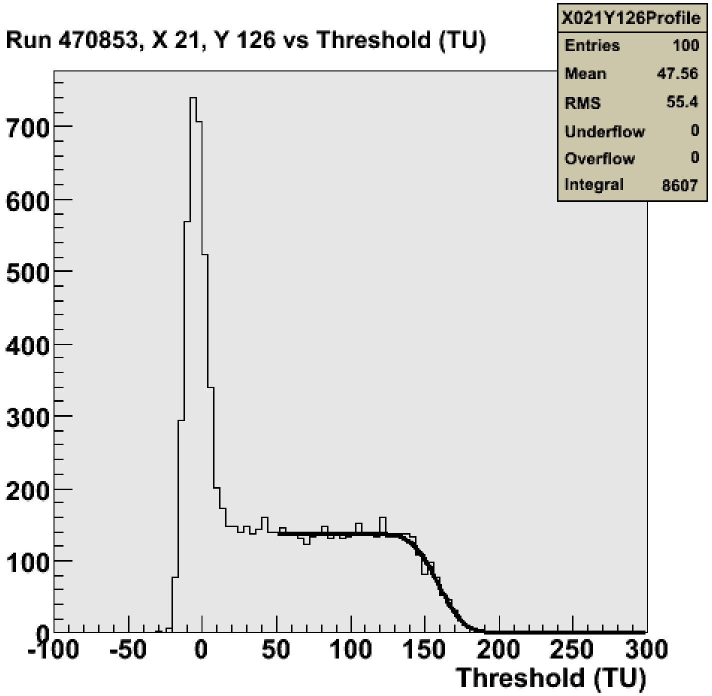
- Also need threshold scan to see pedestal and noise
  - Comparator fires on signal going high across threshold level
  - No hits when far above or below threshold
  - Width of distribution equivalent to noise



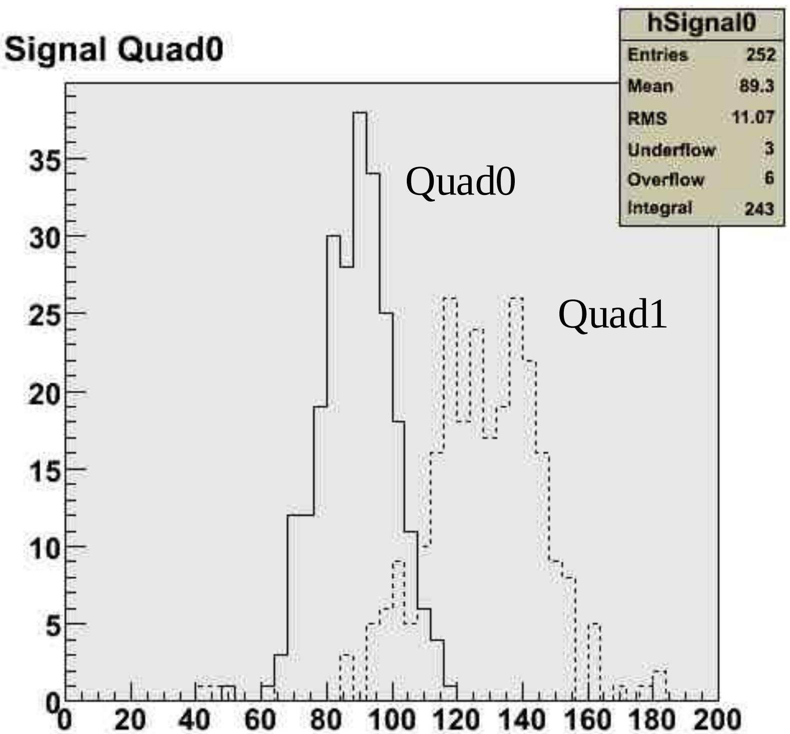




- RMS ~ 5.5TU ~ 44e$^-$ ~ 170eV on average
  - Minimum is ~ 4TU ~ 32e$^-$ ~ 120eV
  - Target level was ~ 90eV
  - No correlation with position on sensor
  - Spread not fully understood
  - Quad1 ~ 20% larger than Quad0

# Single pixel relative gain



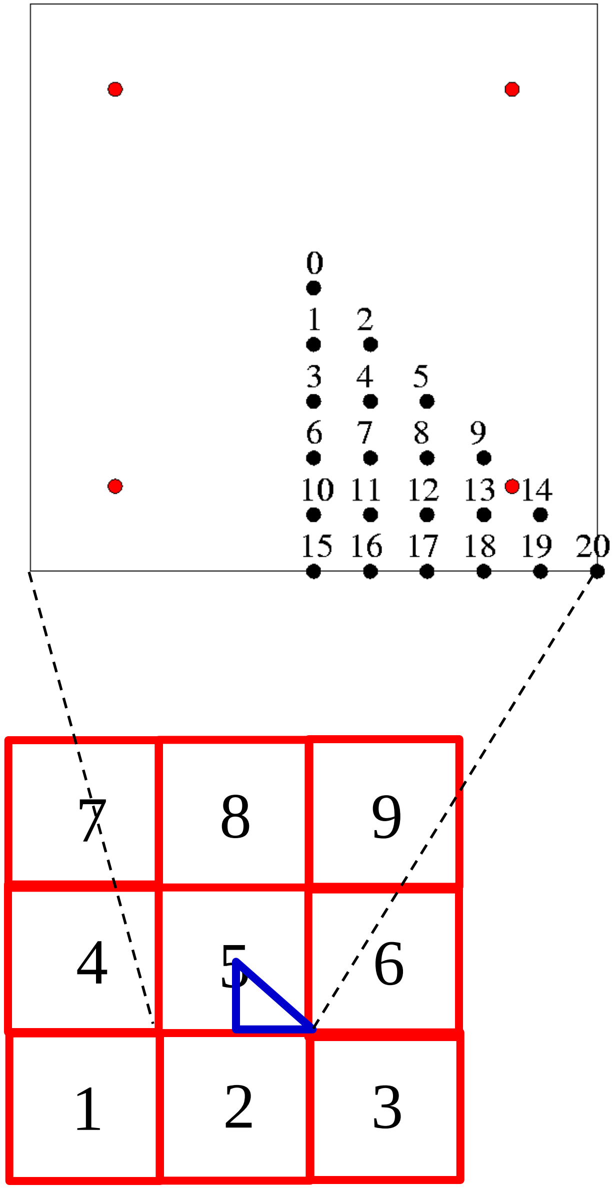

- Measured using laser
  - Silicon transparent to 1064nm light so illuminate from back side of sensor
  - Focus on epitaxial layer
  - Again need to do threshold scan and find edge to measure laser signal



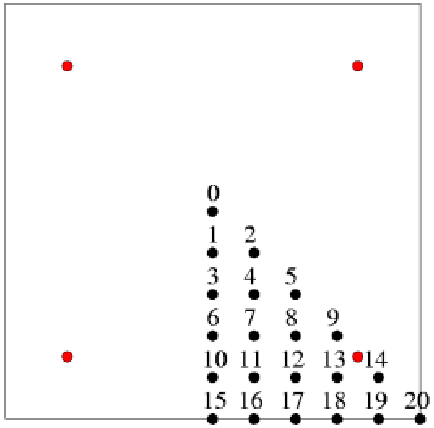

- Fixed laser intensity gives relative gain for individual pixels
  - Can do hundreds of pixels automatically
  - Gain uniform to 12%
  - Quad1 ~40% more gain than Quad0
  - Quad1 ~20% better S/N than Quad0

# Charge diffusion

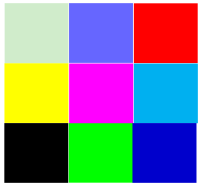
- Charge diffuses to neighbouring pixels
  - Reduces signal in “hit” pixel
  - Causes hits in neighbouring pixels
  - Need to make sure this is correctly modelled
- Simulation using Sentaurus package
  - Full 3D finite element model
  - 3×3 pixel array = 150×150μm$^2$ area
  - Thickness of silicon to 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”

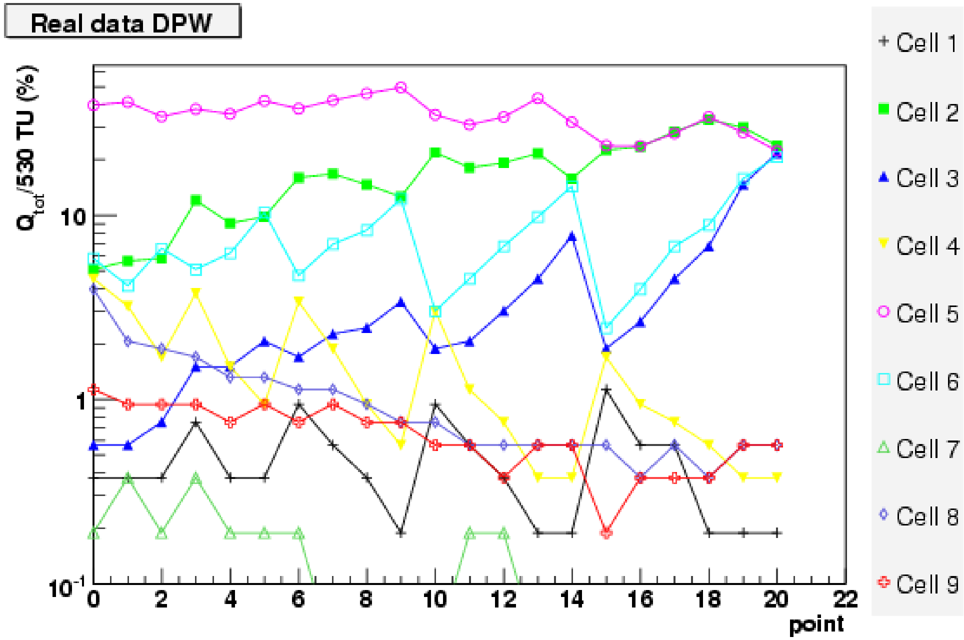


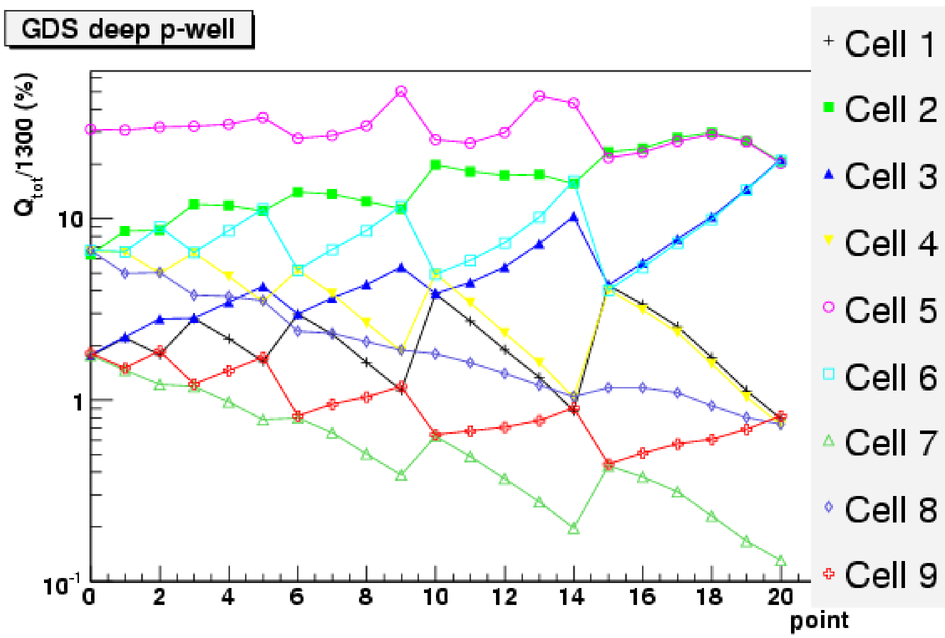
# Charge diffusion results




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

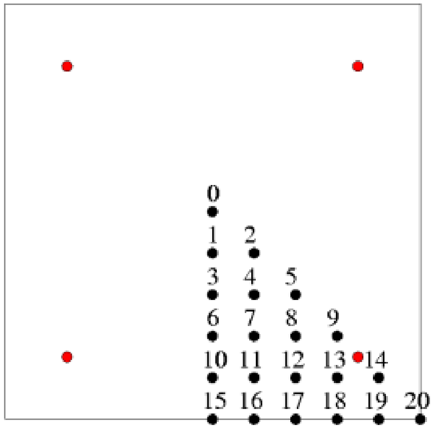


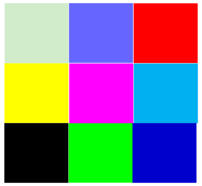


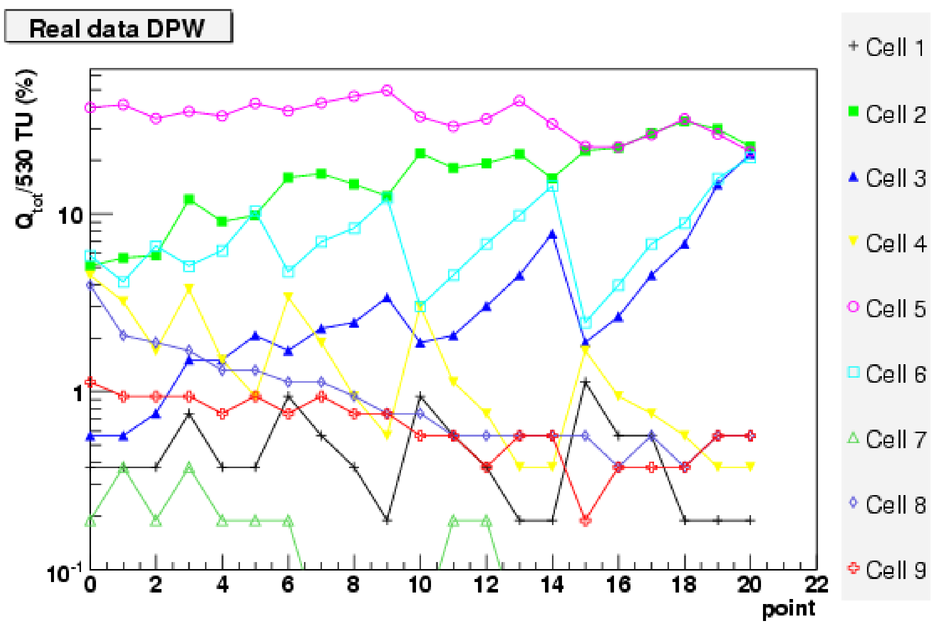



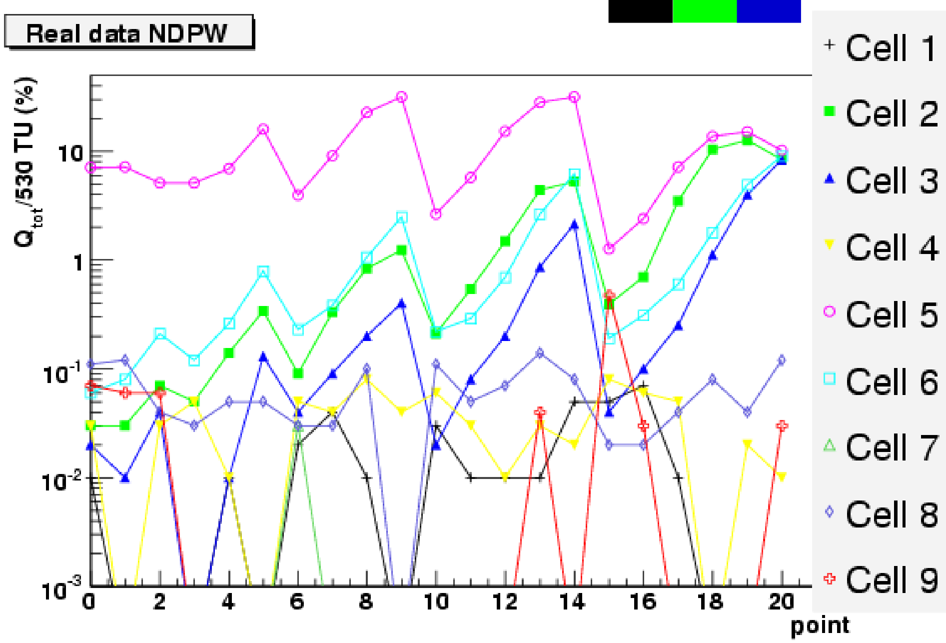
# Effect of deep p-well

- 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 ~10% ~ 130e⁻
  - Worst case ~1% ~ 13e⁻



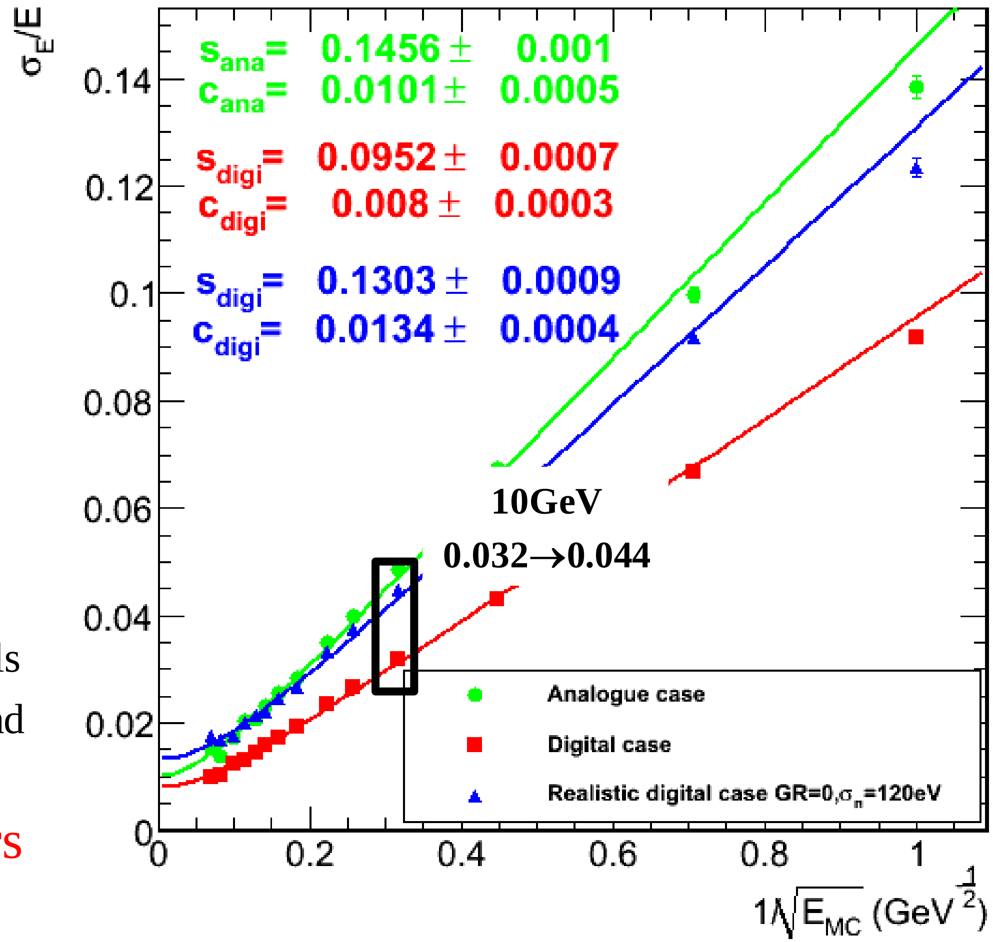



arXiv:0807.2920

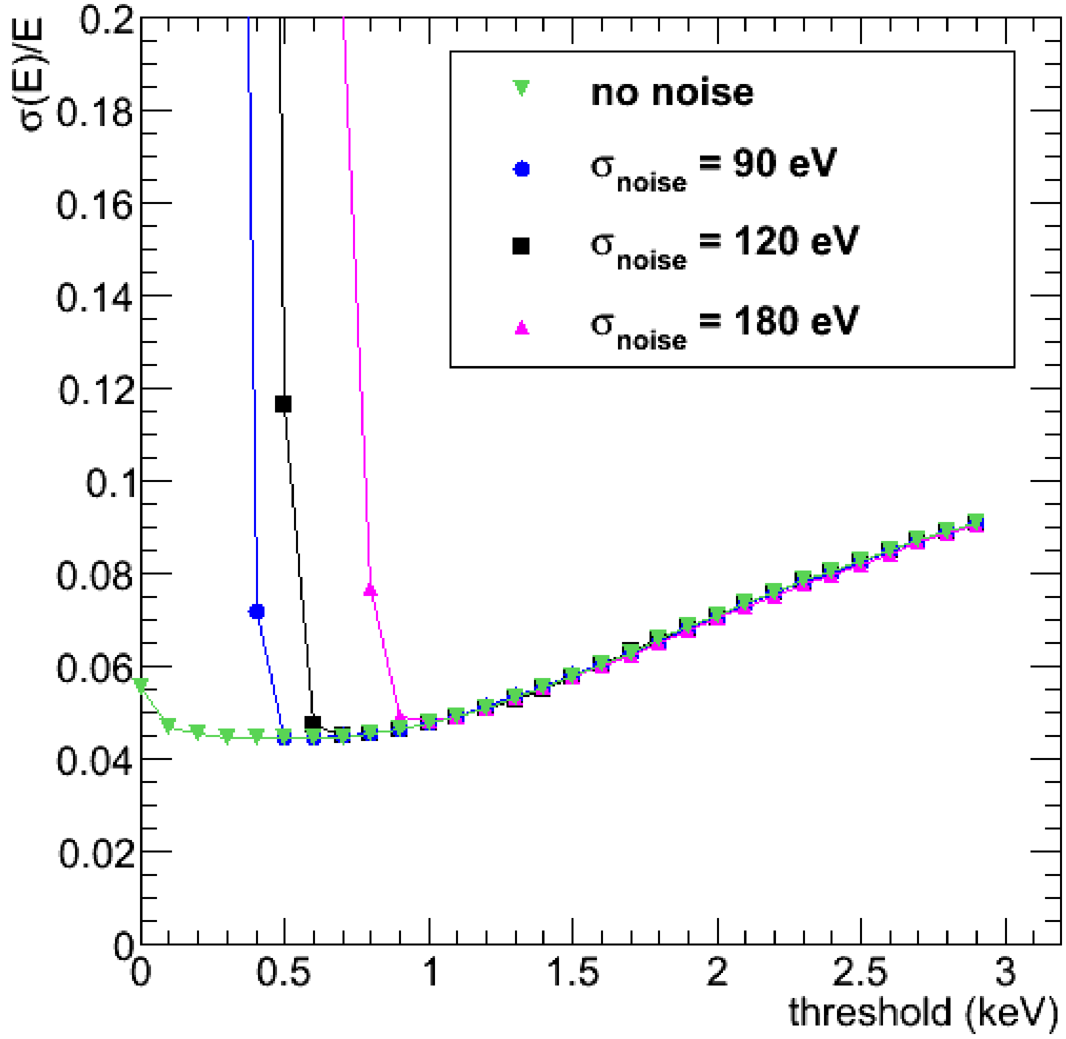
# Simulation expectation

- 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



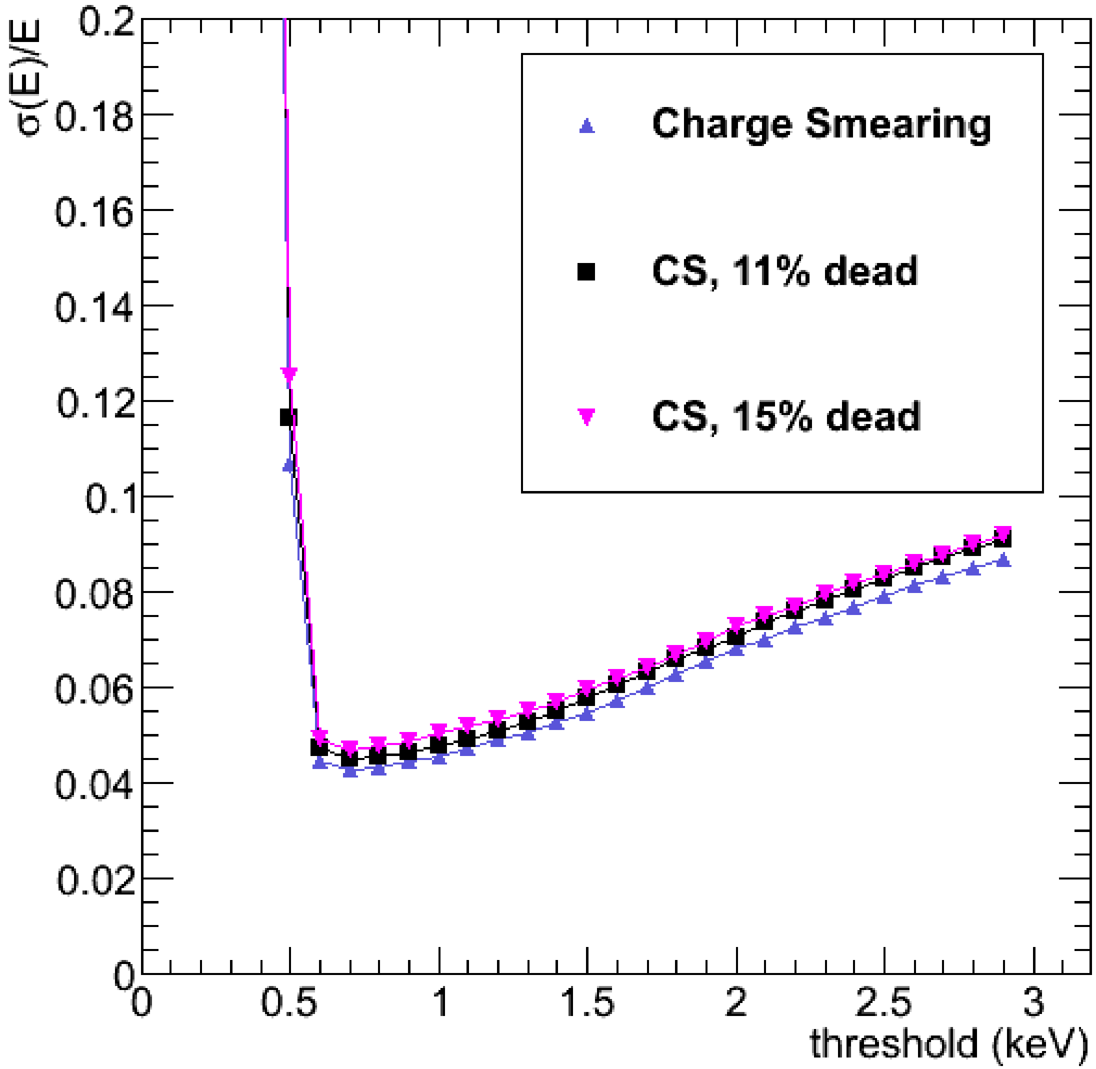
# Effect of noise

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

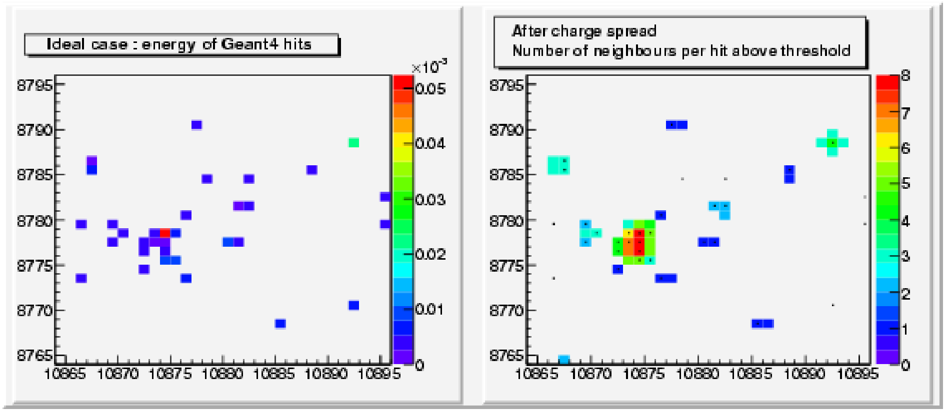


# Effect of dead area

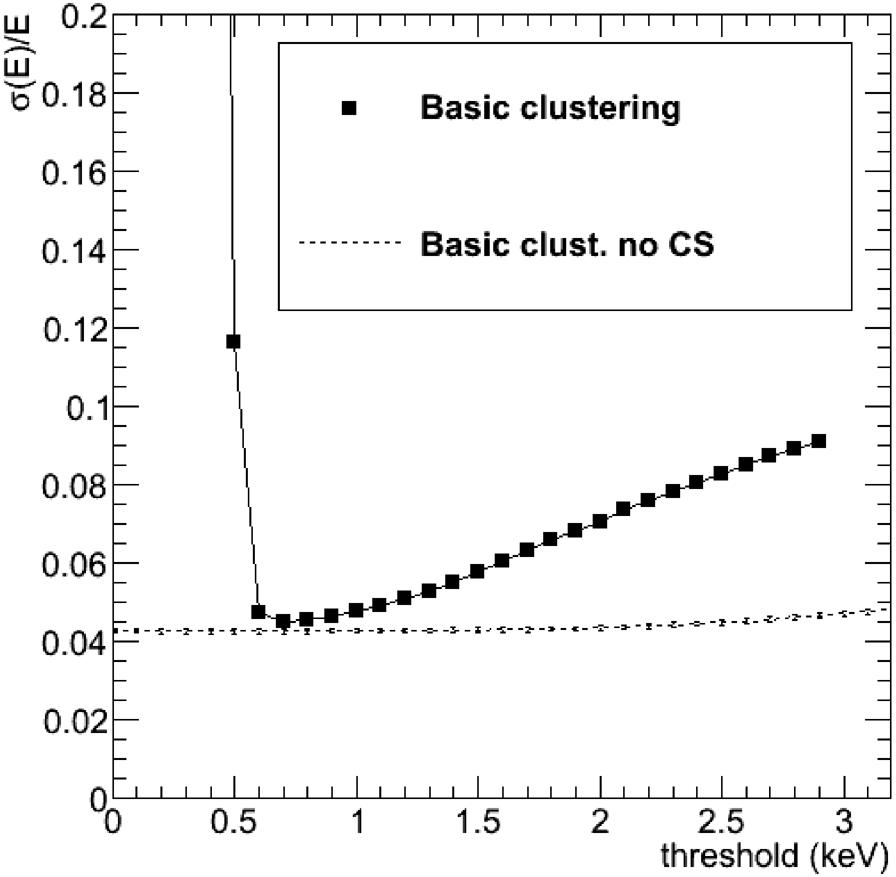
- Sensor has 11% dead region due to on-pixel memory
  - Bands of 250μm wide spaced every 2.4mm
- Shower width ~ 1cm so every shower sees several dead bands
  - Always loses 11% of hits with small fluctuations
- Since $\sigma_E/E \propto 1/\sqrt{N}$, impact is not large
  - Gives $1/\sqrt{(0.89)}$ ~ 1.06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



# Effect of charge diffusion



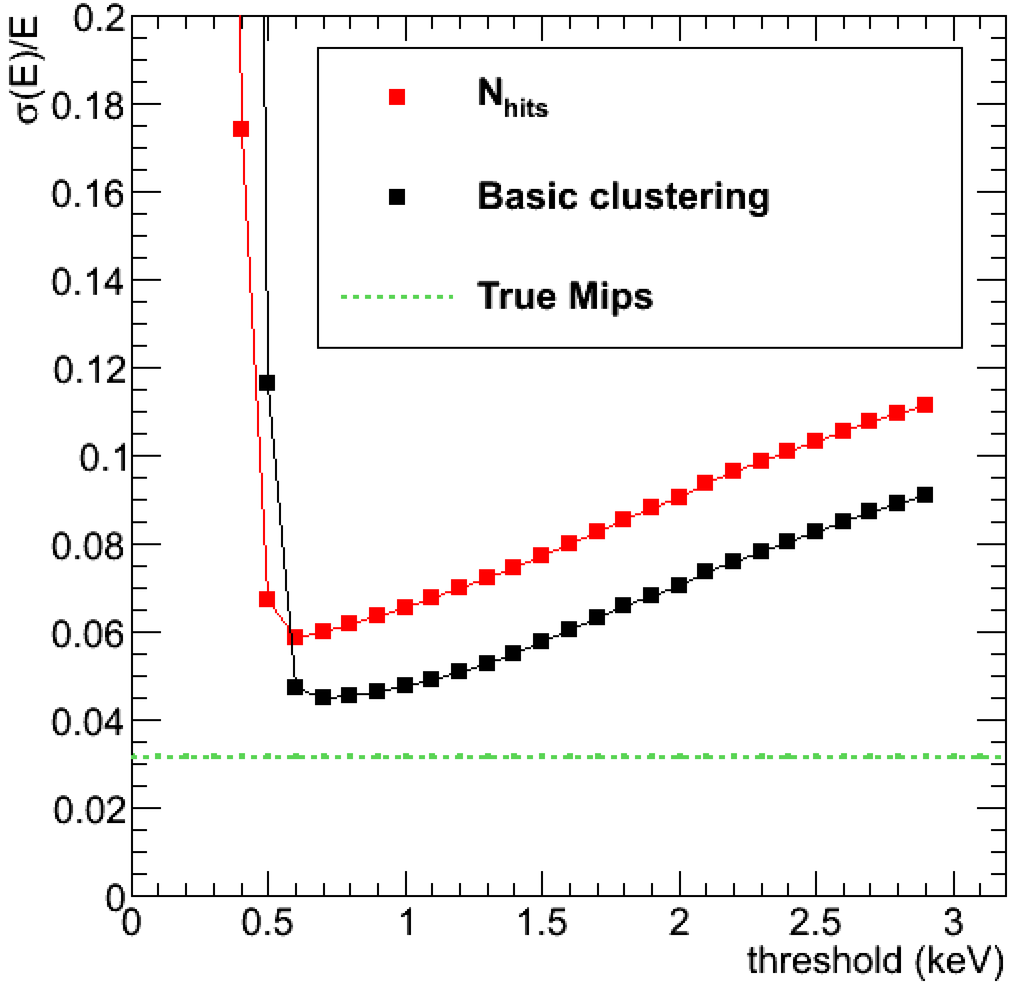

Hits in a layer before and after charge diffusion




- Need to do neighbouring hit "clustering" to convert hits to particle count
  - Following clustering, the effect of charge diffusion on the EM resolution is ~ 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 ~ 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

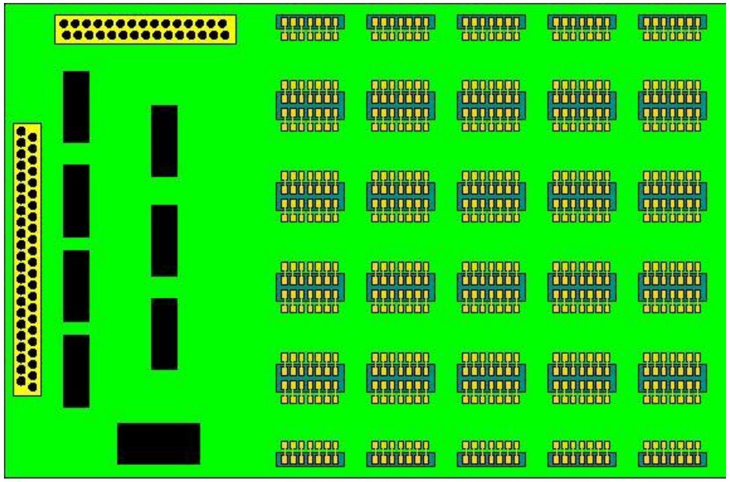


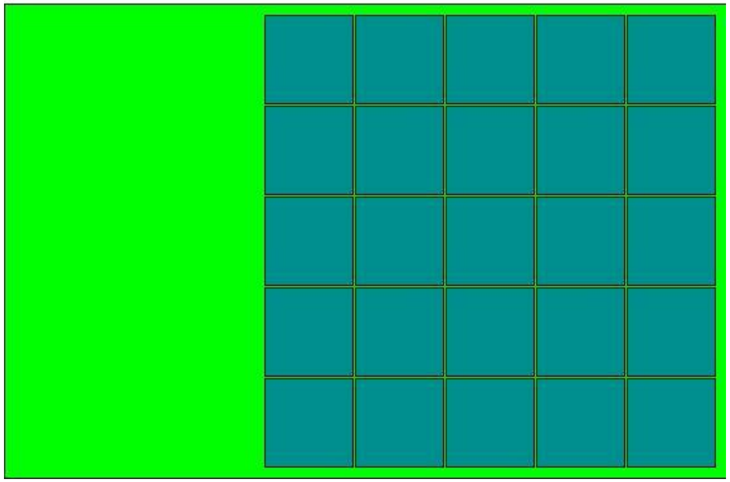
# Short term future plans

- “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 50μm granularity
  - Check critical issues of charged particle separation and keV photon flux
  - But only $1\times1\text{cm}^2$ 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 2.5×2.5cm$^2$; a factor ten in area; otherwise a scaled-up TPAC1.1
  - Bid includes funding for 16-layer Si-W DECAL stack; 5×5 sensors = 12.5×12.5cm$^2$ 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 500µm ~ 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



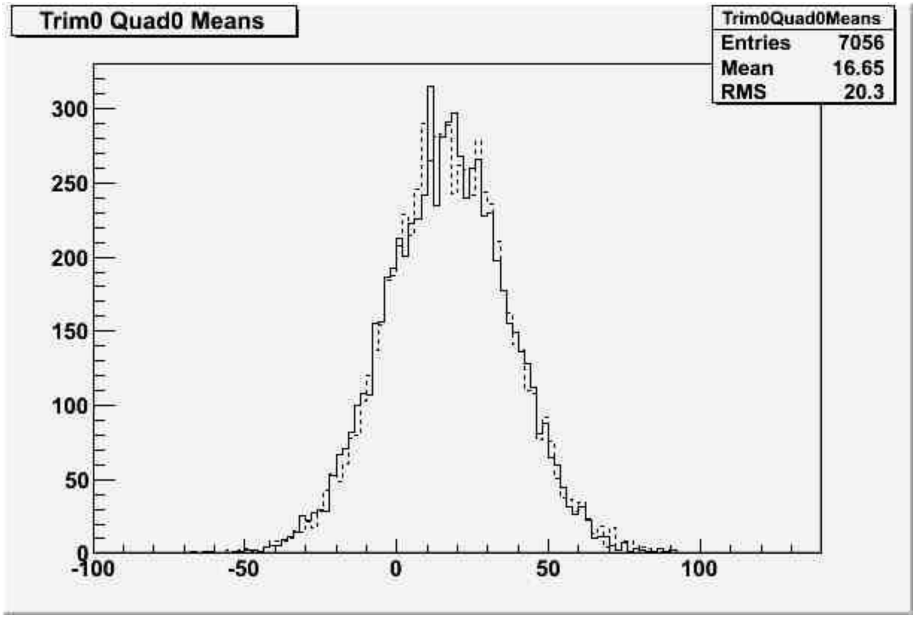


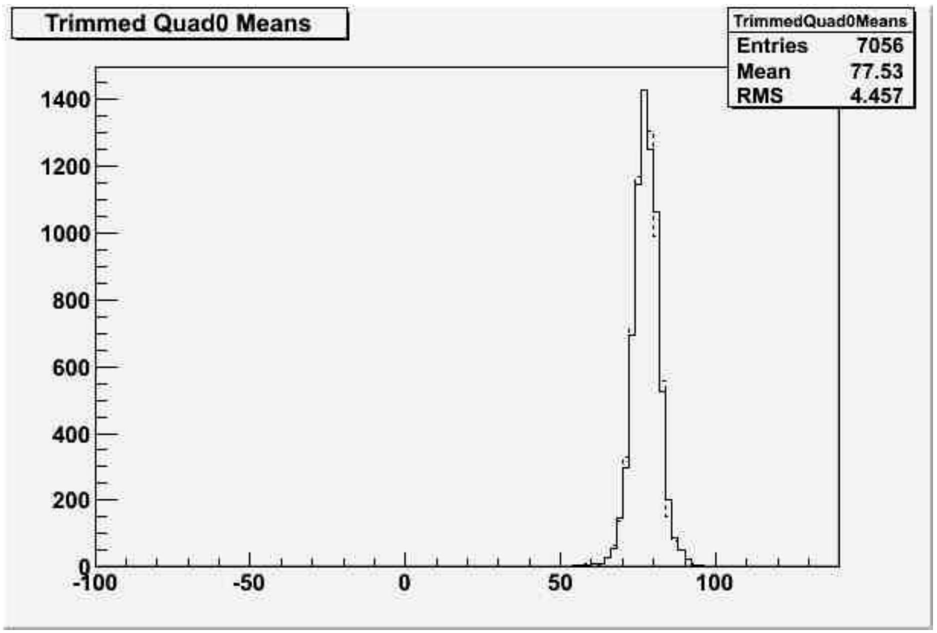
# Conclusions

- 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

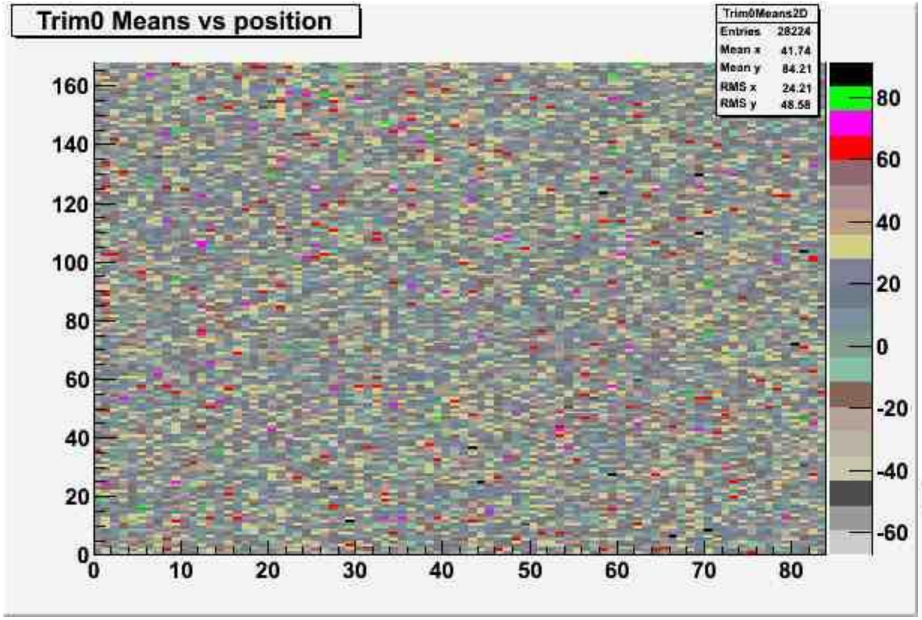
- Pedestal given by mean of threshold scan
  - Pedestal spread is ~ 4 times noise

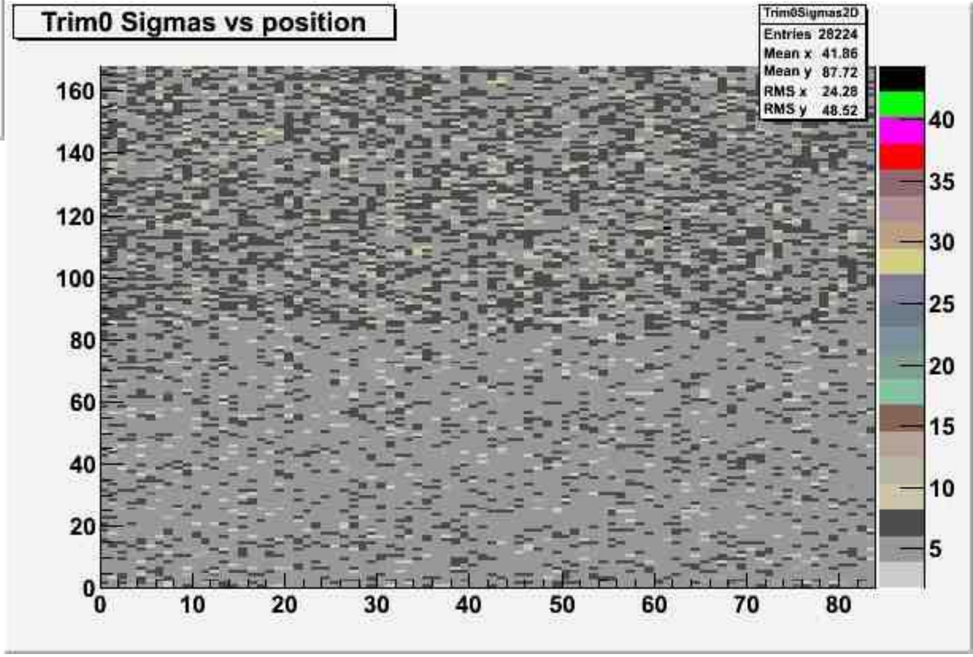



- Must correct using trims to get sensible data
  - Trimming works reasonably well; down to RMS of ~ 4.5TU
  - Still not completely below noise level so more trim bits would help

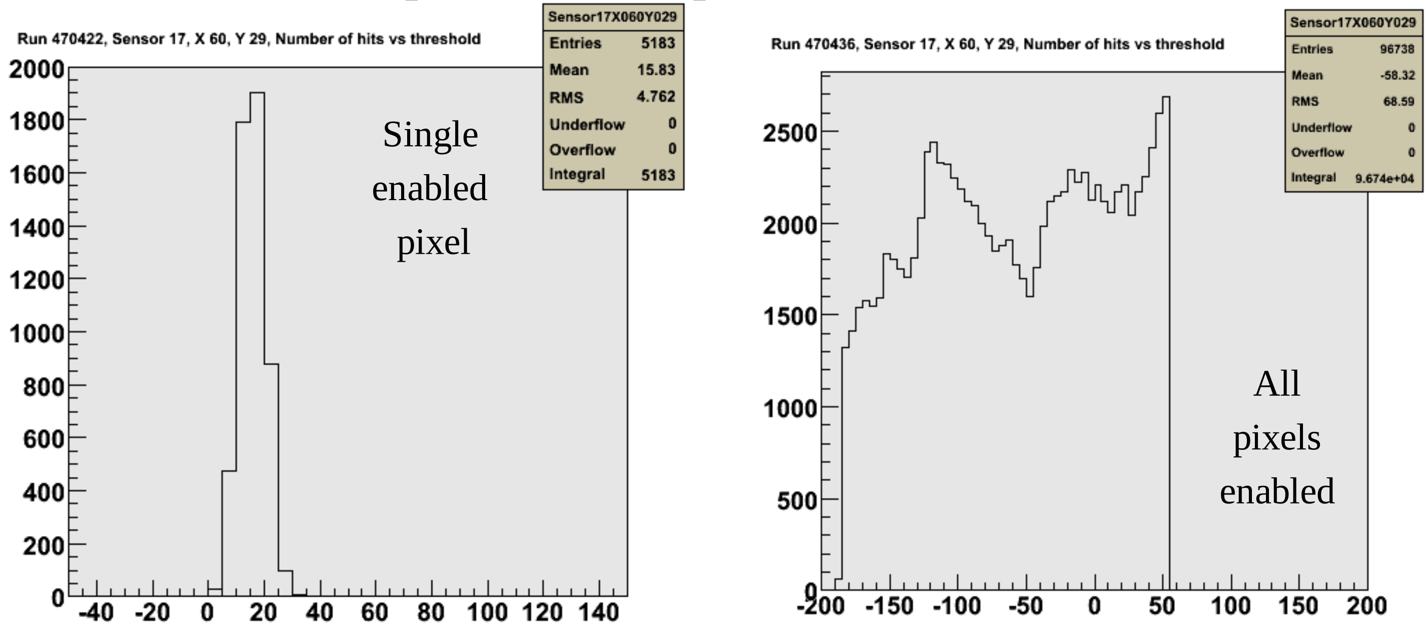
# Backup: Pedestal and noise over sensor



# 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 >~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 ~ 2
- Funding not available for more layers
- Hopefully extrapolate to realistic calorimeter sampling using simulation