MAPS/DECAL Status
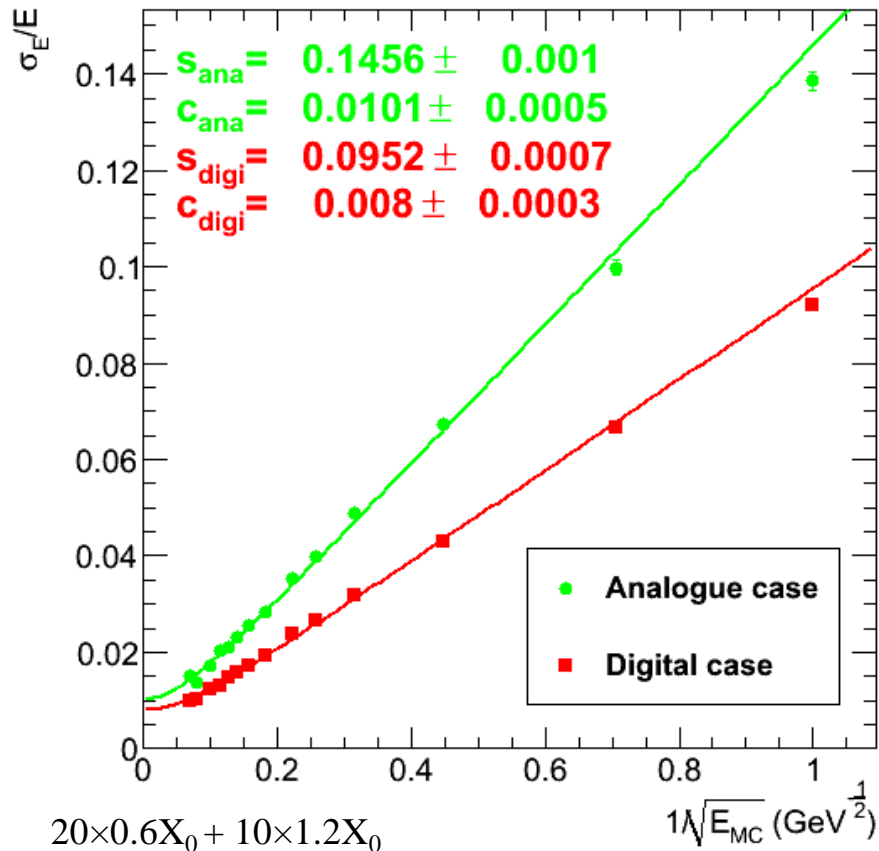
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for the CALICE-UK MAPS group

# 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

Graph labels:
σ_E/E vs $1/\sqrt{E_{MC}}$ $(GeV^{-\frac{1}{2}})$

$s_{ana} = 0.1456 \pm 0.001$
$c_{ana} = 0.0101 \pm 0.0005$
$s_{digi} = 0.0952 \pm 0.0007$
$c_{digi} = 0.008 \pm 0.0003$

- Analogue case
- Digital case

$20 \times 0.6 X_0 + 10 \times 1.2 X_0$

- 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?
  - Can we get anywhere near the ideal resolution?

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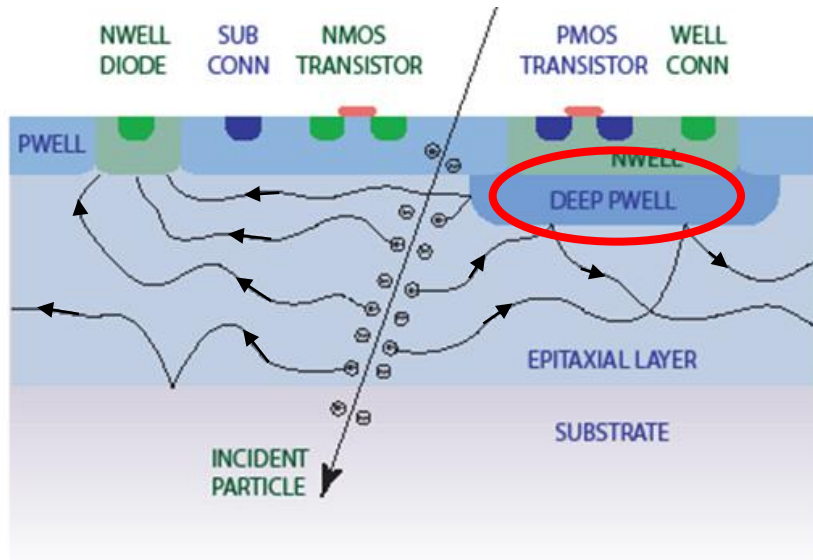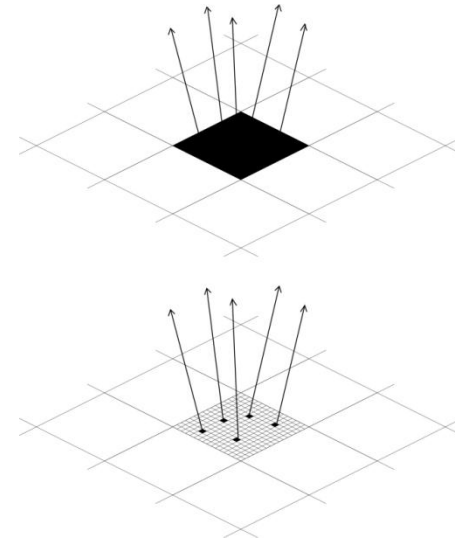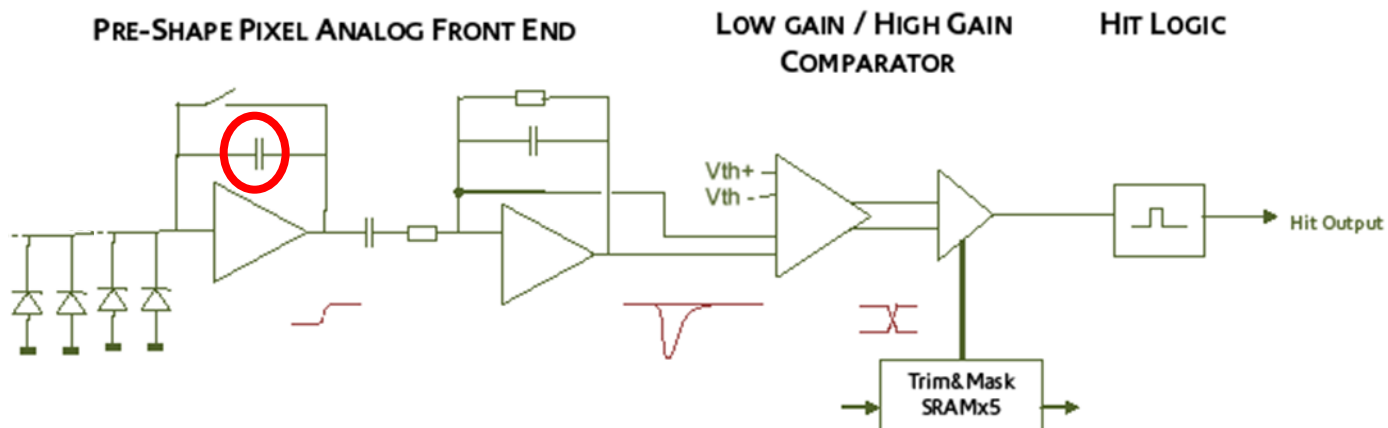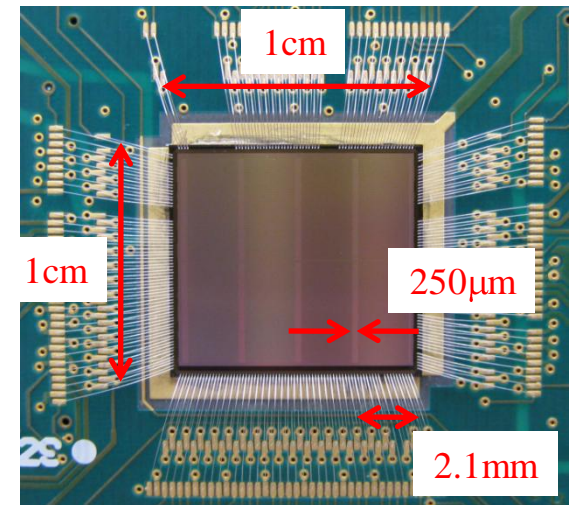
- Cannot afford to have external electronics with individual connections to so many channels
    - Need readout integrated into pixel
    - Implement as CMOS MAPS sensor
    - Includes deep p-well process to shield PMOS circuit transistors

- 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 $50 \times 50 \mu m^2$
- 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

1cm
1cm
250μm
2.1mm

- 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

PRE-SHAPE PIXEL ANALOG FRONT END   LOW GAIN / HIGH GAIN COMPARATOR   HIT LOGIC

Vth+
Vth −

Hit Output

Trim&Mask
SRAMx5

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
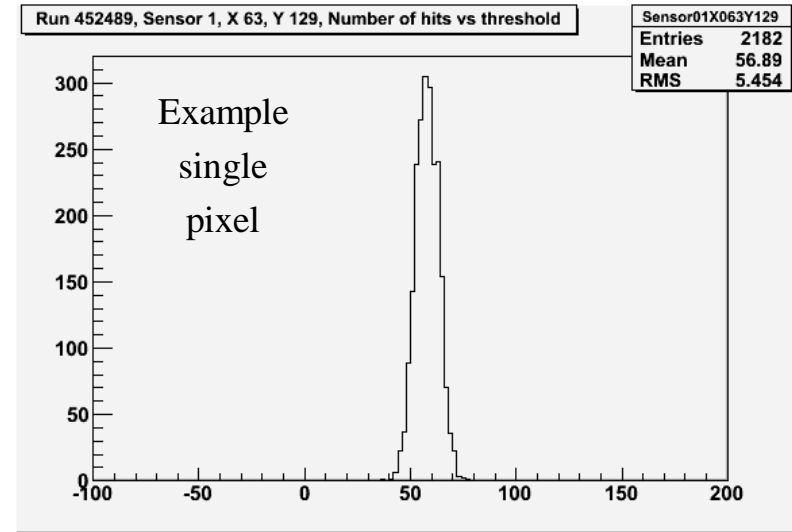 - Need to differentiate distribution to get signal peak in threshold units (TU)

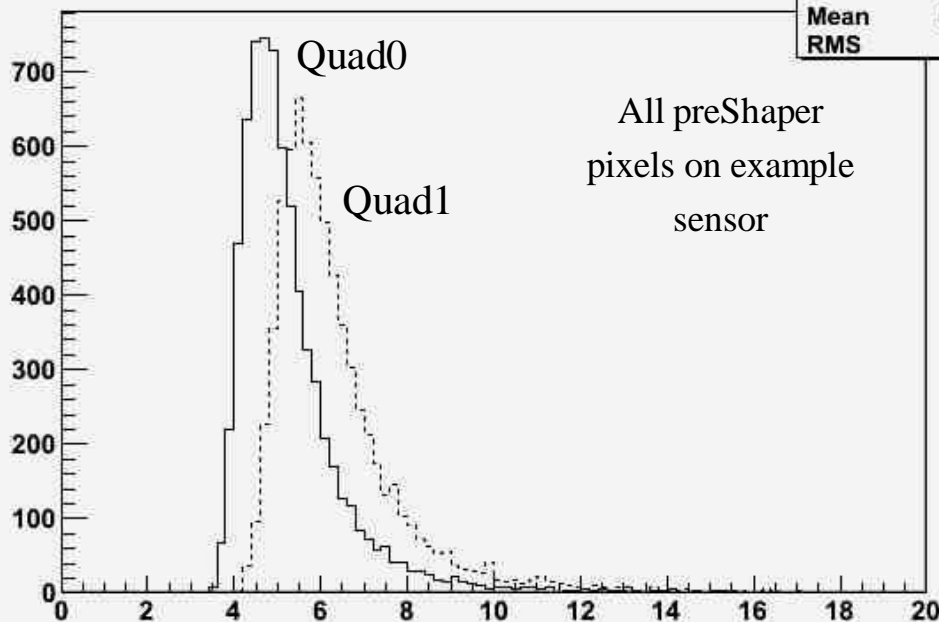Rate vs threshold
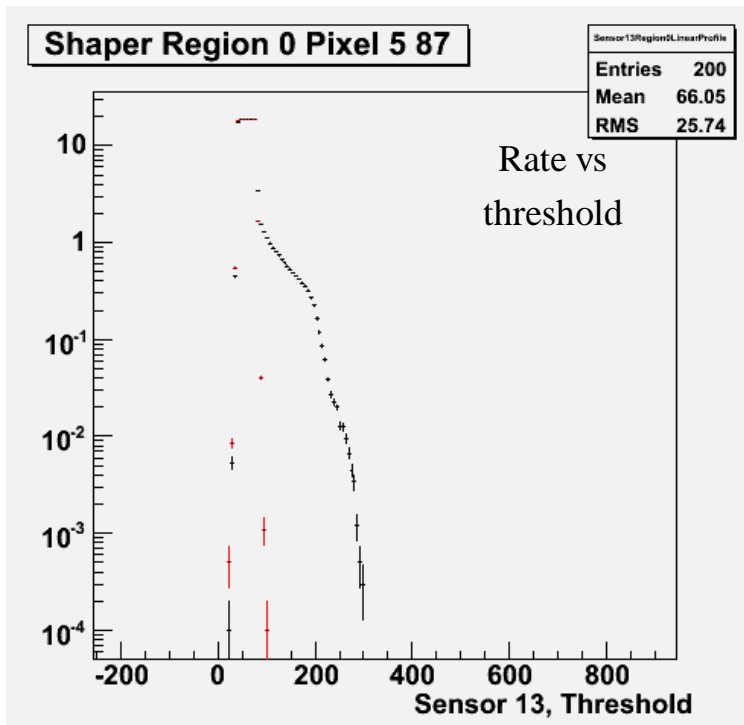
Derivative approximated using previous bin subtraction
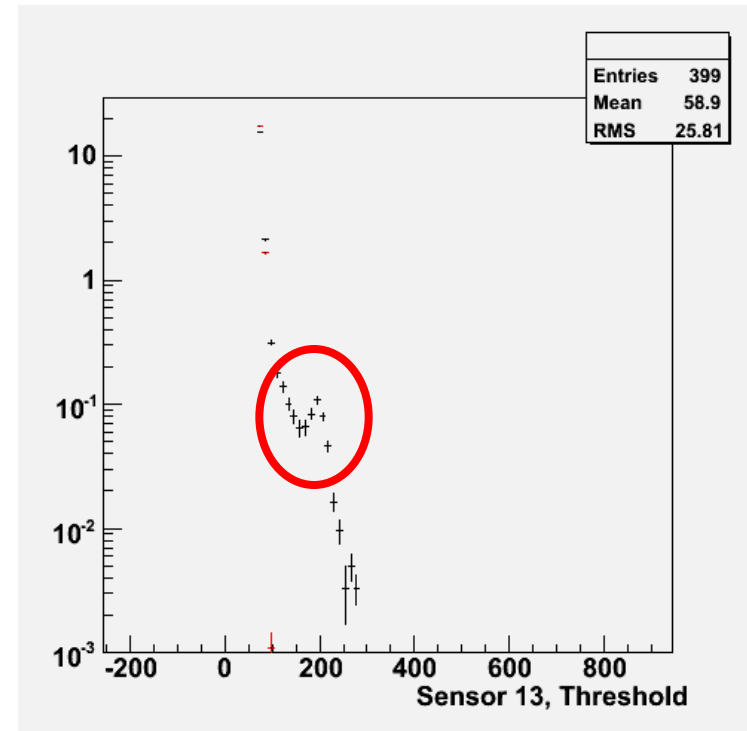
- Signal peak ~200TU above pedestal; 1TU ~ 8e$^-$ ~ 30eV deposited

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

Run 452489, Sensor 1, X 63, Y 129, Number of hits vs threshold

Sensor01X063Y129	
Entries	2182
Mean	56.89
RMS	5.454

Example single pixel

Trim0 Quad0 Sigmas

Trim0Quad0Sigmas	
Entries	7056
Mean	5.339
RMS	1.47

Quad0

Quad1

All preShaper pixels on example sensor

- 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

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

X021Y126Profile	
Entries	100
Mean	47.56
RMS	55.4
Underflow	0
Overflow	0
Integral	8607
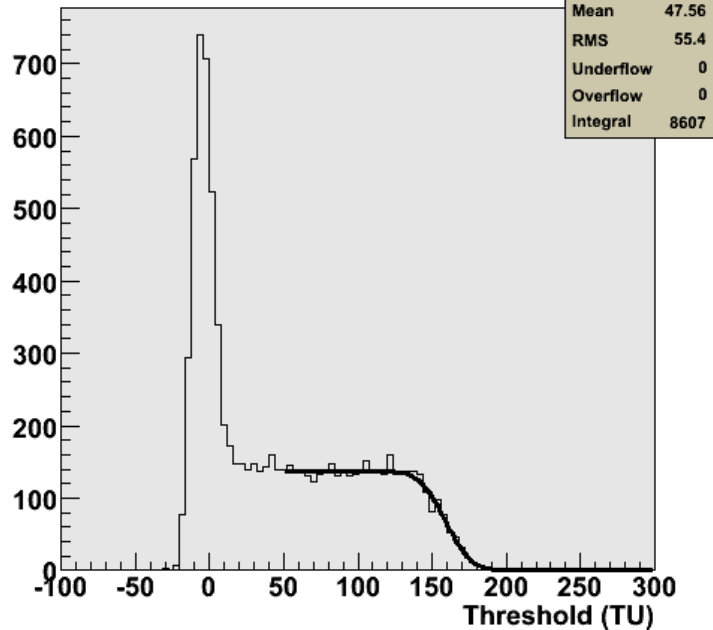
- Measured using laser
  - Silicon transparent to 1064nm light so illuminate from back side of sensor
  - Focus on epitaxial layer
 - Again need to do threshold scan and find edge to measure laser signal

Signal Quad0

hSignal0	
Entries	252
Mean	89.3
RMS	11.07
Underflow	3
Overflow	6
Integral	243

Quad0

Quad1

- 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
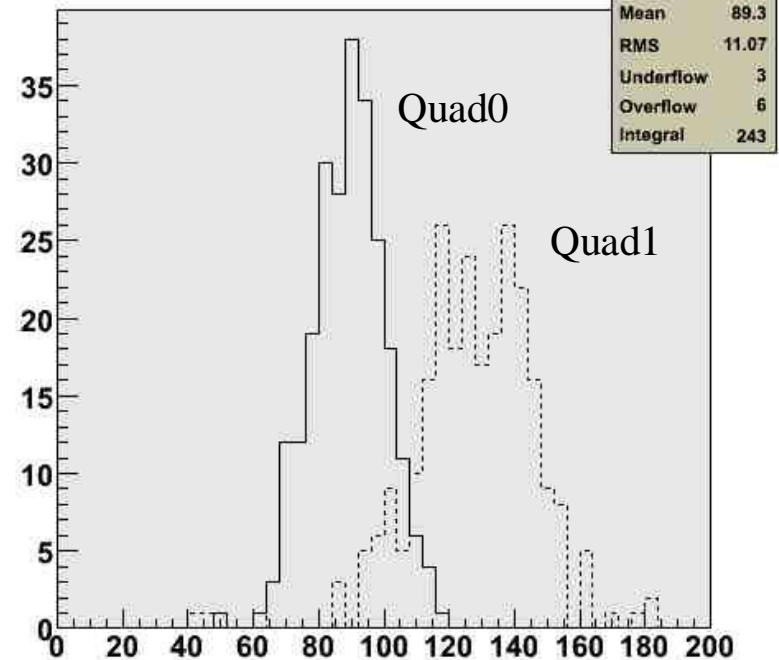
Charge spread

- 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 = $150\times150\mu m^2$ area
  - Thickness of silicon to $32\mu m$ depth; covers epitaxial layer of $12\mu m$ plus some of substrate
- Use laser to fire at 21 points within pixel
  - Laser spot size $< 2\mu m$, step size $1\mu m$
  - 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"
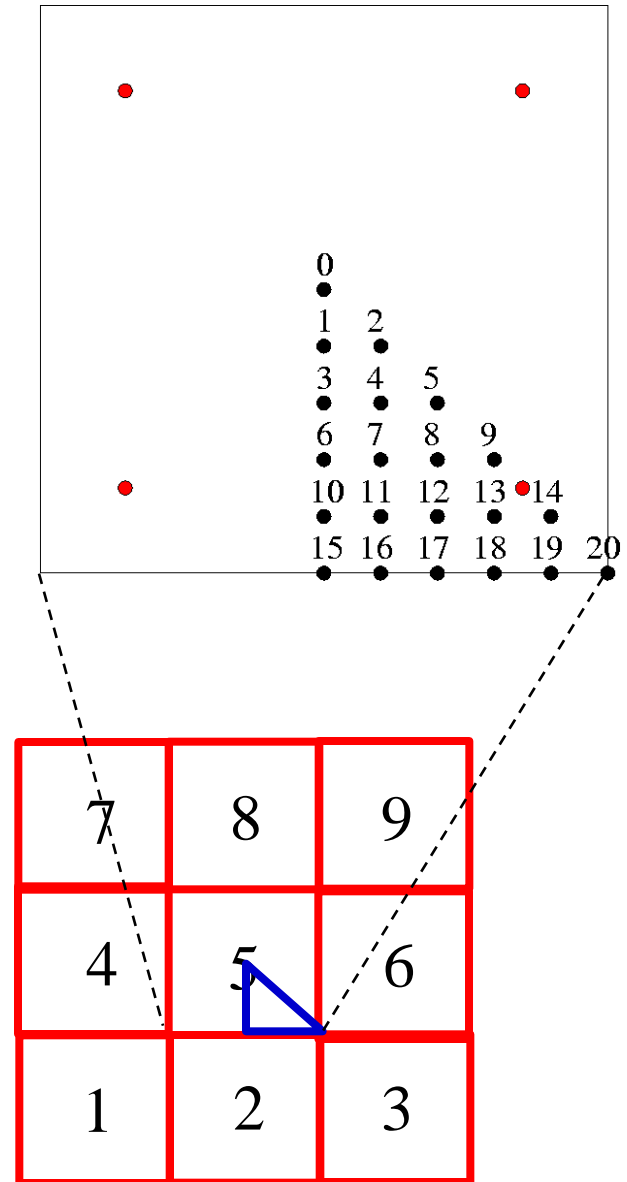
Charge spread results
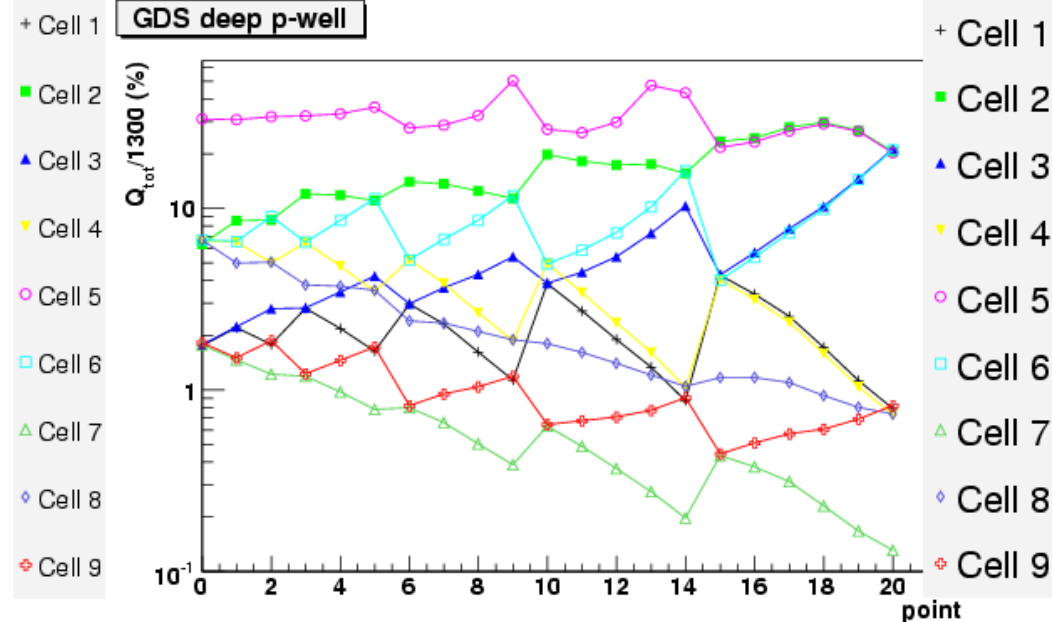
- Simulation reasonably reproduces the spatial dependence
  - Small differences near diodes (points 9,13,14)
- Average signal over whole pixel ~ 35% of deposited signal
  - Total charge is 1300e$^-$ so average ~ 450e$^-$
  - Average signal/noise ~ 10
- Worst case signal in central pixel is when hitting corner
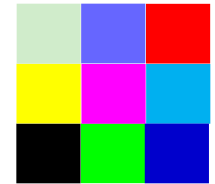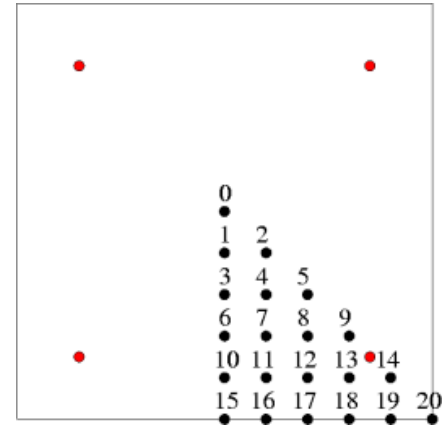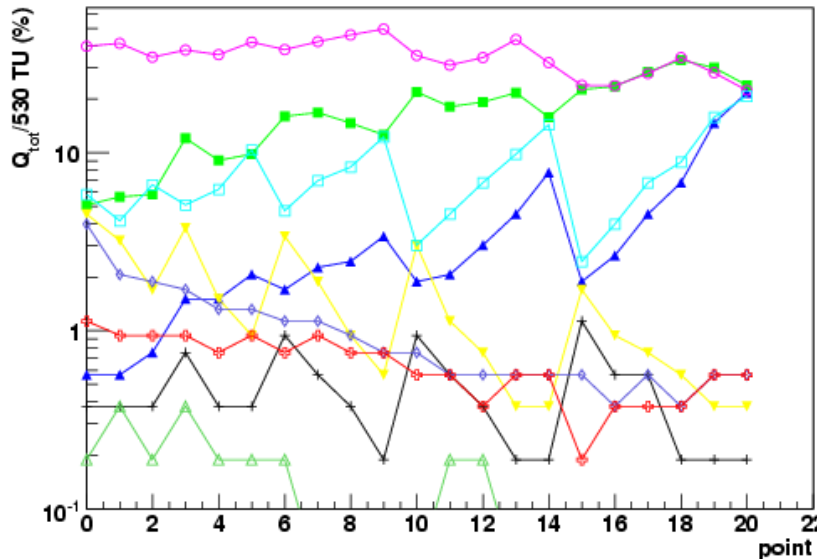 - Gives ~ 24% of total charge so ~ 300e$^-$ and S/N ~ 7
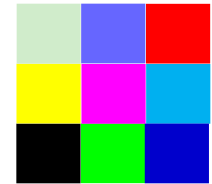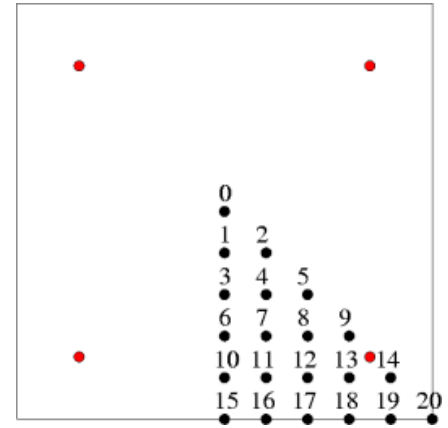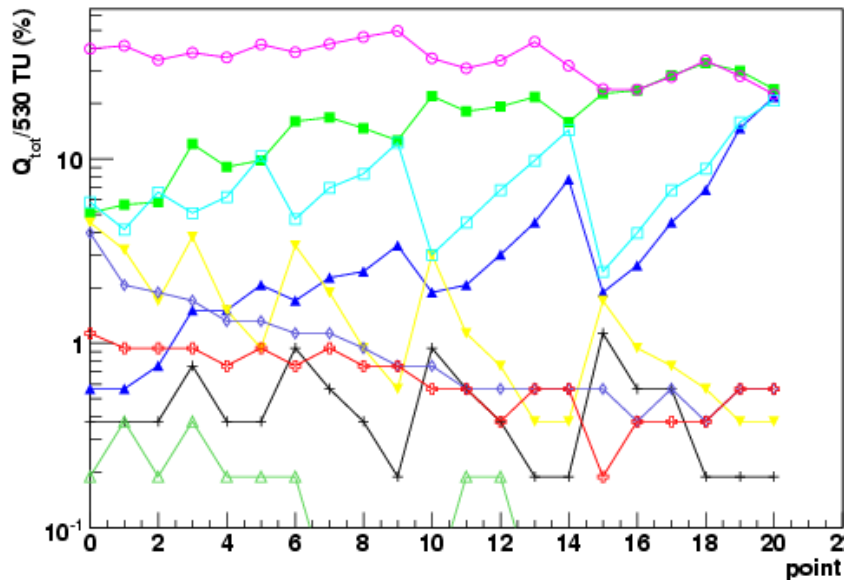
Effect of deep p-well

- 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% ~ $13e^-$

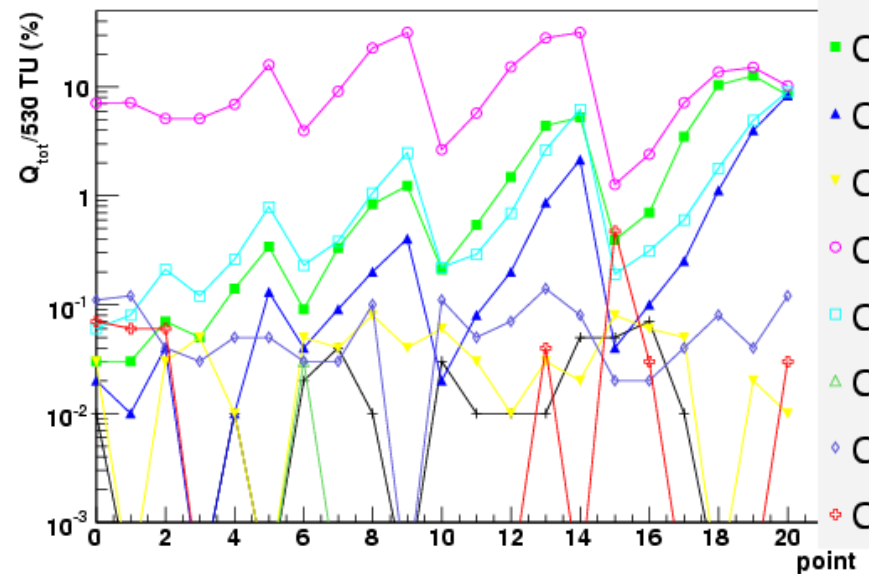**arXiv:0807.2920**

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 if pixels hit not trivially related to number of charged tracks

- Degradation arises from
  - Noise hits
  - Dead area
  - Particles sharing pixels
  - Particles crossing pixels boundaries
  - Charge diffusion to neighbouring pixels

- Importance of various effects differs

s_{ana} = 0.1456 ± 0.001
c_{ana} = 0.0101 ± 0.0005

s_{digi} = 0.0952 ± 0.0007
c_{digi} = 0.008 ± 0.0003

s_{digi} = 0.1303 ± 0.0009
c_{digi} = 0.0134 ± 0.0004

10GeV
0.032→0.044

- Analogue case
- Digital case
- Realistic digital case GR=0,σ_n=120eV

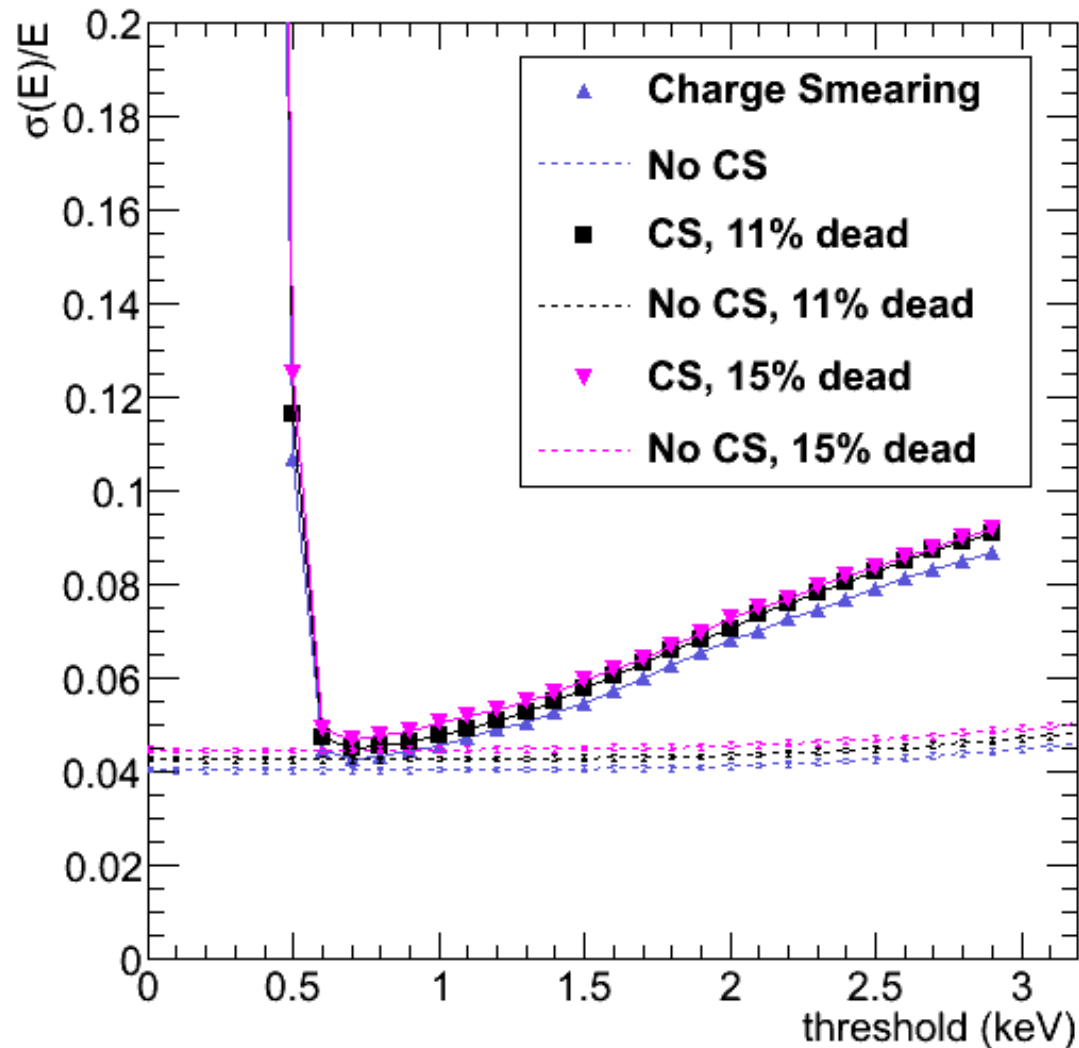σ_E/E versus $1/\sqrt{E_{MC}}$ (GeV$^{-\frac{1}{2}}$)
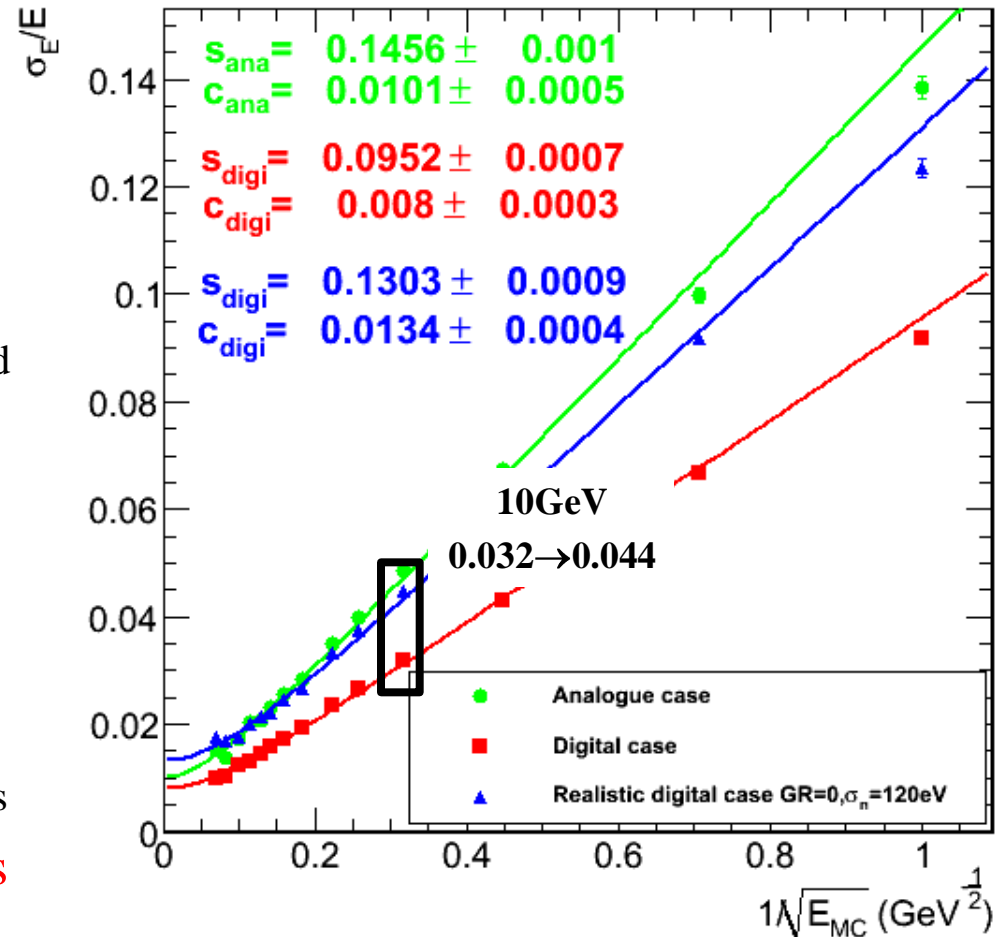
Effect of noise

- 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 ~12% is equivalent to threshold spread here so small effect
- Resolution degradation ~ 10%
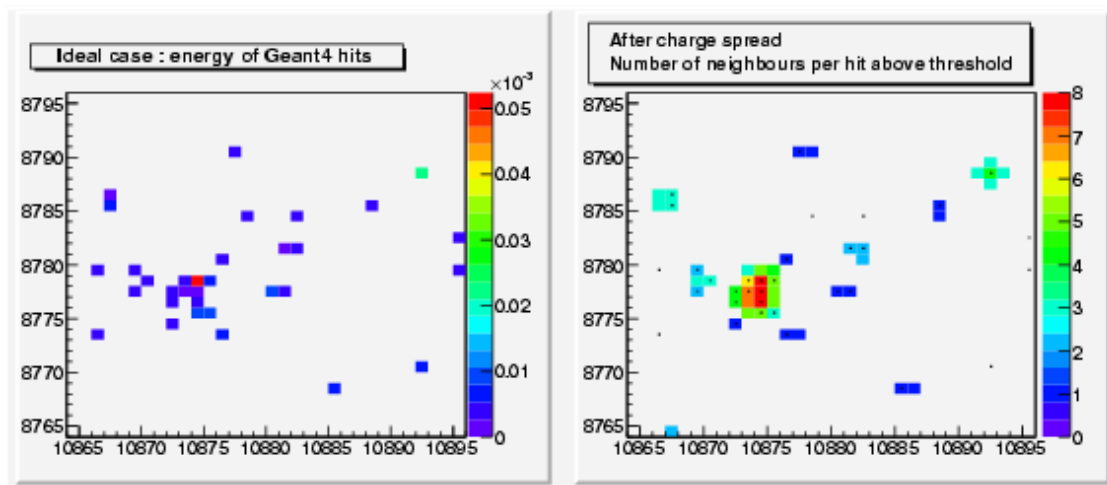 - If S/N can be improved, then get a plateau so noise has no effect on resolution
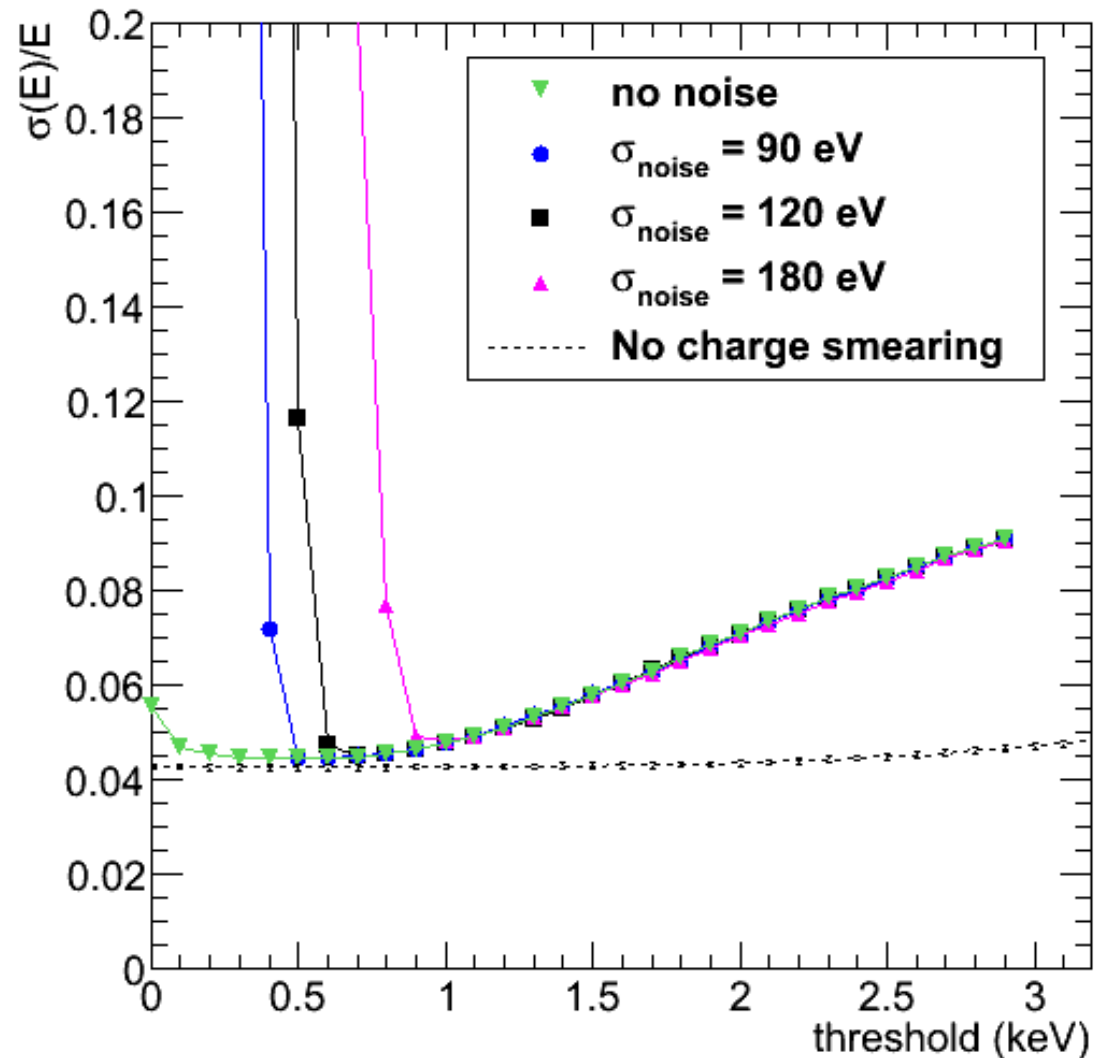
Effect of dead area

- 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 $1/\sqrt{(0.89)} \sim 1.06$ effect
  - Hence ~ 5% degradation
- Assumes sensor large enough that edge effects are negligible
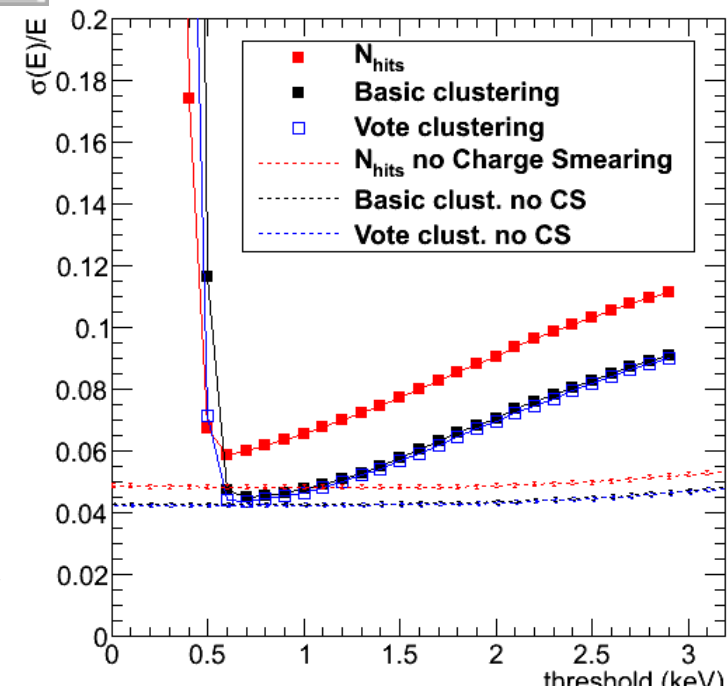 - May add ~ 5% more dead area in reality so ~ 2% more to resolution

Effect of hit confusion per particle

Ideal case : energy of Geant4 hits

After charge spread
Number of neighbours per hit above threshold

- Arises from
  - Particles close together
  - Particles crossing pixel boundaries
  - Charge diffusion

- Only the last is known to be well modelled

- Need to do neighbouring hit "clustering" to convert hits to particle count
  - Algorithm to use depends on effects which may not be modelled well

- Major study of clustering algorithms still to be done
  - Currently gives ~ 20% degradation to resolution so dominates
  - Essential to get experimental data on fine structure of showers to know realistic resolution

Legend:
- N_{hits}
- Basic clustering
- Vote clustering
- N_{hits} no Charge Smearing
- Basic clust. no CS
- Vote clust. no CS

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 (and disrupted beam data)
  - 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 checked sensor performance fully over next year
  - Including beam test at DESY early in 2009
  - Dec 2007 beam test data unusable as bad pedestal trimming (due to pickup)

- Beam test will have at most four layers, each with a single sensor
  - Data in usual CALICE raw data format although LCIO conversion would need work
  - 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 will probably not verify true performance as a DECAL...

Long term future plans

- Submitting a proposal this week for large sensor TPAC2
  - 450×450 pixels and $2.5\times2.5\text{cm}^2$; a factor ten in area; otherwise a scaled-up TPAC1
  - Bid includes funding for 16-layer Si-W DECAL stack; 5×5 sensors $= 12.5\times12.5\text{cm}^2$ per layer
  - Smaller than AECAL but OK for basic 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
 - Would very significantly increase probability of approval if cost split with non-UK groups
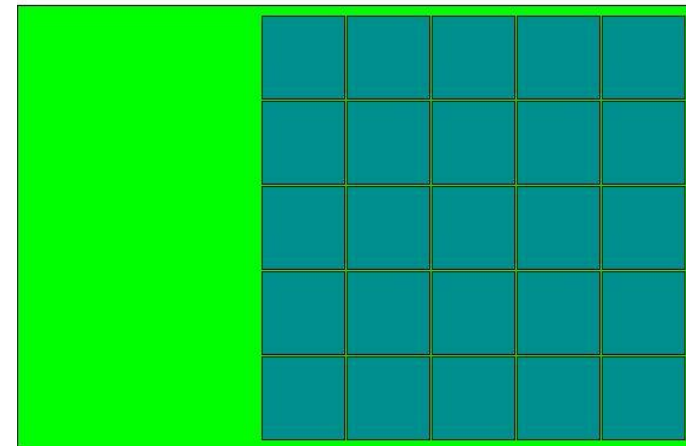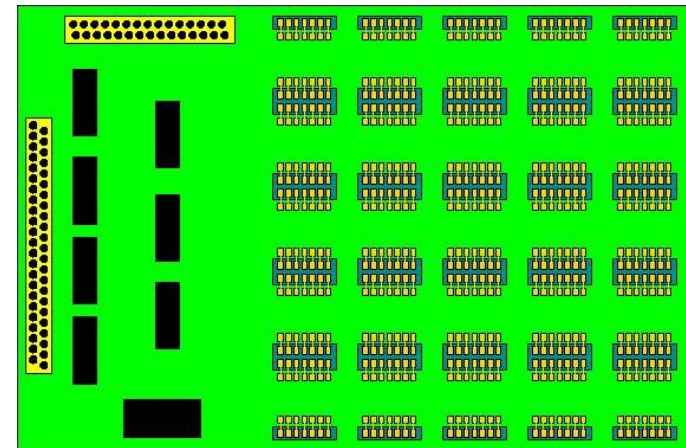
Conclusions

- DECAL seems possible in principle

- Actual EM resolution which would be obtained depends heavily on details of showers and on 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

- Approval very uncertain; collaborators very welcome!

Backup: Single pixel pedestals

- Pedestal given by mean of threshold scan
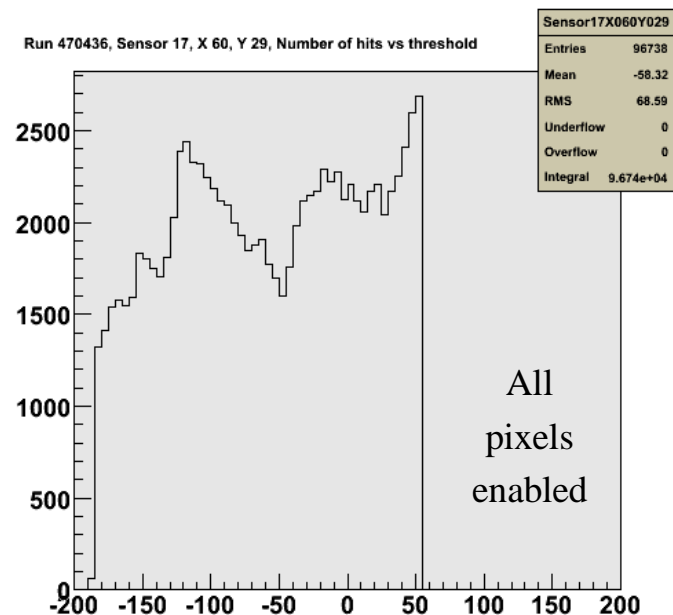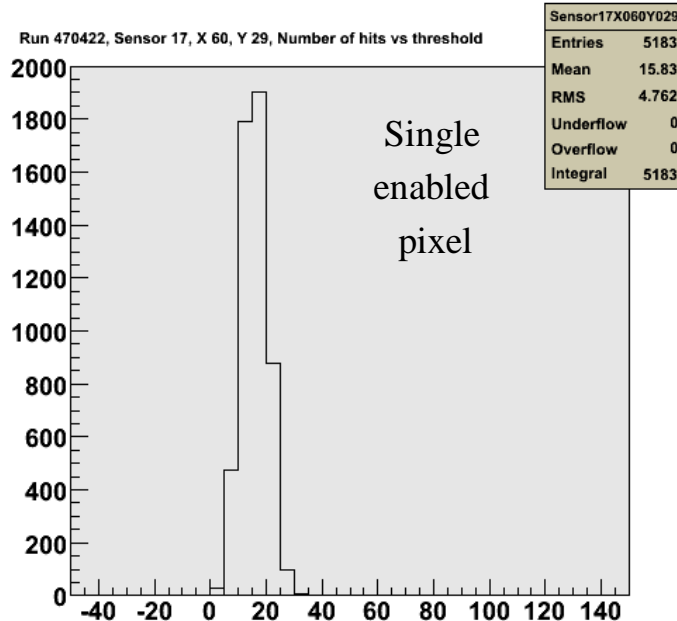 - Pedestal spread is ~ 4 times noise
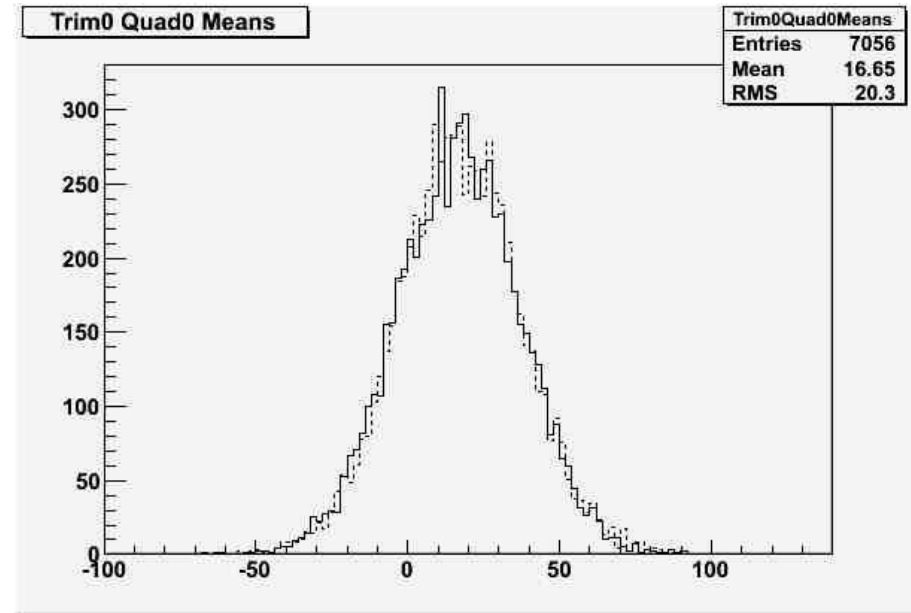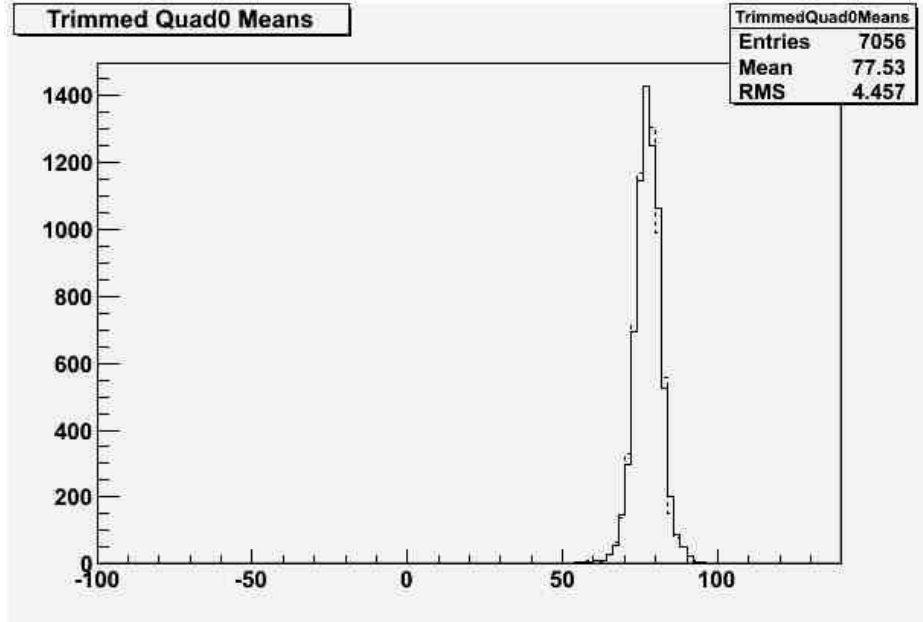
- Must correct using trims to get sensible data
  - Trimming works reasonably well; down to RMS of ~ 4.5TU
  - Still not completely below noise level so more trim bits would help

Backup: Pedestal and noise over sensor

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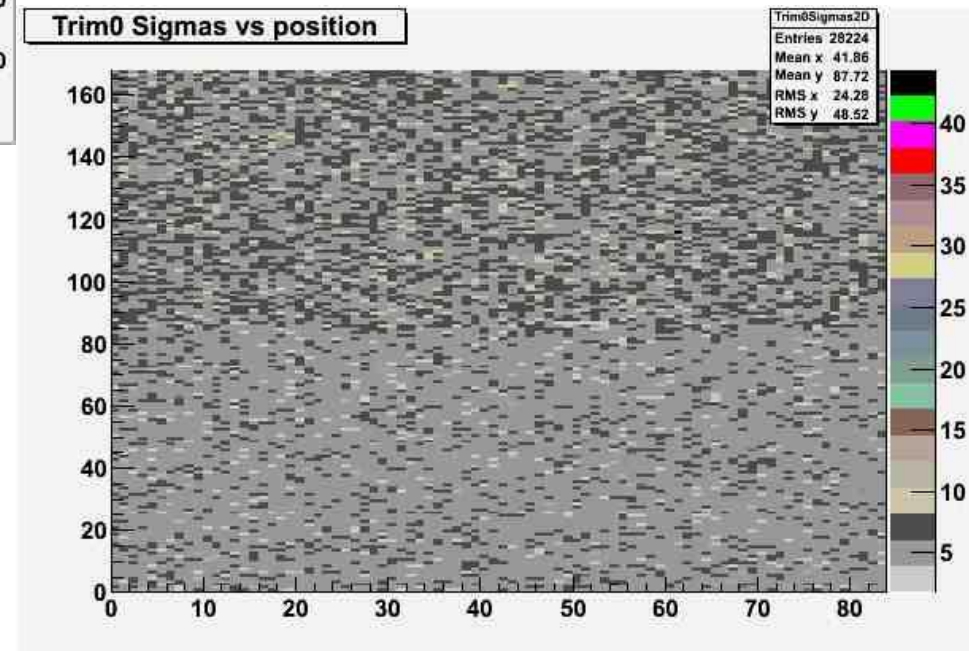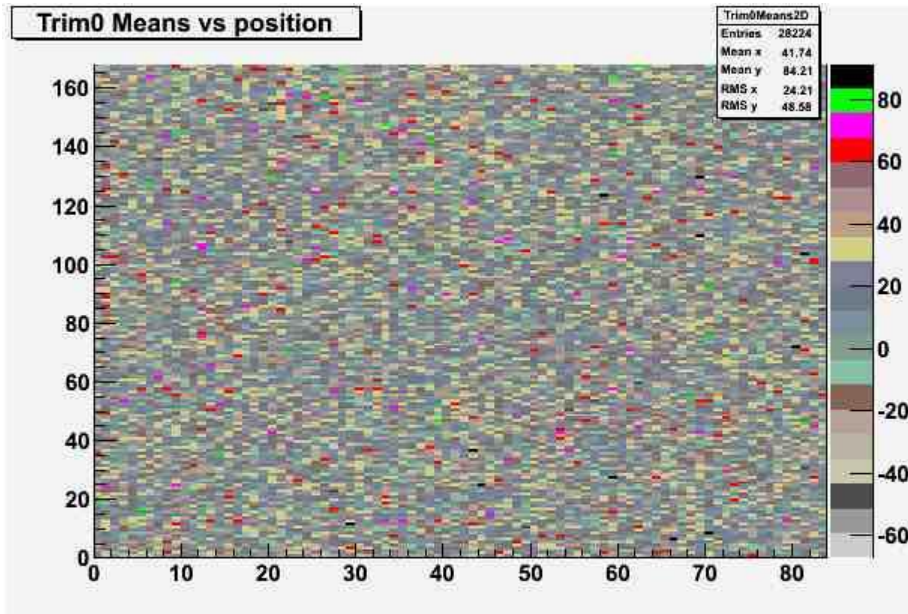
Backup: pixel hit pickup

- Find different results for pixel if other pixels enabled

- Prevented pedestals from being determined until effect understood
  - Plots shown previously had most pixel 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