DECAL: DMAPS Sensors for Digital Electromagnetic Calorimetry

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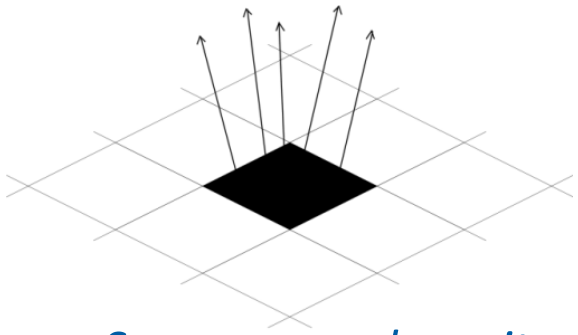
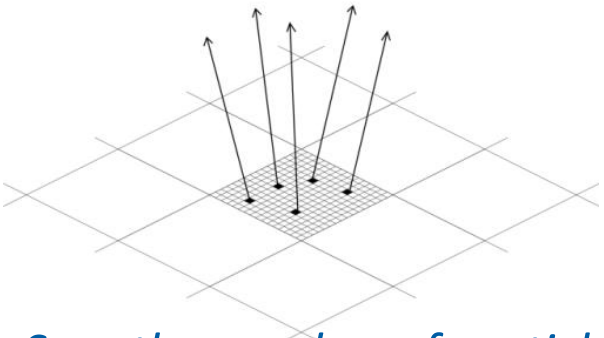
Outline and Overview

- Introduction: Calorimetry with silicon readout
  - Analogue (e.g. CALICE, CMS HGCAL)
  - Digital (e.g. SPiDER, ALICE FoCal)
- Simulation results: Single particle resolutions
- Sensor R&D: Reconfigurable radiation-hard DMAPS
- Conclusions



Analogue: Sum energy deposited in a cell

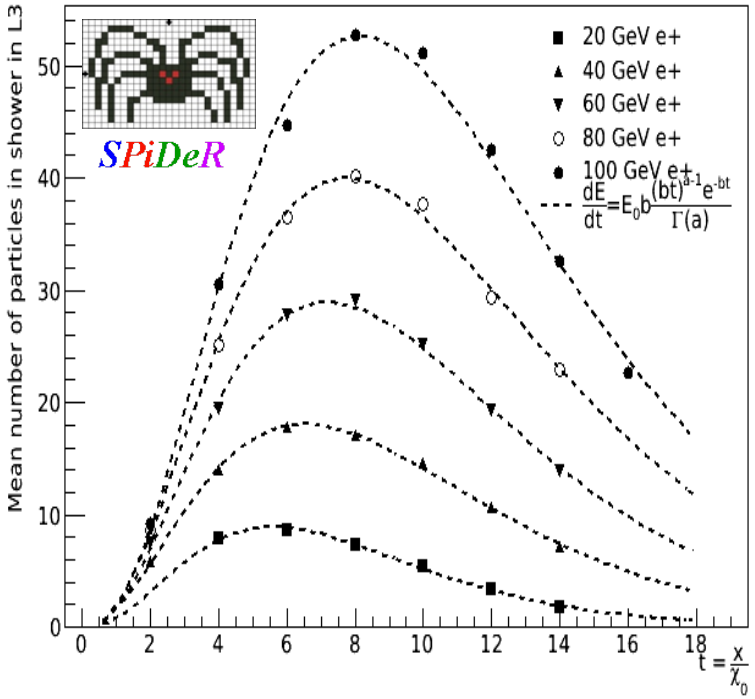


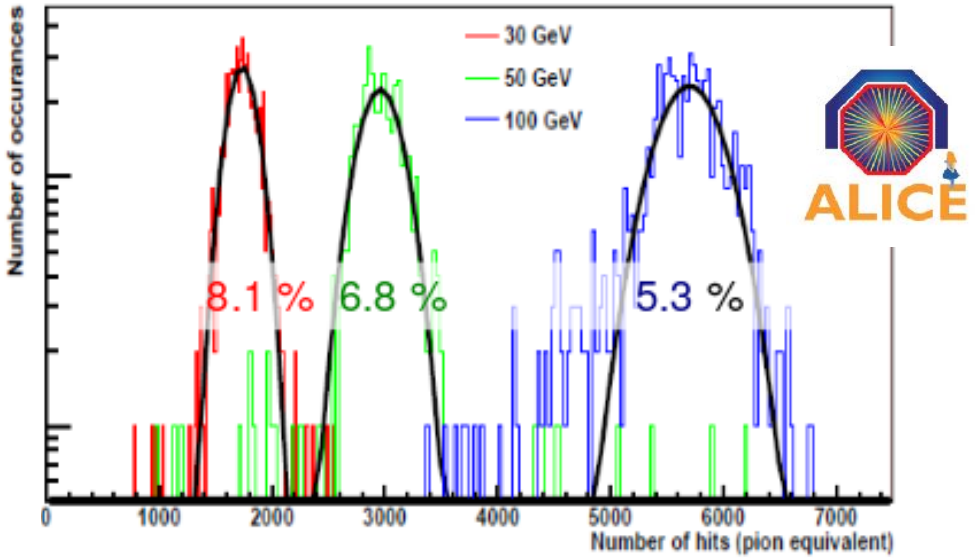
Digital: Sum the number of particles in a cell

DIGITAL CALORIMETRY: TEST BEAMS

[Rocco et al, ICHEP 2016]

- SPiDeR: pixel counting gives correct shower shape
  - CERN testbeam using EU Telescope (Mimosa-26)
  - Tracks in first 3 layers, shower in W, measure core in 4th layer 15 cm from W
- Digital Calo Example: ALICE FoCal
  - High granularity to separate showers
  - DESY & SPS test beams: 24 plane prototype; four Mimosa-23 (30 µm Pitch) with W





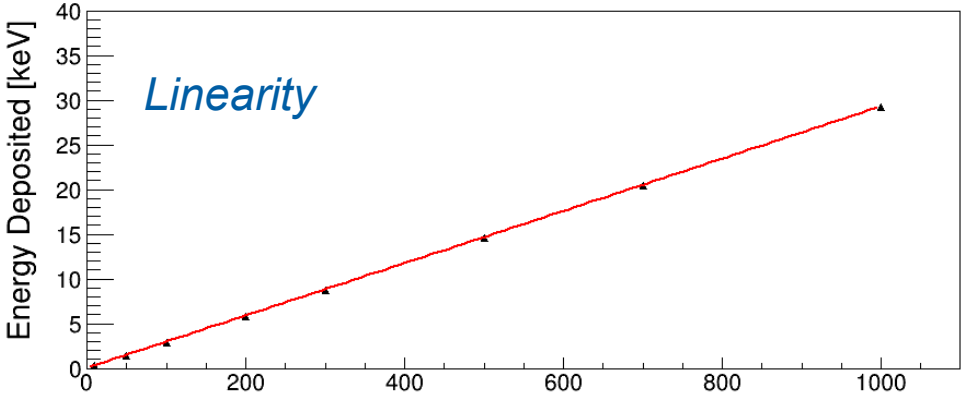
Analogue Readout

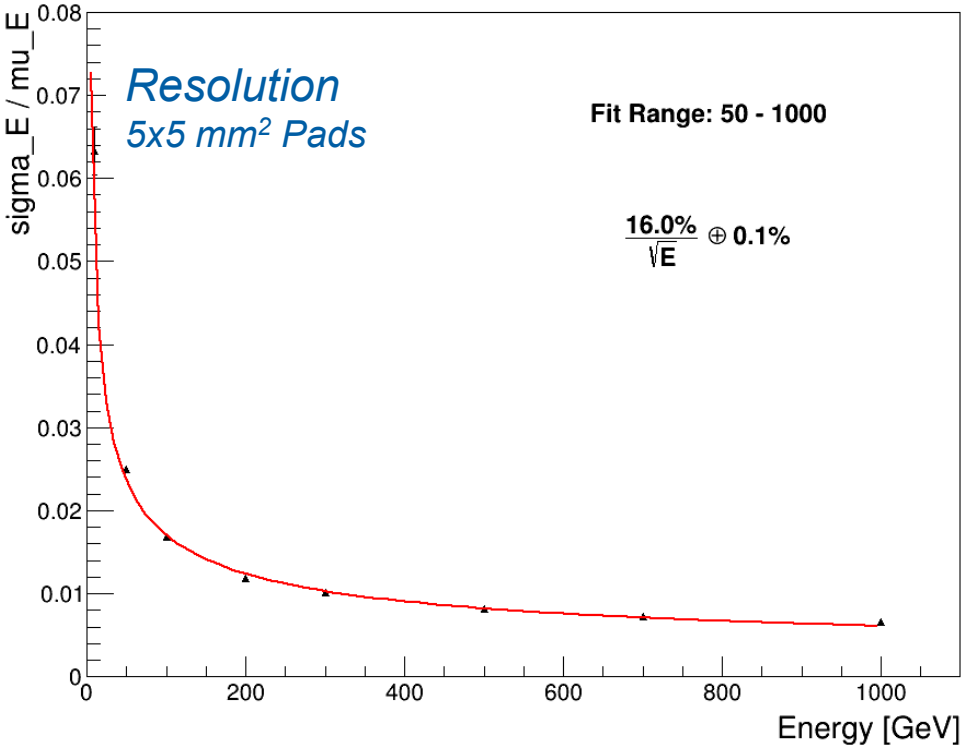
- Detector Configuration
  - Concentric octagonal geometry
  - 50 layers of 0.6 X_0 W
  - 5x5 mm^2 pixels
  - 300 µm thick sensitive region

$$\frac{\sigma_E}{\mu_E} = \frac{16.0\%}{\sqrt{E}} + 0.1\%$$

- PandoraPFA* gives jet energy resolution of <4% for jets up to 250 GeV

Excellent linearity, resolution possible

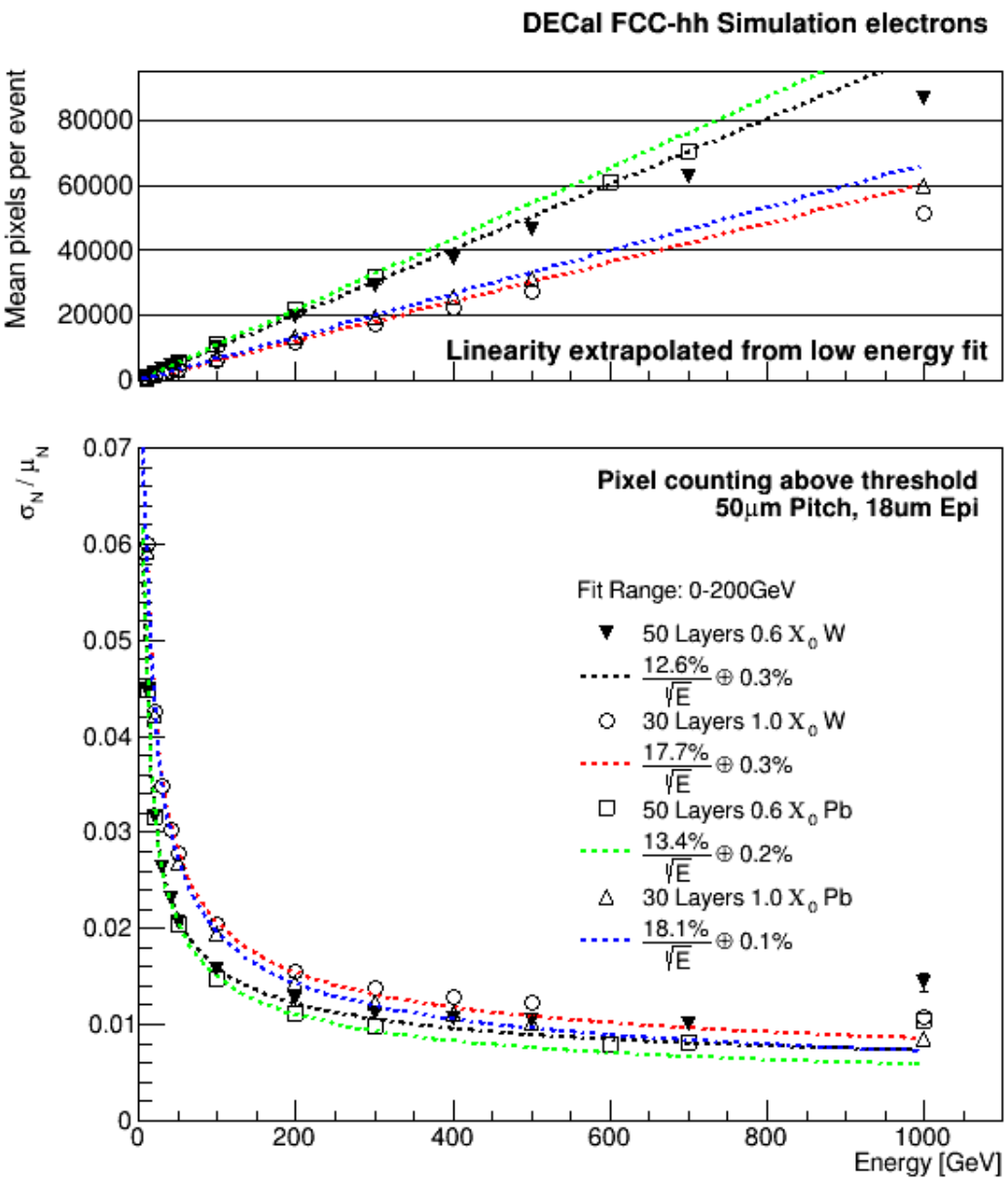




[*https://arxiv.org/abs/0907.3577]

Digital Readout

- Detector Configurations
  - Concentric cylinder geometry
  - 50x50 µm² pixels
  - 18 µm thick epitaxial region
  - ▼ 50 layers of 0.6 X_0 W
  - ○ 30 layers of 1.0 X_0 W
  - □ 50 layers of 0.6 X_0 Pb
  - △ 30 layers of 1.0 X_0 Pb
- MIP MPV ~1400 e- with threshold of 480
- For 50 layers of Tungsten, energy linear up to ~300 GeV

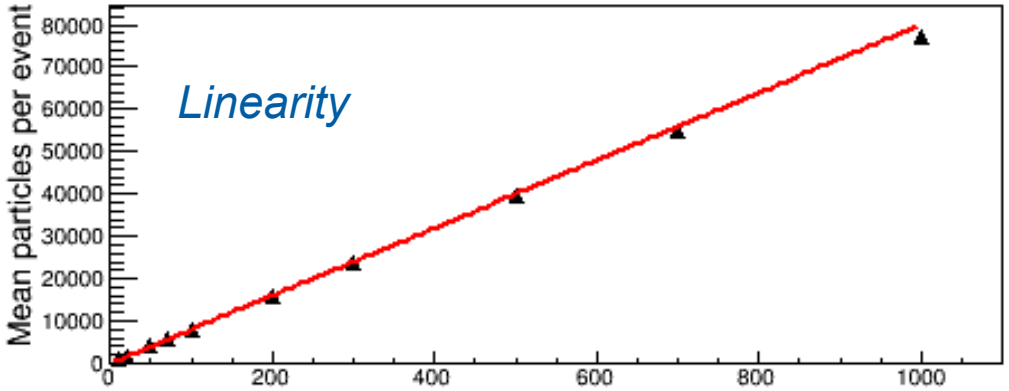


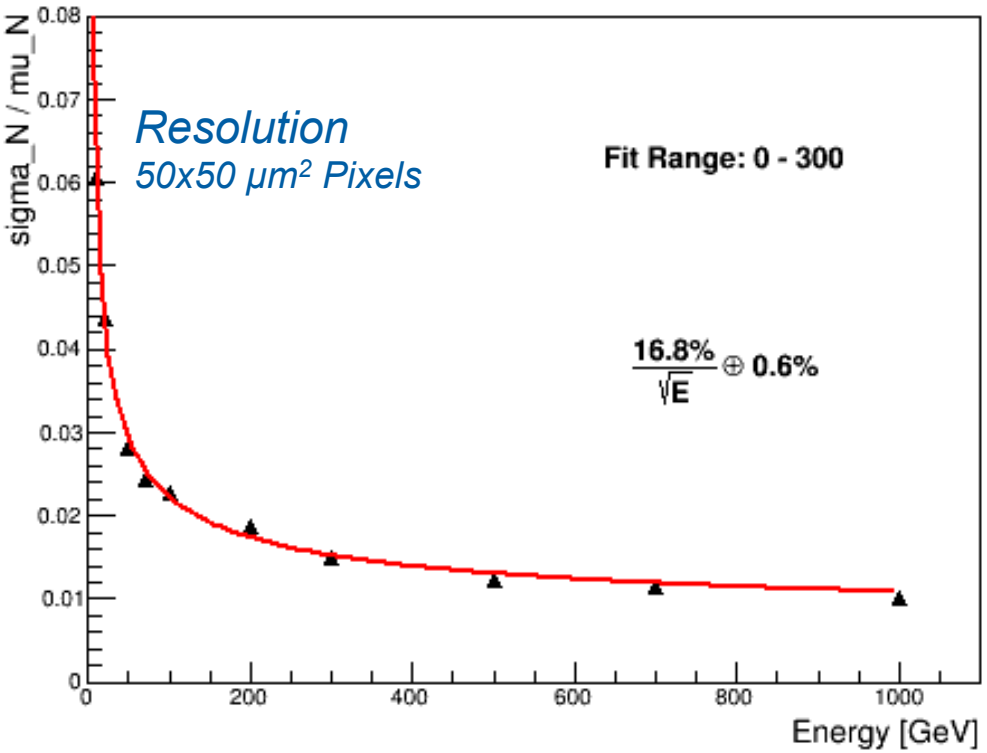
Digital Readout

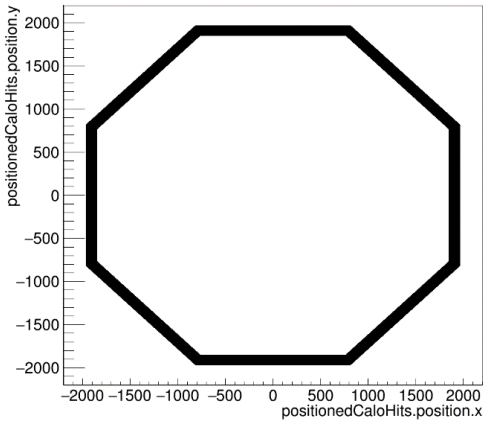
- Octagonal barrel geometry
  - 50 layers of 0.6 X_0 W
  - 50x50 µm^2 digital pixels
  - 5x5 mm^2 counting pads
  - 18 µm thick epitaxial region
  - 3 mm air for PCB, services, etc

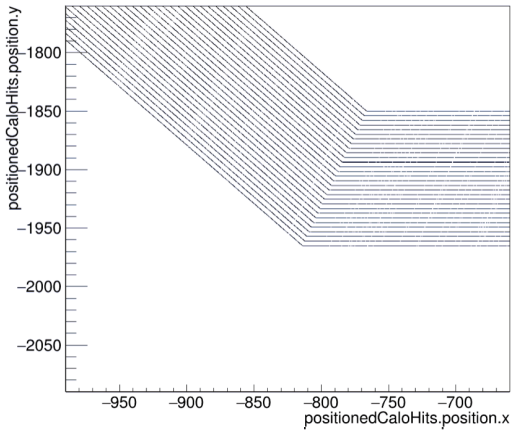
$$\frac{\sigma_E}{\mu_E} = \frac{16.8\%}{\sqrt{E}} + 0.6\%$$

Good performance for realistic geometry





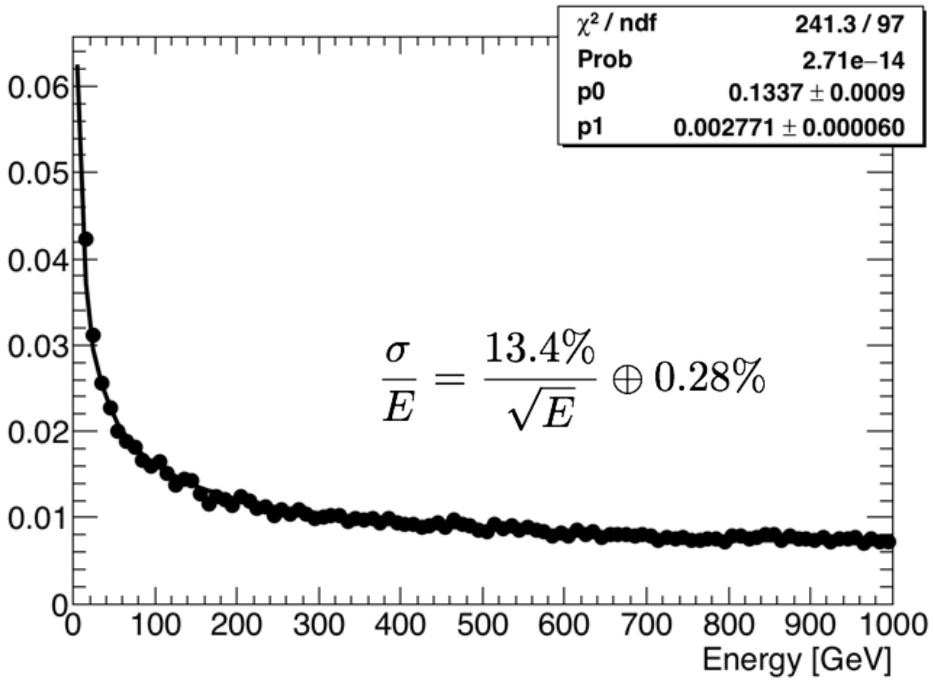


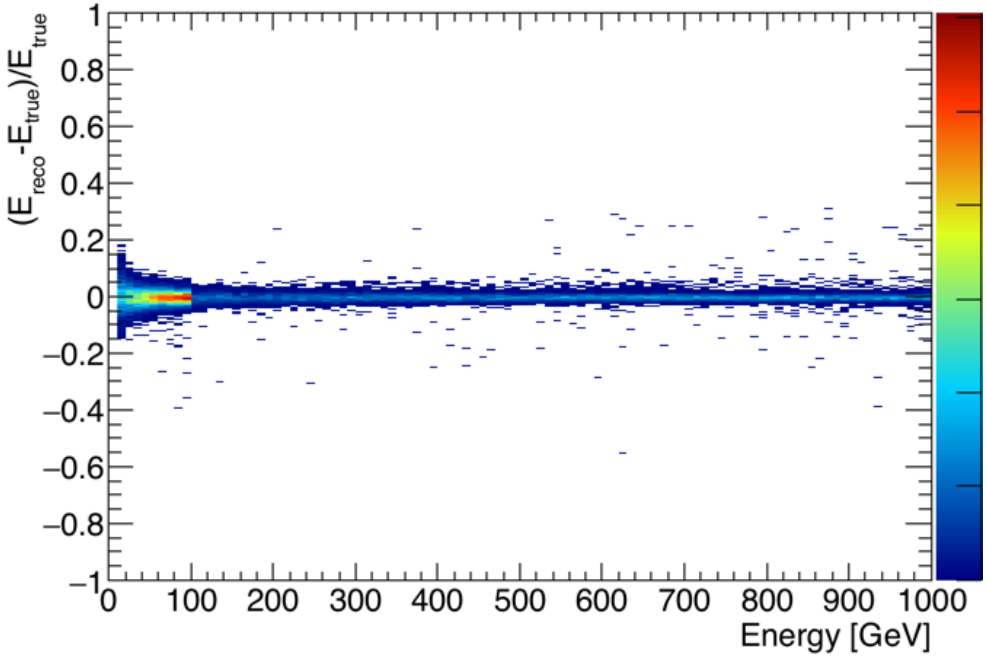


NON-LINEARITY AND MVA

- Can you recover linearity in software?
  - MVA package: LinearDiscriminant, Multi-Layer Perceptron (ANN)
  - Simulated DECAL: energy range 10 - 1000 GeV, 50 layers 2.1 mm W
  - Input: number of pixel hits per layer, grouped in 5 layers (1-5, 6-10, etc)

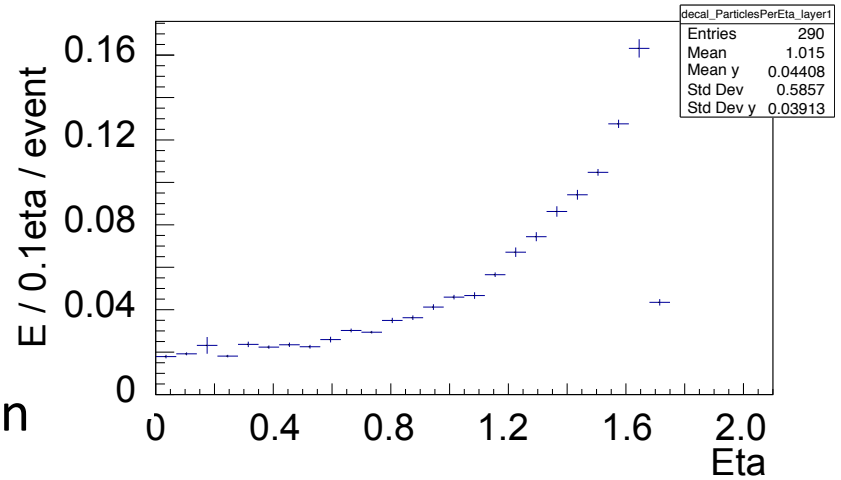
Linearity recovered over full range (to 1 TeV)

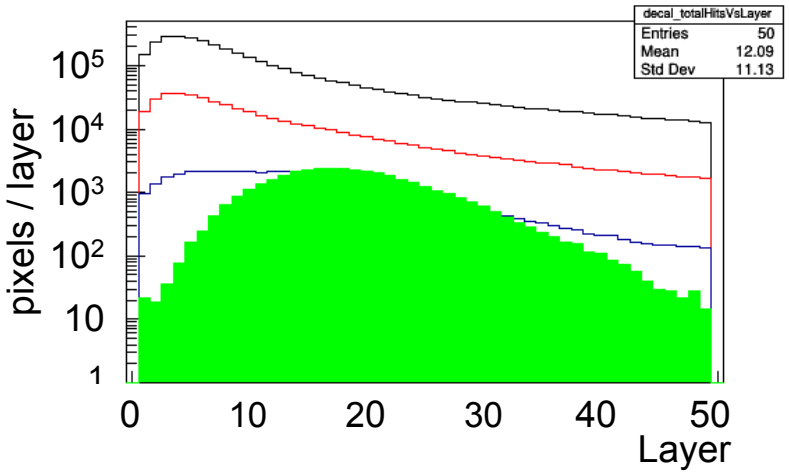


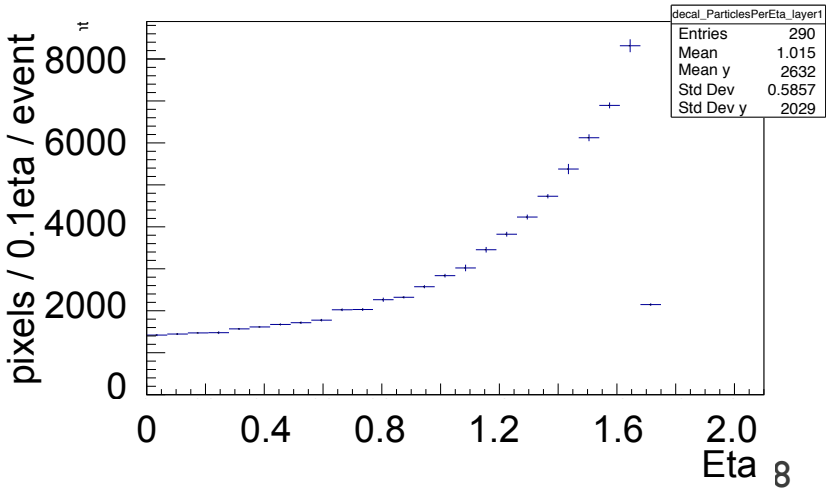


DECAL Pileup Studies

- Simulated pile-up using Pythia min bias events
  - ⟨μ⟩=1000 yields 3.5M pixels above threshold in DECAL barrel
  - Energy in first layer vs eta follows same trend as FCC-hh LAr baseline studies
  - Pixels above threshold vs eta also have similar trend
- 500 GeV e^-; 50k hit pixels swamped by pileup
  - First attempts at reducing hits very promising
  - ALL PIXELS, MAX_STAVE, 10k ROI, TRUTH ⟨μ⟩=0
  - Simple cuts reduce BG by orders of magnitude
- Next: careful study with clustering, energy resolution



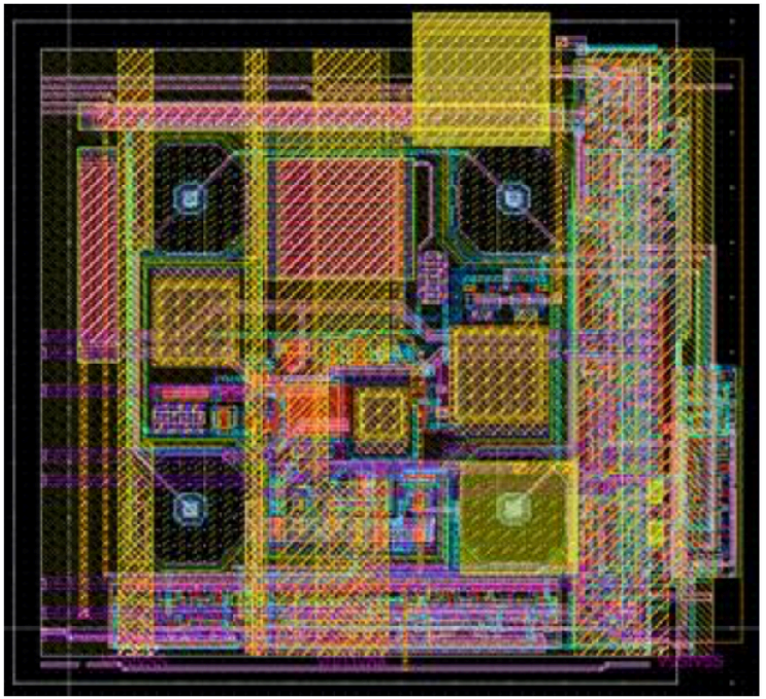




DECAL Test Sensor

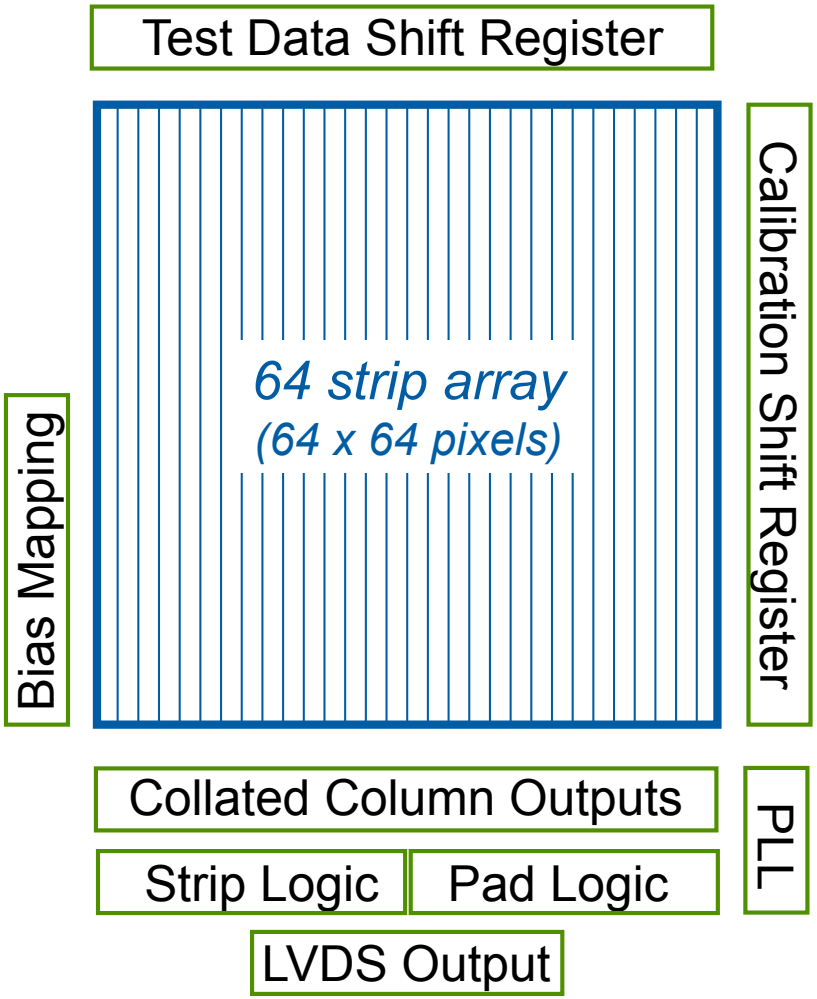
- DECAL monolithic active pixel test sensor features
  - Reconfigurable: strip mode for particle tracking, or pad mode (counts above threshold) for digital calorimetry
  - TowerJazz 180 nm, 18 µm epi, standard (optical) process
  - 5 mm^2 pixel matrix of 64×64 pixels with pitch of 55×55 μm^2
- Sensor matrix now under test
  - Four collection electrodes/pixel
  - Trim, preamp, shaper, discriminator
  - 25 ns digital output
  - Analog and digital tests ongoing

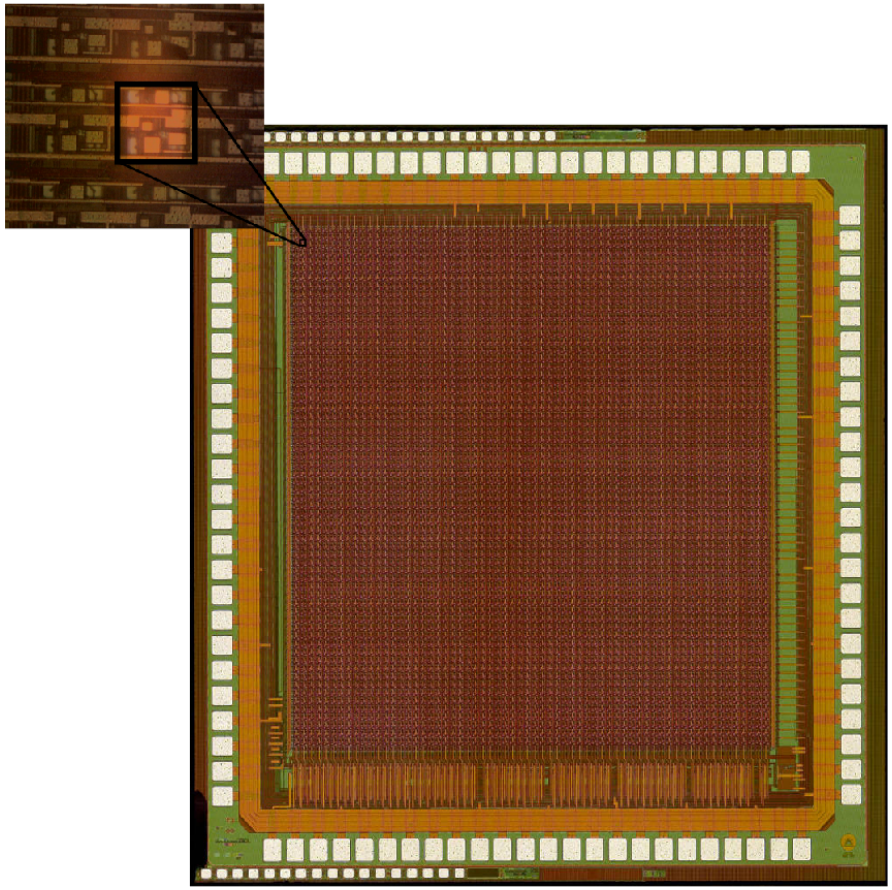
Sensor shows analogue response (works!)



DECAL ARRAY: STRIP MODE

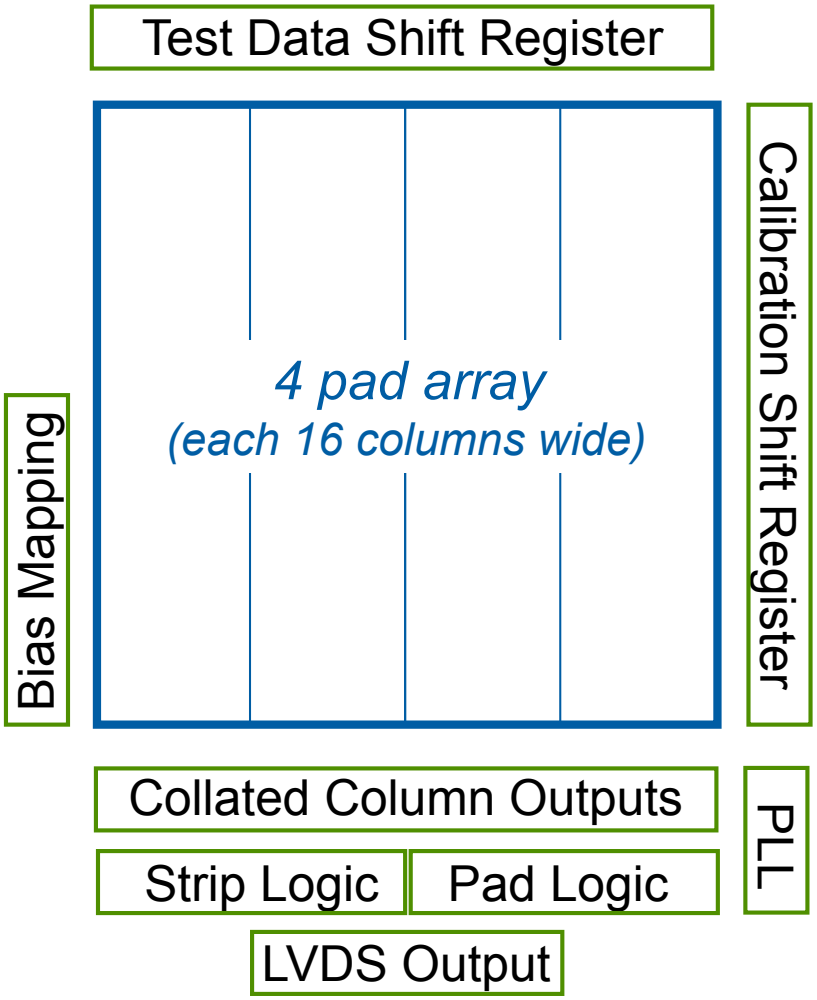
- Strip Mode (1 x 64 pixel array)
  - Counts above threshold: 0, 1, 2 or ≥3 per column
  - Data rate: 320 Mbit/s x 16 = 4.8 Gbit/s

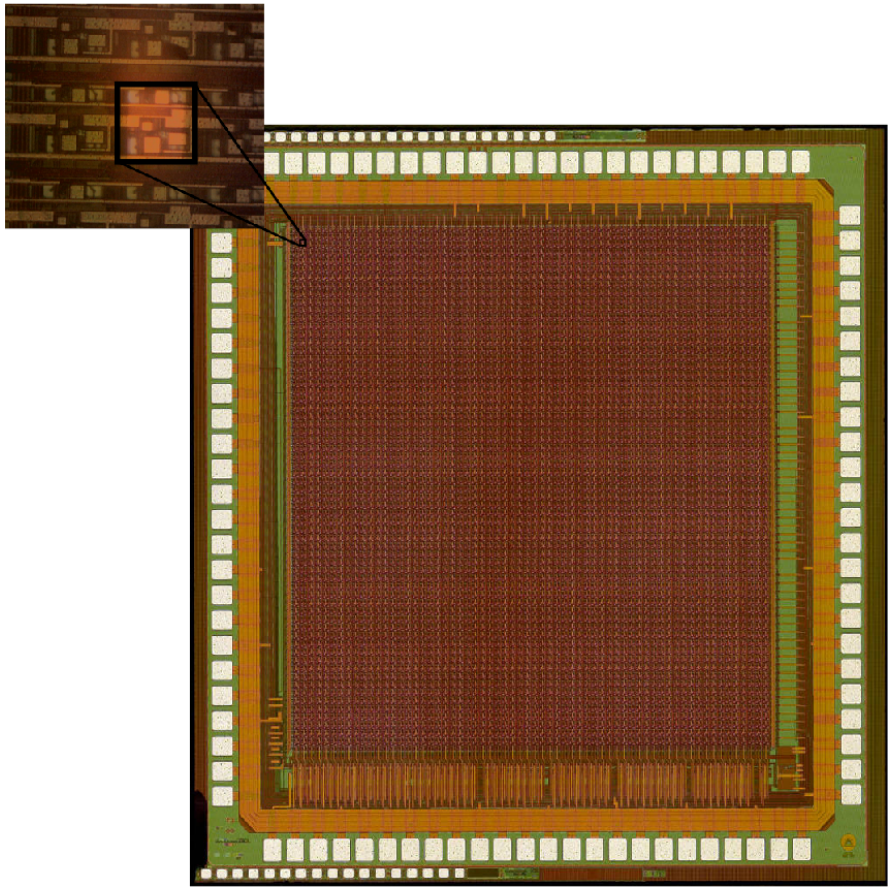




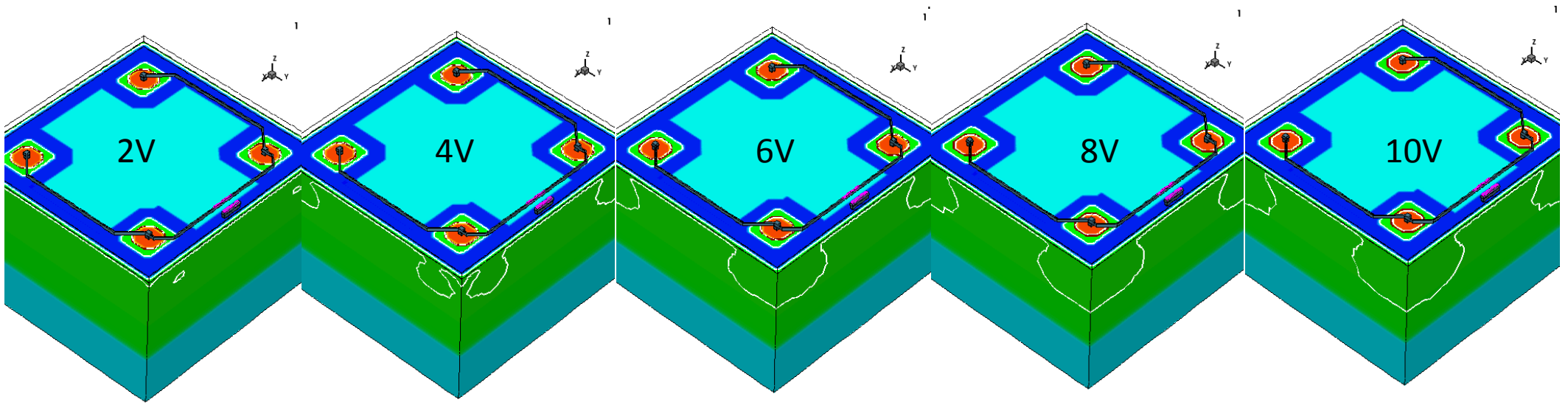
DECAL ARRAY: PAD MODE

- Pad Mode (16 x 64 pixel array)
  - Up to 15 hits in each of 16 columns (240 total)
  - Lower rate; about 1/4 the LVDS lines





DECAL PIXEL



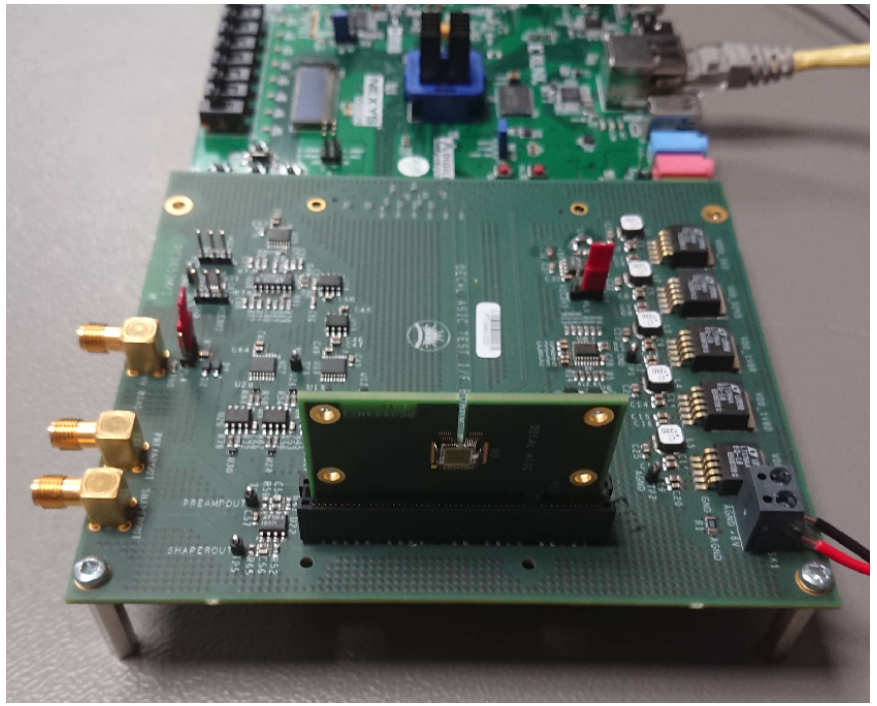
Single pixel field: DC Vbias 2 to 10V, without back contact

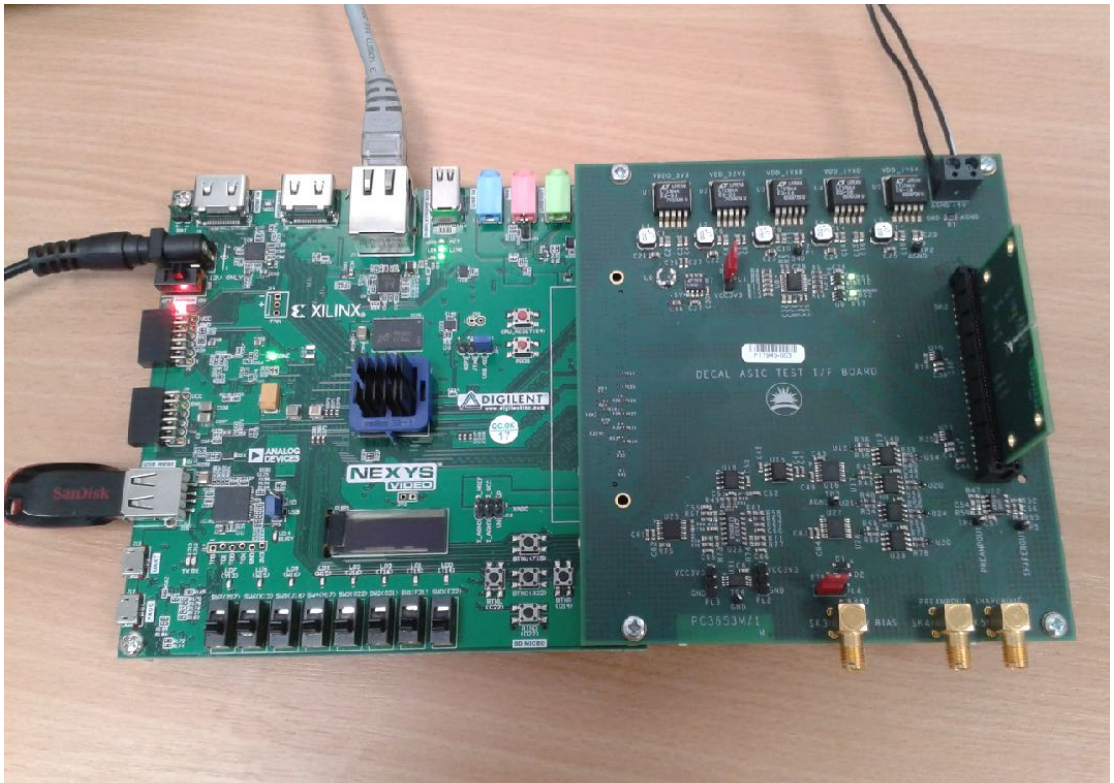
- TowerJazz 180 nm standard (optical) process; 18 µm epi
  - Four collection nodes, low capacitance, expect good signal/noise
  - Operational with 1-2 volts bias; higher voltage for faster collection
- TowerJazz "modified process" also under investigation
  - Test structures submitted in modified TowerJazz process [NIM A V871, 90-96, 2017]
  - Full depletion, low capacitance and good signal/noise demonstrated
  - Rad hard to few 10^{15} neutron equiv. [JINST 12 P06008, 2017]

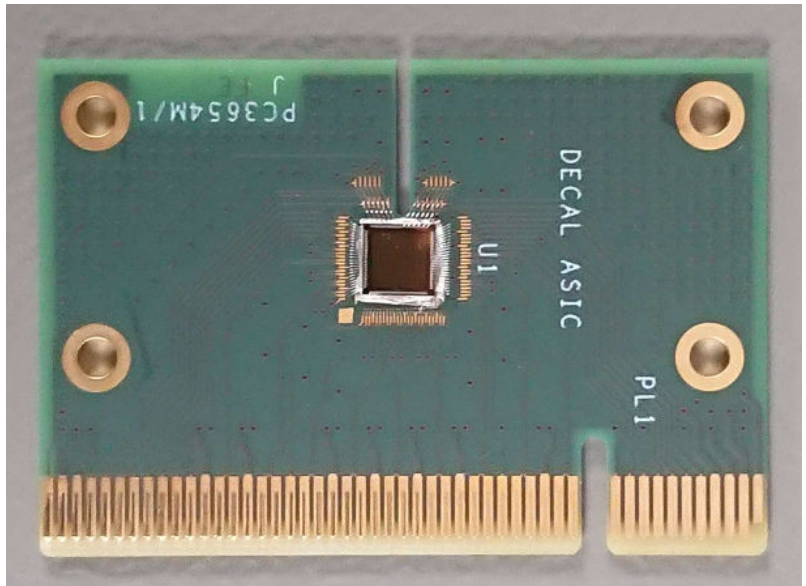
Poster: H. Pernegger
Talk: K. Moustakas

DECAL Data Acquisition and Software

- DECAL Data Acquisition via NEXYS Video board (Digilent)
- Software is based on ATLAS ITSDAQ
- NEXYS board is programmed using Adept



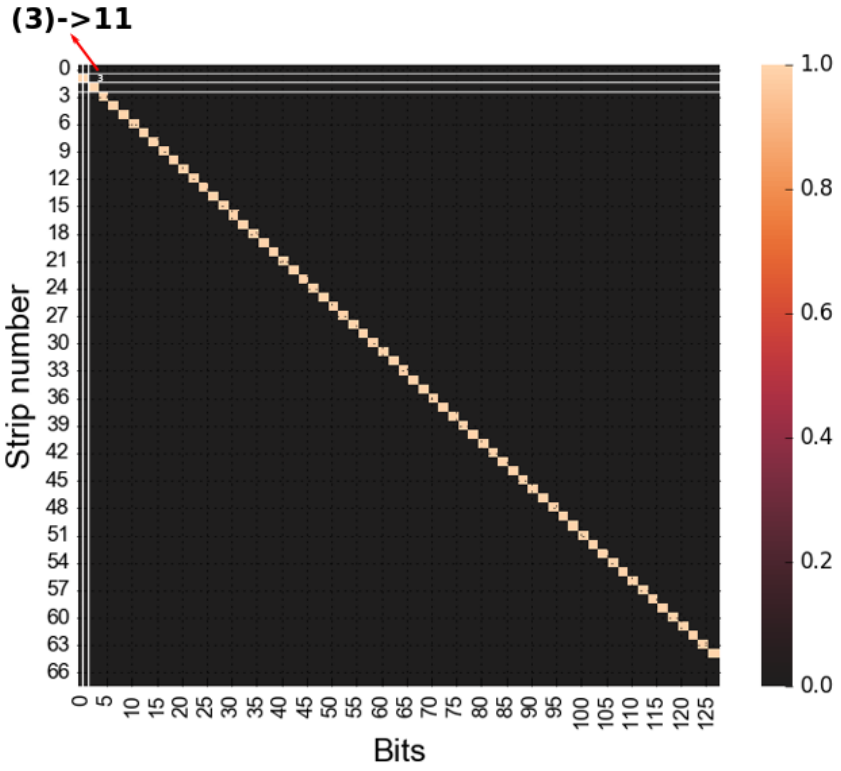




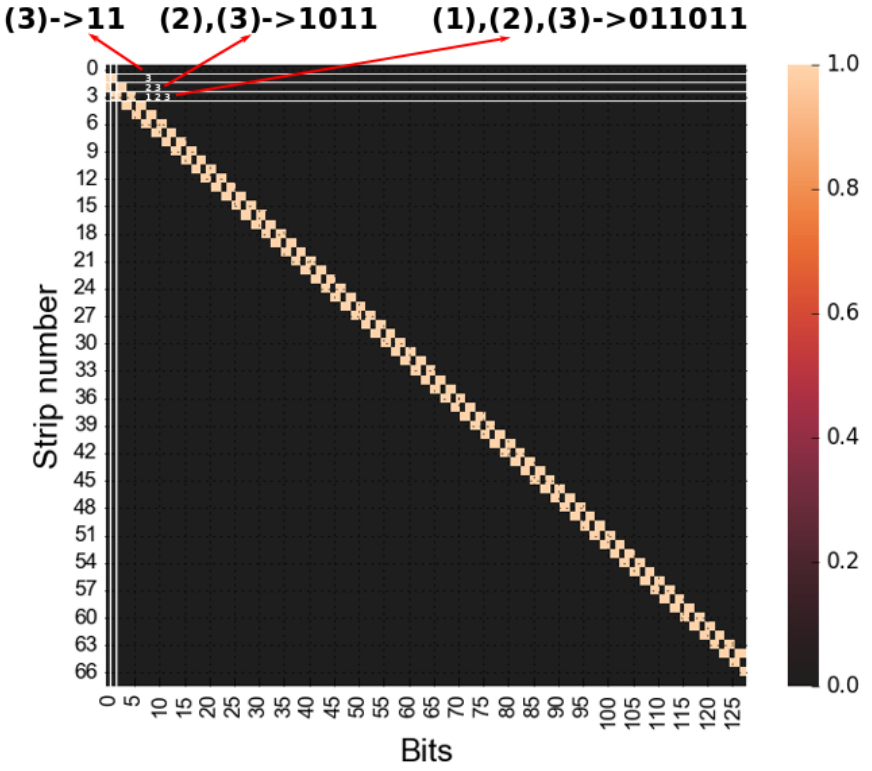
DECAL: Strip Mode Digital Logic

- Operating the chip in strip mode:
  - Inject 3 (binary 11), and shift along the strips
  - Inject 3 (11), then 2 (10), then 1 (01), shift along the strips

Digital logic for strip mode works as expected



Inject number 3 (11)
in the 1st strip

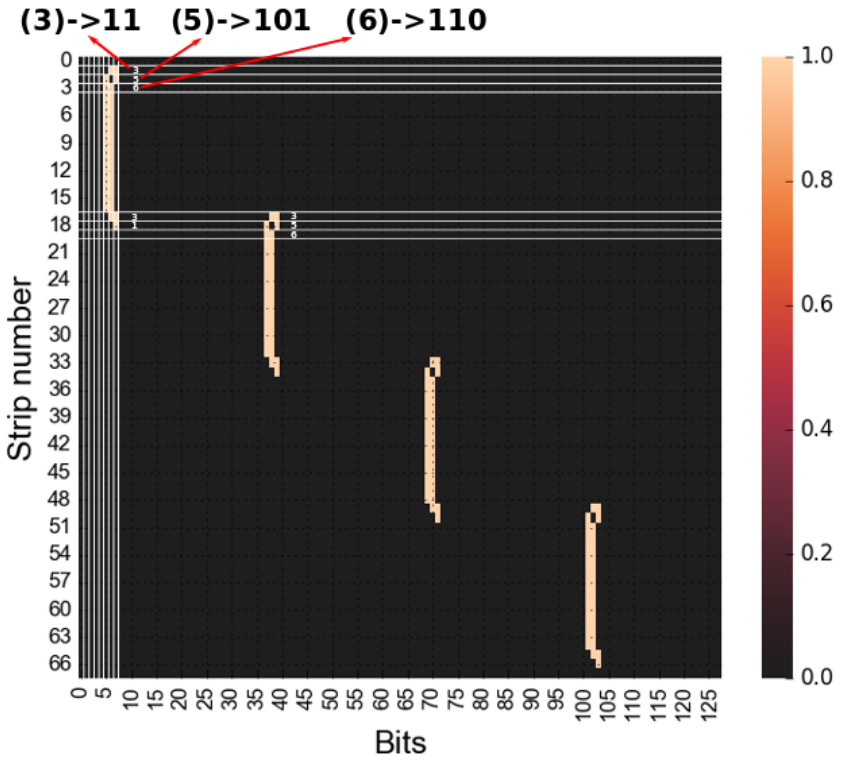


Inject numbers 3, 2, 1
in the 1st, 2nd and 3rd strip

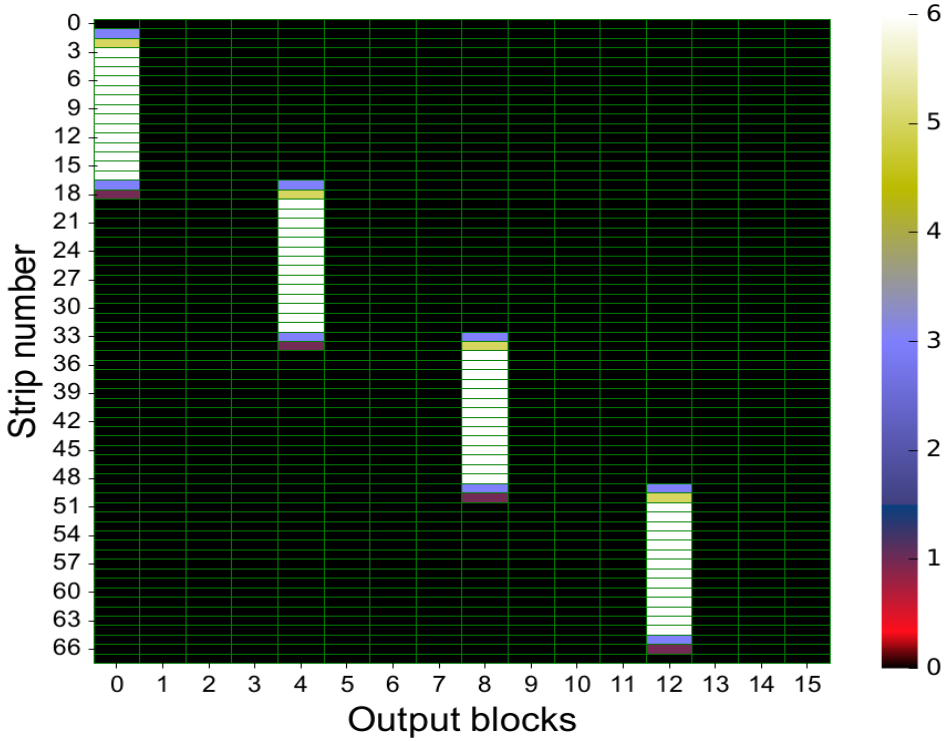
DECAL: PAD MODE DIGITAL LOGIC

- Operating the chip in pad mode:
  - Inject the numbers 3, 2, 1 and shifting along the strips
  - Compare the injected numbers 3, 2, 1 to the total sum of each output block

Digital logic for pad mode also works as expected



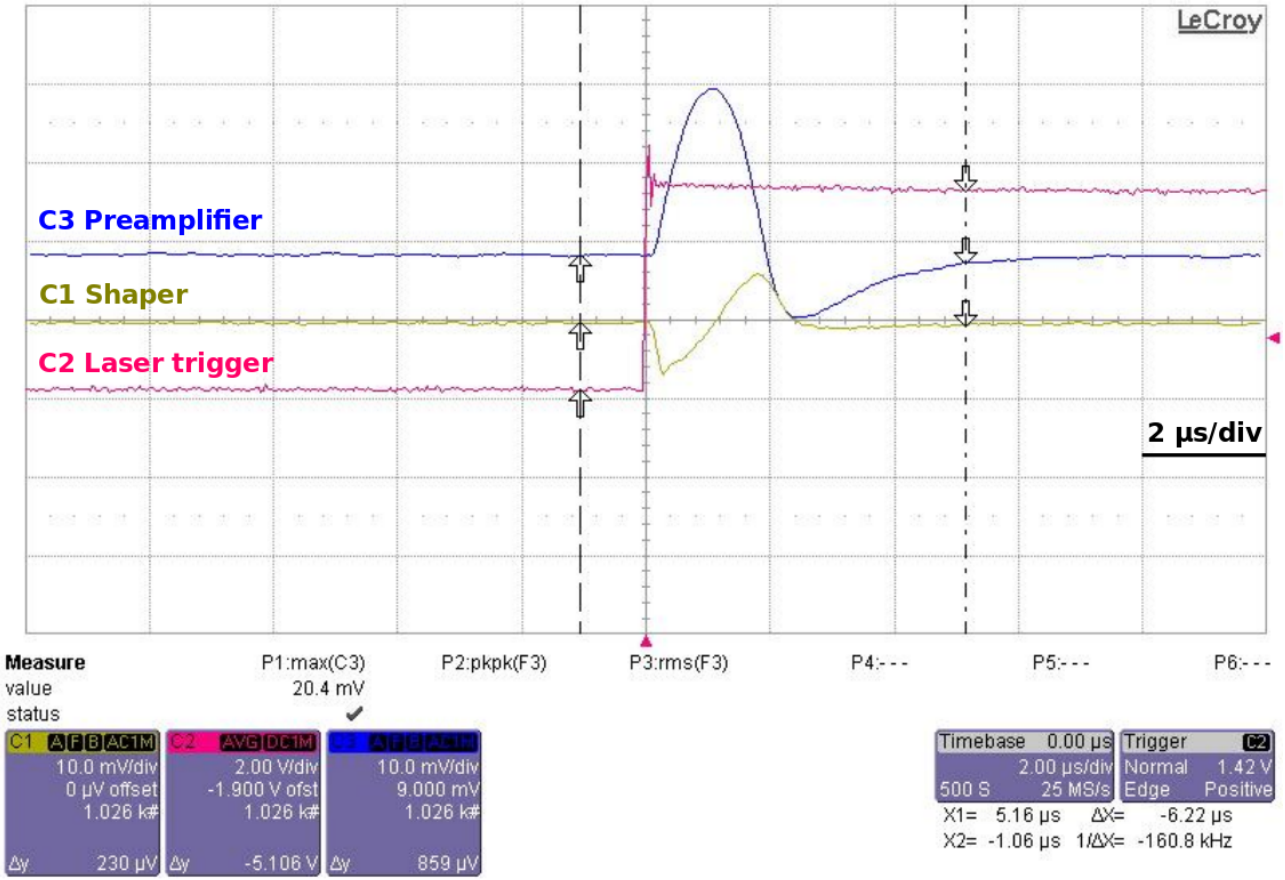
Inject numbers 3, 2, 1
in the 1st, 2nd and 3rd strip



Inject numbers 3, 2, 1
and total sum

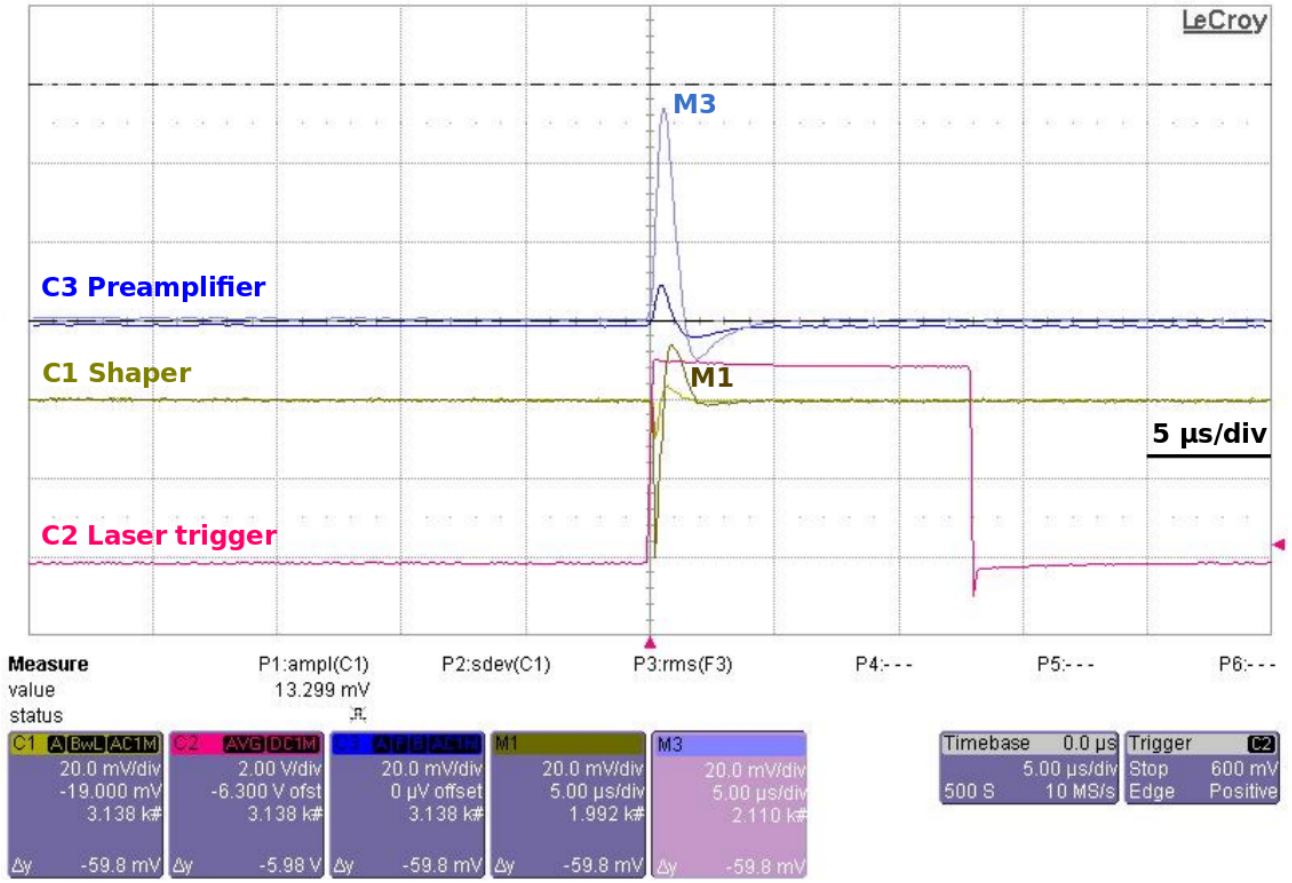
ANALOGUE PIXEL TEST

- Laser illumination for analogue pixel in the top left corner (2nd row 2nd column)
- Laser-inject charge, observe the outputs of the test pixel
- Preamplifier, shaper signals & laser trigger measured



Analogue Pixel Test

- Analogue testing of single pixels getting started
  - Tests vs bias (e.g. 1 or 2 V, below), linearity, etc
  - Laser scan across matrix
  - Source testing & TCT planned



Conclusions

DECAL silicon calorimeter designs are progressing:

- High granularity should allow excellent PFA
- Pixel counting gives good energy resolution at intermediate energies
- Problems from pileup and multiple hits can be mitigated by MVA, clustering
- Prototype reconfigurable CMOS DMAPS for ECAL, pre-shower, and outer tracking fabricated at TowerJazz and under evaluation
- Digital logic works (configurable), analogue now under test