# Digital ECAL: Lecture 2

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# DECAL lectures summary

- Lecture 1 – Ideal case and limits to resolution
  - Digital ECAL motivation and ideal performance compared with AECAL
  - Shower densities at high granularity; pixel sizes
  - Effects of EM shower physics on DECAL performance
- Lecture 2 – Status of DECAL sensors
  - Basic design requirements for a DECAL sensor
  - Current implementation in CMOS technology
  - Characteristics of sensors; noise, charge diffusion
  - Results from first prototypes; verification of performance
- Lecture 3 – Detector effects and realistic resolution
  - Effect of sensor characteristics on EM resolution
  - Degradation of resolution due to sensor performance
  - Main issues affecting resolution
  - Remaining measurements required to verify resolution

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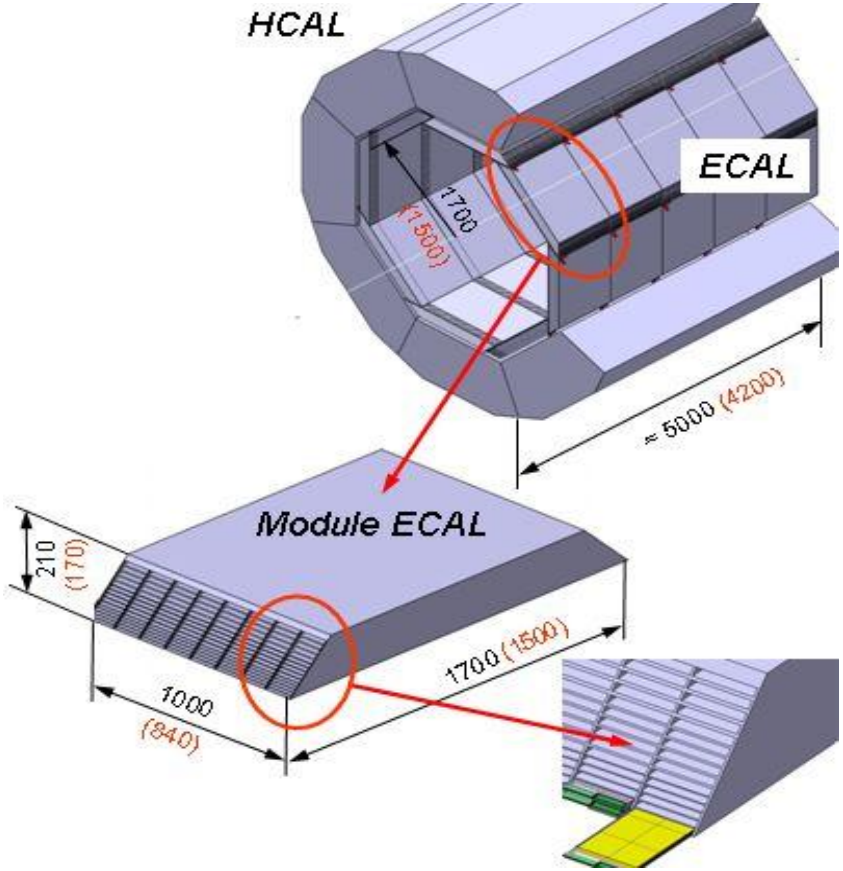
# Basic scale for full DECAL

- Typical ILC SiW ECAL calorimeter
  - 30 layers, each a cylinder of ~ 5m×10m ~ 50m$^2$ surface area
  - Total sensor surface area including endcaps ~ 2000m$^2$ needed
- DECAL sensor aims to be "swap-in" for AECAL silicon
- For DECAL, with pixels ~50×50μm$^2$ i.e. ~2.5×10$^{-9}$m$^2$
  - Need ~10$^{12}$ pixels in total
  - "Tera-pixel calorimeter"



# Constraints for implementation

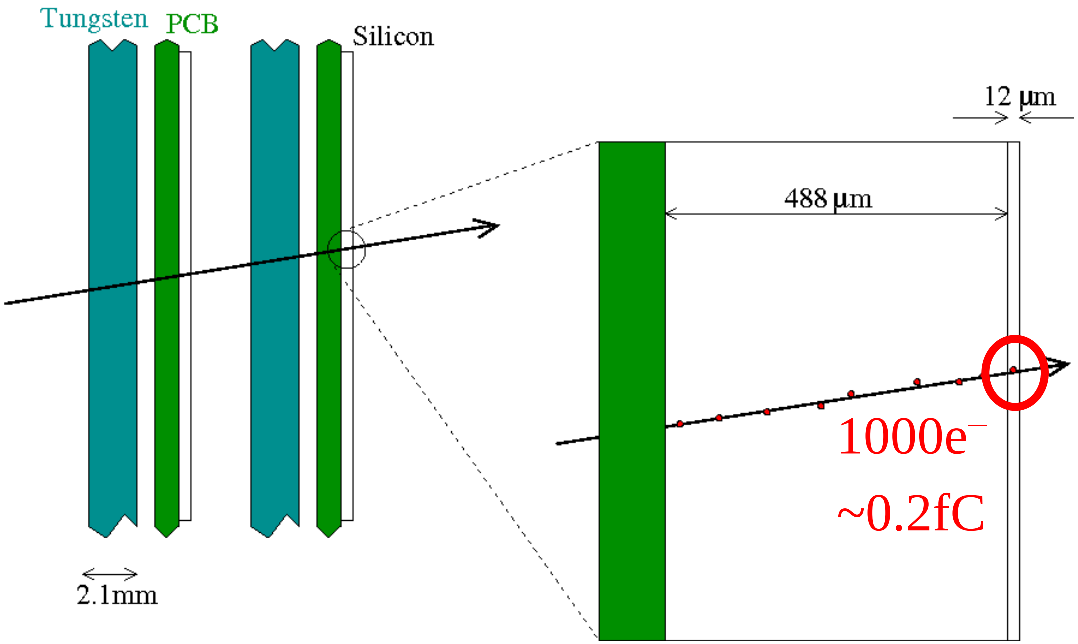
- $10^{12}$ is a VERY large number
- Impossible to consider individual connection for each pixel
  - Needs very high level of integration of electronics
  - Make sensor and readout a single unit
  - "Monolithic active pixel sensor" = MAPS
- Difficult to consider any per-channel calibration
  - Even only one byte per pixel gives 1TByte of calibration data
  - Need to have highly uniform response of pixels

# CMOS as a sensor

- Physical implementation chosen uses CMOS
  - C = Complimentary; can implement both p-type and n-type transistors
  - MOS = Metal-Oxide-Semiconductor; type of transistor
  - Since both types of transistor are available, can have complex readout circuit on sensor
- Readout circuitry is all on top surface of sensor
  - Occupies ~1μm thickness
- Standard production method as for computer chips, digital cameras, etc.
  - Can be done at many foundries; could be cheaper than AECAL sensors!

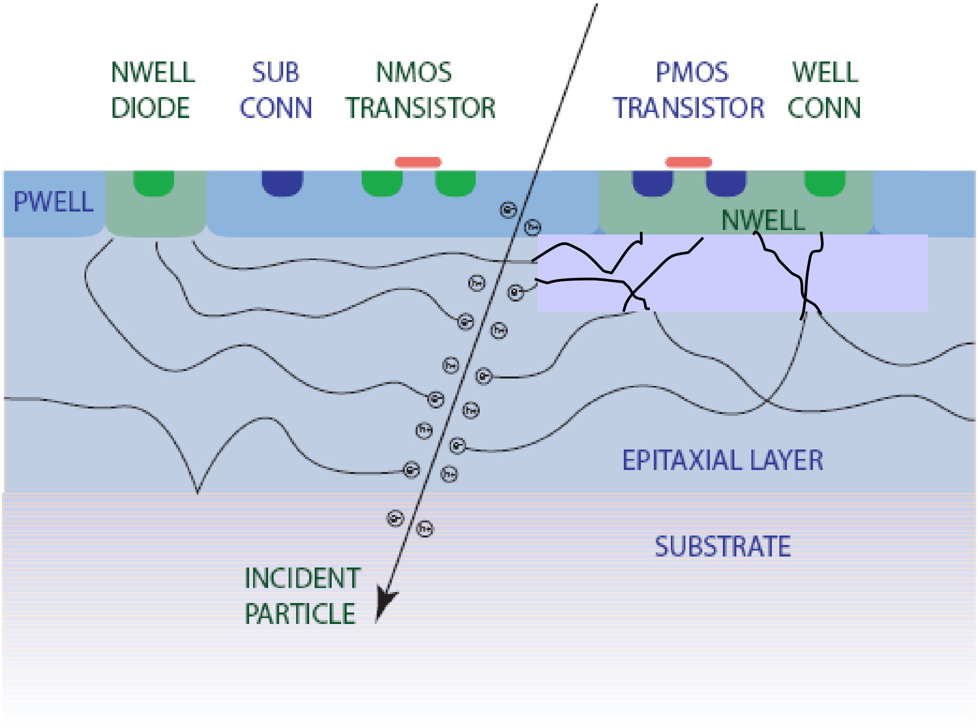
# CMOS epitaxial layer

- Sensor has an "epitaxial layer"
  - Region of silicon just below circuit
- Typically is manufactured to be 5-20μm thick
  - We use 12μm
- Only ionised electrons within this region can be detected



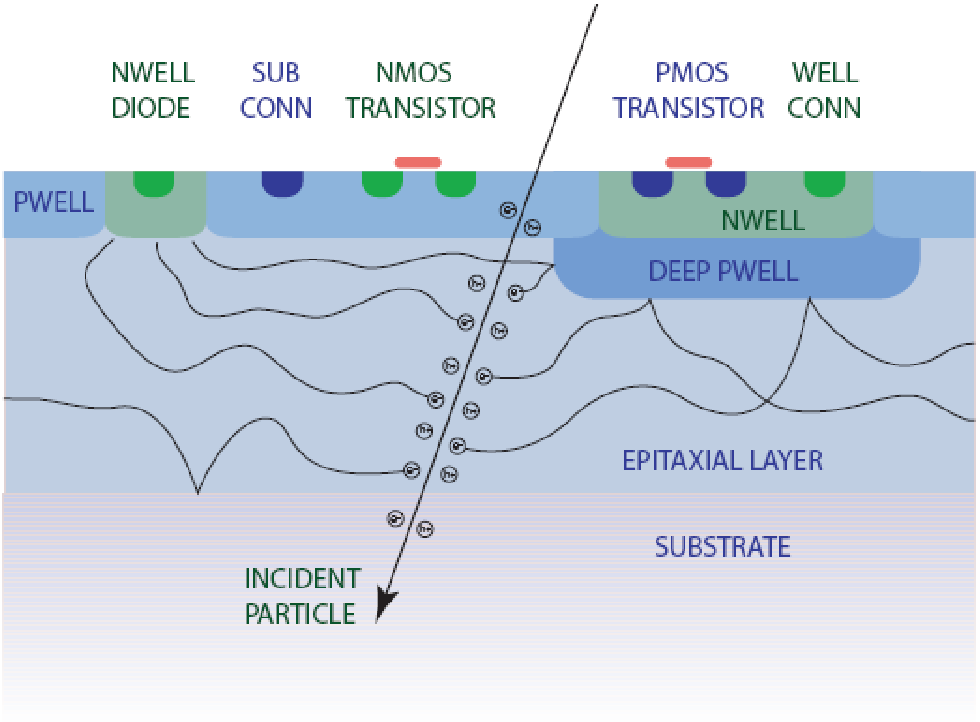
# Signal collection

- Electrons move in epitaxial layer simply by diffusion
  - Ionised electrons can be absorbed by an n-well structure
  - Make n-well diodes for signal collection within circuit layer
  - Takes ~100ns; OK for ILC
- PROBLEM: p-type transistors in CMOS ("p-MOS") also have an n-well
  - Any p-type transistors in circuit will also absorb signal so it is lost
  - Low collection efficiency or restrict circuit to use n-type transistors only?



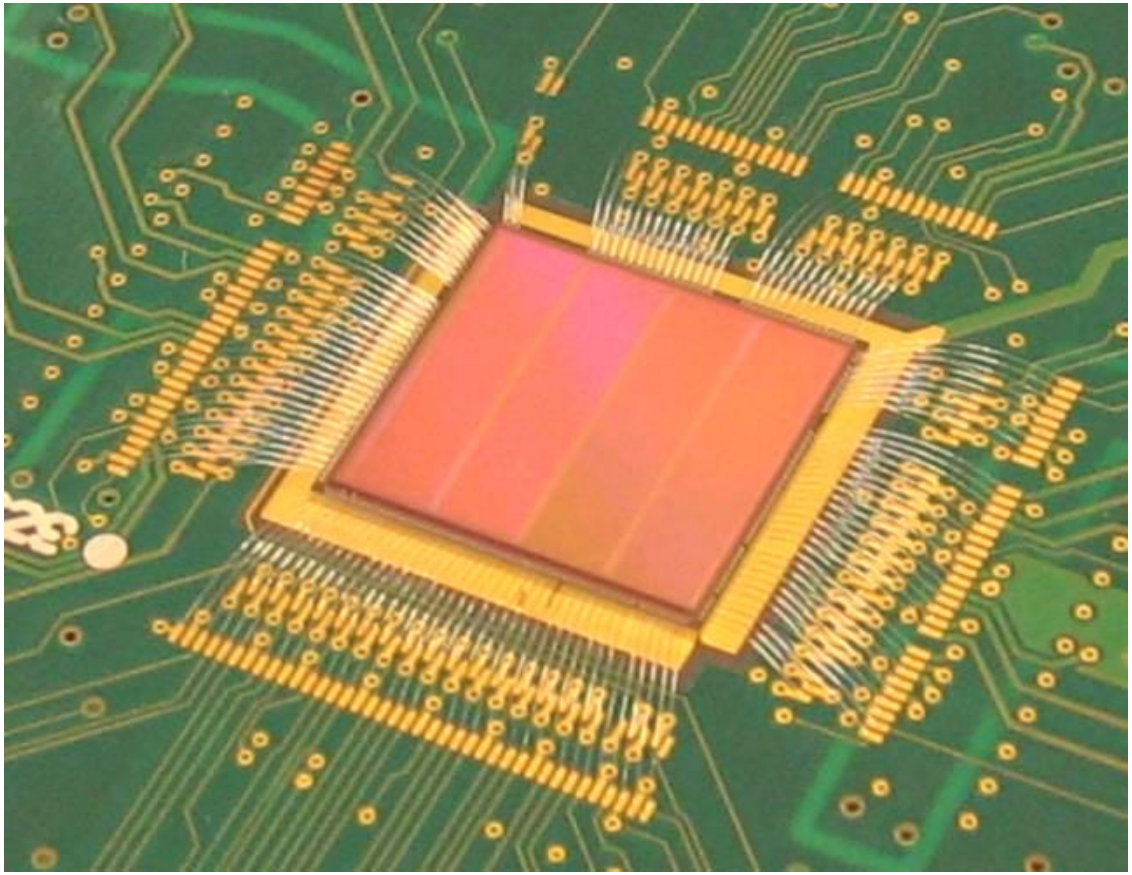
# Deep p-well process

- Developed "protection" layer for circuit n-wells; "deep p-well"
- Cuts off n-wells from epitaxial layer and so prevents them absorbing signal
- Allows full use of both n-type and p-type transistors without large signal loss

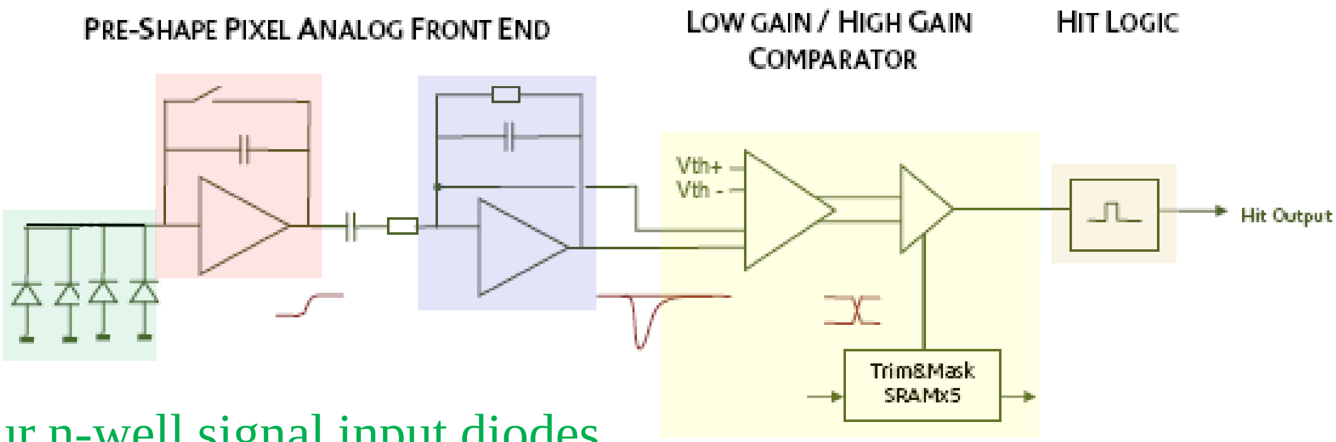


# TPAC1

- Tera-Pixel Active Calorimeter sensor
- To investigate issues of DECAL; not a realistic ILC prototype
- 168×168 array of 50×50μm$^2$ pixels
- Analogue test pixel at edge
- Total ~28,000 pixels
- Size ~1×1cm$^2$
- Made with 0.18μm CMOS deep p-well process

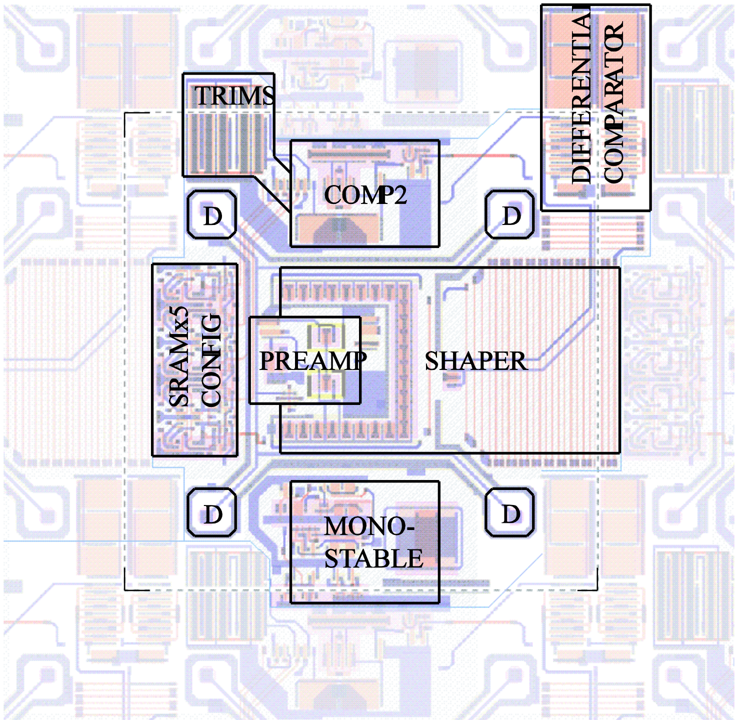


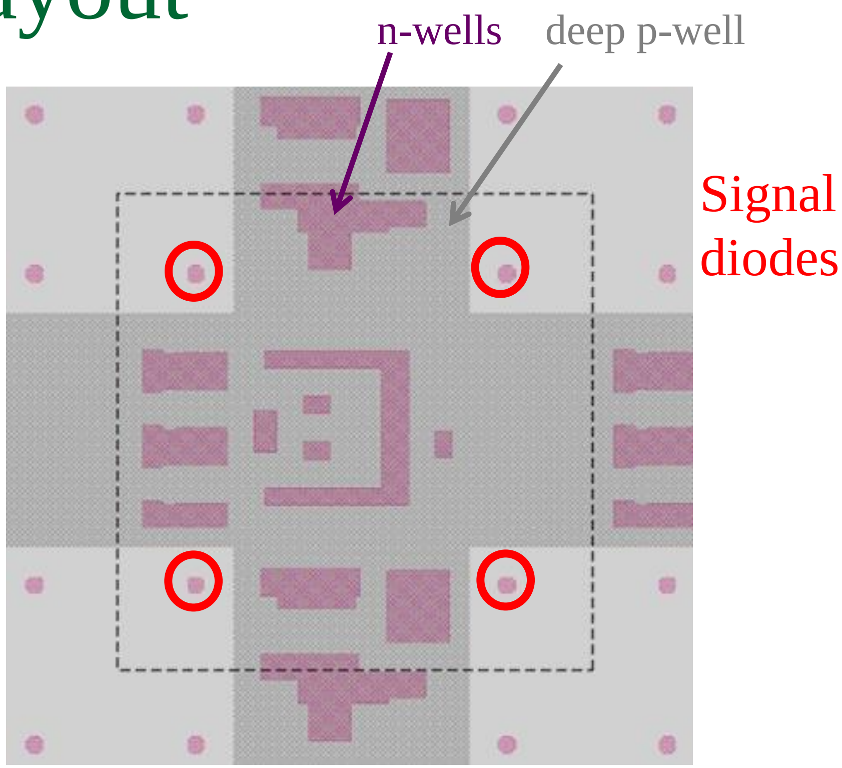
# TPAC1 in-pixel circuit




- Four n-well signal input diodes
- Charge integrating pre-amplifier
- Shaper with RC time constant ~100ns
- Two-stage comparator with configurable per-pixel trim
- Monostable for fixed-length output

# TPAC1 signal diode layout

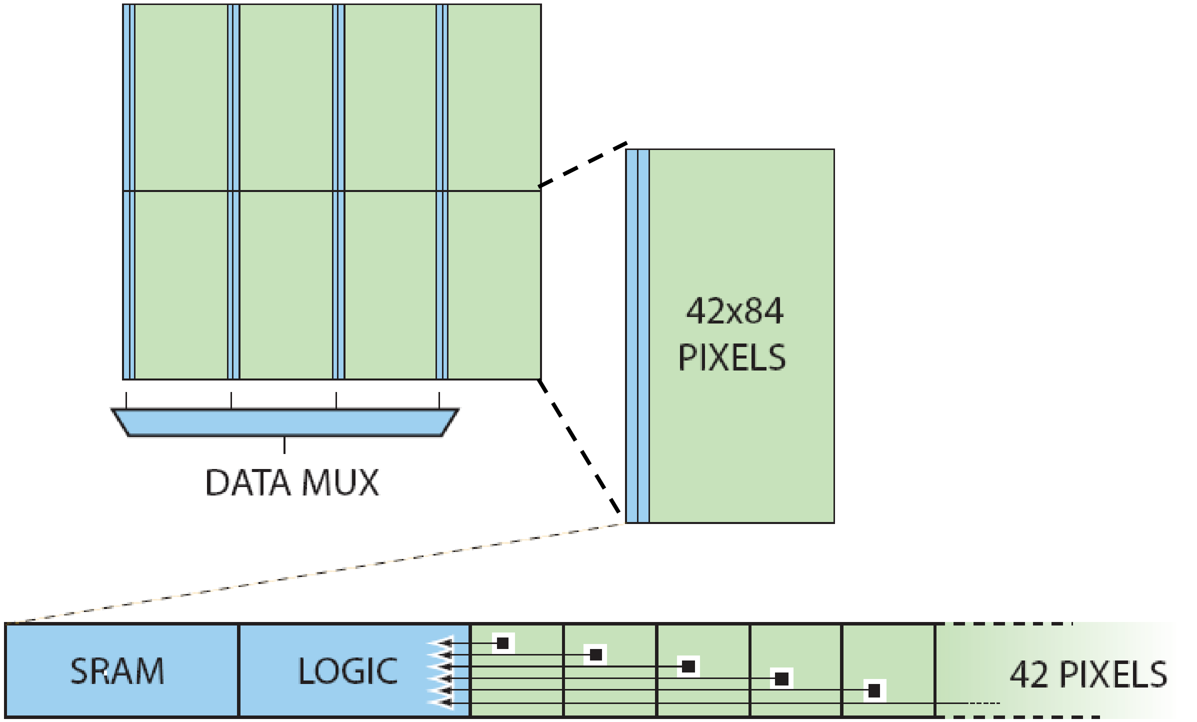


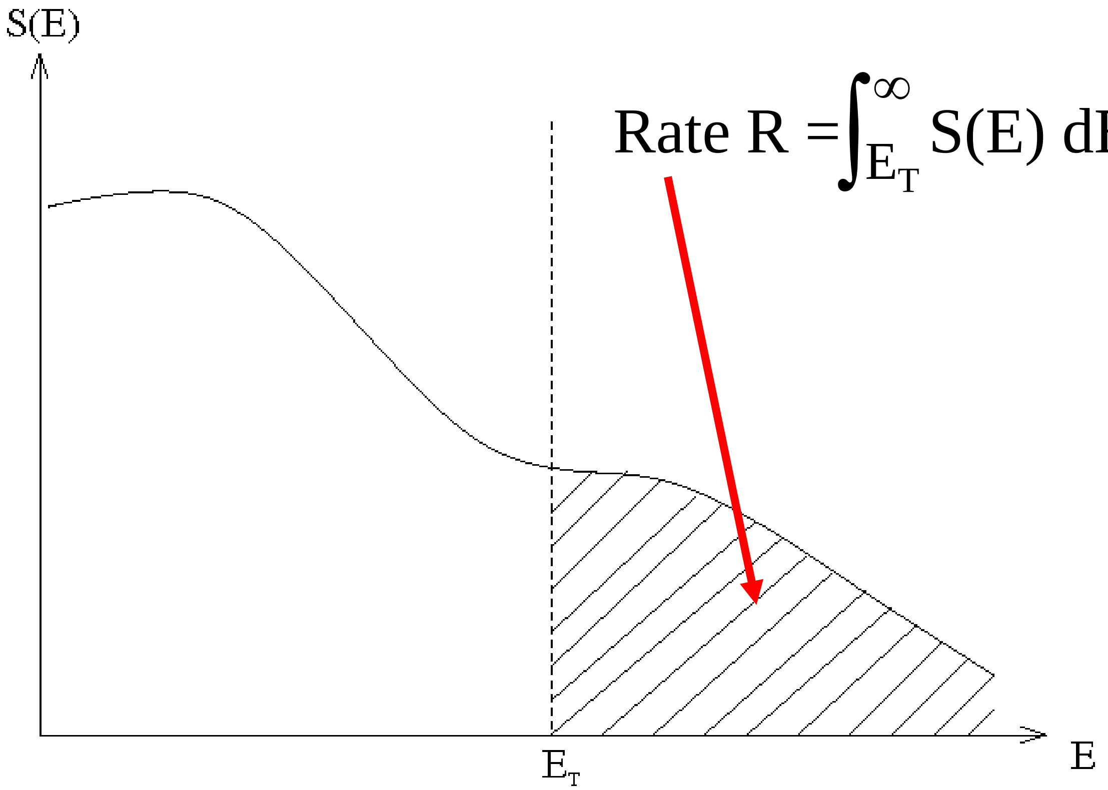

- Pixel effectively completely full; high component density means high power
  - ~10μW/pixel when running; ~40μW/mm$^2$ including ILC power pulsing

# TPAC1 on-sensor memory

- Monostable outputs from 42 pixels in each row tracked to memory regions
- A hit above threshold is stored in memory with timestamp (i.e. bunch crossing ID)
- Need four memory regions, each 5 pixels wide
- Dead space; 5/47 ~ 11%



# Digital readout and threshold

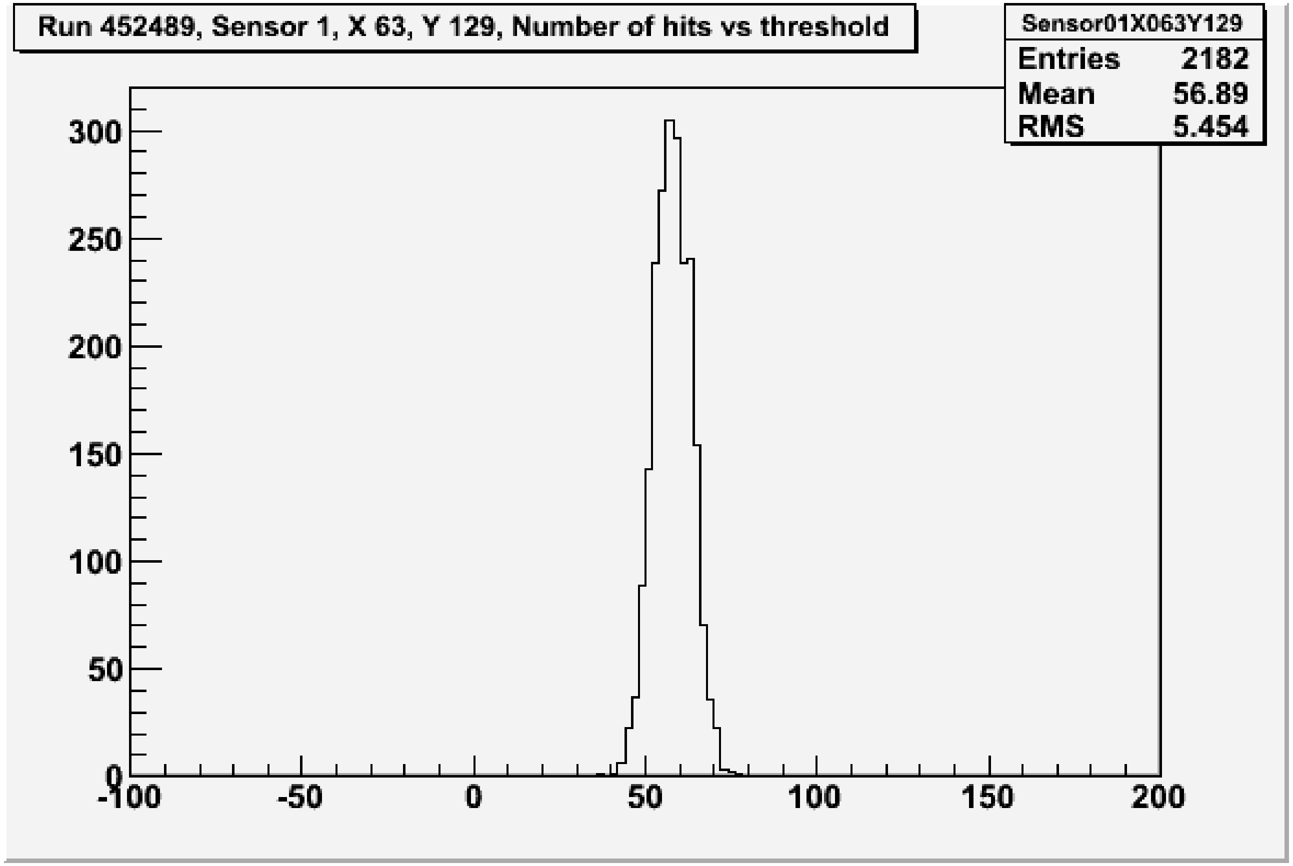



Rate $R = \int_{E_T}^{\infty} S(E)\, dE$

$\rightarrow S = -dR/dE_T$

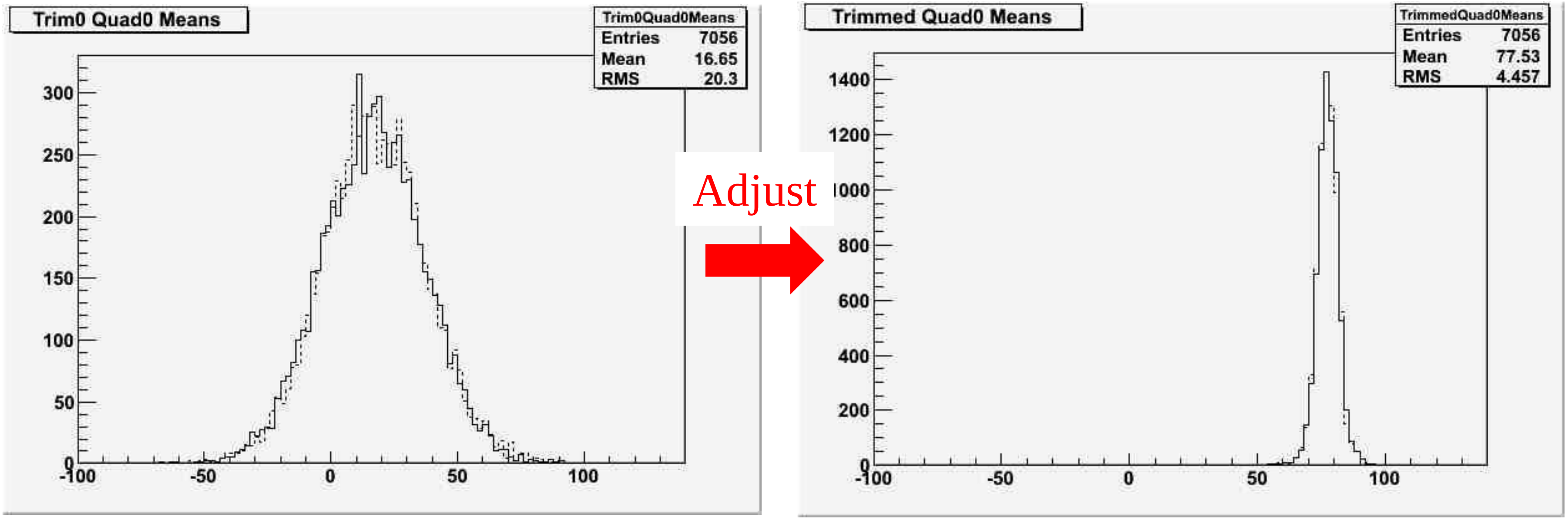
- Can measure spectrum even with digital readout
- Need to measure rate for many different threshold values
- Scan threshold values using computer-controlled DAC

# No signal: pedestal and noise




- Typical single pixel
- Note, mean is NOT at zero = pedestal

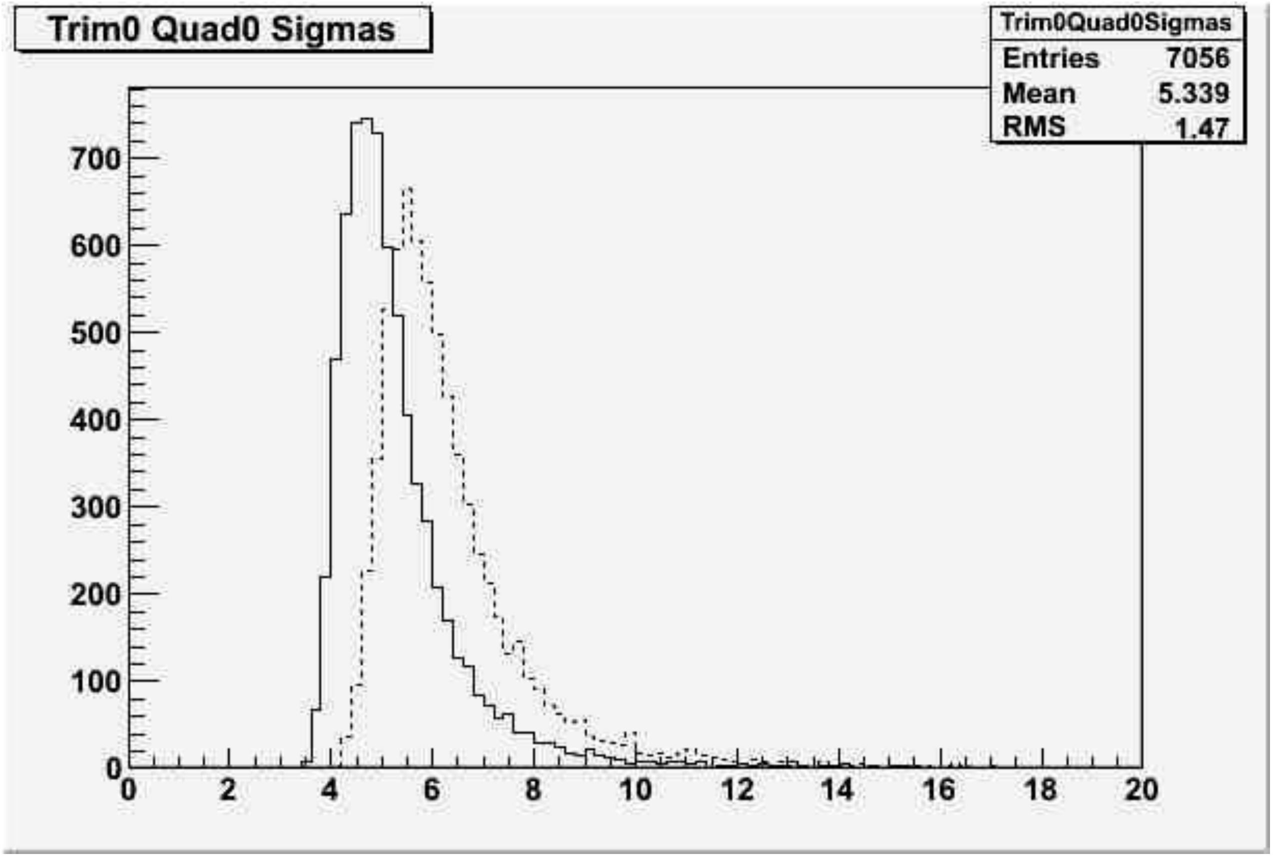
# Pedestal spread




- Pedestals have large spread ~20 TU compared with noise
- Caused by pixel-to-pixel variations in circuit components
  - Pushing component sizes to the limit
- Per-pixel adjustment used to narrow pedestal spread
  - Probably not possible in final sensor

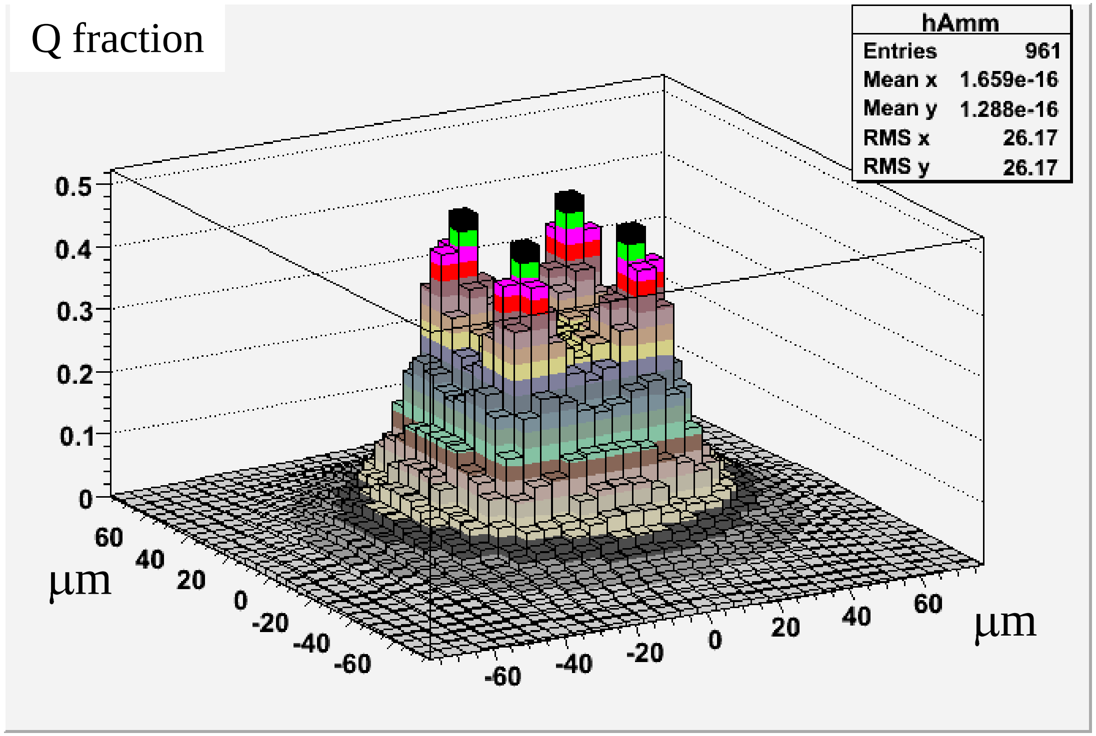
# Noise spread

- Noise also has large spread
- Also caused by variations in components
- Average ~6TU



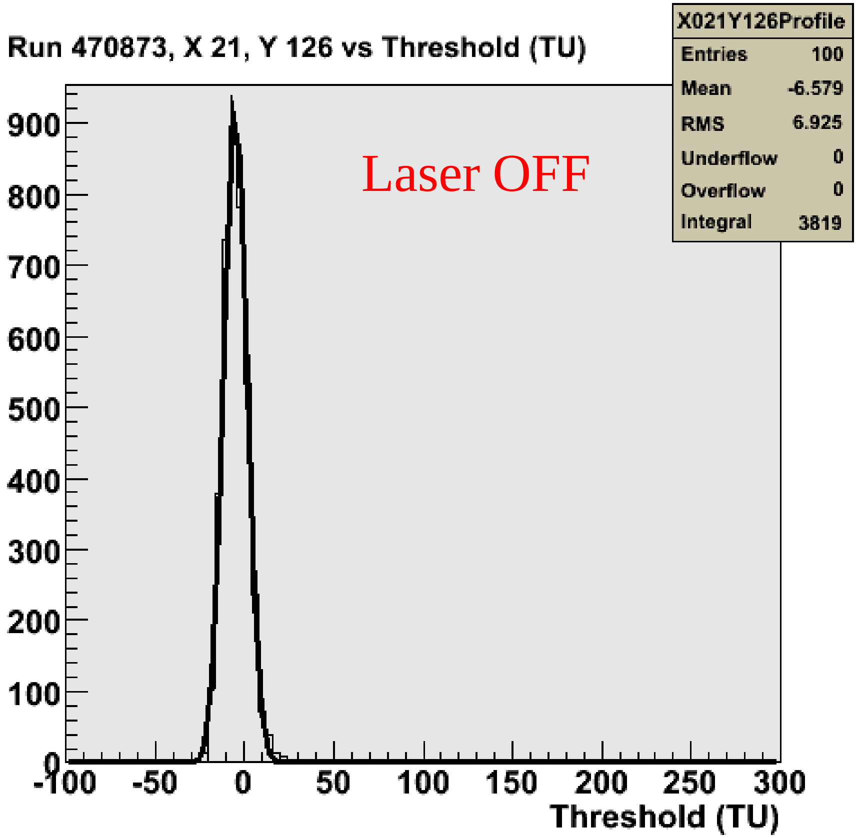
# Charge diffusion

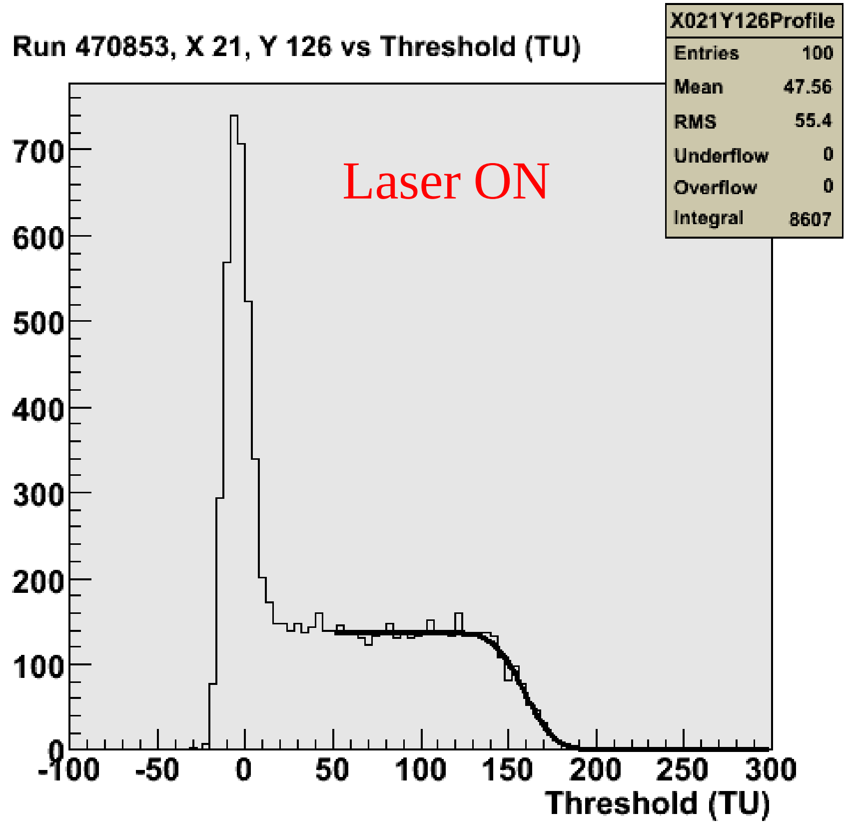
- Signal charge diffuses to signal diodes
- But also to neighbouring pixels
- Pixel with deposit sees a maximum of ~50% and a minimum of ~20%
- Average of ~30% of signal charge
- The rest diffuses to pixel neighbours



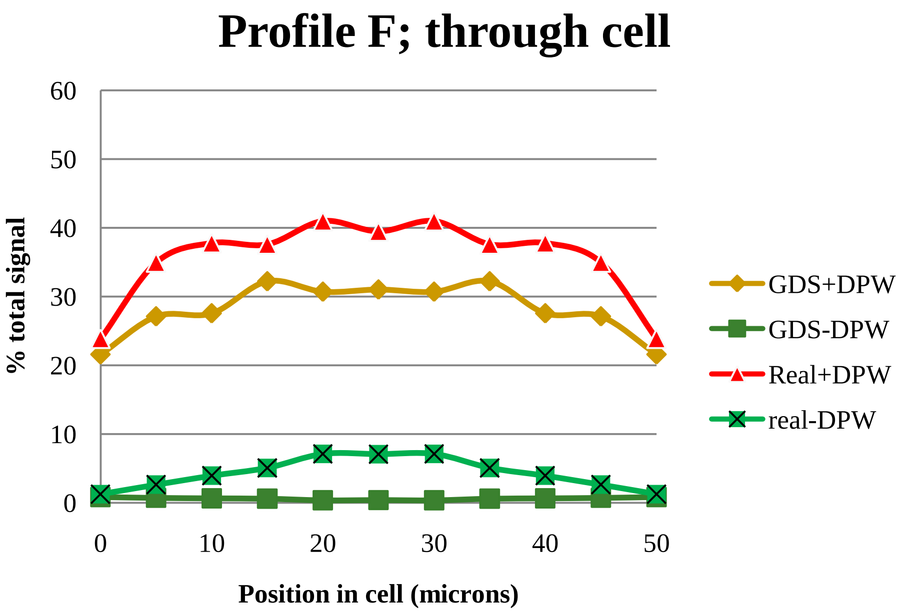
# Charge diffusion measurements

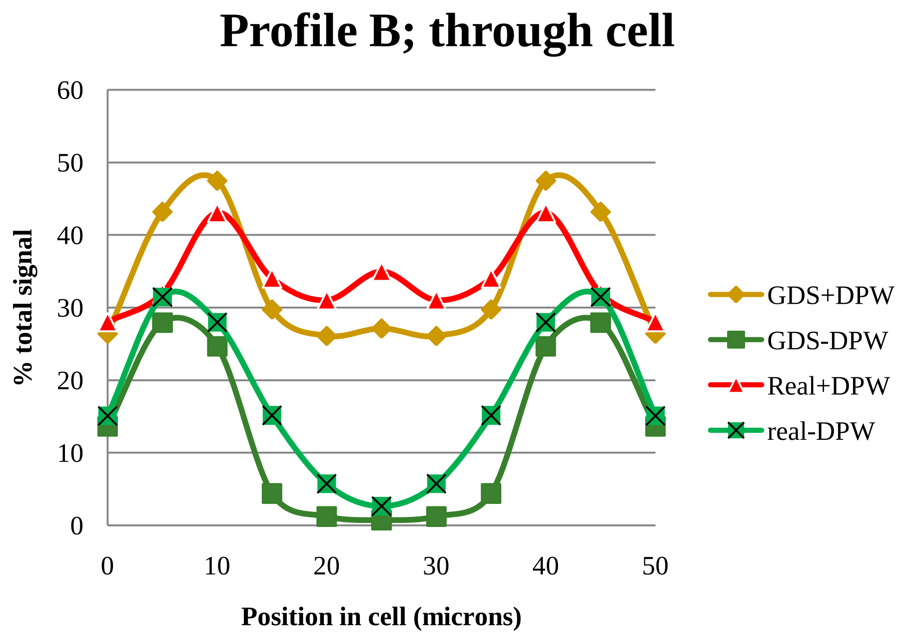
- Inject charge using IR laser, 1064nm wavelength; silicon is transparent

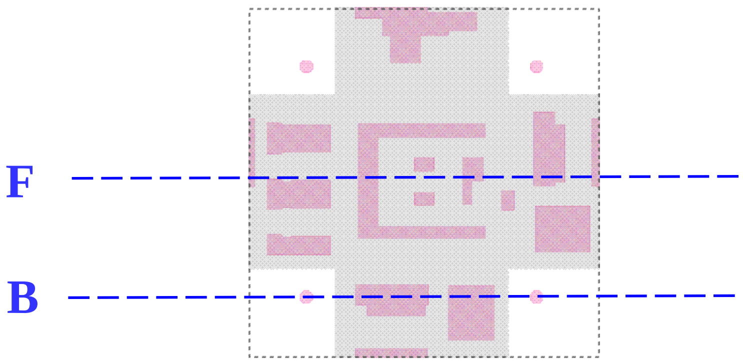


# Charge diffusion measurements

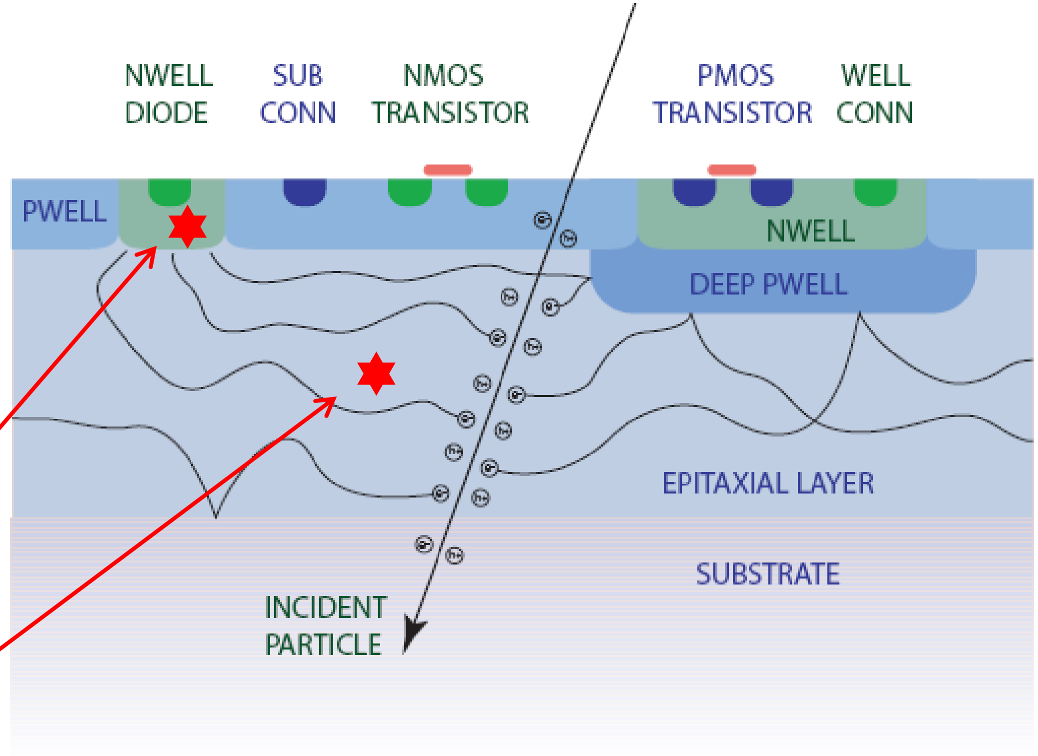


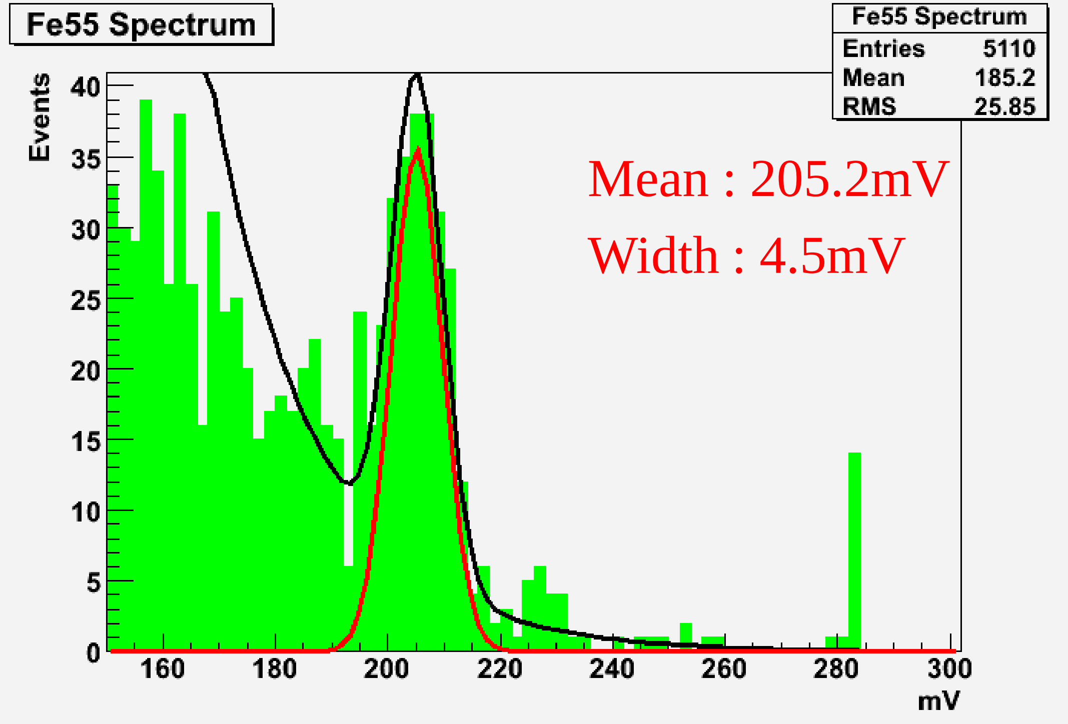
# Calibration: $^{55}$Fe source

- Use 55Fe source; gives 5.9keV photons, compared with ~3keV for charged particle
- Interact in silicon in very small volume ~1μm$^3$ with all energy deposited; gives 1620e$^-$
- 1% interact in signal diode; no diffusion so get all charge
- Rest interact in epitaxial layer; charge diffusion so get fraction of charge



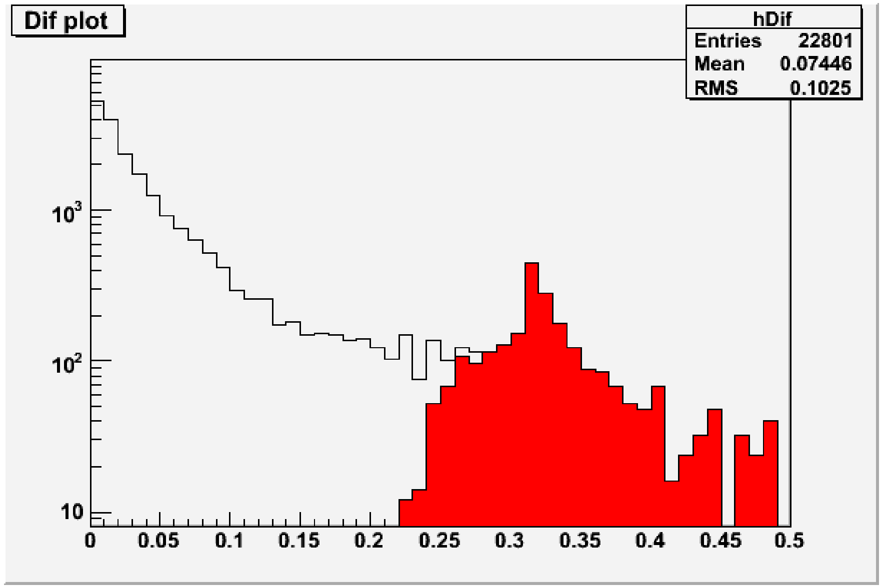
# Calibration: test pixel analogue signal

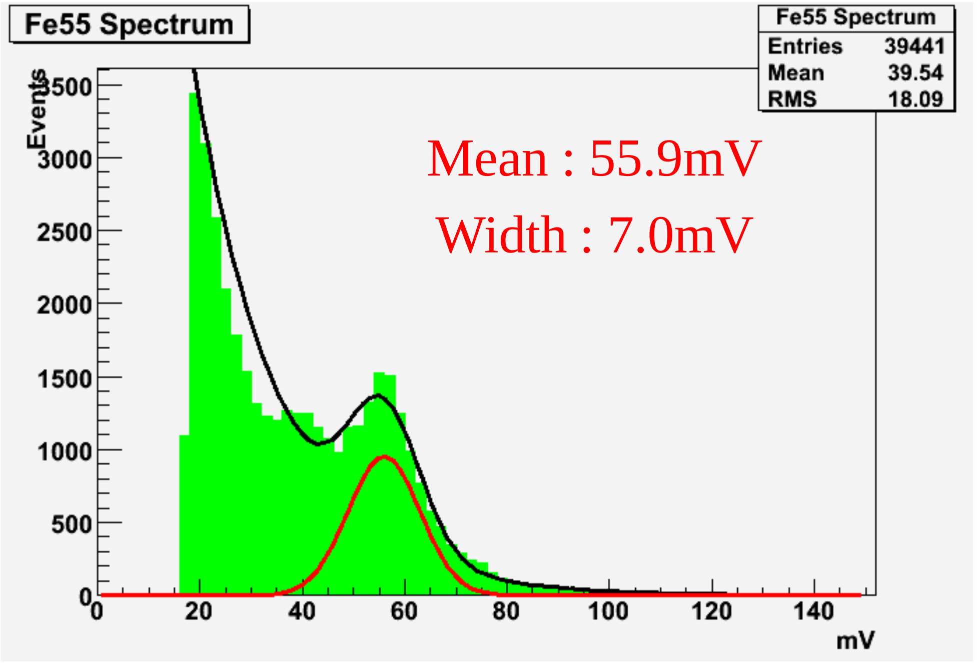
- Interactions in signal diode give monoenergetic calibration line corresponding to 5.9keV
- Can see this in test pixel as analogue measurement of spectrum



# Calibration: test pixel analogue plateau

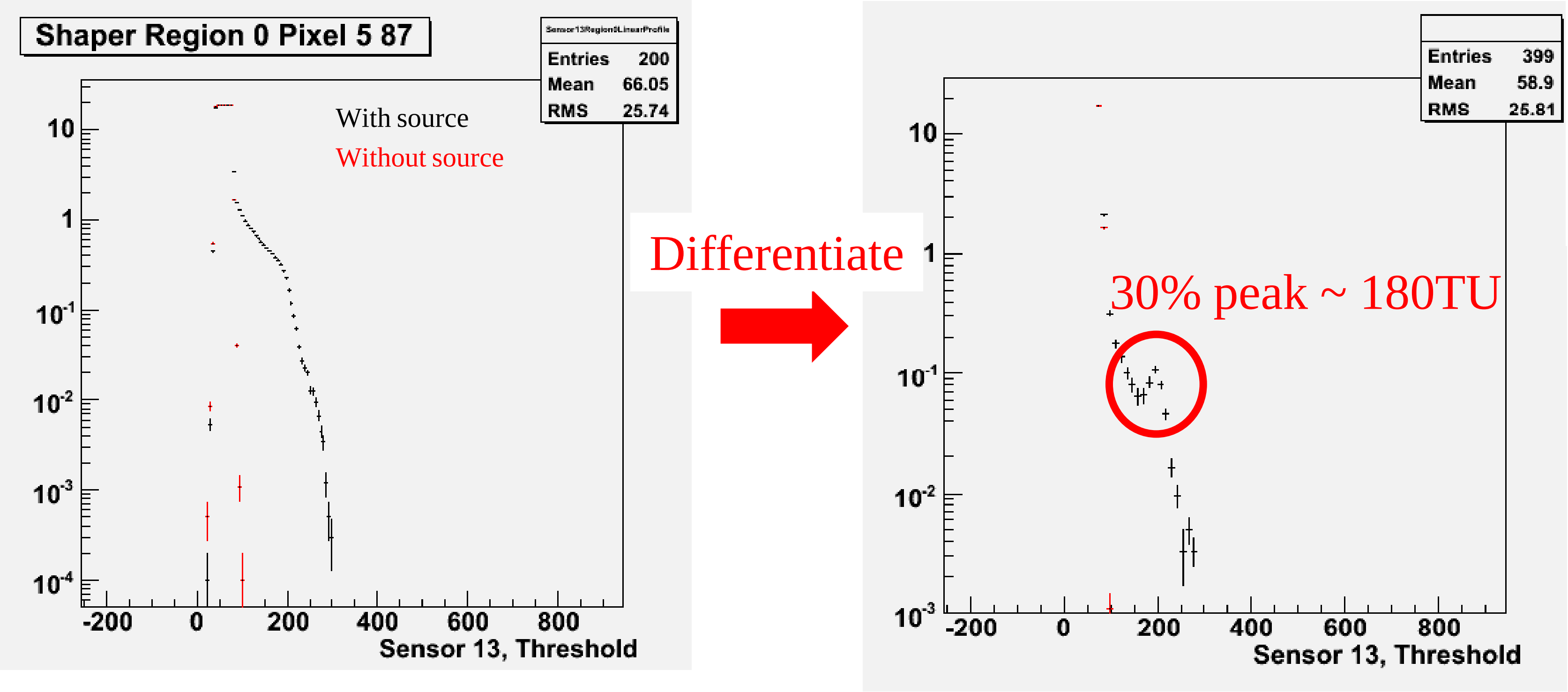
- Can also use lower plateau from charge spread ~30% of 5.9keV



# Calibration: digital pixel analogue plateau

- Comparator saturates below monoenergetic 5.9keV peak; cannot use ☹
- In digital pixels can only use lower plateau
- Sets scale: 1 TU ~ 3e⁻ so noise (ENC) ~ 6TU ~ 20e⁻



# Critical points

- TPAC1 sensor is understood
- Fundamental signal charge ~1000$e^-$
- Charge reduced by diffusion to neighbouring pixels
- Maximum ~ 500$e^-$, minimum ~200$e^-$, noise ~20$e^-$
- Dead area from memory storage ~11%
- Not realistic ILC sensor
  - Too small ~1×1$cm^2$
  - Pixel variations (pedestal, noise) too big
  - Power consumption too high