Calibration of APTS Prototypes Developed in 65 nm CMOS Imaging Technology

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HELMHOLTZ

ATLAS EXPERIMENT

DESY.

Overview of the project

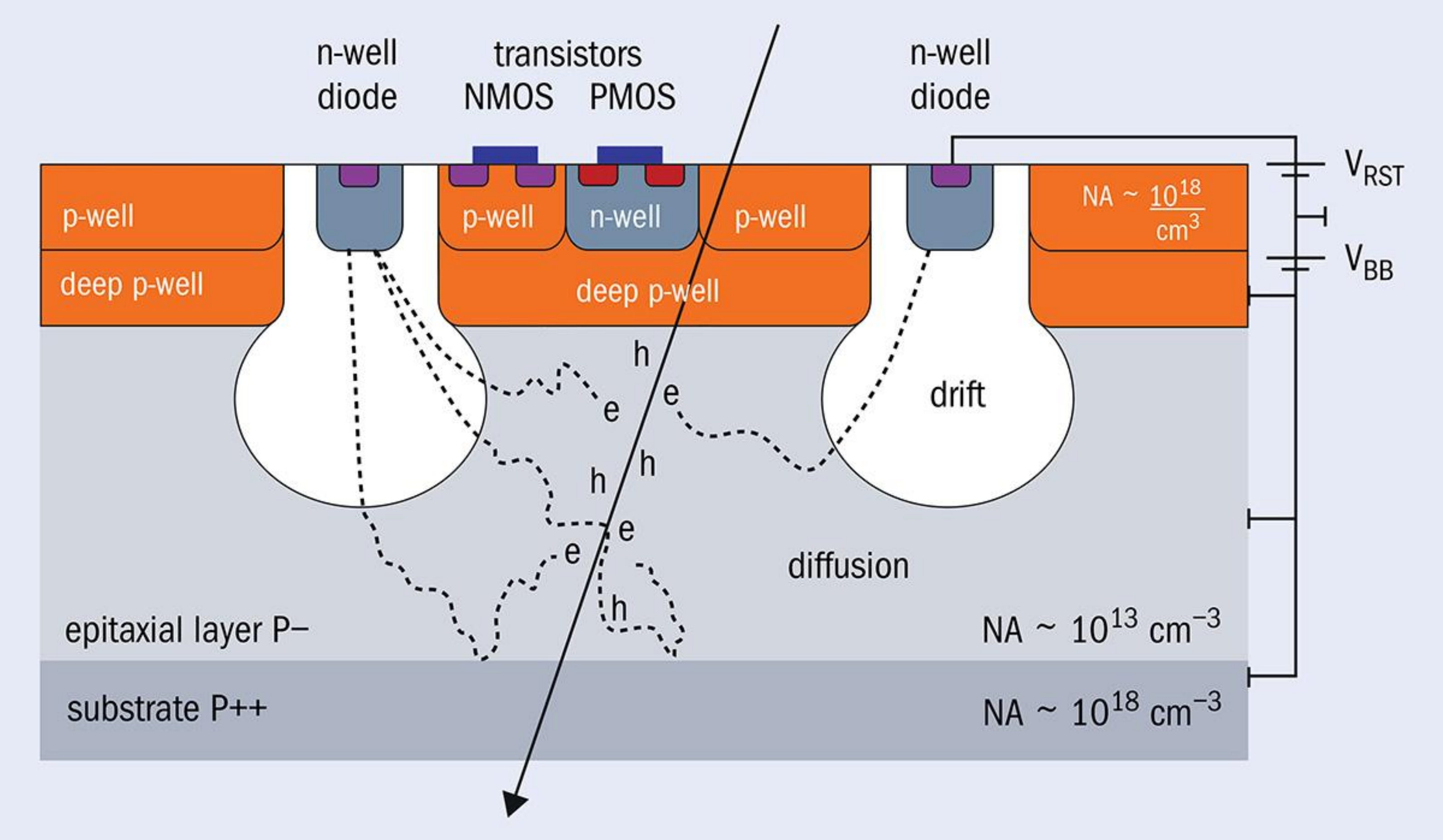
- Laboratory Characterization of Monolithic Active Pixel Sensors (MAPS)

Summary of main steps:

- Waveform Analysis
- Gain Characterization
- Charge Calibration Using Fe-55 Source
- Getting the Calibration Curve

MAPS Detectors

- CMOS: Complementary Metal-Oxide Semiconductor
- A charged particle or X-ray in Si creates e^{-}/h^{+} pairs.
- Depleted region steers e^{-} to the n-well diode (fast drift); the rest comes by diffusion.
- In-pixel CMOS electronics turn the collected charge into a signal level.

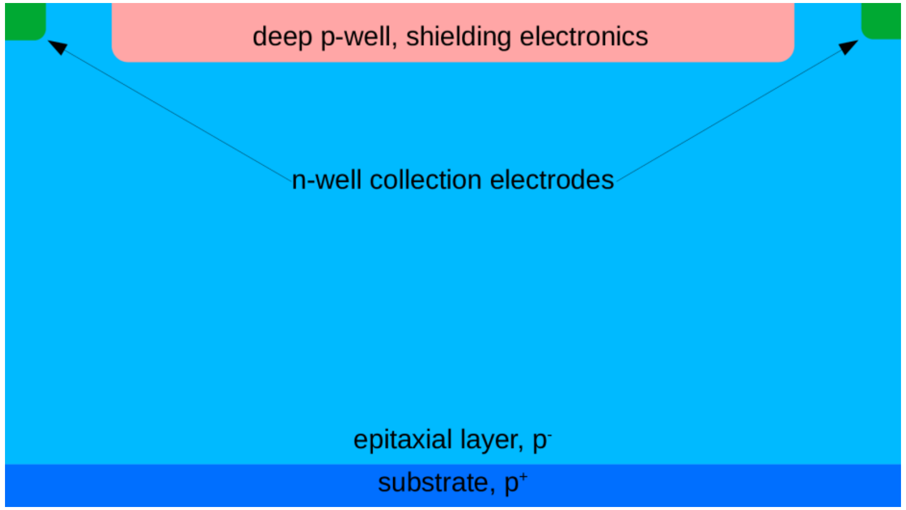


We need a calibration to express signals in meaningful physical units and map per-pixel gain/charge differences, to have a clearer picture of the detector's behavior.

MAPS Layouts

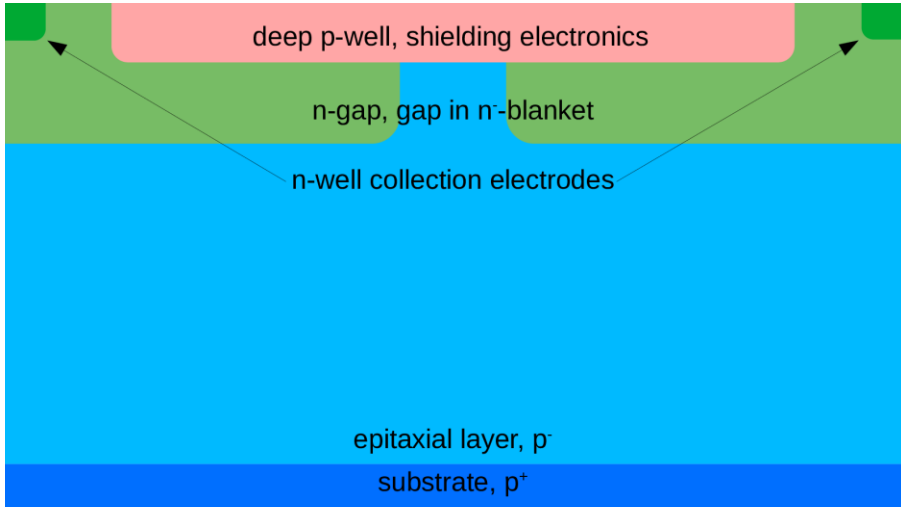
Standard

- Slow Charge Collection
- More shared charge (Higher Spatial Resolution)
- Low efficiency at High Thresholds



N-Gap

- Fast Charge Collection
- Less shared charge (Lower Spatial Resolution)
- High efficiency at High Thresholds



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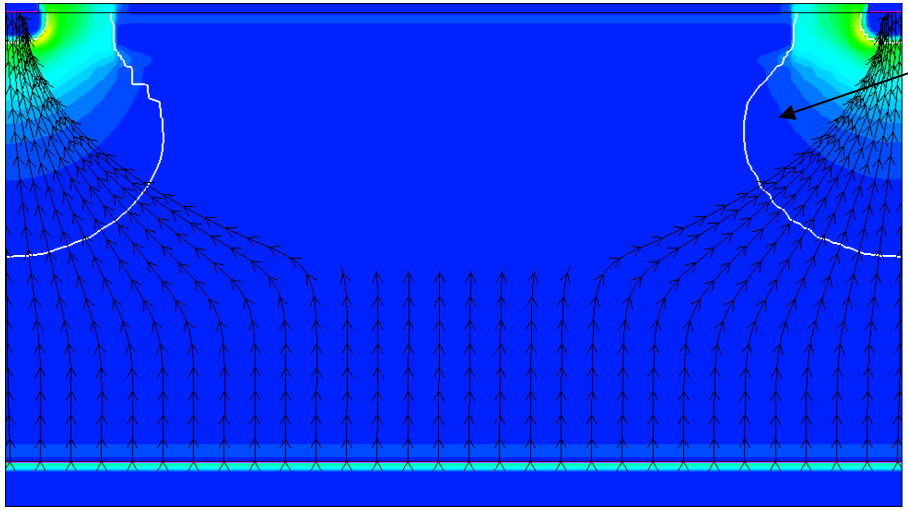
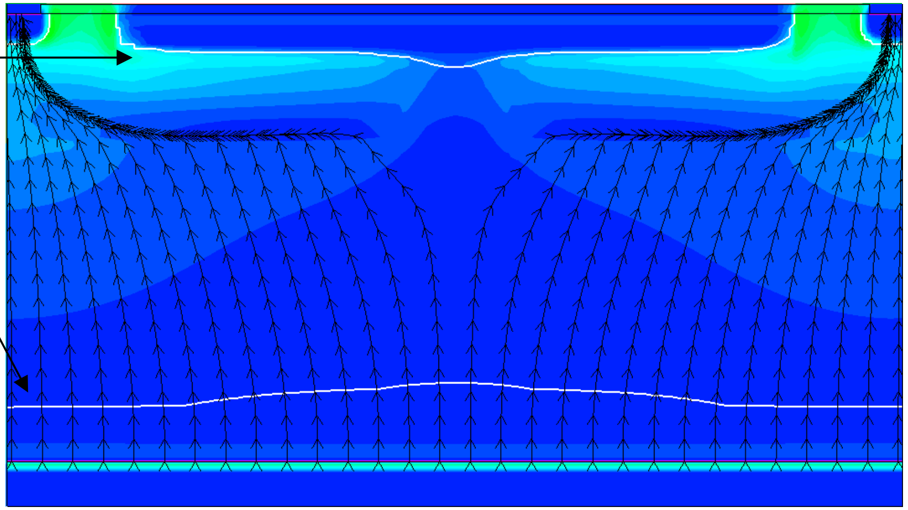
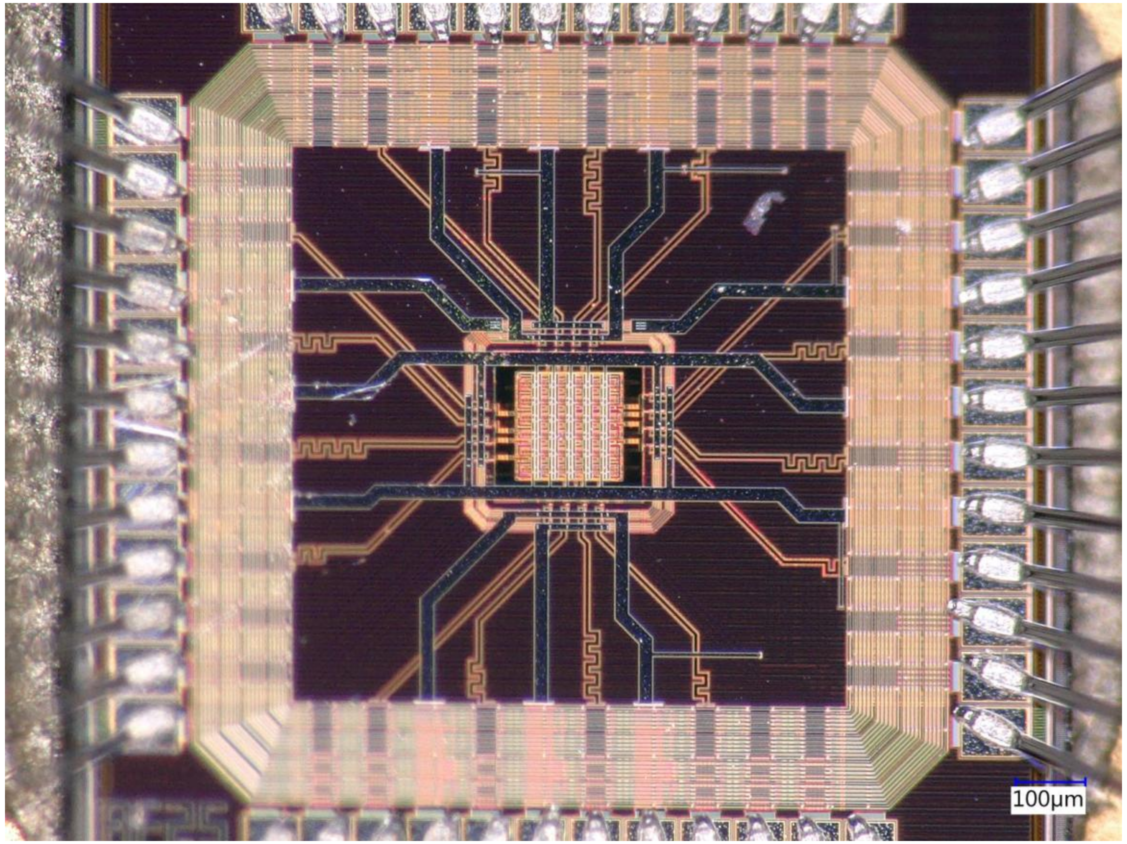




Details of APTS Chip ID 27



- Layout: N-Gap
- Gap Size: 2.5 μm
- Die size: 1.5 mm × 1.5 mm
- Matrix: 6 × 6 pixels
- Readout: Direct analogue of central 4 × 4 pixels
- Pixel Pitch 15 μm × 15 μm

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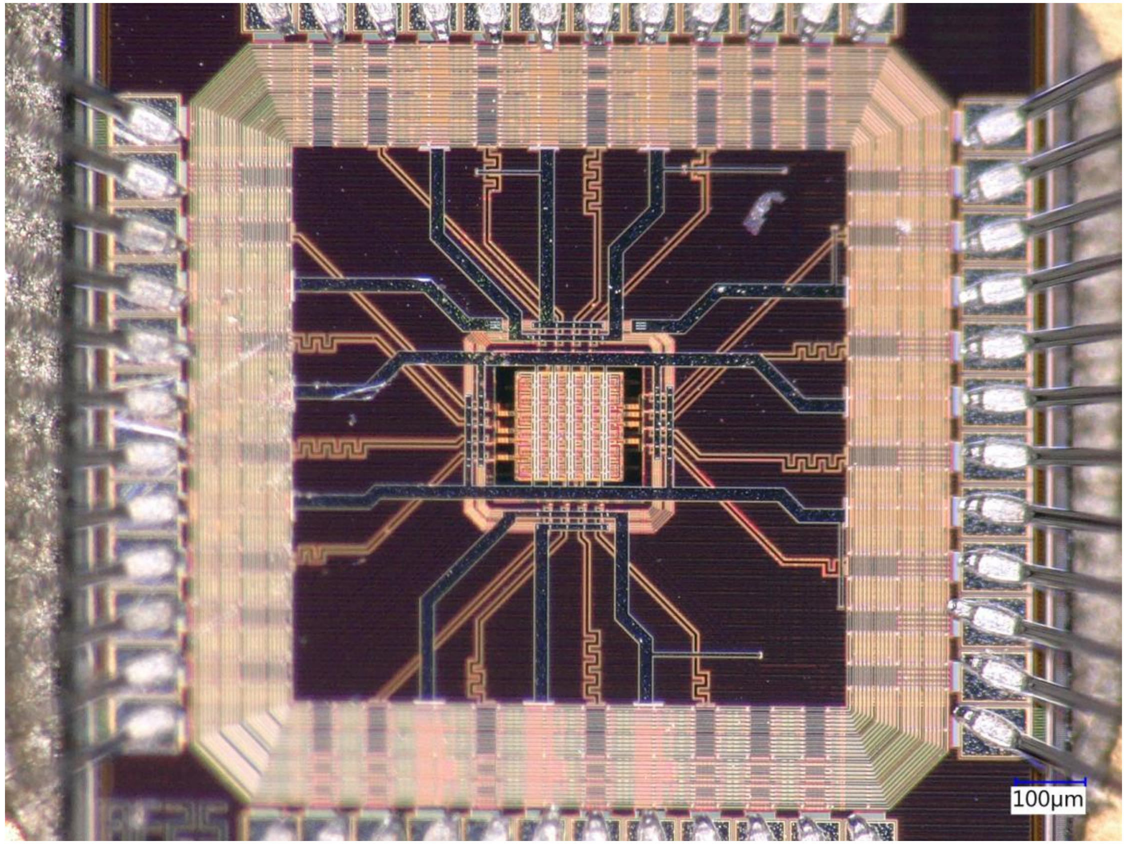
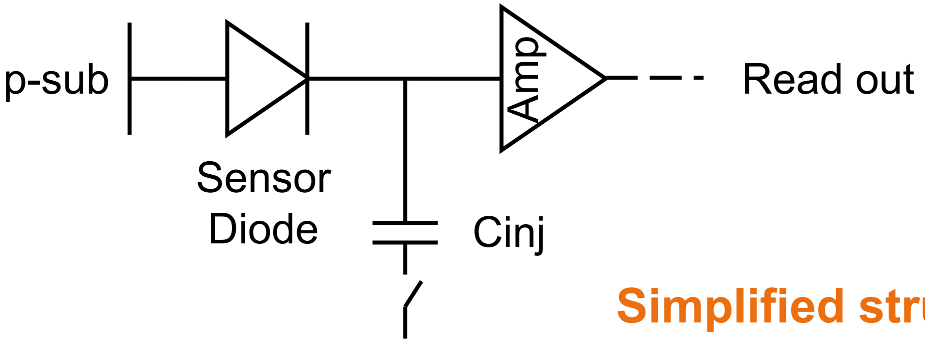
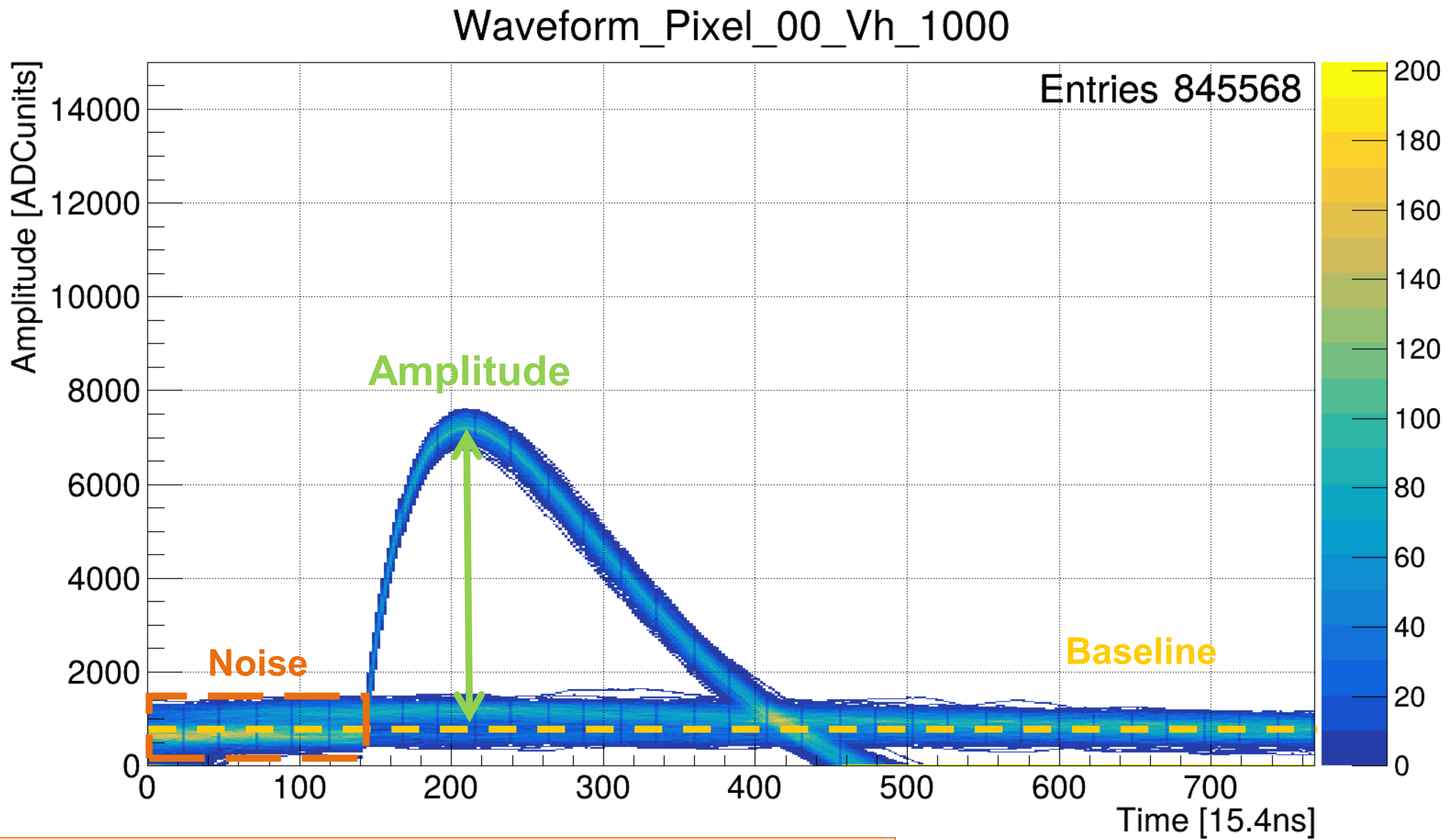


From diode to analog voltage
- The diode collects electrons and makes a small voltage step on the pixel node.
- A tiny amplifier copies/boosts that voltage to the analog output.
- A gentle reset current brings the node back to baseline after the pulse.
- For tests, a small injection capacitor (C_inj) can fake a hit with a voltage step



Simplified structure of the electronics

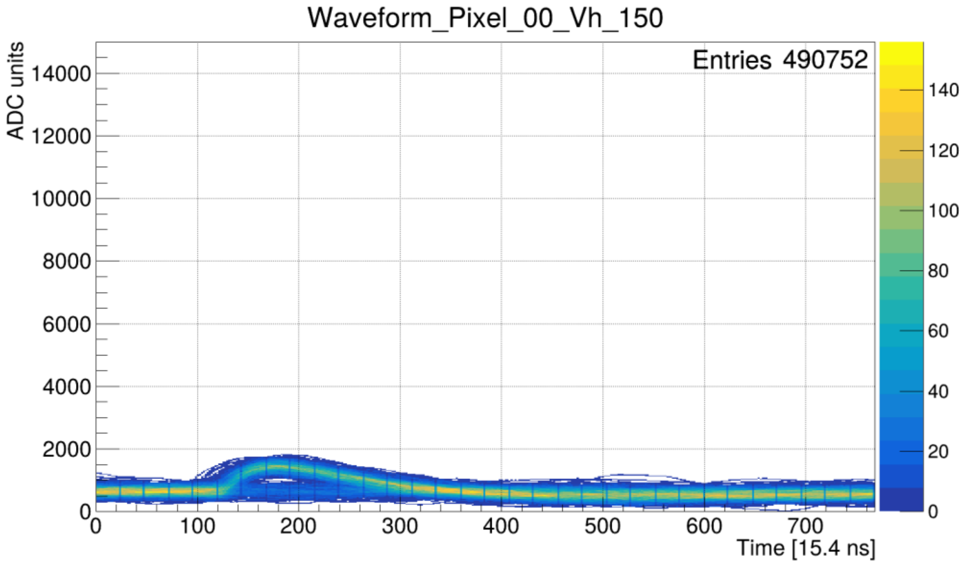
Waveform Analysis

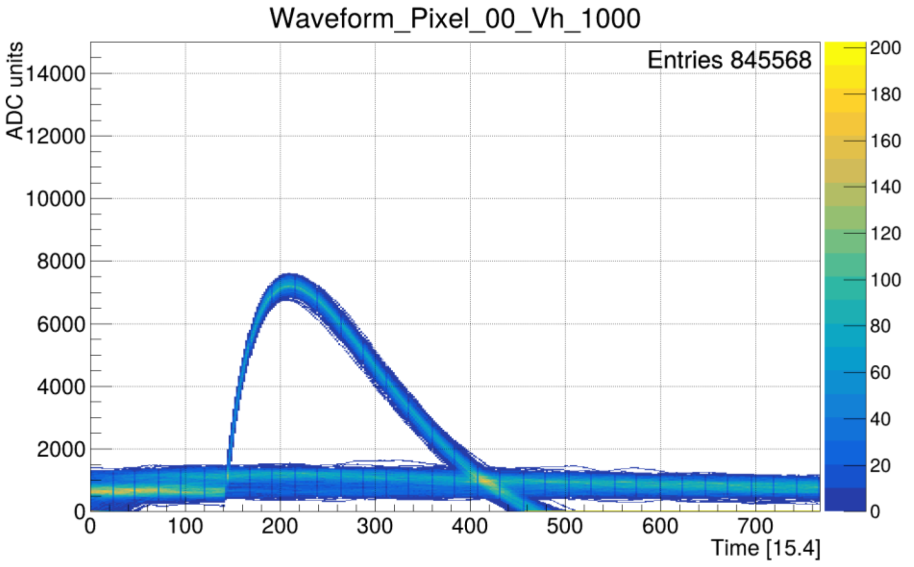


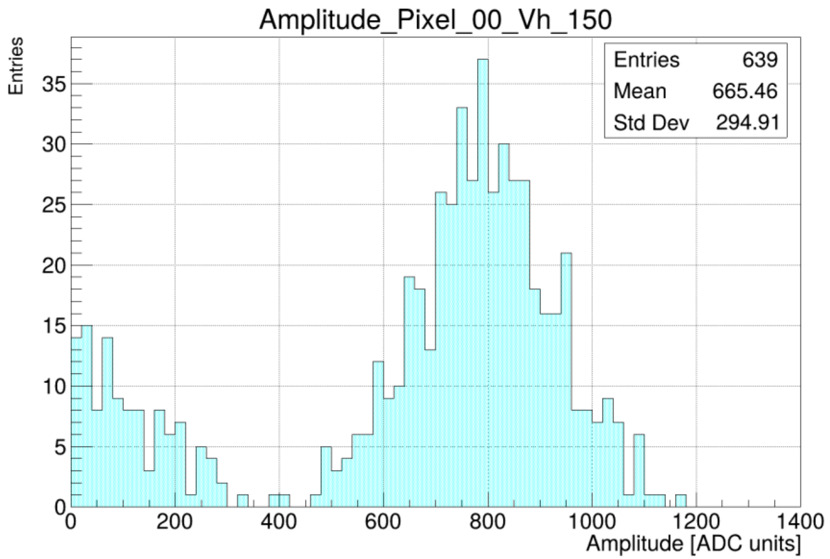
- Baseline (BL): Mean of pre-signal samples; used to remove DC offsets per waveform.
- Noise (σ): RMS fluctuation around BL; higher σ means harder hit discrimination.
- Amplitude (A): Peak height above BL (Max − BL) in ADC counts.
- S/N: Ratio of signal strength to noise (A/σ); higher is better.
- ADC: Analog-to-Digital Converter; digitizes the analog voltage into discrete counts.

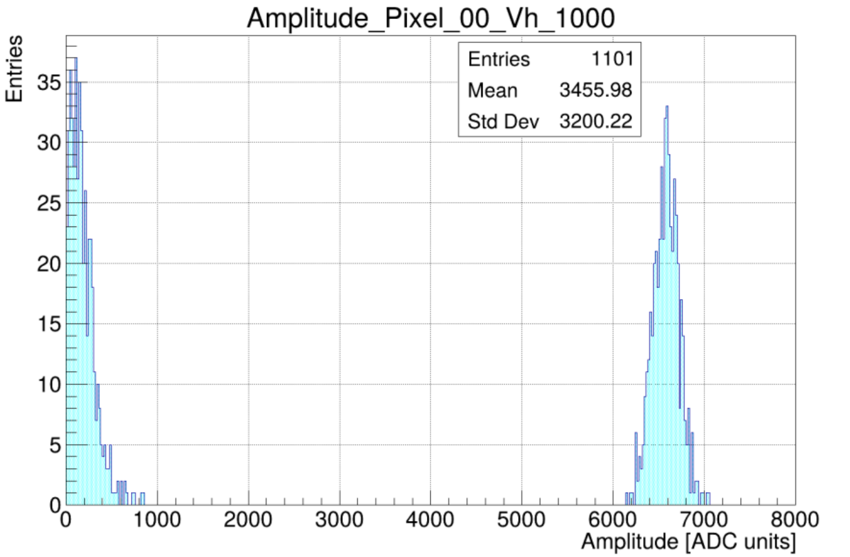
- **Voltage test-pulse scan: 0 → 1200 mV** in **10 mV** steps.

Behavior of Waveforms at High and Low Amplitude Test Pulse









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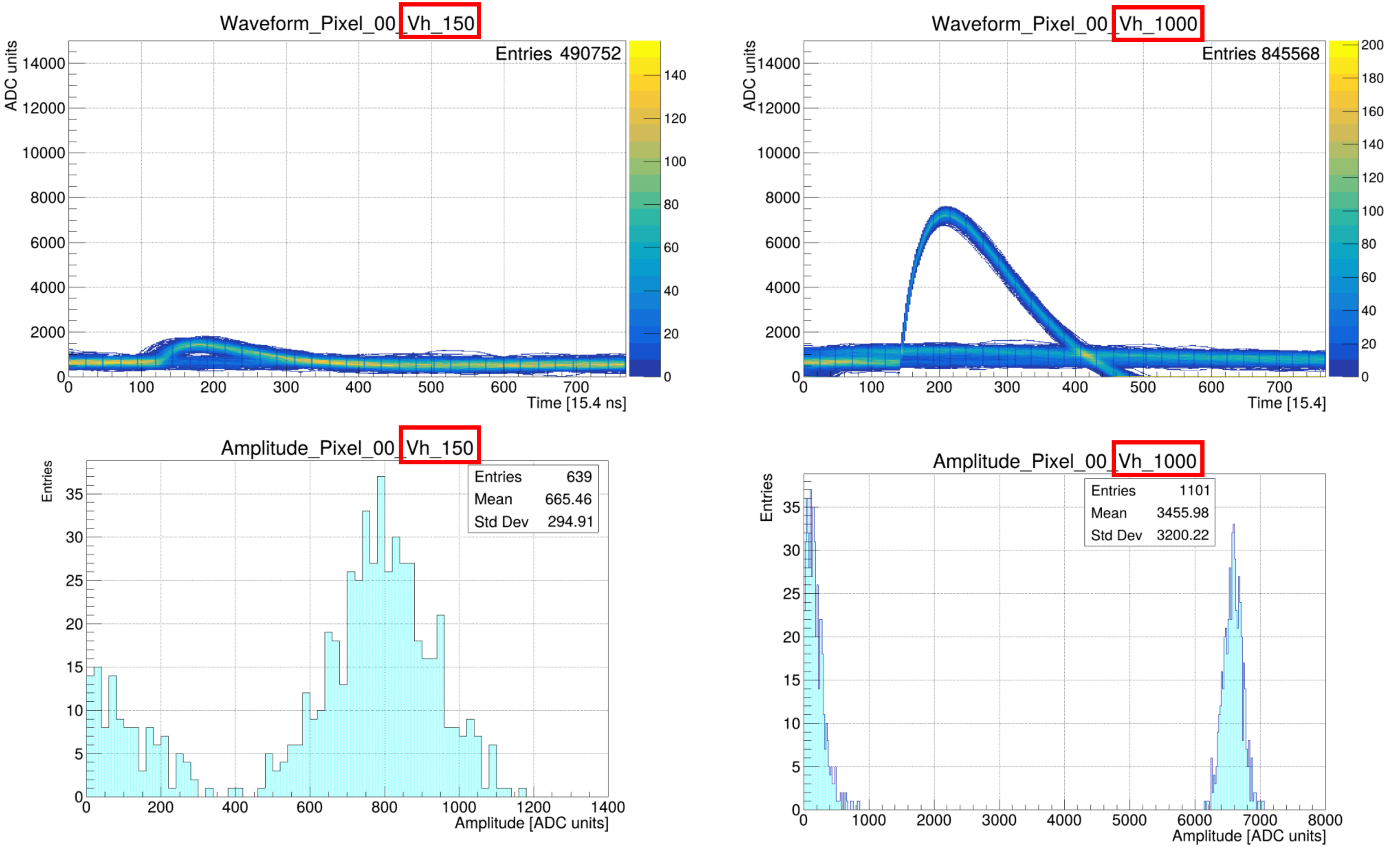
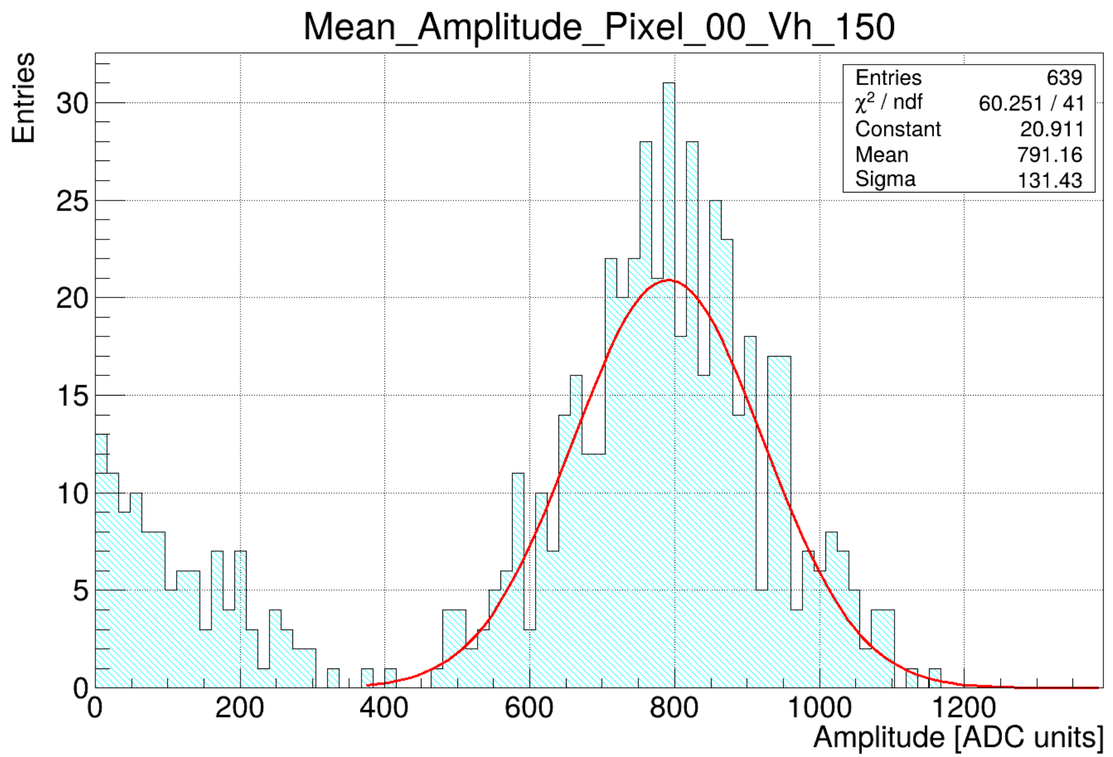
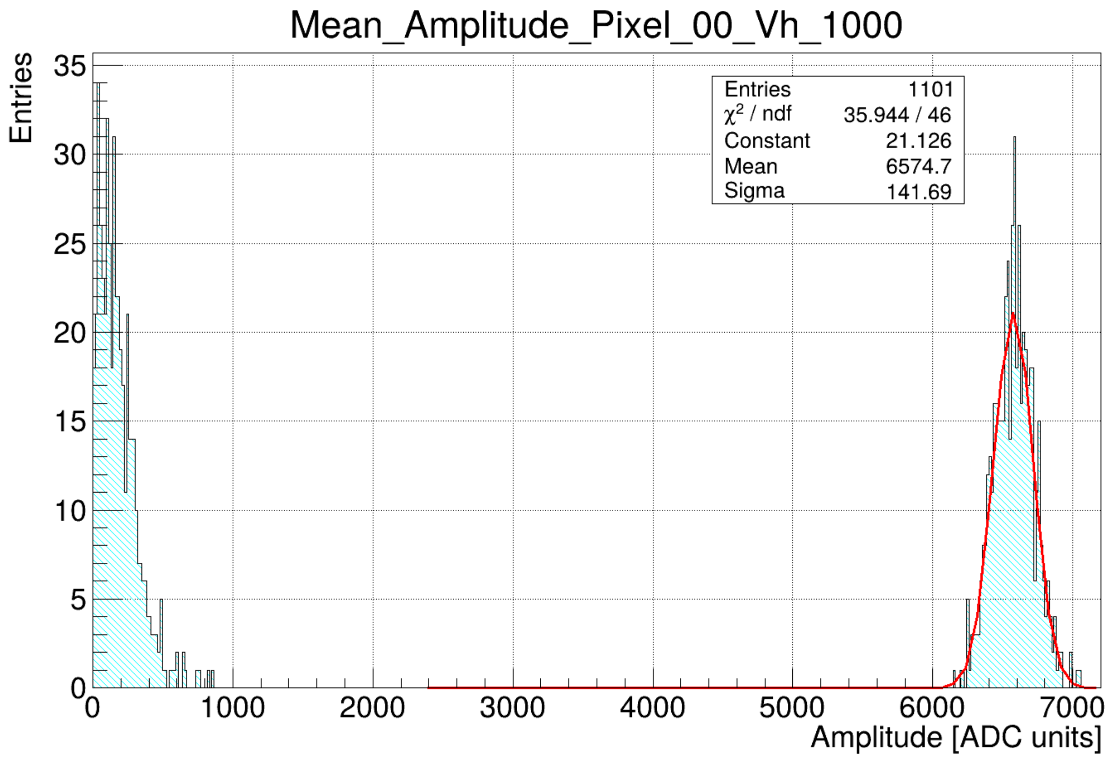


How did we get the elements for our Gain curve

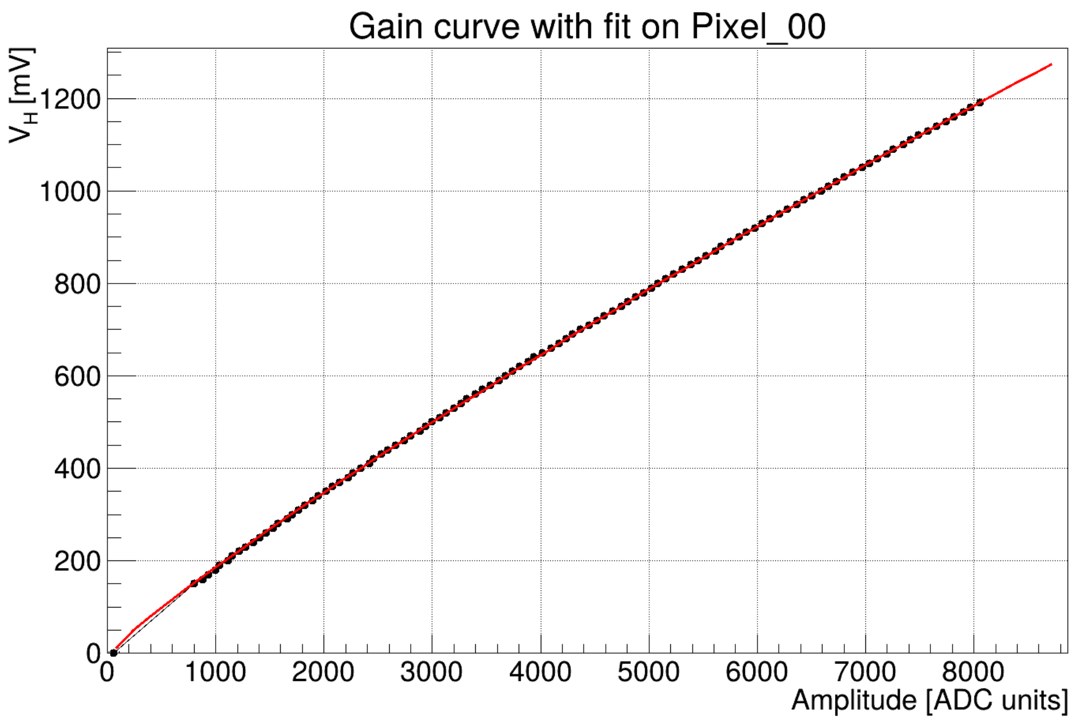
Robust mean extraction: quantile-centered Gaussian fit

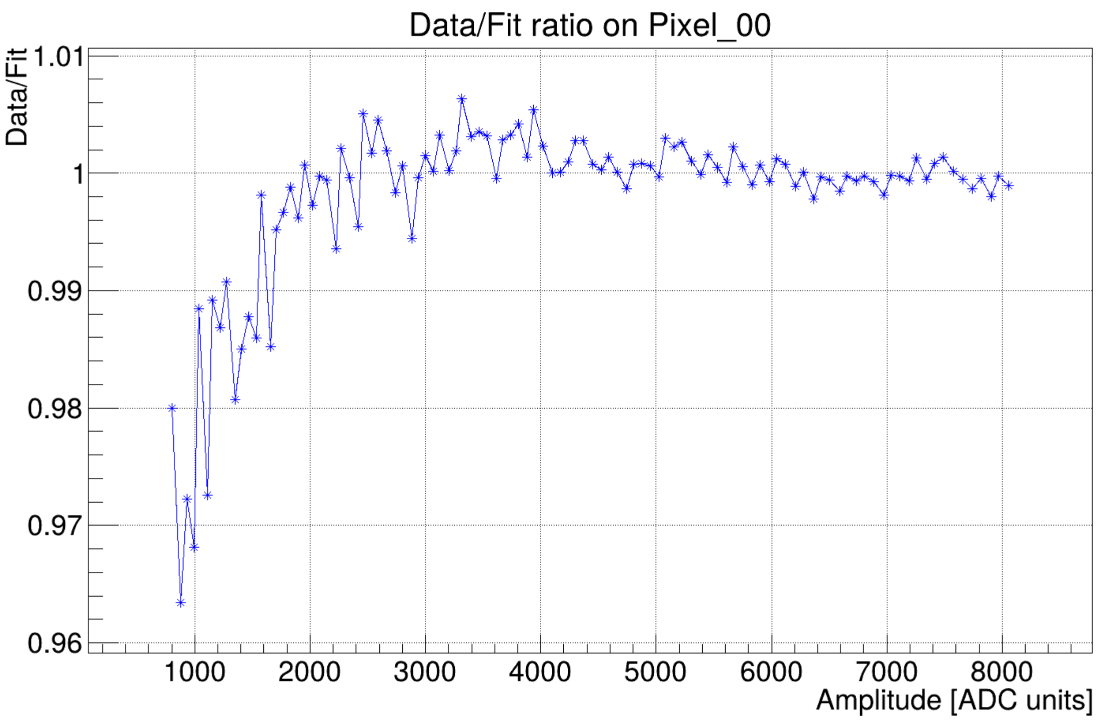
- **Fix:** Use a **quantile** (e.g., **q = 0.8**) as the **initial fit center**.
- **Window:** Fit a Gaussian in a **±2σ** window around that center.





Gain curve





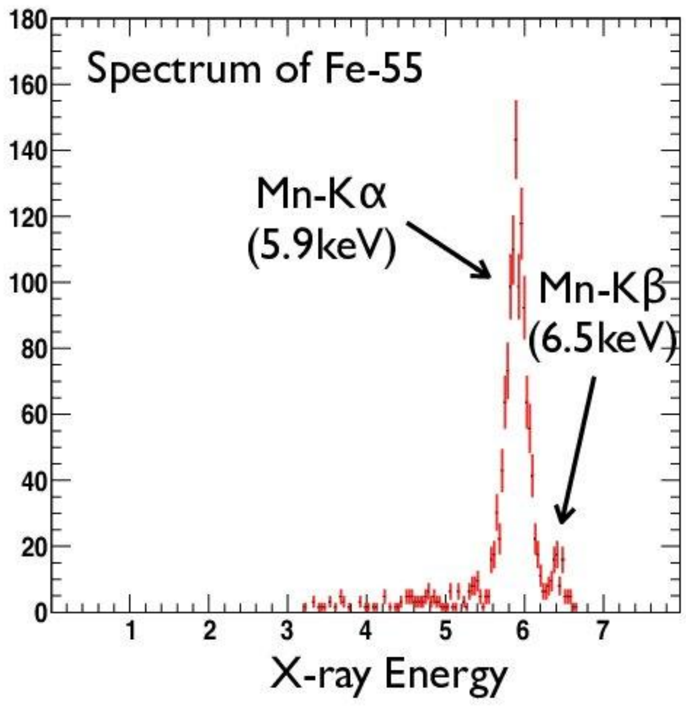
- We obtained a **per-pixel mapping** of how amplitude grows with test pulses: **V_H = g(x)**, where x = average waveform **amplitude (ADC counts)** and x_0 the mean of the Baseline.
- We use a **stable empirical function** where the **gain curve** in **VH units is** ready for charge calibration.

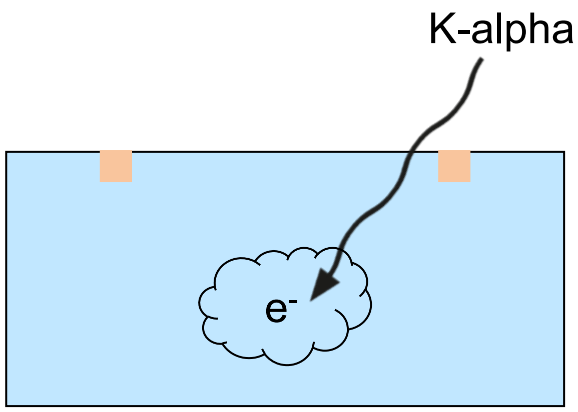
$$V_H = (p_0(x - x_0) + p_1|x - x_0|^{0.5}) \times (p_2 x + p_3),$$

Charge Calibration Using Fe-55 Source

Why use Fe-55?

- Fe-55 is a **stable, low-rate X-ray source** that decays by **electron capture** to Mn-55.
- The Mn emits **characteristic X-rays**, mainly **K-α (~5.9 keV)** and a smaller **K-β (~6.49 keV)** line.
- These X-ray energies are **narrow and repeatable**, giving a **known deposited energy**—perfect to define an absolute **charge scale**.



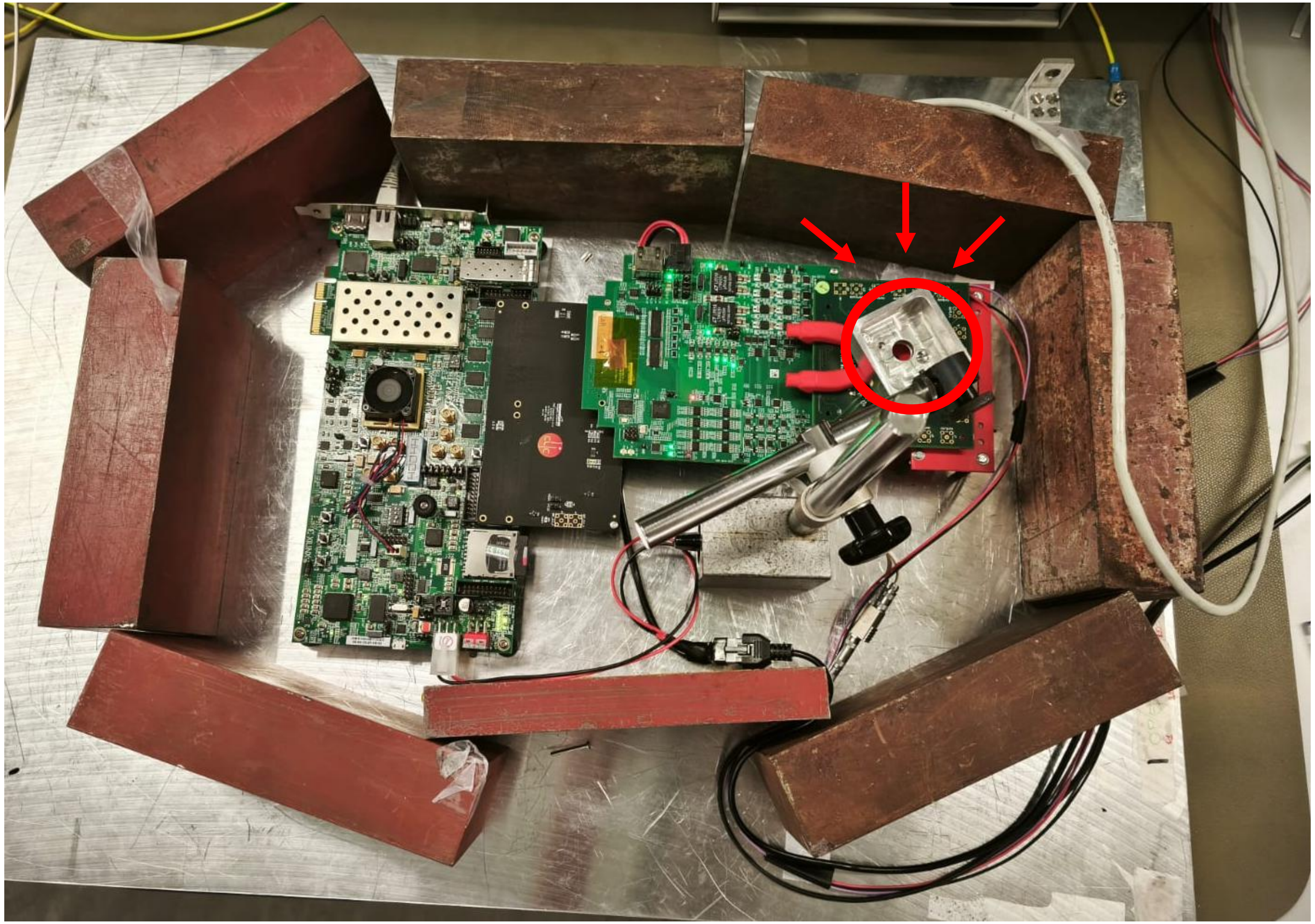


What happens in silicon?

- A 5.9 keV (K-α) X-ray is absorbed creating a **localized cloud of electron–hole pairs**.
- In silicon, it takes about **3.6 eV** to make one **e–h pair**; in our calibration we use **K-α ≈ 1609 electrons** as the reference charge.

Fe-55 Source Data-Acquisition Setup

- Setup: Place the Fe-55 source in front of the sensor.
- Data: ~124k events acquired; raw files processed with corryvreckan.



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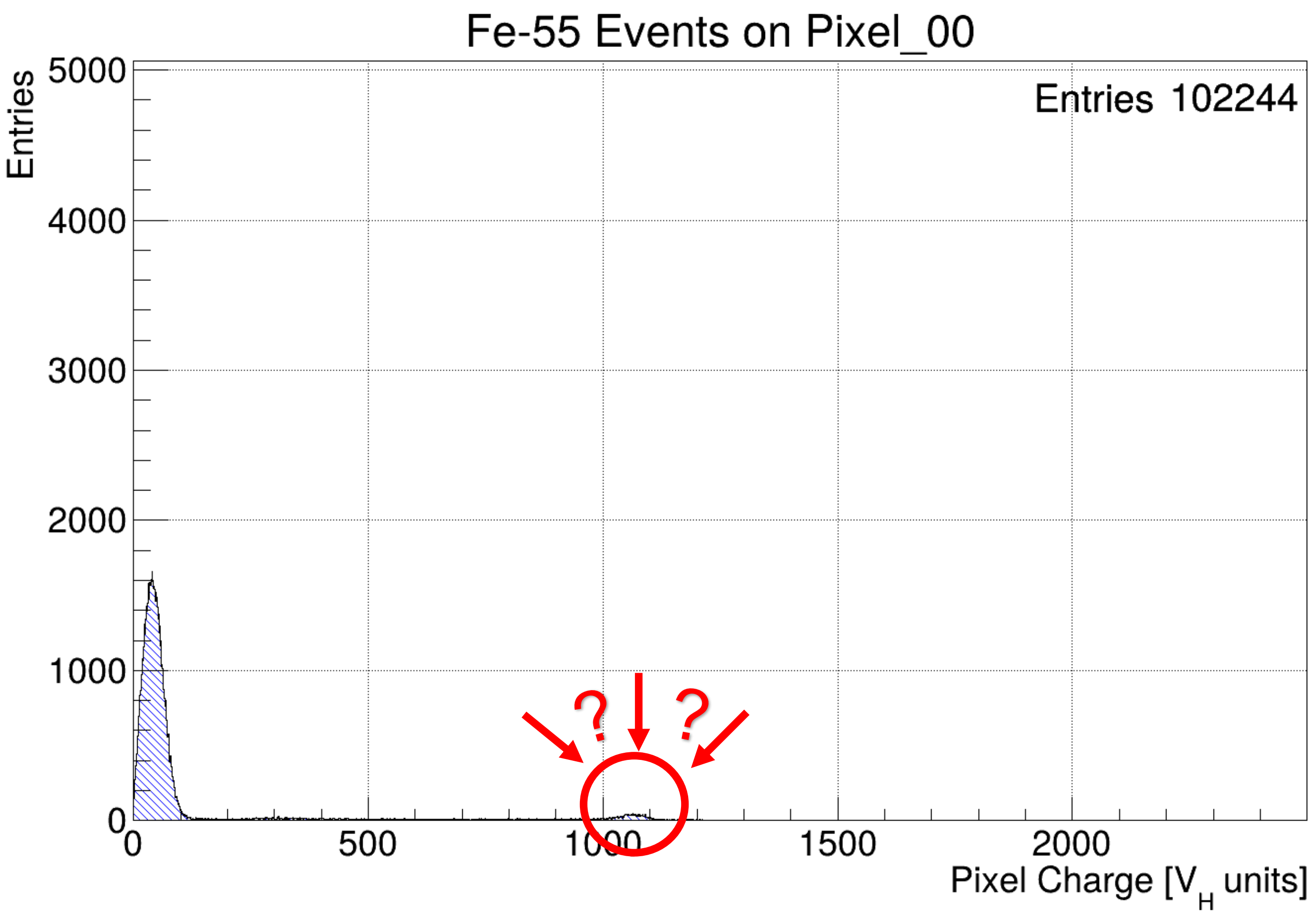

- Per pixel, we build **amplitude histograms in Amplitude test pulse units**.
- Identify the **K-α peak** in the Fe-55 spectrum.
- **Known charge:** K-α ≈ **1609 e^-** in silicon.
- **Gaussian fit** → Peak mean $\mu_{K\text{-}\alpha}$ (in **Amplitude test pulse** units) per pixel.
- **Scale factor** $S = 1609 / \mu_{K\text{-}\alpha}$.
- **Converts to electrons:**
  $$e^- = S \times (p_0(x - x_0) + p_1 |x - x_0|^{0.5}) \times (p_2 x + p_3)$$
- Result: A **charge calibration curve** in **electron units**, comparable **across pixels**.

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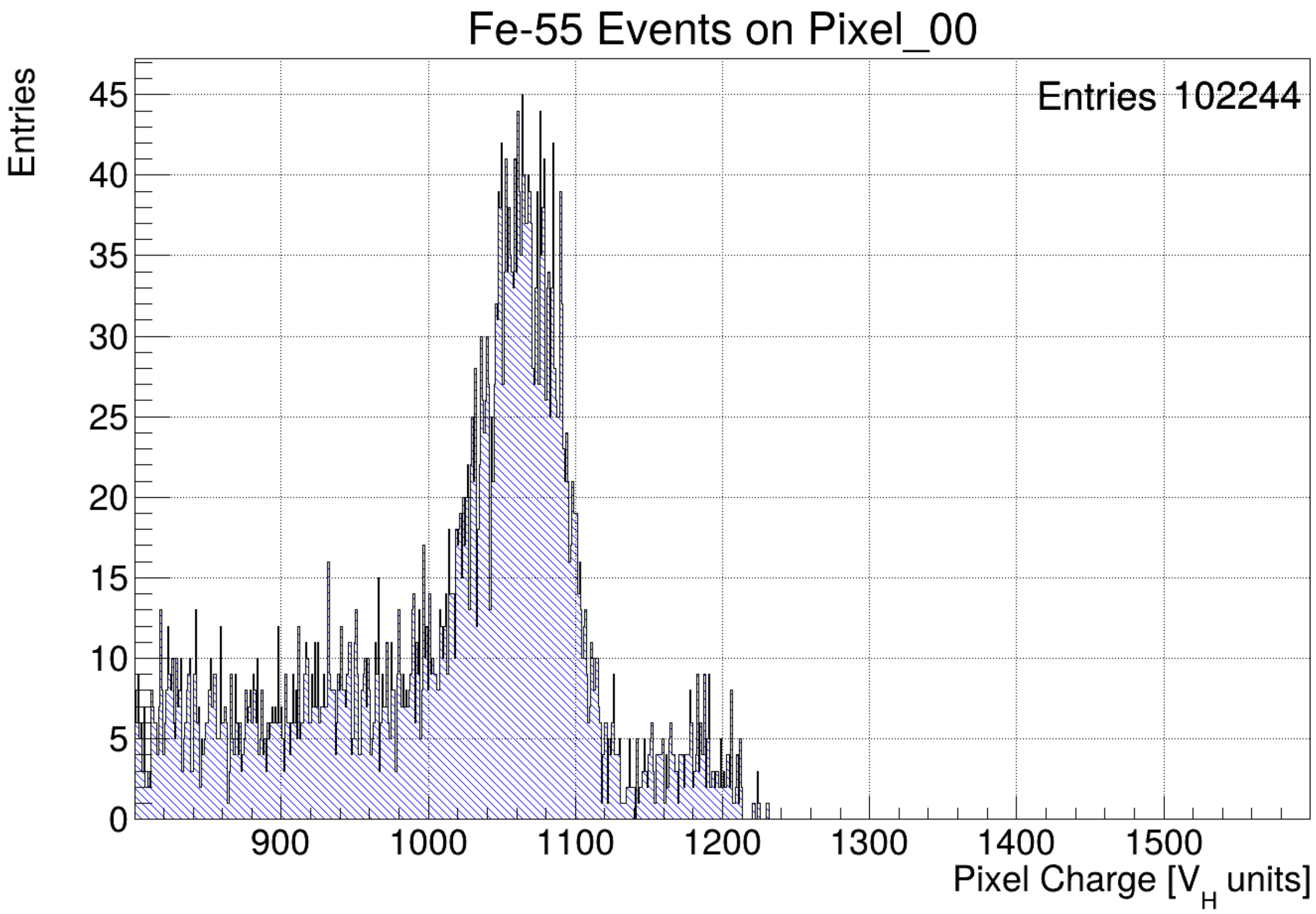

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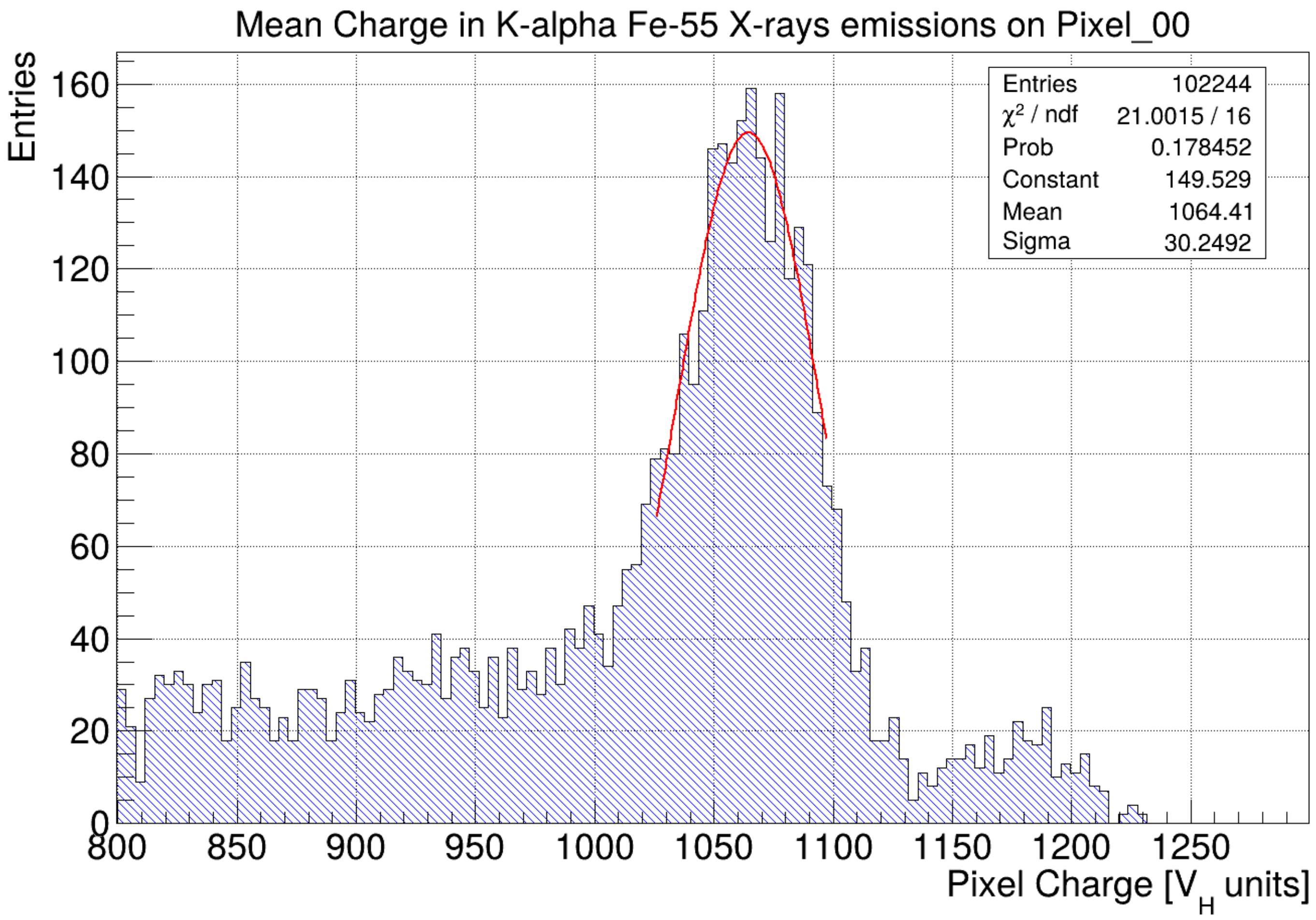

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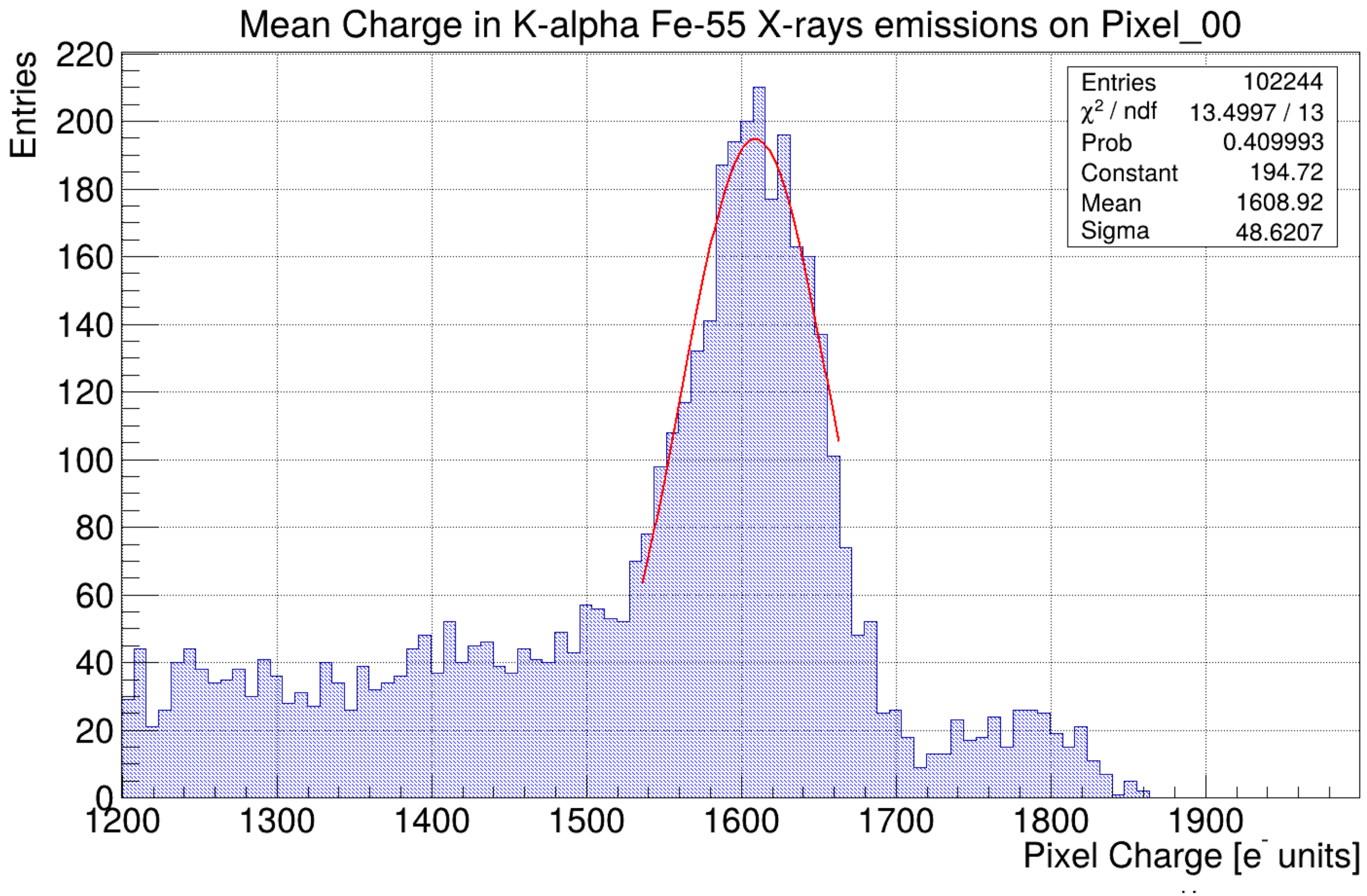

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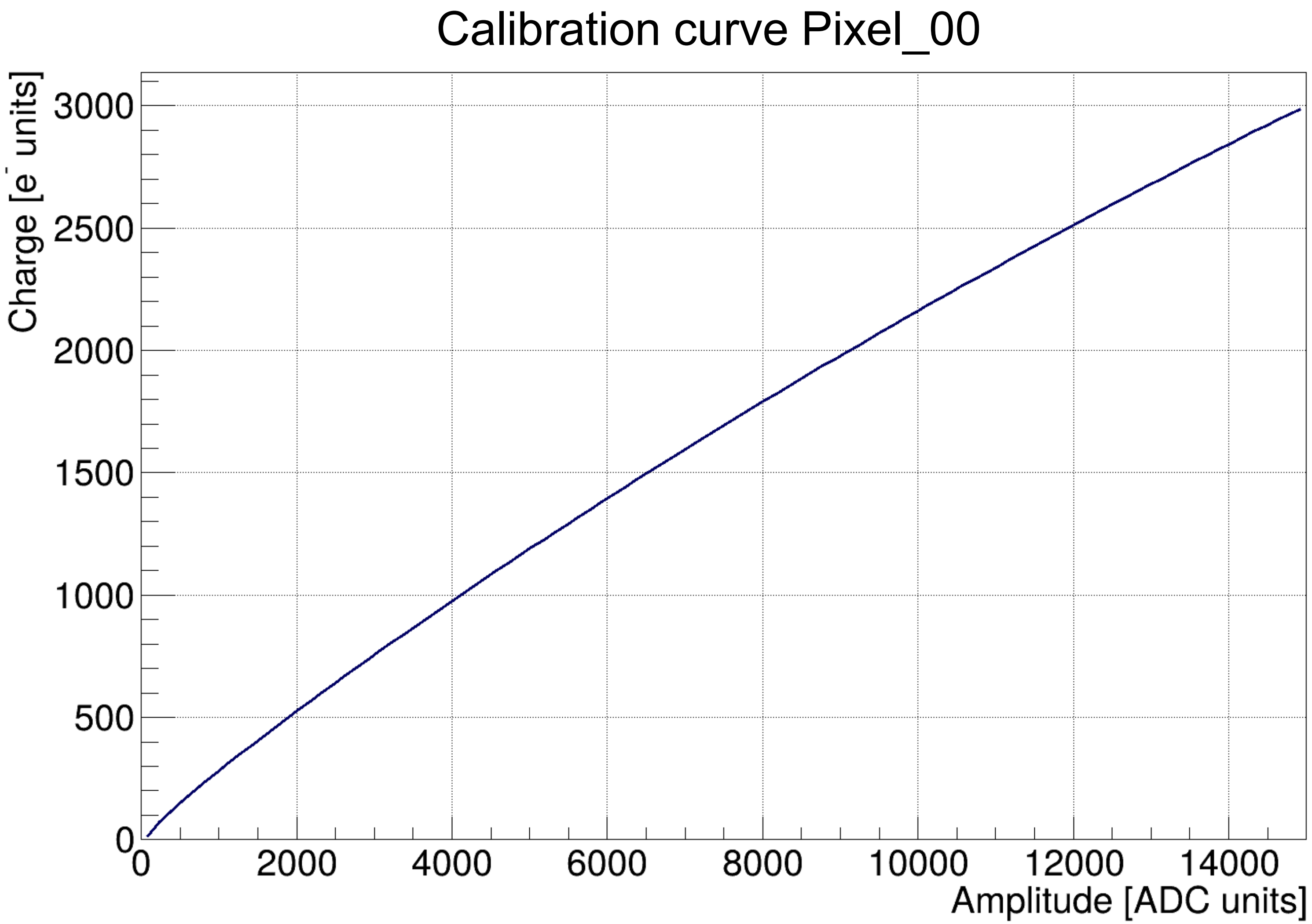
Example of calibration curves



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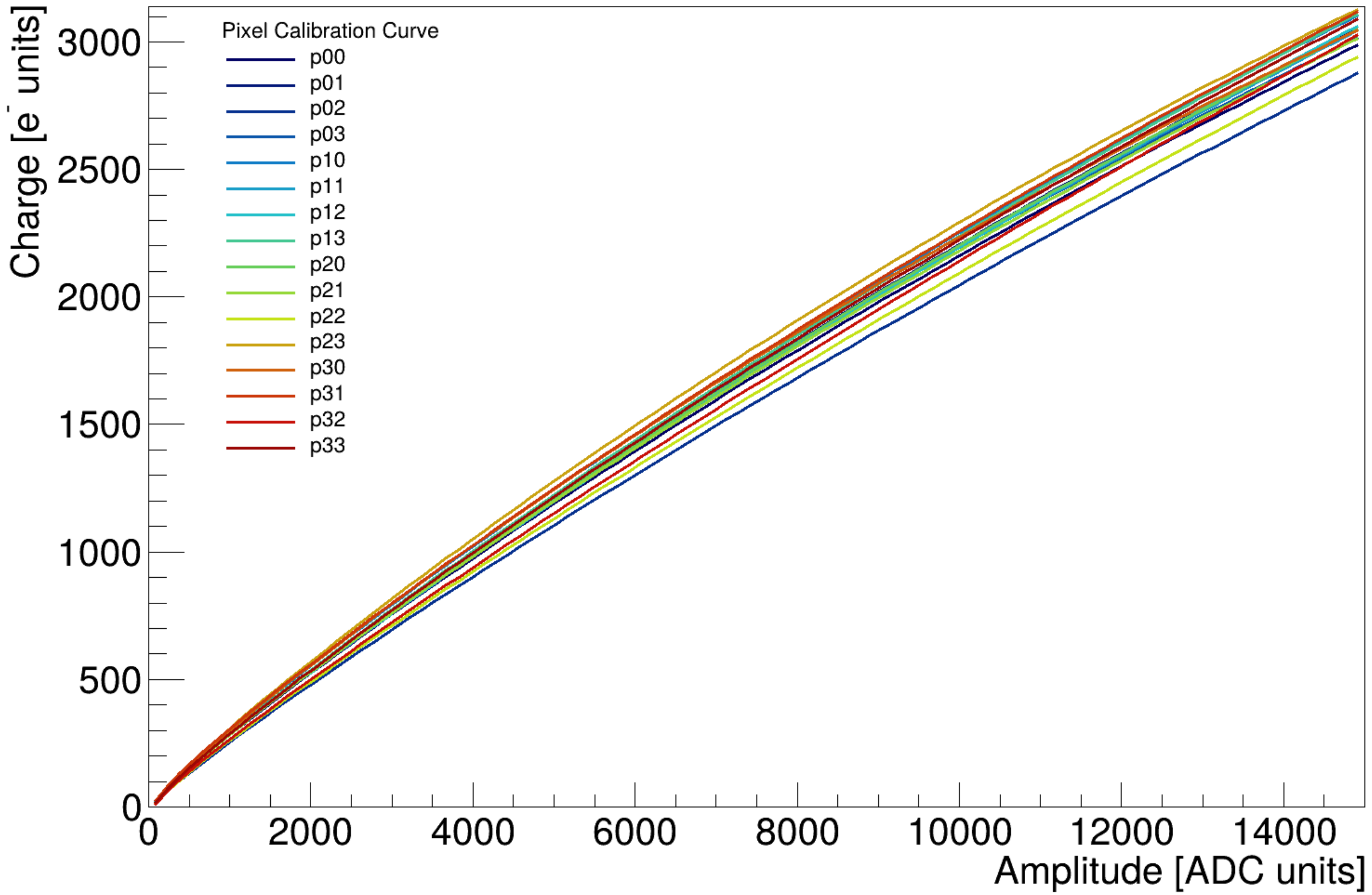
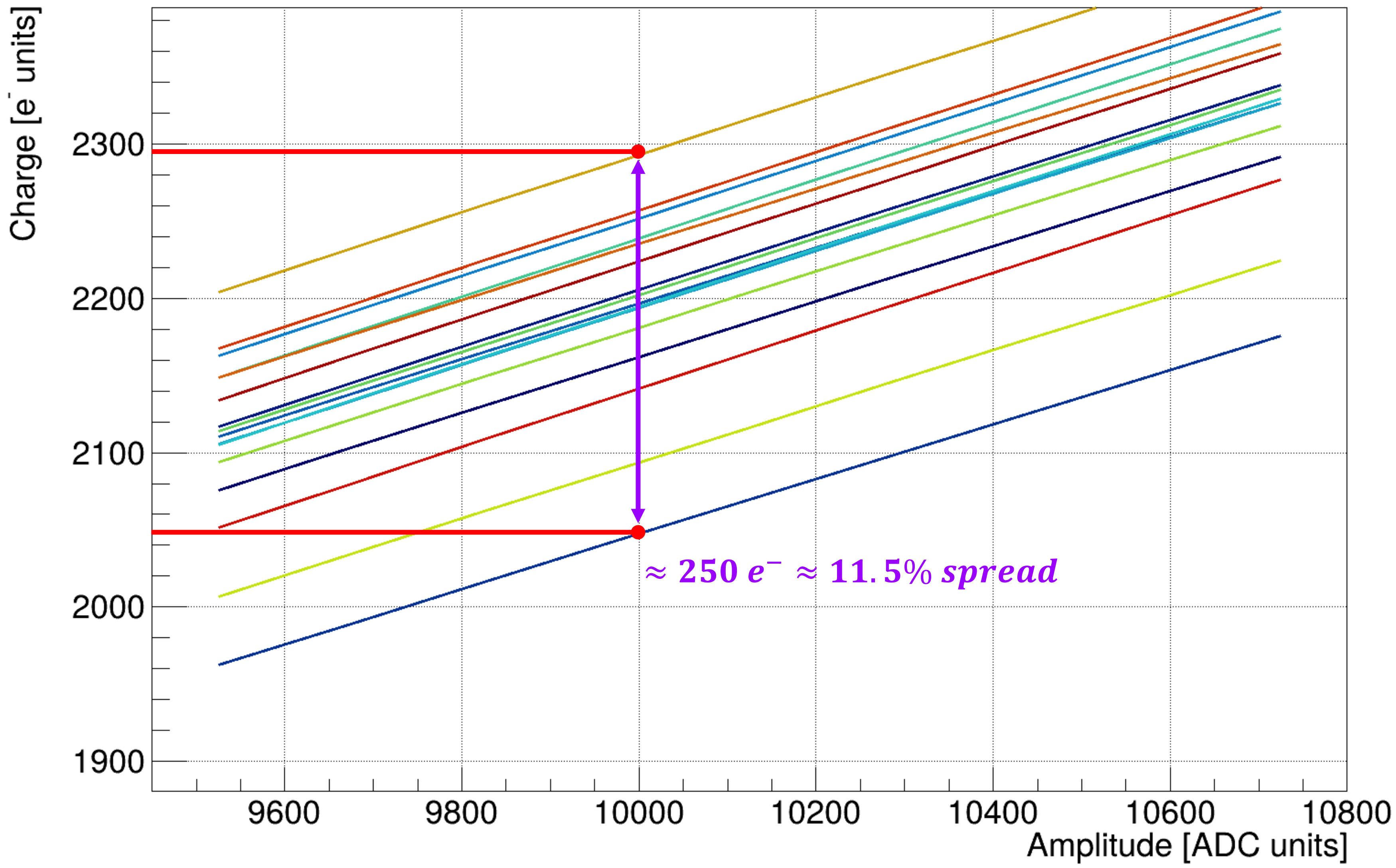
Calibration Curves of all the Pixels



Difference between Highest and Lowest



Conclusions

What we achieved in this first calibration step

- Built a per-pixel charge calibration for APTS Chip ID 27 (15×15 µm, N-gap).
- Derived a smooth Amplitude to e^- mapping using a high-correlation empirical fit
  $e^- = S \times (p_0(x - x_0) + p_1|x - x_0|^{0.5}) \times (p_2 x + p_3)$ (per pixel).
- Pixel behaviors are consistent: all curves overlap closely; only a small spread remains.
- Example spread at a fixed amplitude (~10 k ADC units): ≈ 250 e^- between highest and lowest pixel.

Next steps

- Clustering & efficiency studies on the calibrated data.
- Spatial resolution vs. charge sharing.
- Compare with simulations
- Progress on the test-beam studies

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Thank you