“Characterization of SiPMs using Radiation Sources for Quantum Random Number Generation”

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Master Thesis

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Hamburg, 23–25 November 2025
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Contents

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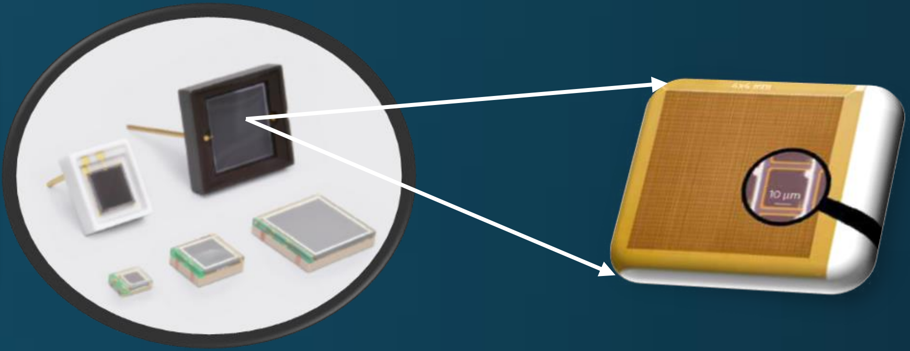
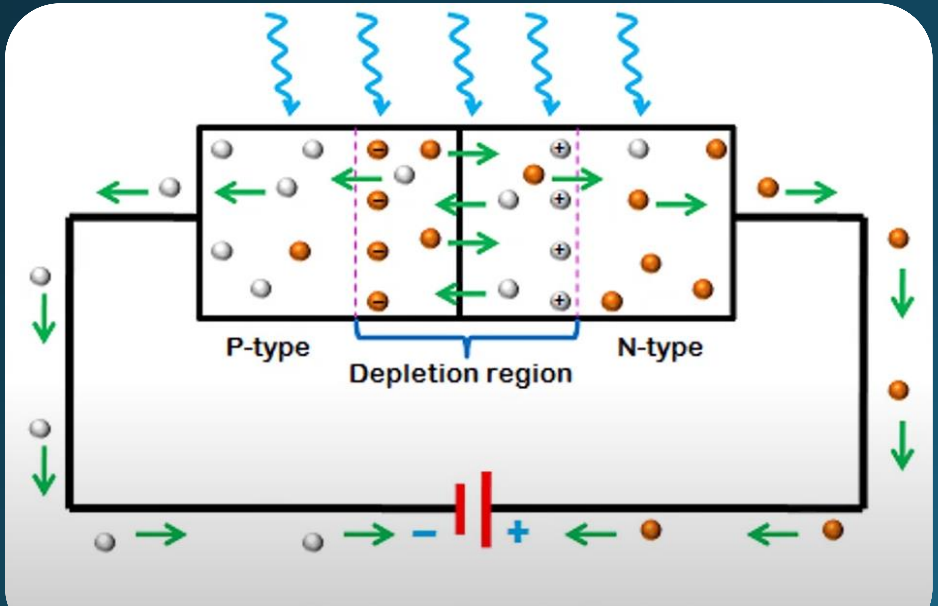
SiPM Operating Principle

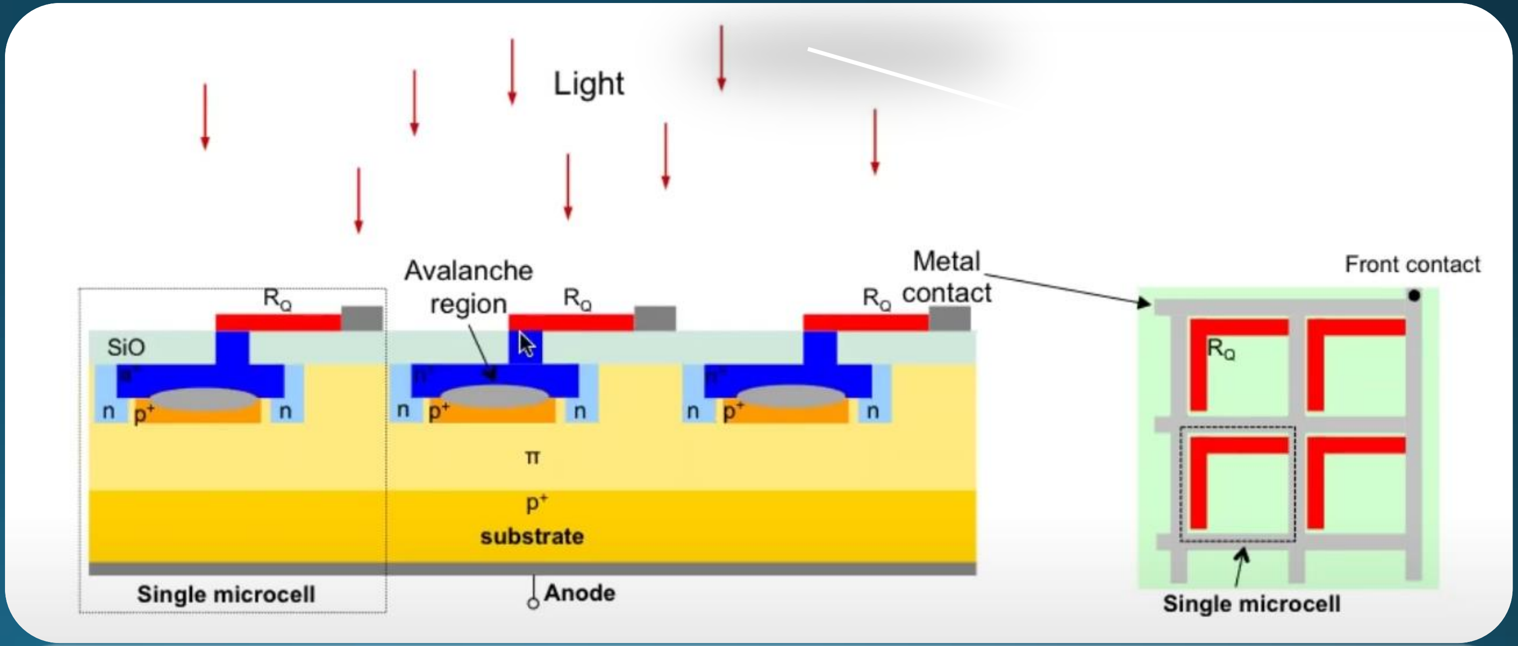
- Solid state PN Junction photodetector
- Produces current pulses of $\sim 10^6 e^-$ as response to absorption of a photon (Gain)
- Pixelated device
- Each pixel-microcell is an Avalanche photodiode (APD) connected in parallel
- Externally biased above breakdown voltage

- Photon Absorption
- Electron–Hole Pair Creation
- Avalanche Multiplication-Gain
- Pulse Generation by quenching
- Final Signal



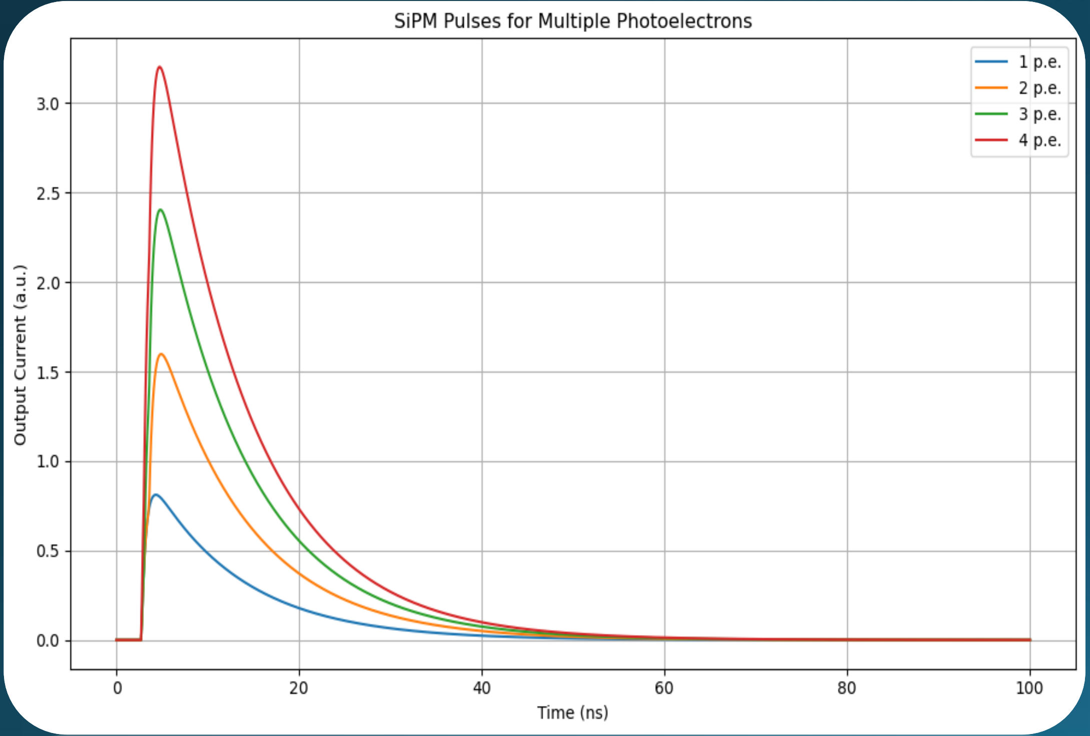


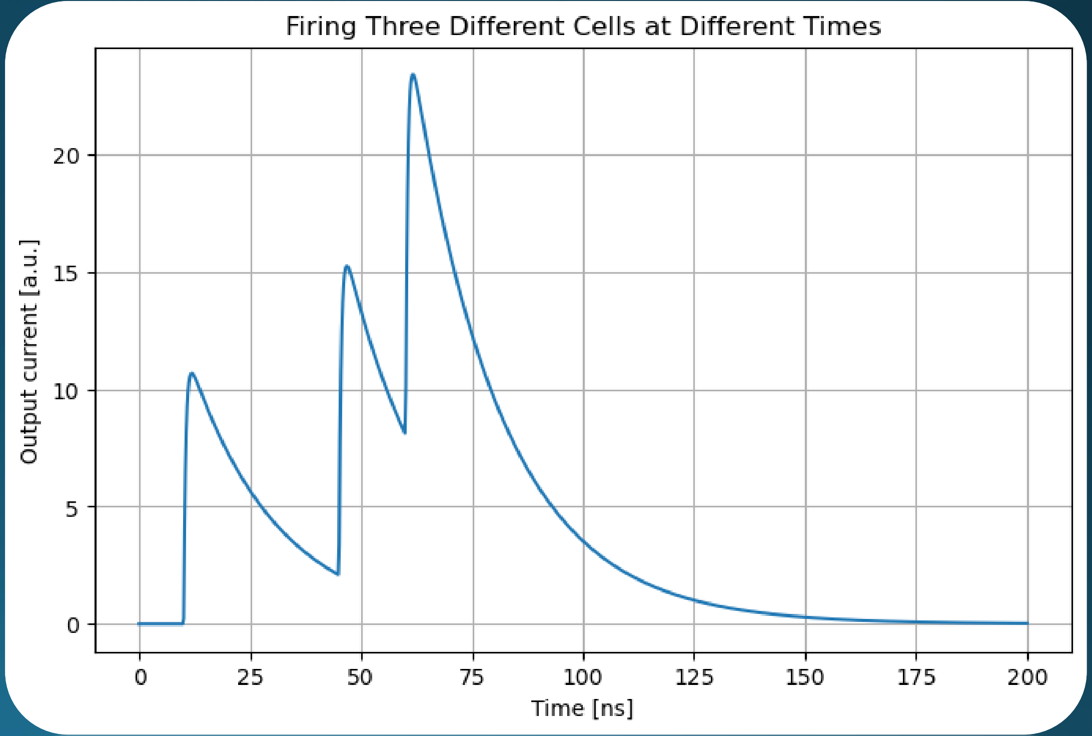
PN Junction photodiode



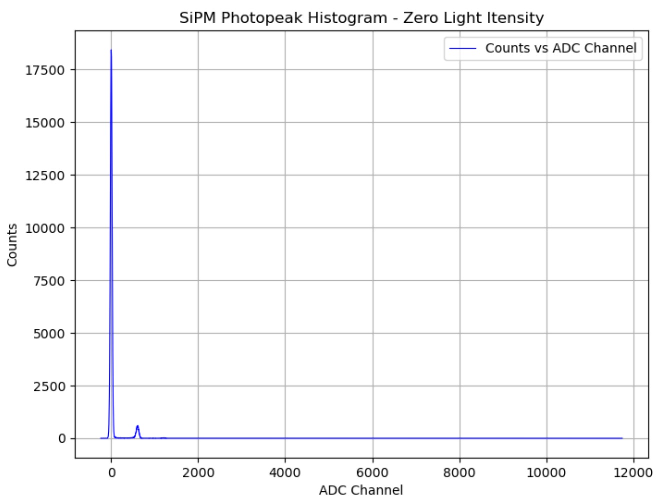
SiPM Signal

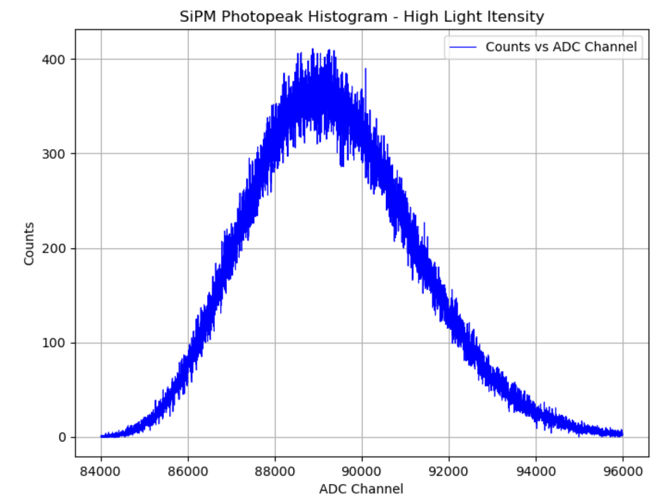
- The **final SiPM signal** corresponds to the **total output pulse**
- It is the **sum of the individual microcell pulses**
- Triggered either **simultaneously** or at **slightly different times**
- **Gate Time** is the fixed time window during which the detector **integrates the signal**



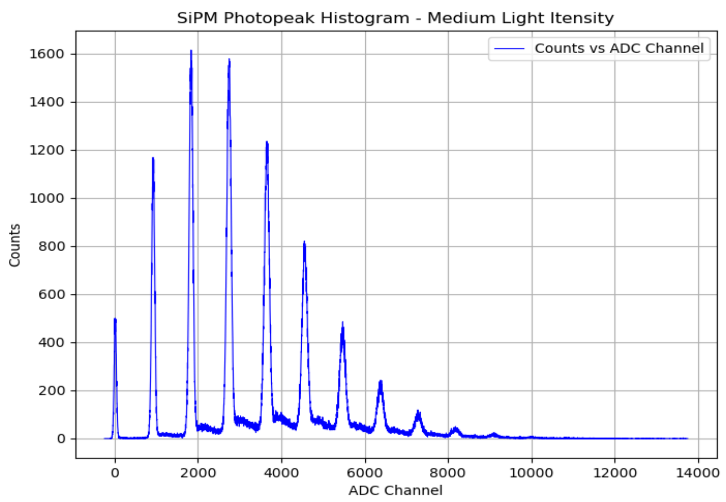


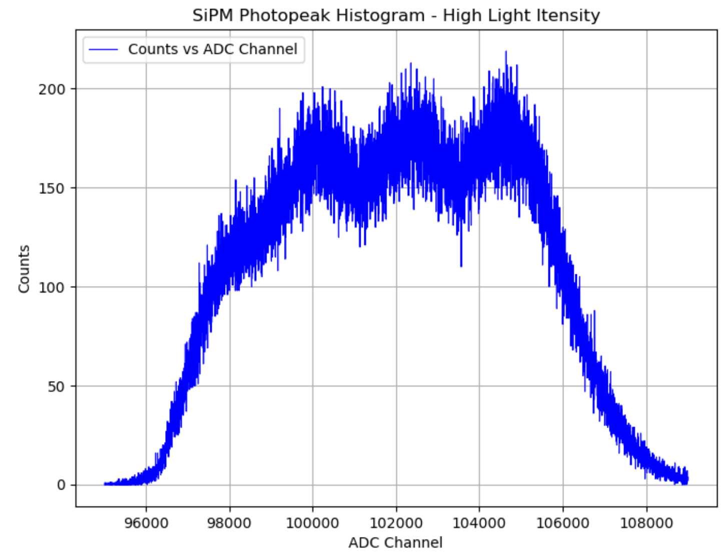
2 Laser Measurements





- **Photo-peaks** correspond to the **number of detected photons**
- **First peak** represents the baseline signal - **pedestal (i.e., 0 detected photons)**
- **The second peak** corresponds to **1 detected photon,** and so on.
- **High Light Intensity** leads to **saturation**

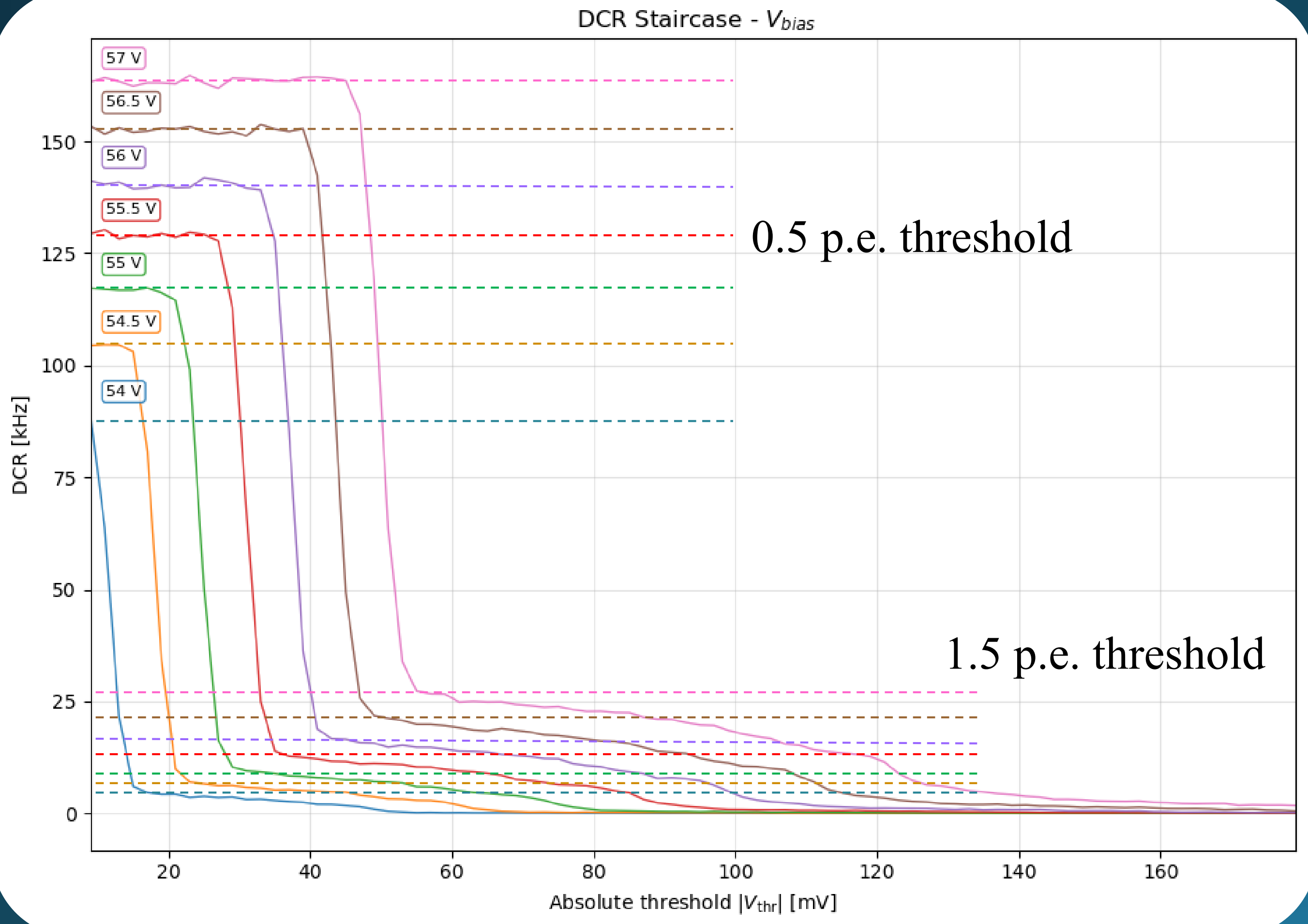




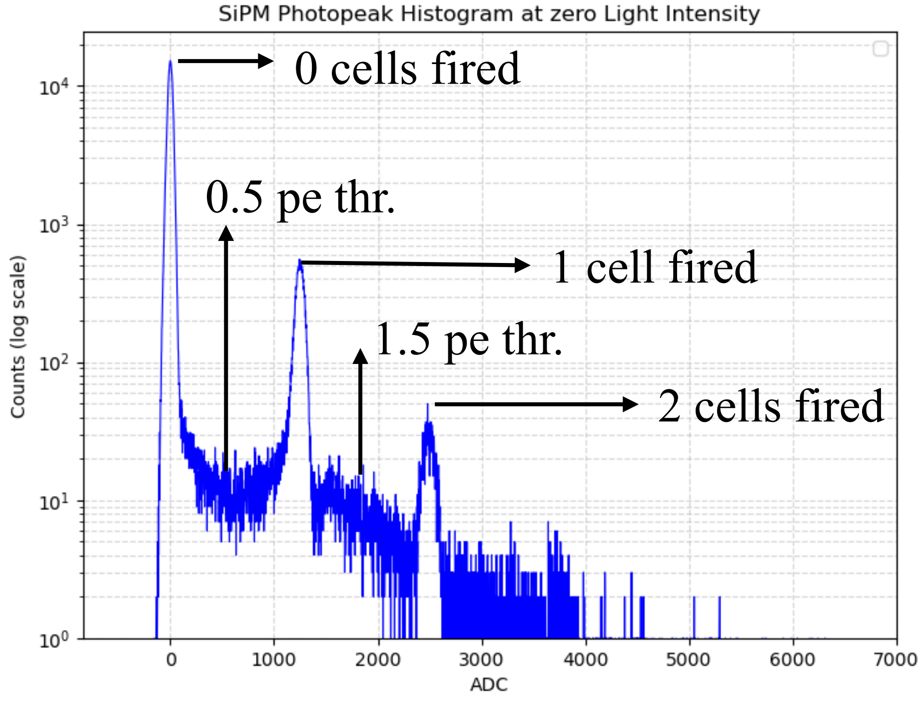
3

SiPM Characterization

Dark Counts Rate - DCR
The rate of **spontaneous SiPM pulses** occurring **without incident light**, caused by thermal carrier generation

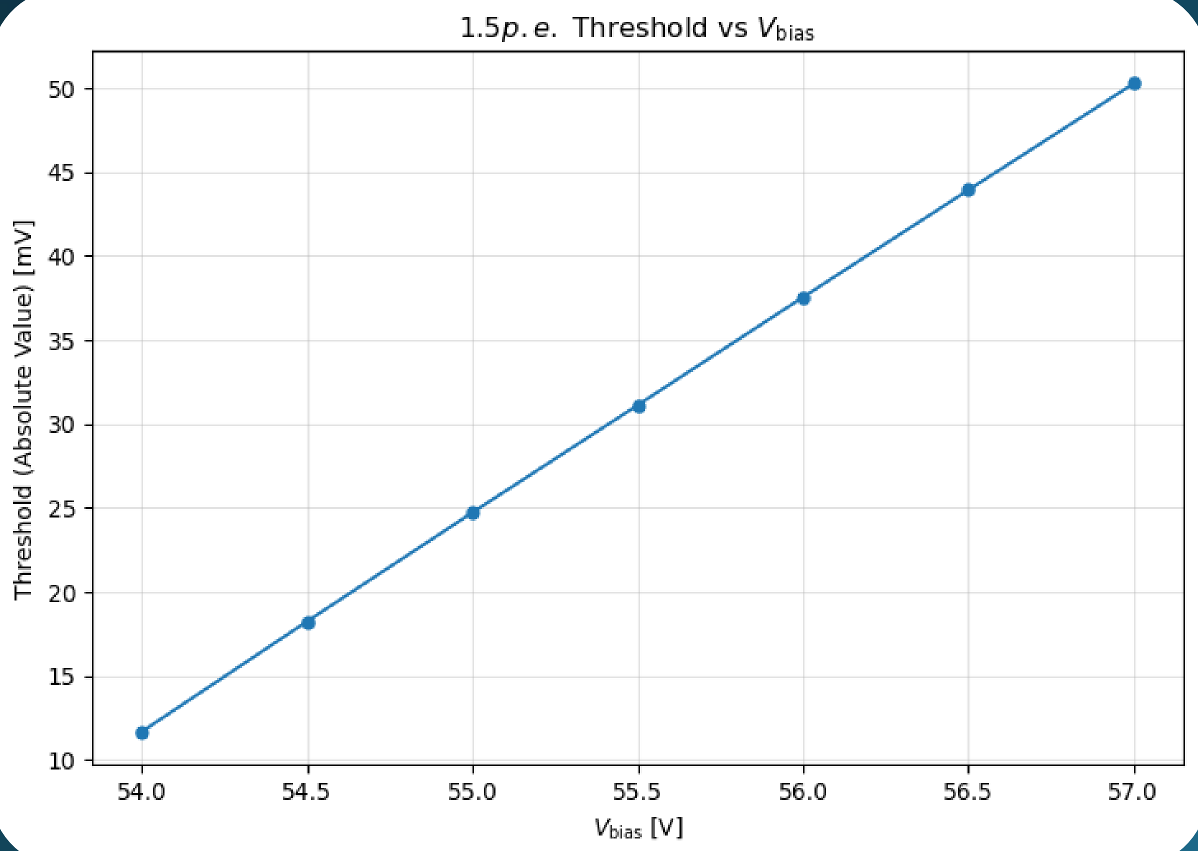


1.5 pe thr. :The **discrimination level** set **halfway between the 1st and 2nd photo-peak** to **separate single cell's pulses from 2 cell's pulses**

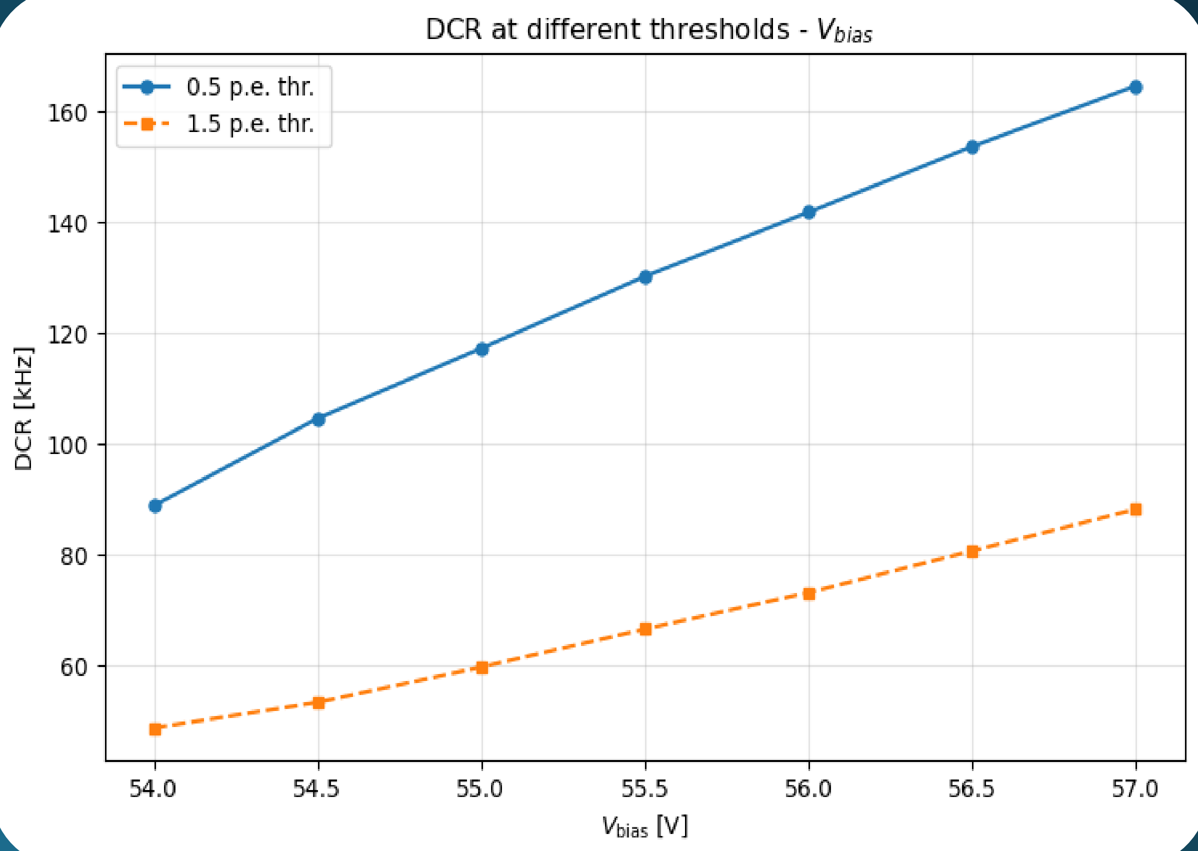


DCR - V_{bias}

1.5 p.e. Point per V_{bias}



$DCR_{0.5}$ and $DCR_{1.5}$



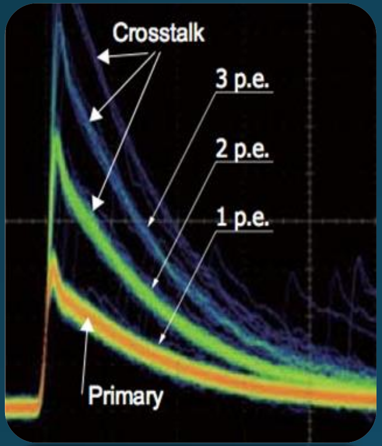
Optical Cross-Talk Probability

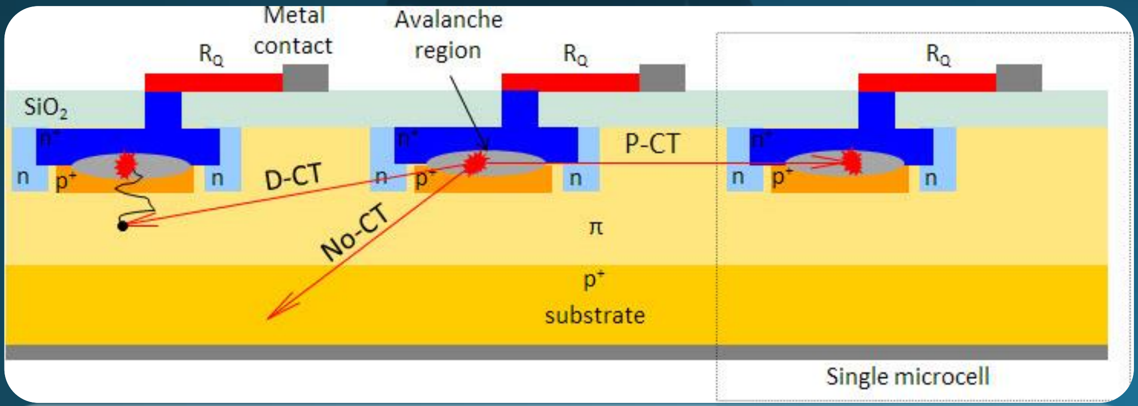
A single photon creates 1 p.e.-sized pulse

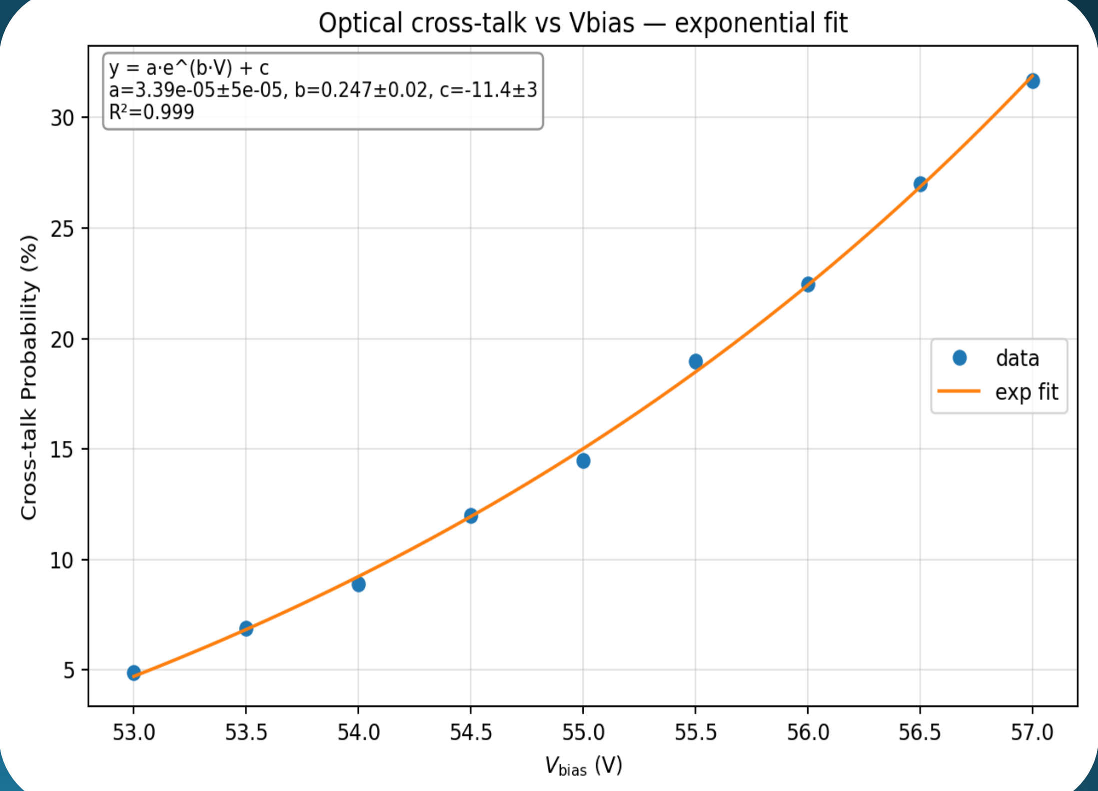
- $DCR_{0.5}$: single cell's pulses included
- $DCR_{1.5}$: single cell's pulses not included

Optical Cross-Talk: An avalanche in one microcell optically **triggers a neighboring cell**

$$OCT = \frac{DCR_{1.5}}{DCR_{0.5}}$$

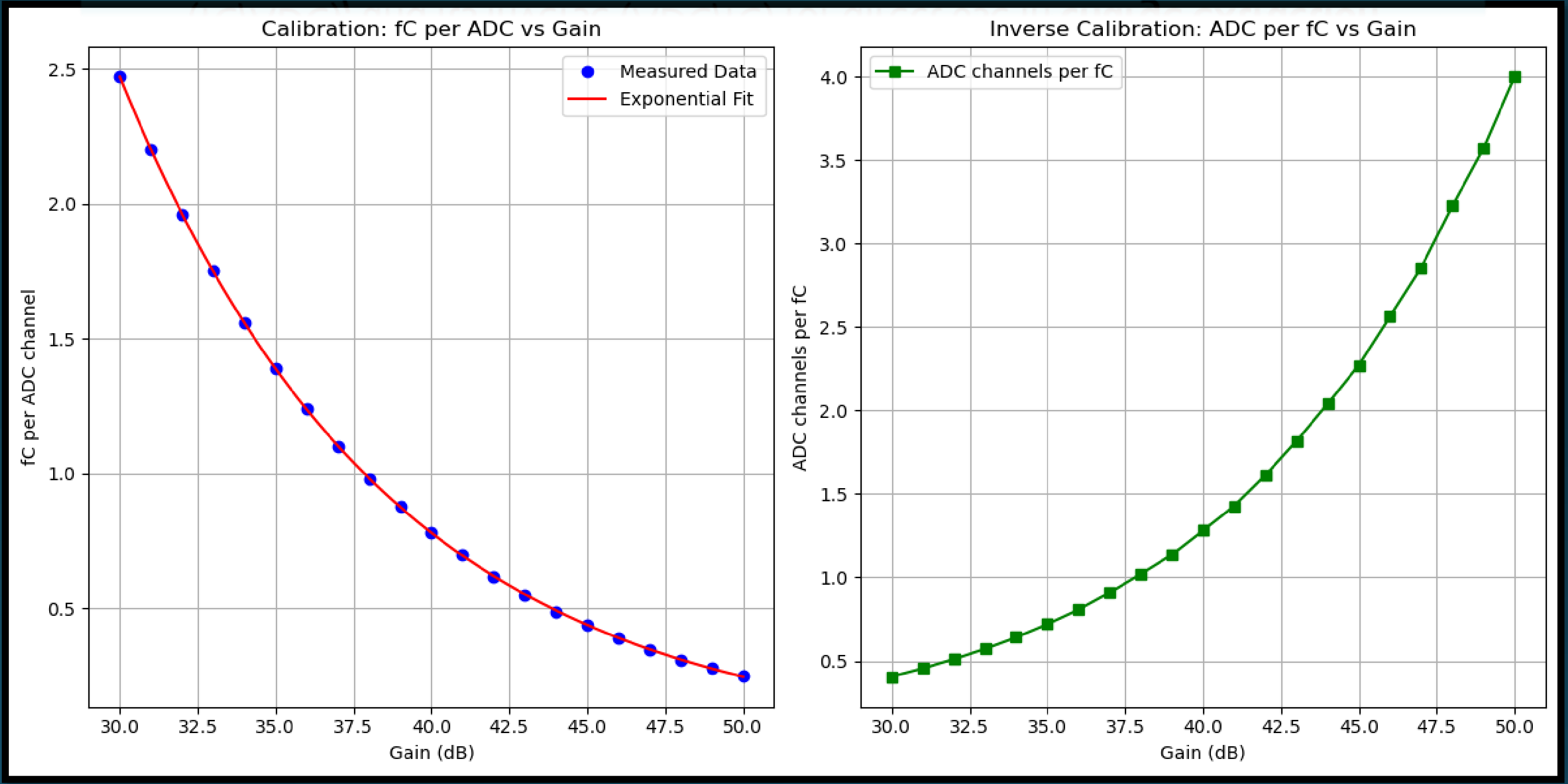






Digitizer Gain Calibration

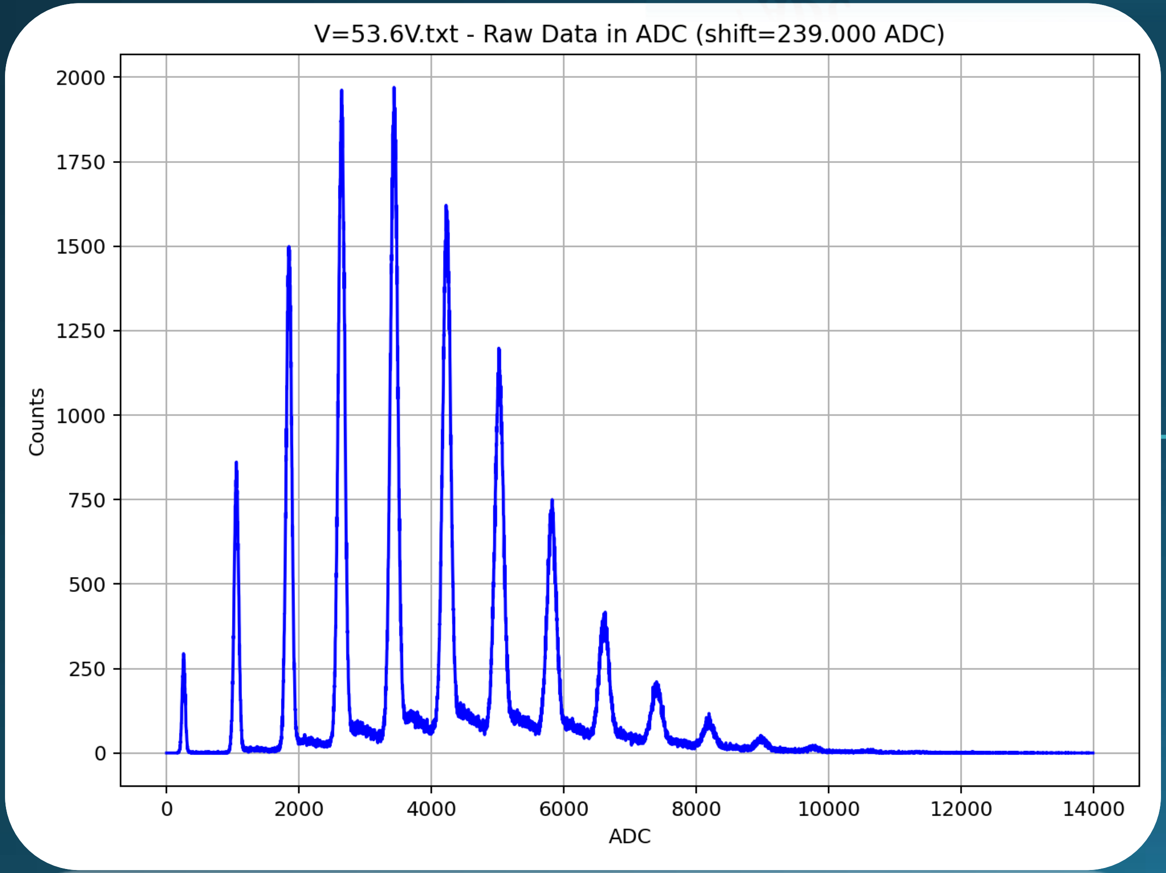
These exponential fits describe the **gain-dependent conversion factor** (fC/ADC), and its inverse (ADC/fC) for direct use in **charge extraction**

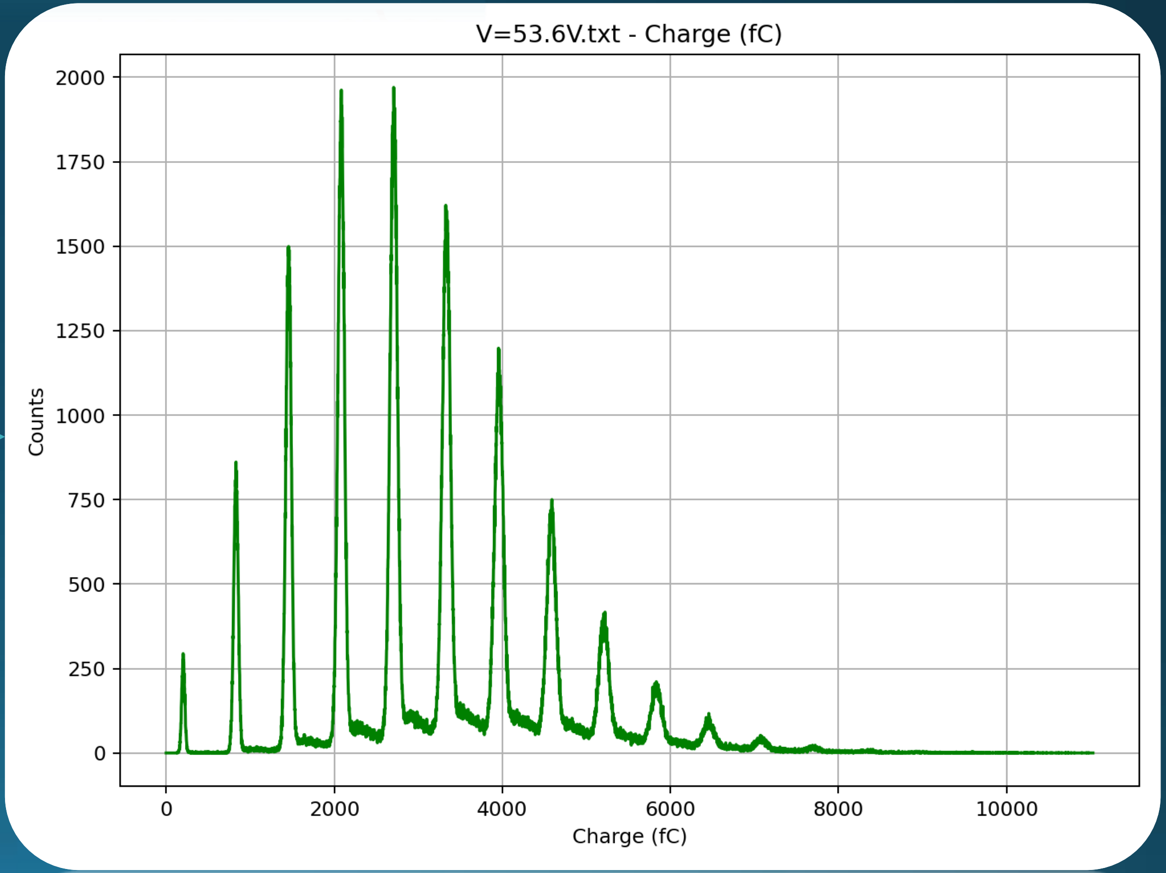


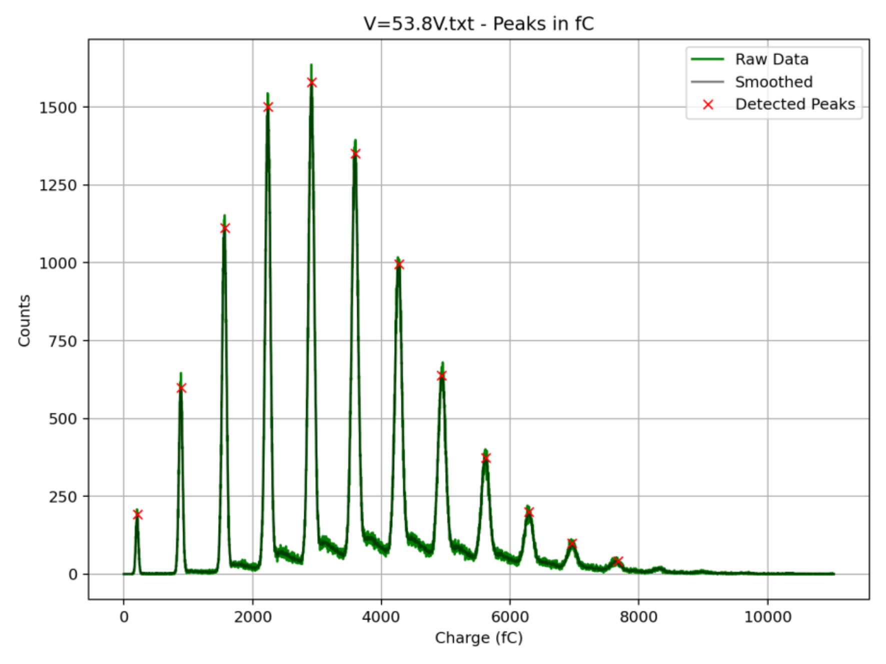
ADC to Charge transition

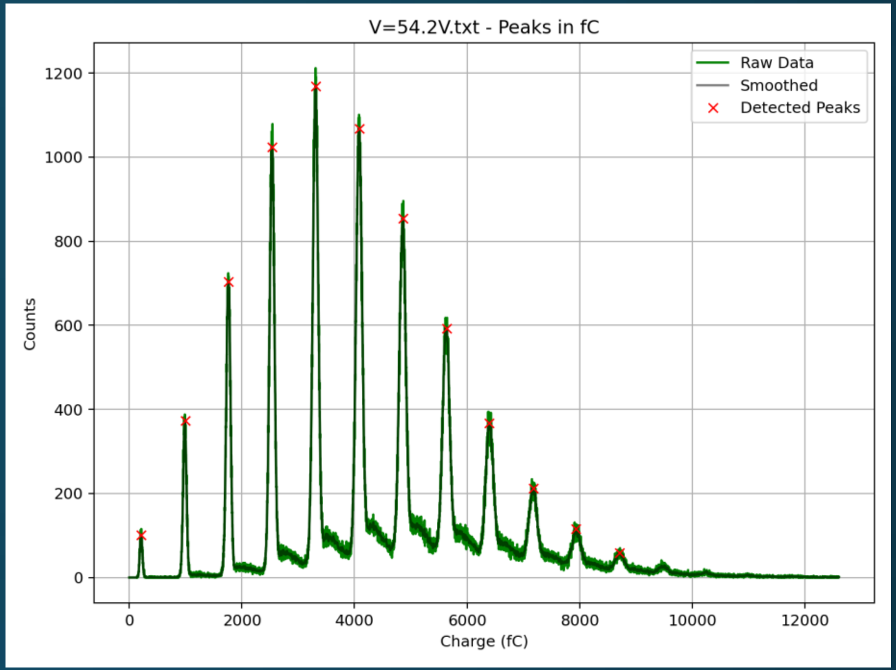
Example: Gain=40dB

$$^{fC}/_{ADC} = 78.337 \cdot e^{(-0.115 \cdot 40)} + 0.001 \cong 0.788$$

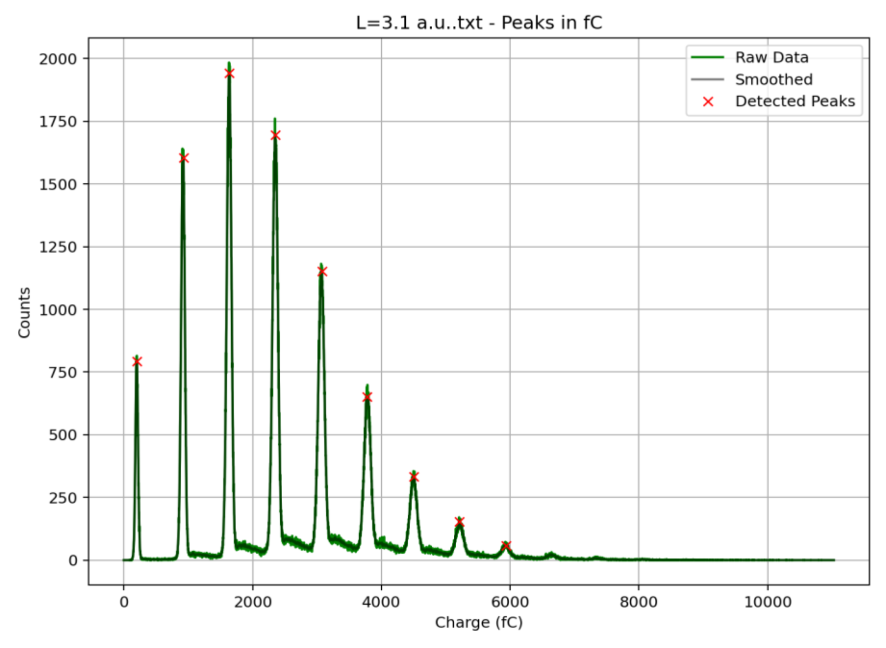


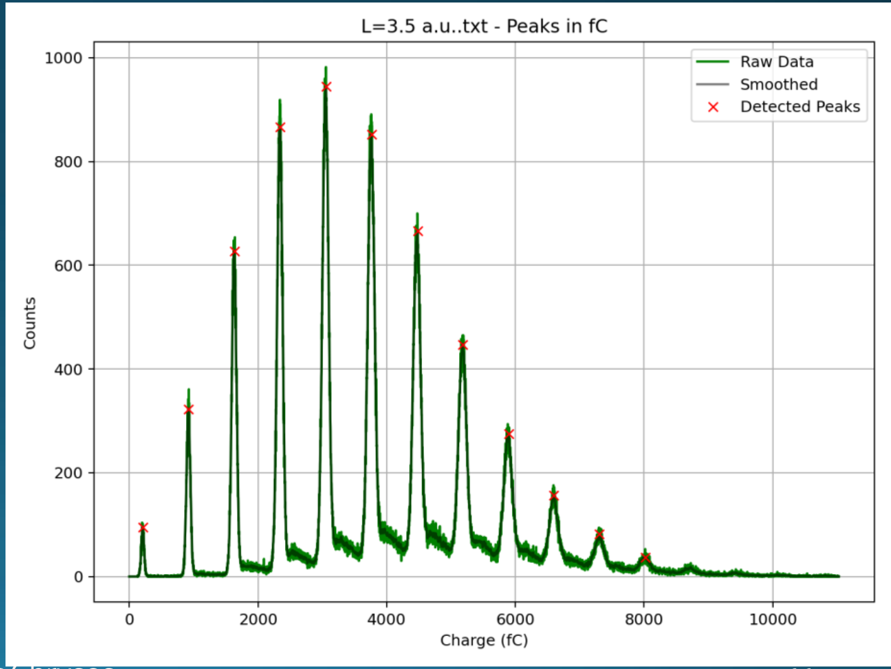






Constant Light Intensity
-
Constant number of peaks



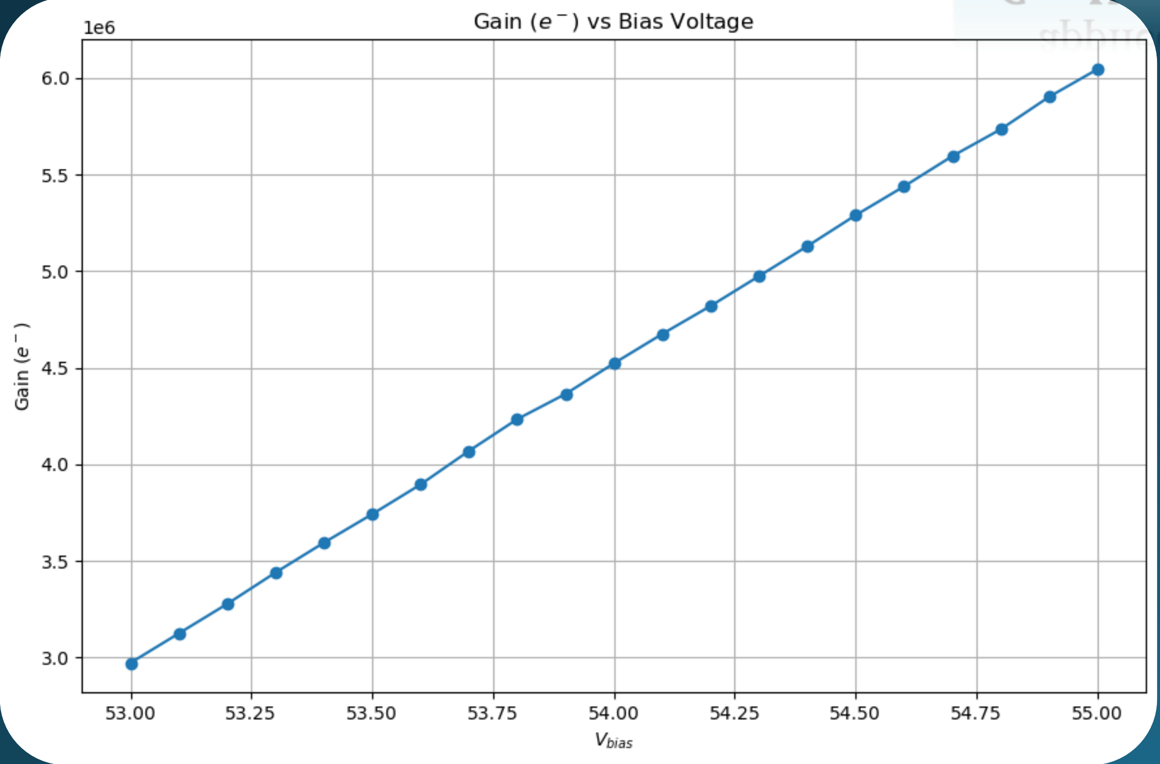


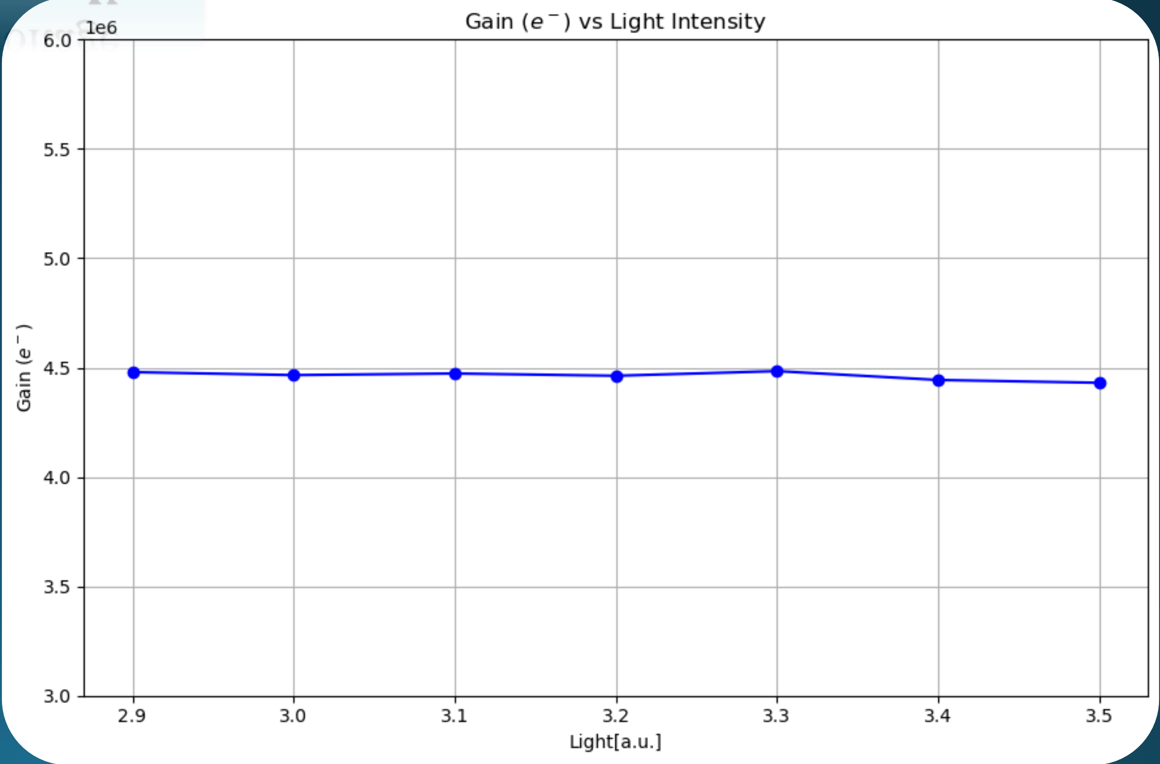
Constant
V_{bias}
-
Increasing number of peaks

SiPM Avalanche Gain

It solely depends on the applied bias voltage

$$G \propto V_{ov} = V_{bias} - V_{bd}$$

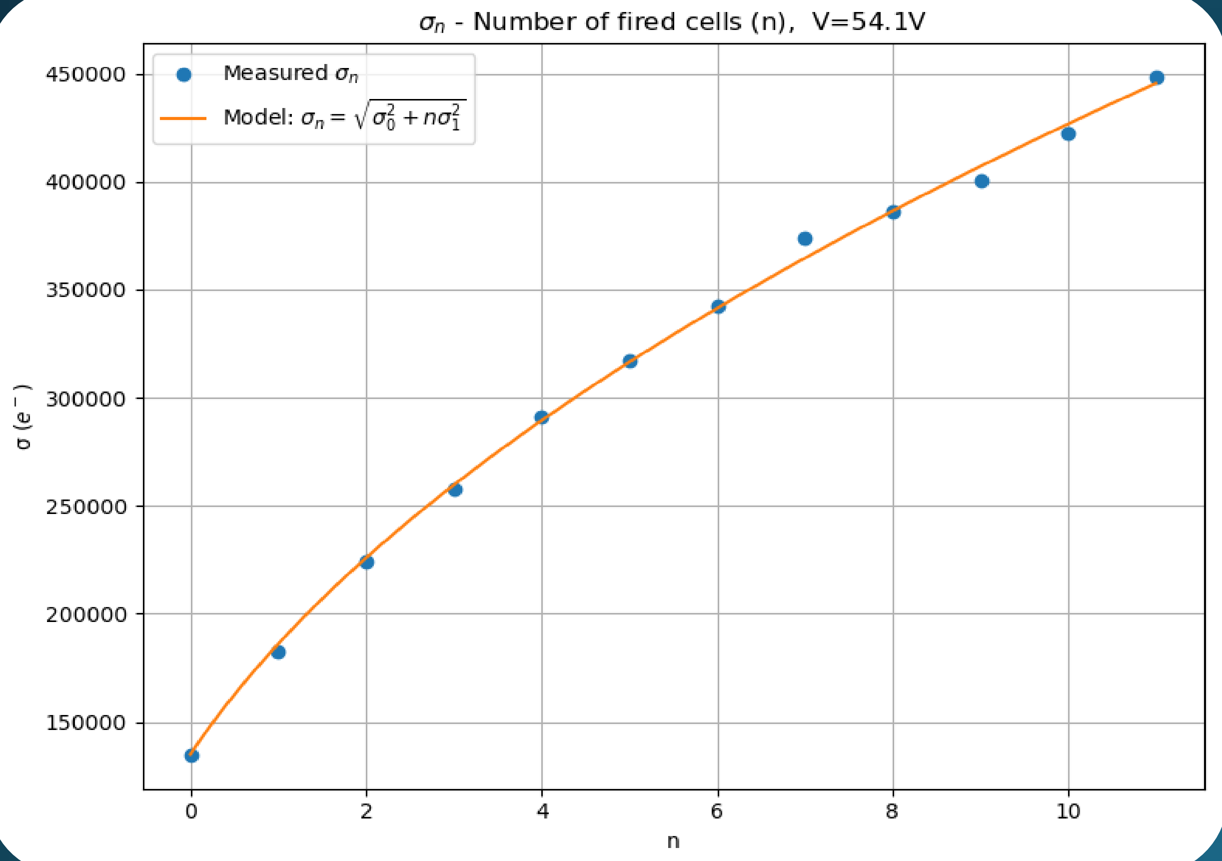


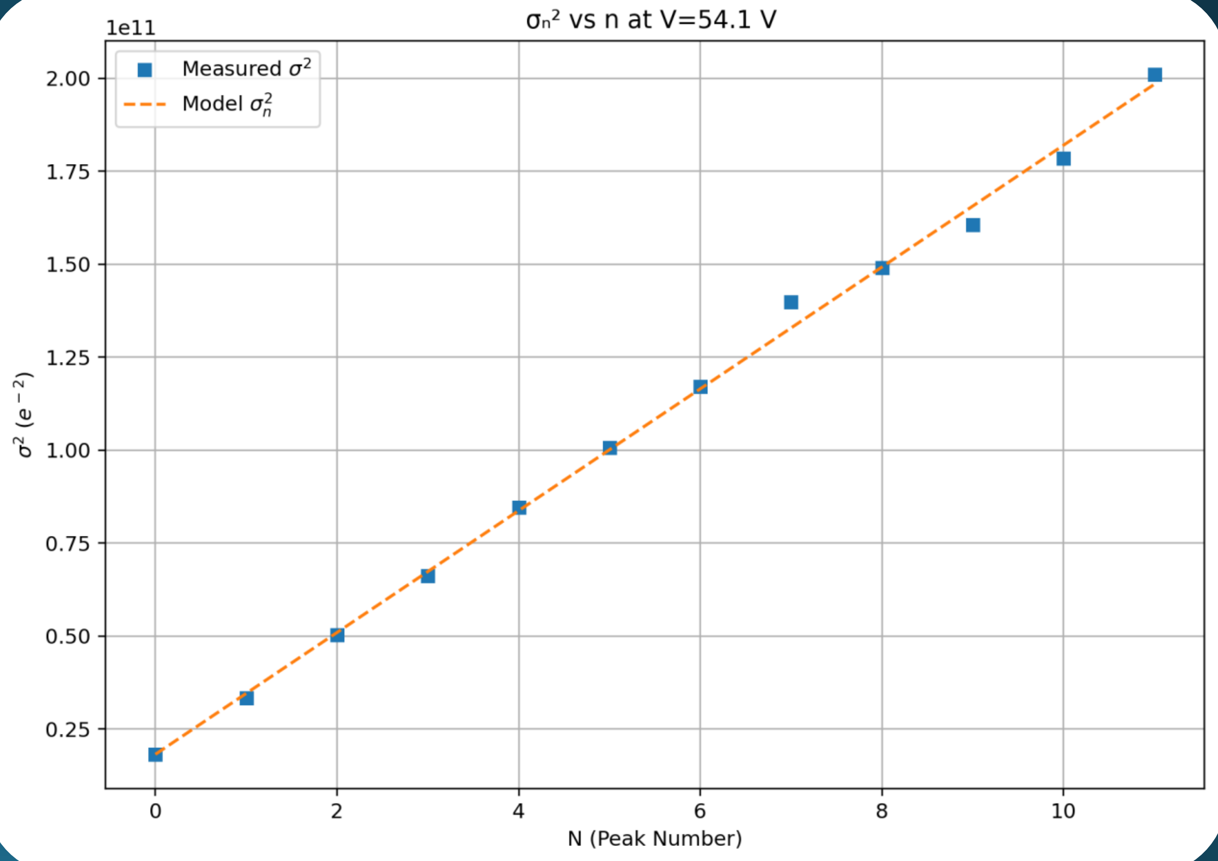


Standard Deviation & Variance

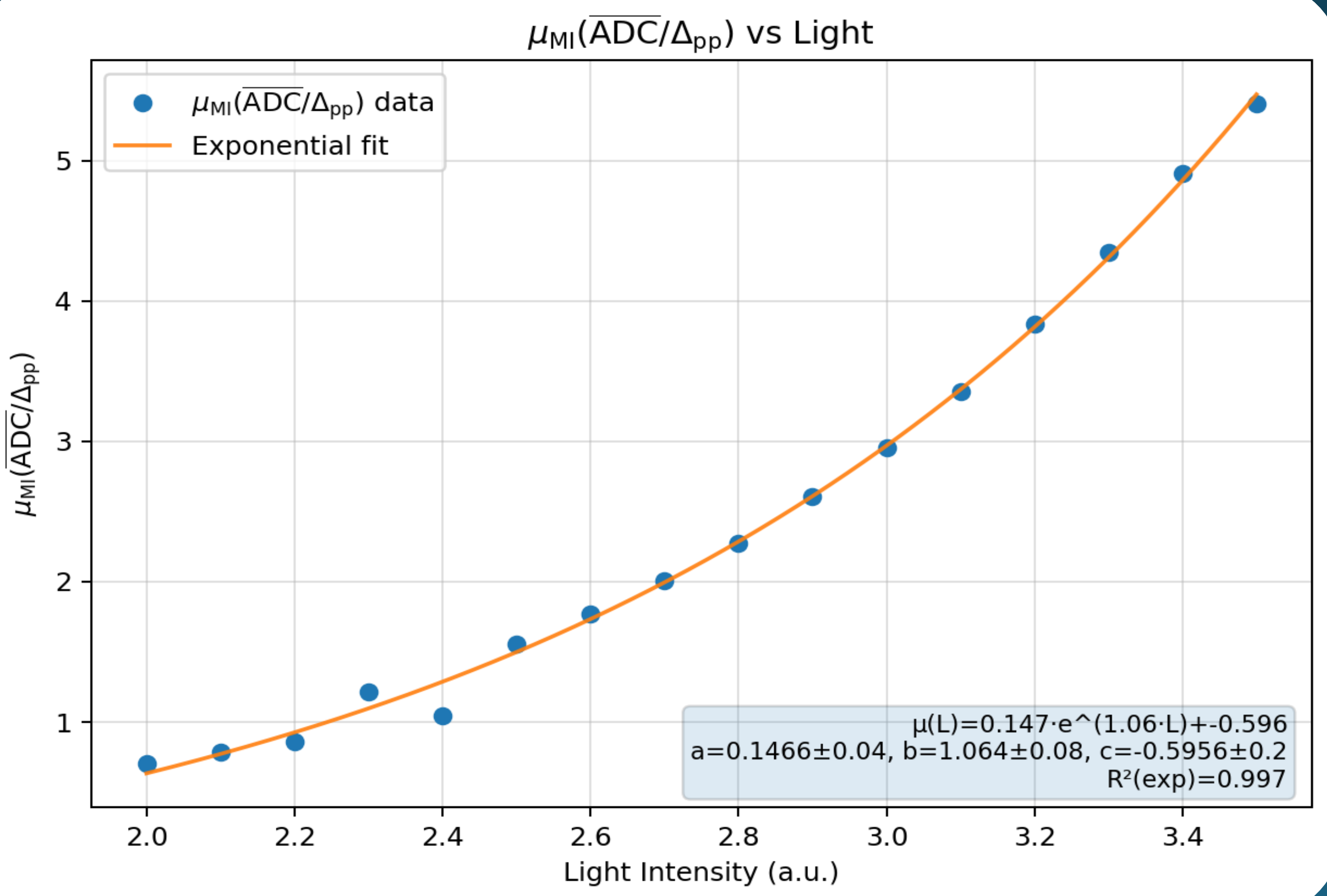
$$\sigma_n = \sqrt{\sigma_0^2 + n\sigma_1^2}$$

$$\sigma_n^2 = \sigma_0^2 + n\sigma_1^2$$

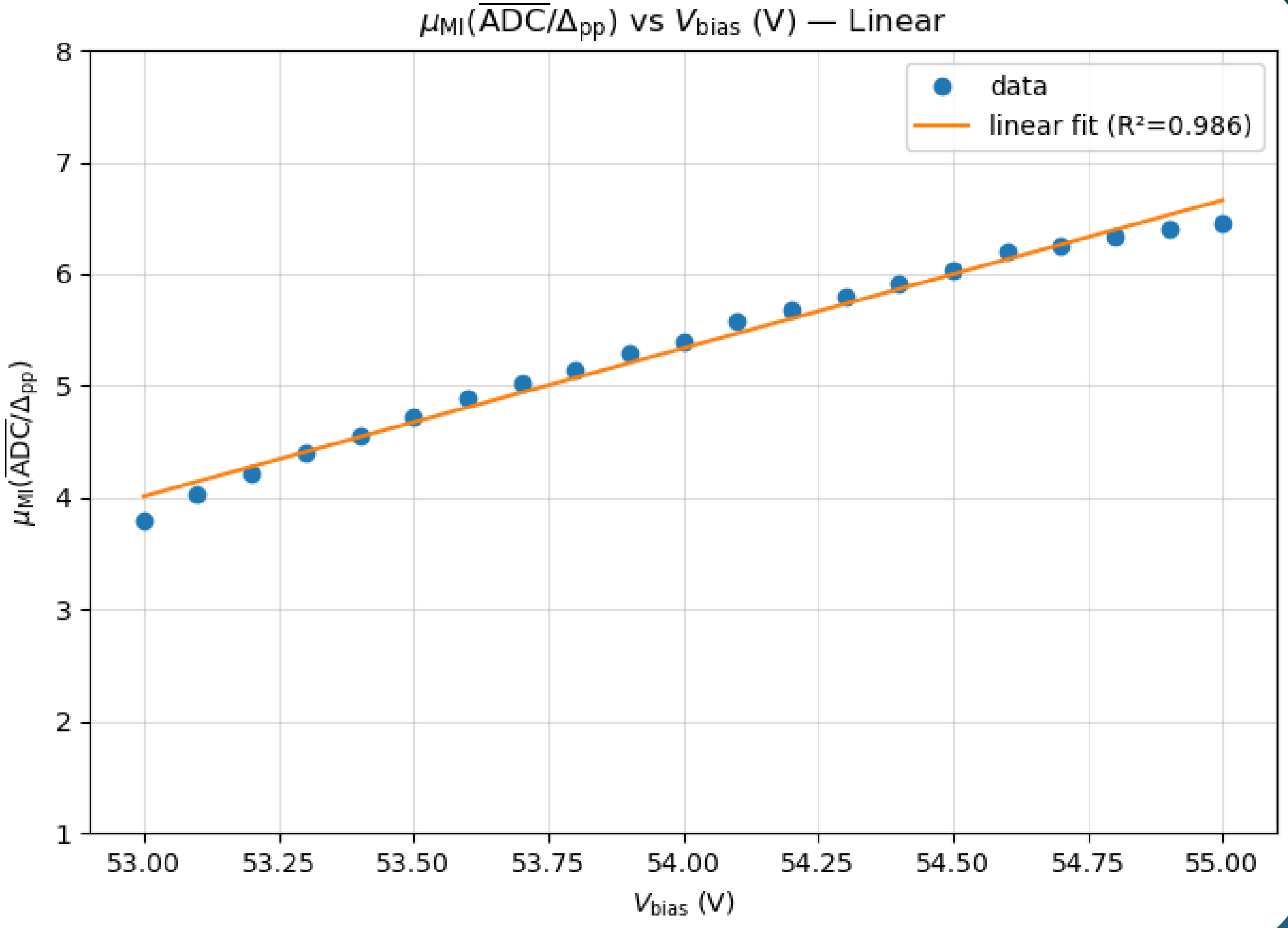




Mean Number of Fired Cells (Detected Photons) as function of Light Intensity



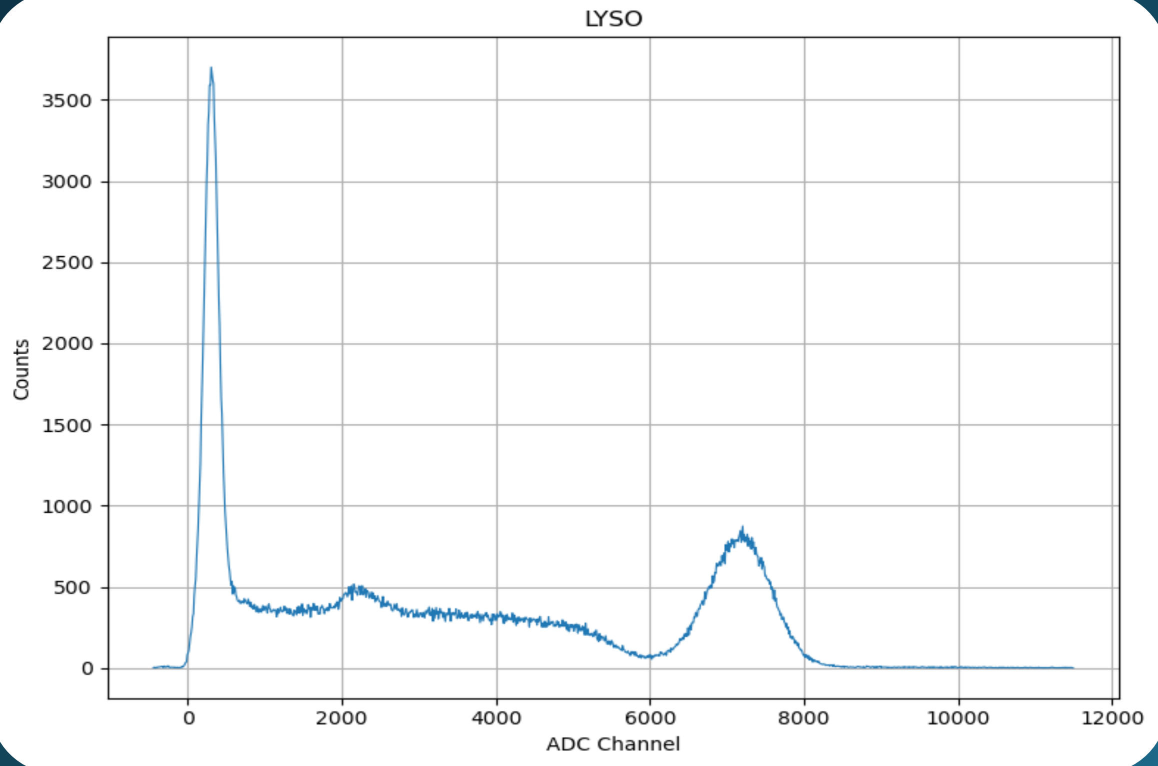
Mean Number of Fired Cells (Detected Photons) as function of V_{bias}

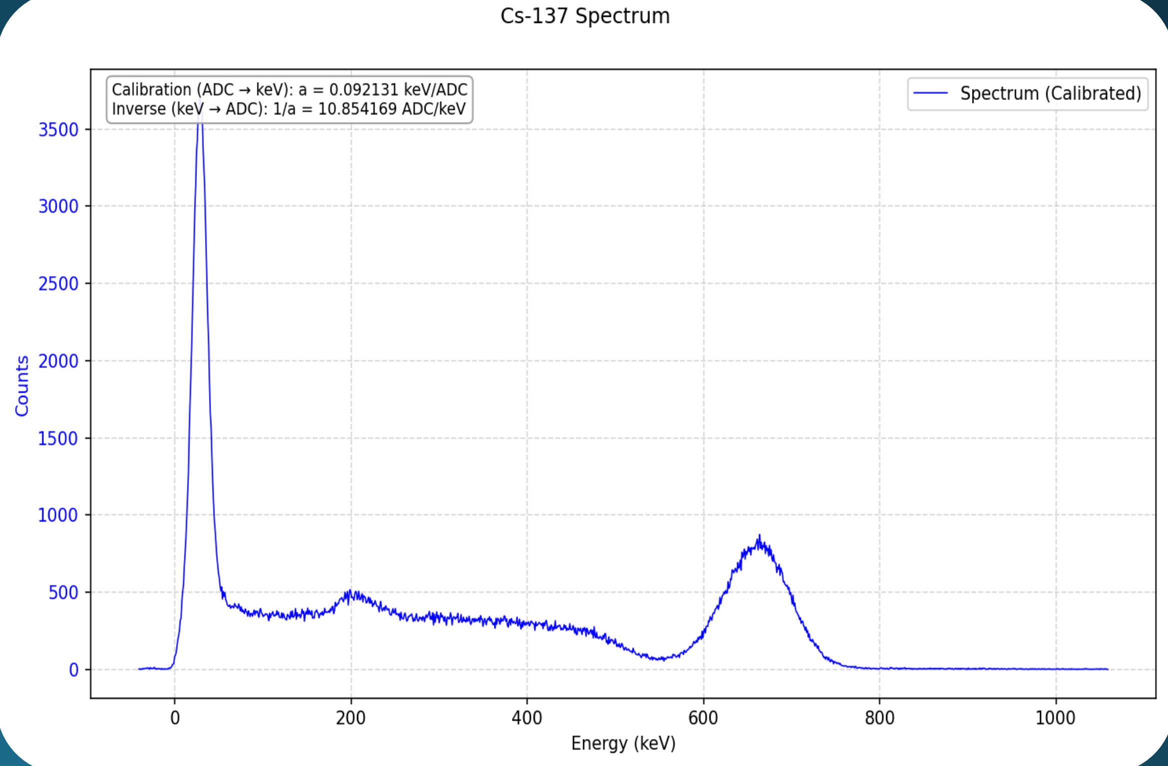


4

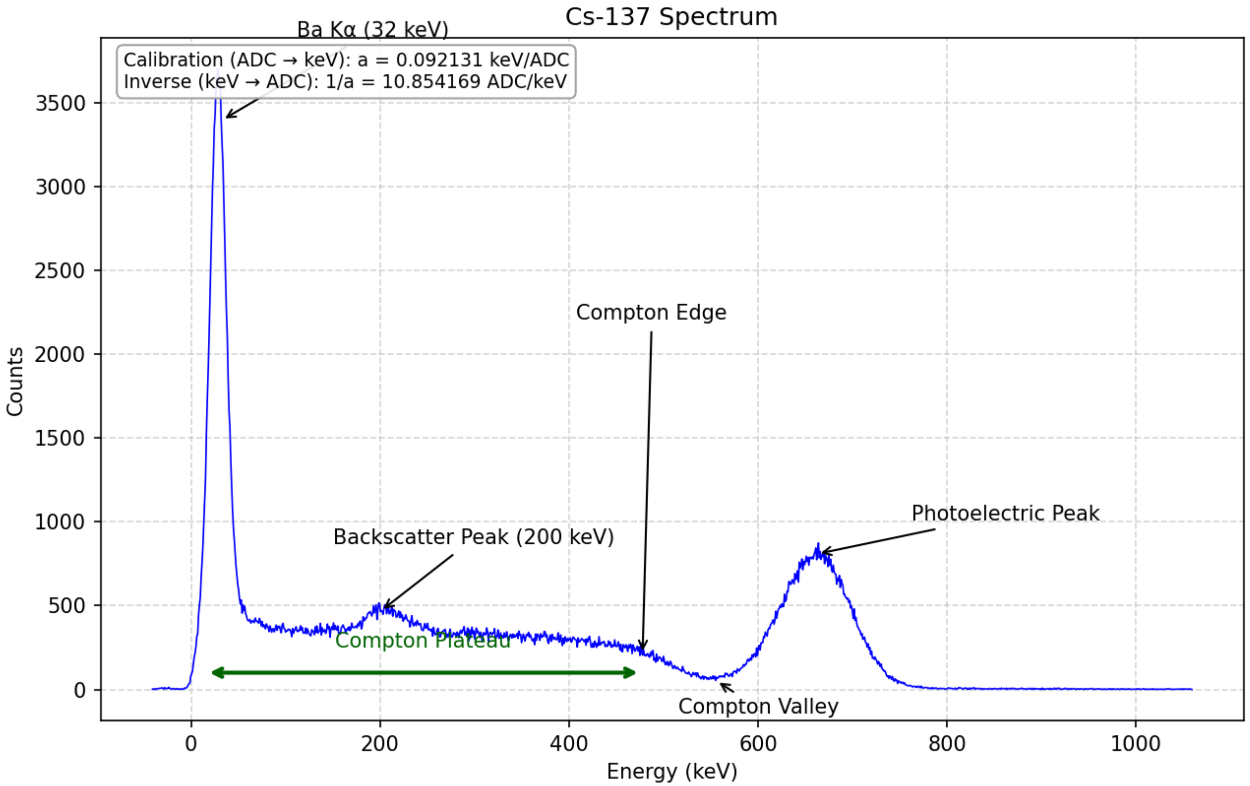
Radioactive Source Measurements [Cs-137]

Spectrum Calibration
Use of the 662 keV γ-Photon

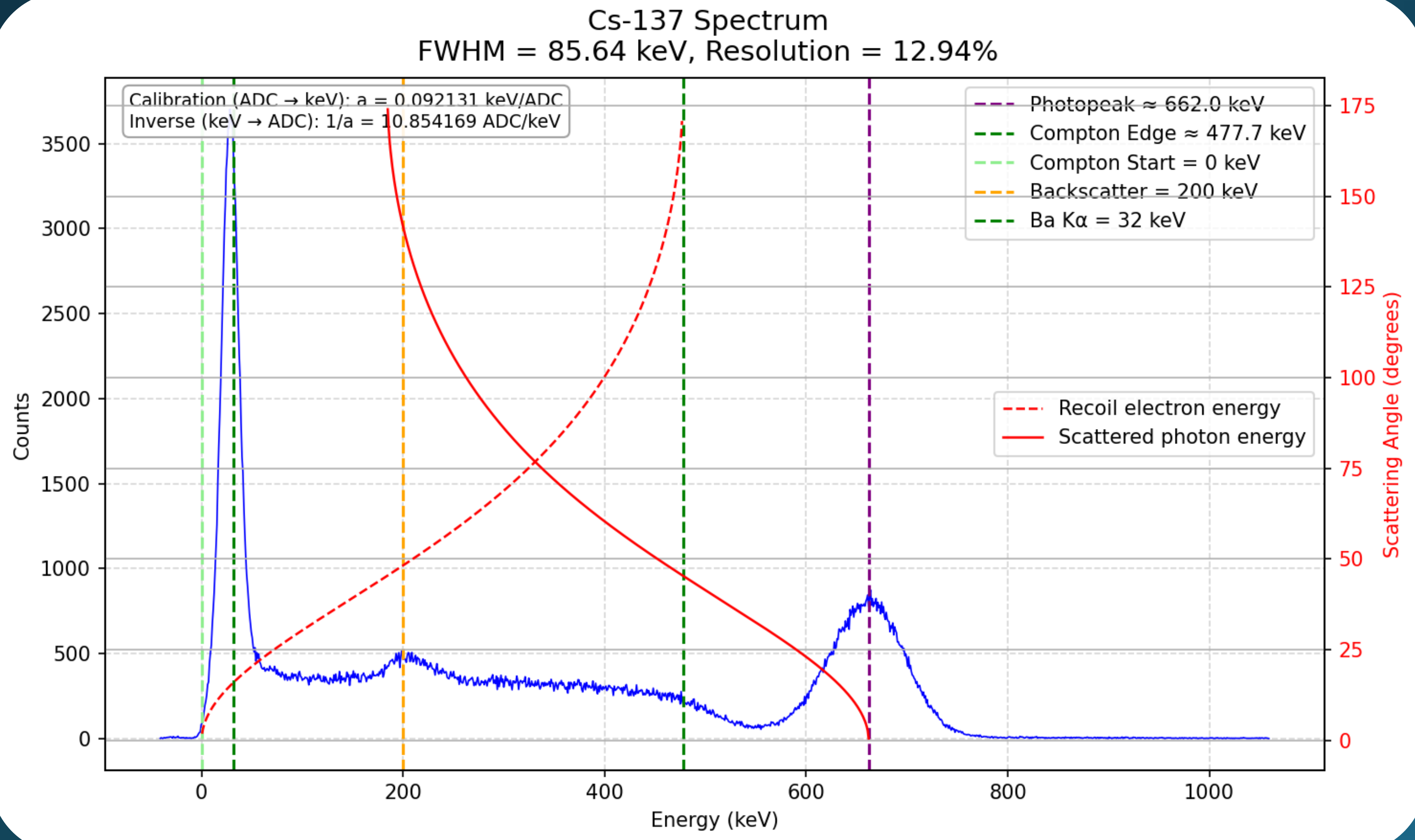




Peak Recognition



Spectrum Resolution



Scattered photon energy

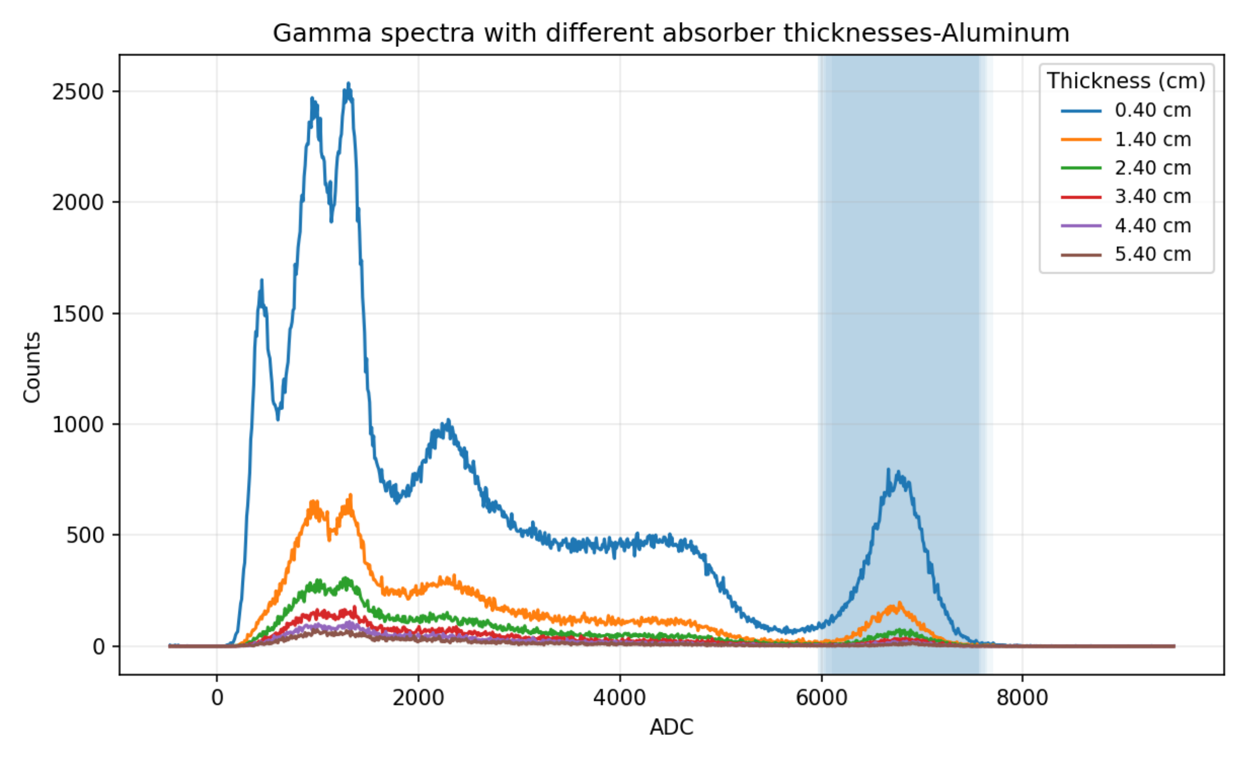
$$E'_\gamma(\theta) = \frac{E_\gamma}{1 + \frac{E_\gamma}{mc^2}(1 - \cos\theta)}$$

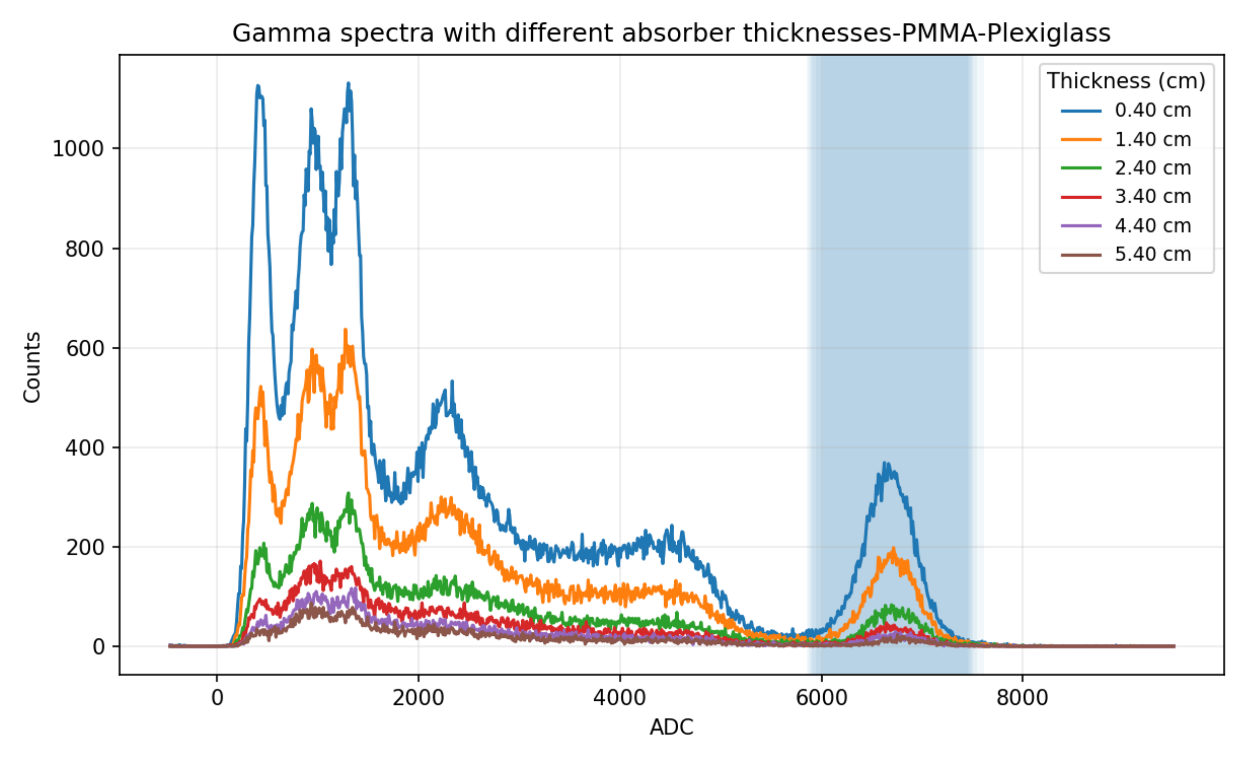
Recoil electron energy

$$K_e(\theta) = E_\gamma - E'_\gamma$$

$$= E_\gamma \left(\frac{\frac{E_\gamma}{mc^2}(1 - \cos\theta)}{1 + \frac{E_\gamma}{mc^2}(1 - \cos\theta)} \right)$$

γ-Radiation Absorption

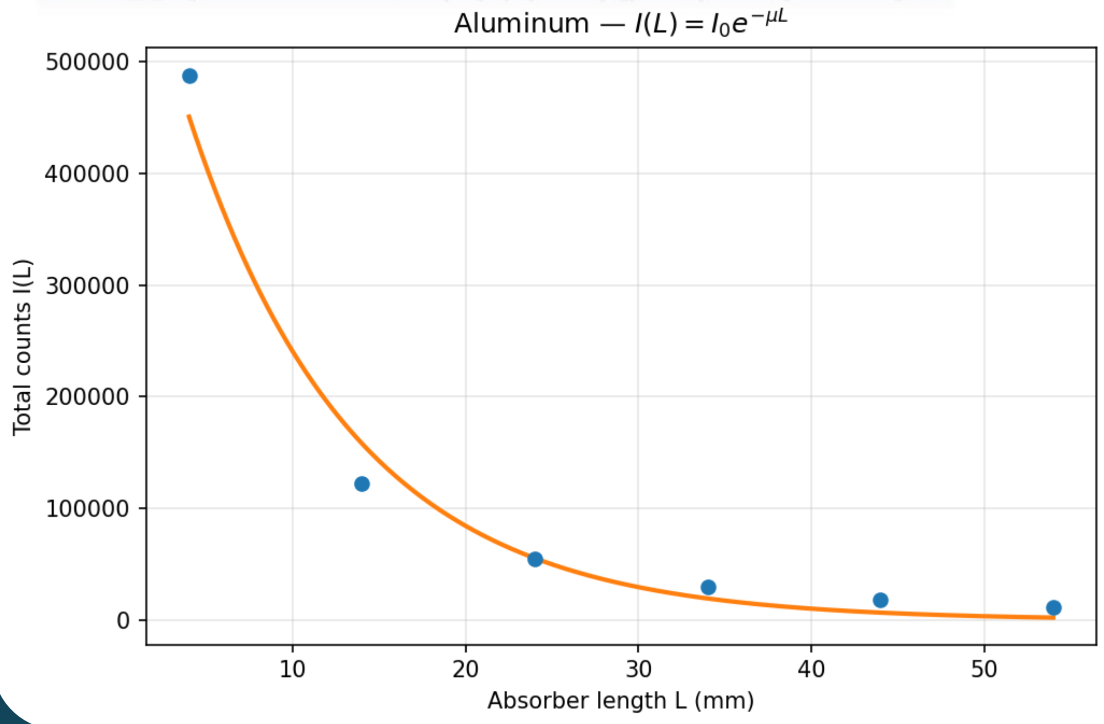


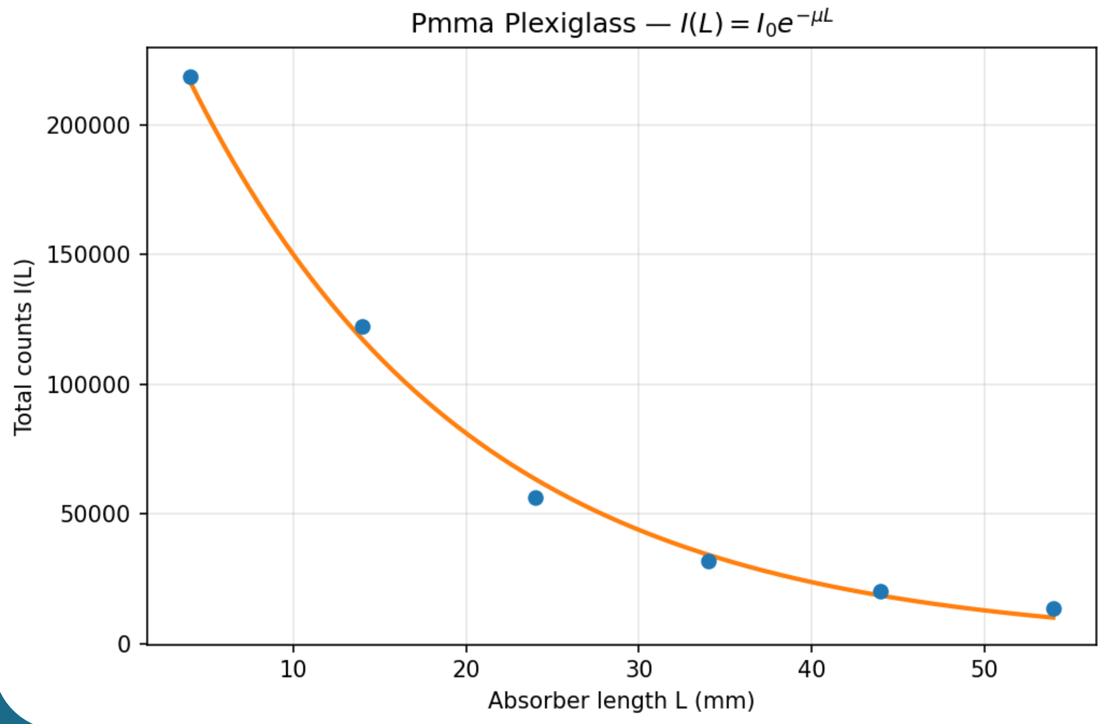


Exponential Absorption Law

Applications:

- Material thickness measurement
- Unknown material identification through attenuation coefficient (μ)





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QRNG

Exploitation of Quantum Detection Randomness

Generation of a sequence of random numbers using experimental data, by harnessing the genuine **quantum randomness** in the number of detected photons during the SiPM experiment.

If x_n denotes the first number of the generated random sequence, then the next one is produced through the recursive relation:

$$x_{n+1} = f(x_n)$$

followed by a conversion into **binary** form for the final output (01110001…).

- **Verification of the randomness** of the generated number sequence through the **NIST Statistical Test Suite**
- **Utilization** of the resulting random sequence as an **input source** for **Monte Carlo simulations,** with accuracy up to more than **99%**

Test	Generated	Theoretical	Accuracy (%)
Monte Carlo π	3.146960	3.141593	99.829
European Call Price	8.871317	8.916037	99.498
Decay N(T=150.0)	154.920000	156.250000	99.668

6

Conclusion

- ***Assembly of the Experimental Setup***

Complete integration of the SiPM, scintillator, electronics, and data-acquisition chain.

- ***Measurements***

Systematic acquisition of spectra and charge histograms under controlled conditions (LED, radiation sources, varying bias & light intensity)

- ***Characterization***

Extraction of key SiPM parameters (gain, PDE-related photon statistics, DCR, cross-talk, resolution).

- ***Calibration***

ADC-to-charge and charge-to-photoelectron calibration enabling accurate quantitative analysis.

- ***QRNG Implementation***

Utilization of photon-count randomness and SiPM avalanche statistics to generate and validate quantum-based random numbers.

THANK YOU FOR YOUR ATTENTION

(QUESTIONS)

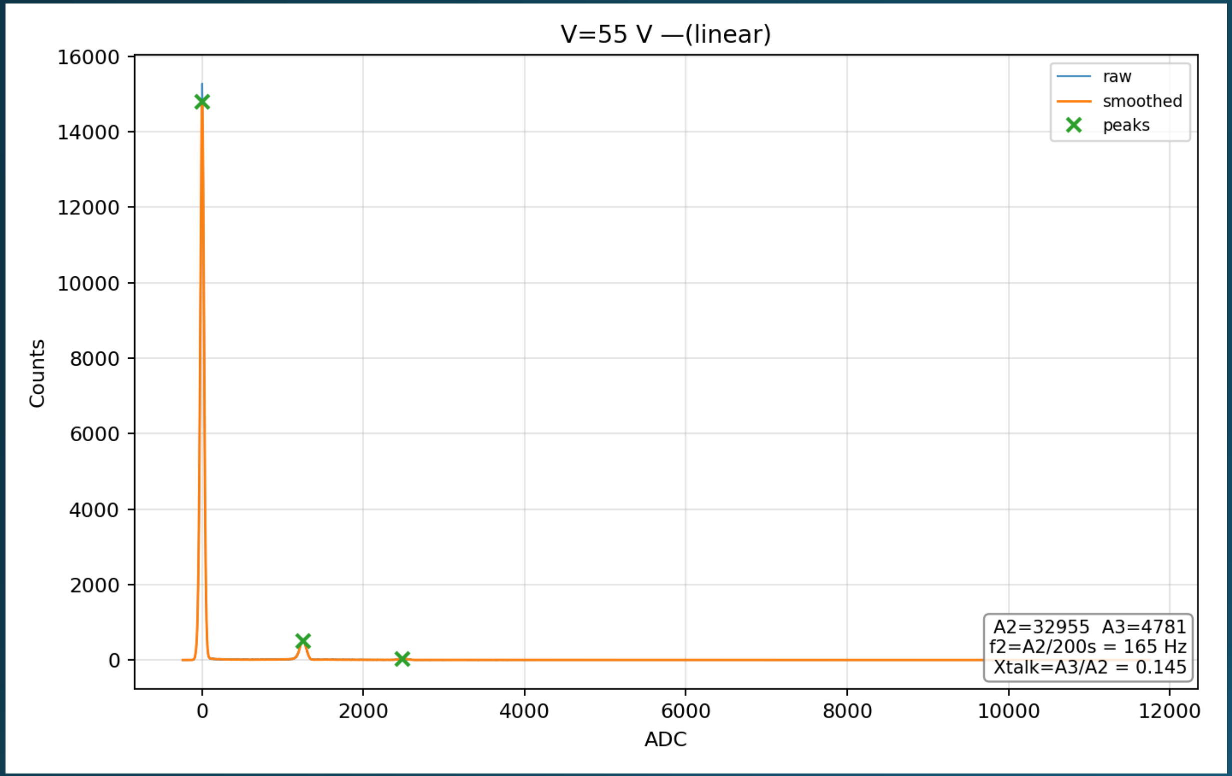
Supplementary Slides

Key Parameters

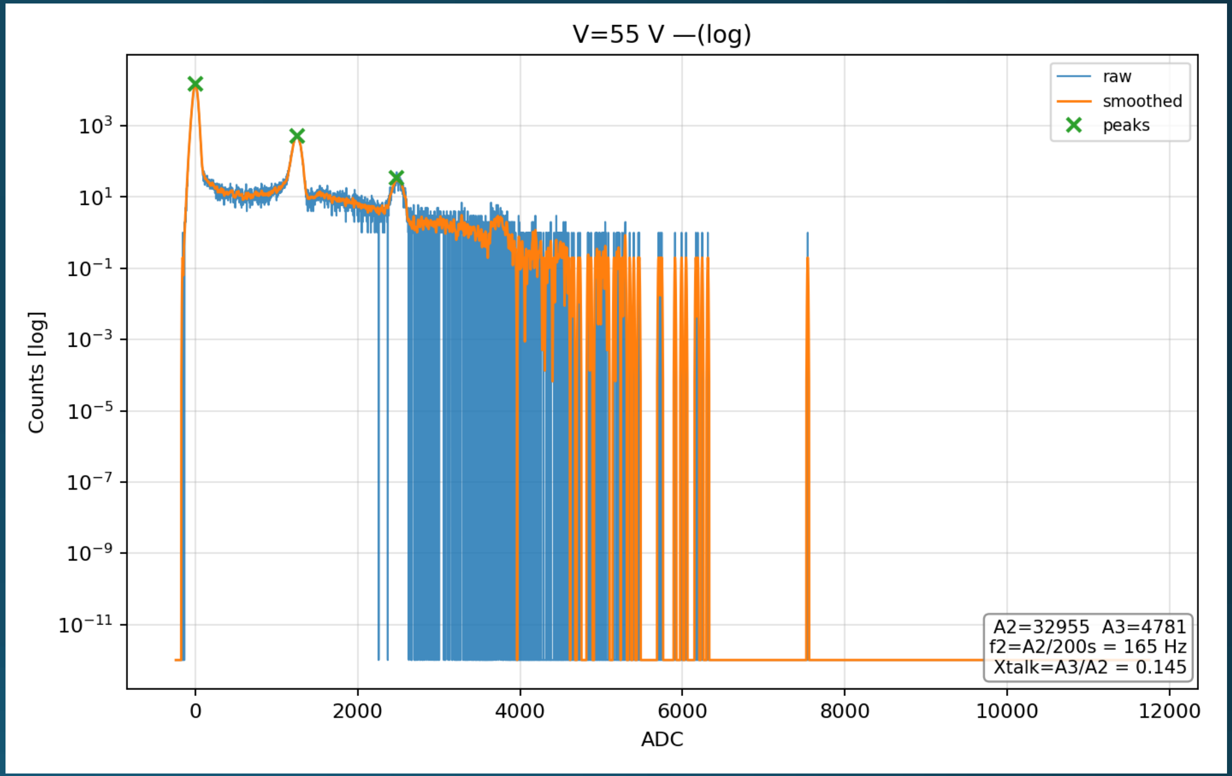
Voltages	Bias Voltage V_{bias}	Breakdown Voltage V_{bd}	Overvoltage $V_{ov} = V_{bias} - V_{bd}$	Turnoff Voltage V_{off}
Definition	The external voltage applied to the SiPM to operate its microcells	The minimum reverse bias voltage at which a microcell undergoes avalanche breakdown	The amount by which the bias voltage exceeds the breakdown voltage.	The voltage below which the avalanche process cannot be sustained and the device completely stops responding to light. Typically $V_{off} \cong V_{bd}$
Role	Determines the operating point of each microcell, influencing many of the detector's parameters	Critical for initiating Geiger-mode operation. Operating above this voltage allows microcells to detect single photons	Determines the gain and the probability of initiating an avalanche. Higher overvoltage generally increases gain but may also elevate dark count rates and noise.	Essential for quenching the avalanche and resetting the microcell for subsequent detections

Key Parameters

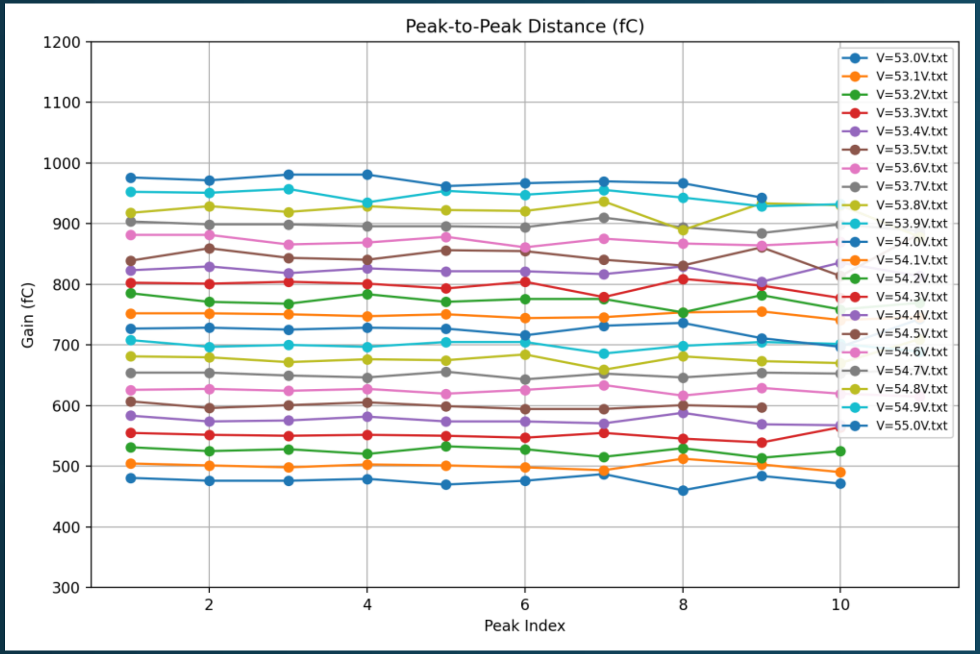
	Photon-Detection Efficiency	Gain	Cross-Talk	After-Pulse	DCR
Definition	$PDE = QE \cdot P_{av} \cdot FF$ The probability that an incoming photon will be detected $\sim(20-40)\%$	The amount of electrical charge generated per detected photon — essentially how much the initial signal is amplified $G \approx 10^6$	Delayed avalanches in the same microcell due to trapped carriers being released after the initial even — Carriers trapped in lattice defects during avalanche and later released	A photon emitted during an avalanche in one microcell may trigger a secondary avalanche in a neighboring cell — Internal photon emission during carrier recombination	The rate at which microcells fire spontaneously (without photon input) due to thermal excitation or tunneling
Role	A measure of sensitivity. Higher PDE means more efficient photon detection — critical for low-light applications	Determines the amplitude of the output signal; crucial for digitizing and quantifying light intensity	Creates false secondary pulses; degrades timing resolution and distorts pulse shape	Leads to overestimation of the number of detected photons; worsens resolution and introduces non-linearity	Acts as a form of background noise; high DCR reduces the signal-to-noise ratio and can mimic real photon events



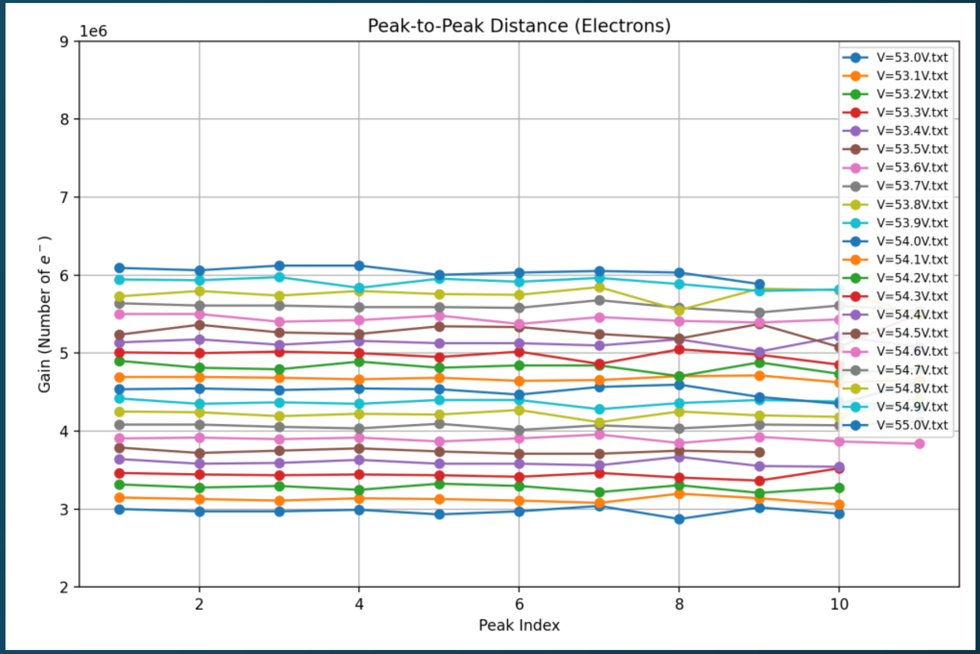
V=55 V —(linear)
Counts
ADC
raw
smoothed
peaks
A2=32955 A3=4781
f2=A2/200s = 165 Hz
Xtalk=A3/A2 = 0.145

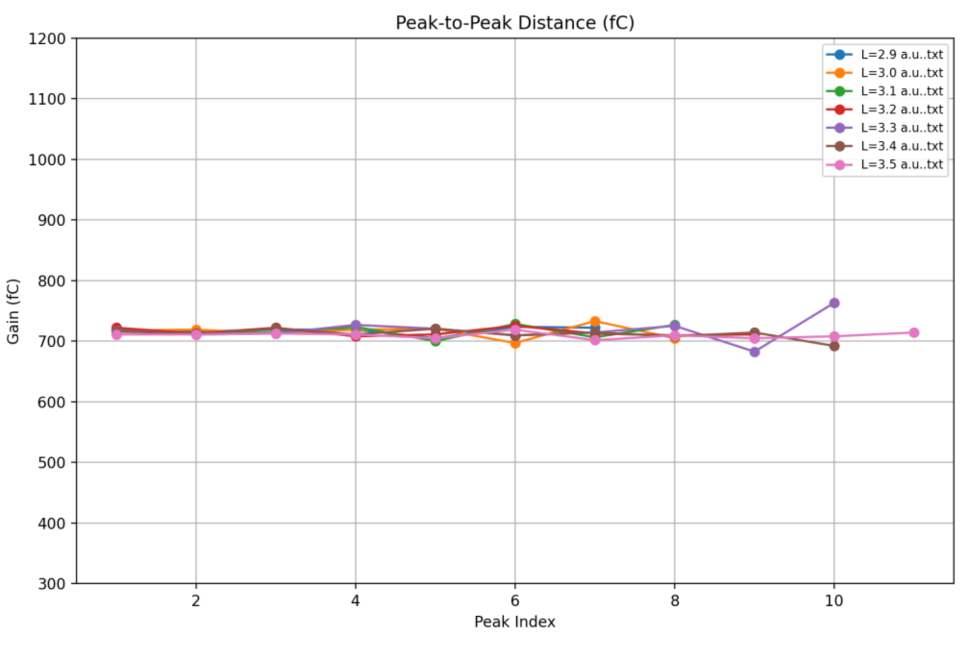


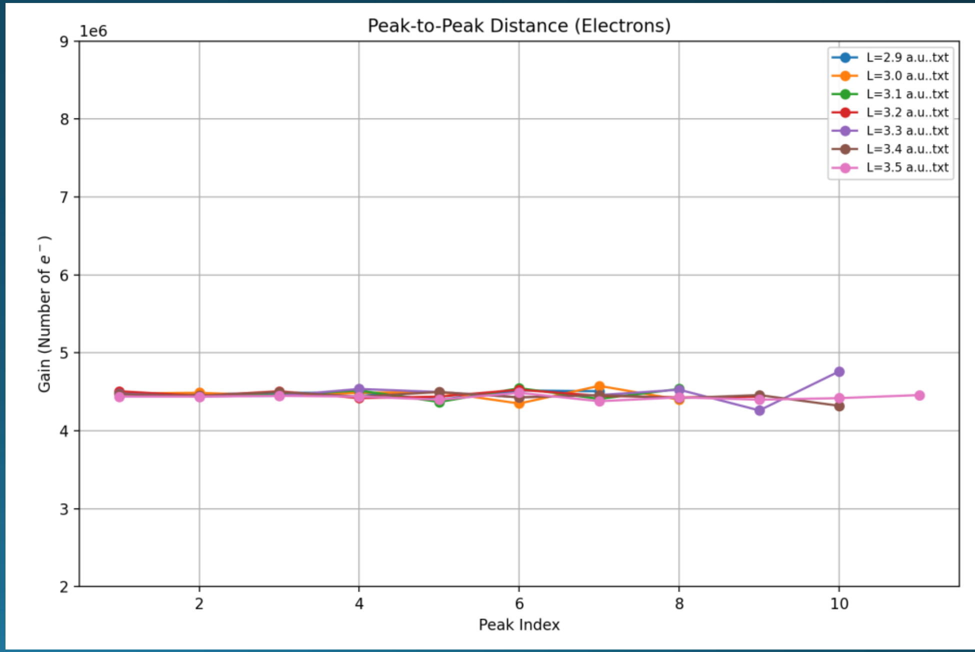
V=55 V —(log)
Counts [log]
ADC
raw
smoothed
peaks
A2=32955 A3=4781
f2=A2/200s = 165 Hz
Xtalk=A3/A2 = 0.145

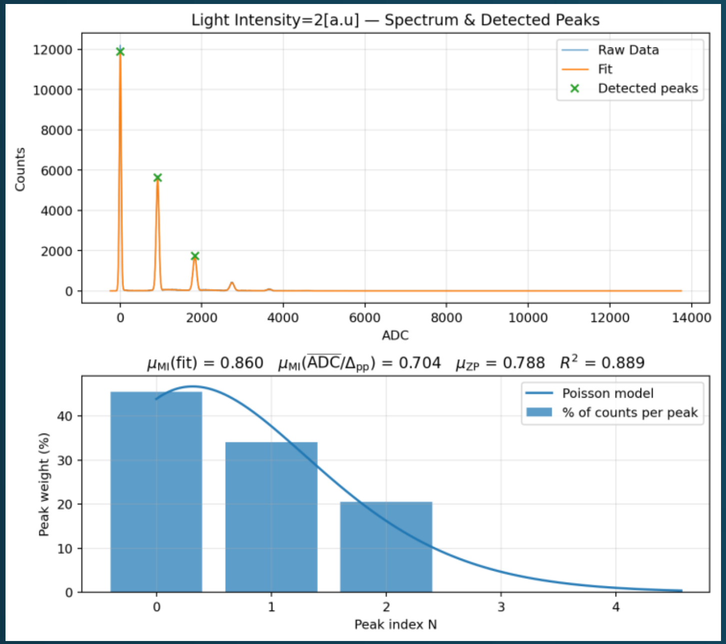


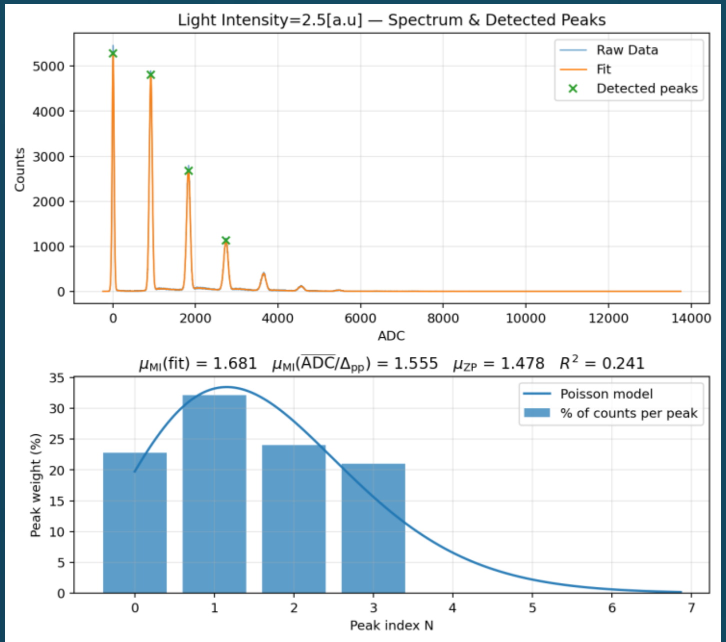
SiPM Avalanche Gain

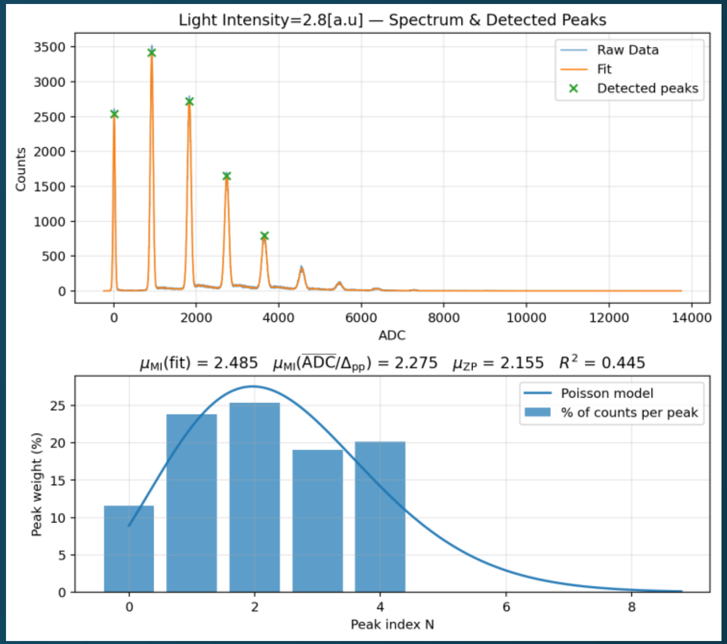


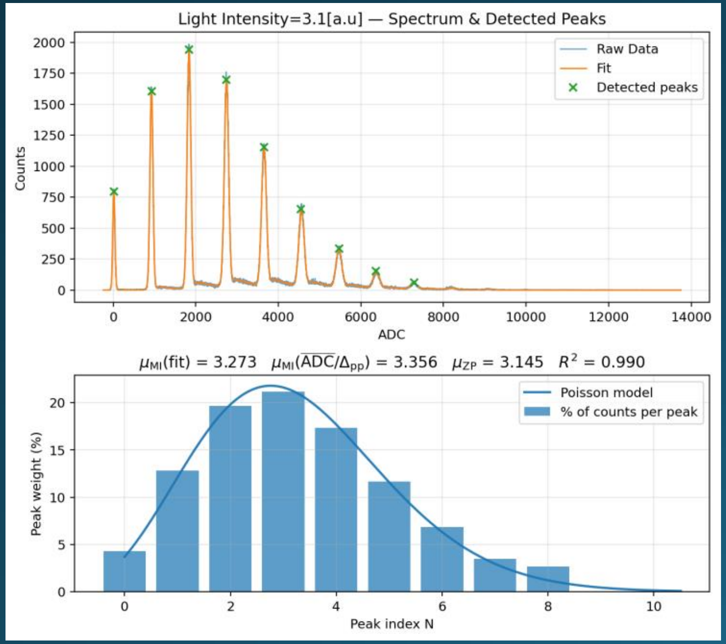


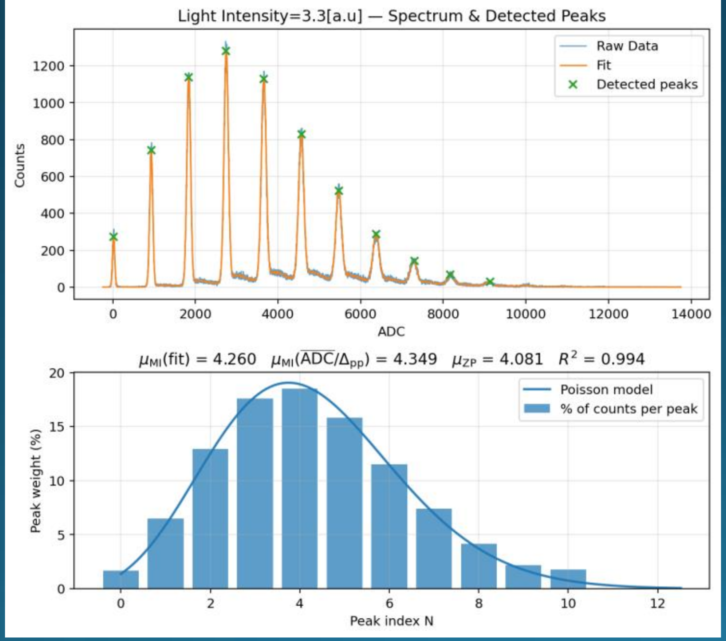


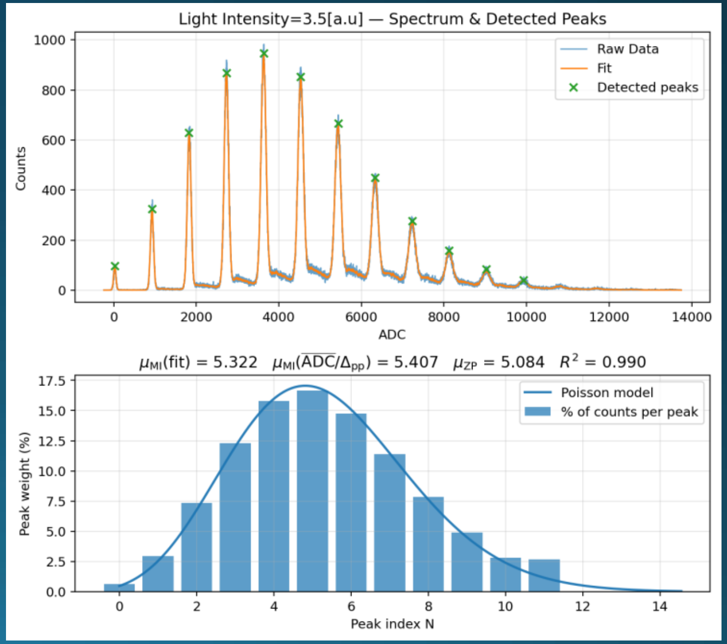

Light Intensity=2[a.u] — Spectrum & Detected Peaks
Raw Data
Fit
Detected peaks
Counts
ADC
$\mu_{MI}(\text{fit}) = 0.860$ $\mu_{MI}(\overline{ADC}/\Delta_{pp}) = 0.704$ $\mu_{ZP} = 0.788$ $R^2 = 0.889$
Poisson model
% of counts per peak
Peak weight (%)
Peak index N

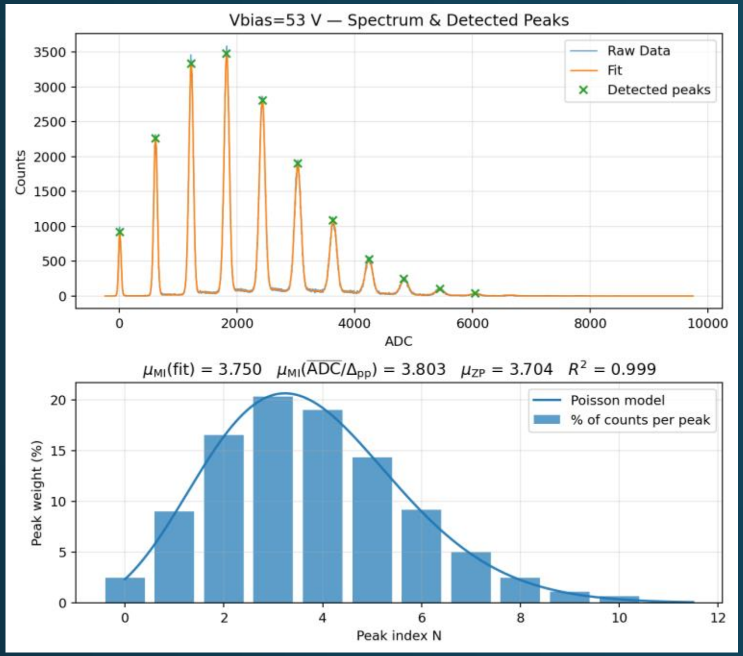

Light Intensity=2.5[a.u] — Spectrum & Detected Peaks
Raw Data
Fit
Detected peaks
Counts
ADC
$\mu_{MI}(\text{fit}) = 1.681$ $\mu_{MI}(\overline{ADC}/\Delta_{pp}) = 1.555$ $\mu_{ZP} = 1.478$ $R^2 = 0.241$
Poisson model
% of counts per peak
Peak weight (%)
Peak index N


Light Intensity=2.8[a.u] — Spectrum & Detected Peaks
Raw Data
Fit
Detected peaks
Counts
ADC
$\mu_{MI}(\text{fit}) = 2.485$ $\mu_{MI}(\overline{ADC}/\Delta_{pp}) = 2.275$ $\mu_{ZP} = 2.155$ $R^2 = 0.445$
Poisson model
% of counts per peak
Peak weight (%)
Peak index N

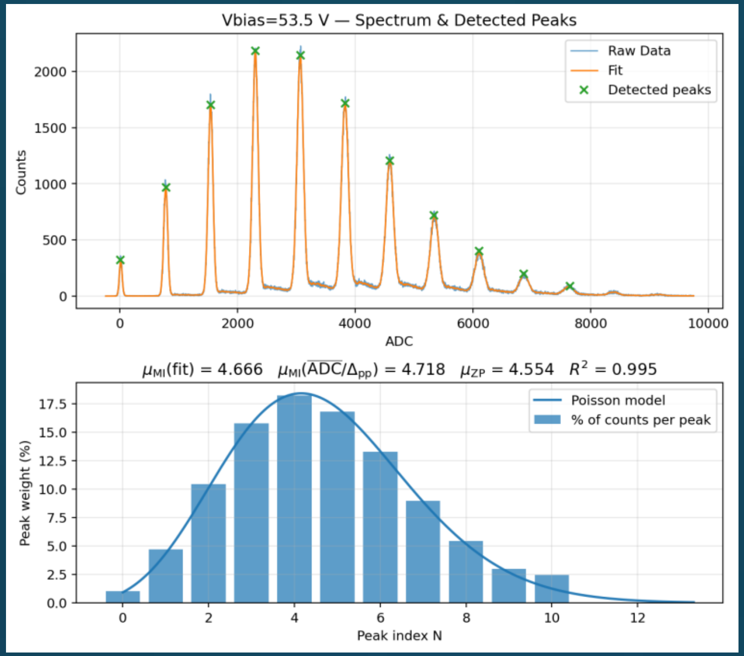

Light Intensity=3.1[a.u] — Spectrum & Detected Peaks
Raw Data
Fit
Detected peaks
Counts
ADC
$\mu_{MI}(\text{fit}) = 3.273$ $\mu_{MI}(\overline{ADC}/\Delta_{pp}) = 3.356$ $\mu_{ZP} = 3.145$ $R^2 = 0.990$
Poisson model
% of counts per peak
Peak weight (%)
Peak index N


Light Intensity=3.3[a.u] — Spectrum & Detected Peaks
Raw Data
Fit
Detected peaks
Counts
ADC
$\mu_{MI}(\text{fit}) = 4.260$ $\mu_{MI}(\overline{ADC}/\Delta_{pp}) = 4.349$ $\mu_{ZP} = 4.081$ $R^2 = 0.994$
Poisson model
% of counts per peak
Peak weight (%)
Peak index N

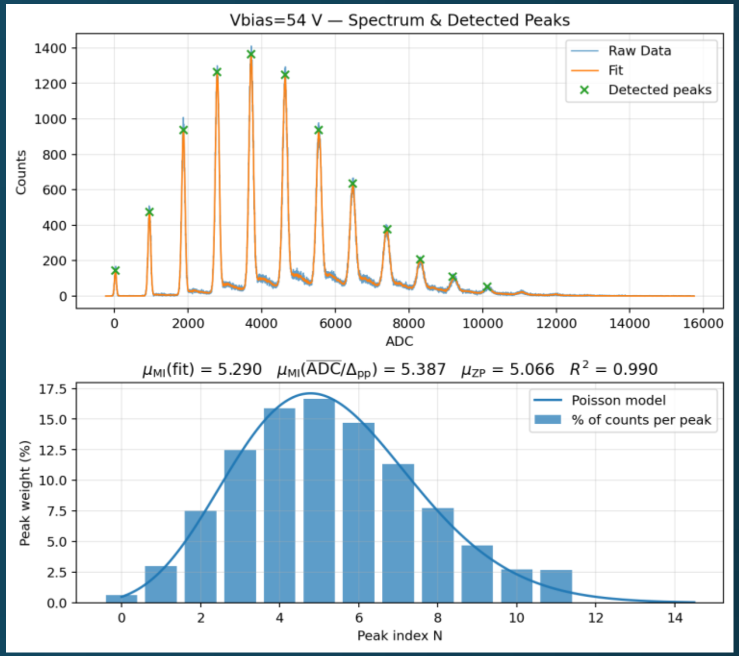

Light Intensity=3.5[a.u] — Spectrum & Detected Peaks
Raw Data
Fit
Detected peaks
Counts
ADC
$\mu_{MI}(\text{fit}) = 5.322$ $\mu_{MI}(\overline{ADC}/\Delta_{pp}) = 5.407$ $\mu_{ZP} = 5.084$ $R^2 = 0.990$
Poisson model
% of counts per peak
Peak weight (%)
Peak index N



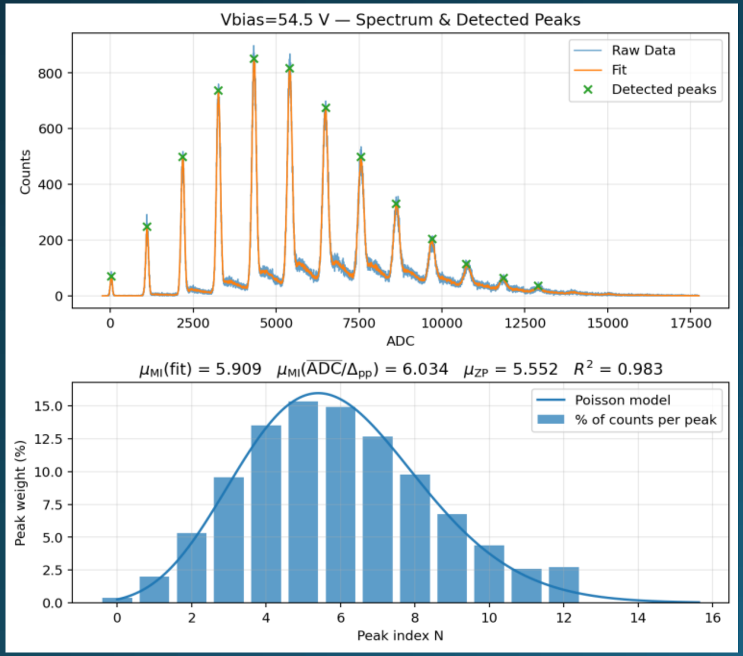
Vbias=53 V — Spectrum & Detected Peaks
Raw Data
Fit
Detected peaks
Counts
ADC
μ_{MI}(fit) = 3.750 $\mu_{MI}(\overline{ADC}/\Delta_{pp})$ = 3.803 μ_{ZP} = 3.704 R^2 = 0.999
Poisson model
% of counts per peak
Peak weight (%)
Peak index N



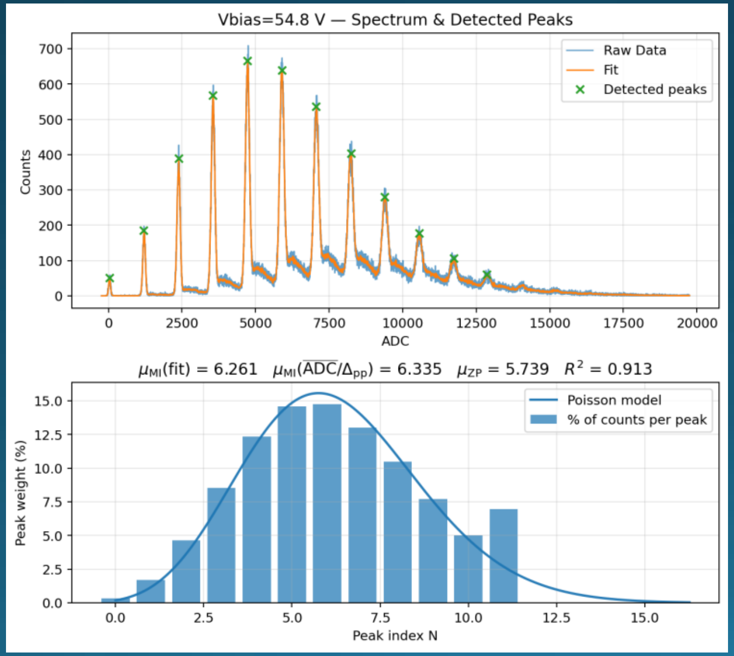
Vbias=53.5 V — Spectrum & Detected Peaks
Raw Data
Fit
Detected peaks
Counts
ADC
μ_{MI}(fit) = 4.666 $\mu_{MI}(\overline{ADC}/\Delta_{pp})$ = 4.718 μ_{ZP} = 4.554 R^2 = 0.995
Poisson model
% of counts per peak
Peak weight (%)
Peak index N



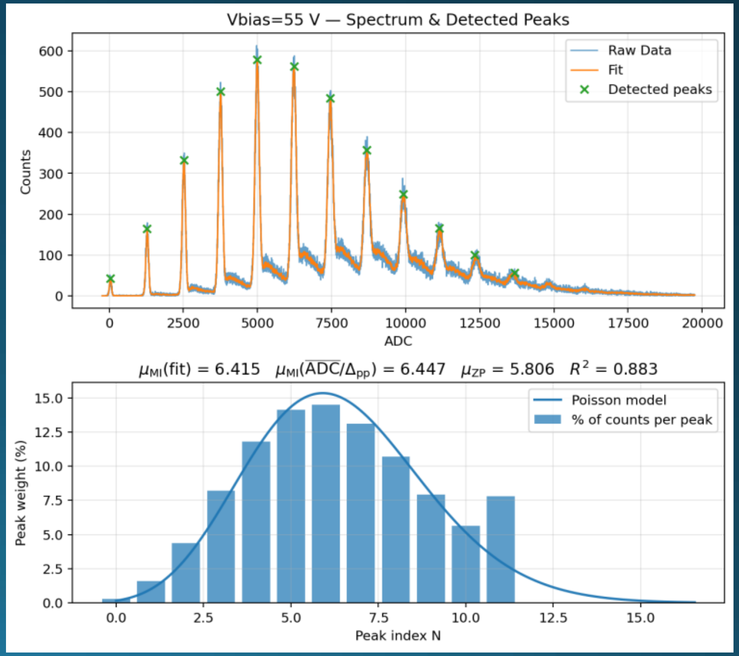
Vbias=54 V — Spectrum & Detected Peaks
Raw Data
Fit
Detected peaks
Counts
ADC
μ_{MI}(fit) = 5.290 $\mu_{MI}(\overline{ADC}/\Delta_{pp})$ = 5.387 μ_{ZP} = 5.066 R^2 = 0.990
Poisson model
% of counts per peak
Peak weight (%)
Peak index N



Vbias=54.5 V — Spectrum & Detected Peaks
Raw Data
Fit
Detected peaks
Counts
ADC
μ_{MI}(fit) = 5.909 $\mu_{MI}(\overline{ADC}/\Delta_{pp})$ = 6.034 μ_{ZP} = 5.552 R^2 = 0.983
Poisson model
% of counts per peak
Peak weight (%)
Peak index N

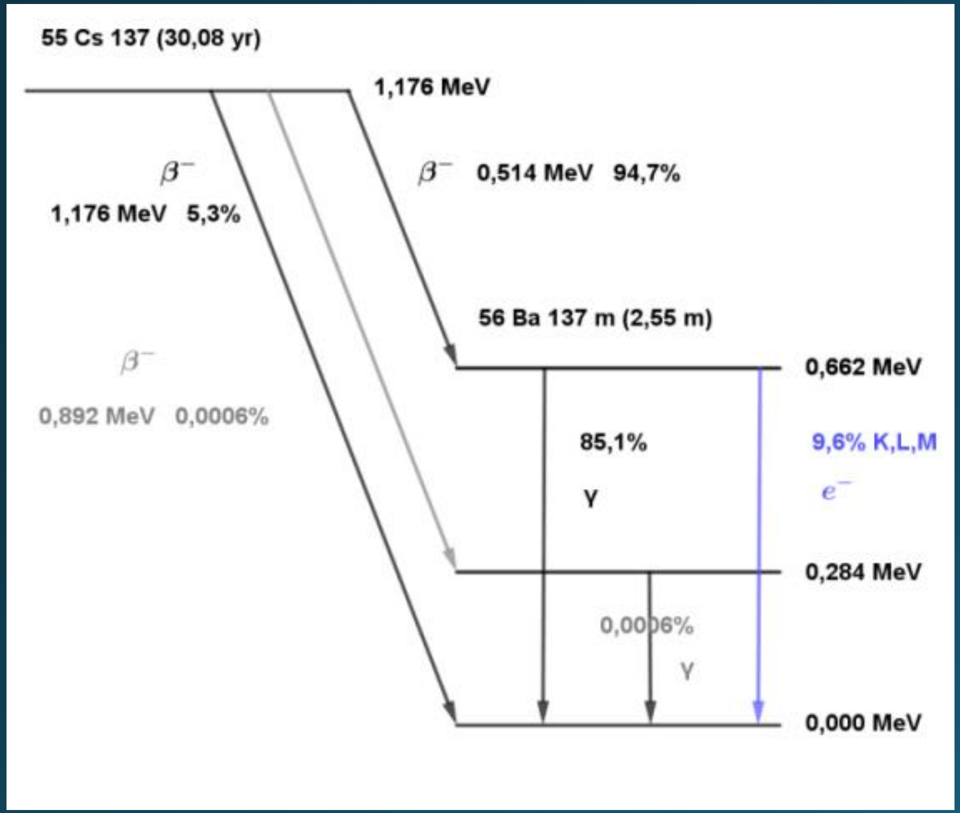


Vbias=54.8 V — Spectrum & Detected Peaks
Raw Data
Fit
Detected peaks
Counts
ADC
μ_{MI}(fit) = 6.261 $\mu_{MI}(\overline{ADC}/\Delta_{pp})$ = 6.335 μ_{ZP} = 5.739 R^2 = 0.913
Poisson model
% of counts per peak
Peak weight (%)
Peak index N



Vbias=55 V — Spectrum & Detected Peaks
Raw Data
Fit
Detected peaks
Counts
ADC
μ_{MI}(fit) = 6.415 $\mu_{MI}(\overline{ADC}/\Delta_{pp})$ = 6.447 μ_{ZP} = 5.806 R^2 = 0.883
Poisson model
% of counts per peak
Peak weight (%)
Peak index N

Cs-137 Decay



$^{137}_{55}Cs$

94.7%

$^{137}_{55}Cs \rightarrow {}^{137}_{56}Ba^* + {}^{0}_{-1}e + \overline{\nu_e}$

5.3%

$^{137}_{55}Cs \rightarrow {}^{137}_{56}Ba + {}^{0}_{-1}e + \overline{\nu_e}$

Beta radiation

85.1%

$^{137}_{56}Ba^* \rightarrow {}^{137}_{56}Ba + \gamma$

Ba characteristic γ-ray

9.6%

$^{137}_{56}Ba^* \rightarrow {}^{137}_{56}Ba + e^-_{IC} + \gamma$

Ba characteristic X-ray

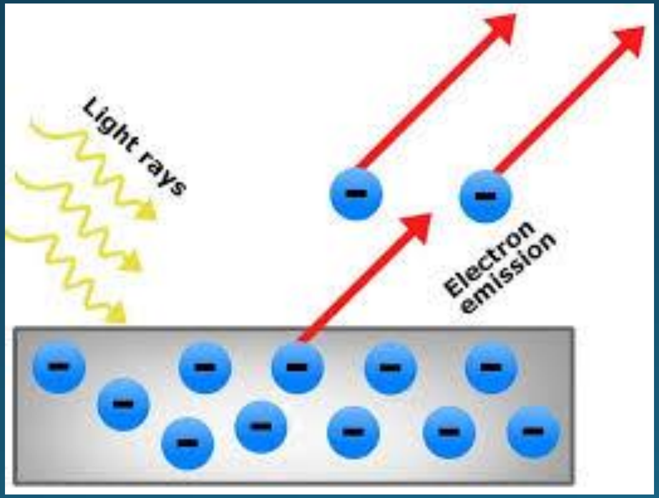
Photoelectric Effect

Incident Gamma Photon Energy

$$E_0 = 662keV$$

Dominant at energy less than 100Kev

$$\gamma + atom \rightarrow ion + e^-$$



$$E_e = E_\gamma - E_b = 662 - E_b$$