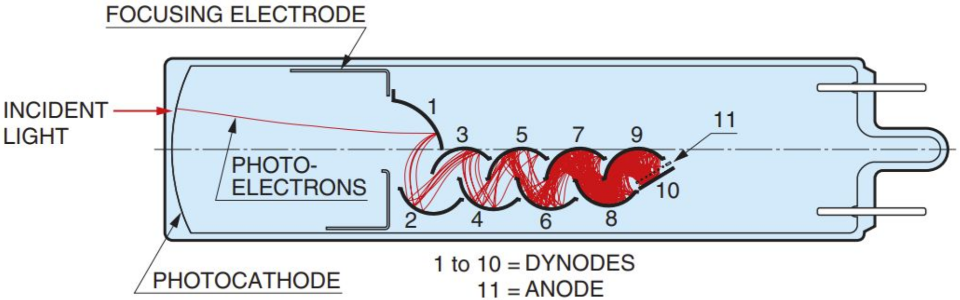
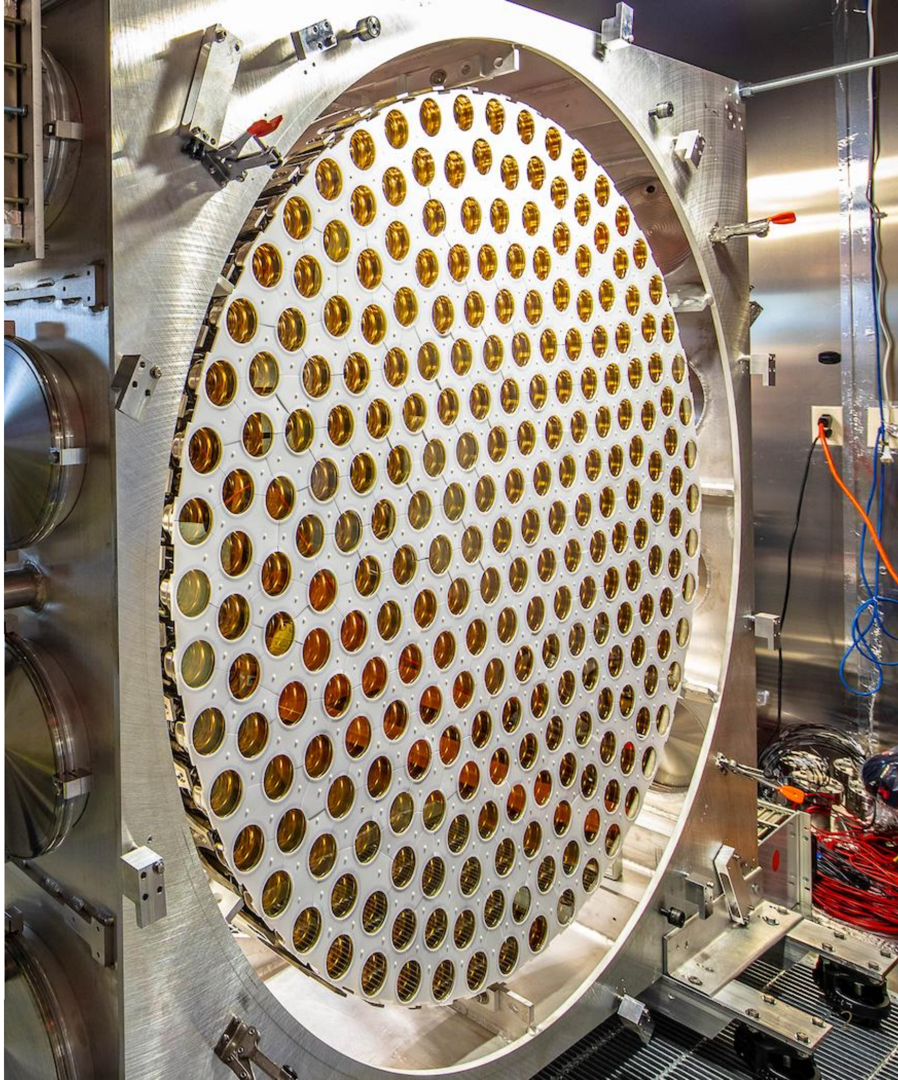
SiPM Project

Emma Ellingwood and Miguel Hernandez
Tutors : Alessandro Razeto and Nicola Rossi
05/10/2023

Photomultiplier Tubes

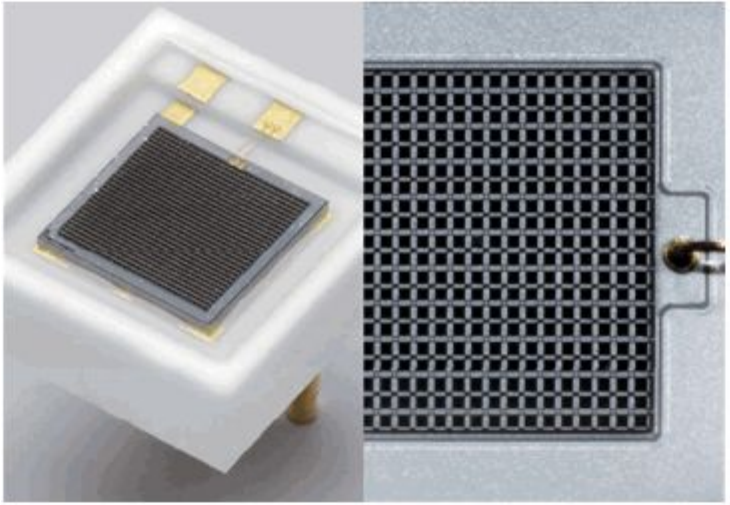
- Photocathode converts incident photons into photoelectrons
- Series of biased dynodes amplify incoming signal
- Sensitive for VUV to Near-infrared light
- Fast response time ~ns
- Low radioactivity
- Suitable for LXe (~160k) but not LAr (~80k)~)

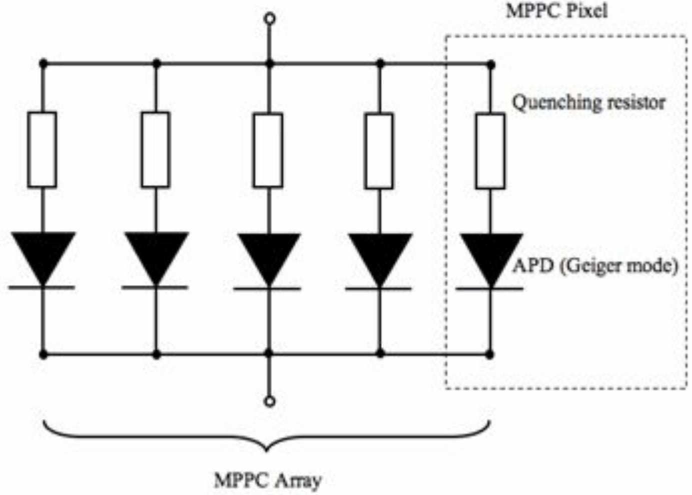




Silicon photomultipliers

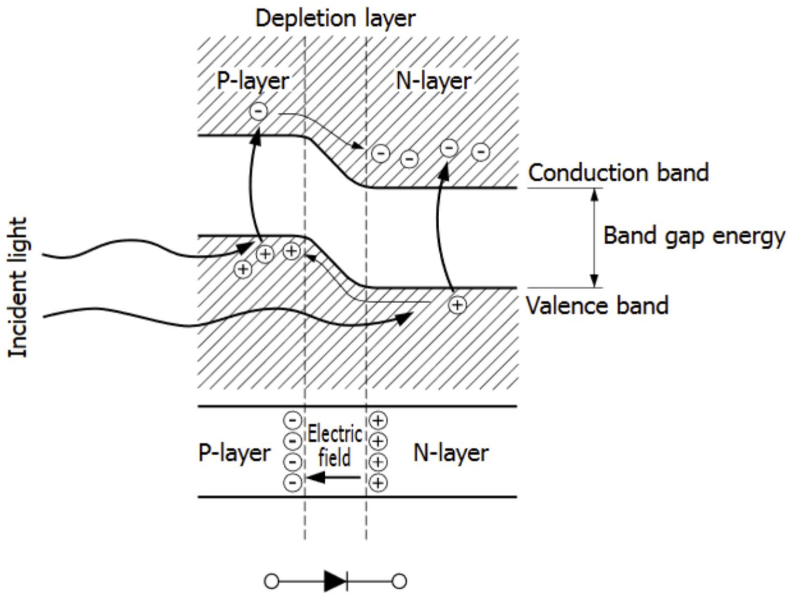
- Consists of single-photon avalanche diodes in parallel
- Higher quantum efficiency / detection efficiency
- Significantly cheaper than PMTs
- More susceptible to radiation damaging
- Higher dark rate at equivalent temperature to PMTs

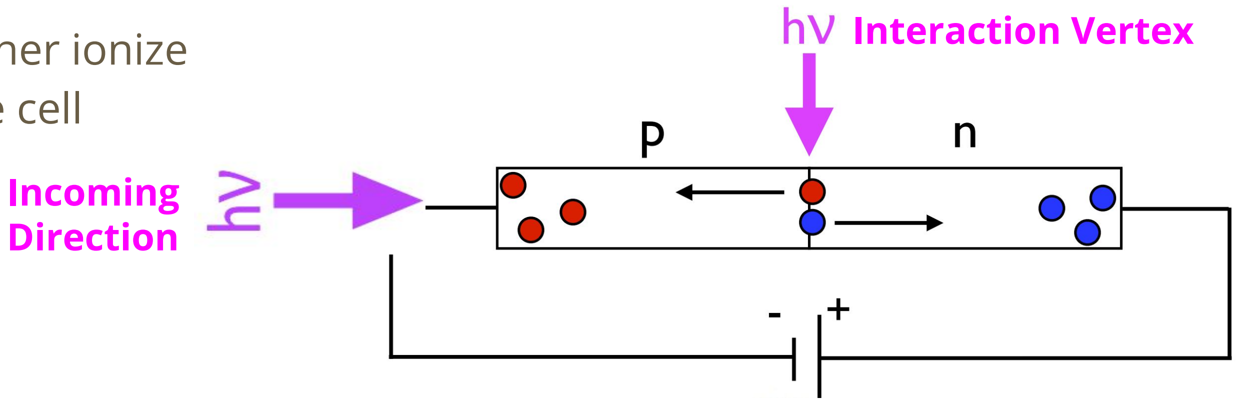




Silicon photomultipliers

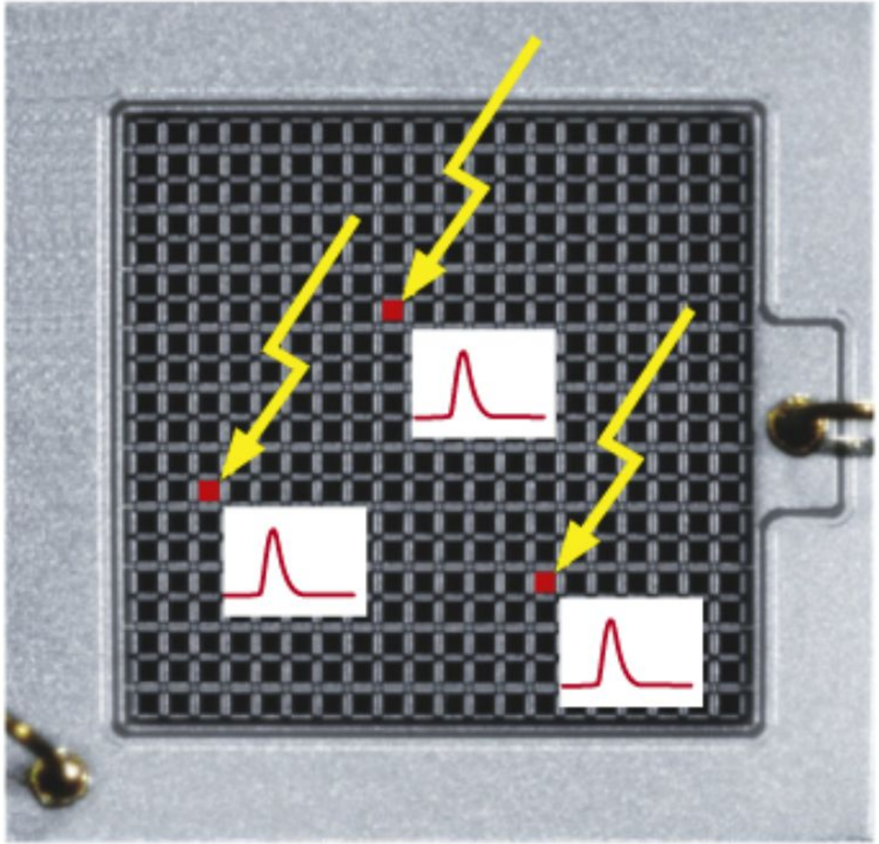
- Doping allows for depletion layer
- Incoming light deposits energy in Silicon valence band
- With sufficient energy, electrons “jump” the band gap
- Electron hole left in valence band and drift to cathode
- Drifting electrons further ionize avalanching the entire cell





Silicon photomultipliers

- Parallelized lattice allows for multi-photon detection
- Individual cells avalanche, but remaining cells available for signal
- Chance of cells triggering nearby cells (with either “fake” or real emitted signals) known as crosstalk



Crosstalk

Cross talk occurs when photon avalanche in a SPAD emits a photon which triggers a secondary avalanche in nearby SPADs

Internal Crosstalk

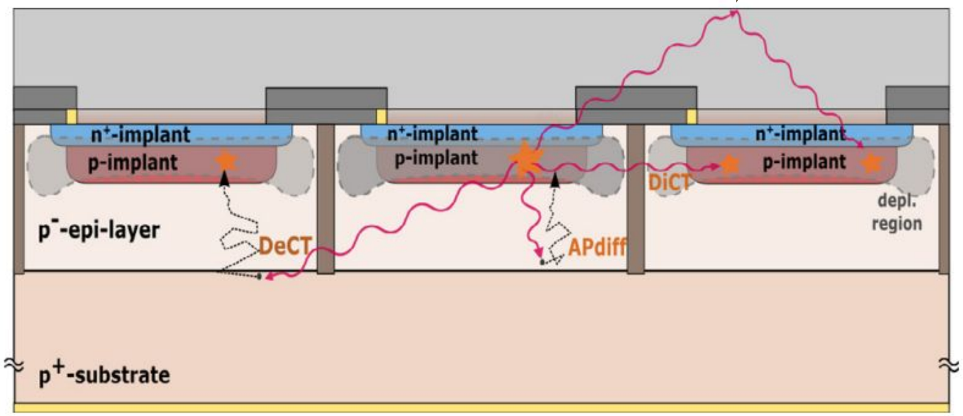
Photon emission from an avalanche in one cell remains in the same SiPM but triggers a neighbouring cell

DiCT = direct (prompt) crosstalk

DeCT = delayed crosstalk

External Crosstalk

Photons are emitted by an avalanche and exit the cell reflecting off the upper SiPM window.

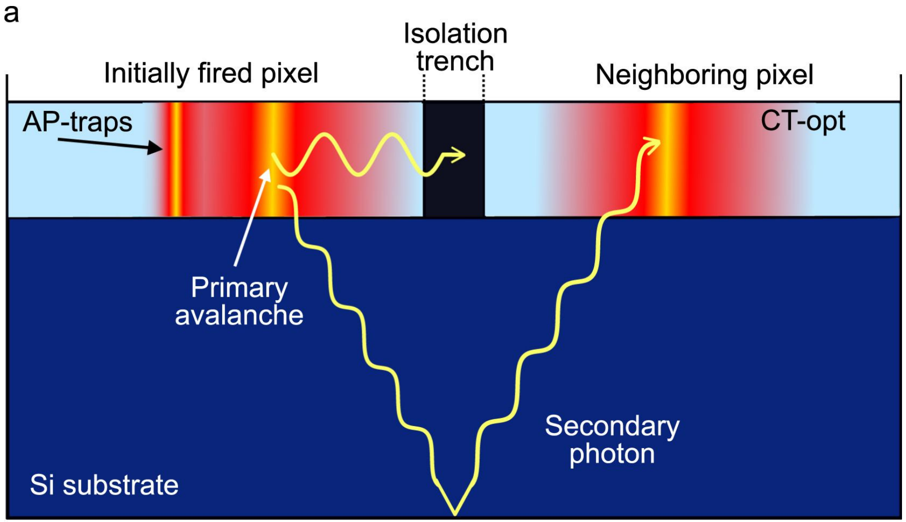


Source : Acerbi, F. & Gundacker, S. (2019) Understanding and simulating SiPMs

Afterpulsing

During an avalanche, an electron can be trapped in a silicon lattice impurity then released in the same cell.

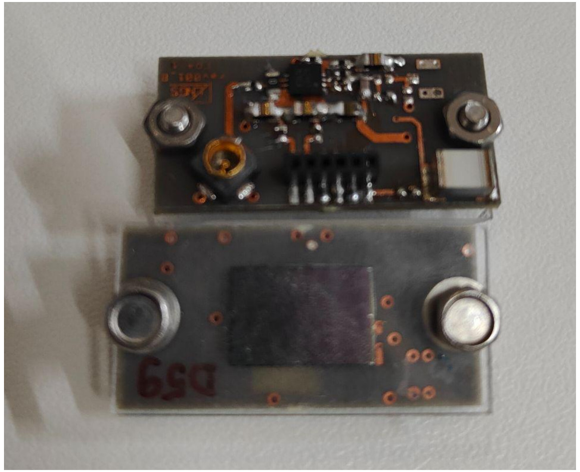
Occurs on the time scale O(100 ns)-O(µs)



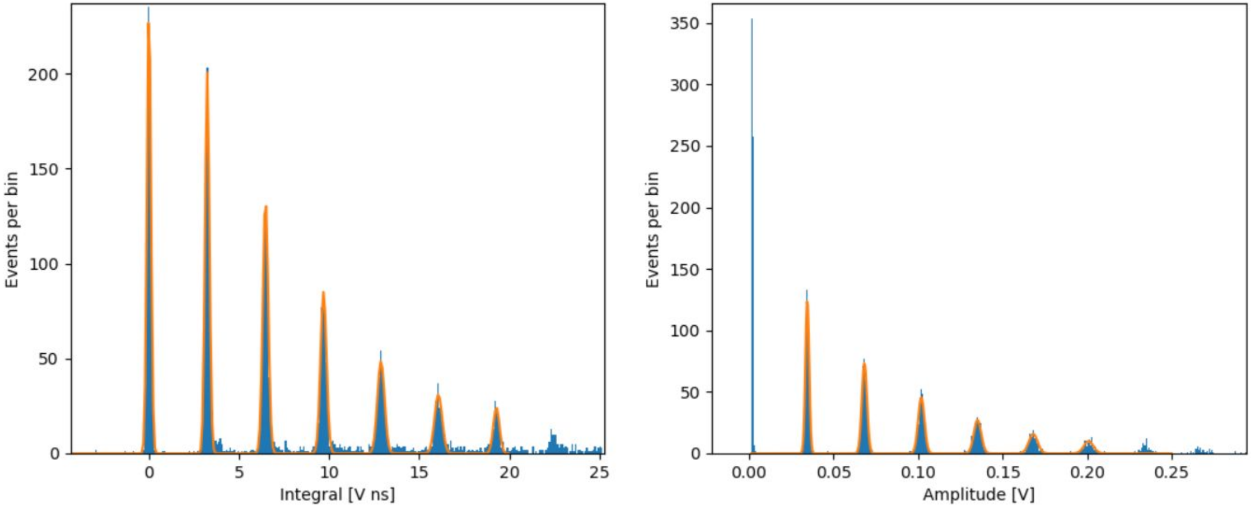
Source : Rosado, J., Aranda, V. M., Blanco, F., & Arqueros, F. (2015). Modeling crosstalk and afterpulsing in Silicon Photomultipliers.

Laser Data

Fitting amplitudes and integrals

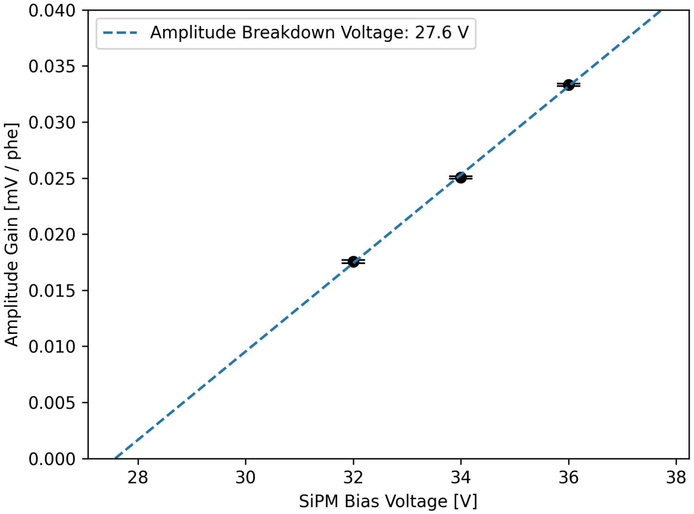


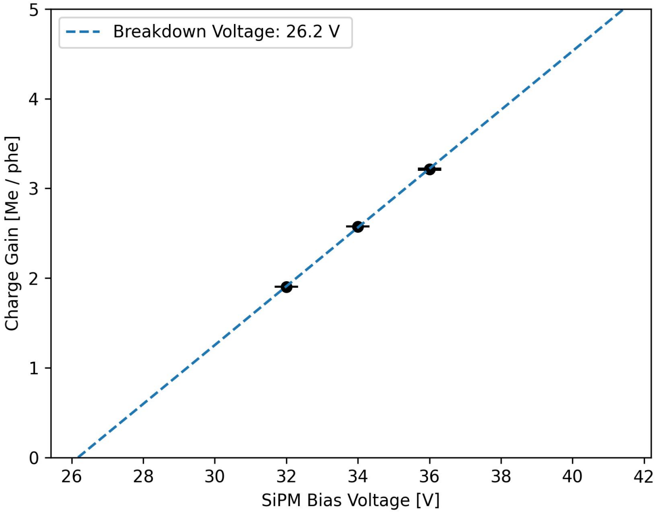
- Charge, Amplitude can be plotted in finger-plots
- Each “finger” represents a multiplicity in SiPM cells
- Calculated baseline before pulse, subtracted the baseline from the waveform.
- The charge is the integral of the rest of the pulse, amplitude is the maximum of the waveform. Fit with gaussians.



Gain Calibration

- Gain can be calculated from Charge, Amplitude Finger-plots
- Results in two distinct breakdown voltages
- Using amplitude breakdown voltage, can define overvoltage
    - Overvoltage = Bias - Breakdown
- SiPMs are able to provide similar charge gain to PMTs





Crosstalk Likelihood Models

$$f_k(p,L) = \frac{\exp(-L)\cdot\sum_{i=0}^{k} B_{i,k}\cdot[L(1-p)]^i\cdot p^{k-i}}{k!}$$

where

$$B_{i,k} = \begin{cases} 1 & \textit{if} \quad i=0 \textit{ and } k=0 \\ 0 & \textit{if} \quad i=0 \textit{ and } k>0 \\ \dfrac{k!\cdot(k-1)!}{i!\cdot(i-1)!\cdot(k-i)!} & \textit{otherwise} \end{cases}$$

Compound / Branching Poisson

$$\lambda_{\mathrm{iCT}}(V) = \xi_{\mathrm{iCT}}\cdot\left(V - V_{bd}^{\mathrm{C}}\right)\cdot P_T^h\left(V - V_{bd}^{A}\right),$$

$$\mathcal{F}_{\mathrm{iCT}}(V) = \delta\cdot\left(1 - \lambda_{\mathrm{iCT}}(V)\right)^{\alpha},$$

$$P_T^h(\Delta \mathrm{V}) = 1 - e^{\frac{\Delta \mathrm{V}}{-\mathrm{V}_h}},$$

$$P_T^e(\Delta \mathrm{V}) = 1 - e^{\frac{\Delta \mathrm{V}}{-\mathrm{V}_e}}$$

Analytical Model

$$\epsilon^{\mathrm{oV}} = -ln\left(\mathcal{R}_0^{\mathrm{oV}}\right),$$

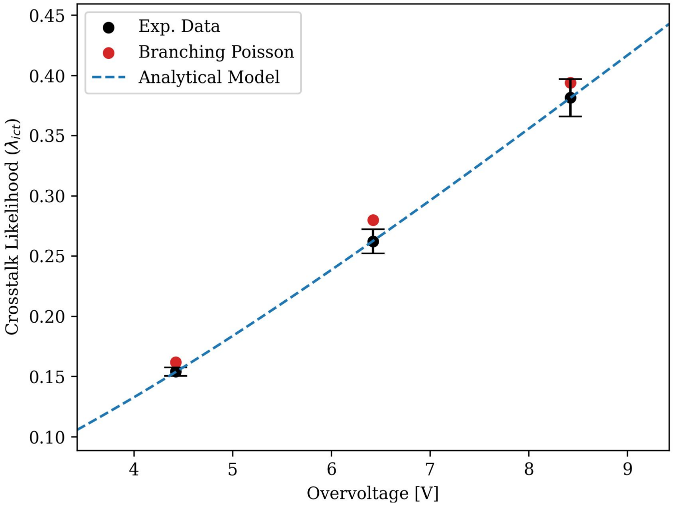
$$\lambda_{\mathrm{iCT}}^{\mathrm{oV}} = 1 - \frac{\epsilon^{\mathrm{oV}}}{\langle n\rangle},$$

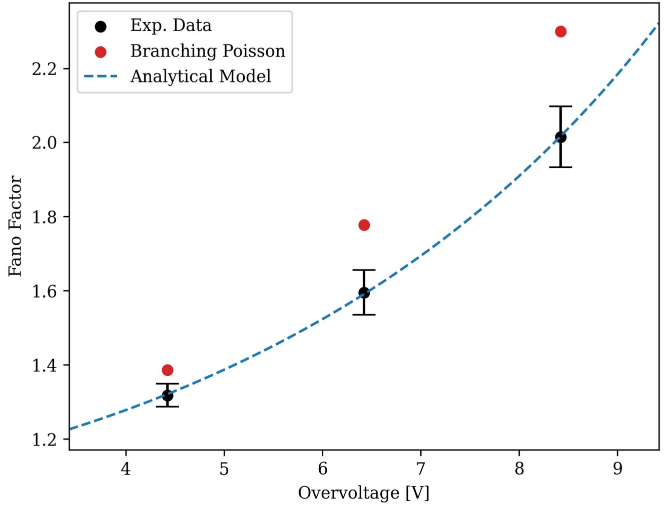
$$\mathcal{F}_{\mathrm{iCT}}^{\mathrm{oV}} = \frac{\mathrm{Var}[n]}{\langle n\rangle},$$

Experimental Data

Crosstalk Likelihood

- From finger-plots, can gain insight on crosstalk likelihood
- Number of detector photons distribution follows poissonian distribution
- Crosstalk likelihood can thus be calculated
- Deviation from poissonian can be also characterized into Fano Factor (variance/mean)
- Traditional Branching Poisson model shows deviations from data





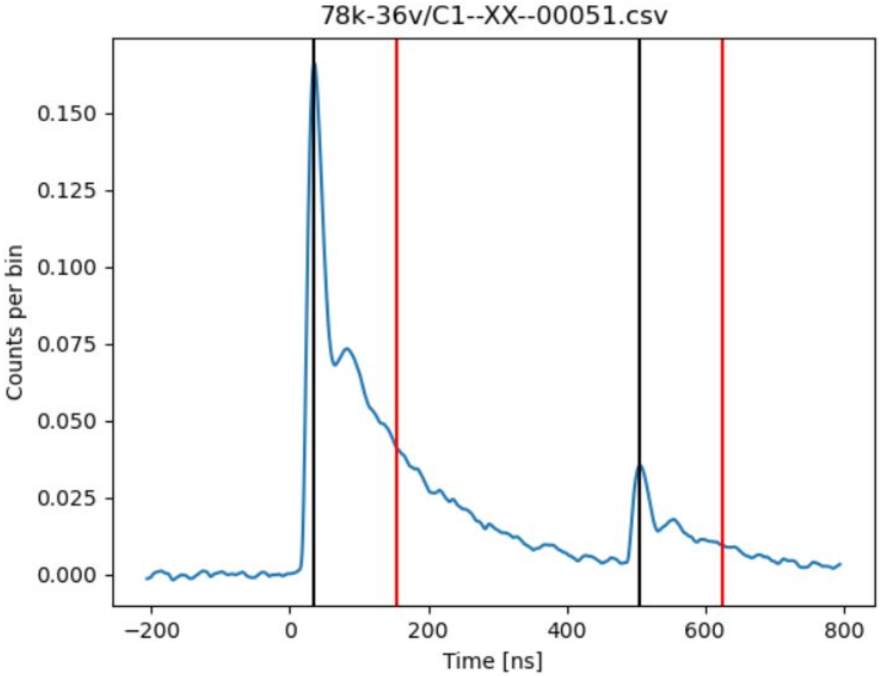
Identifying afterpulsing in data

Tune peak identification function to identify pulses in data.

Function requires some time between pulses and a certain prominence of the pulse above the baseline.

Extract:

- Number of pulses
- Time between pulses
- Amplitudes of each pulse



Afterpulsing as a function of bias voltage

Breakdown voltage ~ 27 V

Applying a higher bias voltage increases the probability of afterpulsing

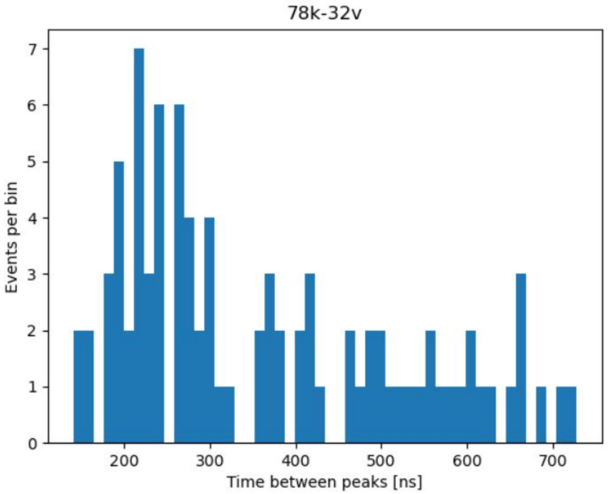
At 36V, 6.31% of events have afterpulsing

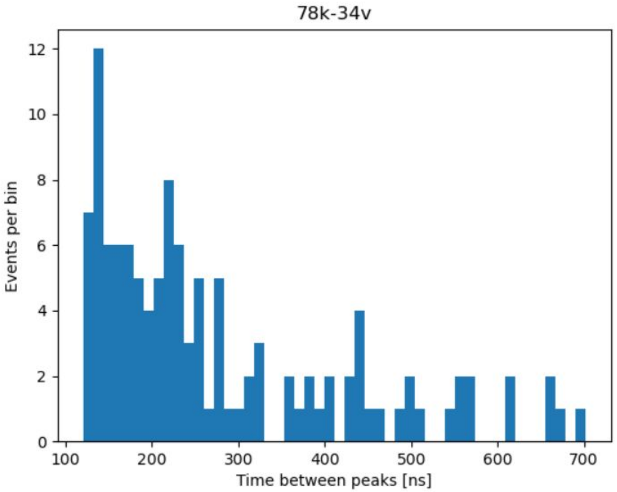
At 34V, 3.83% of events have afterpulsing

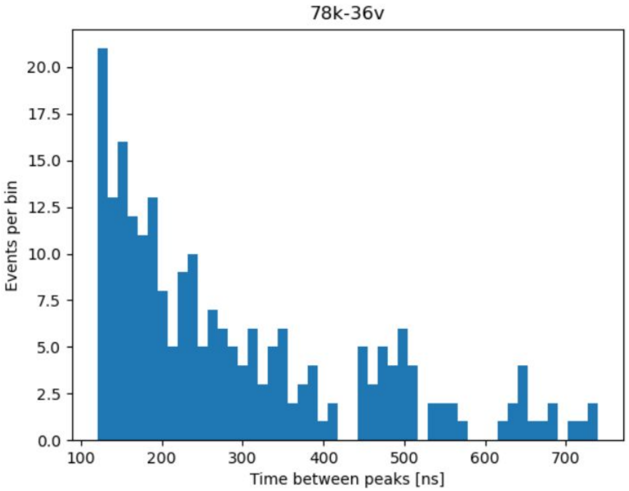
At 32V, 1.39% of events have afterpulsing

Consistent with literature (F. Acerbi, S. Davini, A. Ferri et al., IEEE Trans. Electron Dev. 64(2), 521 (2017)) and (C.E. Aalseth, F. Acerbi, P. Agnes et al., JINST 12(09), P0)

Time between main pulse and afterpulse





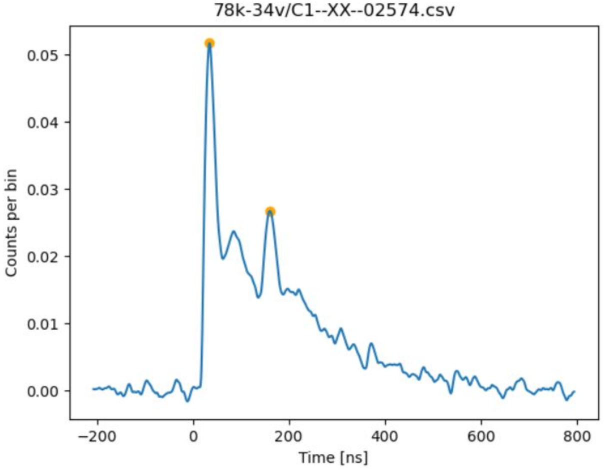


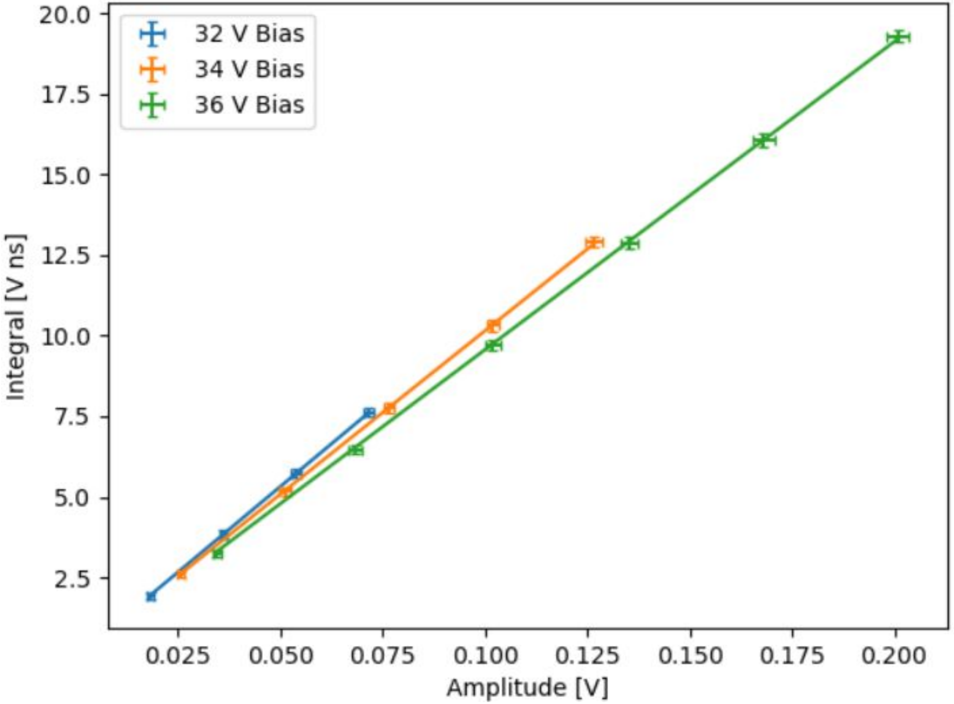
Determining charge in second pulse

T = total integral

$S_1 = k\ A_1$, where k=slope from this plot

$S_2 = T - S_1$

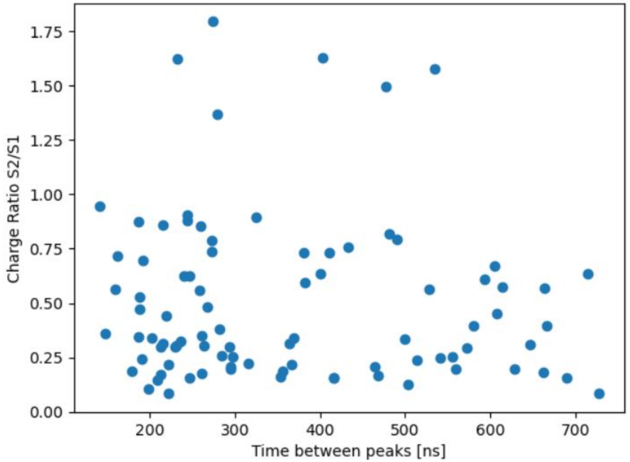




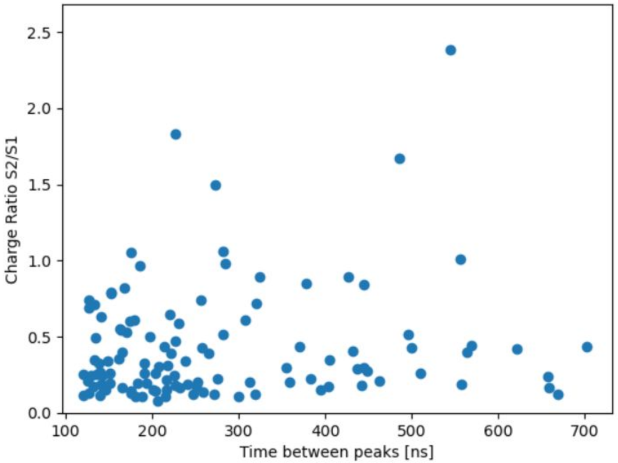
Charge ratio

Afterpulses should be a smaller amplitude (~1 pe) compared to the primary pulse

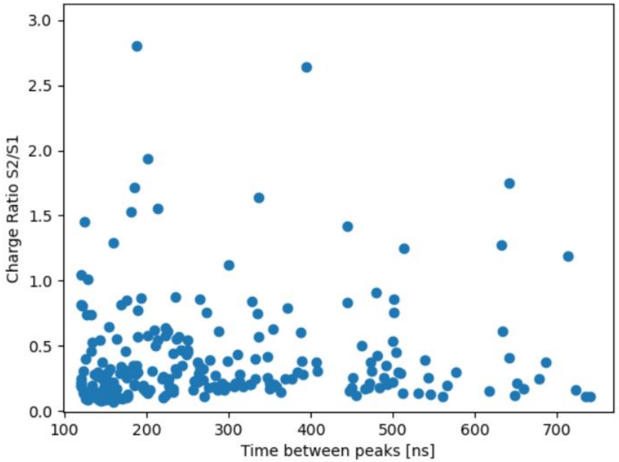
As the pulses become more separated the ratio of S_2 to S_1 should tend to 1. More work needs to be done to properly calculate this.



32 V Bias



34 V Bias



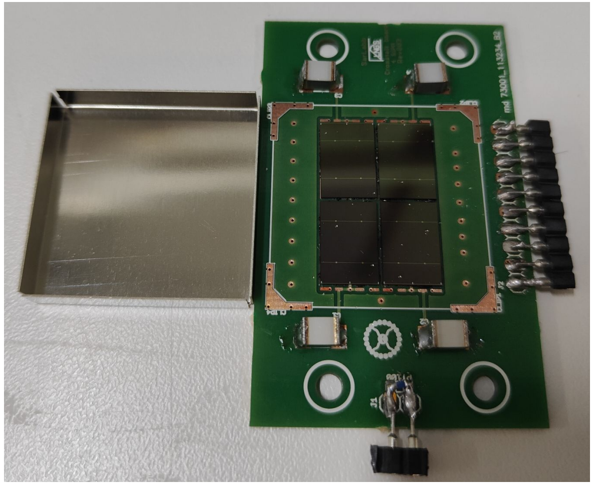
36 V Bias

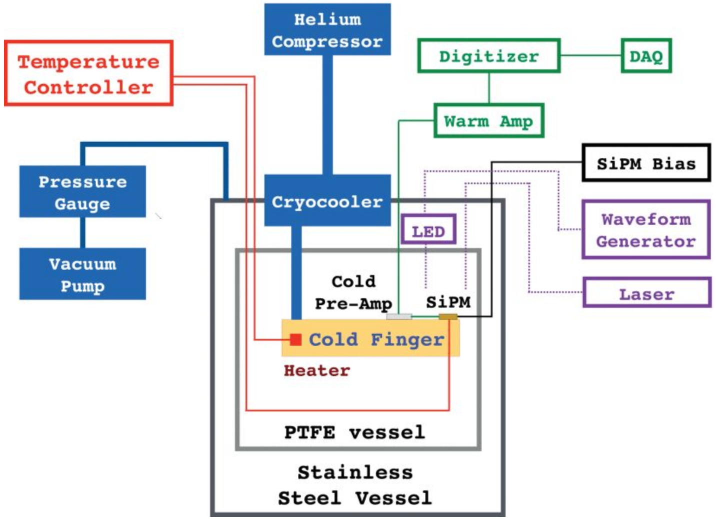
Cryostat Data

Experimental Setup

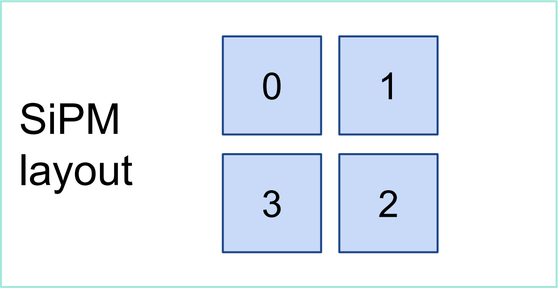
Cryostat set at 80K at around 1 mbar of pressure.

Four SiPMs arranged in a square in cryochamber to reduce noise.





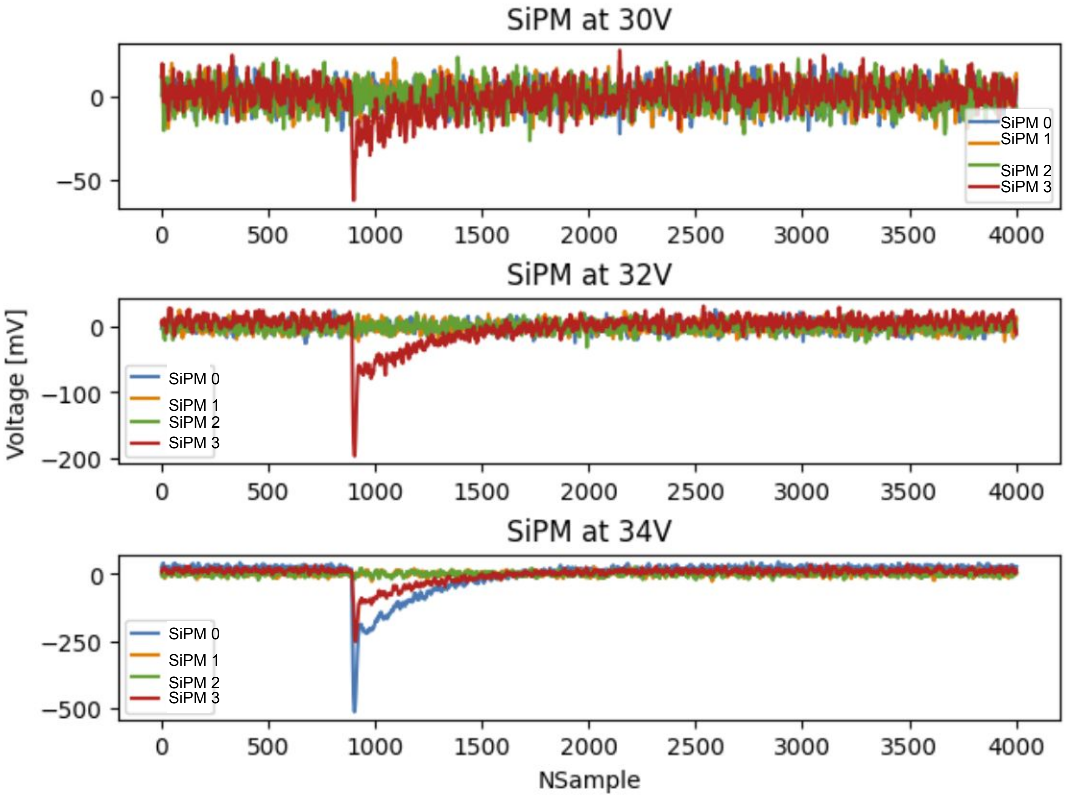
Source : Acerbi, F., et al. (2017). Cryogenic characterization of FBK HD near-UV sensitive sipms.



SiPM layout

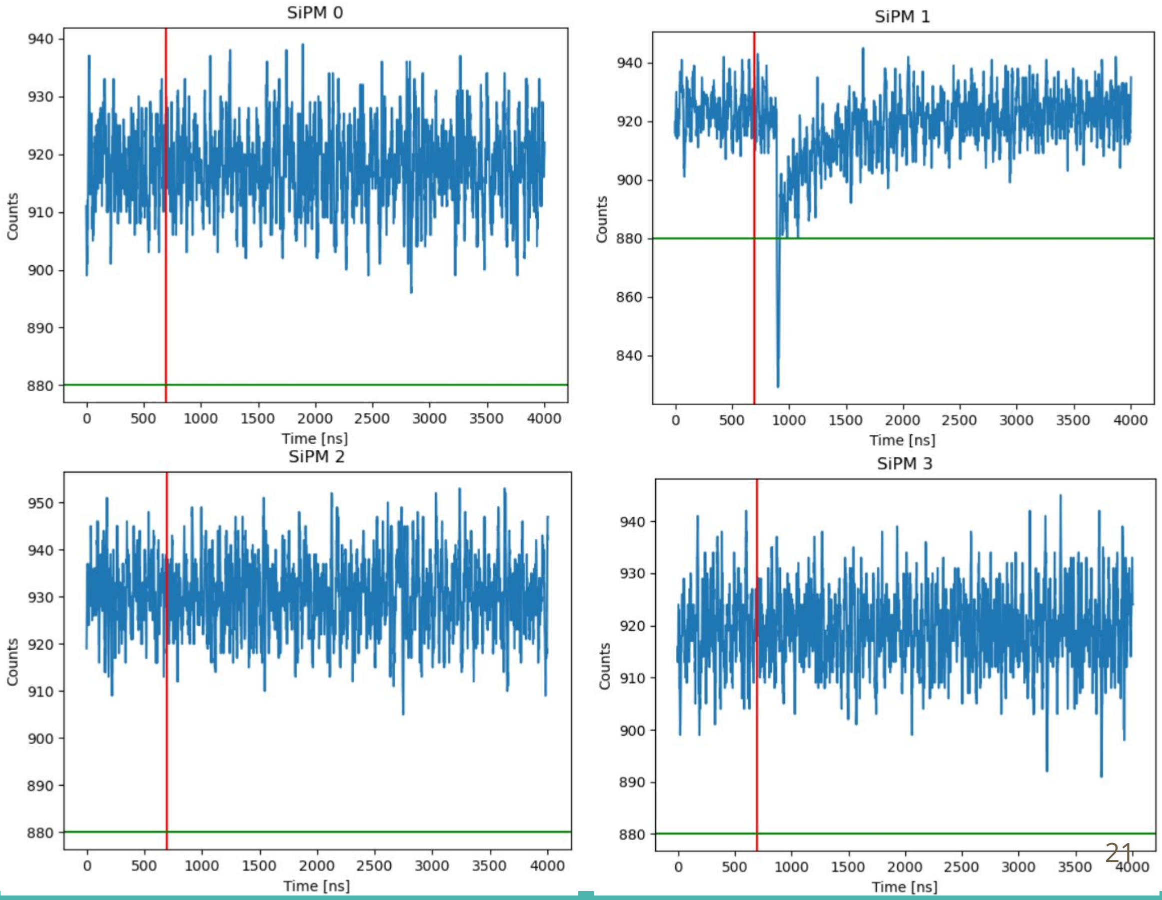
0	1
3	2

Example Waveform



Crosstalk in cryostat data

Example of an events where only a single event passed the trigger threshold.



Observing crosstalk by comparing amplitudes

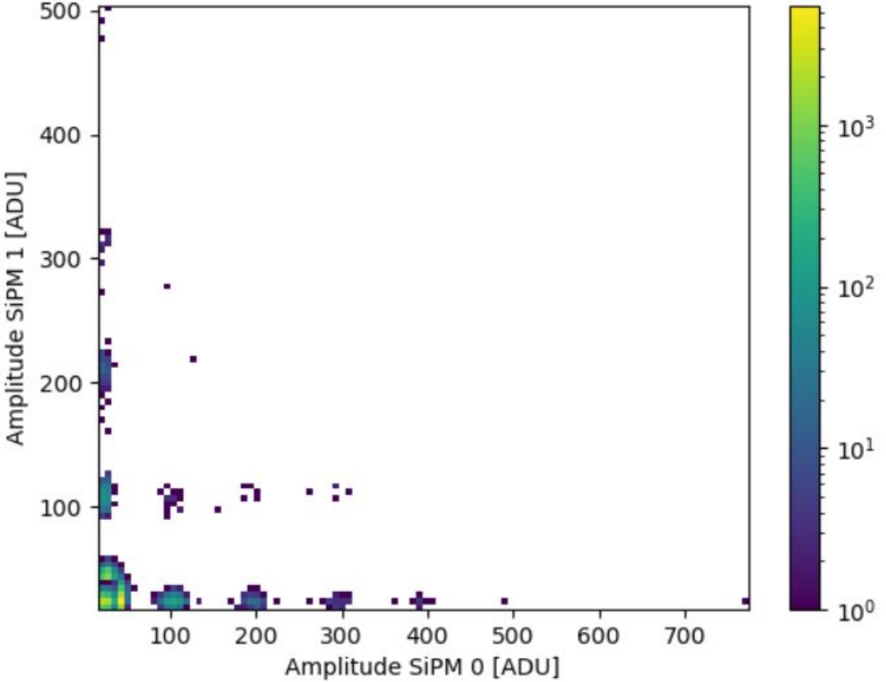
Each event has at least 1 SiPM that passed the trigger threshold. ($n_{trigger} \geq 1$)

If $n_{trigger}=1$: One of the SiPMs will have a higher amplitude, the other will be small.

⇒ Events fall along x or y axes

If $n_{trigger}>1$: At least two SiPMs have pulses producing a higher amplitude.

⇒ Events are in the central region of the plot

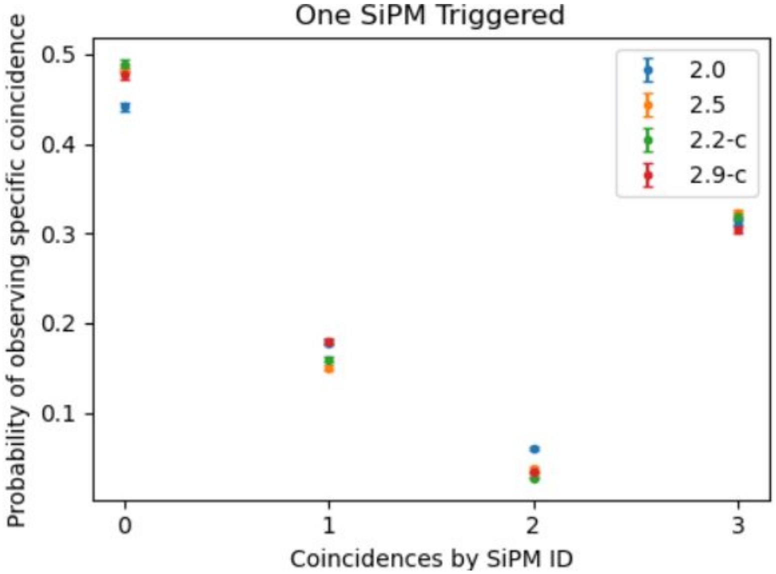


Single SiPM Triggered

Can look at how many SiPMs triggered for a specific event and turn this into the probabilities of observing each unique combination of SiPMs to trigger.

Since these are identical SiPMs we expect the the probability of a single SiPM to have a pulse to be the same for all of them.

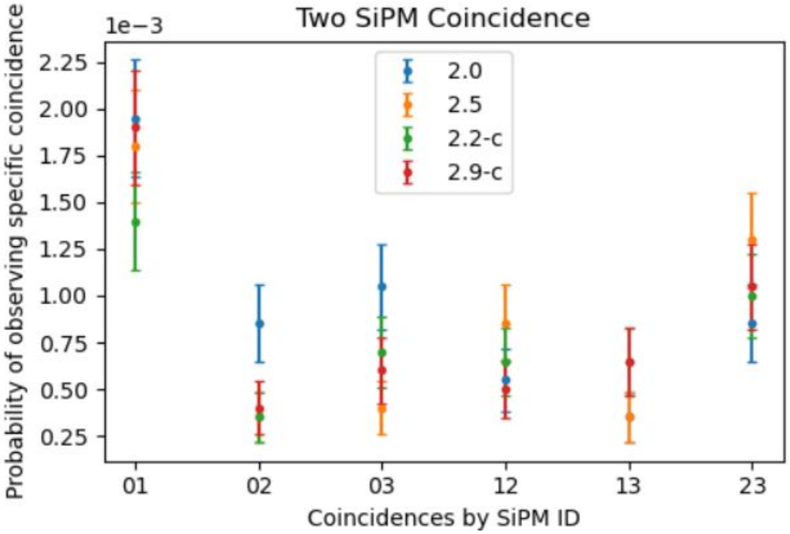
Probabilities are consistent between runs with the same bias voltage

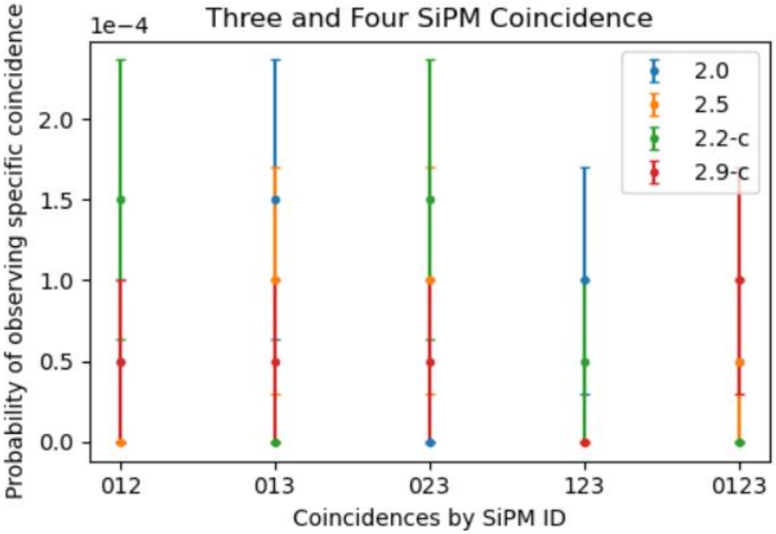


Crosstalk events

Probabilities of observing specific coincidences

E.g. ’01’ is for a pulse past threshold observed in SiPM 0 and 1 in a single event



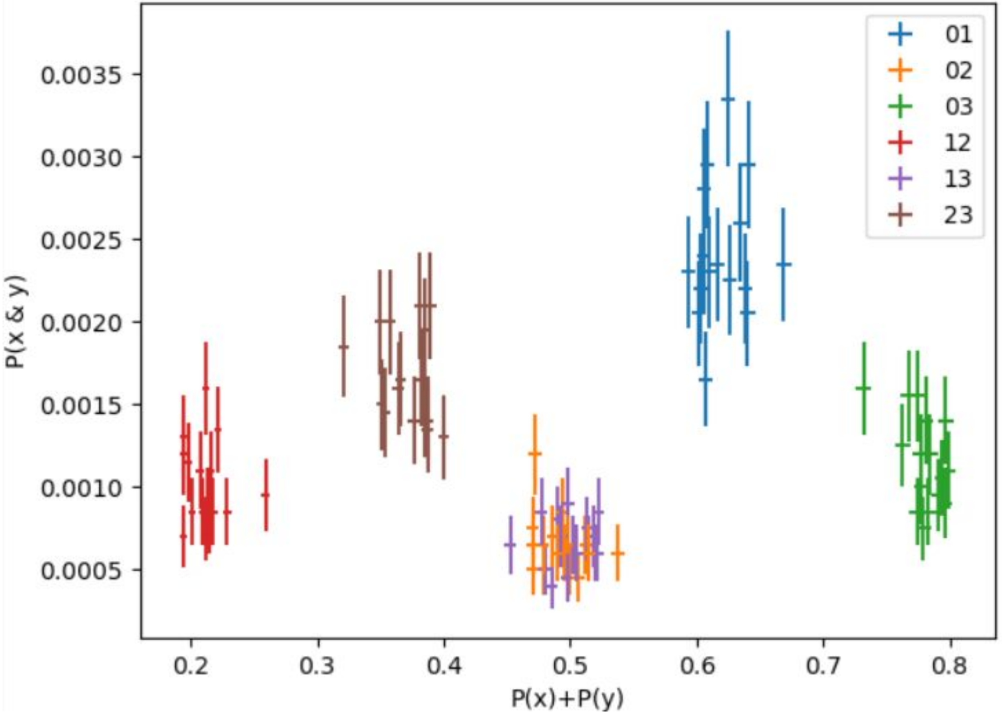


Coincidence Probabilities

For a fixed bias voltage (34 V) and temperature (80K) plotting all runs

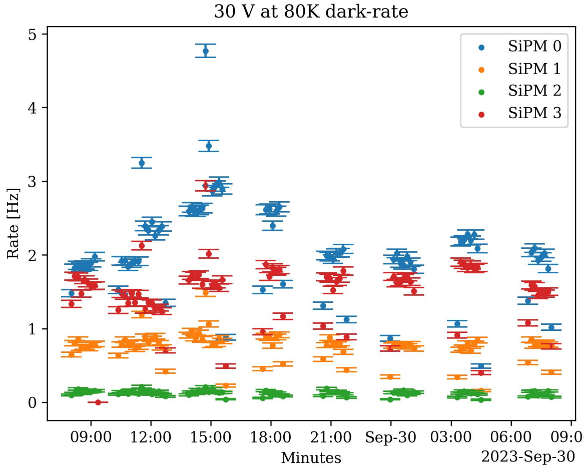
P(x & y) = probability of observing coincidence between a pair of SiPMs, no signal in other two

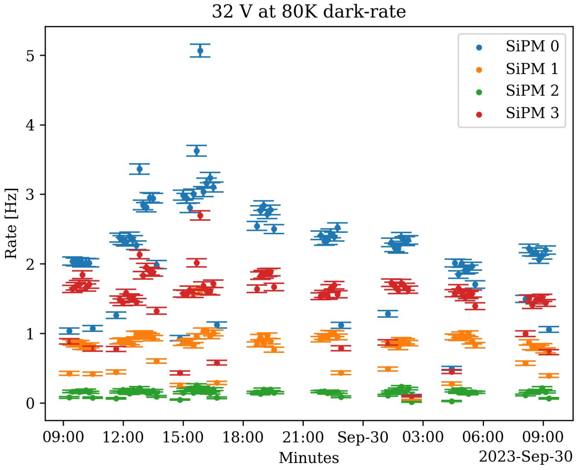
P(x)+P(y) = sum of probabilities of observing only a single pulse in a given SiPM, no signal in other three

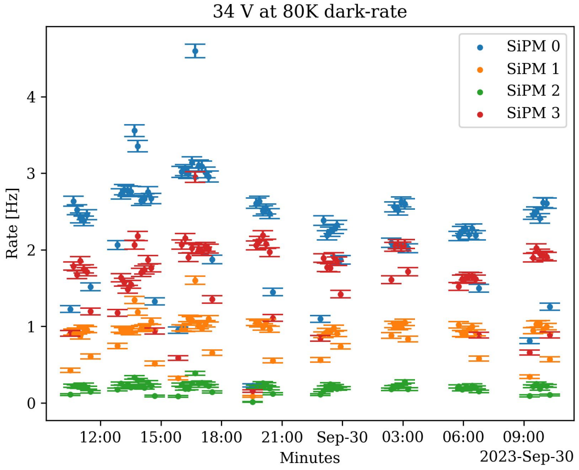


Dark Rate

- Overvoltage has minimum effect on dark rates
- Large fluctuations between SiPMs
- Unknown uptick observed Saturday at ~3pm


30 V at 80K dark-rate


32 V at 80K dark-rate


34 V at 80K dark-rate

Overview

- SiPMs are sensitive, cheap, LAr compatible, alternative to PMTs
- Observe non-negligible indiscriminable cross-talk
- Have intrinsic dark-rates, and afterpulsing comparable to PMTs
- With further research and improvements, SiPMs will play a crucial role in the future of a broad span of physics
- Additional research and development should hopefully increase consistency in manufacturing

Questions?