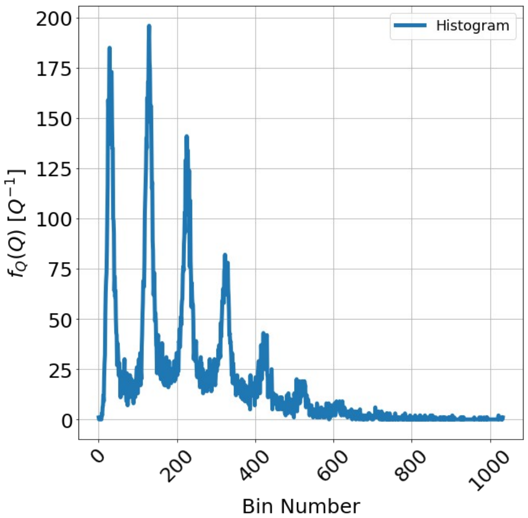
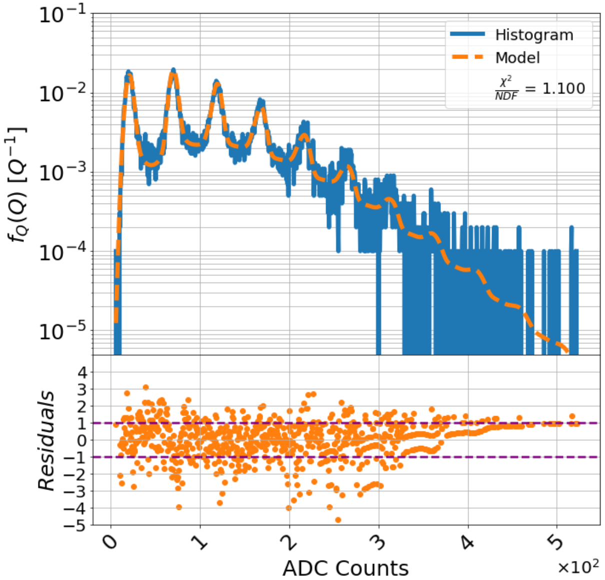
PeakOTron: A Tool For SiPM Characterisation





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High-D Consortium Meeting

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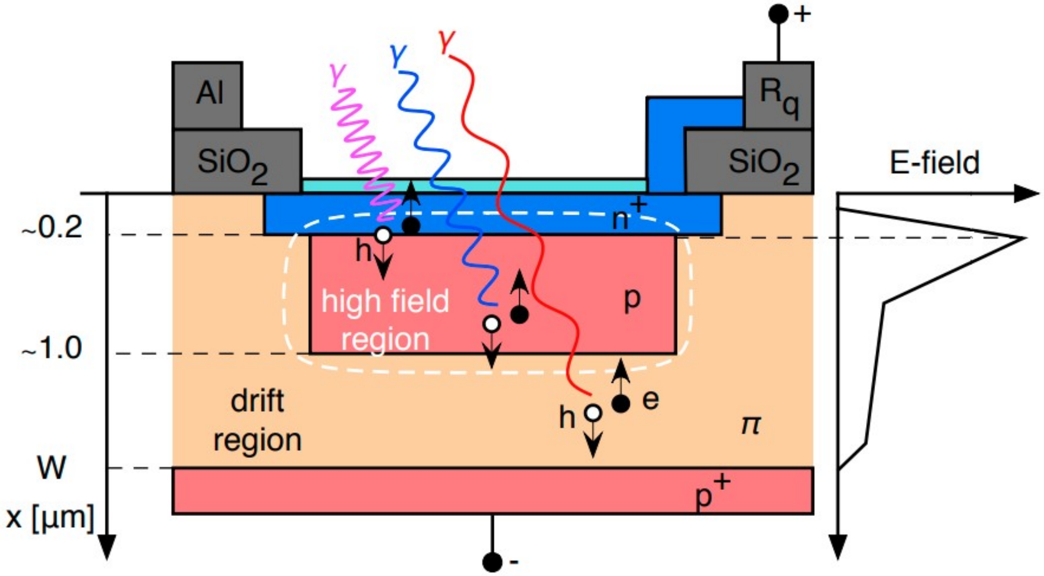
What is a SiPM?

- A Silicon Photomultiplier (SiPM) is a photo-detector operating in the red-to-near-ultraviolet frequency range;
  - This type of detector has several useful properties:
    - high photon-detection efficiency (>50%);
    - good time resolution (< 100 ps);
    - low noise;
    - single-photon counting capability;
    - insensitivity to magnetic fields;
  - How it works:
    - incident photons induce the photo-electric effect in silicon;
    - the p-n junction is operated in reverse bias above the breakdown point;
    - the charge carriers accelerate in a very high electric field region (>300 kV/cm);
    - Geiger avalanche produces $10^5 - 10^6$ electrons for one photon and allows single photon counting.



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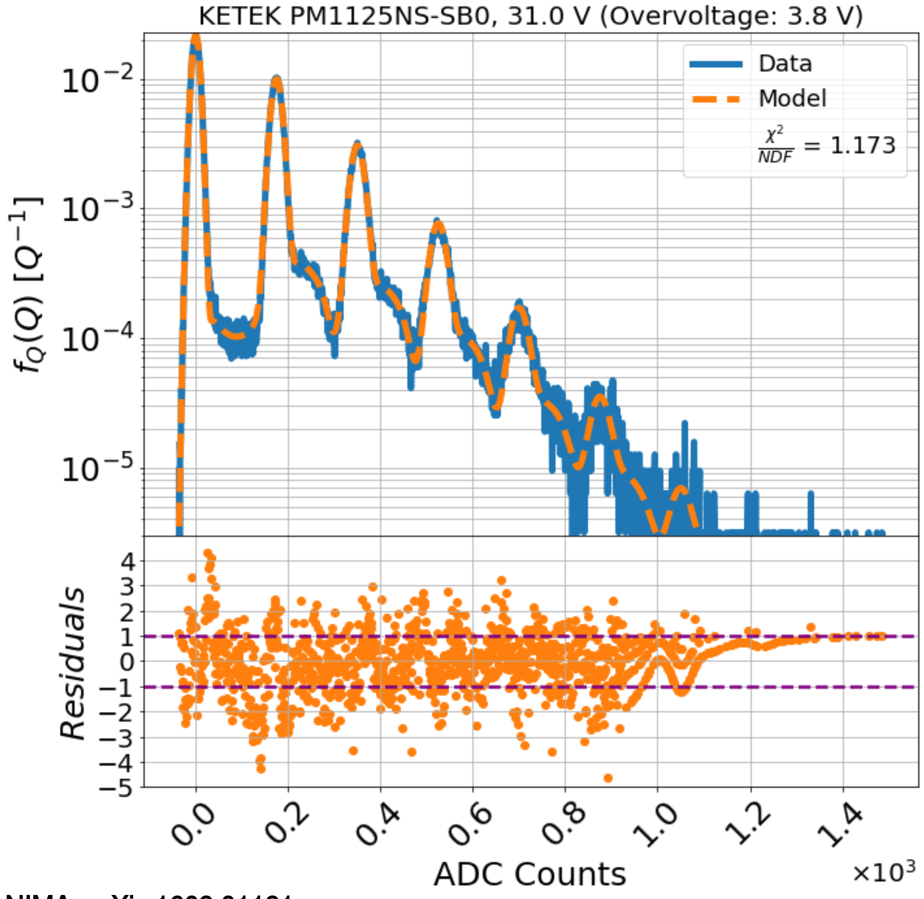
Modelling SiPMs

- The response of an SiPM to low light intensity presents the typical single-photoelecectron structure: it is possible to count photons.
- There are many benefits of fitting the whole spectrum, describing the full behaviour of the device:
  - Characterising SiPMs according to a physical model allows a measurment of devices under different operating conditions (temperature, fluence);
  - Can provide mass characterisation for experiments consisting of many SiPMs i.e. CALICE AHCAL;
- UHH Detector Group has developed a model to describe single photon spectra [1] determining, among other quantities:
  - Primary Geiger discharge peaks;
  - Cross-talk;
  - Afterpulsing probability;
  - Dark count rate;
- The model is high-dimensional and complex: requires careful parameter pre-estimation.

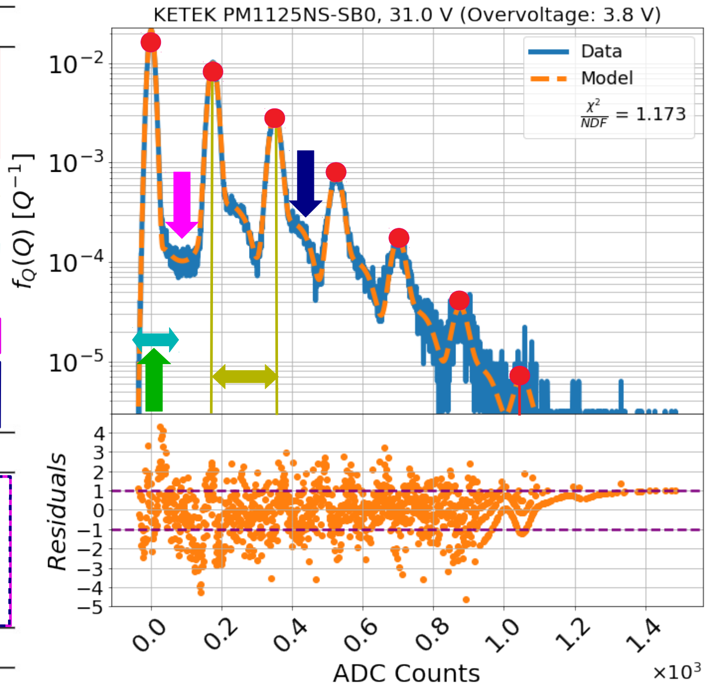


[1] V. et al Chmill. "On the characterisation of SiPMs from pulse-height spectra". In: NIMA arXiv:1609.01181

Model overview

- Model consists of 9 free parameters, and 3 fixed user parameters.
- Main underlying assumptions:
  - Primary Geiger discharges are distributed according to a Generalised Poisson distribution (Poisson with cross-talk branching) i.e. under illumination by laser;
  - Afterpulses are binomially distributed with time-dependent probability;
  - Dark discharges are Poisson distributed and uniformly distributed in time;
  - The time constant of the SiPM pulse is approximately the same as its recovery time.
  - Proportion of fast component of the SiPM pulse is small relative to the slow component.
- MAIN PURPOSE OF PEAKOTRON:
  - Pre-estimate, in a consistent and stable manner, as many model parameters as possible and perform a fit to data.

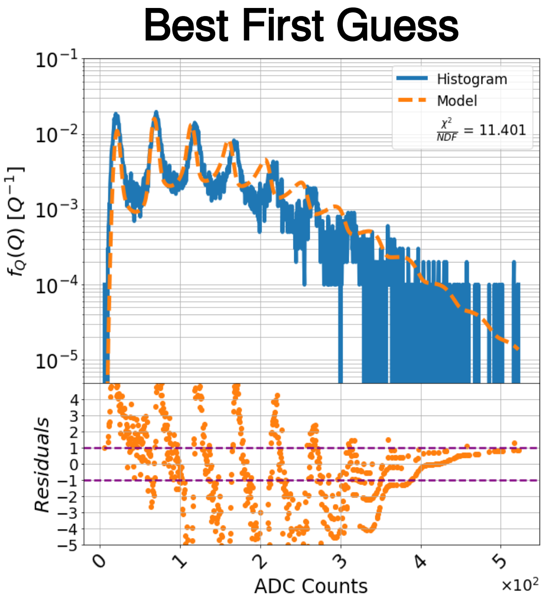
Parameter	Definition
Free	
μ_{GP}, $\langle N_{pG} \rangle$	Mean number of primary Geiger discharges
λ_{GP}	GP-distribution λ
G	Gain
Q_0	Pedestal position
σ_0	Pedestal width
σ_1	Electronics noise width
DCR	Dark Count Rate
p_{AP}	Afterpulse probability density
τ_{AP}	Afterpulse time scale
Fixed (Input)	
$\tau \pm \mathrm{d}\tau$	Slow time-scale of SiPM Pulse
$t_0 \pm \mathrm{d}t_0$	Total integration time before gate, relative to gate start
$t_{gate} \pm \mathrm{d}t_{gate}$	length of integration gate
Fixed (Calculated)	
$i^{\max}_{\text{light}}$	Max # light discharges
$i^{\max}_{\text{dark}}$	Max # dark discharges

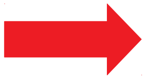


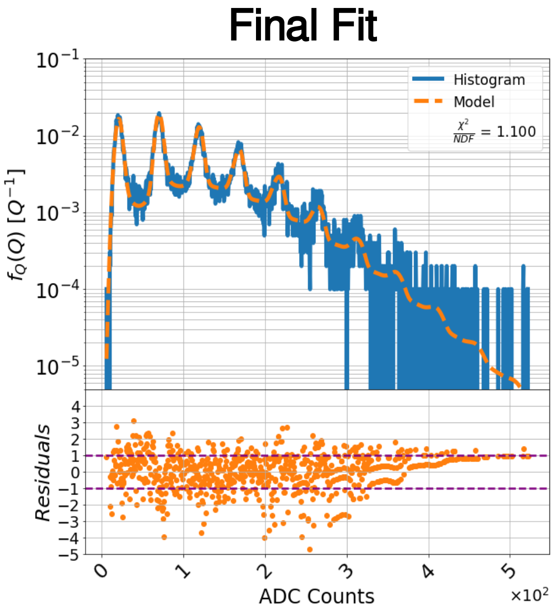
PeakOTron: what it does

- PeakOTron is a Python program that estimates the expected parameters for the distribution automatically from input and then fits the model described in the previous slide.

  Data can be provided in the format of either:
  - A pre-existing histogram, or;
  - raw unbinned discharge measurements.
- More information on the process in the backup slides;
- Model fit can be performed with both unbinned or binned likelihood fits;
- MIGRAD and HESSE algorithms from Minuit [2] used as the fitting/error routines;
- Produces a fitted charge spectrum, with errors on parameters.
- The agreement of model with simulation, obtained from [3]
- is typically in the order $\chi^2=1$;







[2] iminuit URL:https://pypi.org/project/iminuit/

[3] E. Garutti et al. "Simulation of the response of SiPMs; Part I: Without saturation effects". In:NIMA, arXiv:2006.11150

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Validation on simulation

- The fitting tool was validated on simulation from [3].
- A set of 100 simulations were made of 20,000 events in steps, relative to a baseline, over a scan range indicated by the table on the right.
- The median and robust standard deviation of the output values are used as summary statistics:

$$\sigma \simeq 1.4826\ \mathrm{MAD}$$

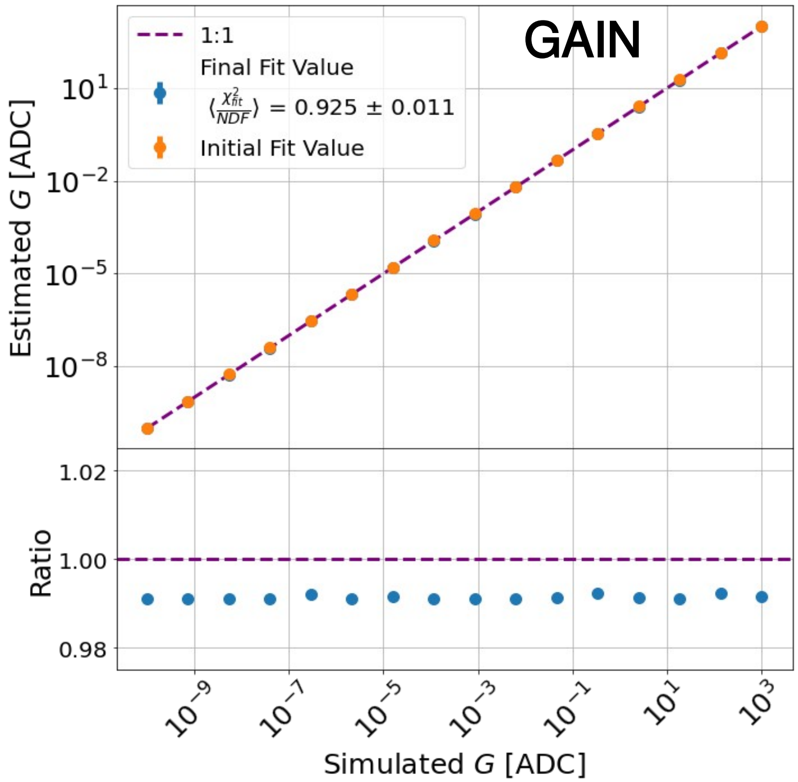
where MAD is the median absolute deviation.

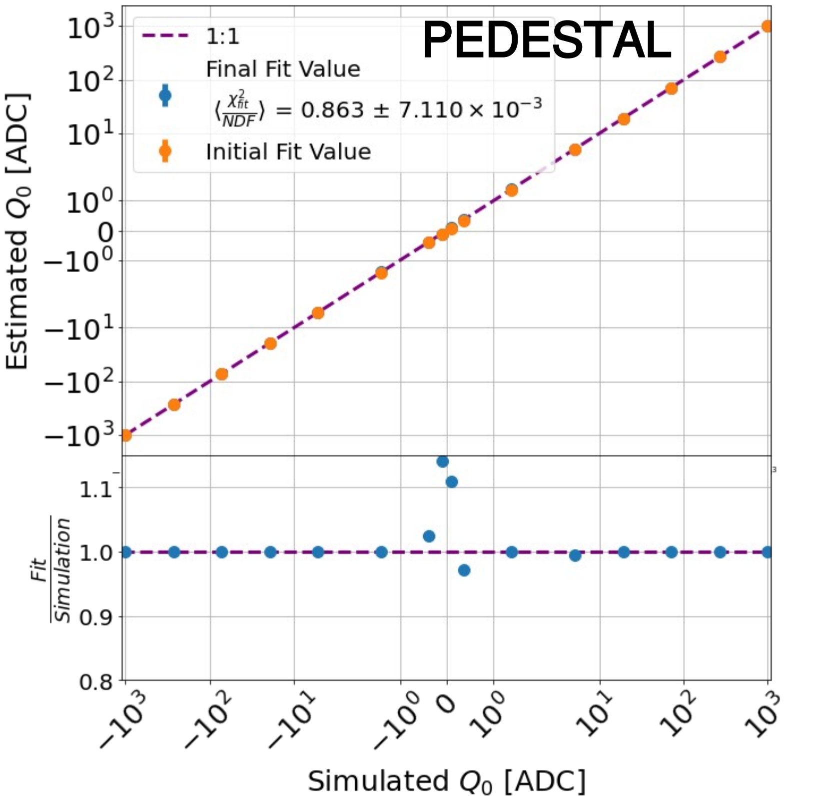
- In the following, the median and robust standard deviation are presented

Parameter	Baseline	Scan Range	Scaling
μ_{GP}	$1\mathrm{p.e}$	$0.5 - 8\mathrm{p.e}$	linear
λ_{GP}	$p_{pXT} = 0.1$	$0.01 - 0.3(p_{pXT})$	linear
	$p_{dXT} = 0.1$		
G	$50\mathrm{ADC}$	$1 \times 10^{-10} - 1 \times 10^{3}\mathrm{ADC}$	logarithmic
Q_0	$20\mathrm{ADC}$	$-1 \times 10^{3} - 1 \times 10^{3}\mathrm{ADC}$	logarithmic
σ_0	$0.075G^{-1}$	$0.02 - 0.15G^{-1}$	linear
σ_1	$0.02G^{-1}$	$0.02 - 0.15G^{-1}$	linear
DCR	$1 \times 10^{-4}\mathrm{GHz}$	$1 \times 10^{-4} - 1 \times 10^{-2}\mathrm{GHz}$	logarithmic
p_{Ap}	0.1	$0.01 - 0.3$	linear
τ_{Ap}	$7.5\ \mathrm{ns}$	$4 - 19\ \mathrm{ns}$	linear
τ	$20\ \mathrm{ns}$	–	constant
t_0	$100\ \mathrm{ns}$	–	constant
t_{gate}	$100\ \mathrm{ns}$	–	constant
r_{fast}	0.1	–	constant

Validation on simulation – selected results

- The estimated gain and pedestal agree within 1% for all studied values;



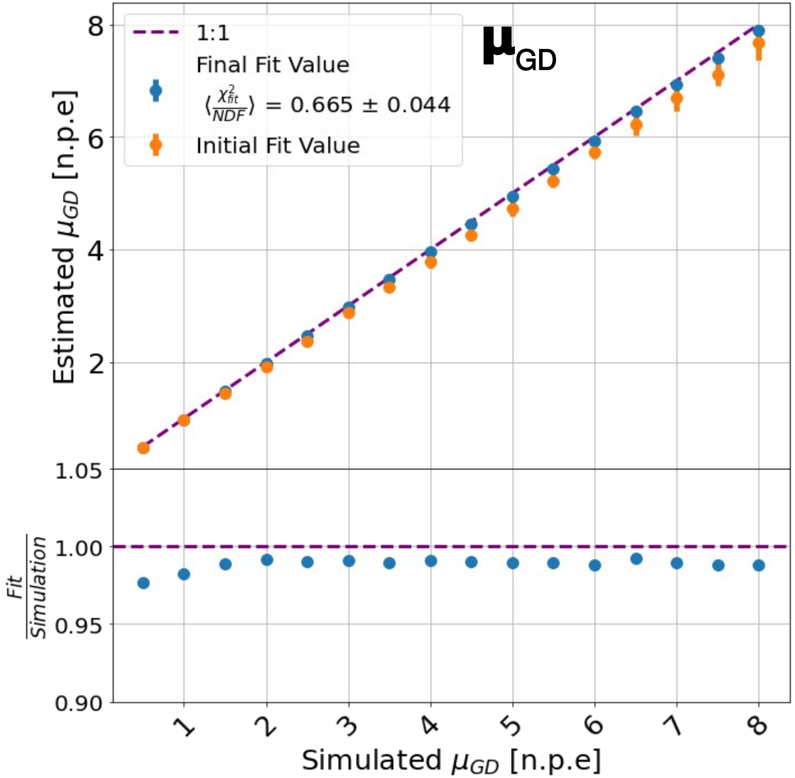


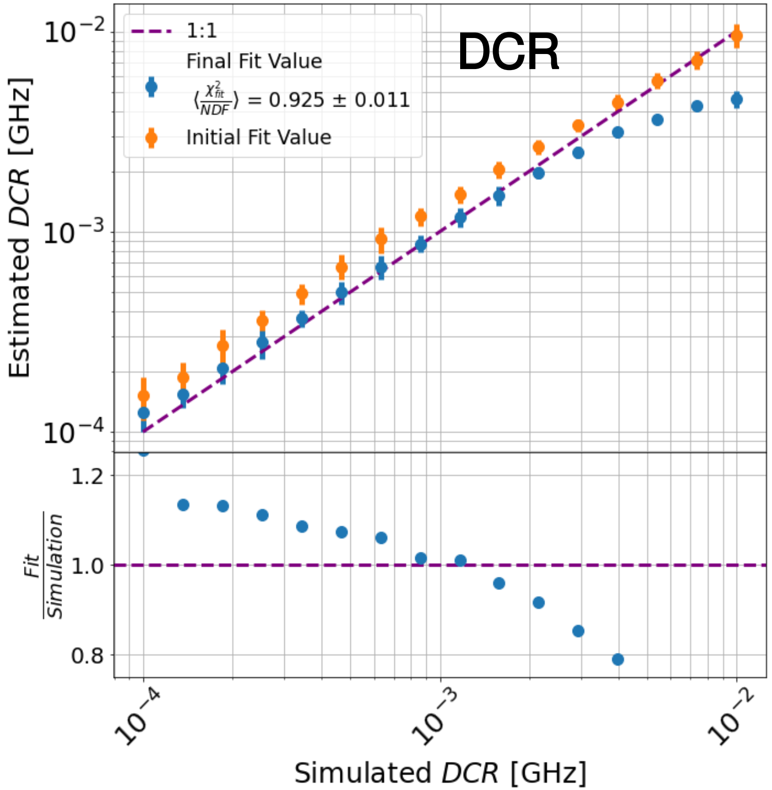
Validation on simulation – selected results

- The estimated mean number of Geiger Discharges (μ_{GD}) agrees within around 1-3% for all studied values;

- The estimated DCR agrees within 10% up to 4 MHz;

  (Note: DCR model currently limited to 4th order discharges, can resolve in future with higher-order terms)

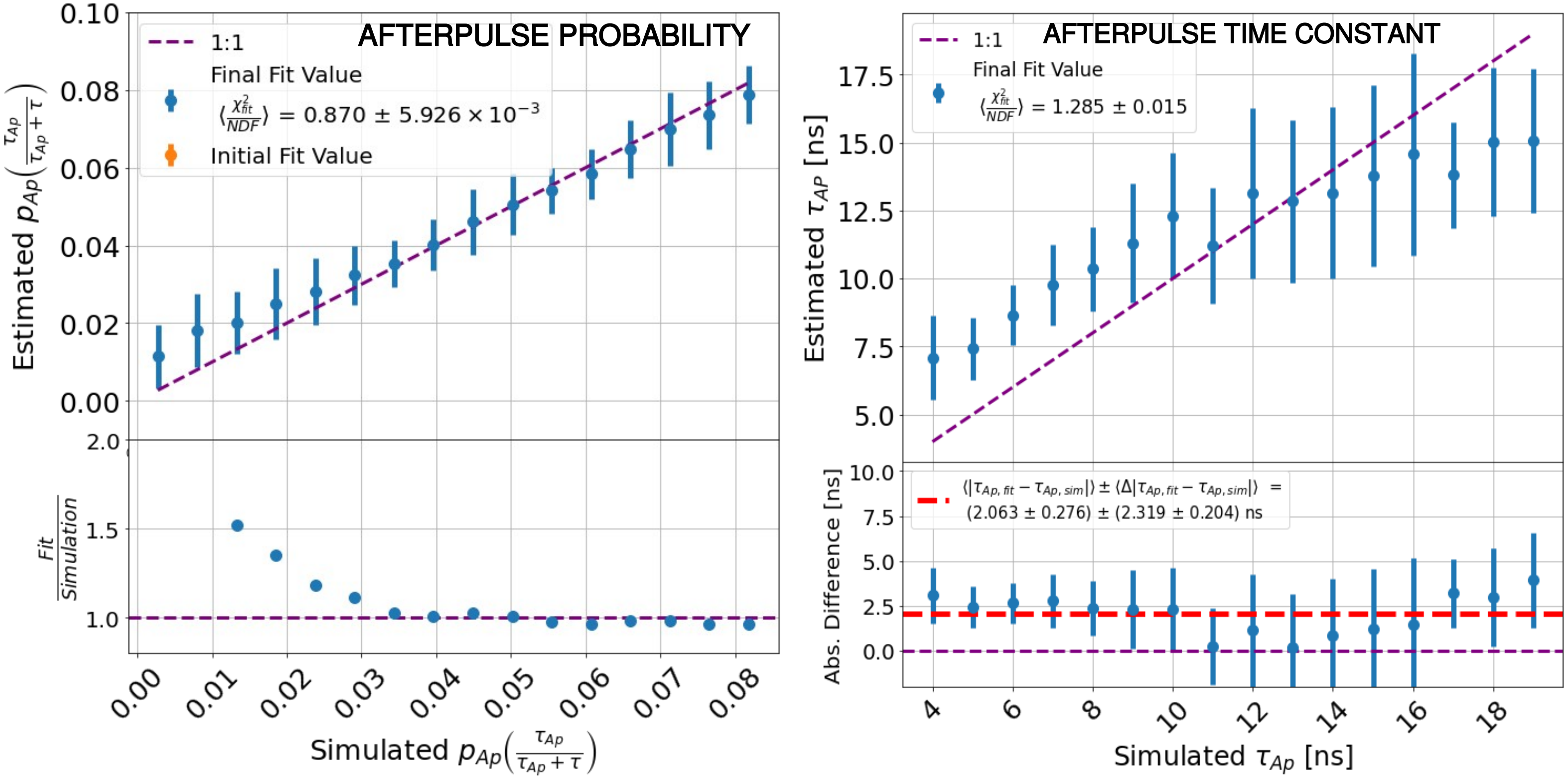




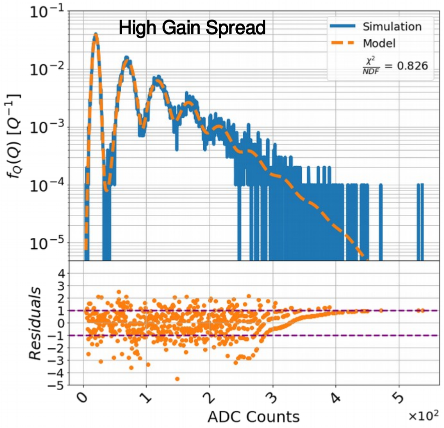
Validation on simulation – selected results

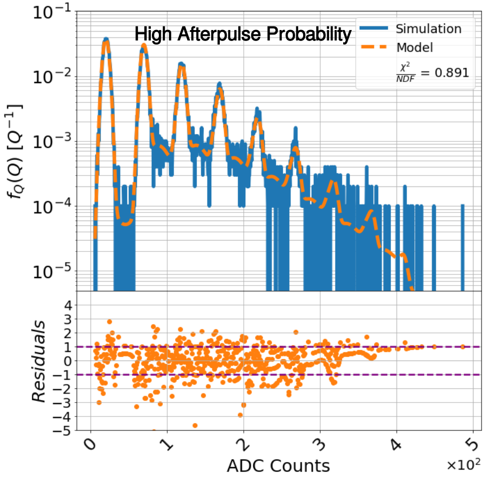
- Median afterpulse probability estimated within 1% for probabilities above 3%;
- Median afterpulse time constant resolvable with 2 ± 2.3 ns precision for 20,000 events.

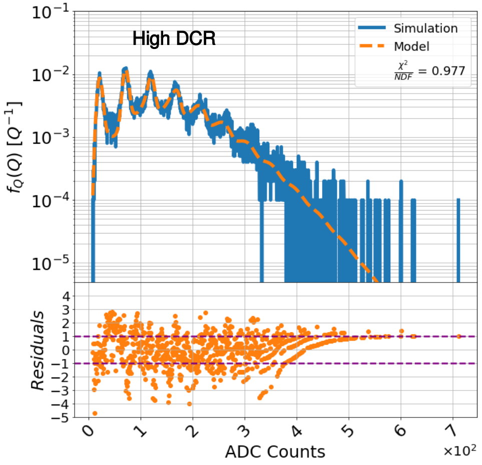
(Note: Model does not yet incorporate afterpulses induced by dark counts.)

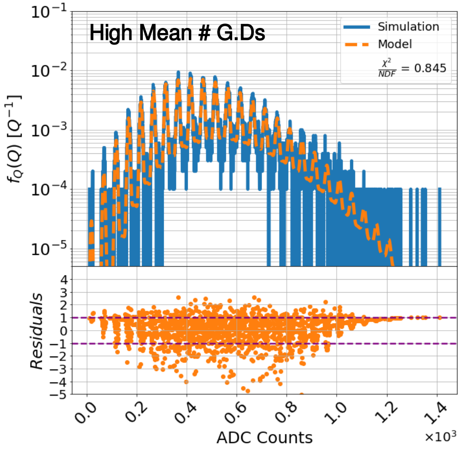


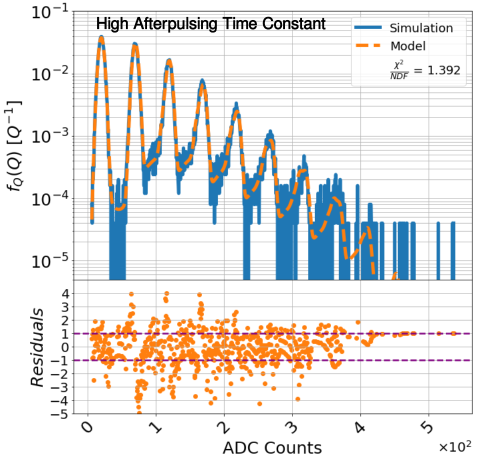
Simulation – example fits









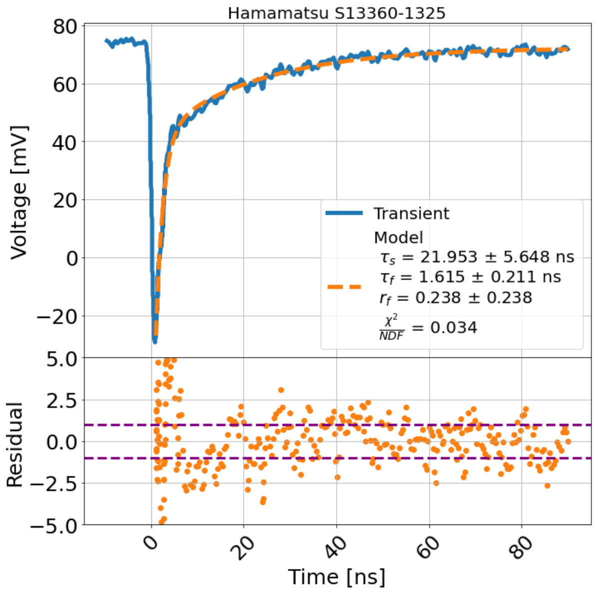


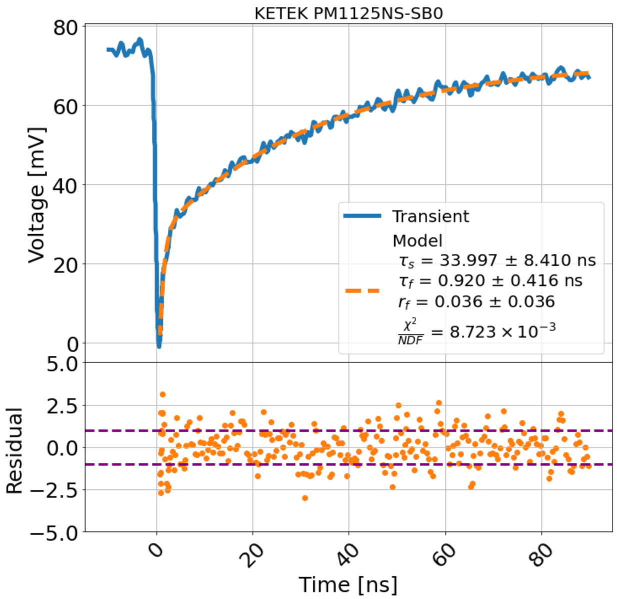
- Model can describe a variety of different photoelectron spectra with different parameters.

Measurement of experimental data

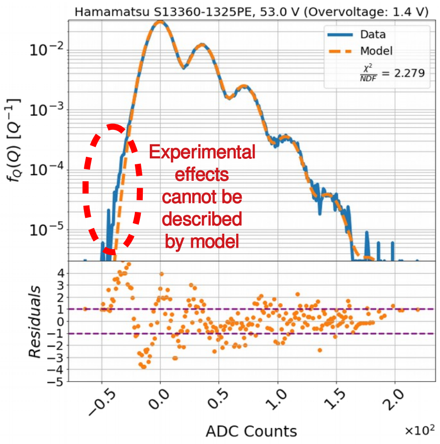
- Fits were made of two SiPM brands as a function of increasing overvoltage:
  - KETEK PM1125NS-SBO
  - Hamamatsu S13360-1325
- For each case:
  - Gate Length = 104 ns
  - Pre-Gate Integration Time = 64 ns
  - Slow time constants extracted from a single transient fit;
    - Hamamatsu: τ = 22.0 ± 5.7 ns
    - KETEK: τ = 34.0 ± 8.4 ns
- PeakOTron was applied to the measured spectra and the results evaluated.

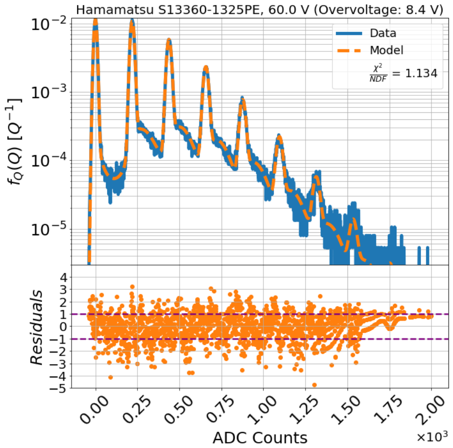
Sensor	Eff. area [mm^2]	Pixel size [μm]	Pixels	PDE [%]	Gain [$\times 10^6$]	Typ. DCR [kHz/mm^2]	V_{bd} [V]
PM1125NS-SB0	1.2×1.2	25	2304	25	1.5	210	27.3
S13360-1325PE	1.3×1.3	25	2668	30	0.7	41	51.1



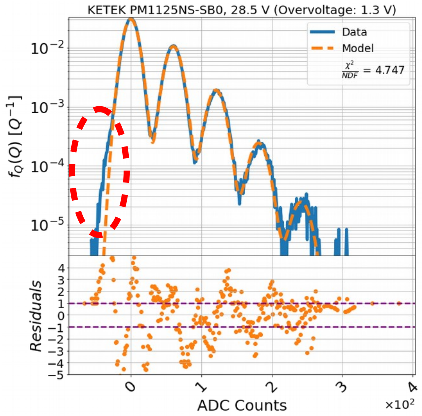


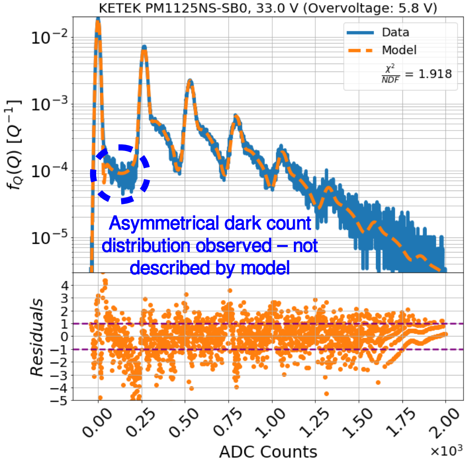
Experimental data – example fits



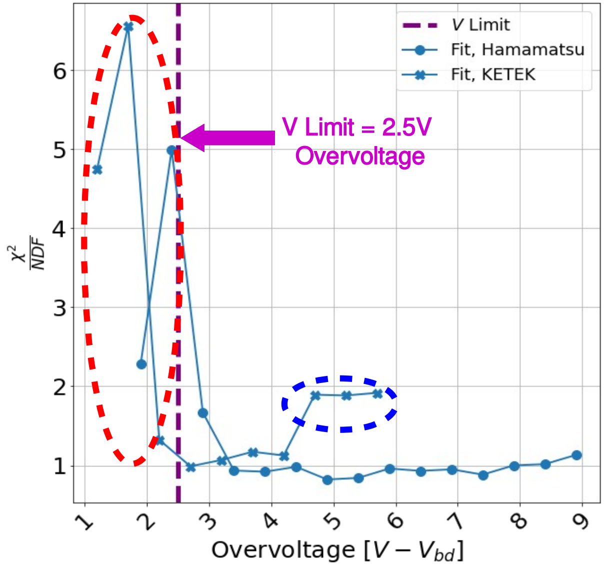


Increasing Overvoltage





χ^2 Goodness Of Fit



Below 2.5 V overvoltage:

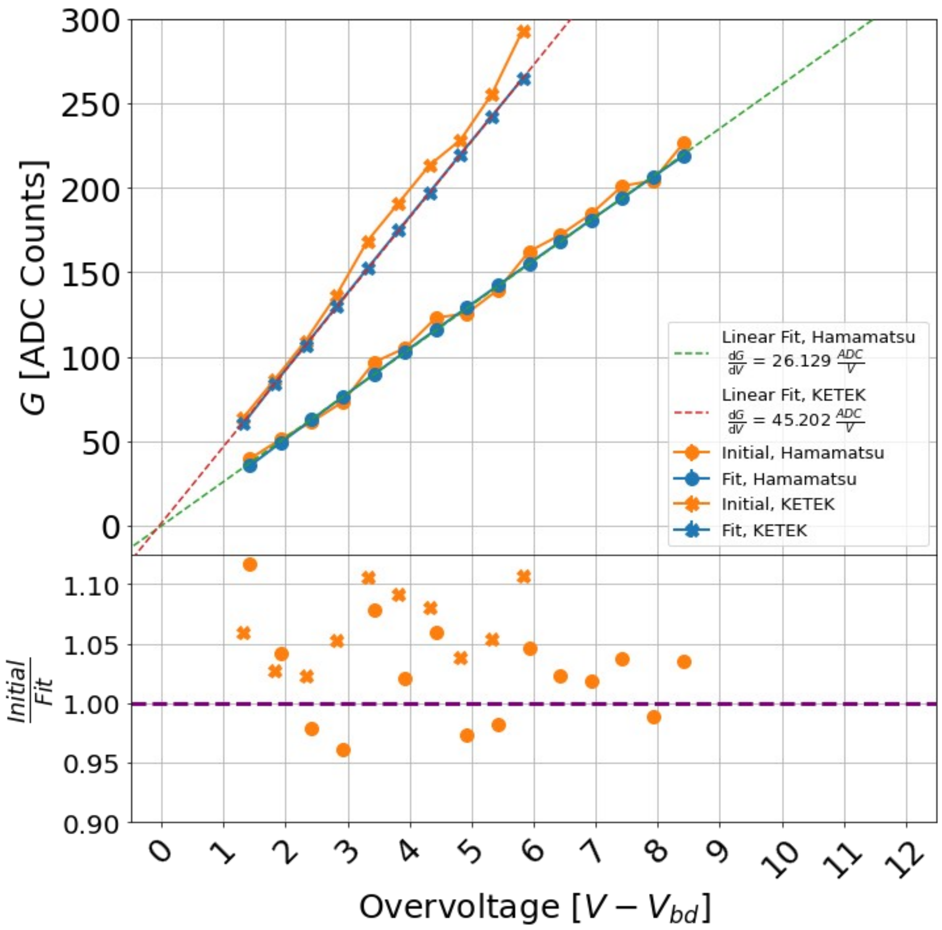
- experimental effects before pedestal increase χ^2;
- no gaps between G.D peaks means unreliable afterpulse/ DCR measurements.

Above 2.5 V overvoltage:

- Most measurements consistent with χ^2=1;
- Asymmetrical dark count distribution observed for KETEK SiPM above 4 V overvoltage.

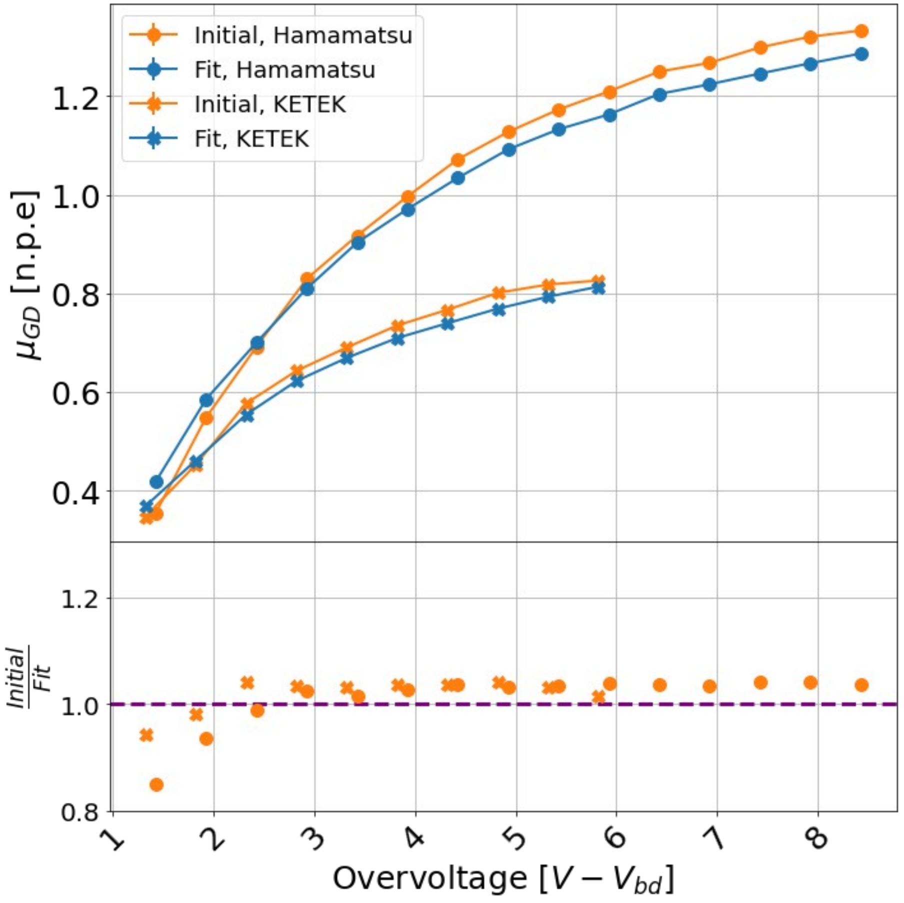
Selected results: gain

- Gain found to increase linearly with overvoltage, according to expectations.
- Breakdown voltage measured with linear fit to gain:
  - Hamamatsu:
    - Manufacturer value (average): 51.1 V
    - Fitted value: 51.6 ± 8.7 x 10^{-4} V
  - KETEK:
    - Manufacturer value (average): 27.3 V
    - Fitted value: 27.1 ± 4.5 x 10^{-4} V
- All subsequent plots use the breakdown voltage measured for each SiPM under test.



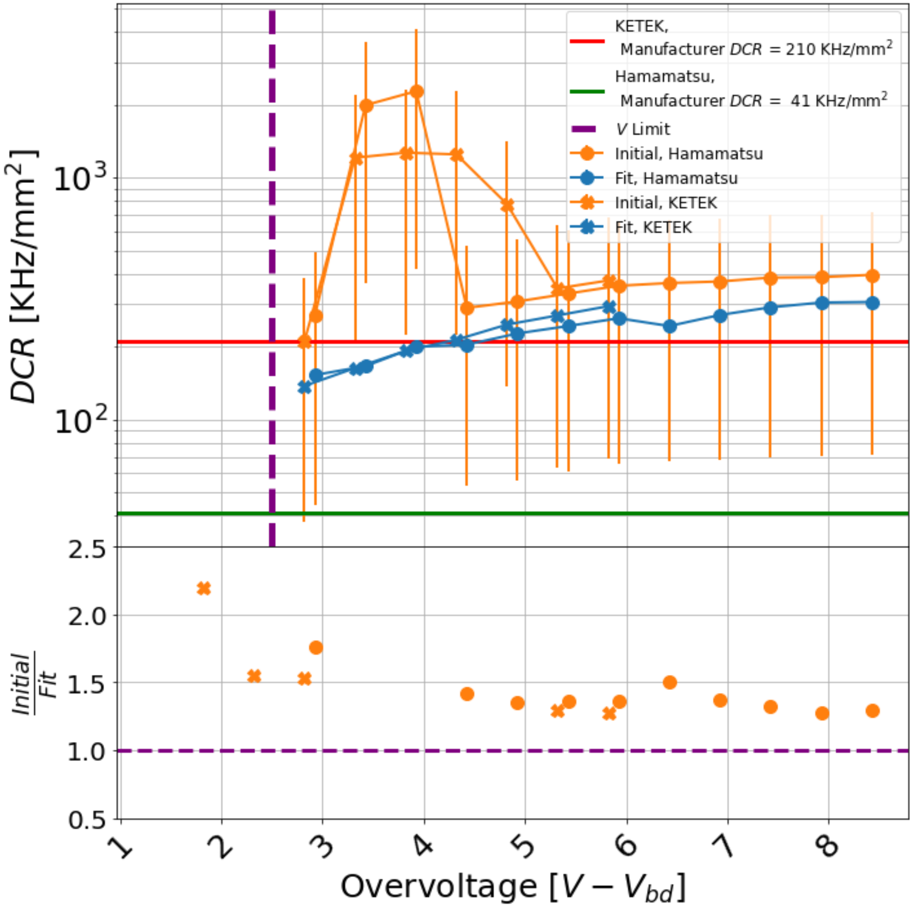
Selected results: mean # Geiger discharges

- The number of Geiger Discharges observed is proportional to the photon detection efficiency (PDE)
- It is expected that the mean Geiger Discharges/ PDE saturates with increasing overvoltage.
- The expected effect is observed in the measured data.



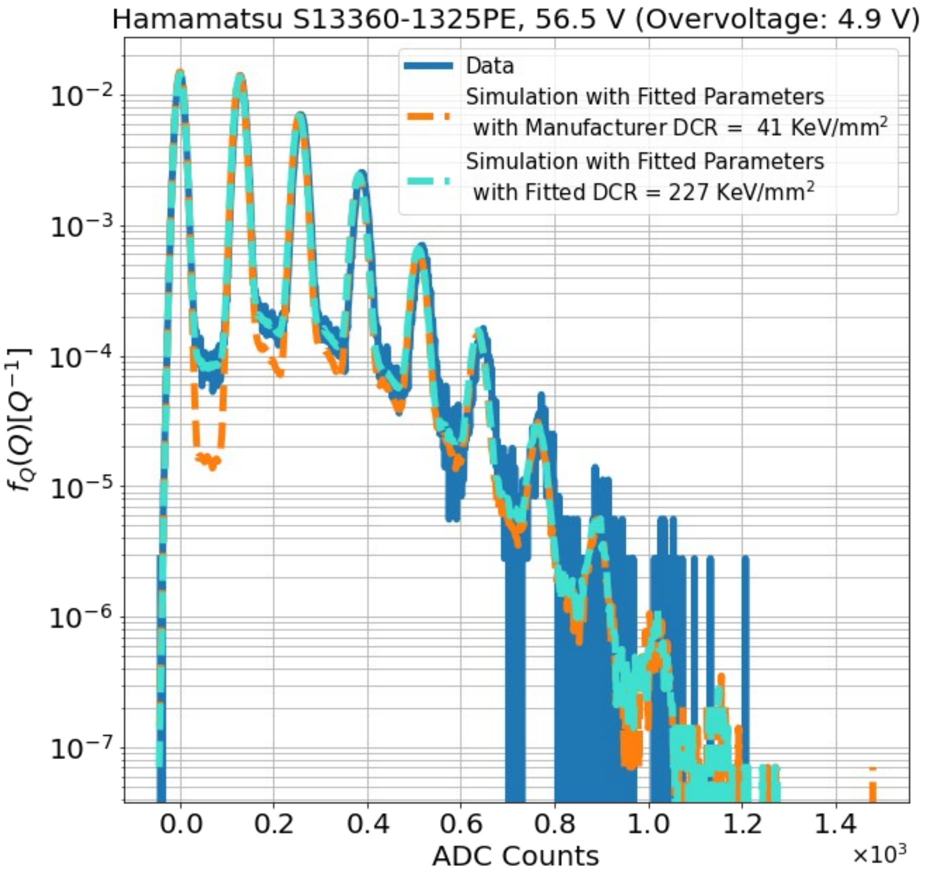
Selected results: DCR

- Dark Count Rate found to increase and saturate with overvoltage;
- KETEK SiPM found to be consistent with quoted manufacturer DCR values;
- However, the Hamamatsu SiPM found to deviate significantly from the quoted manufacturer DCR values;



Selected results: cross-check of Hamamatsu DCR with simulation

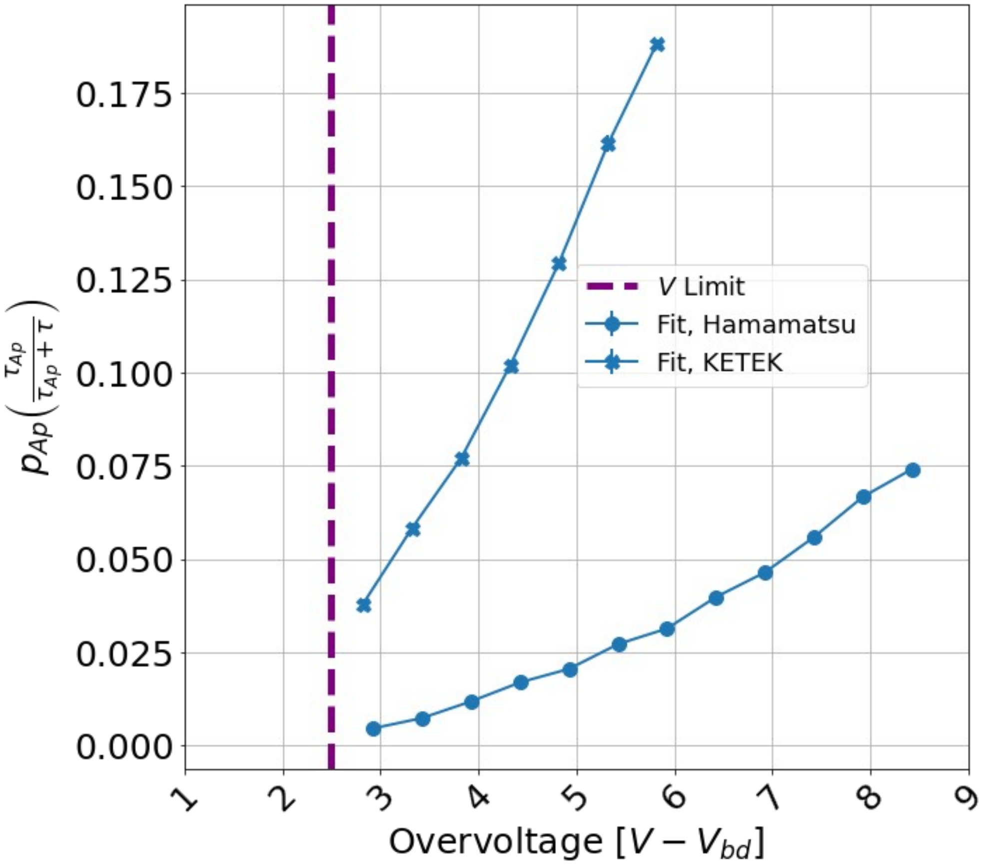
- A useful property of the fit is that parameters obtained from the fit can be used directly in the companion simulation program, LightSimtastic [3] to build simulations of a specific SiPM operating under the same conditions as the one which was fitted.
- Using the same fit values for all other parameters, the Hamamatsu SiPM was modelled in simulation using the quoted manufacturer DCR value and the fitted value at an overvoltage specified by the manufacturer (around 5V), at using 5 million events.
- The cyan curve shows that the PeakOTron has fitted values much closer to the expected DCR according to the model defined in [3] than the quoted Manufacturer DCR, shown as the orange curve in the case studied.
- This suggests that PeakOTron fit value more adequately describes data than the Manufacturer value according to the model described in [1] and [3].
- Further study of this discrepancy is required.



Selected Results: afterpulse probability

- Below an overvoltage of 2.5V, there is insufficient information between peaks to assess afterpulse probability.

- Afterpulse probability found to increase with overvoltage, at a greater rate for the KETEK SiPM than for the Hamamatsu SiPM.



Selected Results: afterpulse time constant

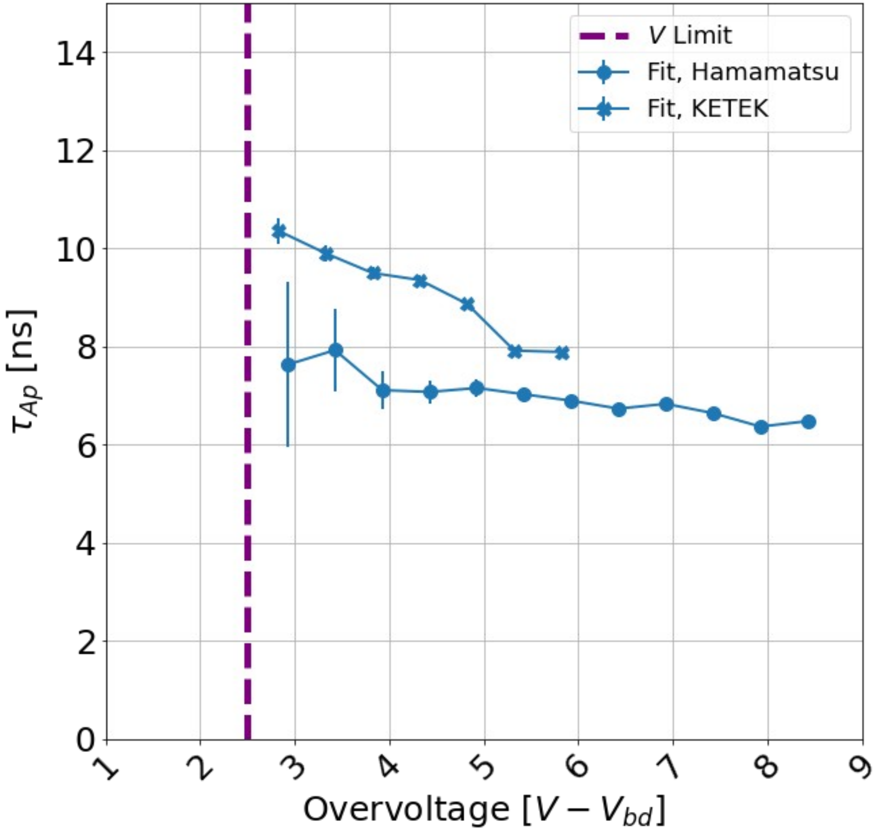
- Afterpulsing time constant found to be:
  - KETEK: 8 - 10 ns
  - Hamamatsu: 6 - 8 ns

- Possible decreasing afterpulse time constant observed with Ketek SiPM;

- Few measurements of detrapping time in literature – yet of the order of 10ns expected from literature [4]:

  "This indicates that the fast trap (τ j ~ 10 ns) is 2.5 times more effective at trapping avalanche carriers than the slow trap (τ j ~ 100 ns)."

- The result is suggestive that the PeakOTron is sensitive to fast trapping times from charge spectra.



[4] Probability Distribution of After Pulsing in Passive-Quenched Single-Photon Avalanche Diodes G. Kawata, J. Yoshida, K. Sasaki, and R. Hasegawa, in IEEE Transactions on Nuclear Science, vol. 64, no. 8, pp. 2386-2394, Aug. 2017, doi: 10.1109/TNS.2017.2717463.

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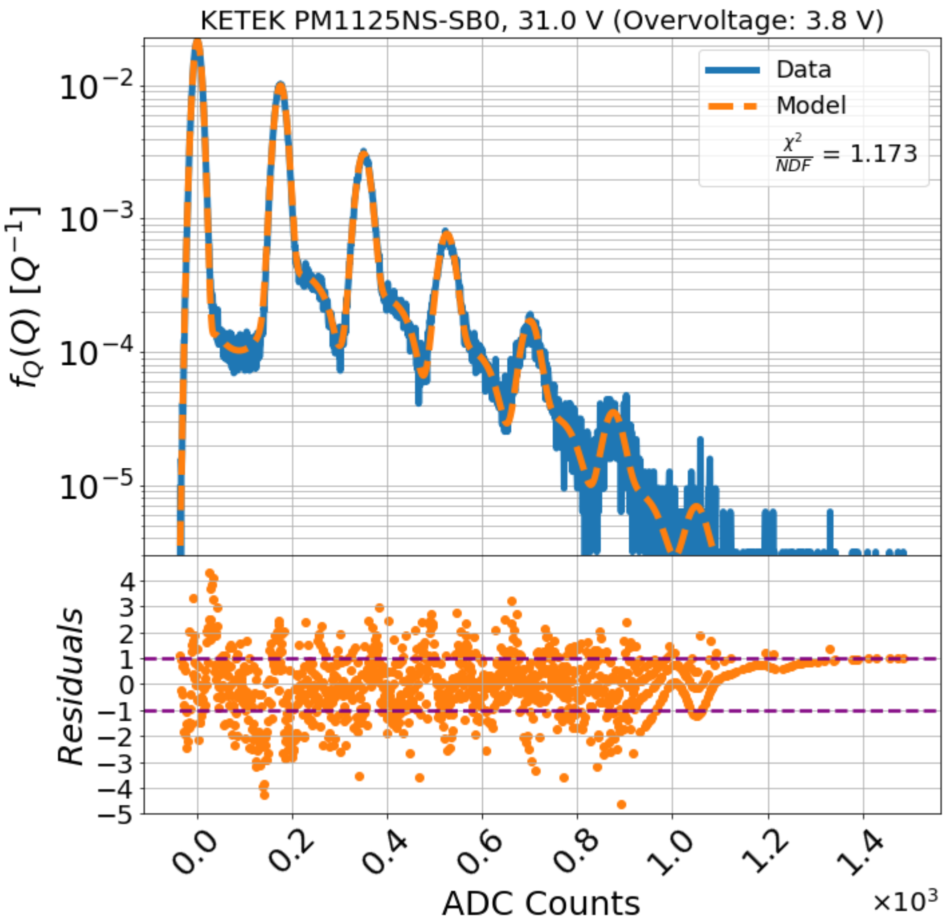
Conclusion

- A tool was developed to characterise SiPM charge spectra;
- The SiPM performance parameters can be extracted from fits, including afterpulse information;
- Pre-estimation of parameters sufficient to perform the high-dimensional analysis;
- Soon, the program will be published and we can start characterising SiPMs with the PeakOTron!



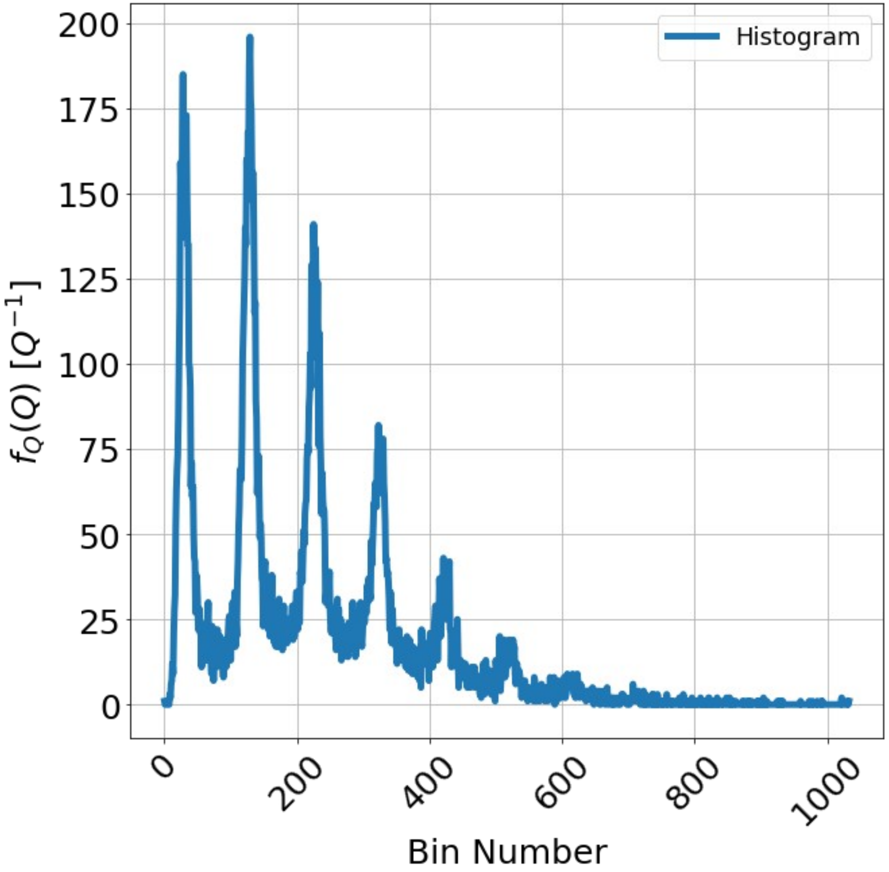
Backup: How PeakOTron Works

<u>OBTAINING A HISTOGRAM</u>

- **PeakOTron** begins with an **SiPM Spectrum** that can be provided as:
  - **a histogram**
  - **raw, unbinned charge measurements;**
- The program will **automatically optimise binning if provided with unbinned data;**
- **To overcome challenge of unknown measurement units, the histogram is transparently analysed in bin-units during fitting, and re-scaled after.**
- <u>RESULT:</u>

A histogram from which the analysis chain may begin extracting parameters.

Note: the example is a simulated charge spectrum obtained from [3].

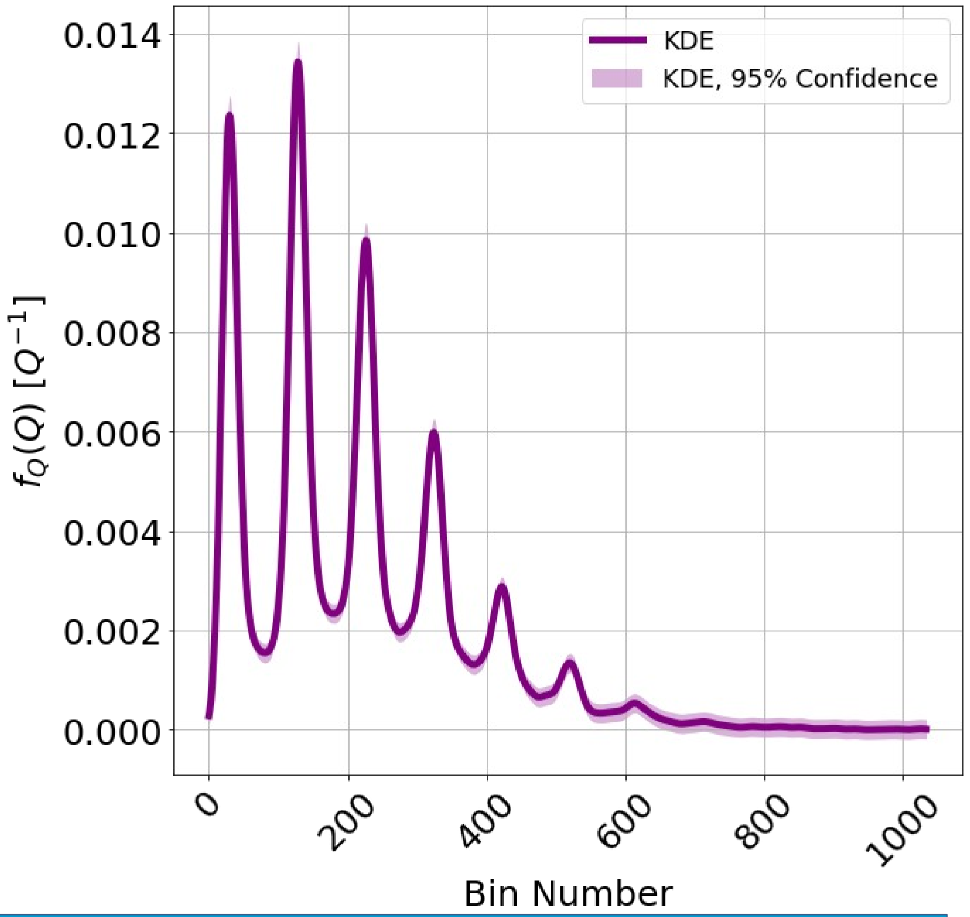


Backup: How PeakOTron Works

<u>NON-PARAMETRIC SMOOTHING</u>

- It is **challenging to extract information** from a histogram **with few statistics/challenging experimental effects;**
- **Histogram is smoothed** using a non-parametric smoothing method: **Kernel Density Estimation (KDE).**
- **KDE depends** on a **bandwidth parameter** that **determines** the **level of smoothing.**
- **Bandwidth is optimised** using an **automated log-likelihood fit;**
- **Confidence intervals/errors** are **estimated** using **bootstrap resampling of the data;**
- <u>RESULT:</u>

A smoothed density estimate from which peak positions, widths and gain may be extracted.



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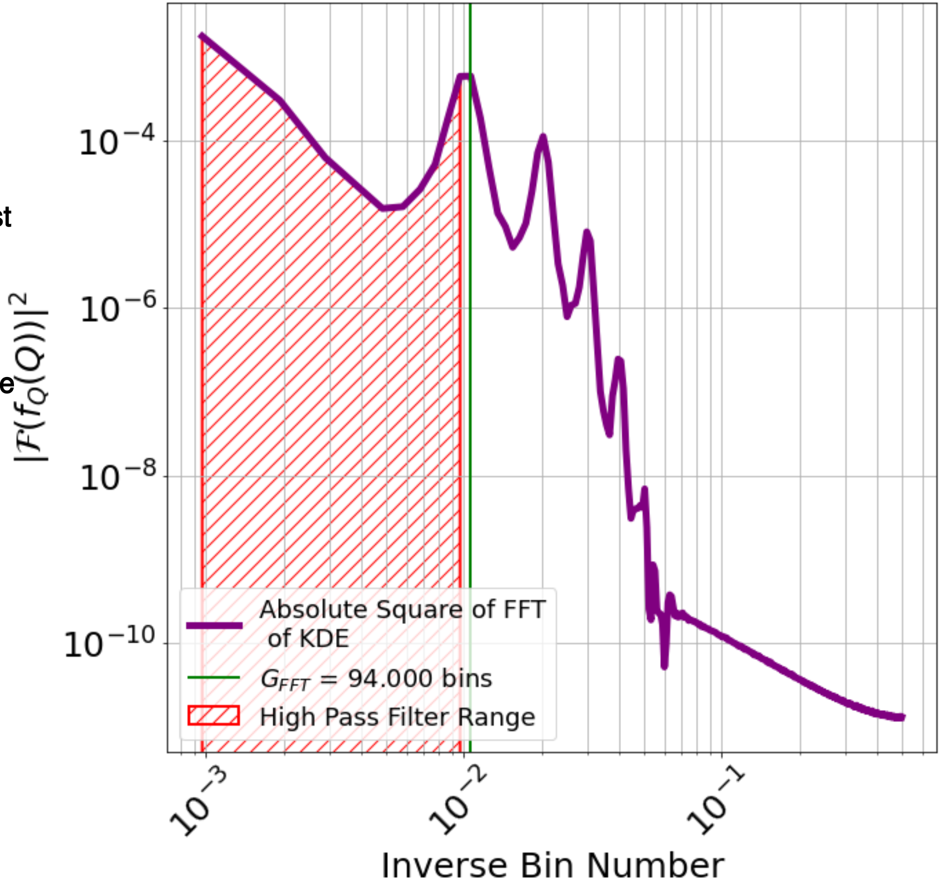
Backup: How PeakOTron Works

GAIN EXTRACTION

- GAIN: Number of avalanche electrons detected per initial Geiger Discharge;
- A 'power spectrum' is made of the smoothed distribution using the Fast Fourier Transform (FFT);
- The peak frequency of the distribution yields the gain.
- A high pass filter range defined between the lowest frequency up to the gain is selected while in Fourier space;
- This is for background subtraction. More on this in the next slide.
- RESULT:

  - Gain estimate has been extracted.
  - Noise frequency range' selected.

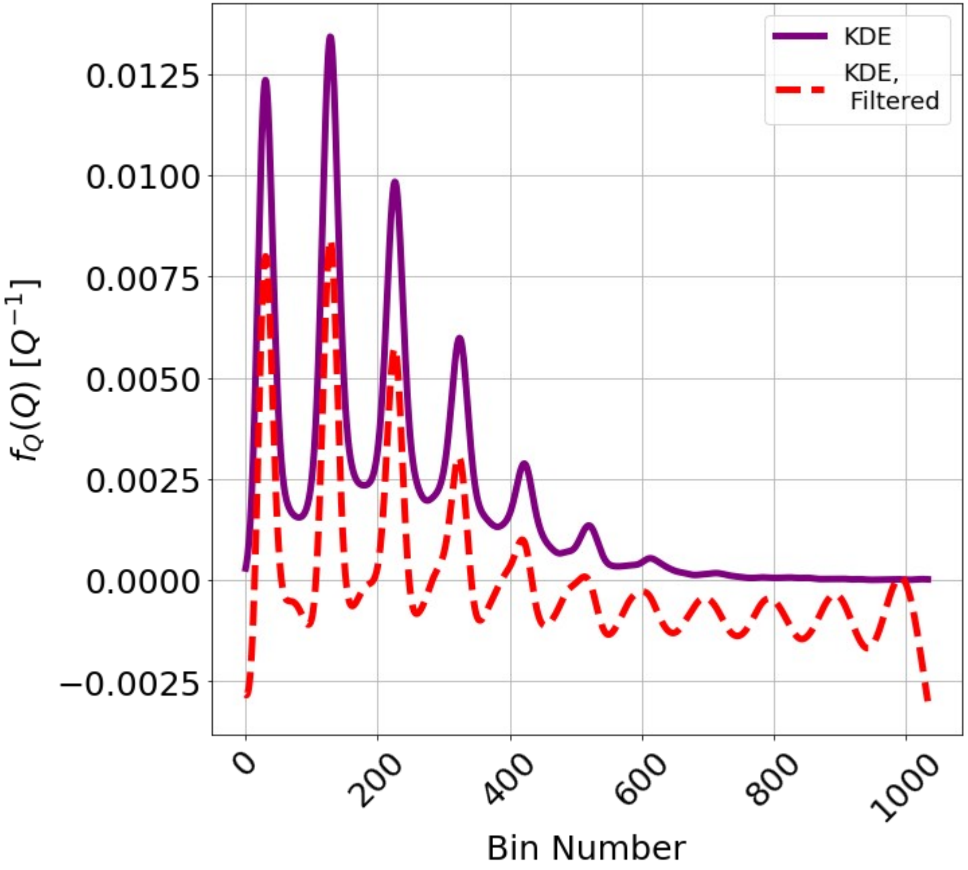


Backup: How PeakOTron Works

TEMPORARY BACKGROUND SUBTRACTION FOR PEAK FINDING

- In the presence of dark counts, the Primary Geiger discharges, peaks will 'sit' atop a distribution of dark counts.
- MAIN POINT: noise skews the position of the peaks.
- A high pass filter using the frequencies we extracted, giving a temporary spectrum we can use to extract peaks positions and widths.
- RESULT:

A temporary background-subtracted spectrum has been obtained for peak finding.



Backup: How PeakOTron Works

PEAK FINDING AND PEDESTAL ESTIMATION

- An 'out of the box' peak finder is used to extract the peak positions and widths from the background-subtracted spectrum;
- Gain is used to filter any noise peaks;
- The background subtracted spectrum is then discarded.
- PEDESTAL: Mean charge measured if no primary Geiger discharge was observed (i.e. first peak in the spectrum)
- Pedestal estimate found by numerically minimising the difference between the theoretical value for gain from a Generalised Poisson distribution from statistics and the previously extracted gain:

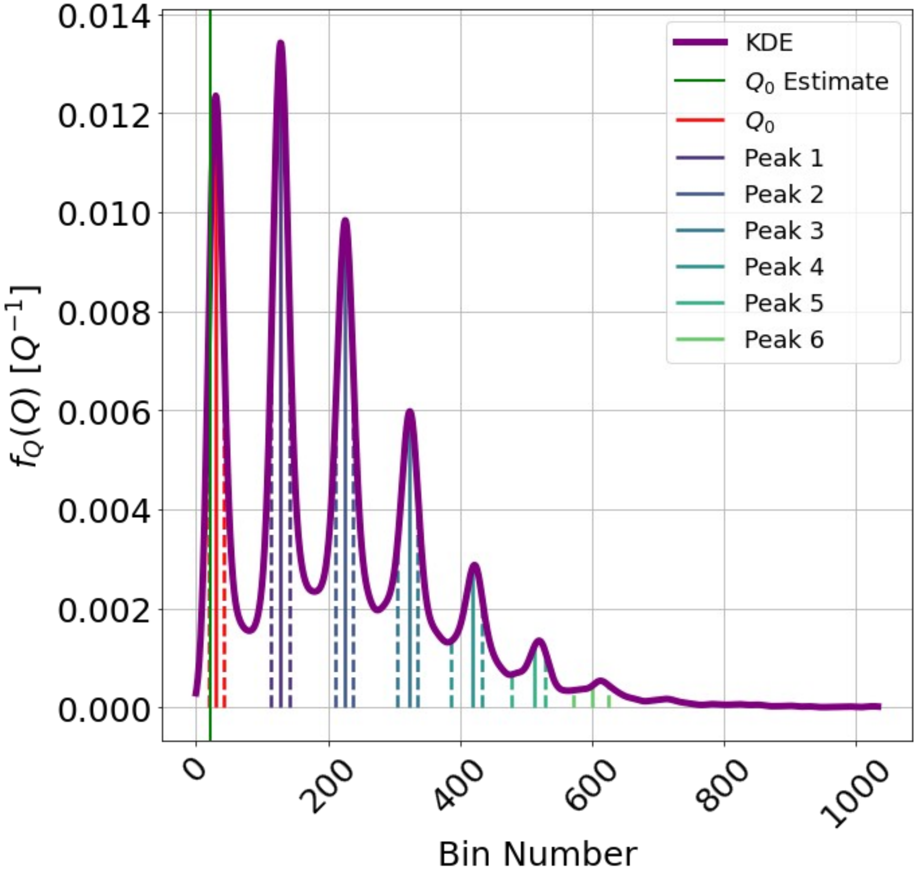
$$Q_0 \simeq \arg\min((G_{GP}(Q_0, \text{mean}, \text{variance}, \text{skewness}) - G_{FFT})^2)$$

$$G_{GP}(Q_0, \text{mean}, \text{variance}, \text{skewness}) = \left(\frac{\text{variance}}{(\text{mean} - Q_0)^2}\right)(1 - \lambda_{GP})^2$$

$$\lambda_{GP}(Q_0, \text{mean}, \text{variance}, \text{skewness}) = \frac{1}{2}\left(\frac{(\text{mean} - Q_0)\text{skewness}}{\sqrt{\text{variance}}} - 1\right)$$

- The pedestal is chosen to be the closest peak found to this value.
- RESULT:

- Pedestal estimate has been extracted.
- Peak positions and width limits have been extracted,



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Backup: How PeakOTron Works

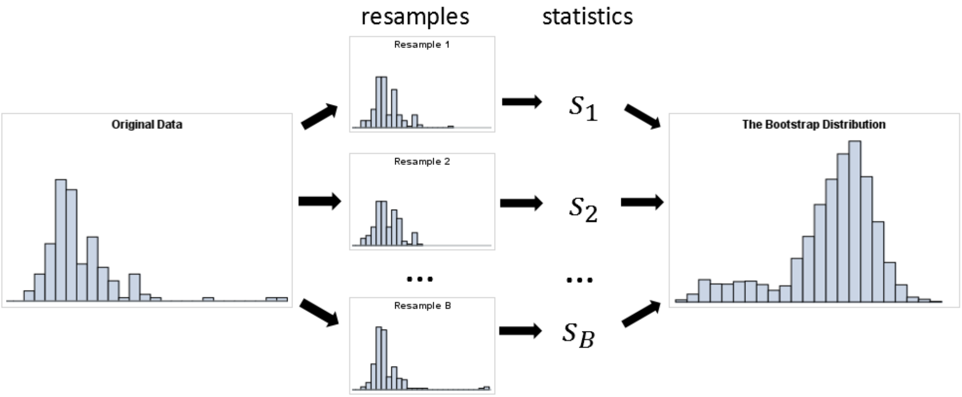
μ and λ ESTIMATION

- **μ** : mean number of Geiger discharges measured by the SiPM;
- **λ** : cross-talk branching parameter;
- The values and errors on parameters **μ** and **λ** are estimated via bootstrap resampling of the theoretical statistical properties of the Generalised Poisson distribution:

$$\lambda_{GP}(Q_0, \text{mean}, \text{variance}, \text{skewness}) = \frac{1}{2}\left(\frac{(\text{mean} - Q_0)\text{skewness}}{\sqrt{\text{variance}}} - 1\right)$$

$$\mu_{GP}(Q_0, \text{mean}, \text{variance}, \text{skewness}) = \frac{(\text{mean} - Q_{ped})^2}{\text{variance}}\left(\frac{1}{1-\lambda_{GP}}\right)$$

- BOOTSTRAPPING:
  Bootstrapping is a metric that uses random sampling with replacement (i.e. mimicking the sampling process)
- Highly 'robust' method of determining parameters and errors without requiring a fit.



- RESULT:

- **μ** and **λ** estimates obtained.

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Backup: How PeakOTron Works

PEDESTAL WIDTH/ELECTRONICS NOISE ESTIMATION

AND GAIN/PEDESTAL POSITION CORRECTION

- Once again, using bootstrap resampling, the variances in the widths and their means are extracted.
- PEDESTAL WIDTH: Intrinsic electronics noise of the detector;
- GAIN SPREAD: Increase in noise due to gain spread between and in SiPM pixels

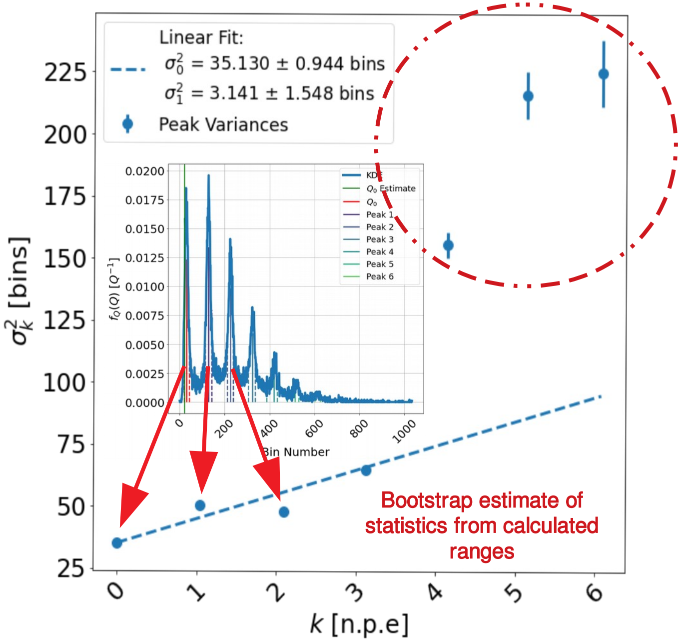
Linear fits of peak index vs. variance and means are made using a Robust Huber Regression [5]:

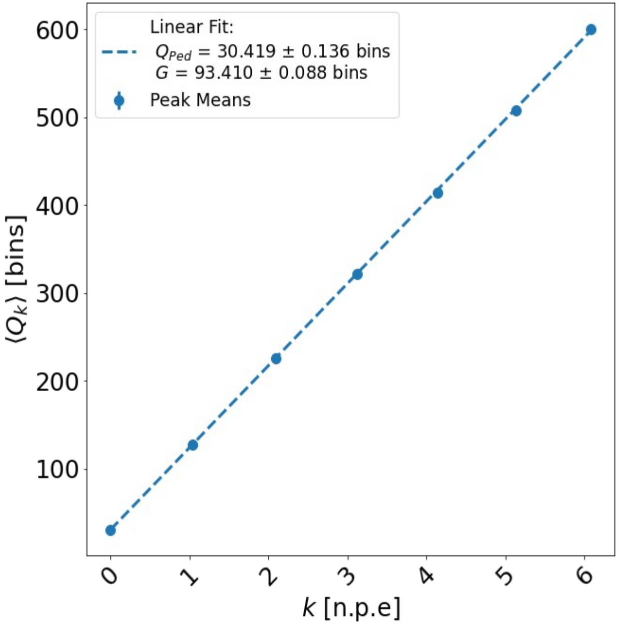
$$L_\delta(z) = \begin{cases} \frac{1}{2} z^2 & \text{for } |z| \le \delta \\ \delta\left(|z| - \frac{1}{2}\delta\right), & \text{otherwise} \end{cases} \quad z = \frac{\hat{y} - y}{\sigma_y}$$

- Pedestal width/electronic noise widths and errors extracted from offset/slope of variance fit;
- Pedestal/Gain are limited to bin units. By performing a fit, continuous estimates and errors may be extracted;
- RESULT:

- Pedestal Width/Electronics noise estimated;
- Gain and Pedestal estimate corrected.

Huber Loss
resistant to outliers





[5] Peter J. Huber. "Robust Estimation of a Location Parameter". In:The Annals of Mathematical Statistics 35.1 (1964),pp. 73–101. DOI:10.1214/aoms/1177703732. URL:https://doi.org/10.1214/aoms/1177703732.

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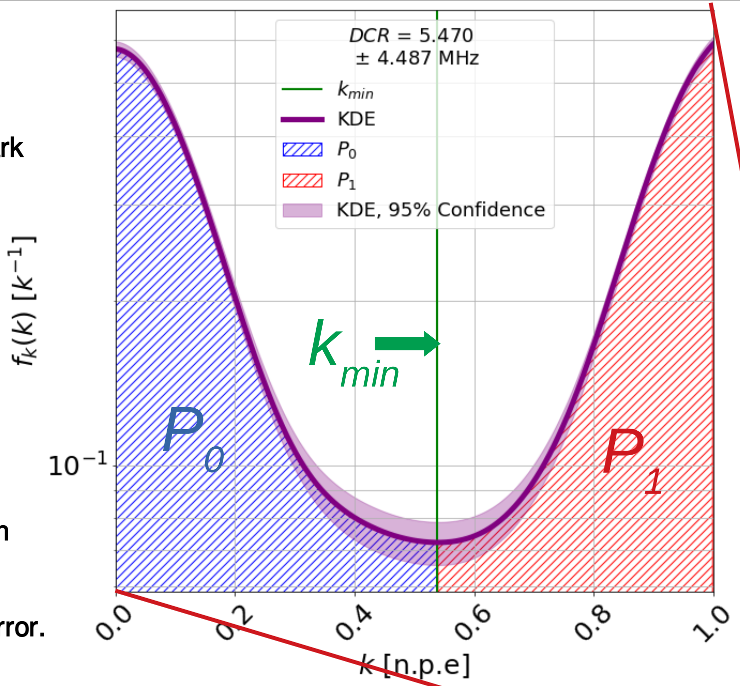
Backup: How PeakOTron Works

DARK COUNT RATE ESTIMATION

- DARK COUNT RATE (DCR): Rate, in gigahertz, at which dark discharges (e.g. thermal charge carriers) are observed by the detector.
- Dark count estimated using the smoothed KDE distribution in photo-electron units (k), from the range 0 (pedestal) to 1 (first Primary Geiger peak).
- Here, only dark counts are expected.
- DCR given by a scaled ratio shown on right hand side.
- KDE used because it is easy to perform numerical integration on the continuous estimate;
- Errors on integrals calculated using the bootstrapped KDE error.
- See [1] for more theory.
- RESULT:

  - DCR estimated.



$$DCR = \frac{f_k(k_{min})}{4\tau\left(P_0 + \frac{P_1}{2}\right)}$$

$$k_{min} = \arg\min f_k(k)$$

$$P_0 = \int_0^{k_{min}} f_k(k)\,\mathrm{d}k$$

$$P_1 = \int_{k_{min}}^{\min(2k_{min},1)} f_k(k)\,\mathrm{d}k$$