SiPM single photon time resolution measured via bi-luminescence

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Motivation

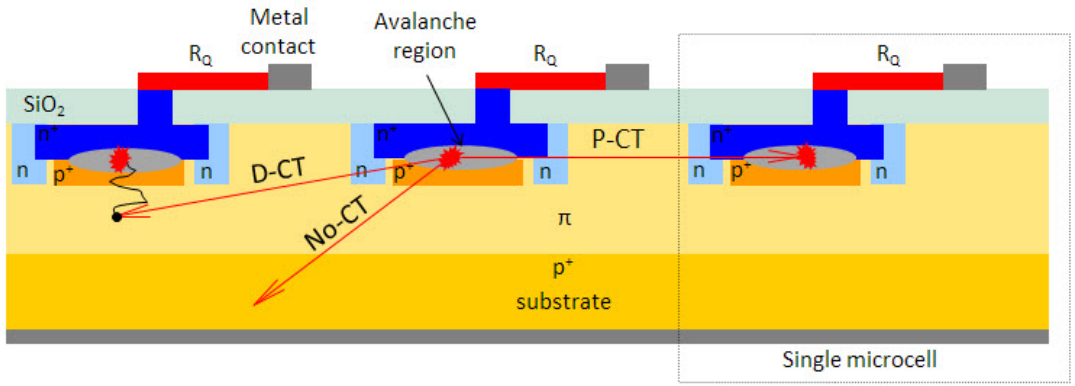
- Silicon photomultipliers (SiPM) have found widespread use in scientific experiments
  $\rightarrow$ From HEP to Medical Science
- Characterization of such devices include:

  Breakdown Voltage
  Cross-talk probability
  Dark Count Rate
  Photon detection efficiency
  Single Photon Timing Resolution (SPTR)

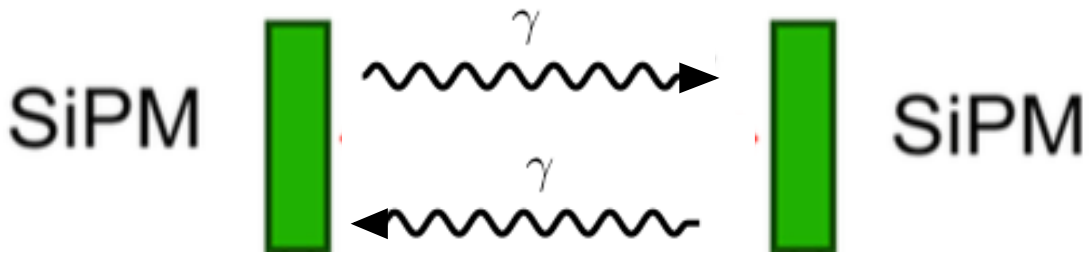
- Some measurements are easy, some require more advanced equipment
  $\rightarrow$ e.g. measuring the SPTR usually requires external laser sources
- Can we measure the SPTR without the need fancy equipment? Yes, via bi-luminescence!

Cross-talk and bi-luminescence

- During an avalanche, some electrons recombine producing secondary photons
- These photons can enter a neighboring cell, causing additional avalanches (Optical Cross-talk)
- Bi-luminescence refers to the process where one or more of these photons leaves the device and causes an avalanche in a neighboring device
- Our light detector is actually a light source
  $\rightarrow$ Can use as a source to measure single photon events

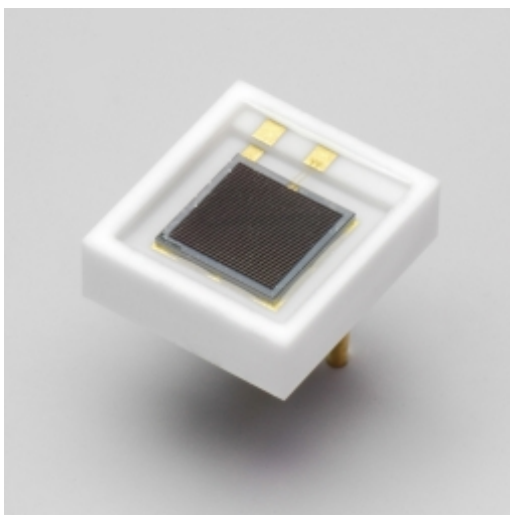


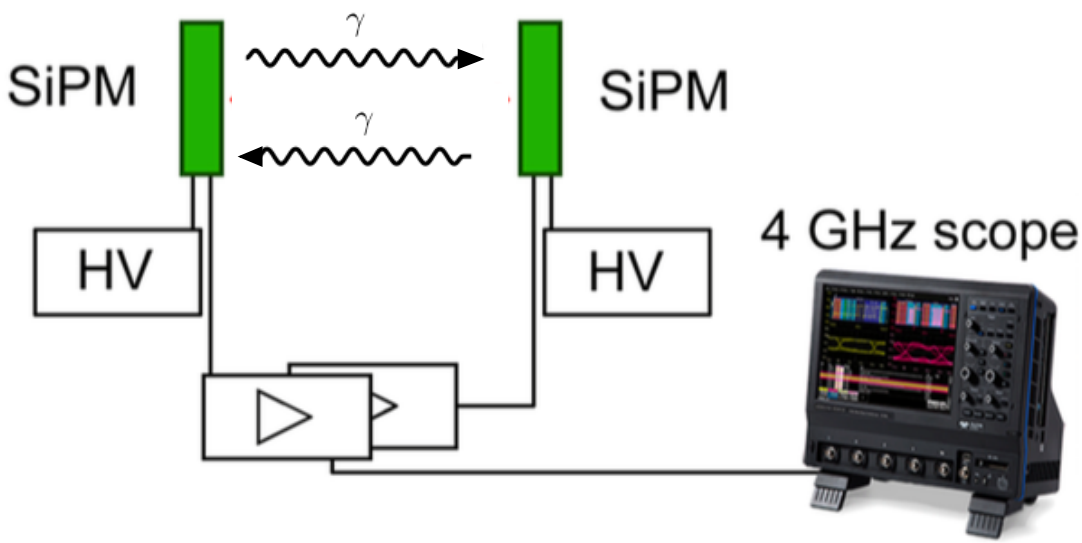
[courtesy of Hamamatsu Photonics]



Set-up

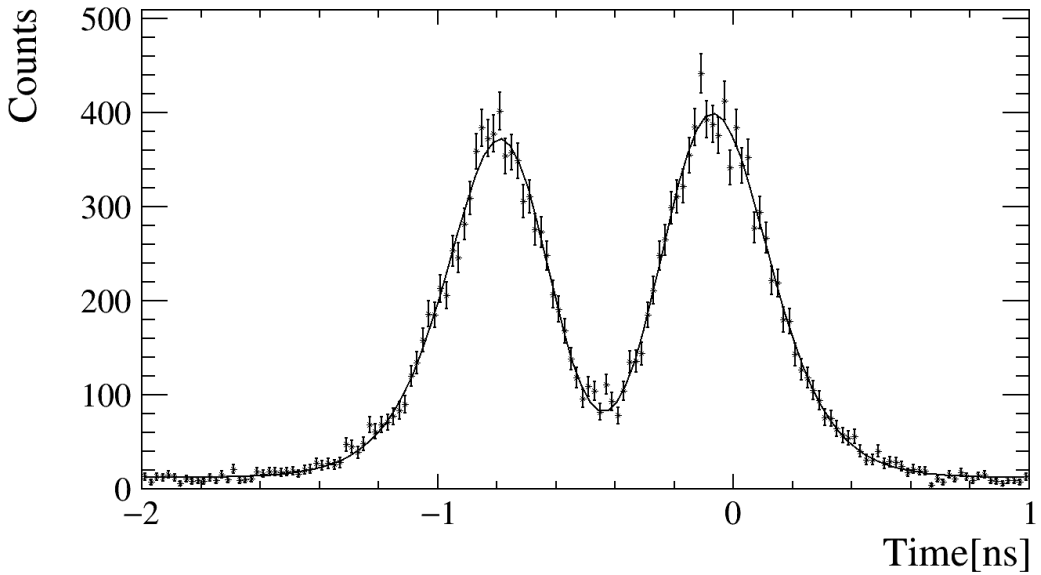
- 2x HPK S13360-3050CS (3 x 3 mm^2 area, 50 μm pitch)
- Each connected to custom amplifier boards and a HV source
- Signals recorded with a 4-ch 4 GHz oscilloscope
- Set-up is housed in a freezer (not the scope!) flushed with dry air allowing for T as low as -30°C
- Waveforms are timestamped using a CFD method (optimized at 24%)





The model

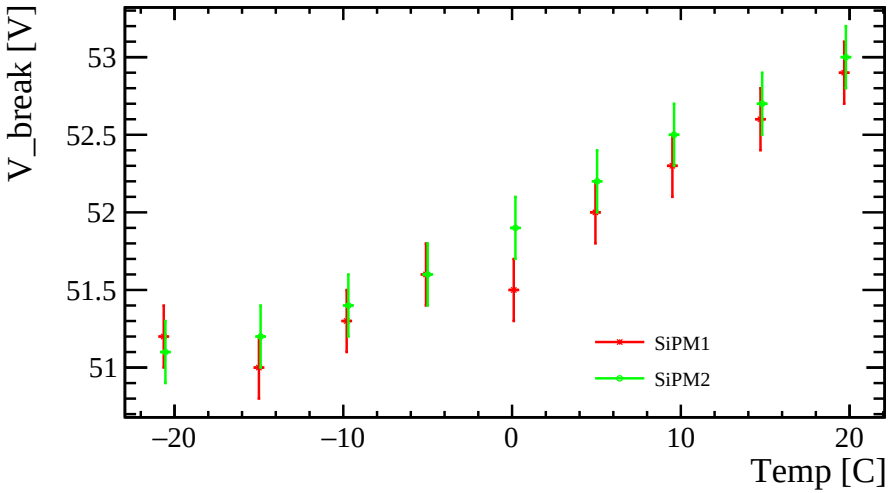
- The resulting $\Delta t = t_1 - t_2$ distribution shows a double peaked structure
- Each peak can be described by a gaussian convoluted with and exponential
- The Gaussian term includes contributions from emission and absorption ($\sim \sqrt{2}$ x SPTR)
- Exponential term arises from uncertainty in the time of emission due to afterpulsing

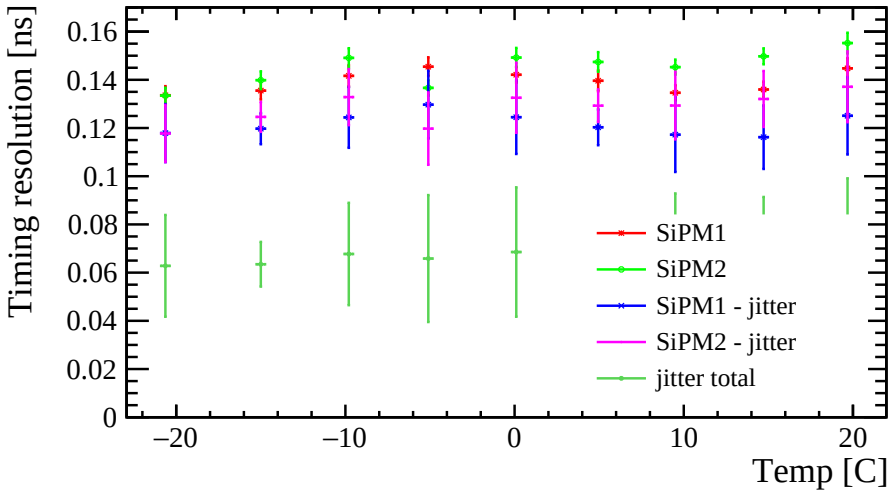


$$f(\Delta t; \mu, \sigma\, \lambda) \propto e^{\frac{\lambda}{2}(2\mu+\lambda\sigma^2-2\Delta t)}\, erfc\left(\frac{\mu+\lambda\sigma^2-\Delta t}{\sqrt{2}\sigma}\right)$$

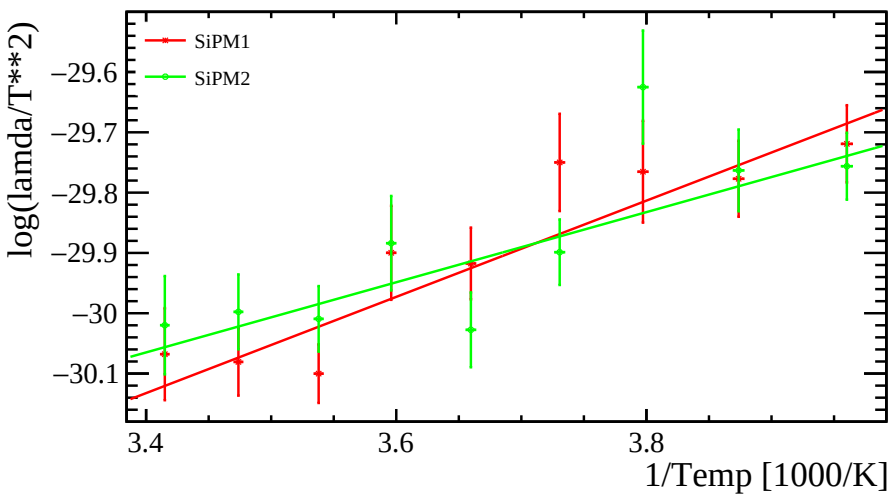
σ: Uncertainty from emission and absorption process
μ: Mean of the gaussian
λ: Afterpulse rate

Results





- Measurements carried out from -20 to $+20\ ^\circ$ C, OV $= +3$ V
- SPTR(20°C) $= 145/\sqrt{2} = 103 \pm 3$ ps $\rightarrow$ Const vs. T
- $\lambda(20^\circ\text{C}) = 7.5 \pm 0.5$ GHz
- Arrhenius plot used to extract energy of defect responsible for λ
  $\Delta E_1 = E_c - E_1 = 0.07 \pm 0.01$ eV
  $\Delta E_2 = E_c - E_2 = 0.05 \pm 0.01$ eV



Summary

- The SPTR of SiPMs is an important characterization parameter
- We present a simple method of measuring the SPTR using bi-luminescence
- Δt distribution modeled with a Gaussian convoluted with an exponential
  $\rightarrow$ accounts for afterpulsing
- SPTR $\sim$ 100 ps, similar to literature values
- Afterpulse rate $\sim$ 7-8 GHz
  $\rightarrow \Delta E = 0.05 - 0.07$ eV

BACKUP

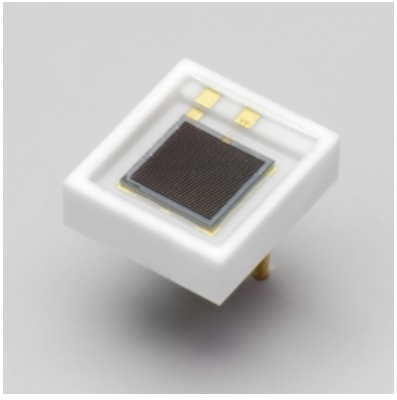
SiPM characterization

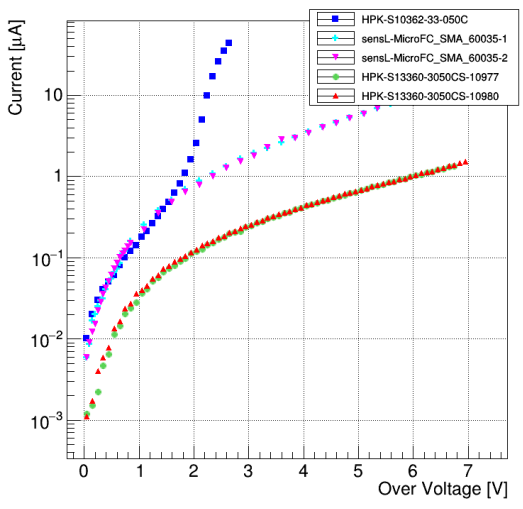
- SiPMs from two manufacturers:

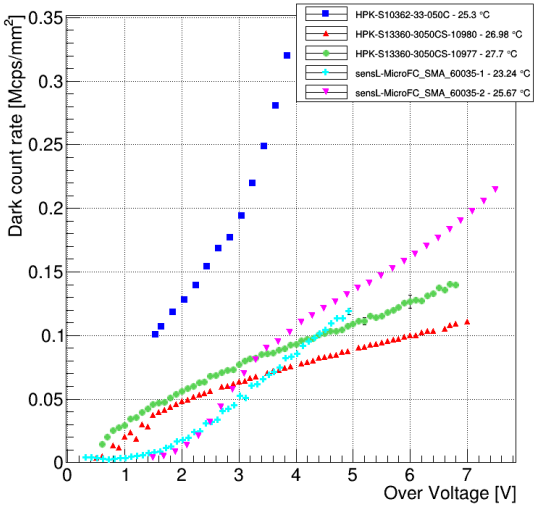
  Hamamatsu Photonics
  SensL

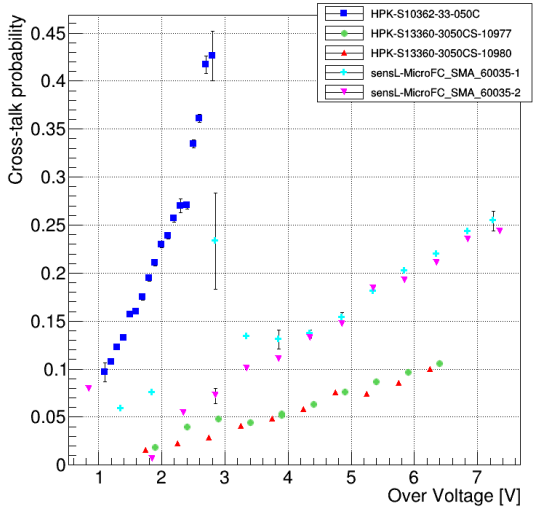
- SiPM characterized by:

  Current-Voltage behavior
  Dark count rate
  Cross-talk probability
  Single photon time resolution



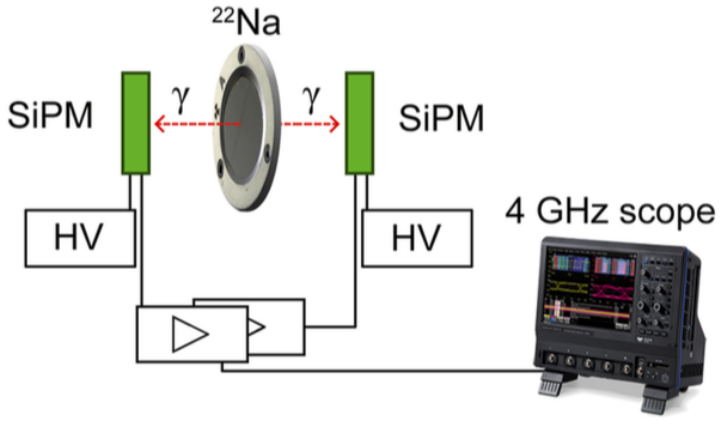


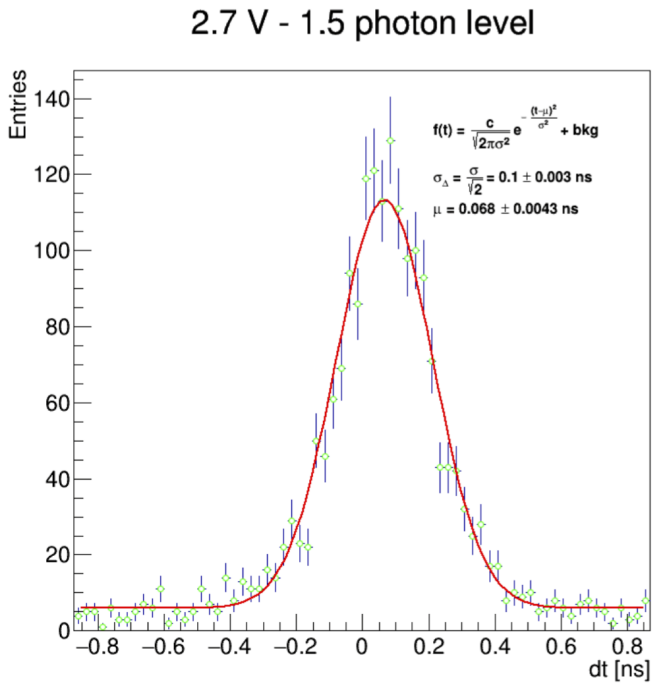


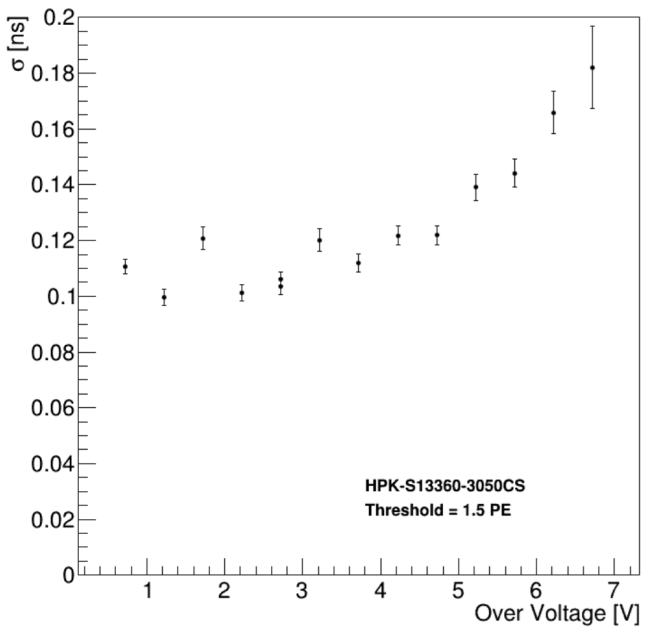


SiPM single photon time resolution

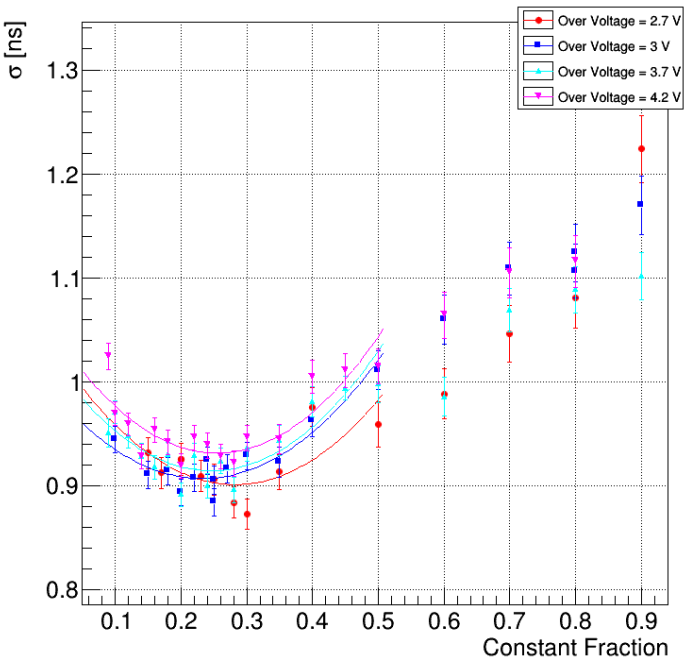
- Back-to-back γs from pair-annihilation in ^{22}Na is used as a source
- Single photon time resolution is taken as the Gaussian width in the time difference spectrum from coincidence signals
- Very good resolution $\sim$ 100 ps is observed in 3 $\times$ 3 mm HPK SiPM

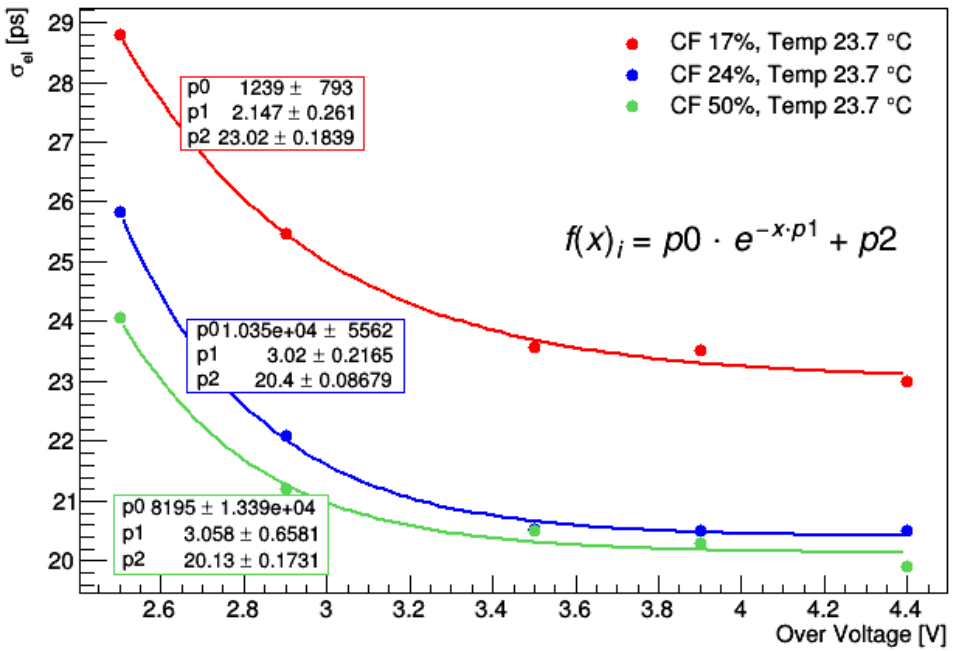






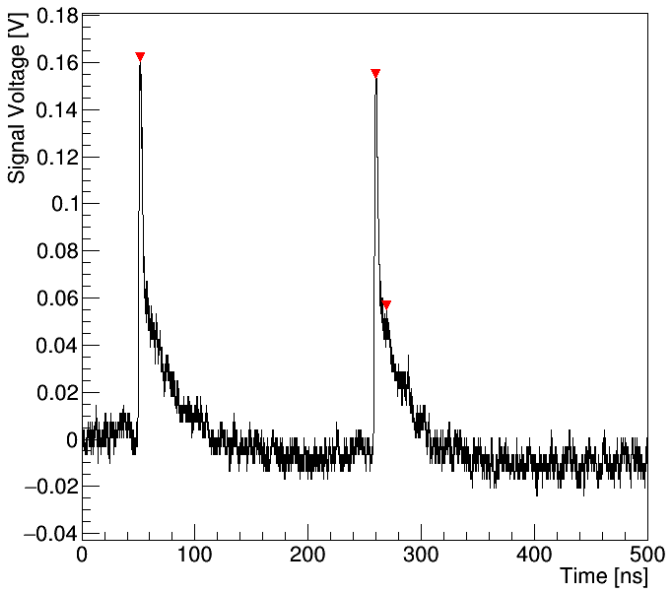
CFD optimization and electronic noise

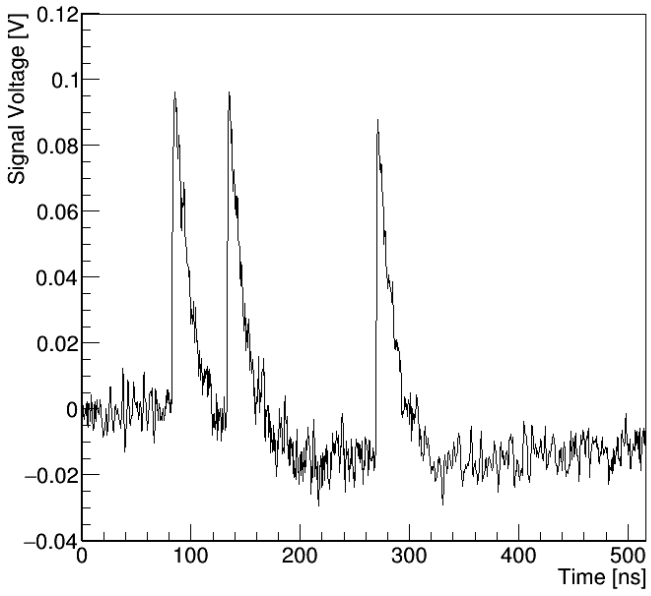


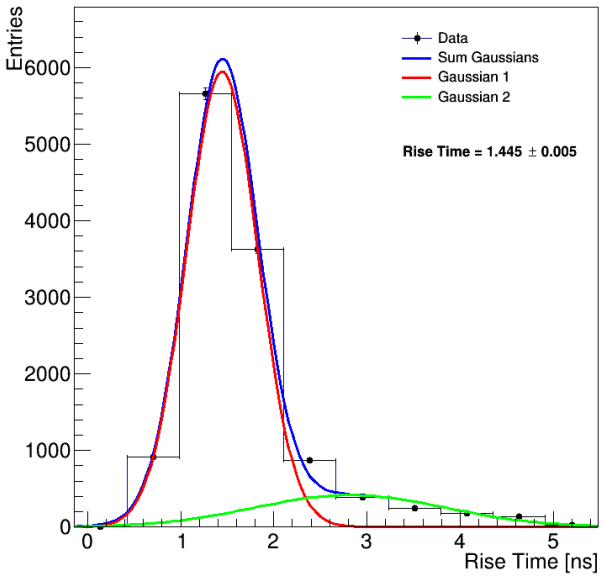


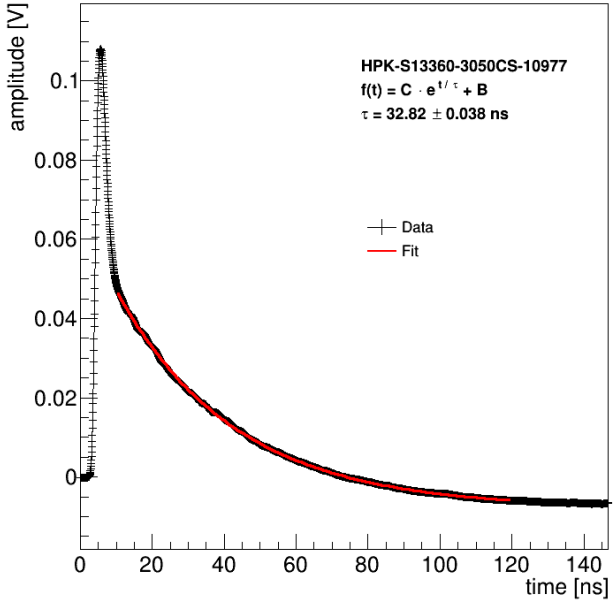
- Scan of CFD threshold indicated an optimal value of 24%
- Electronic noise at this value is $\sigma_{el} = 22$ ps for the optimal OV = 3 V

Waveforms, rise time and decay time









DCR and cross talk