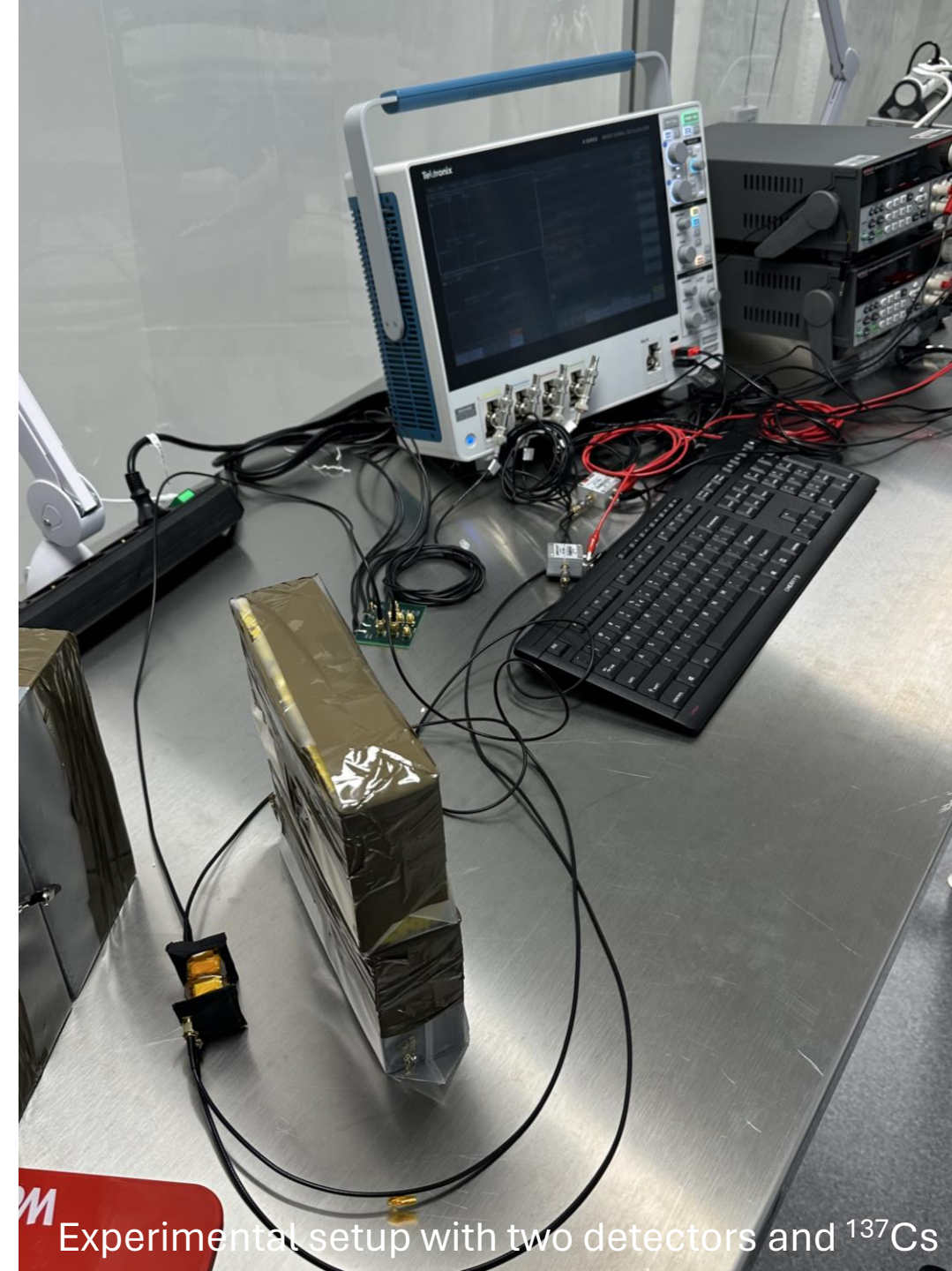


Study of the performance of polystyrene-based plastic scintillators

Bachelor Thesis Colloquium

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29.09.2026, Hamburg



Experimental setup with two detectors and ^{137}Cs

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Introduction

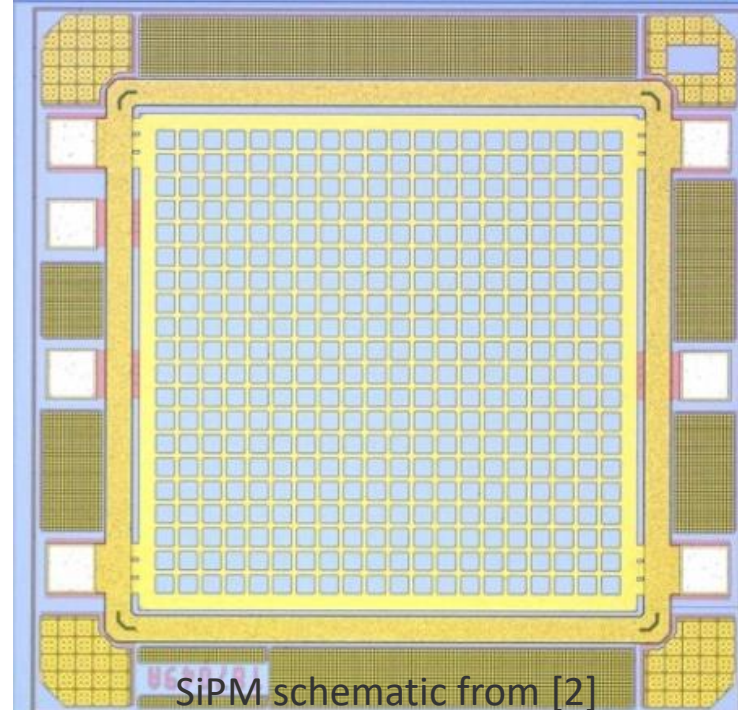
- Study of polystyrene-based plastic scintillators using a radioactive source
 - Allow assembly of inexpensive detectors with a fast response time and high resolution
- Characterization of the single-photon response
- Study of the Compton edge position of ^{137}Cs
- Study of signal correlations in two detectors

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Background

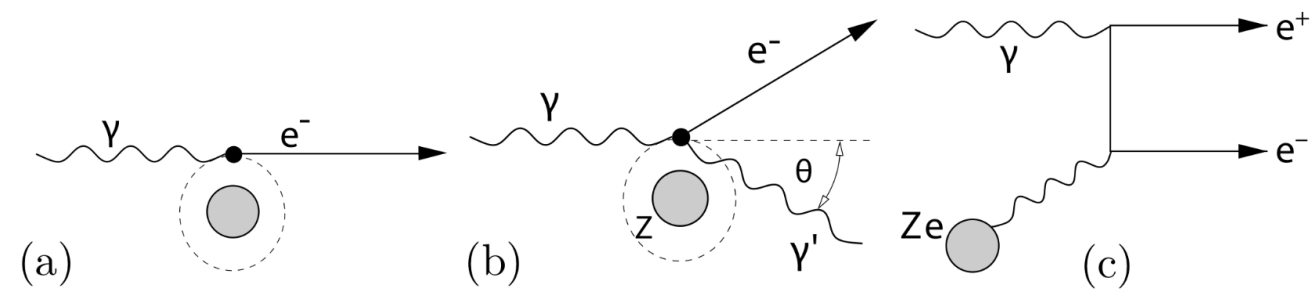


Plastic scintillators from [1]



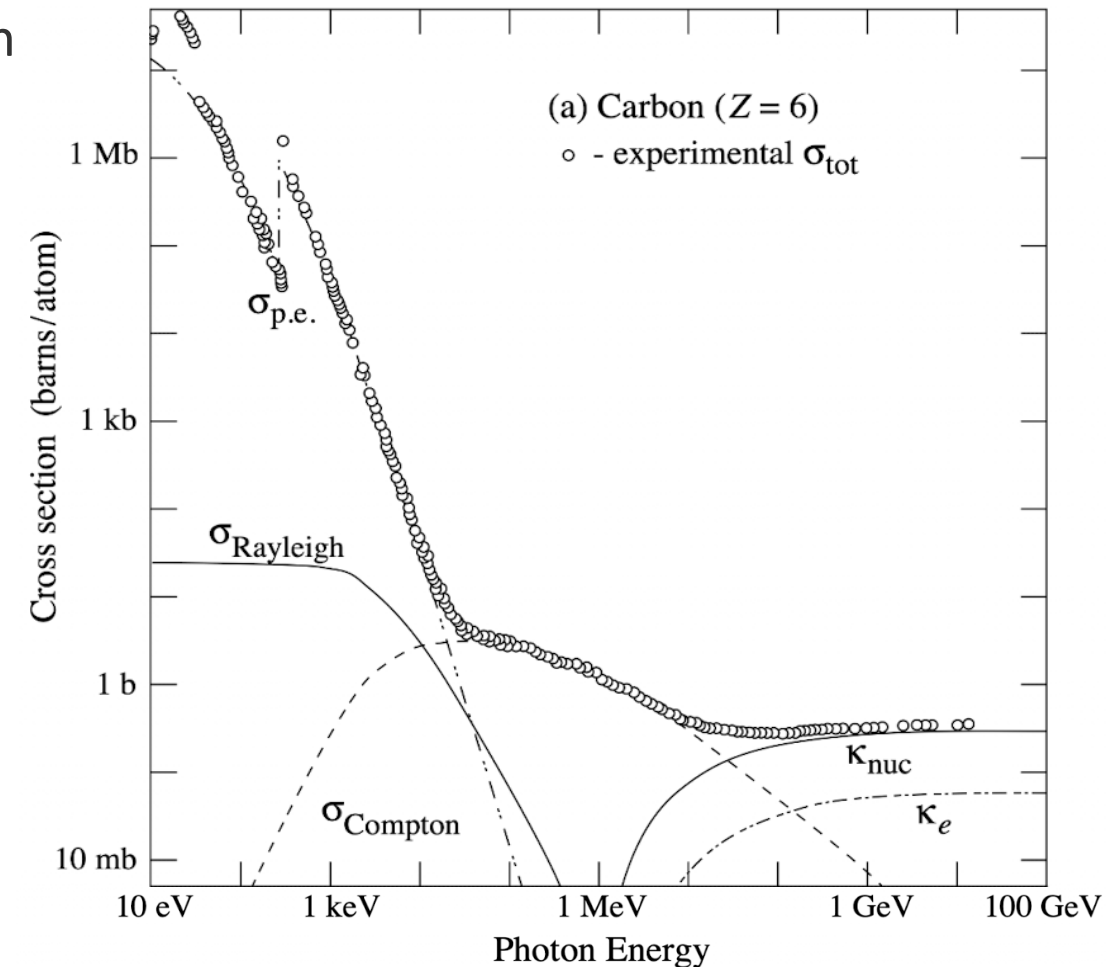
SiPM schematic from [2]

Photon Interaction with Matter



Feynman diagrams from [3]

- Photoelectric effect (a)
 - Entire energy from photon transferred to electron
 - Up to tens of keV
- Compton scattering (b)
 - Photon scatters off a practically free electron
 - In the hundreds keV to few MeV range
- Pair production (c)
 - Photon converts into electron-positron pair
 - In the MeV range, at minimum larger than two electron masses

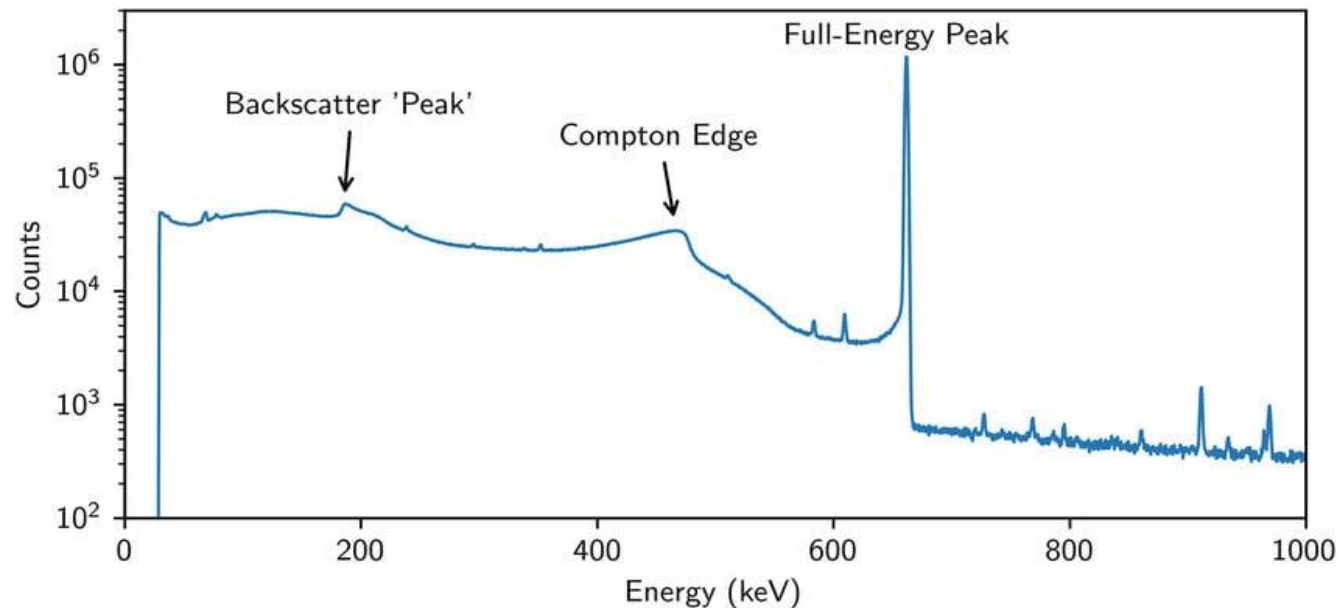


Cross section for Carbon $Z=6$ from [3]

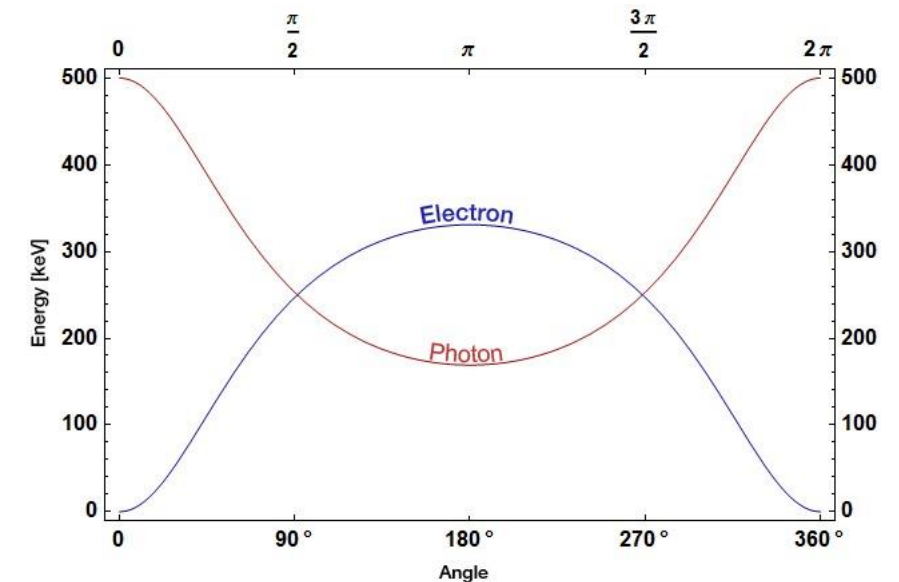
Compton Scattering

- Energy after scattering depends on scattering angle:
- Maximum energy deposition for a 180° scattering angle
 - Causes Compton edge in the energy spectrum
- Second order Compton edge: Photons scatter with a 180° angle twice

$$E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2} (1 - \cos\theta_\gamma)}$$



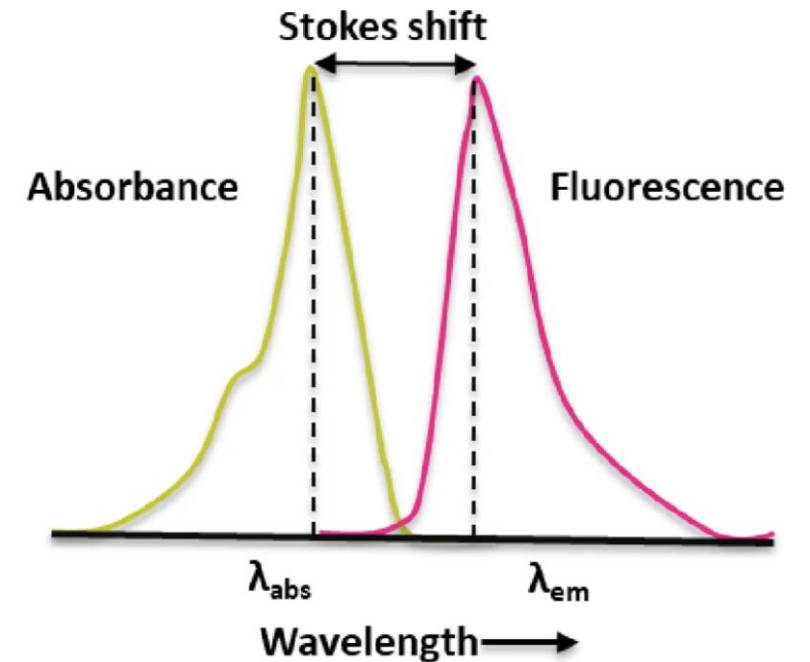
^{137}Cs spectrum from [4]



Energies of photon and electron after scattering from [5]

Scintillating Materials

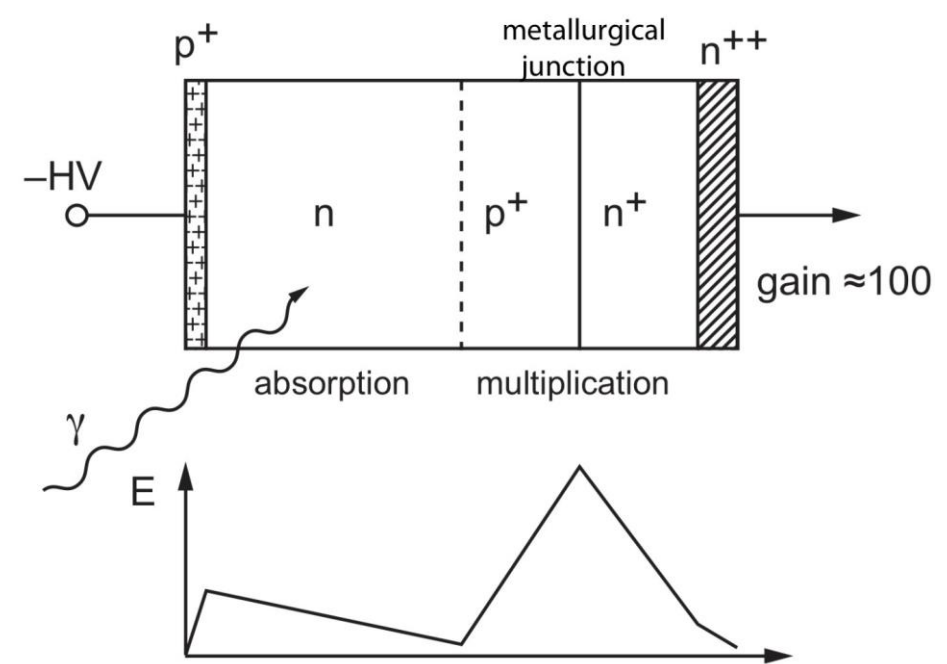
- Scintillation: Luminescence caused by ionising radiation
- Example: charged particles/ γ -rays cause excitation of molecules
 - De-excitation by emitting photons
- Reabsorption of emitted photons suppressed by Stokes shift
- Plastic scintillators:
 - Solvent, slow scintillator
 - Additives, faster scintillation and wavelength shift
 - Fast signals, inexpensive, wide variety forms
 - Typical combination: PVT, p-terphenyl, POPOP



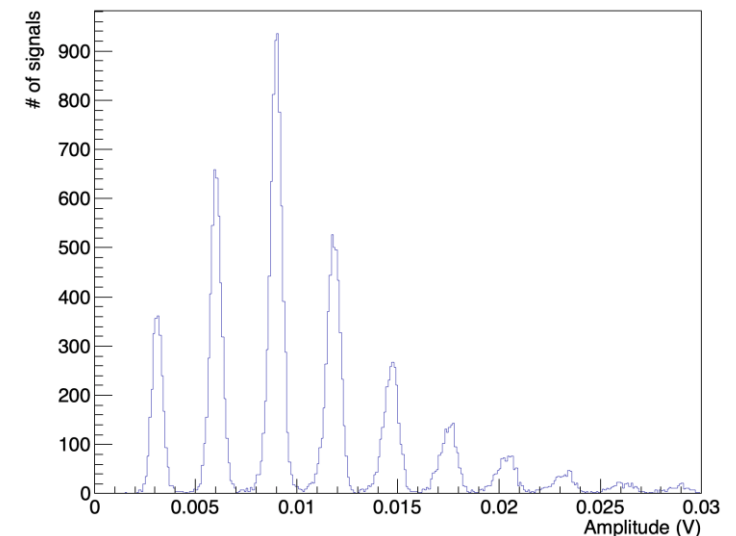
Stokes-shift from [6]

Silicon Photomultipliers

- Array of Avalanche Photodiodes:
 - Photon absorbed and creates charge carriers
 - Electrons are accelerated in electric field and create an avalanche through ionization
- APDs operated in photon-counting mode:
 - Operated at a voltage high enough for every photon to cause a self-sustaining avalanche
- Single-photoelectron spectrum: separation and distance between peaks of the spectrum describe single-photon resolution



Schematic structure of an APD from [3]

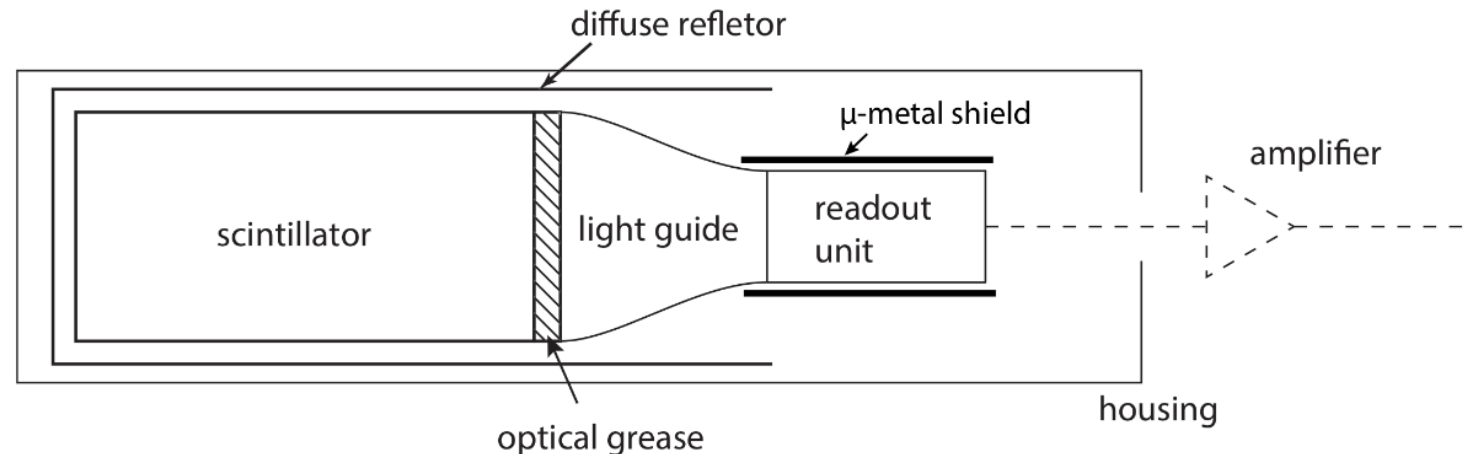


SPE spectrum example

Detector Structure

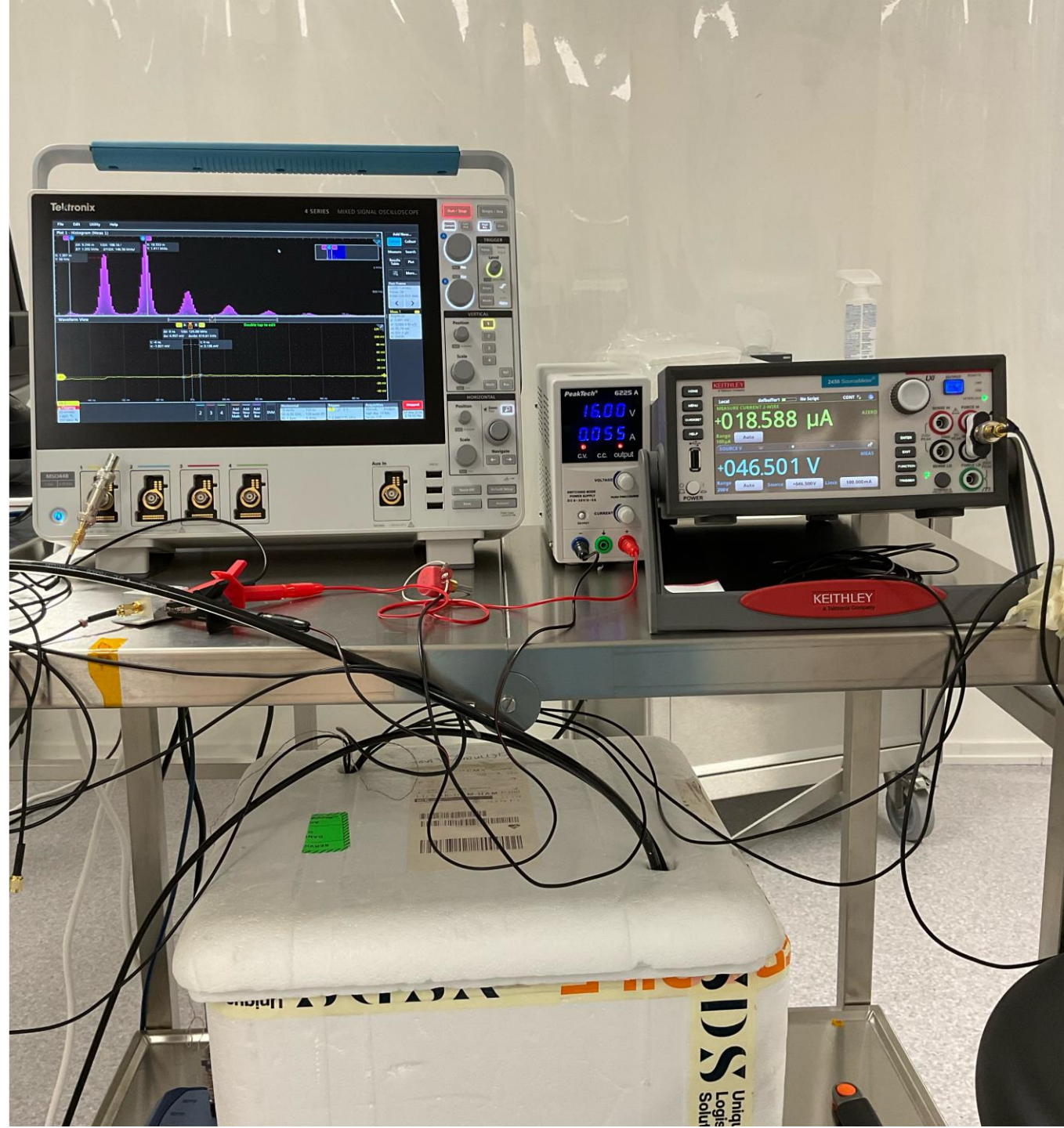
- Four main components:
 1. **Scintillator**: converts deposited energy into photons, wrapped in light-reflective material
 2. **Light guide**: reduces loss of photons for detectors with incompatible scintillator and Photodetector window geometries
Or **wavelength shifter**: if photodetector cannot detect scintillation light wavelength
 3. **Photodetector**: converts photons into electrons, emits an electric signal
 4. **Amplifier**: in case of low output signals
- Optical grease with similar refractive index to components for optical coupling and light-tight wrapping

Schematic structure of a scintillation detector from [5]



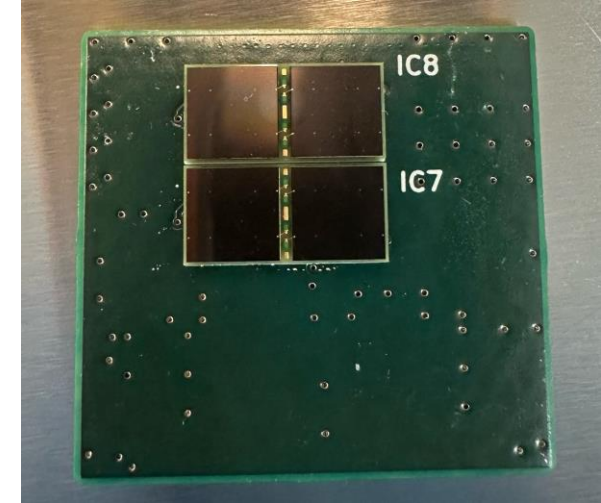
3

Experimental Setup and Data Collection



Detector information

- Scintillators:
 - Two $1.1 \times 1.1 \times 1.5 \text{ cm}^3$ **polystyrene-based scintillators** (EPS100 by Epic Crystal Co.,Ltd.) wrapped in **aluminum foil**
 - Two $1.1 \times 1.1 \times 1.5 \text{ cm}^3$ **polystyrene-based scintillators** (EPS100 by Epic Crystal Co.,Ltd.), **painted¹**
 - One $5 \times 5 \times 5.9 \text{ cm}^3$ **polyvinyl toluene scintillator** (BC-408 by Luxium Solutions), wrapped in **Tyvek (Dry)**
- SiPMs:
 - 2in1: One NUV-MT **dual channel SiPM** (AFBR-S4N66P024M by Broadcom)
 - 4in1: Two NUV-MT **dual channel SiPMs** (AFBR-S4N66P024M by Broadcom)
- Silicone **Optical grease** (EGZ-SD65WH by Epic Crystal Co.,Ltd.)
- **Black masking tape** (T137-1.0 by Thorlabs, Inc.)
- ¹**Reflective paint** with TiO_2 pigments (EJ-510 by Eljen Technology)

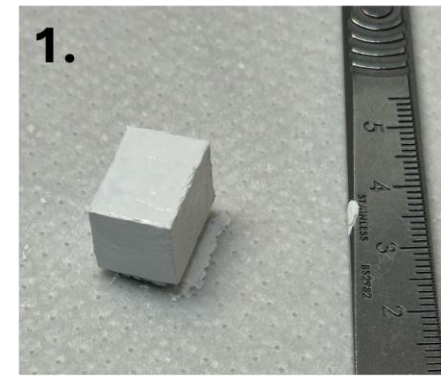


4in1 SiPM

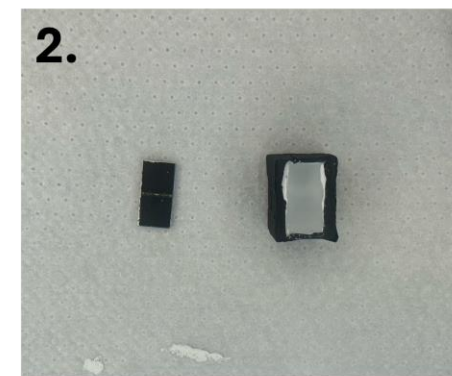
Detector Assembly

Three types of detector structure:

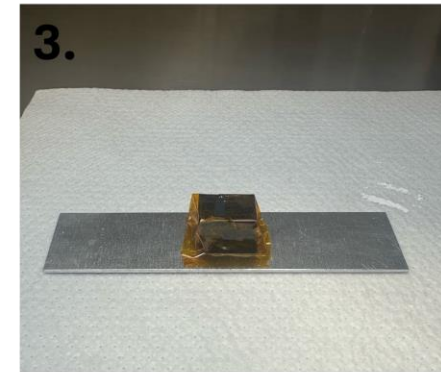
- Two **OD**:
 - PS scintillator wrapped in aluminum foil, attached to five sides
 - One 2in1 SiPM
- Two **ND**:
 - PS scintillator painted with reflective paint with TiO_2 pigments
 - One 2in1 SiPM
- One **BD**: PVT scintillator wrapped in Tyvek (Dry)
 - One 4in1 SiPM



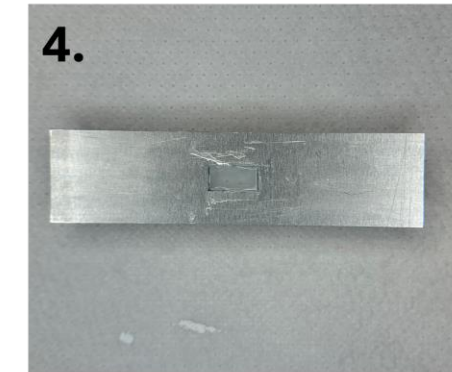
Coated in reflective paint



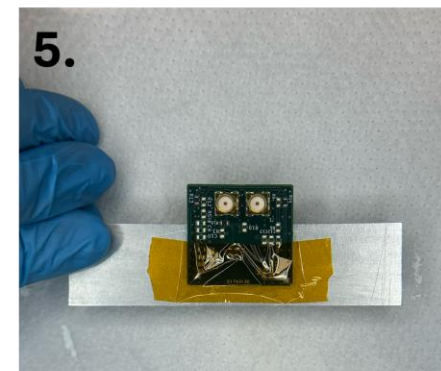
Wrapped in light-tight tape



Taped to a metal sheet



Optical grease



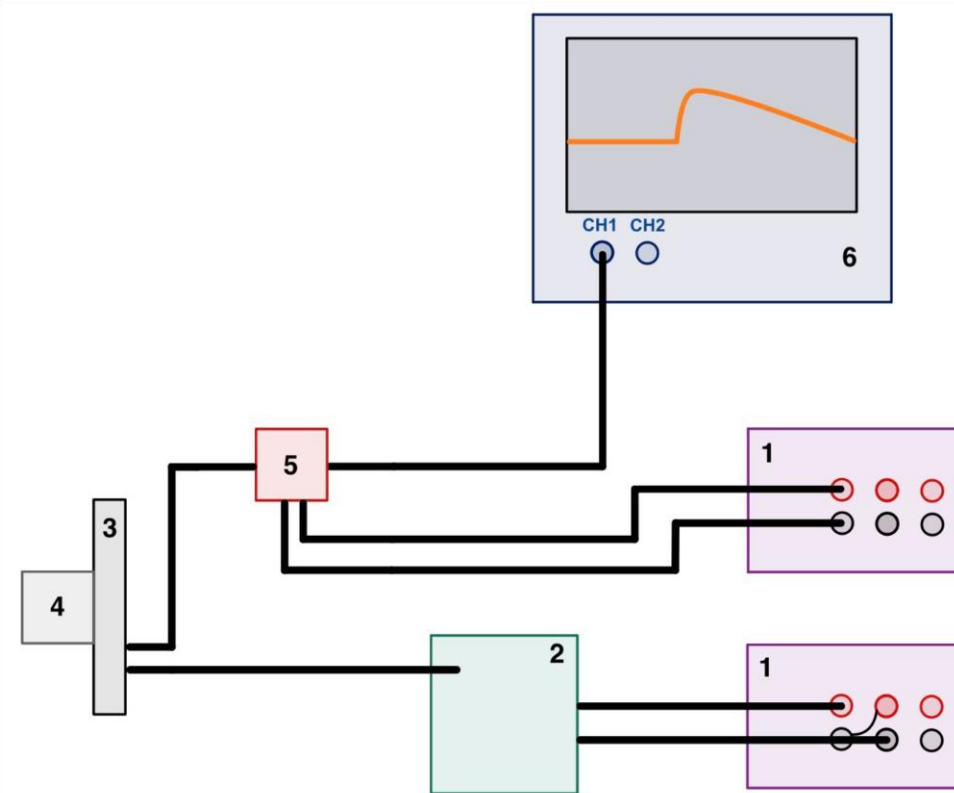
SiPM attached to the other side



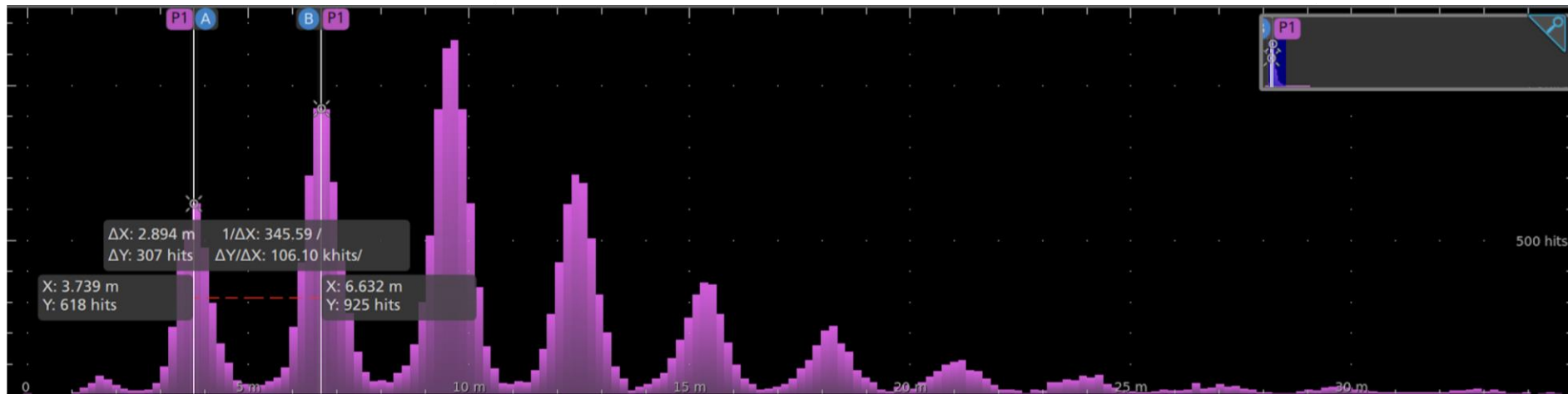
Entire detector wrapped in light-tight tape

Single Photo-Electron Spectrum

- 1 Power supply
- 2 PCB
- 3 SiPM
- 4 Scintillator
- 5 Amplifier
- 6 Oscilloscope

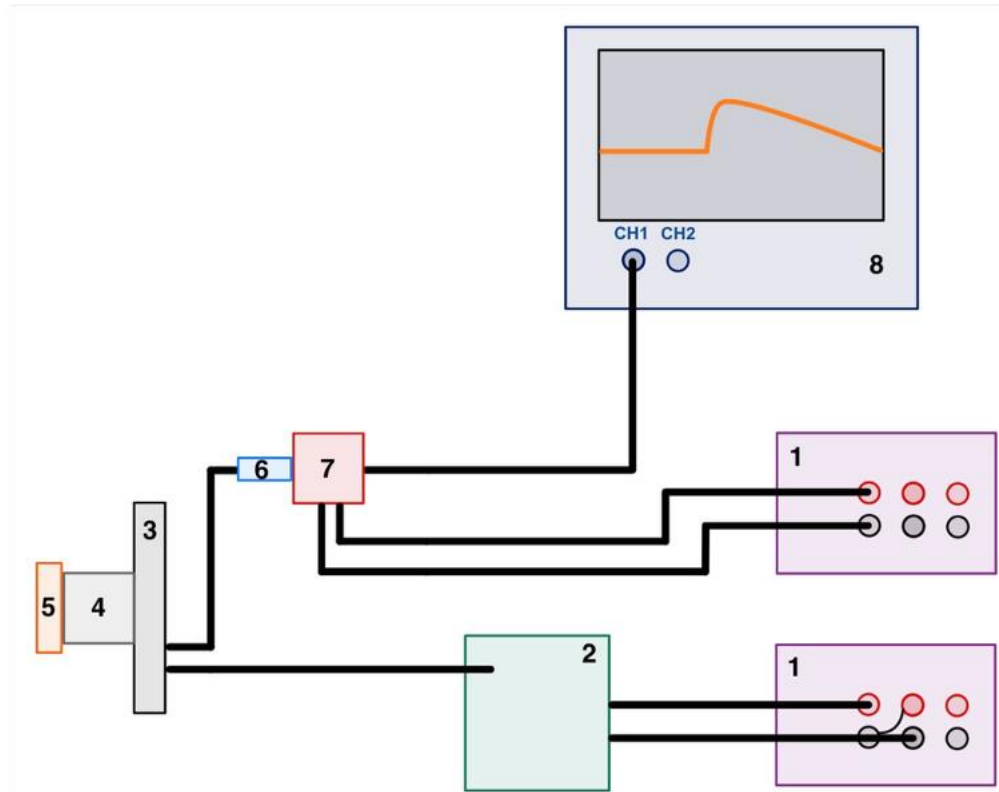


SPE spectrum as
shown by the
oscilloscope

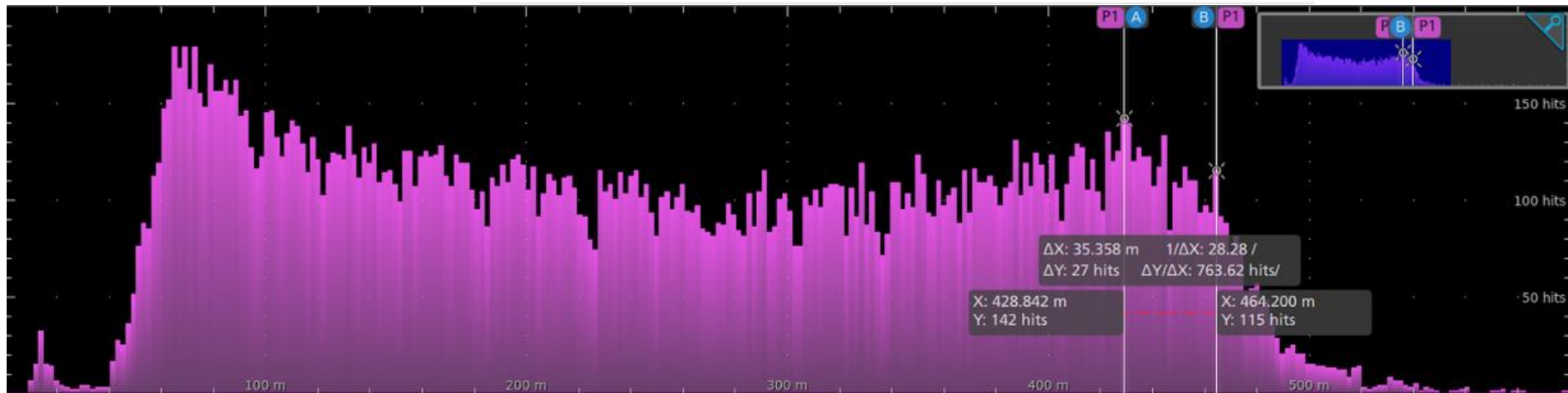


Uncorrelated Signals

- 1 Power supply
- 2 PCB
- 3 SiPM
- 4 Scintillator
- 5 ^{137}CS source
- 6 Attenuator
- 7 Amplifier
- 8 Oscilloscope

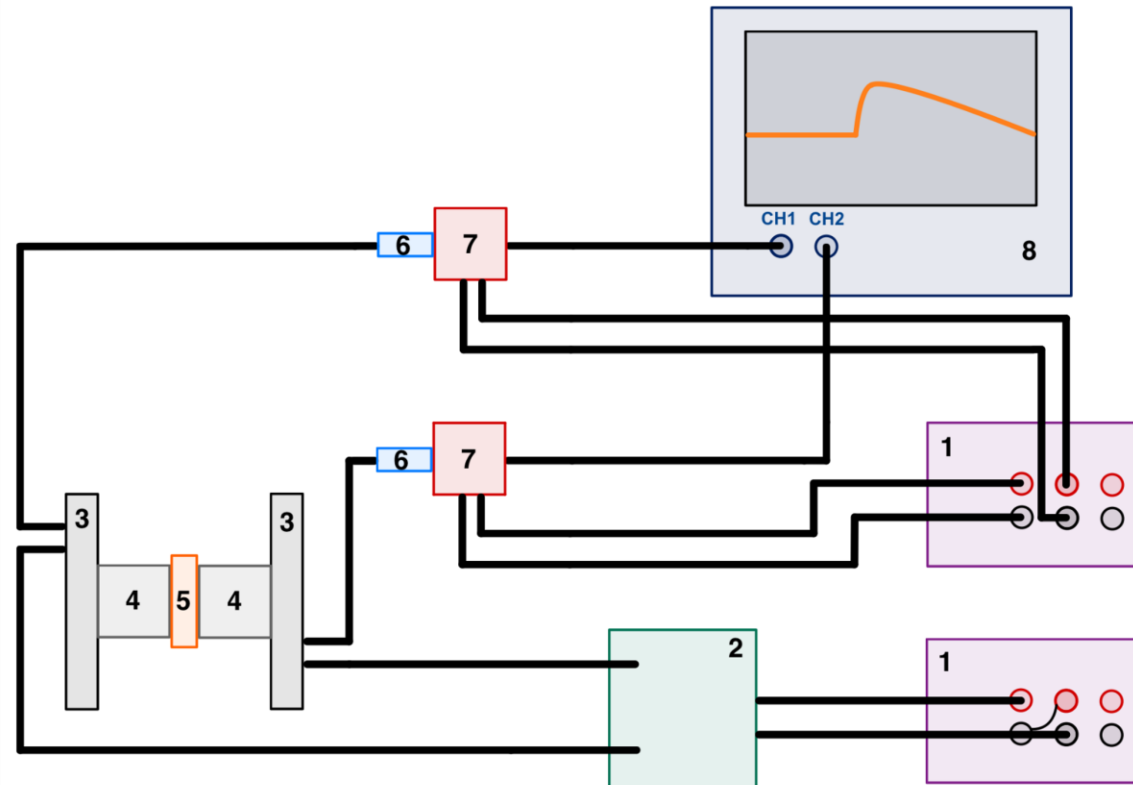


Oscilloscope screen for uncorrelated data measurement

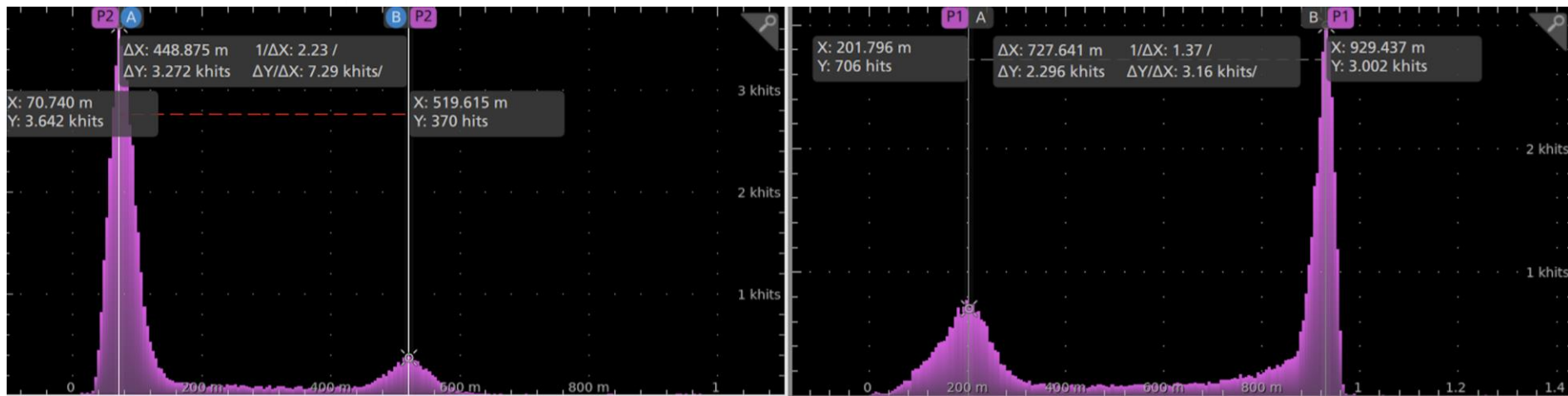


Correlated Signals

- 1 Power supply
- 2 PCB
- 3 SiPM
- 4 Scintillator
- 5 ^{137}CS source
- 6 Attenuator:
here: 10 dB
- 1 Amplifier
- 2 Oscilloscope

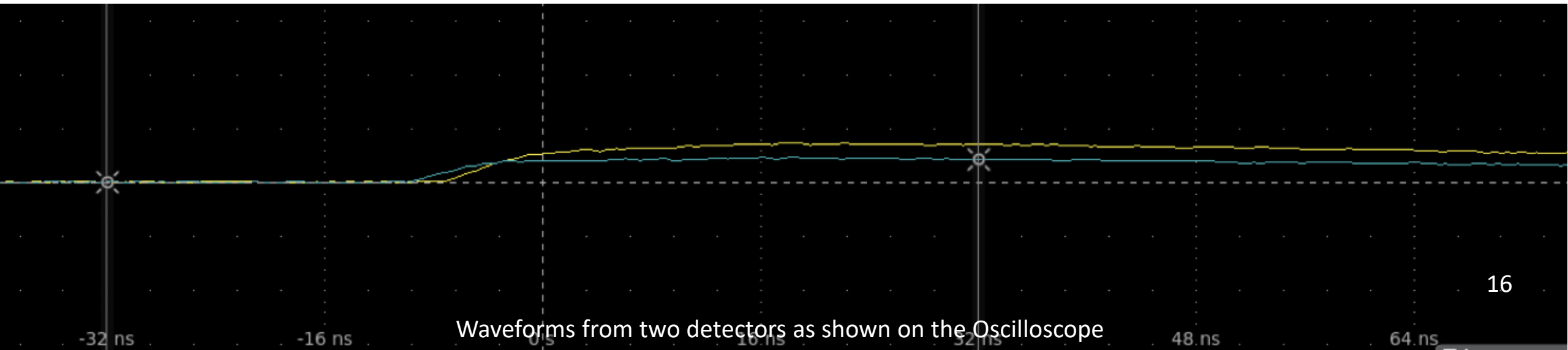
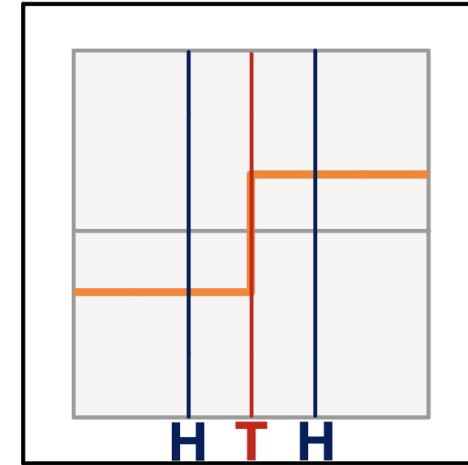


The output of two channels as seen on the oscilloscope



Trigger Logic

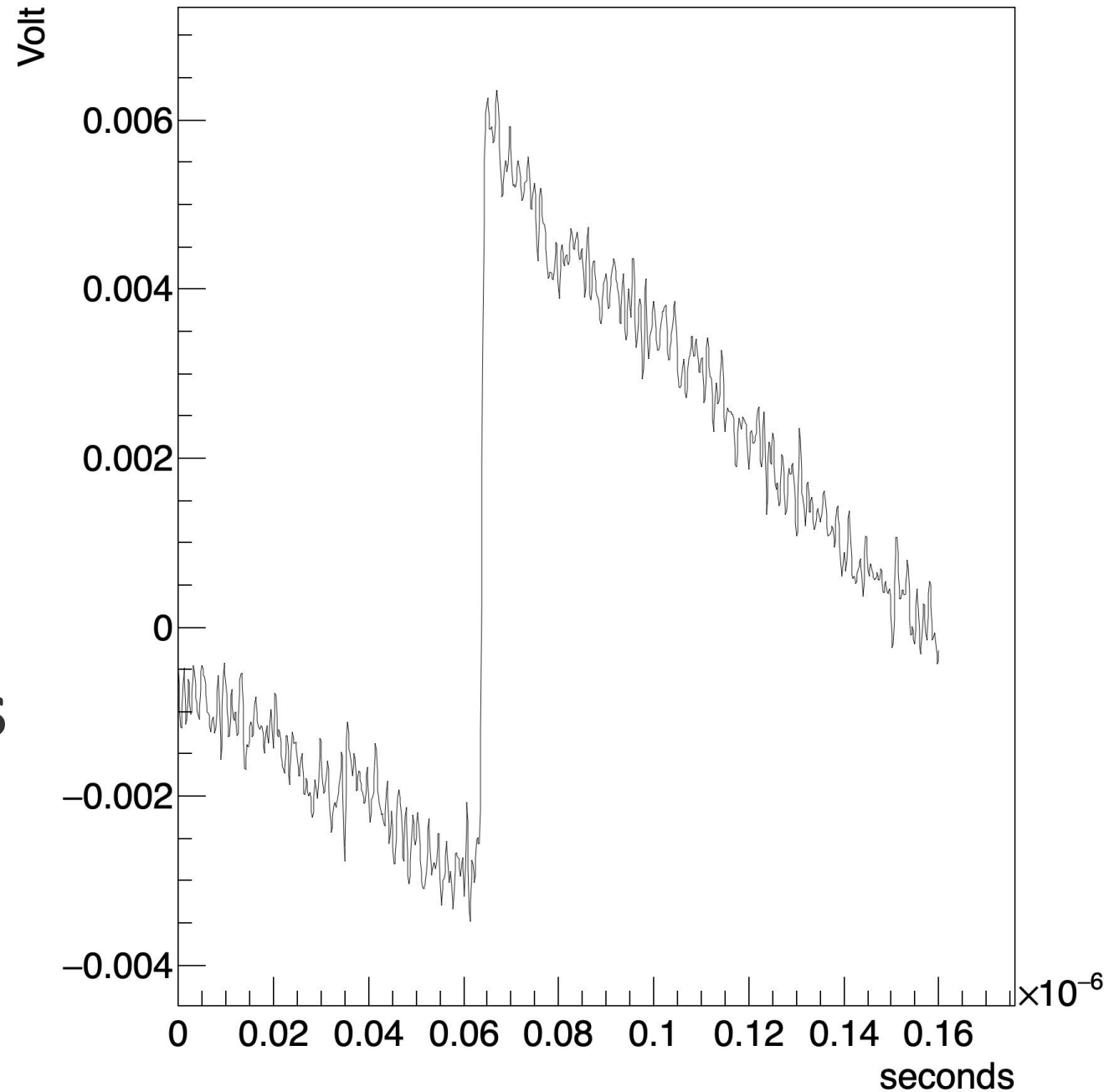
- Trigger on one channel
- Hold for ± 4 ns
- Event is kept if the other channel also produces a signal in the ± 4 ns window



Waveforms from two detectors as shown on the Oscilloscope

4

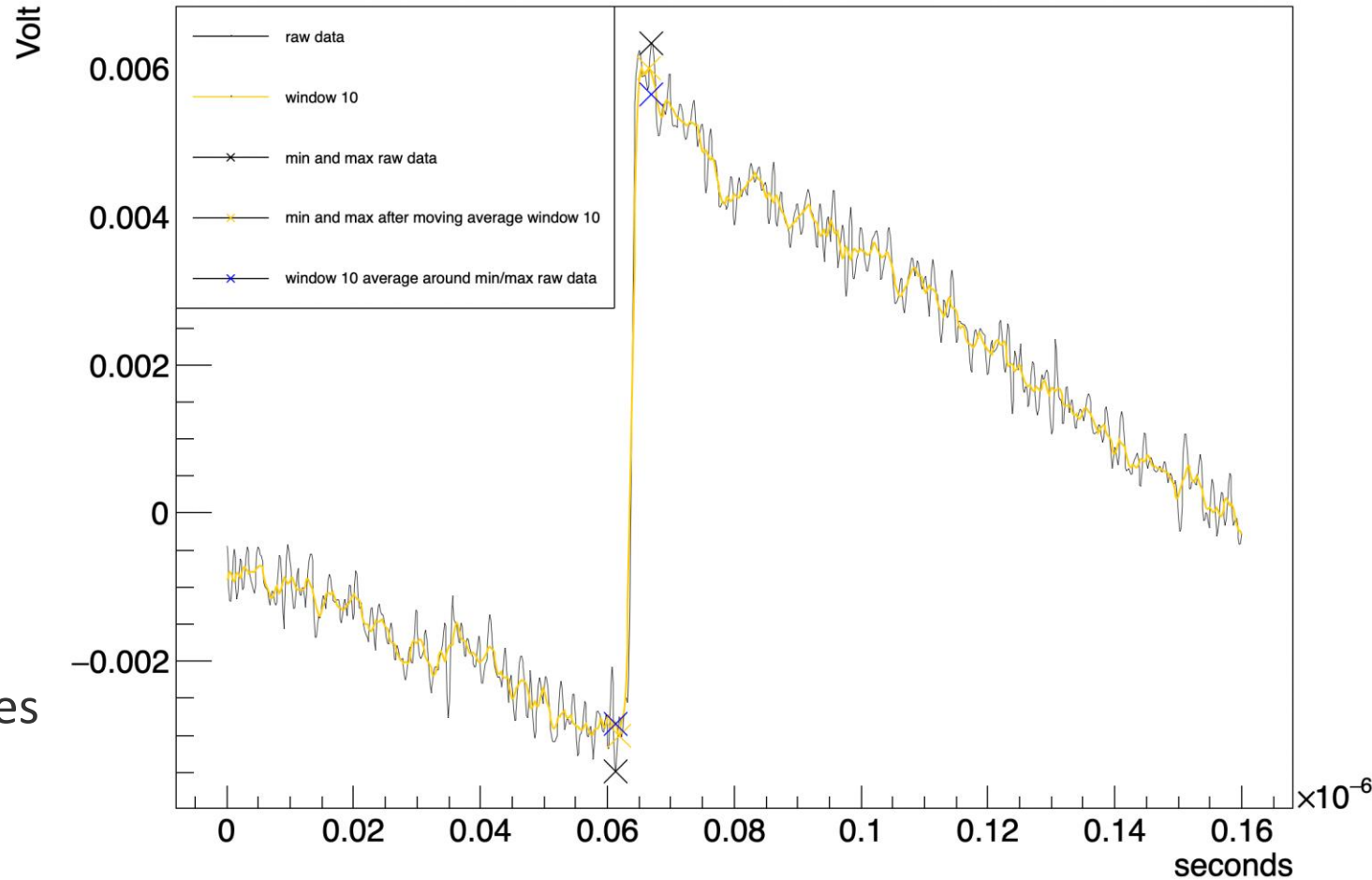
Data Analysis and Results



Example waveform SPE spectrum – OD1

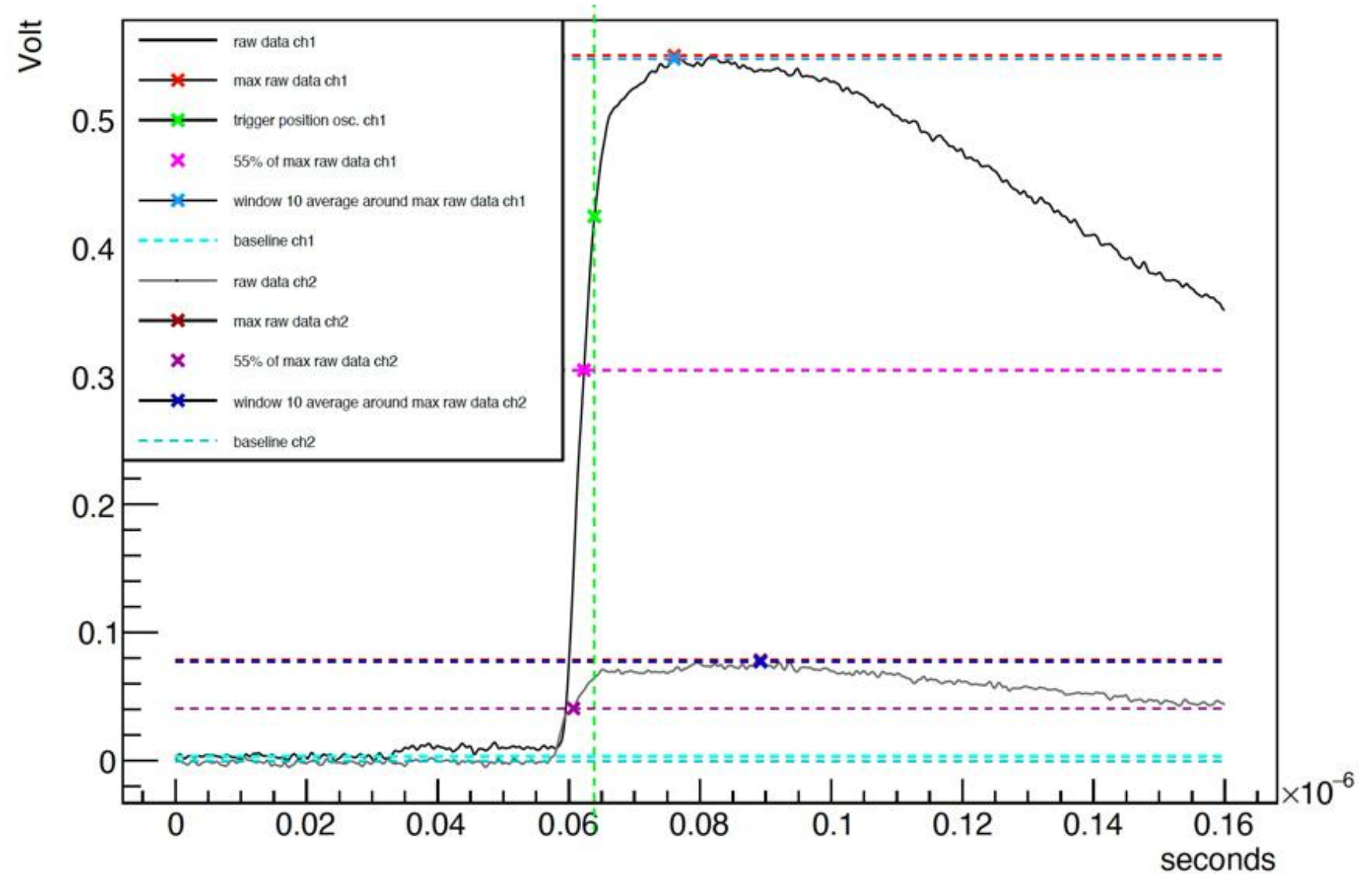
Analysis

- Input: binary waveform output file from Oscilloscope
- Method 1:
 1. Smooth waveform with a moving average filter
 2. Find amplitudes
- Method 2:
 1. Find amplitudes
 2. Calculate average of the amplitudes within a window



Example waveform of the SPE spectrum – OD1

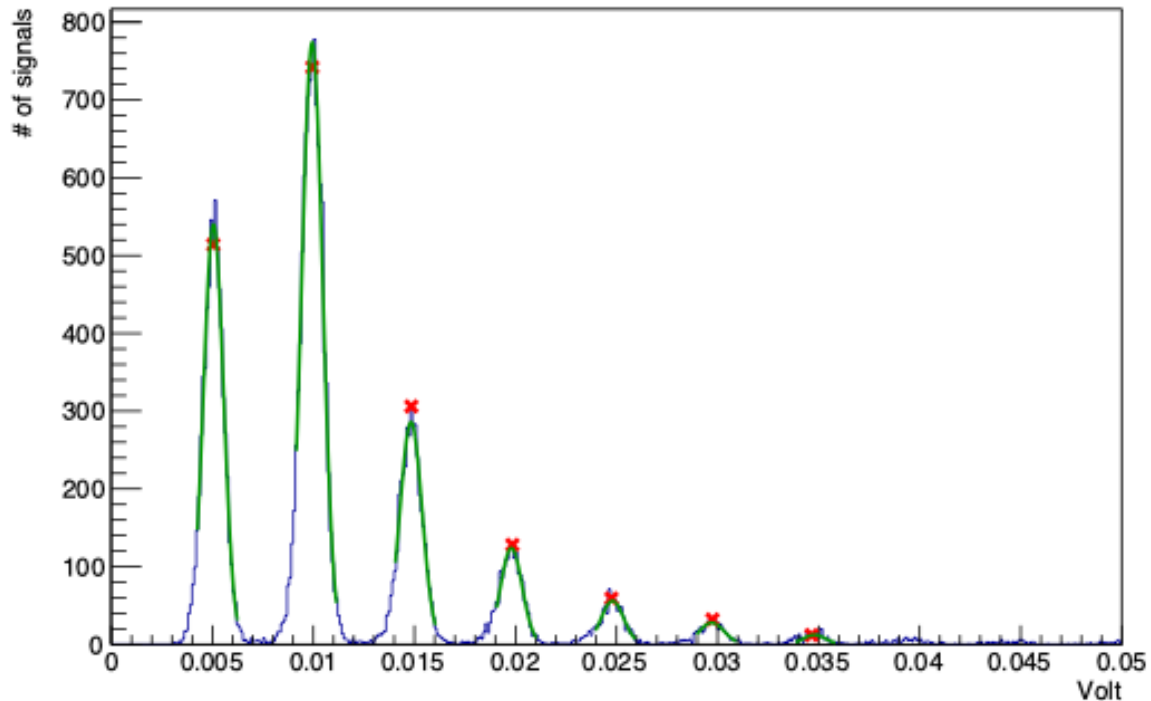
- Example waveform from the Correlated signals
- Two waveforms from two channels
- Find trigger times at e.g. 55% of the total amplitude
- Baseline in light blue



Example waveforms: OD1-OD2, trigger on OD1

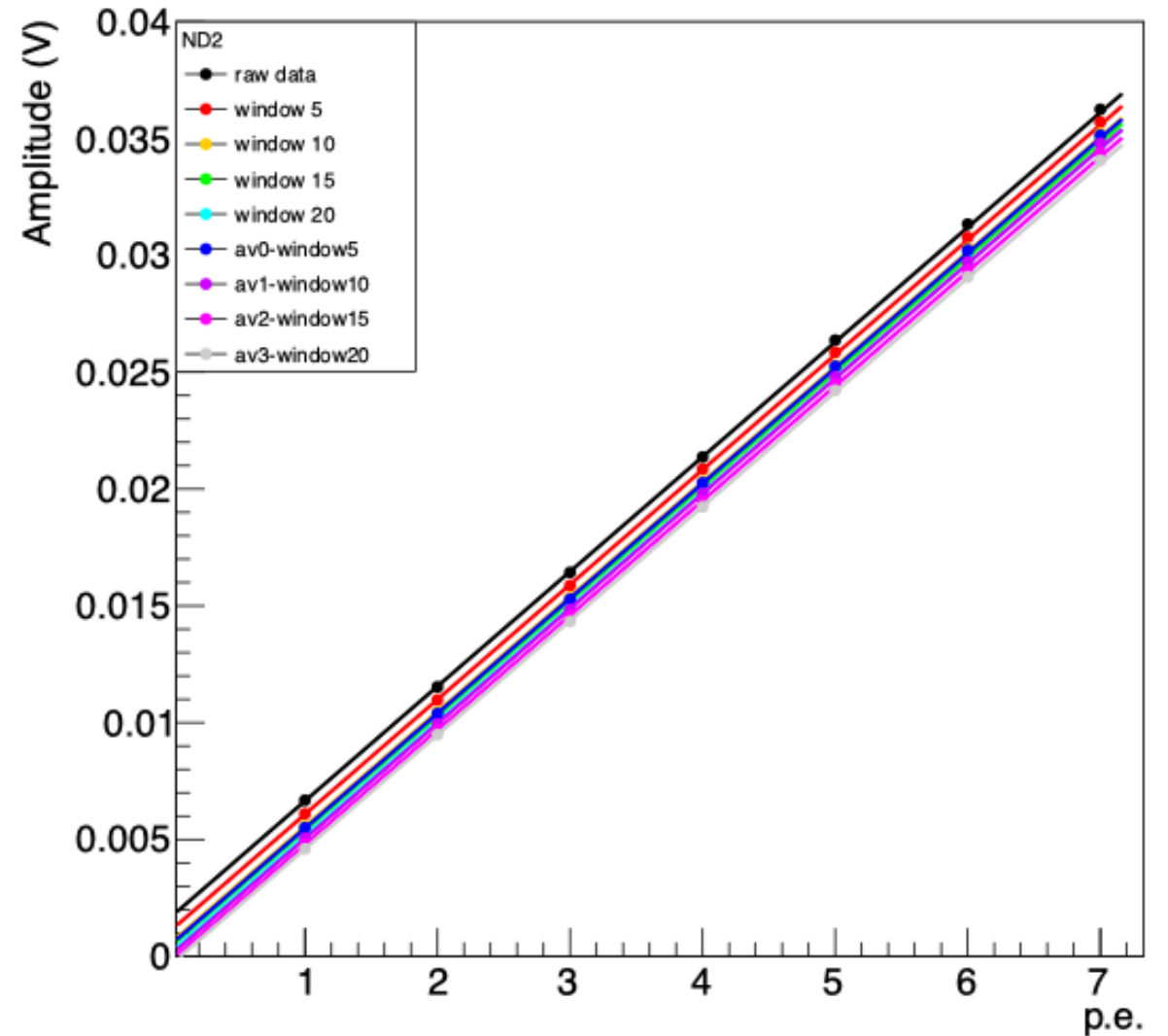
SPE Spectrum

- Find peaks
- Gaussian fit around each peak
- Gaussian statistics kept in a CSV file



SPE spectrum NPCB2

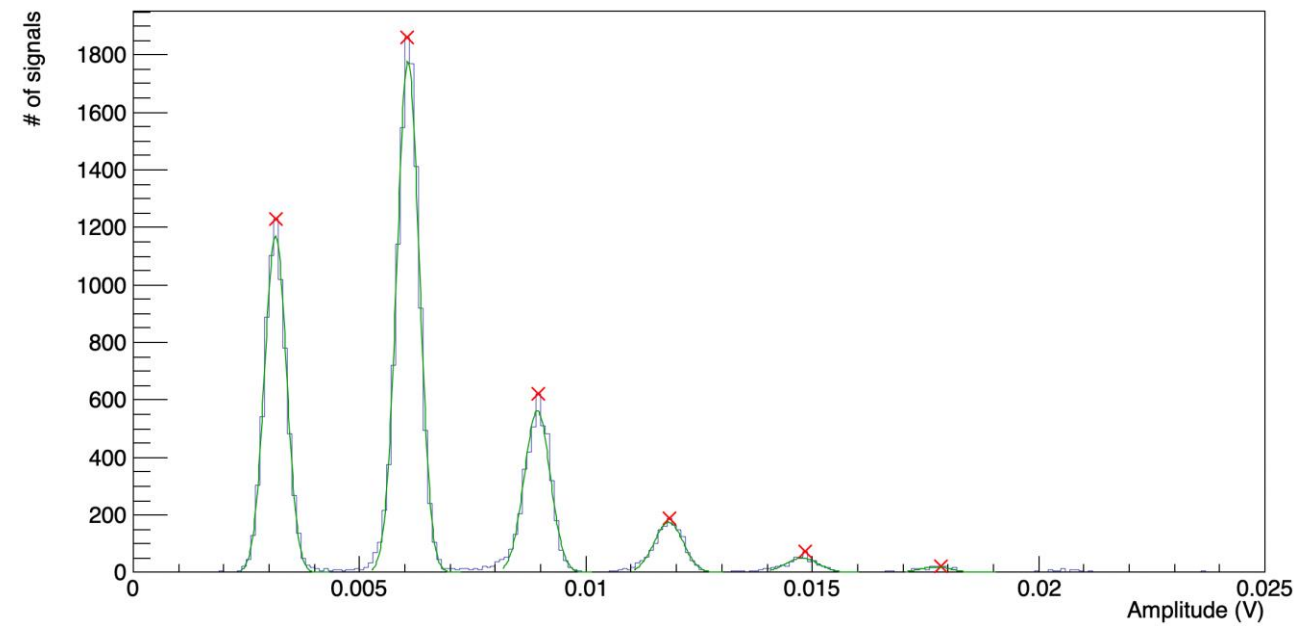
Amplitude (V)



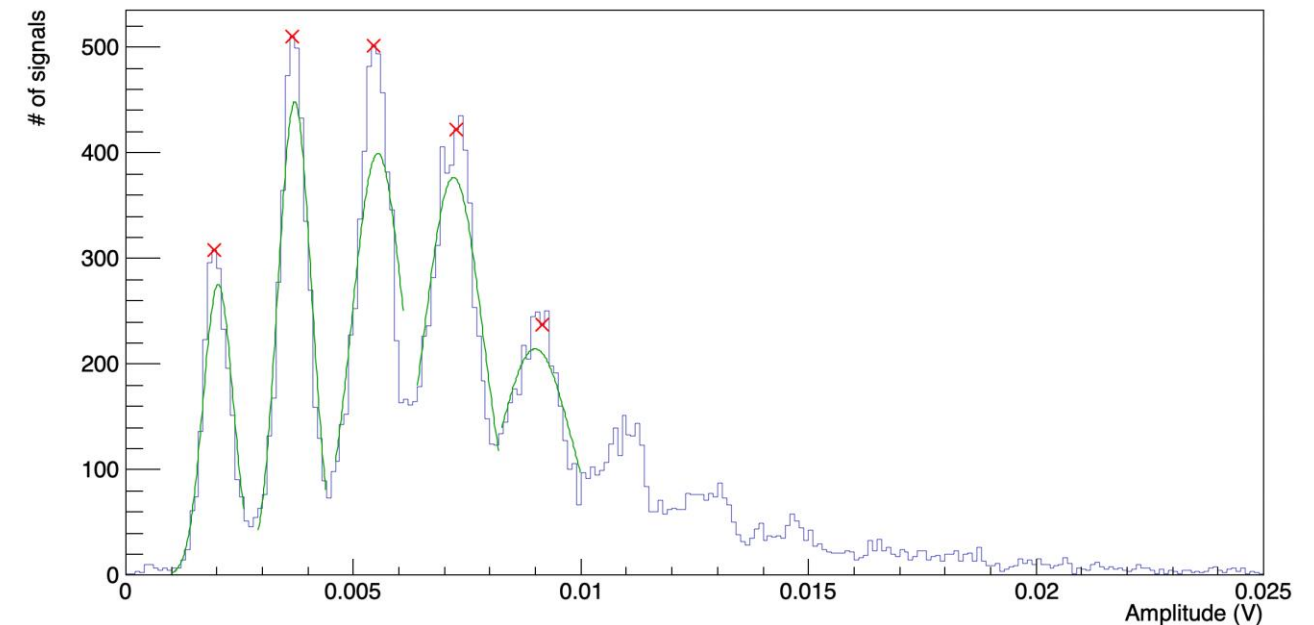
Calibration line for the conversion from amplitude to photoelectrons – ND2

SPE Spectrum

- Single-photon resolution: well separated discrete peaks of the SPE Spectrum
- BD: uses 4in1 SiPM instead of 2in1 SiPM
 - Worsens single-photon resolution



SPE spectrum OD1



SPE spectrum BD

Uncorrelated Signals

- Compton edge of ^{137}Cs spectrum: 477.34 keV

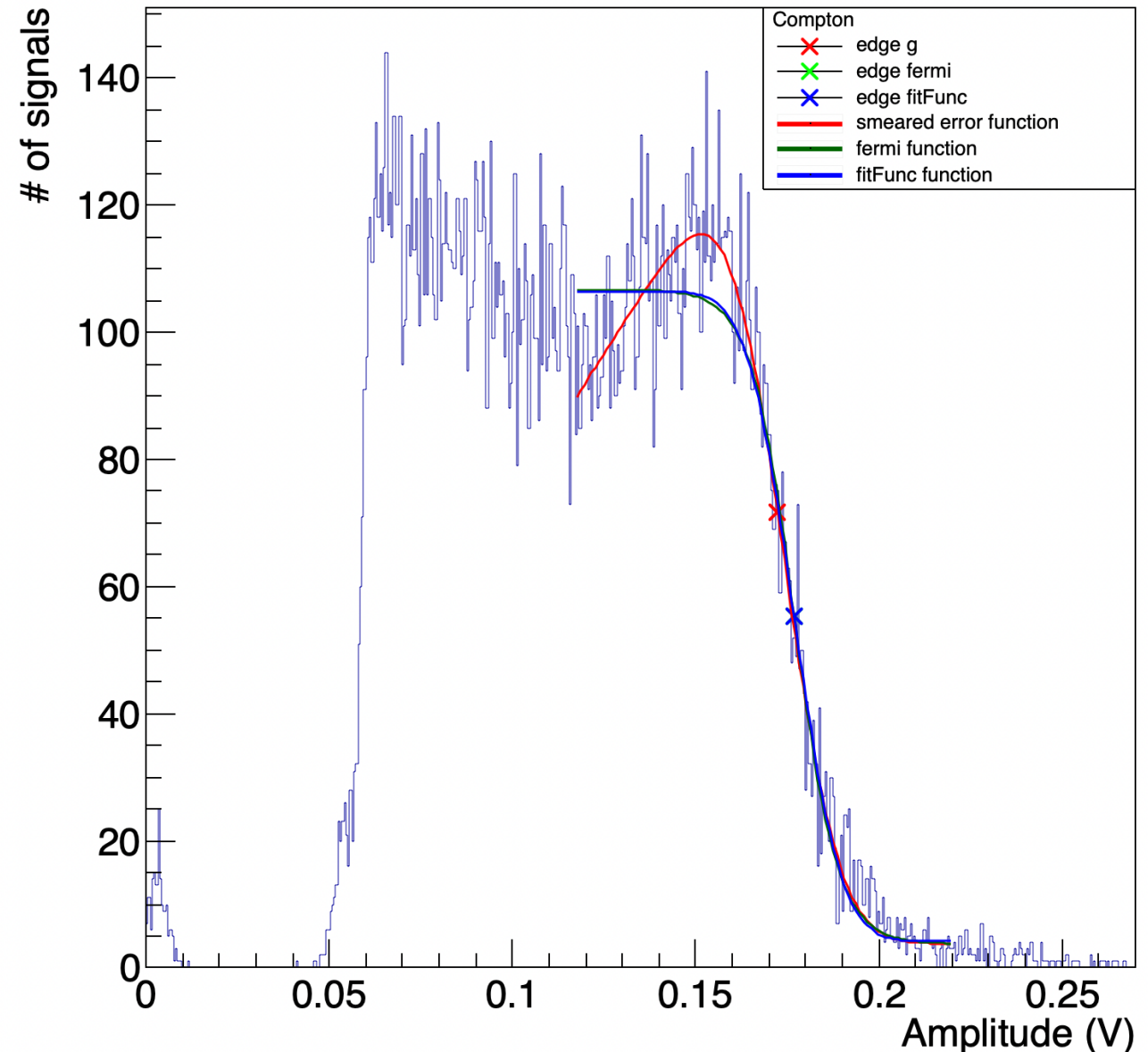
- Fit functions for the Compton edge:

$$g = \frac{a + bx}{2} \cdot \left(1 - \operatorname{erf}\left(\frac{x - x_0}{\sigma}\right)\right) + c$$

$$\text{fermi} = \frac{a}{1 + e^{\frac{x - x_0}{\sigma}}} + c$$

$$f = \frac{a}{2} \cdot \left(1 - \operatorname{erf}\left(\frac{x - x_0}{\sqrt{2}\sigma}\right)\right) + b$$

- Parameter describing Compton edge: x_0



OD1 Compton spectrum

Uncorrelated Signals – Compton Edge Study

- Fit function provides Compton edge position
- Comparison of detector performance:
 - Compensate attenuation of 10 dB ($\times 3.162$) or 20 dB ($\times 10$)
 - Convert from amplitude to photoelectrons (pe)
- Best performance: reflective paint
- Worst performance: larger scintillator volume and Tyvek

detector	CE477 [p.e.]	uncertainty [p.e.]
OD1	593.4	2.7
OD2	562.2	2.3
ND1	1660.7	5.1
ND2	1569.5	3.8
BD	470.6	2.5

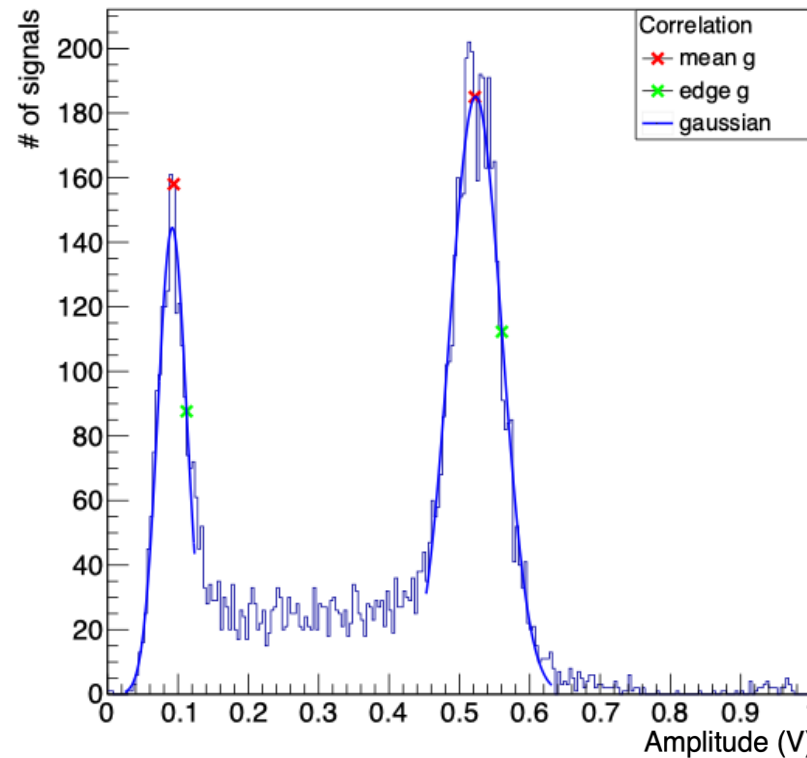
The number of detected photoelectrons corresponding to 477.34 keV

Correlated Signals

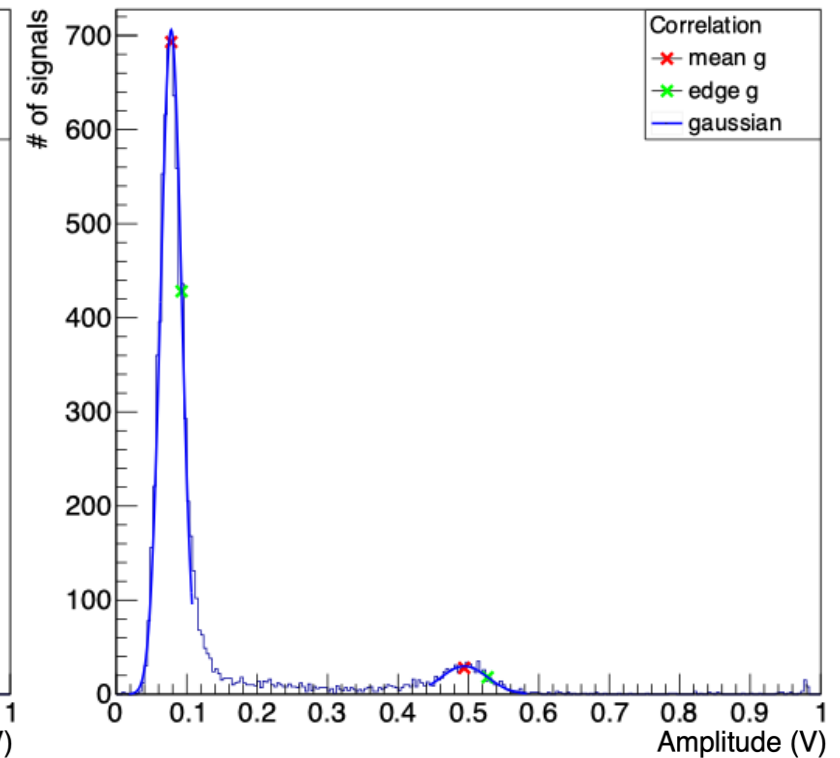
- Expected:

- Amplitude distributions showing two peaks of the same height
- Both channels produce identical distributions for the same measurement

- Second order Compton edge of ^{137}Cs spectrum: 77.25 keV (CE77)



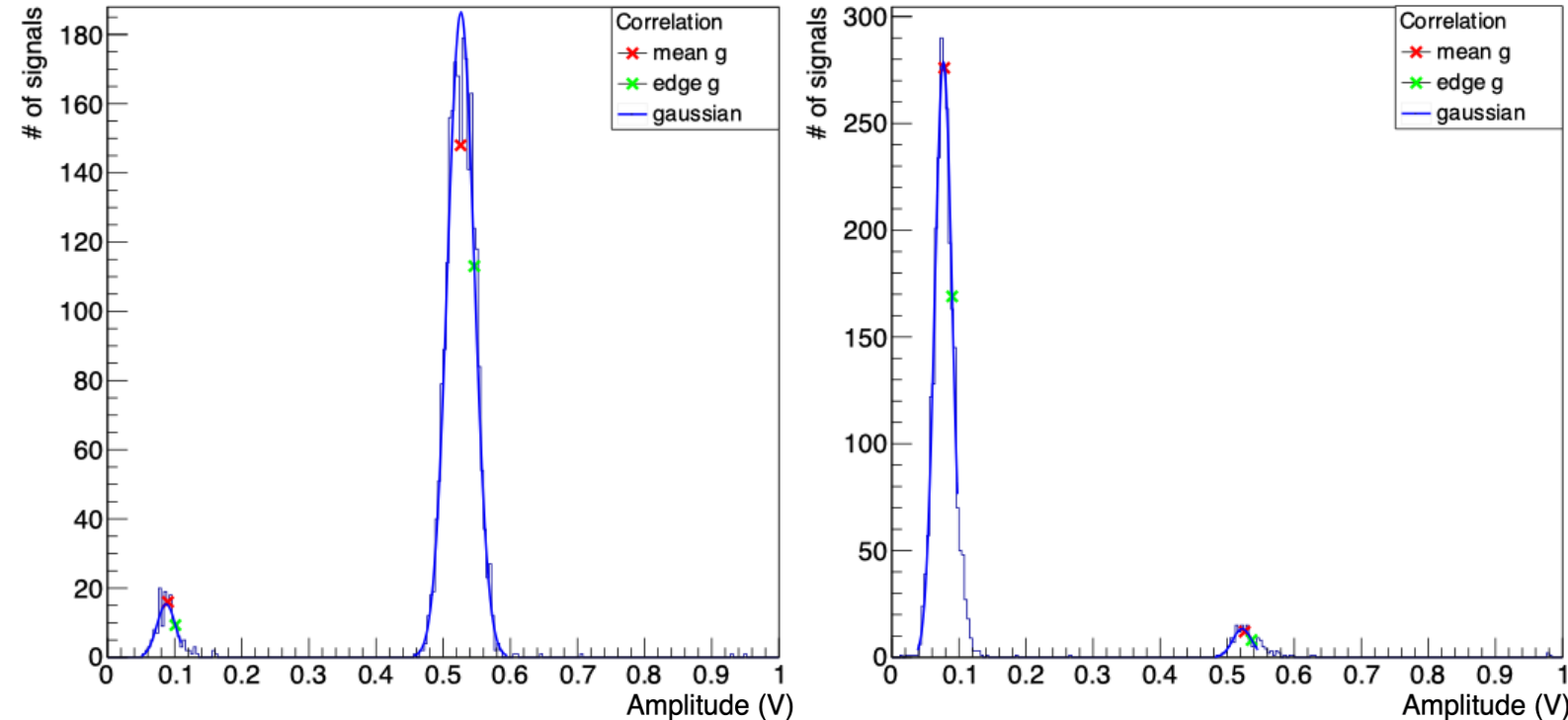
Channel one Amplitudes



Channel two Amplitudes

Output of two channels from the same data run OD1-OD2, trigger on OD1

Correlated Signals



Output of two channels from the same data run OD1-OD2, trigger on OD1
Energy difference selection criterion

- Selection criteria for signals within one event:

- Expected total energy a γ -ray deposits in both detectors
 $477 \text{ keV} + 77 \text{ keV} = 554 \text{ keV}$
- Expected energy difference between the signals of the two detectors
 $477 - 77 = 400 \text{ keV}$
- Margin of error: 15%

$$\text{Ratio: } 77.25 \text{ keV} / 477.34 \text{ keV} = 16.2\%$$

Correlated Signals

- OD1-OD2 setup, trigger on OD1:

detector	CE77 [p.e.]	CE477 [p.e.]	ratio
OD1	99.9 ± 0.7	610.1 ± 1.4	$16.4\% \pm 0.1\%$
OD2	85.8 ± 0.3	581.3 ± 3.7	$14.8\% \pm 0.1\%$

- OD1-OD2 setup, trigger on OD2:

detector	CE77 [p.e.]	CE477 [p.e.]	ratio
OD1	99.4 ± 0.7	596.2 ± 1.4	$16.7\% \pm 0.1\%$
OD2	85.1 ± 0.3	580.1 ± 3.5	$14.7\% \pm 0.1\%$

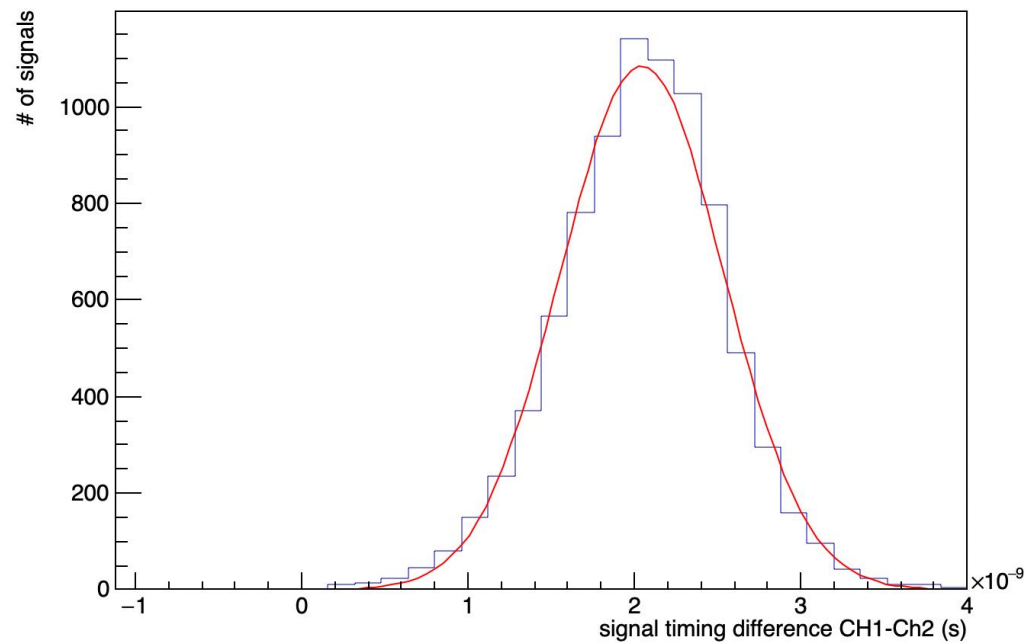
detector	expected CE77 [p.e.]	CE477 [p.e.]
OD1	96.0	593.4
OD2	91.0	562.2
ND1	269.6	1660.7

Expected values for Ce77 and CE477 in p.e.

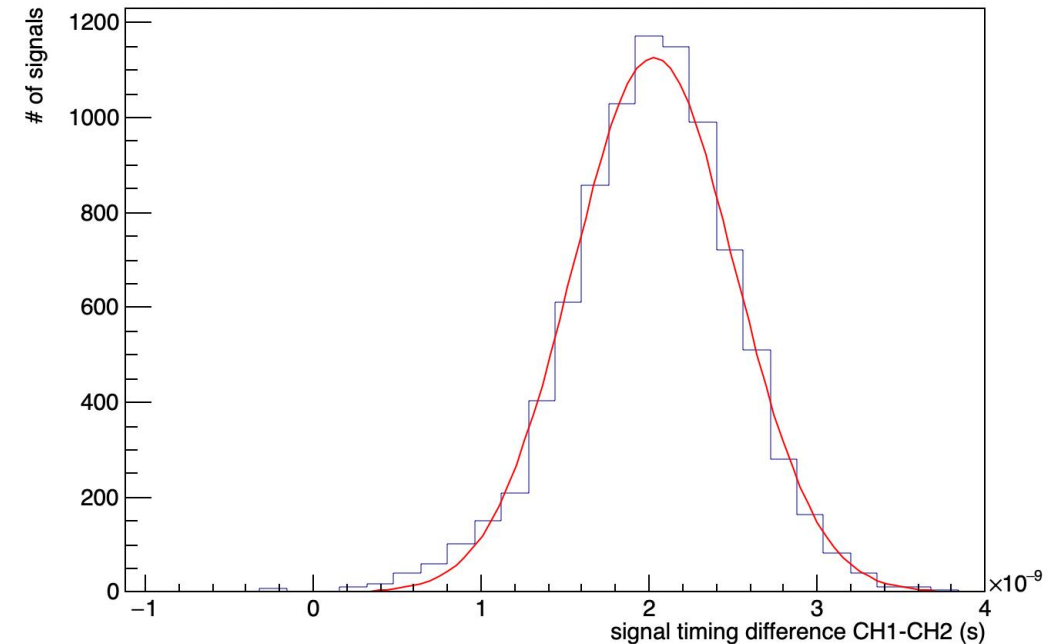
- Differences negligible: the choice of trigger channel does not affect the measurement

Correlated Signals: Signal Timing Difference

- Estimated signal timing at 55% of the amplitude
- Expected signal timing difference between two detectors: centered around 0 ns
- Hypothesis: different cable lengths



Trigger on channel one



Trigger on channel two

Conclusion

- One 2in1 (dual-channel) SiPM delivers a better single-photon resolution than a 4in1 SiPM
- Detector performance improves for scintillators covered in reflective paint: three times the photoelectrons compared to aluminum foil
- Lower collection efficiency with the larger scintillator
- Correlated data produced spectra that showed the Compton edge as well as the second order Compton edge
 - Experimental setup was successfully used to detect γ -rays interacting with two detectors sequentially
- Setup-And-Hold trigger channel does not influence the signal timing and measurement

Thank you for listening!
Questions?



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