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Ljubljana, Slovenija

LOW LIGHT INTENSITY TIMING WITH SIPM

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Contents

- Motivation
- Photon detection
- Silicon photomultiliers
- Timing measurements
- Conclusion

LHCb RICH1 upgrade after LS4

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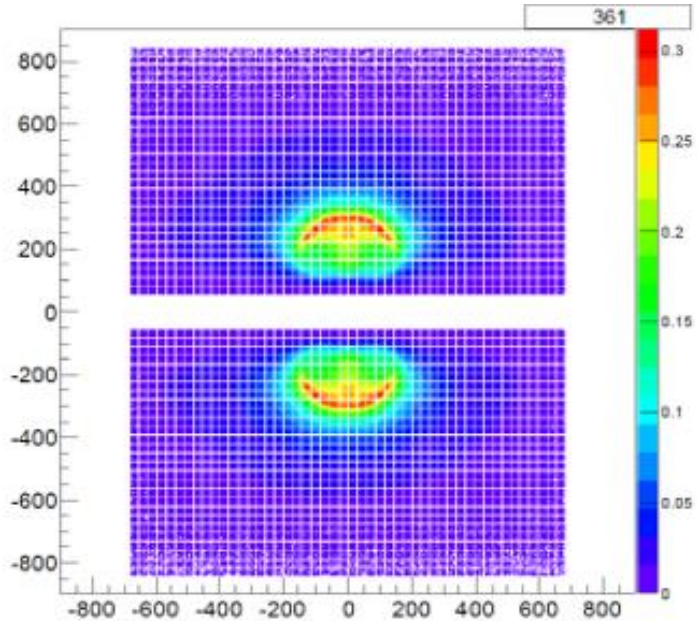
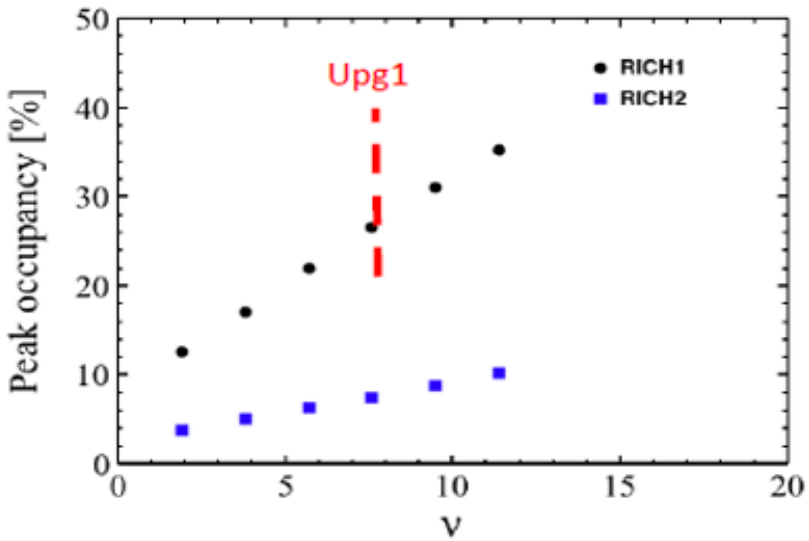
Photon Occupancies for 3x3mm channels of MAPMTs installed during Upgrade 1

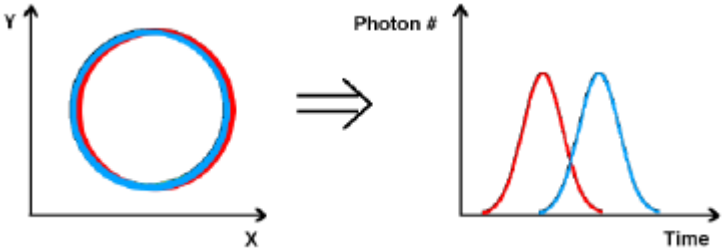




To exploit full potential of HL-LHC a substantial upgrade of LHCb is required:

@ L= 10^{34} $cm^{-2}s^{-1}$

- ❑ Number of PVs per collision 38
- ❑ Ocupancies in RICH1 > 130%
  - ❑ Decrease pixel size to 1x1 mm2
  - ❑ Measure time of the photons with resolution ~150 ps



MAPMTs → silicon photomultiplier

Positron emission tomography

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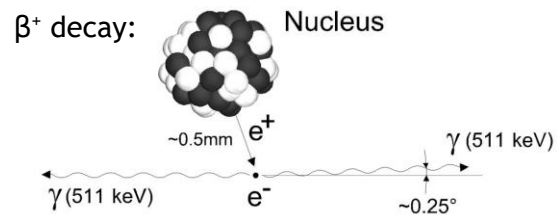
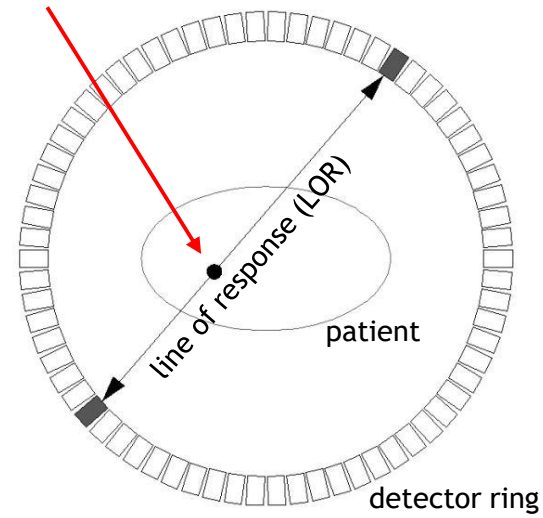
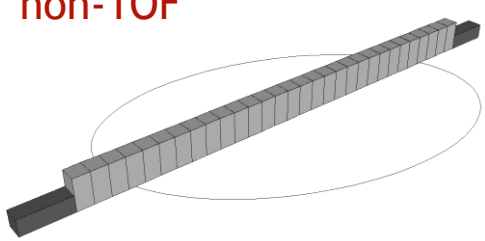
- Positron emission tomography (PET)
  - medical physics modality, enabling in-vivo imaging of biological processes via coincident detection of 511 keV annihilation γ rays

- Time-of-flight (TOF)
  - measurement of arrival times of the two γ can be used to limit the reconstructed position of annihilation
  - improves the quality (contrast-to-noise ratio) of reconstructed images

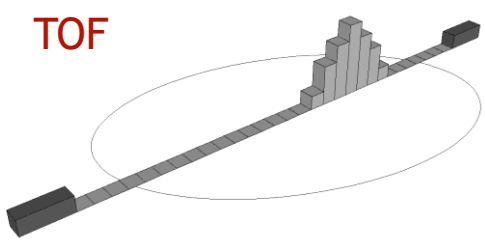




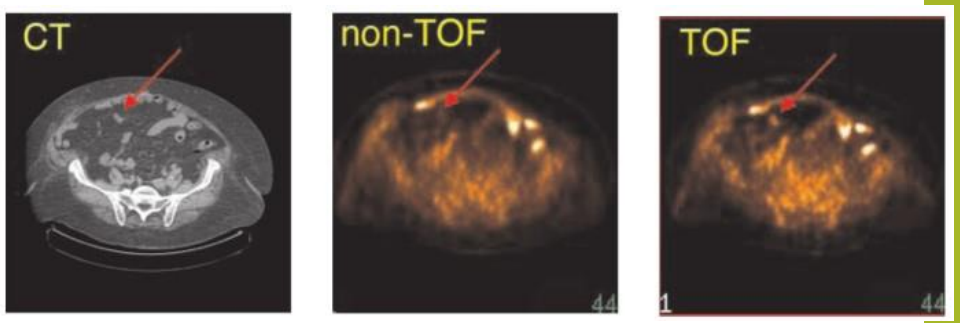
non-TOF



TOF



$$\Delta x = \frac{c_0 \cdot \Delta t}{2}$$



Philips Gemini TF PET/CT, TOF resolution of 600 ps
[PET Center of Excellence Newsletter, Vol.3 Issue 3 (2006)]

Gamma detectors for PET

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gamma → Scintillator | Photo detector | Pulse height measurement

- Scintillating crystal
  - converts gamma energy into optical photons
- Photodetector (photomultiplier tubes)
  - converts optical photons into electrical pulses
- Time resolution in TOF PET limited mainly by
  - photodetector response
  - scintillation rise and decay time constants
  - optical photon travel time spread in the crystal

Figure of merit for tomographic images: $\frac{\varepsilon^2}{\sigma_t}$

Wish list:

- ❑TOF-PET timing resolution 10ps
- ❑**corresponds to 1.5mm resolution** along LOR
- ❑Direct imaging possible – no need for reconstruction of PET images

Cherenkov radiation in TOF PET

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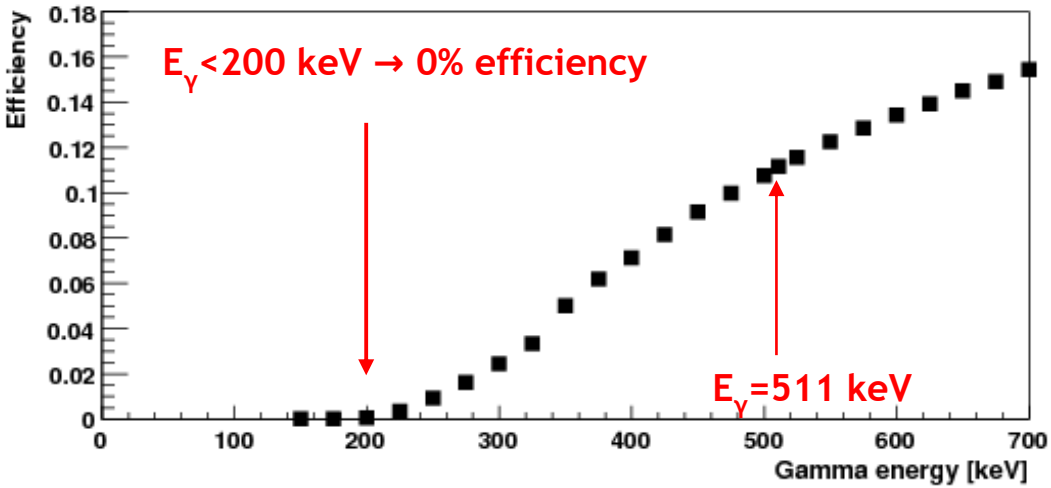
Only about 10 Cherenkov photons can be produced by 511 keV gamma, only a couple reach the photodetector → **single photon detection**

Photodetector efficiency a limit for efficiency of the whole method

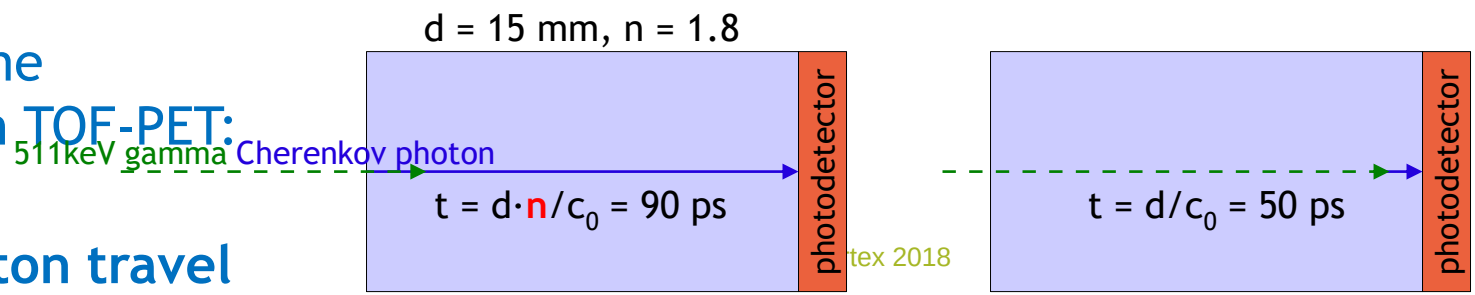


No energy resolution

intrinsic Compton **scatter suppression** & less scattering in crystals (very high Z)

Limit for time resolution in TOF-PET:

optical photon travel time spread



→ Δt = **40 ps**

tex 2018

Time of Flight with Cherenkov photons

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Limitations due to scintillators can be avoided by using radiators of Cherenkov light instead

Charged particles passing through matter at velocity $v > c_0/n$
radiate **prompt** Cherenkov photons

Only electrons from γ with high enough energy radiate Cherenkov photons
→ Intrinsic threshold and rejection of Compton scattered gammas

Disadvantage:
Small number of photons produced per interaction.

→ Most promising available radiator: n=1.8 PbF_2
→ detection of **single photons** is required
- ❑ Multianode Photomultipliers : x poor timing resolution
- ❑ Micro channel plate PMT: measured CTR of 100 ps FWHM
- ❑ Can Silicon Photomultiplier be used for it ?

Silicon Photo Multiplier SiPM

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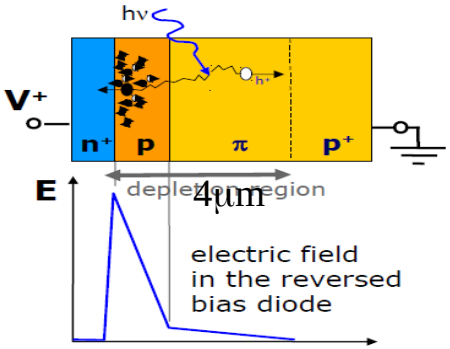
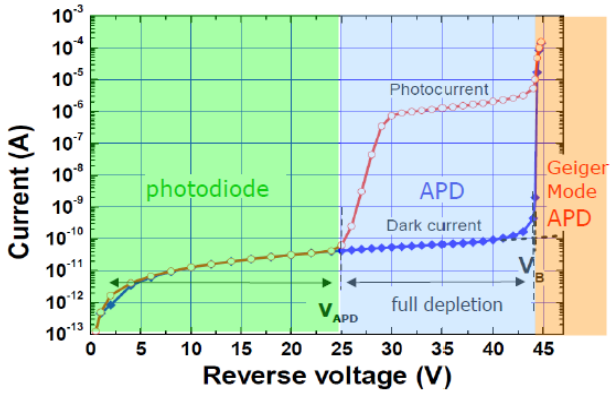
A special kind of reverse bias photo-diode

- the photon is absorbed and generates an electron/hole pair.
- the electron/hole drifts to the high-electric field multiplication region.
- the drifted charge undergoes impact ionization and causes an avalanche breakdown.

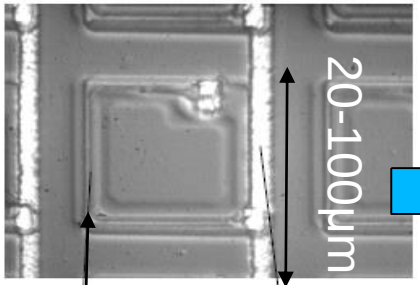


diode characteristic



- $V_{bias} > V_{breakdown}$
- high field in multiplication region

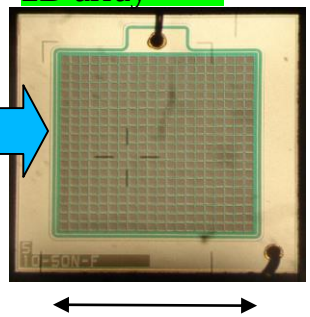
micro cell



poly silicone resistors

Al - conductor

2D array



~mm

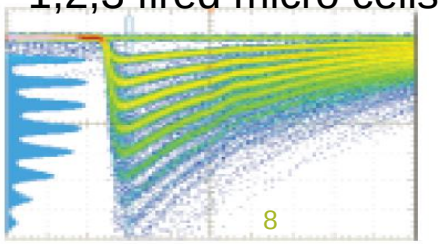
- resistor in series quenches the avalanche (limited Geiger mode).
  - the signal is independent of the particle energy → 0/1

    $A_i \propto C \cdot (V - V_{breakdown})$
- To count photons: 2D array of micro cells (20-100μm) structures in a common silicon substrate.

  the total output

$$A = \sum A_i$$

Clear separation of 1,2,3 fired micro cells



Silicon photomultiplier ...

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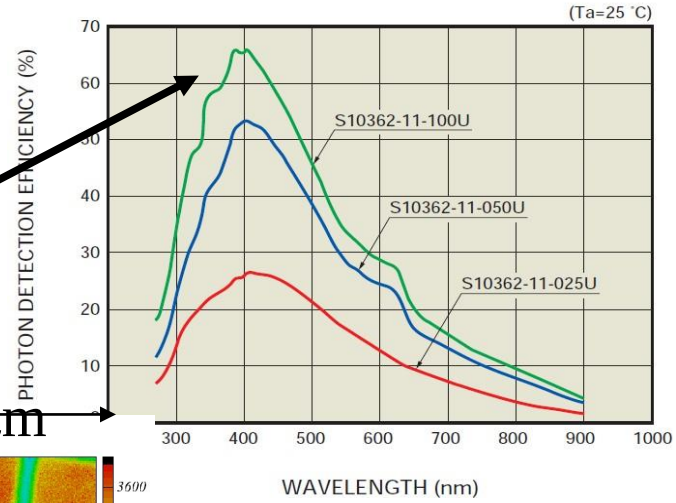
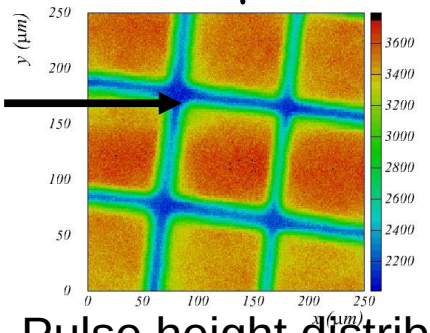
Photon detection efficiency



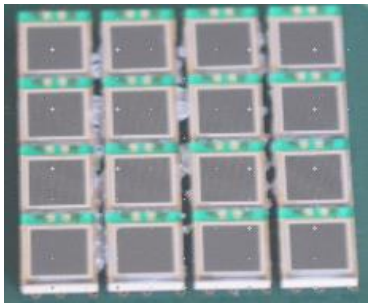
Advantages:

- low operation voltage~ 10-100 V
- gain ~ 10^6
- peak PDE up to 65%(@400nm)
- PDE = QE x ε_{geiger} x ε_{geo}
- ε_{geo} – dead space between the cells
- ε_{geiger} – Geiger discharge probability
- intrinsic timing resolution ~ 100ps
- can be combined in larger modules
- in contrary to PMT
- it works in the magnetic field

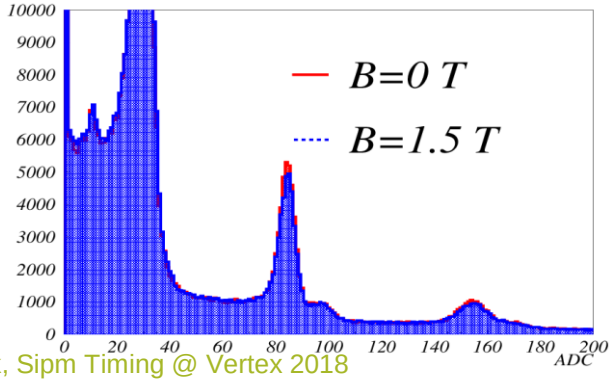
250μm



Array of 4x4 SiPMs



Pulse height distribution



Disadvanteges:

- dark counts ~ few 100kHz/mm^2
- radiation damage (p,n)

SiPMs from different producers
Technology break through at the beginning of the millennium
A lot of improvements has been done to optimize different operational parameters

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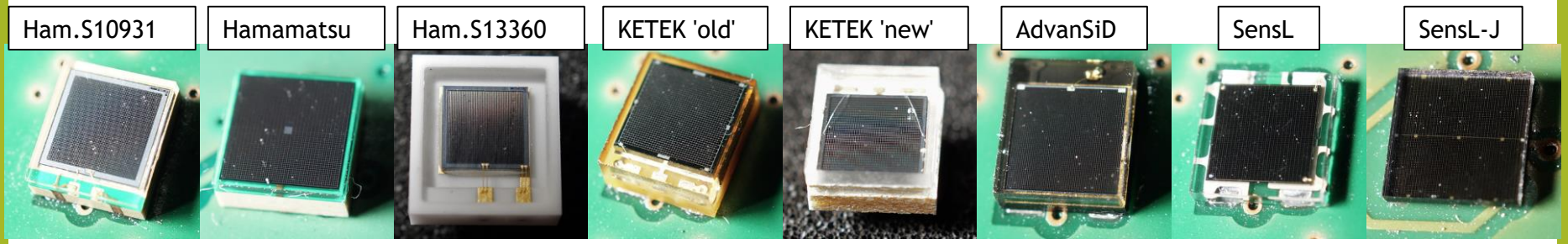
Label	Producer	Model	Pixel pitch [μm]	Breakdown [V]	Dark counts	Cross talk	After-pulses
Ham.S10931	Hamamatsu	S10931-050P	50	69	0.77 MHz		
Hamamatsu	Hamamatsu	S12641-PA-50	50	65	2 MHz	40%	
Ham.S13360	Hamamatsu	S13360-3050CS	50	50	0.5 MHz	3%	
AdvanSiD	AdvanSiD	ASD-NUV3S-P-40	40	26	<100 kHz/mm^2		<4%
KETEK 'old'	KETEK	PM3375TS-SBO	75	25	<500 kHz/mm^2	36%	
KETEK	KETEK	PM3350TP-SBO	50	25	<500 kHz/mm^2		
SensL	SensL	MicroFC-30050-SMT	50	25	300 kHz	10%	0.6%
SensL-J	SensL	MicroFJ-30050-TSV	50	25	300 kHz	6%	0.1%



SiPM Properties

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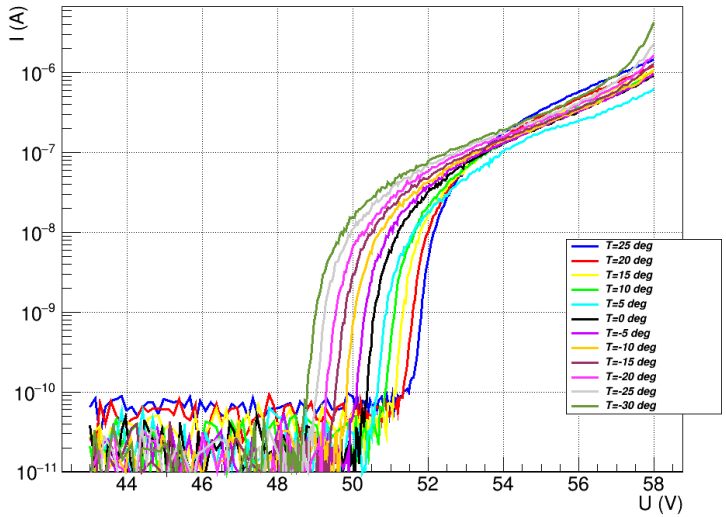
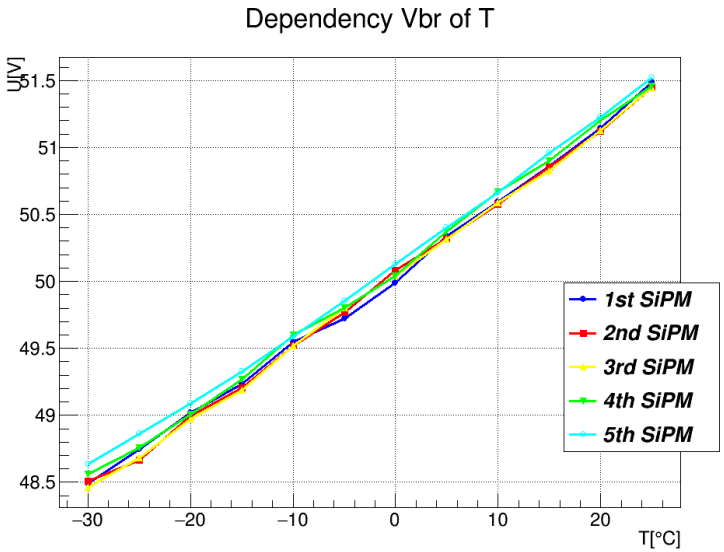
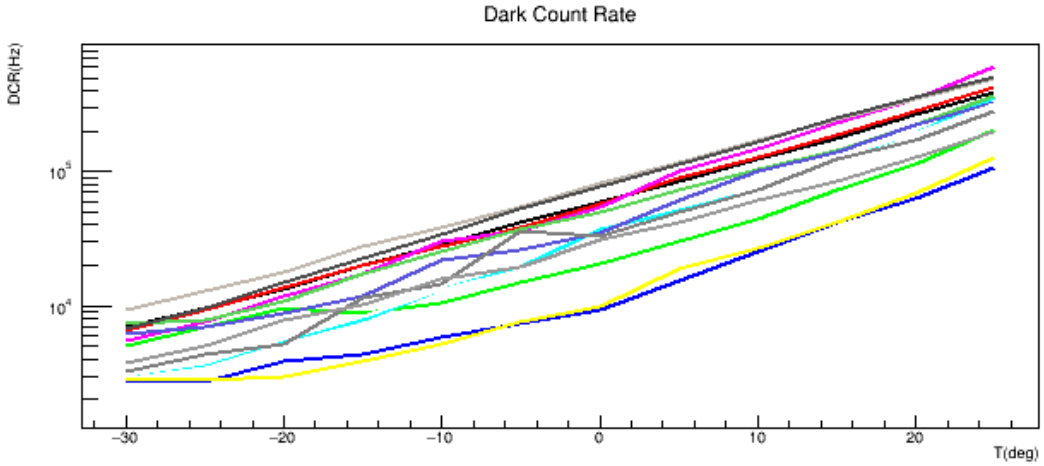
- Temperature dependence of breakdown voltage Vbr





- dark noise reduces with temperature by ~ 2.4x / 10°C



Crosstalk

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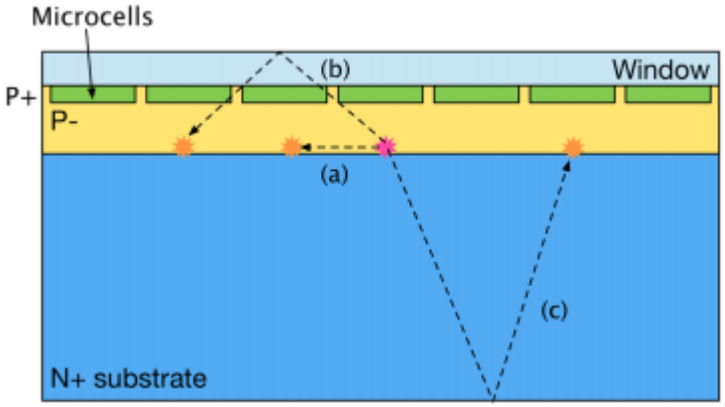
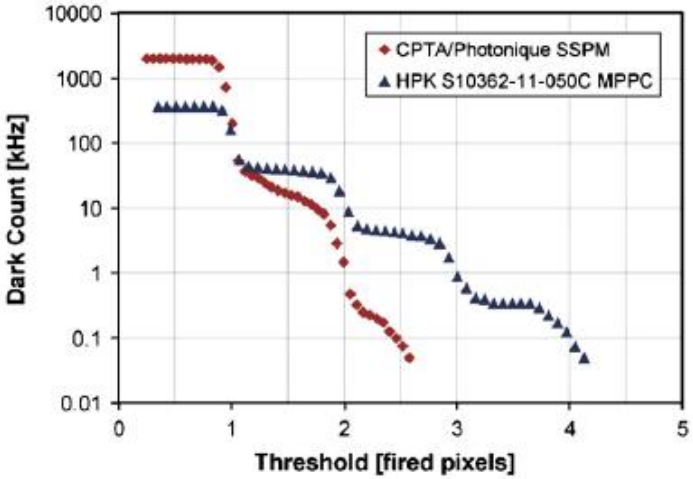
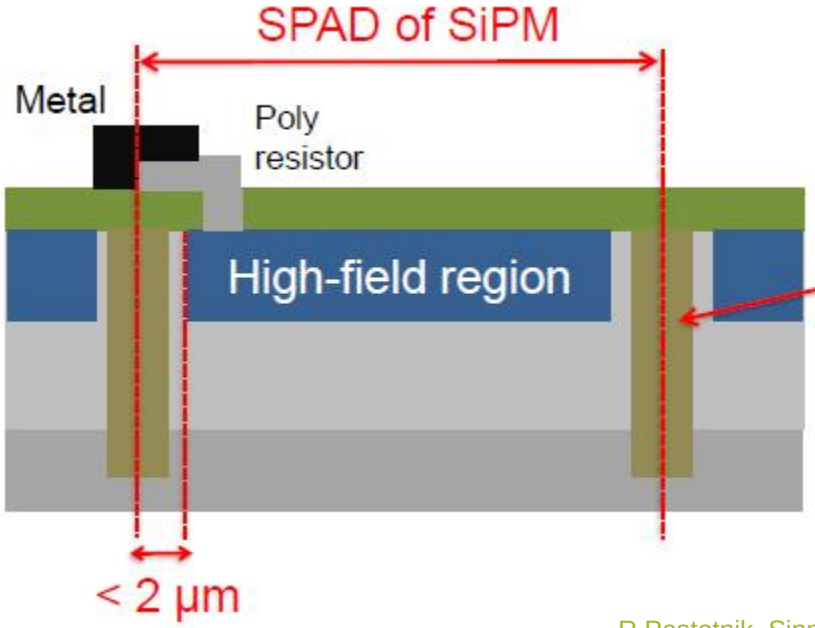
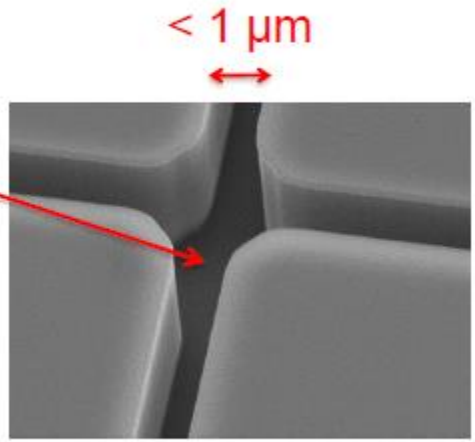
- In an avalanche 3 photons emitted per 10^5 carriers





- Trenches between cells→ Lower Cross-T





Photon detection and Crosstalk

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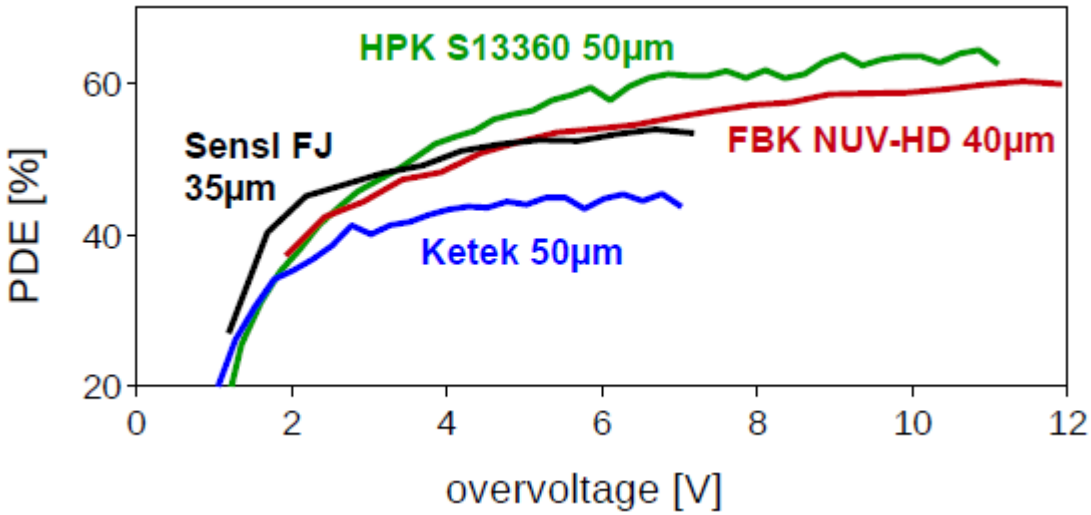
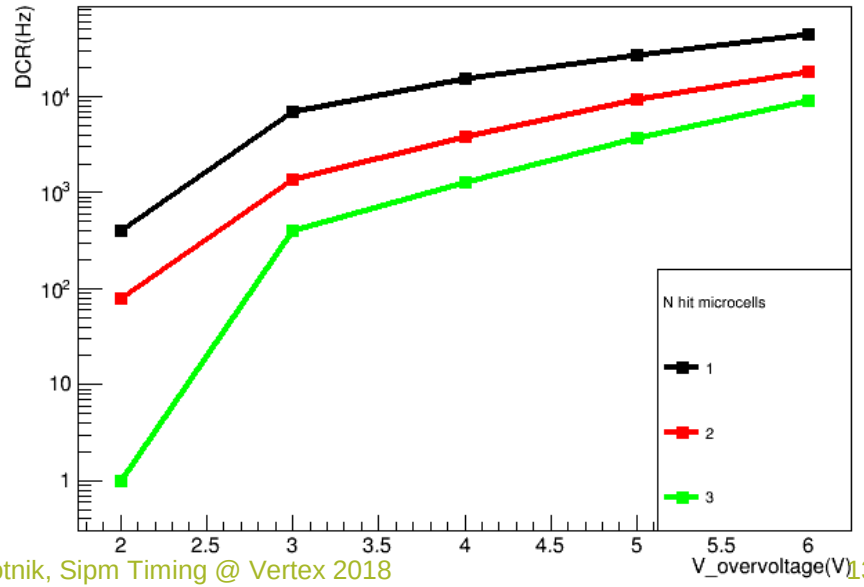
Photon detection efficiency increases with the overvoltage.



As a result also crosstalk increases

Dark Count Rate



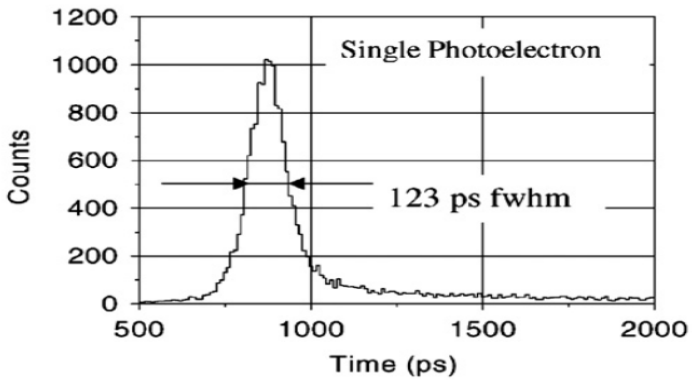
Timing

The active layer very thin:
- the process of breakdown very fast

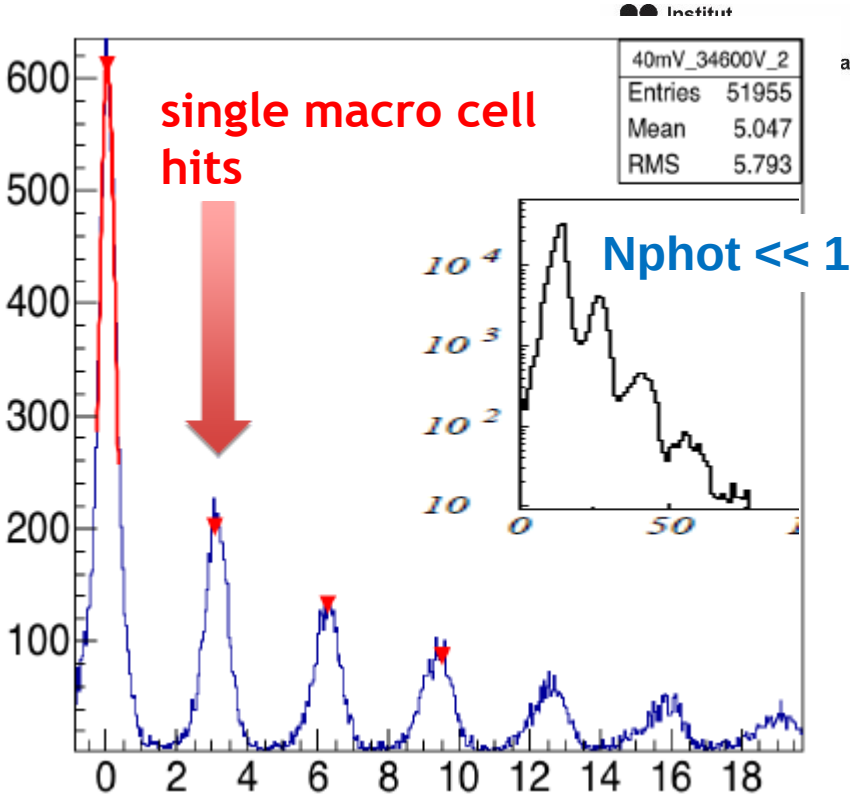
High cell capacitance : big signal

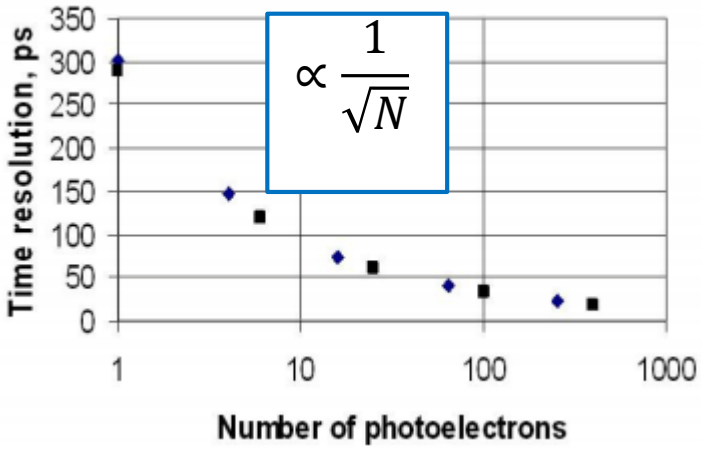
Fluctuations in the avalanche:
- lateral spreading by diffusion
- photons emitted in the avalanche

- For RICH/ Cherenkov TOF-PET: Interested in
  single photon detection



- Timing improves with
  the number of photons





Single photon timing resolution

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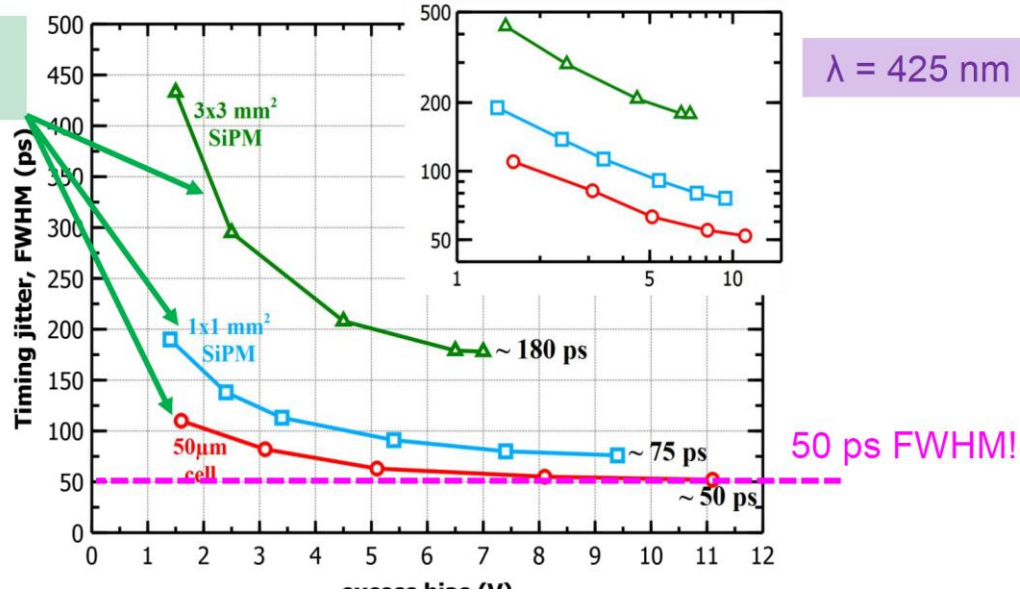
- Operation parameters very important!
- Operation at higher overvoltage improves the timing
- Advansid NUV

Different SiPM sizes

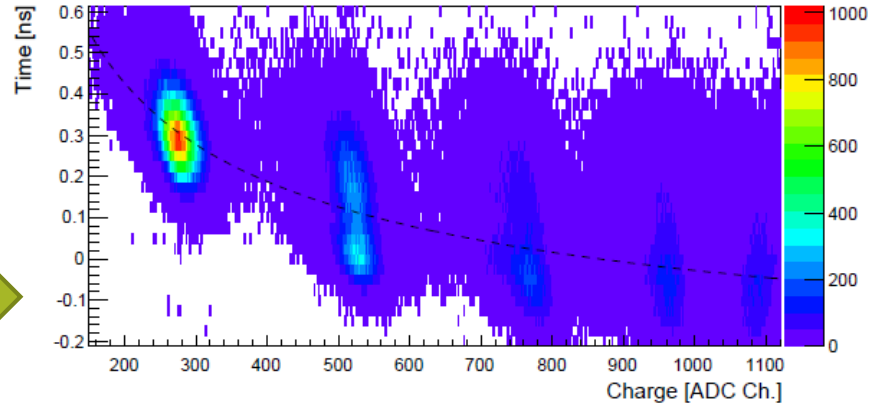


Time resolution is degraded for large SiPMs

Multi macro cell hits cannot be neglected.

Can we improve timing measurement?

Time walk correction.



Study of the response to low light yield laser pulses

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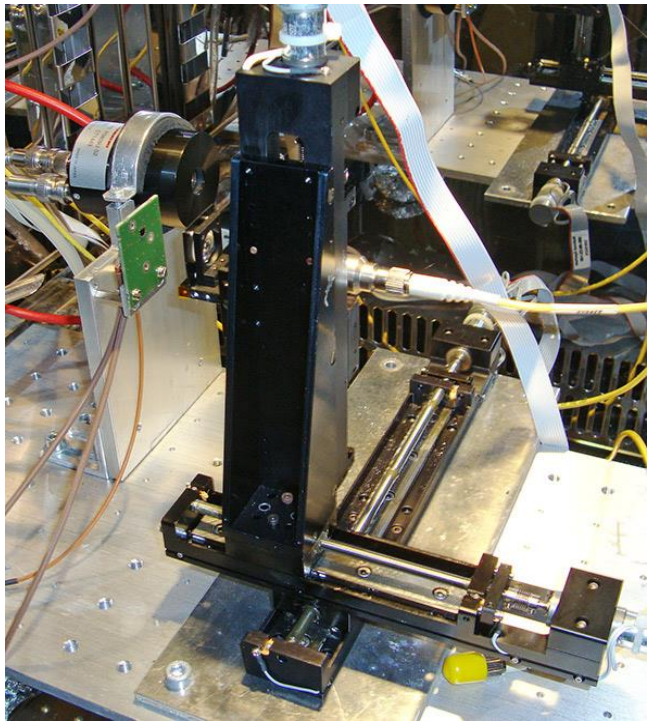
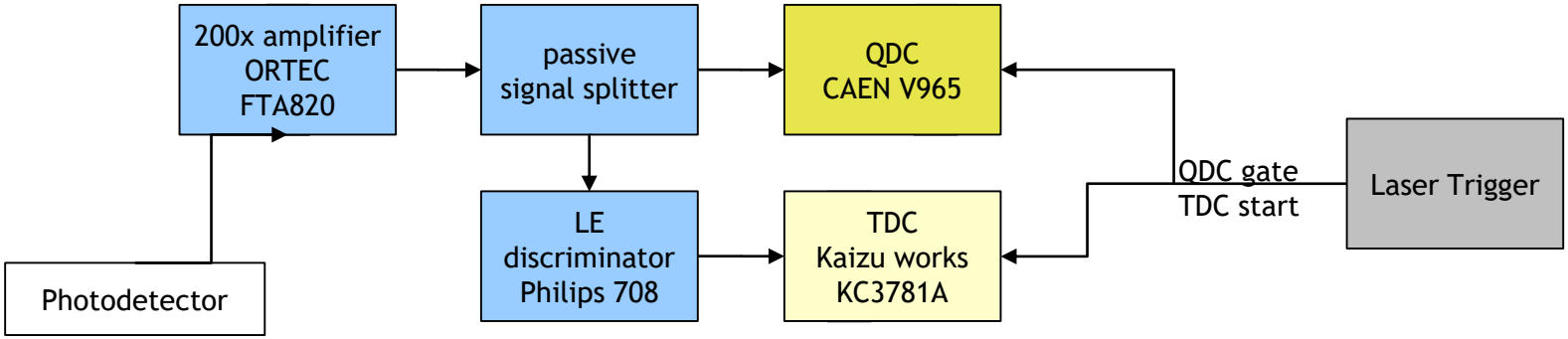
Setup

- PiLas diode laser system EIG1000D, 404 nm and 635 nm laser heads (35 ps FWHM)
- attenuated to single ph. levels using ND filters
- focusing lens (min. spot size σ ~ 3μm)
- 3D computer controlled stage (< μm accuracy)
- temperature controlled chamber (-70°C to 100°C)
- Hamamatsu R3809 MCP PMT reference (25 ps FWHM)
- readout system :
  - NEC uPC2710TB preamplifier (upper limit operating frequency 1.0 GHz) on custom electronics board
  - Kaizu works TDC: 25 ps LSB
  - time-walk correction performed in the analysis





Timing and Delay vs. position

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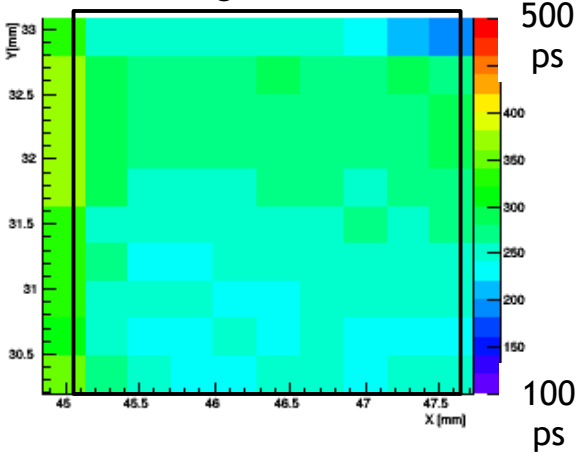
- Red laser defocused to approx. 300 µm, scans over whole active surface (**T = +25°C**)

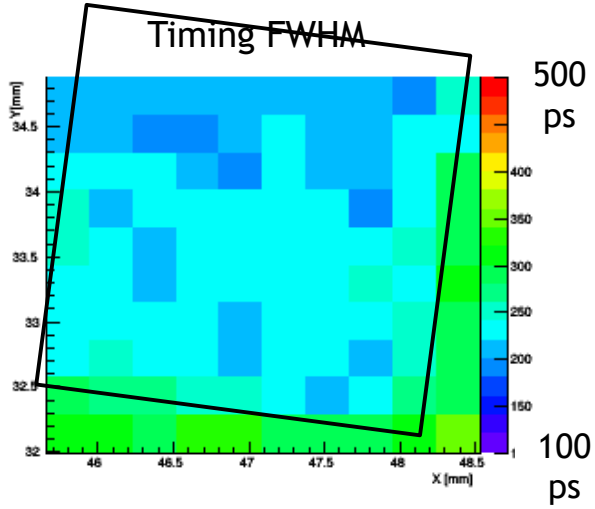
lower V_{ov} !

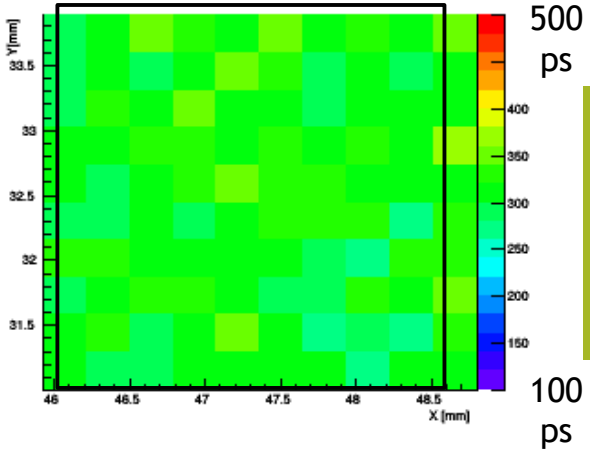
Variation in path lengths from different cells to common output lead to timing degradation of the whole device.

KETEK | **KETEK 'new'** | **AdvanSiD**

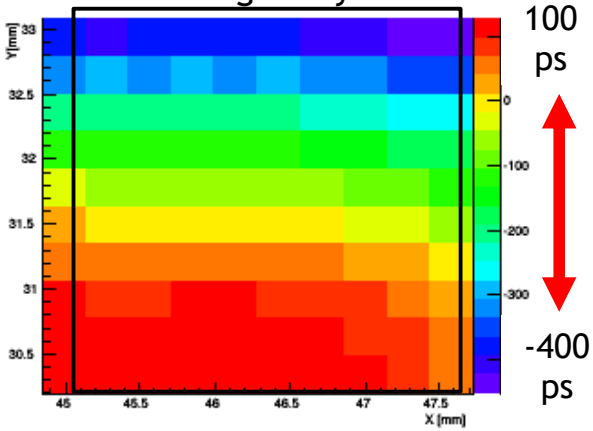
Timing FWHM

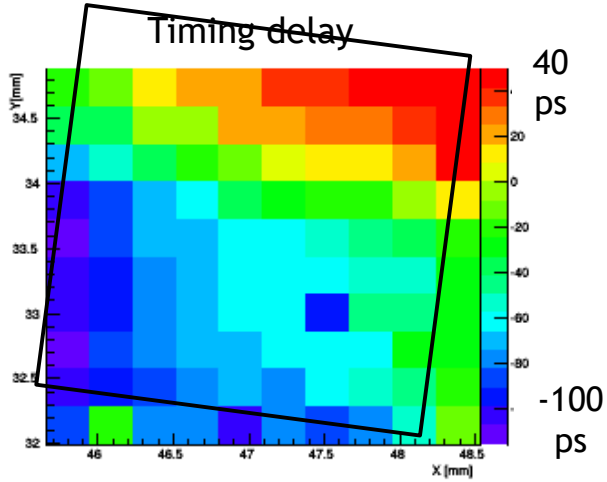


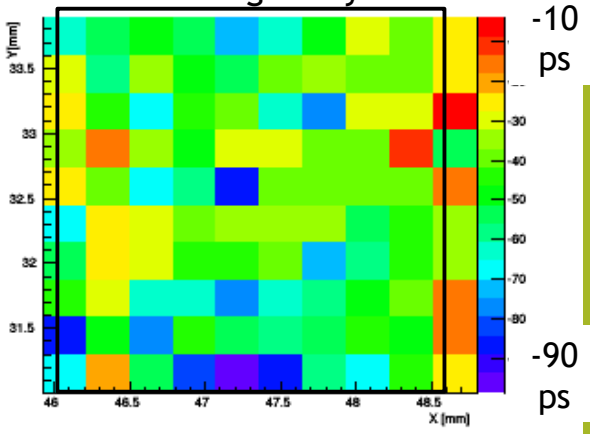




Timing delay







System timing (Reference MCP PMT)

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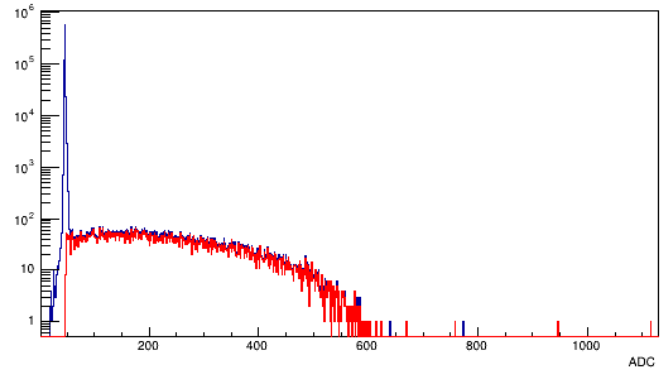
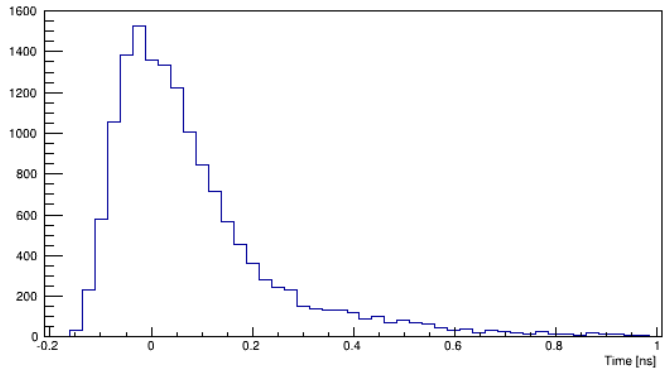
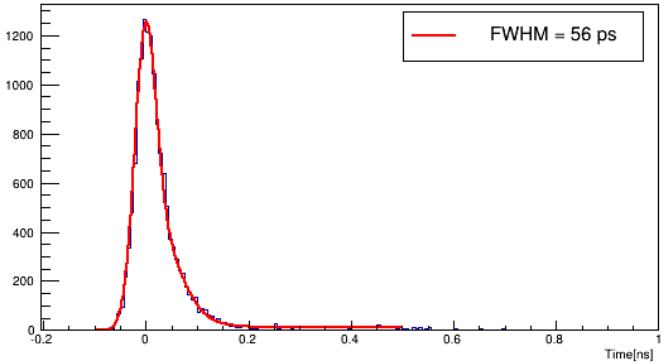
Charge Distribution



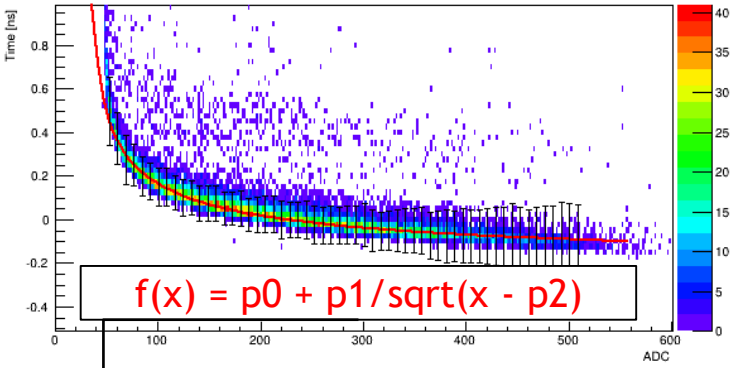
RAW Time Distribution



Corrected Time Distribution



Time/Charge Correlation



cTDC = p0 +p1/sqrt(ADC - p2)

Time-walk correction

- Red laser: **56 ps** FWHM
  - Estimate: 56 (measured) = 35 (laser) ⊕ 25 (MCP PMT) ⊕ 36 (electronics)

Results

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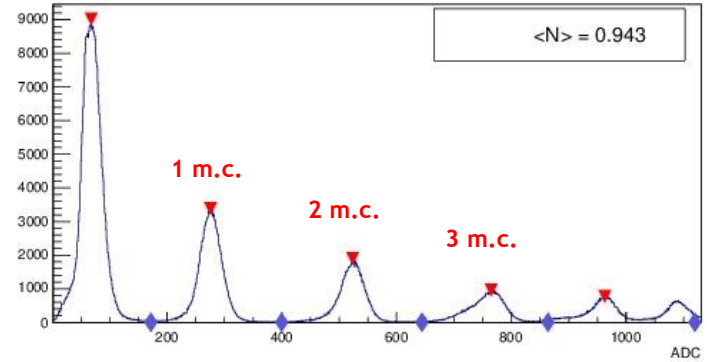
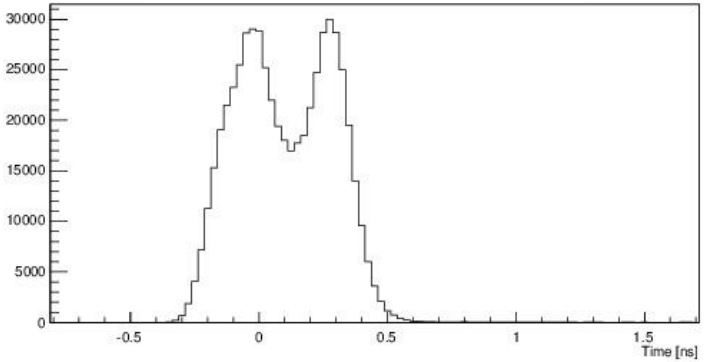
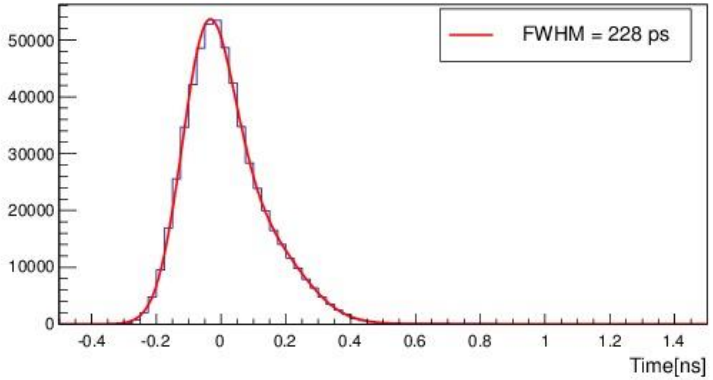
Charge Distribution



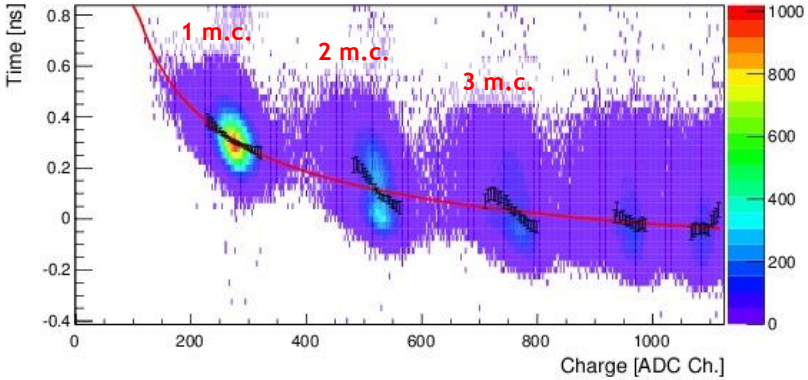
RAW Time Distribution



Corrected Time Distribution



Time/Charge Correlation



- AdvanSiD, V_{OV} = 6 V, T = -25°C
  - laser defocused to illuminate the **whole surface**
  - same time-walk correction algorithm
  - Timing: **228 ps** FWHM

Improving the time resolution

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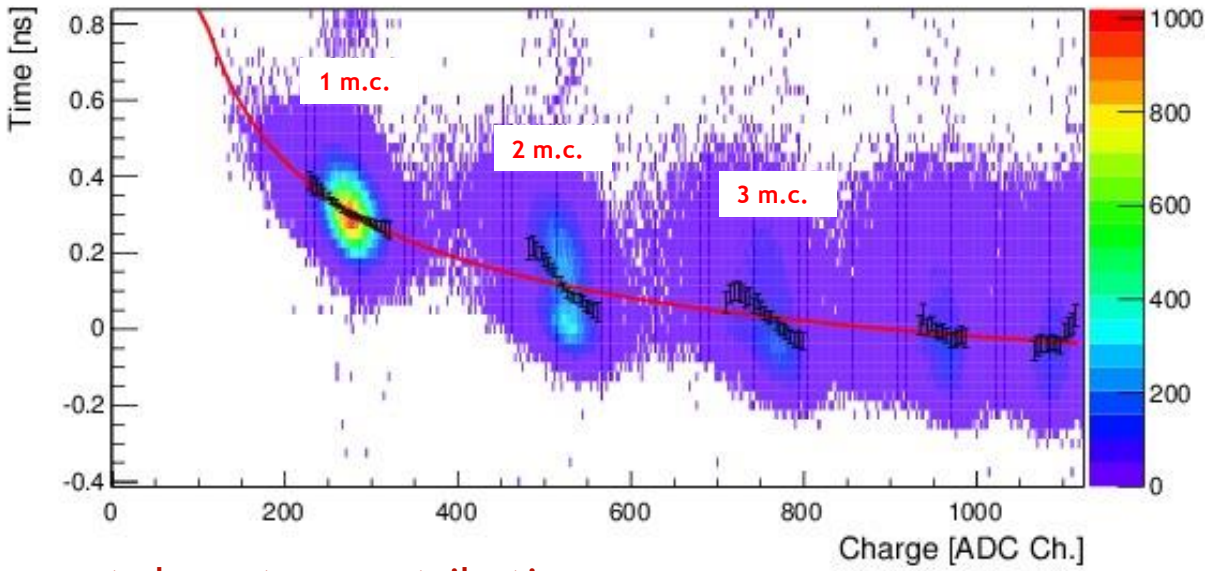
Time/Charge Correlation



- >1 macro cell events have two contributions
  - real multiple photon detections with better resolution
  - additional contribution, detected with ~0.2 ns delay : optical crosstalk
- The delayed contribution degrades the time resolution
  - widens the peak
  - influences the time-walk correction function fit
- Improvement:
  - split data in subsets, corresponding to a certain number of fired m.c.
  - perform time-walk correction on each subset separately
  - combine time-walk corrected time distributions from all subsets

Timing for different number of triggered macro cells

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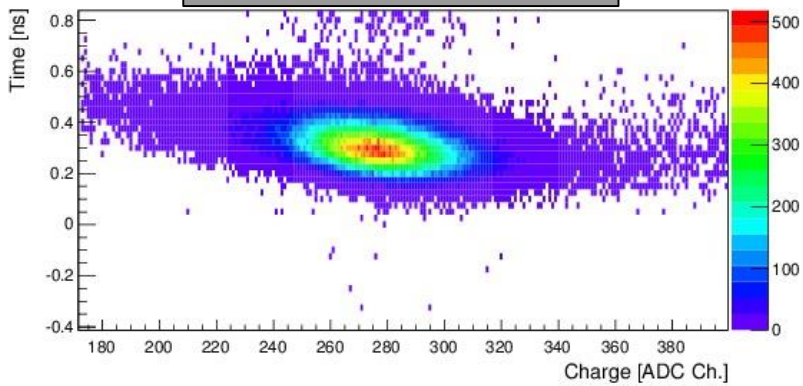
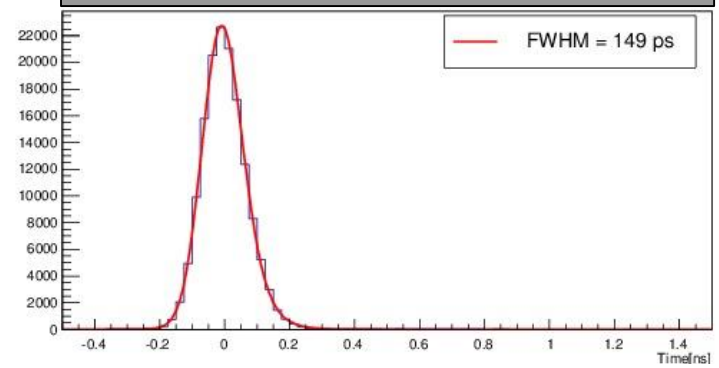
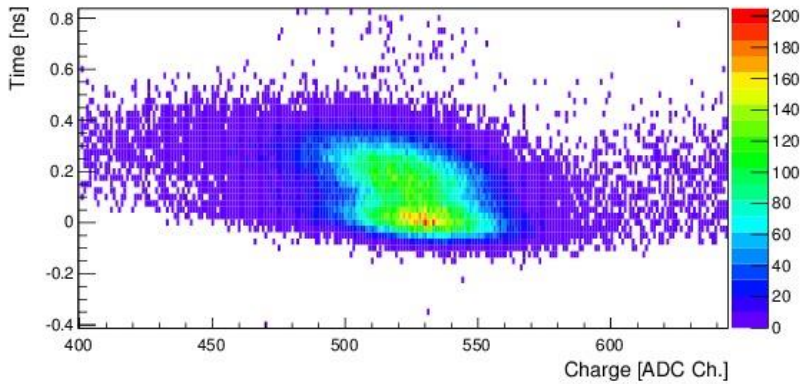
Time vs. charge | Time-walk corrected TDC

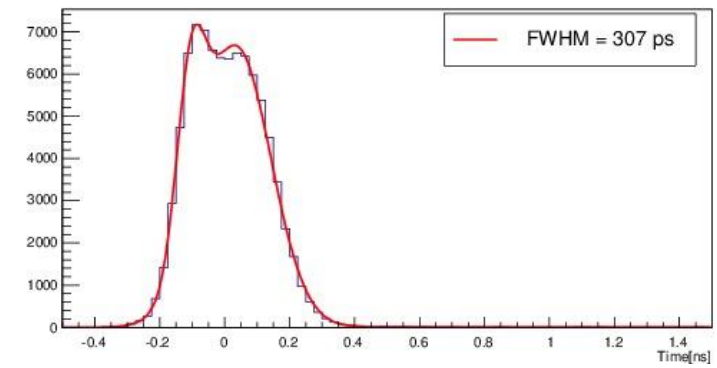
1 m.c.



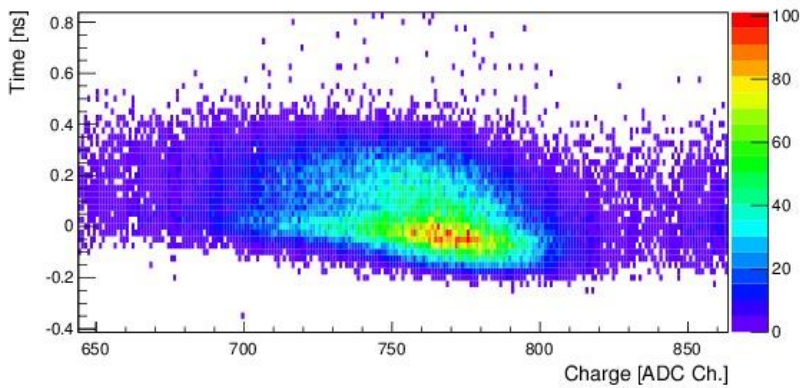


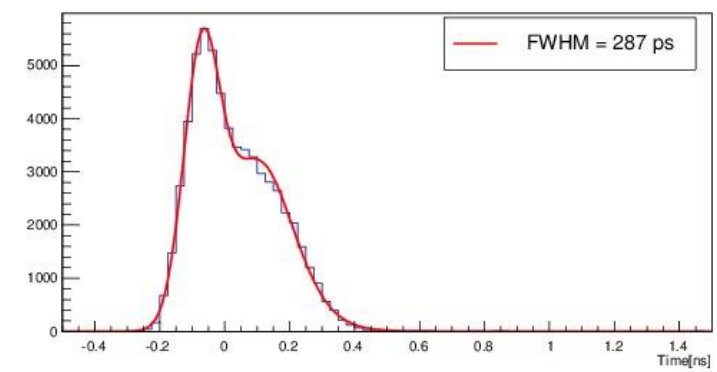
2 m.c.





3 m.c.





AdvanSiD, V_{OV} = 6 V, T = -25°C

Combining the subsets

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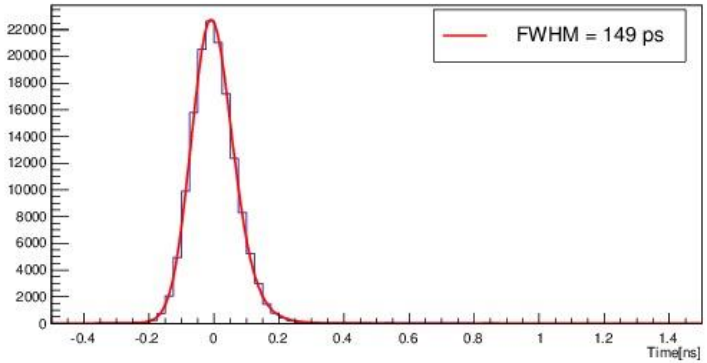
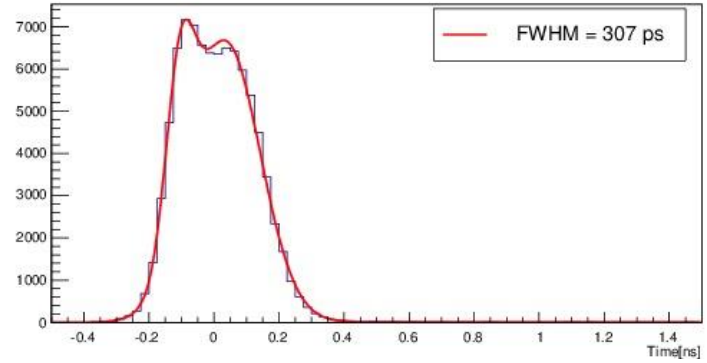
1 m.c.



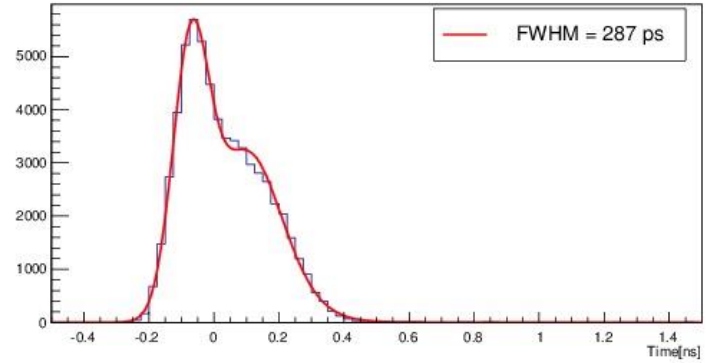
+

2 m.c.



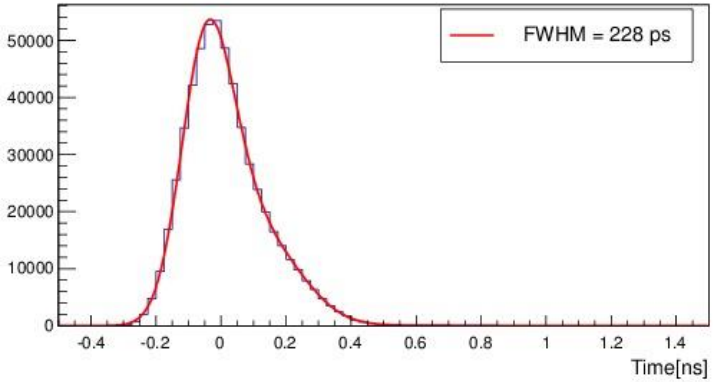
+

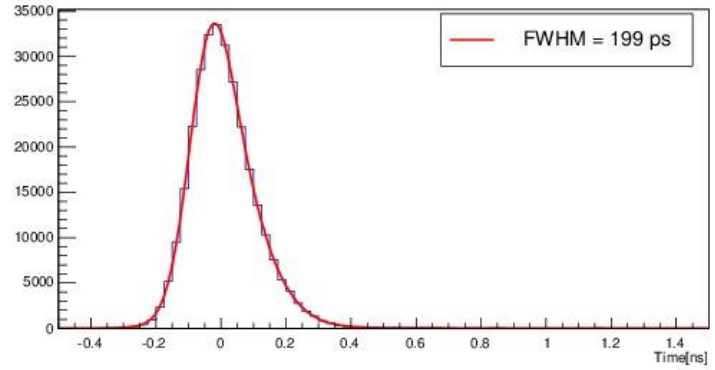
3 m.c.



=

Original time-walk correction





AdvanSiD, V_{OV} = 6 V, T = -25°C

2 macro cell hits for different SiPMs

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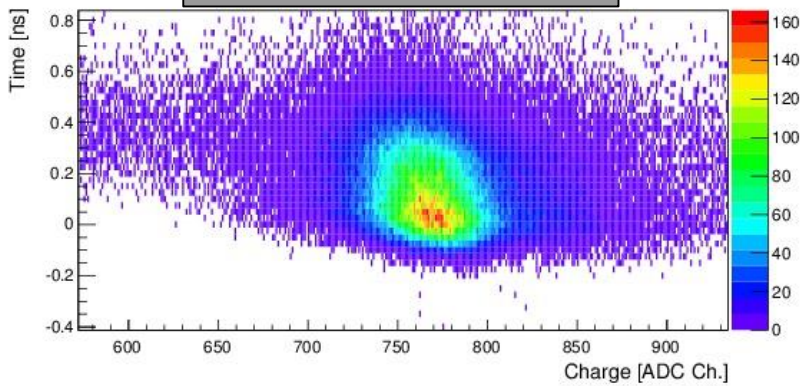
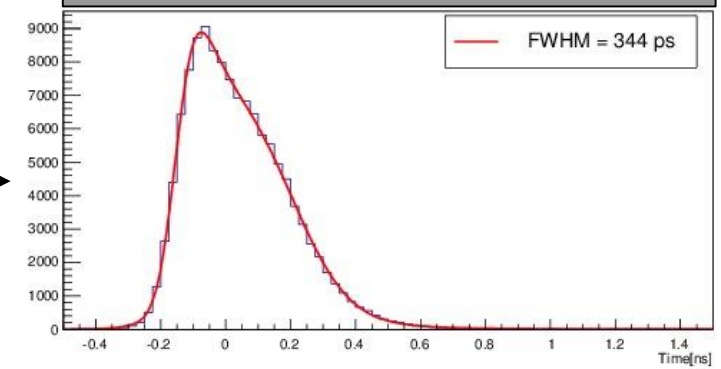
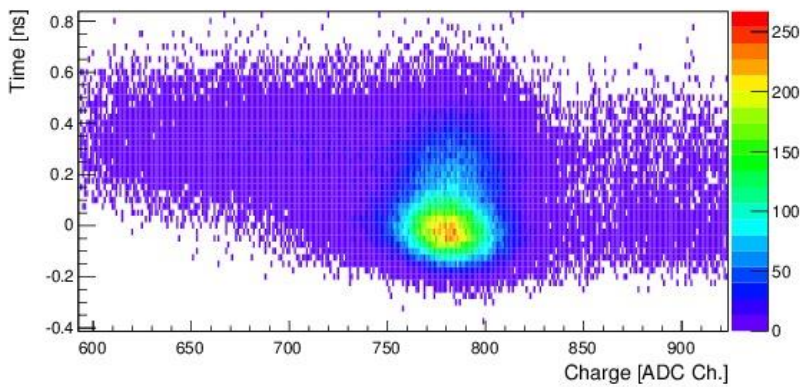
Time vs. charge | Time-walk corrected TDC

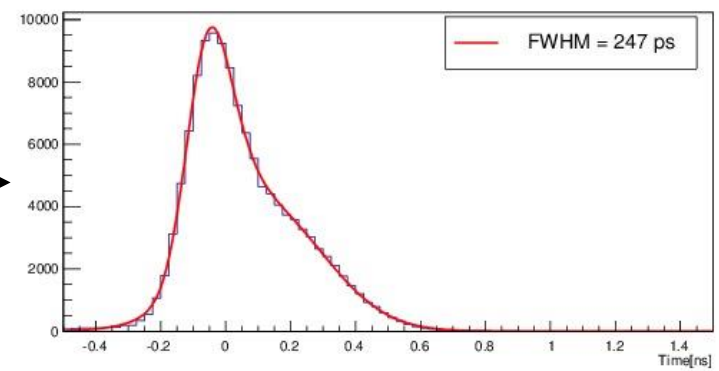
Hamamatsu



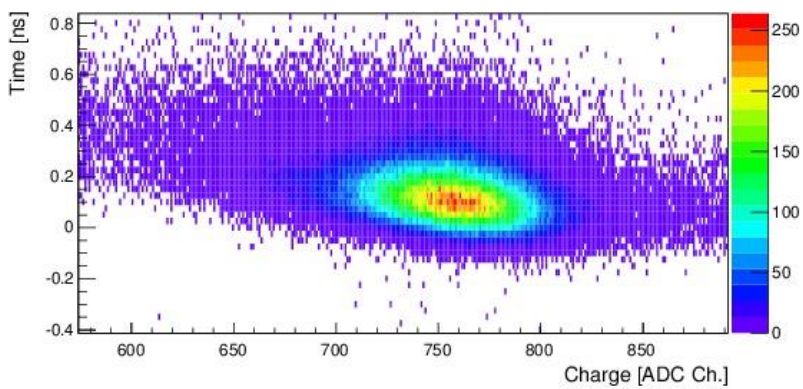


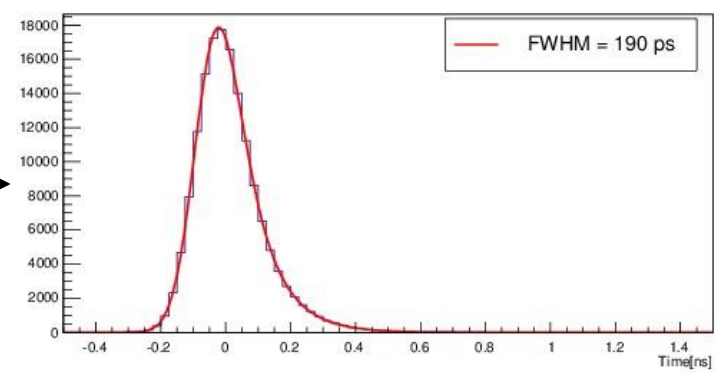
SensL





KETEK





AdvanSiD, V_{OV} = 6 V, T = -25°C

Summary of results

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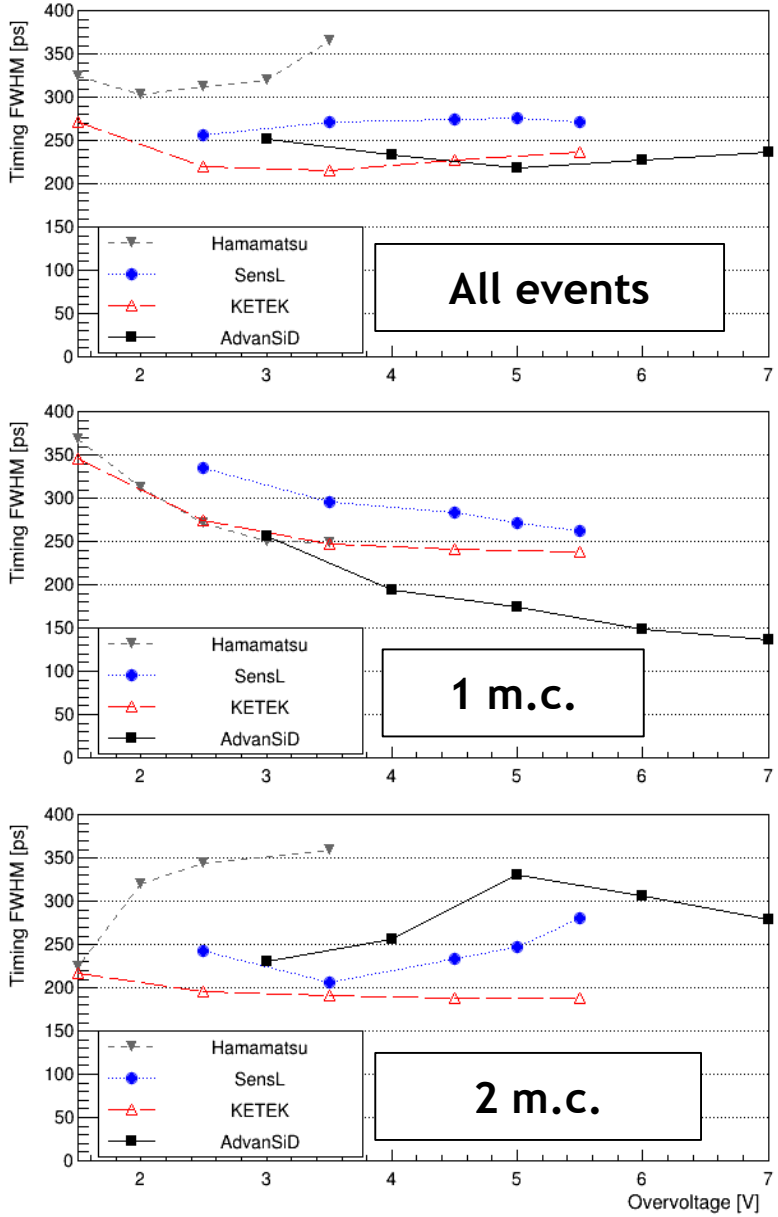

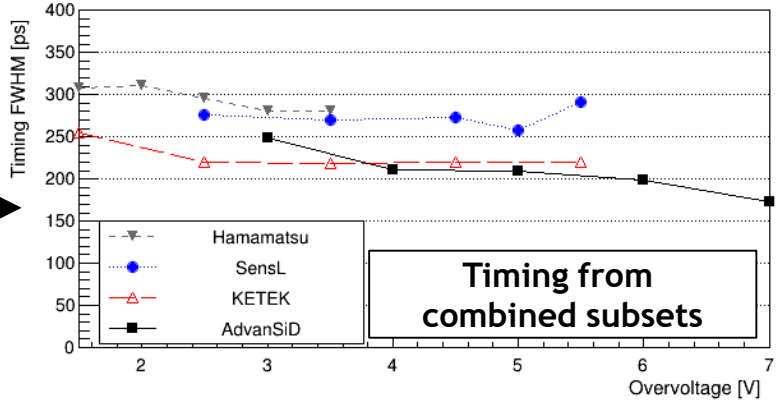

Summary

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Ljubljana, Slovenija

- SiPMs are an attractive photosensor
  - ~300 ps FWHM coincidence timing achieved in Cherenkov TOF.PET configuration
  - <200 ps FWHM if only 1 micro cell signals are used
- Timing properties of different SiPM samples tested in laser setup
  - ~220 ps FWHM single photon level timing was achieved
  - <150 ps FWHM if only 1 micro cell signals are used
- timing is degraded by delayed contribution in multiple m.c. events
  - this contribution is different for different devices
  - presumably caused by optical crosstalk events
- First step to improve - time-walk correction
  - timing slightly improved for all devices by performing the correction separately for subsets, corresponding to a certain number of fired cells
  - ~200 ps FWHM single photon level timing was achieved
- Further improvements
  - separating the contributions by multi-threshold measurement/waveform sampling
  - SiPMs with less optical crosstalk
  - better intrinsic timing

Waveform sampling

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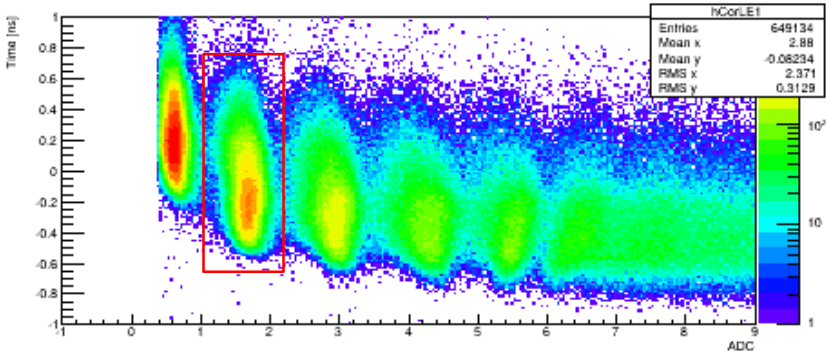
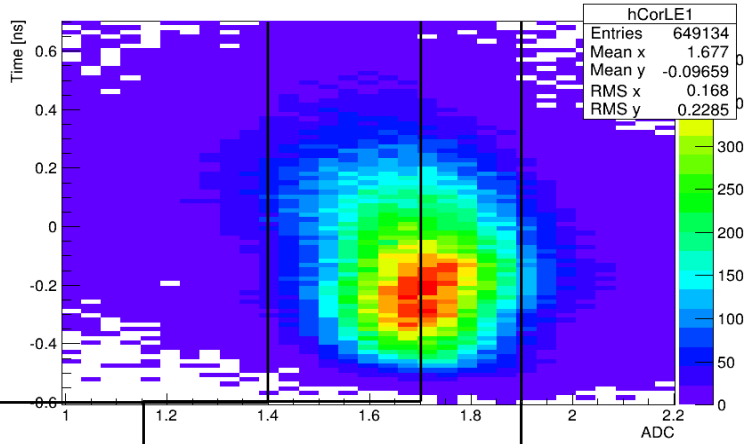
- Measurement with AdvanSiD SiPM repeated using waveform sampler:
  - DRS4, 5 GS/s

Time/Charge Correlation

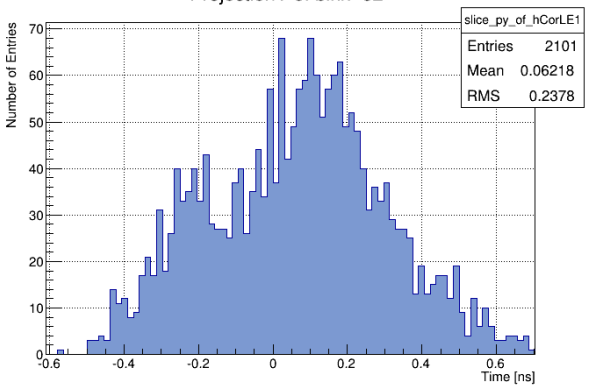


2 m.c. events

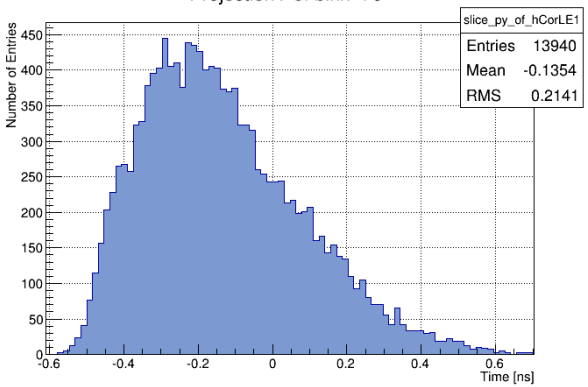


- Worse timing, but the delayed contribution is still somewhat resolved:

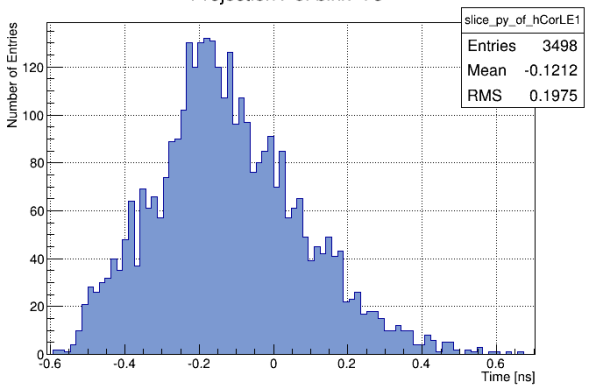
ProjectionY of binx=62



ProjectionY of binx=70



ProjectionY of binx=75



Multi-Threshold measurement

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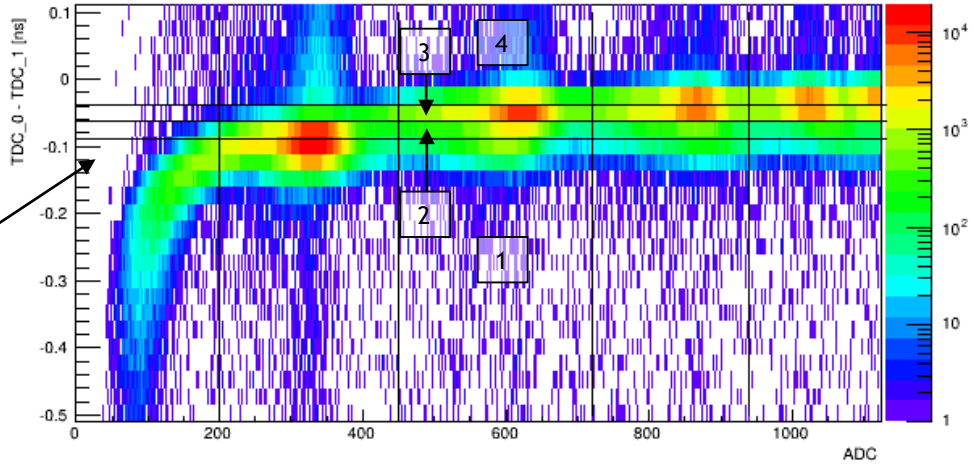
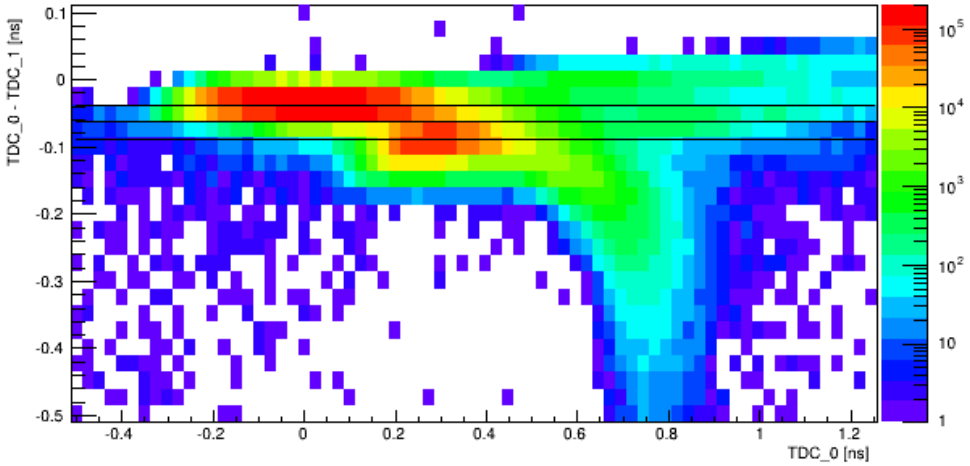
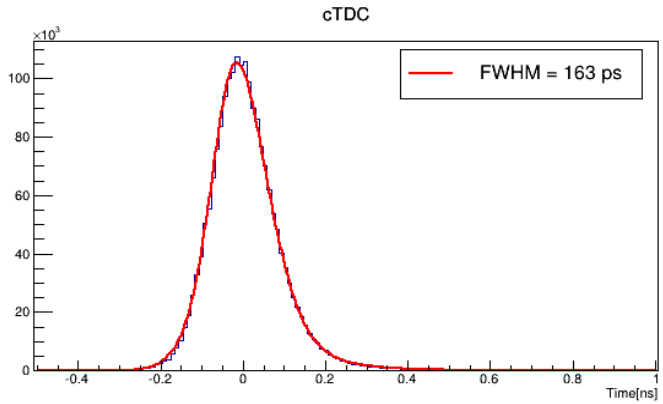
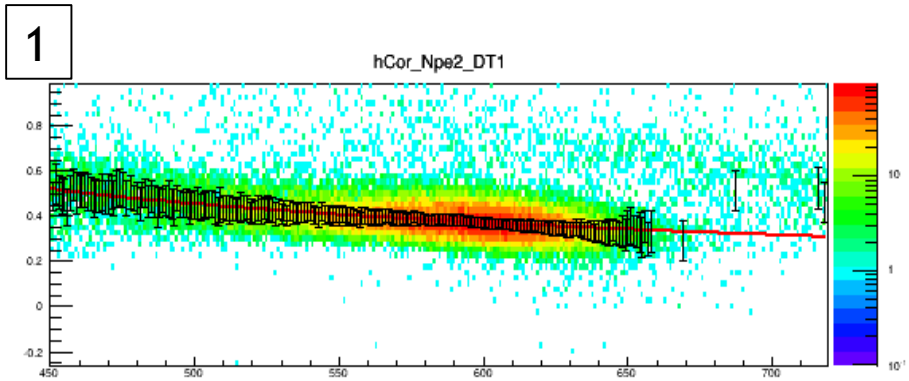
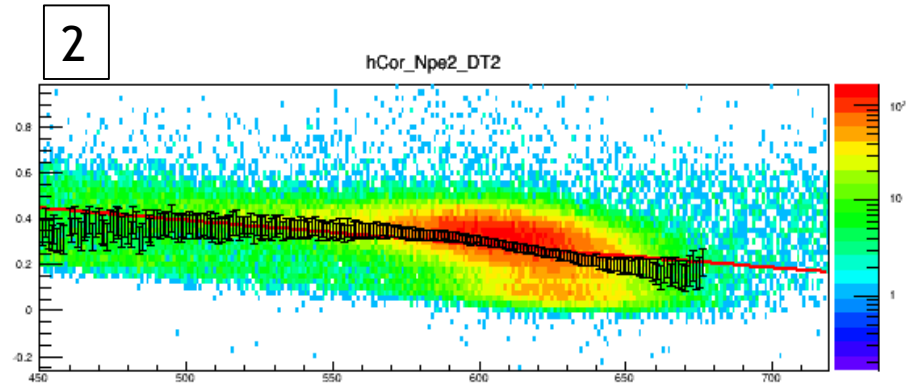
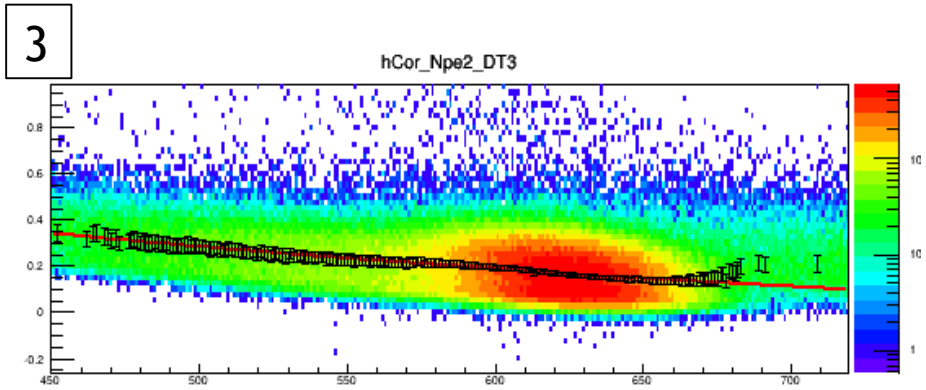
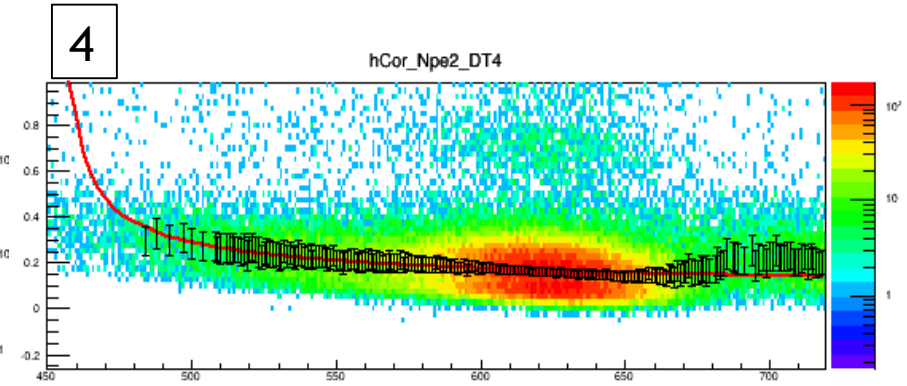
- AdvanSiD, V_{OV} ~ 6 V, T = -25°C, whole surface illuminated
- different signal splitting and threshold, slightly higher gain ->!
  - SiPM signal additionally split after amplification
  - two Discriminator and TDC channels:
    - threshold = 0.2 m.c.
    - threshold = 0.4 m.c.
  - separate time-walk correction for each m.c., 4 regions in Δt

Δt/charge correlation



Δt/time correlation



Multi-Threshold measurement

- **2 m.c.** signal region for the **four regions in Δt**
  - <u>some decoupling of the two contributions!</u>
- **163 ps** FWHM