Improving the Time Resolution in Cherenkov TOF PET with SiPMs

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- Outline:
  - Time-of-flight Positron Emission Tomography (TOF PET)
  - Use of Cherenkov light for TOF PET
  - Summary of previous experimental results and the use of Silicon Photomultipliers in Cherenkov TOF PET
  - Limitations in time resolution due to SiPMs and ways to improve it
  - Conclusion

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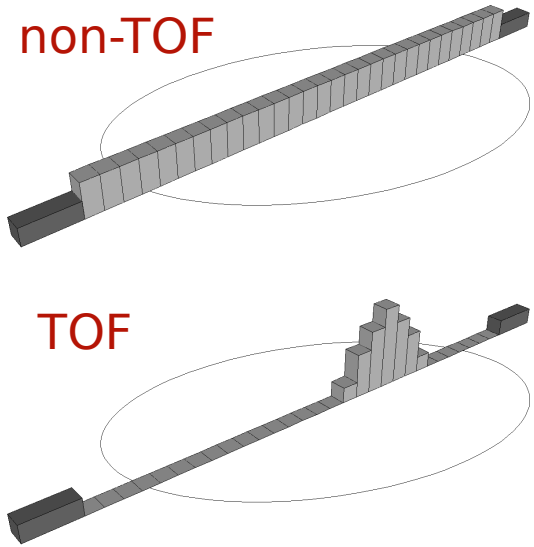
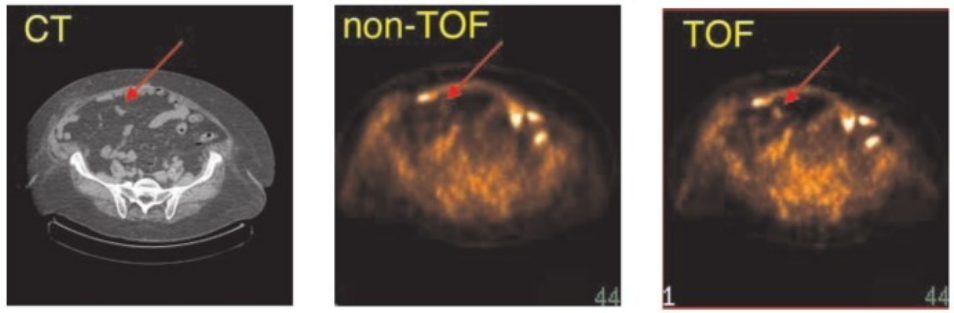
Time-of-flight Positron Emission Tomography

- Positron emission tomography
  - medical imaging modality
  - detection of coincident annihilation gammas (511 keV)
- Contrast of images obtained with PET can be improved by measuring the time-of-flight of the two annihilation gammas
  - localizes source position on line of response (LOR)
  - reduces the spread of noise along the LOR



Philips Gemini TF PET/CT with TOF resolution of 600 ps:



- Time resolution in TOF PET limited mainly by
  - photodetector response
  - scintillation rise and decay time constants
  - optical photon travel time spread in the crystal
- Limitation due to scintillator can be avoided by using Cherenkov light instead

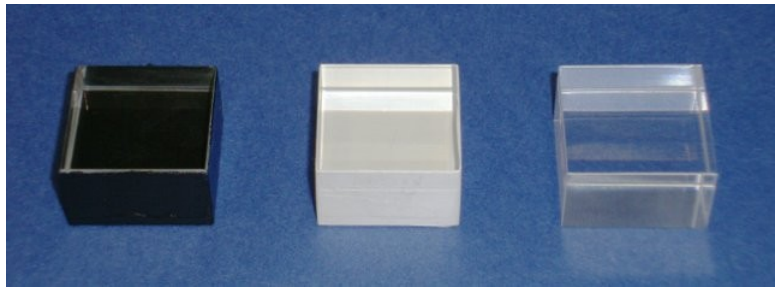
Use of Cherenkov Light in TOF PET

- Comparison between typical scintillation and Cherenkov TOF PET methods:

	Scintillator (LSO)	Cherenkov (PbF_2)
<Z>	56	71
μ_{511keV} [cm^{-1}]	0.87	1.06
Photofraction (511 keV) (*)	0.32	0.46
Light Rise/Decay Time	87 ps (†) / 40 ns	prompt
Light Yield [photons/511keV]	15,000	10 (‡)
Light Production Threshold	-	E_{e-} > 104 keV

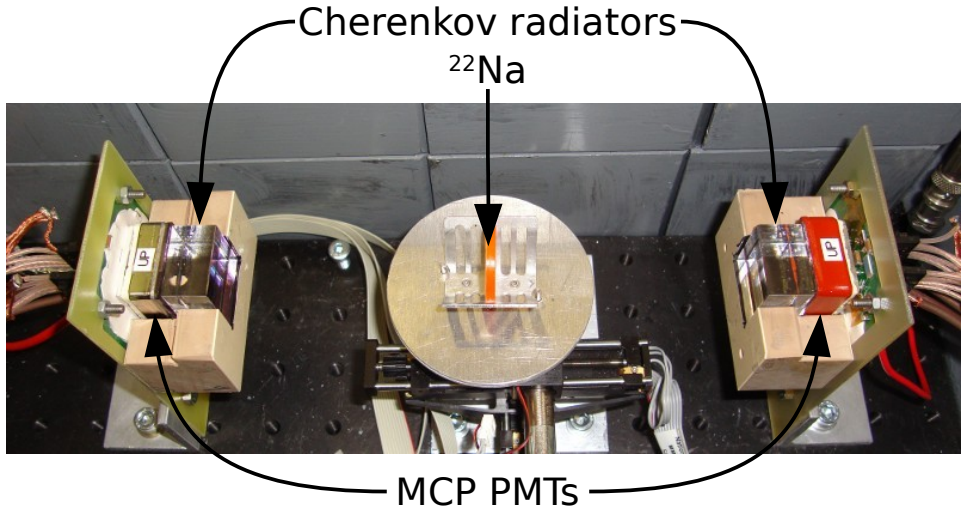
(*) [XCOM: Photon Cross Sections Database]
(†) [NIM A 767 (2014) 206]
(‡) in 250-800 nm wavelength interval

- Remaining limitation for time resolution:
  - **optical photon travel time spread** in the crystal
  - For the fastest timing reflections must be suppressed - crystal surfaces:
    - bare (no reflections from Teflon wrapping)
    - painted with black paint (reduce even the total internal reflections)



Experiments (MCP PMT)

- Two detectors in back-to-back configuration
- Cherenkov radiators: **25x25x(5, 15) mm³ PbF_2**
- Photodetectors: **microchannel plate photomultiplier tubes** (MCP PMTs)
  - single photon timing ~ **50 ps** FWHM
  - active surface 22.5x22.5 mm²



- TOF resolution:
  - 5 mm thick, black painted PbF_2: **71 ps** FWHM
  - 15 mm thick, black painted PbF_2: **95 ps** FWHM

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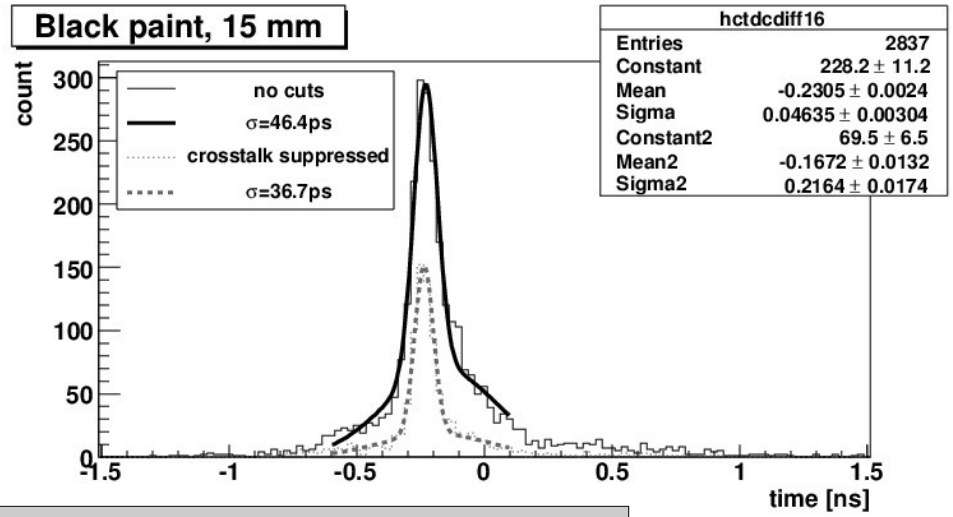
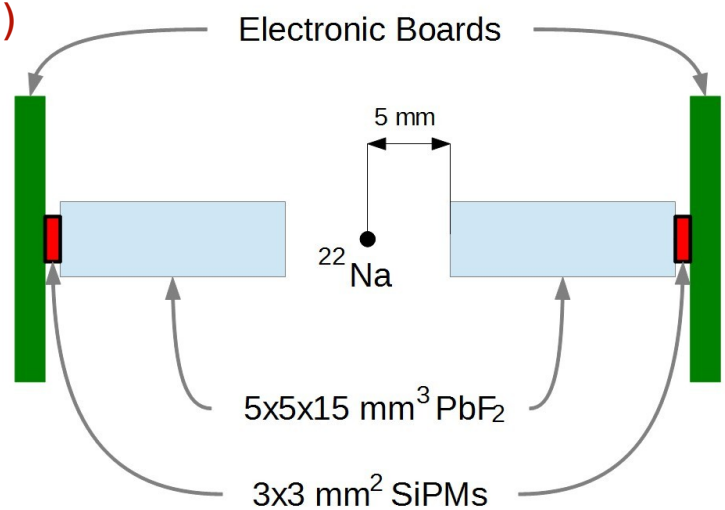


- Single side detection efficiency ~ **6%** **Physics Procedia 37 (2012) 1531**
  - with LSO scintillator in ideal conditions ~ 30%
  - main limitation: photon detection efficiency of MCP PMT samples used

Experiments (SiPM)

- SiPMs as photodetectors in Cherenkov TOF PET:
  - **high photo detection efficiency**
  - slightly limited single photon timing (~200 ps FWHM)
  - **high dark count rates at room temperature (~ 100 kHz/mm²)**
- Experimental setup:
  - 3x3 mm² active area SiPMs
  - 5x5 x 15 mm³ PbF_2 (available at the time of measurements)
  - temperature controlled freezer box (down to -25°C)
- Different devices tested so far:



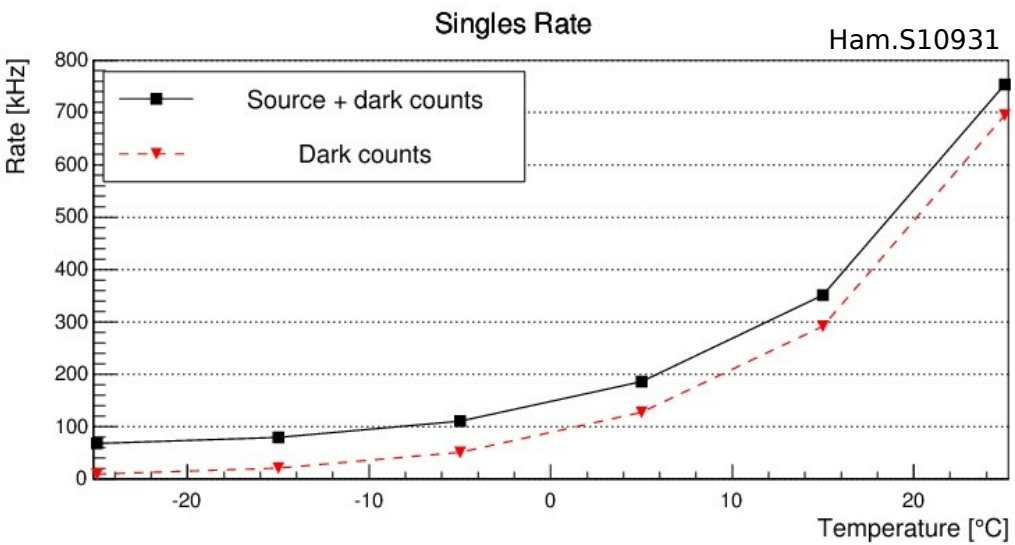
Label	Producer	Model	Pixel Pitch [µm]	Breakdown [V]
Ham.S10931	Hamamatsu	S10931-050P	50	69
Hamamatsu	Hamamatsu	S12641-PA-50	50	65
Ham.S13360	Hamamatsu	S13360-3050CS	50	50
AdvanSiD	AdvanSiD	ASD-NUV3S-P-40	40	26
KETEK	KETEK	PM3375TS-SBO	75	25
KETEK 'new'	KETEK	PM3350TP-SBO	50	25
SensL	SensL	MicroFC-30050-SMT	50	25
SensL-J	SensL	MicroFJ-30050-TSV	50	25

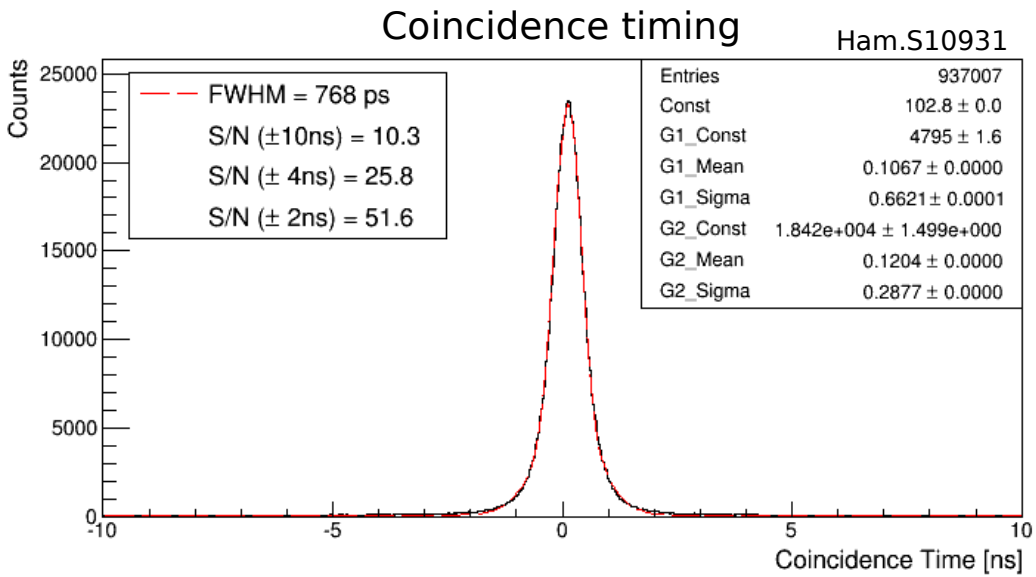
Red: new measurements

Results (SiPM)

- Dark count rate vs. Temperature
  - Hamamatsu S10931-050P at constant gain (V_{ov} = 1.5V)
  - dark noise reduces with temperature by ~ **2.4x / 10°C**

- First results for coincidence timing ~ **800 ps** FWHM
  - Hamamatsu S10931-050P
  - T = -25°C
  - SiPM overvoltage V_{ov} = 1.5V
  - **bare** PbF_2





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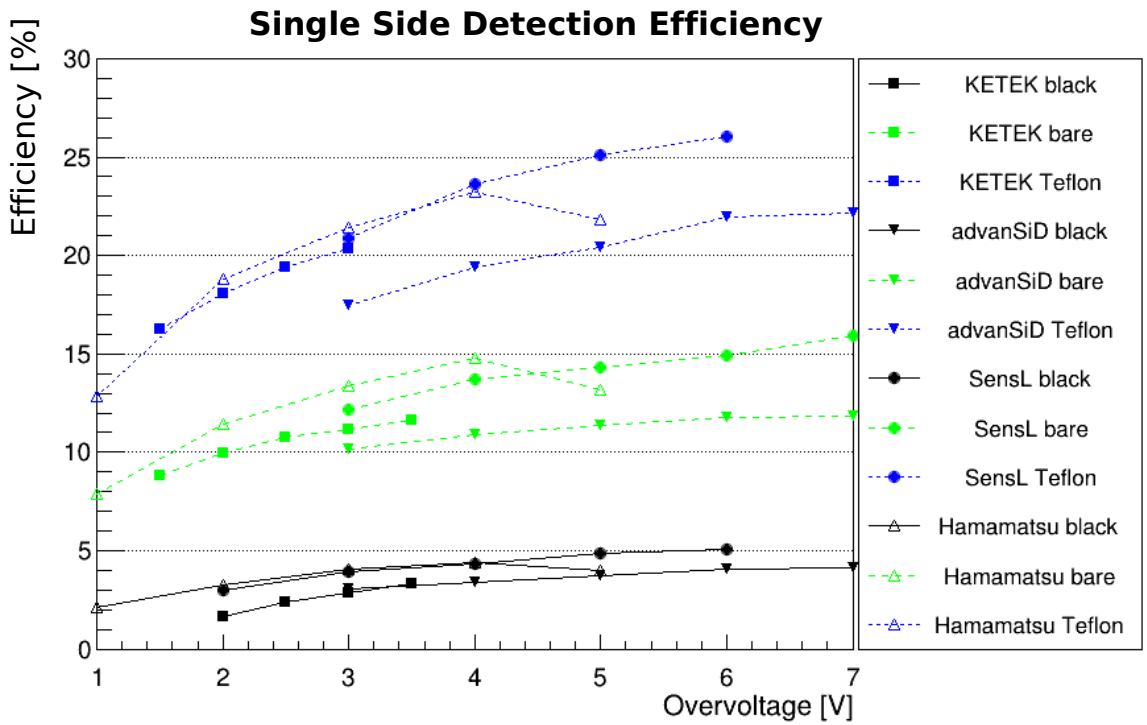
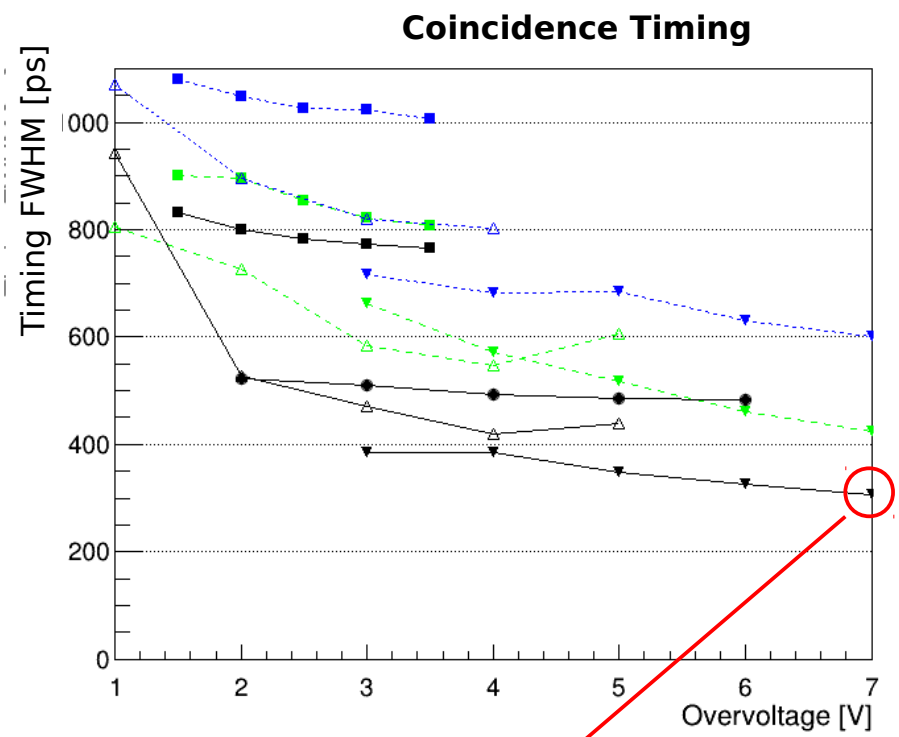
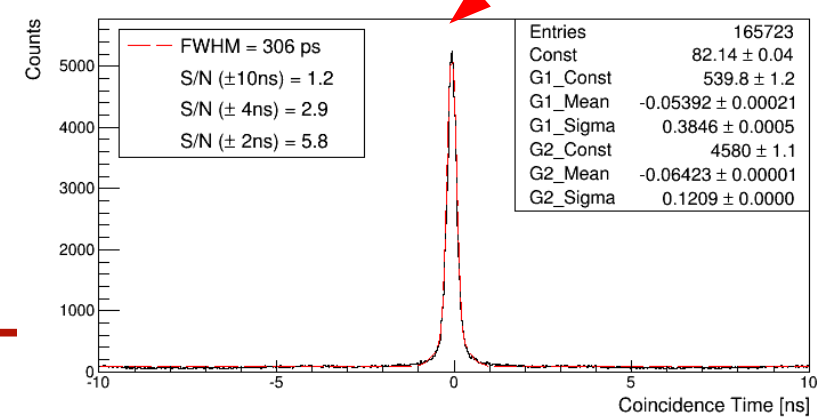
Results (SiPM)

- Results at **T = -25°C** for different crystal surface treatments (**black painted**, **bare**, **Teflon wrapped**)





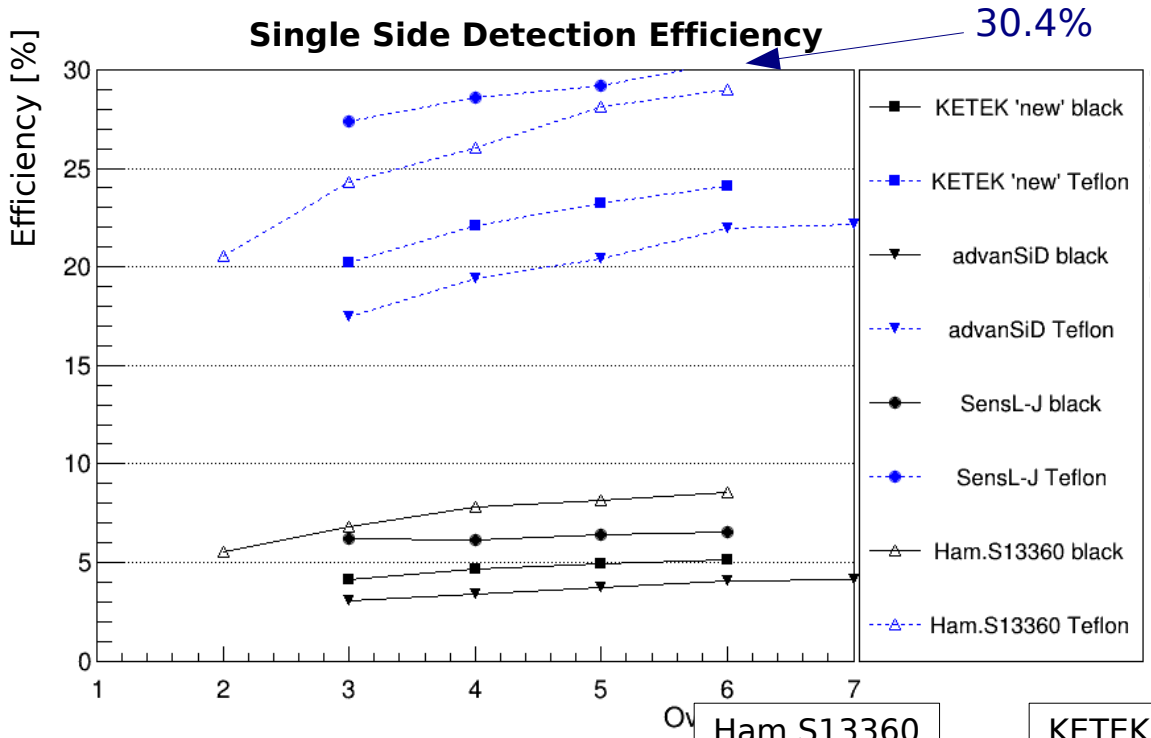


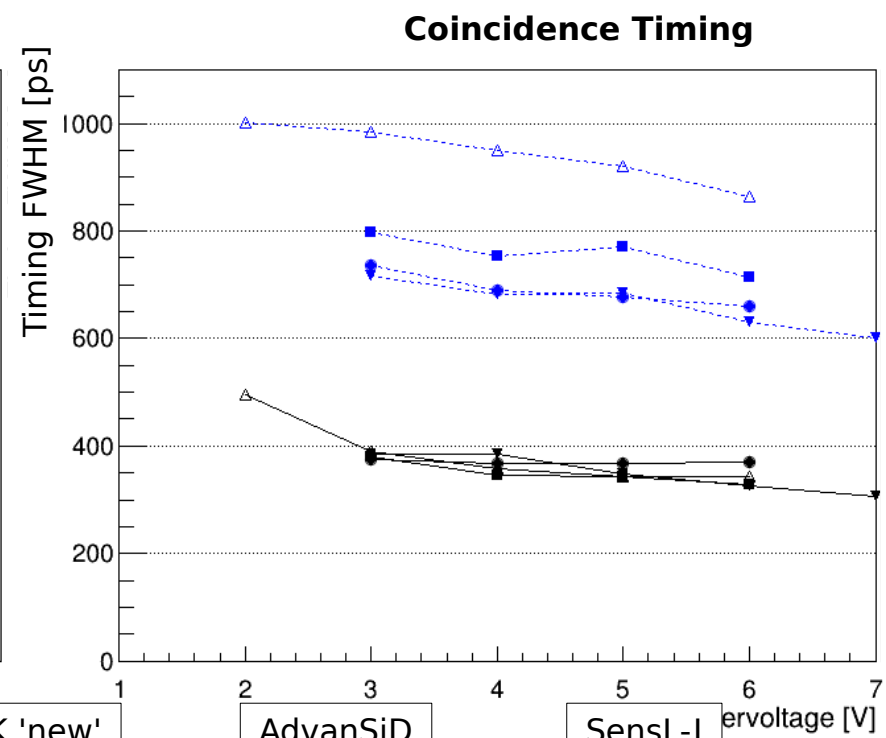
- Best
  - efficiency: **26%** (SensL + Teflon)
  - timing: **306 ps** (AdvanSiD + black paint)

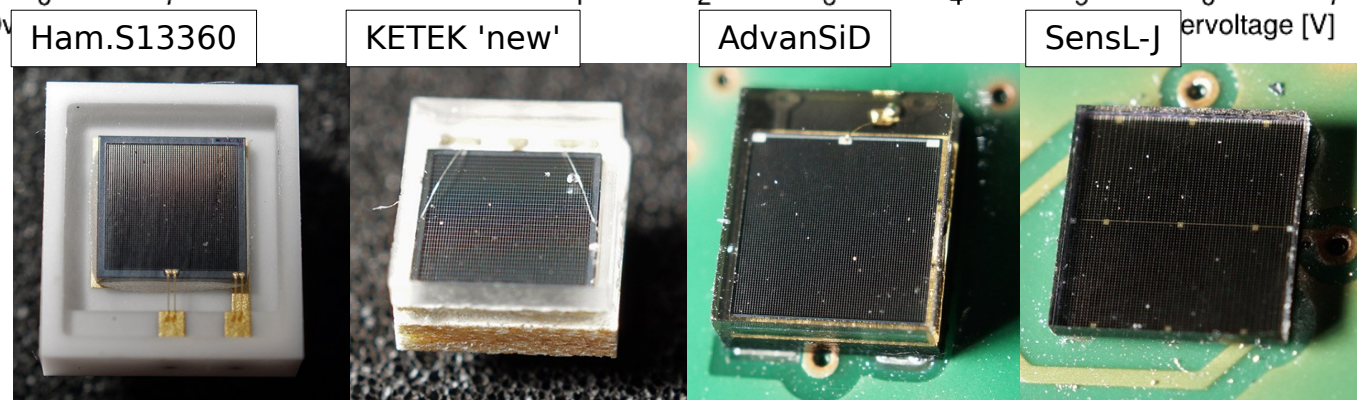
Proceedings of PSMR2015 conference (NIM A)

Results (SiPM) - new

- Results at **T = -25°C** for different crystal surface treatments (**black painted**, **Teflon wrapped**)



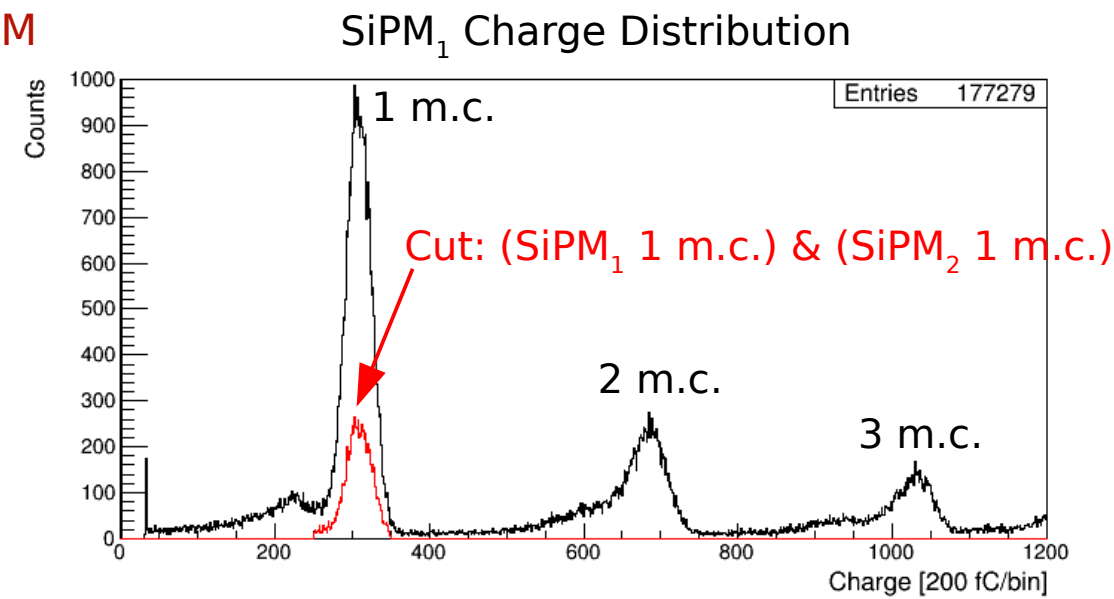


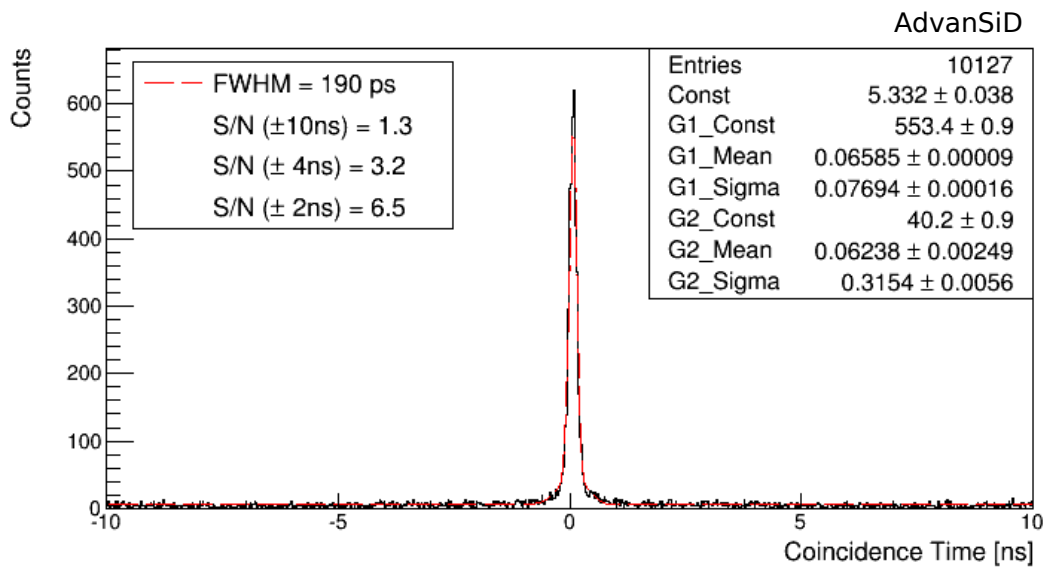


- efficiency: 30% (SensL-J + Teflon)
- timing: 306 ps (still AdvanSiD + black paint)

1 m.c. cut

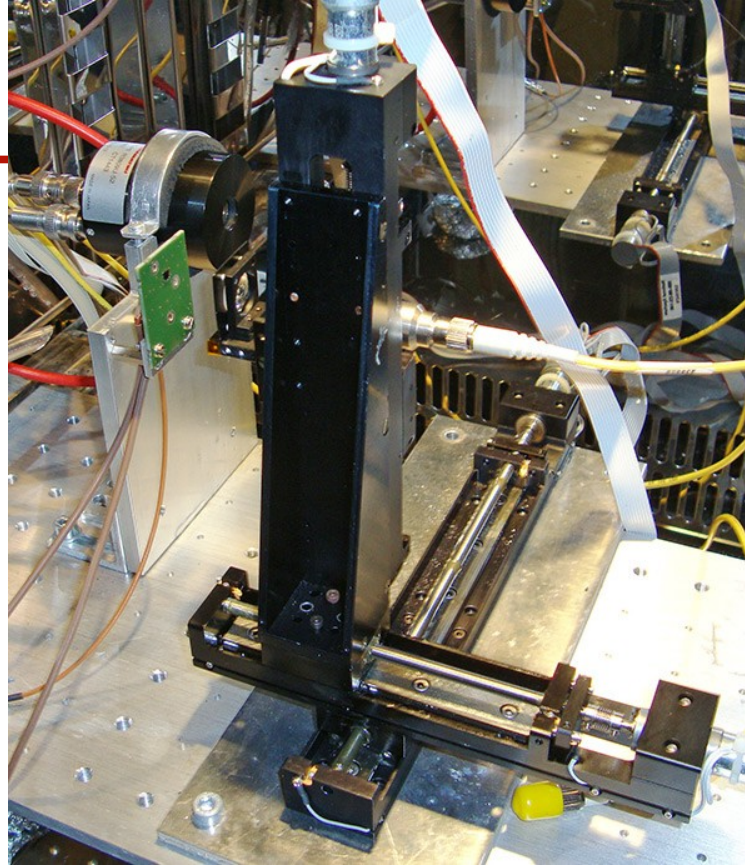
- Single photoelectron cut: **190 ps** FWHM
  - AdvanSiD
  - V_{ov} = 7V
  - black painted PbF_2
  - T = -25°C
- compared to 306 ps FWHM with all events

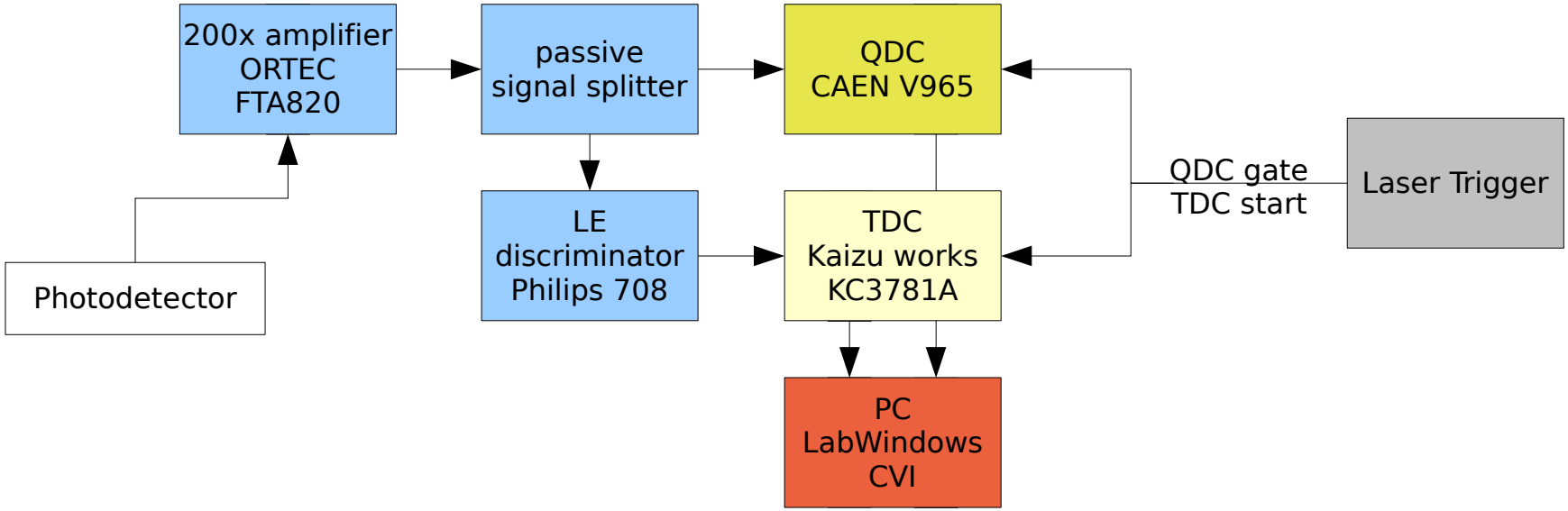




Laser measurements

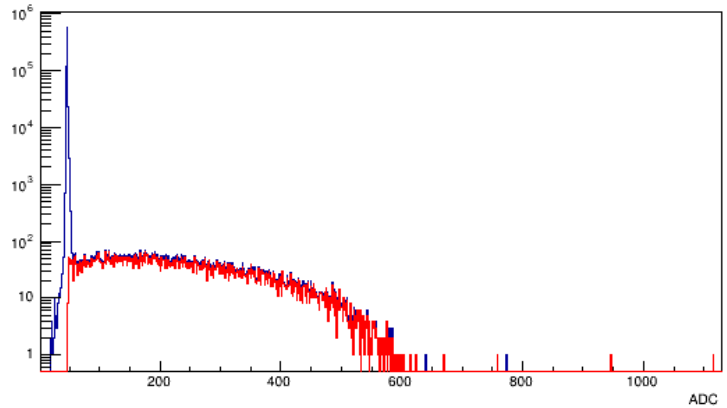
- PiLas diode laser system EIG1000D, 404nm and 635nm laser heads (35 ps FWHM)
- attenuated to single ph. levels using ND filters
- focusing lens (min. spot size σ ~ 3µm)
- 3D computer controlled stage (< µm accuracy)
- temperature controlled chamber (-70°C to 100°C)
- Hamamatsu R3809 MCP PMT reference (25 ps FWHM)
- readout system the same as for coincidences



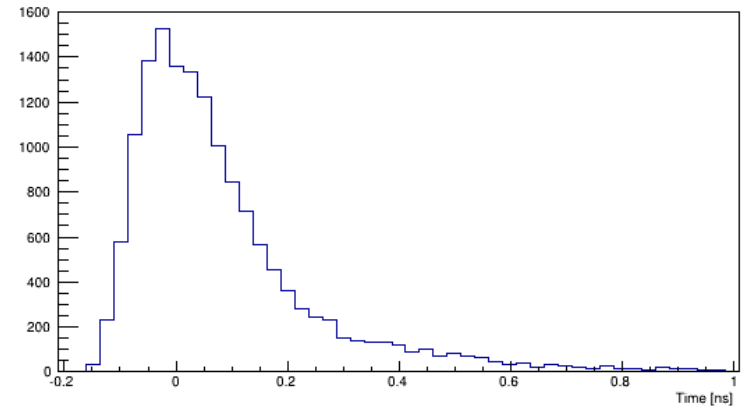


System timing (Reference MCP PMT)

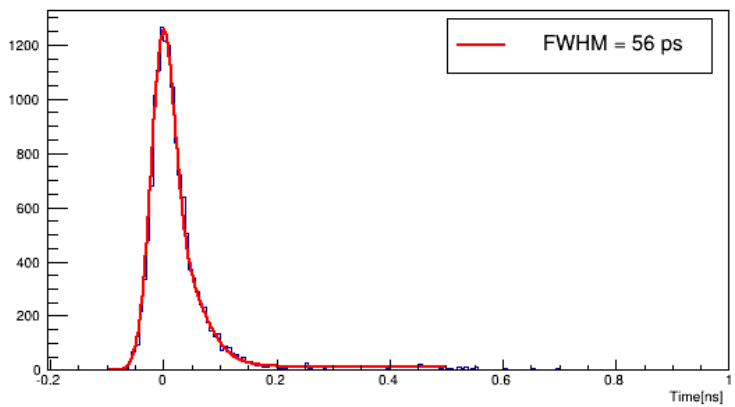
Charge Distribution



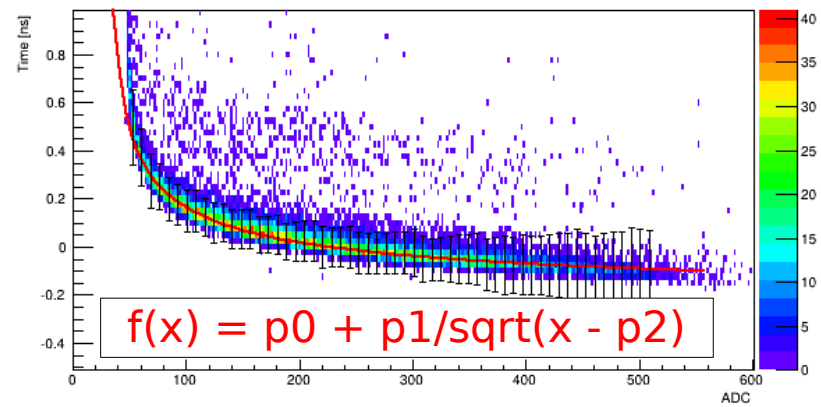
RAW Time Distribution



Corrected Time Distribution



Time/Charge Correlation



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

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

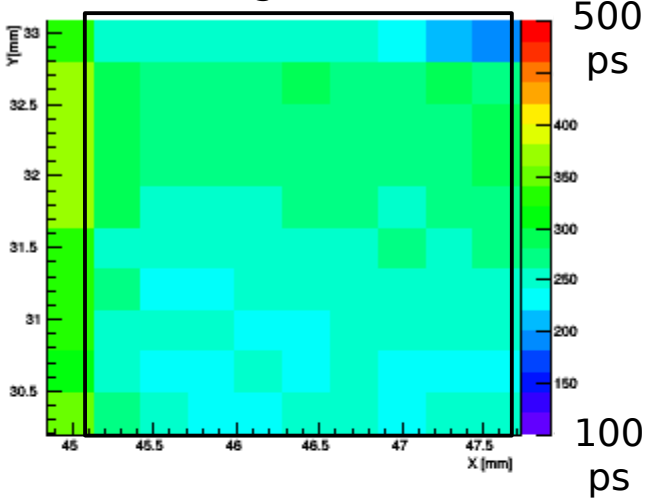
Timing and Delay vs. position

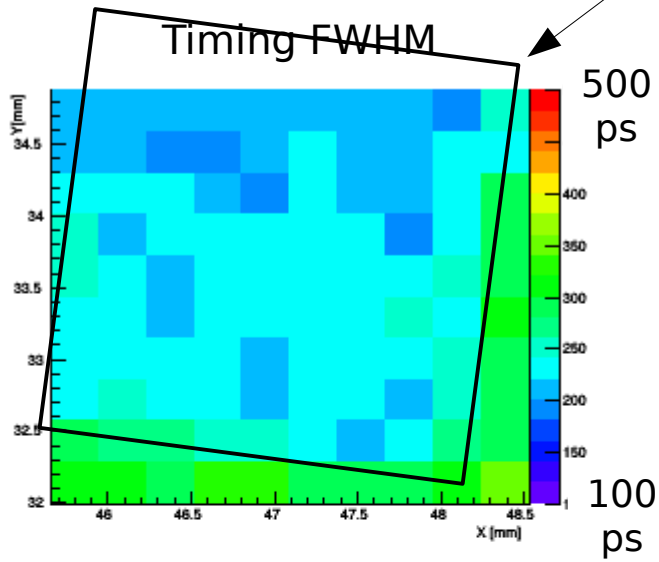
lower V_{ov} !

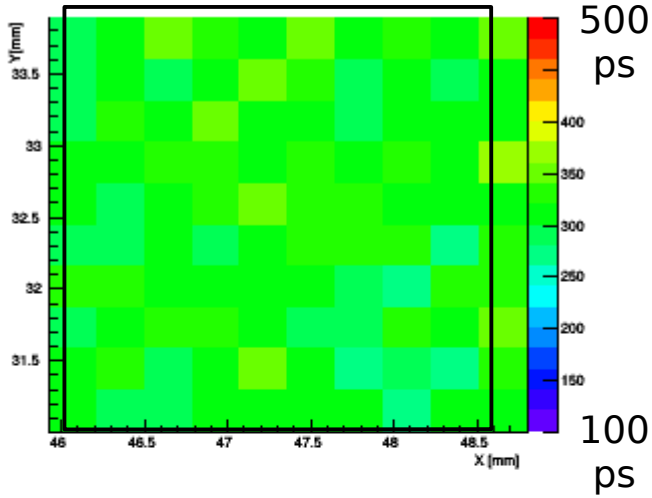
- Red laser defocused to approx. 300 µm, scans over whole active surface (T = +25°C)

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

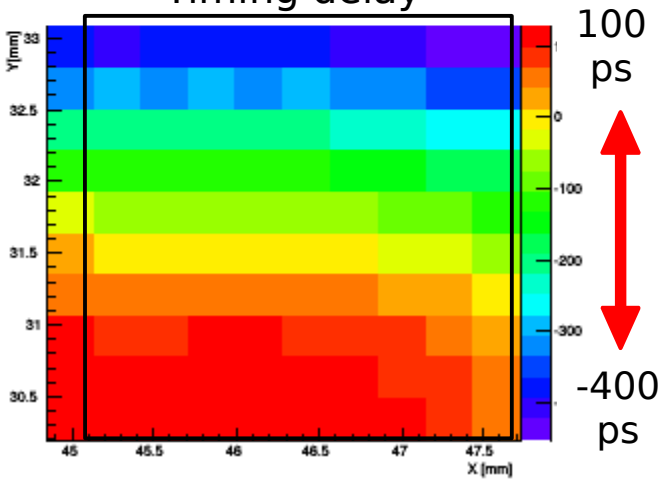
Timing FWHM

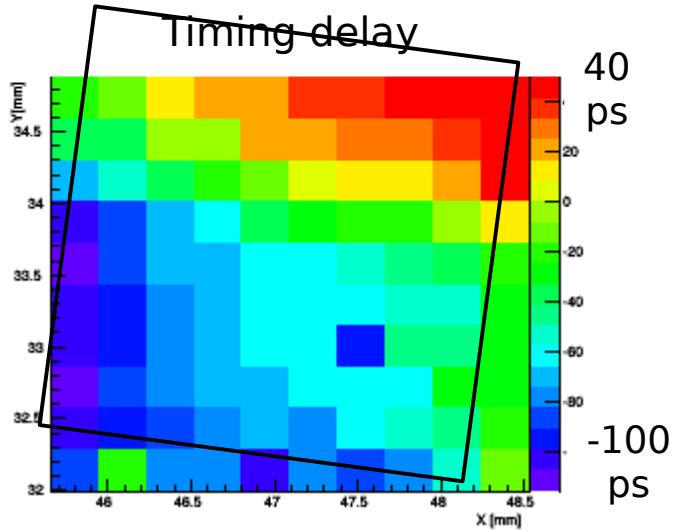


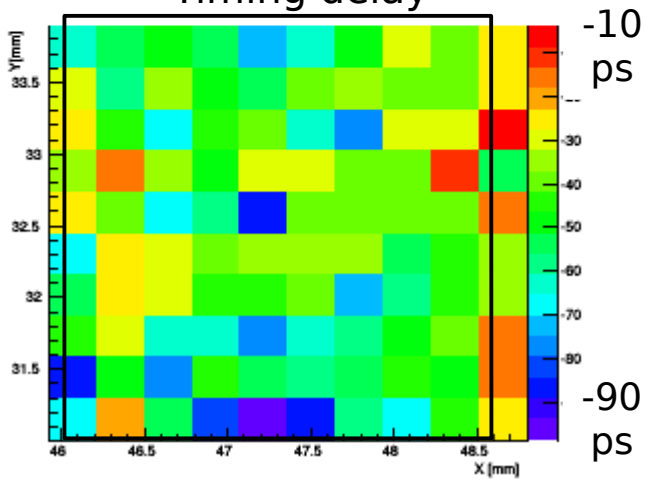




Timing delay

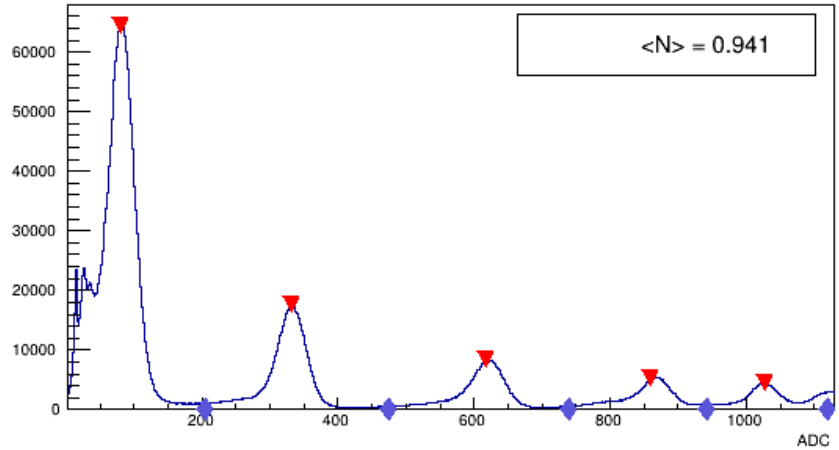




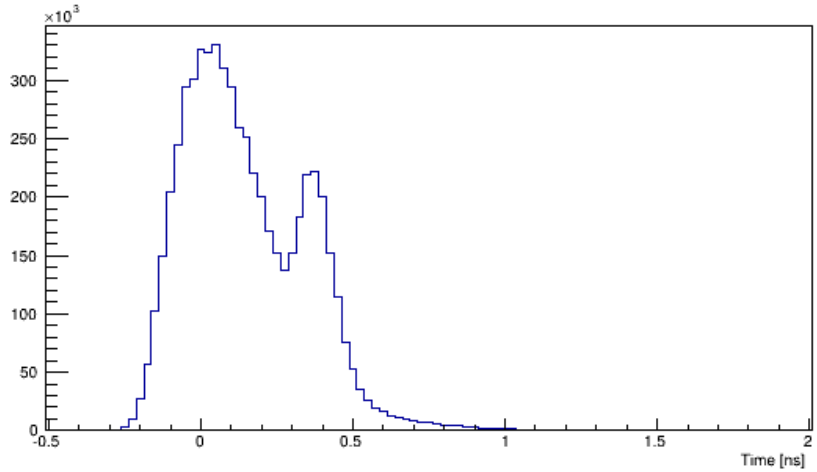


SiPM timing (laser)

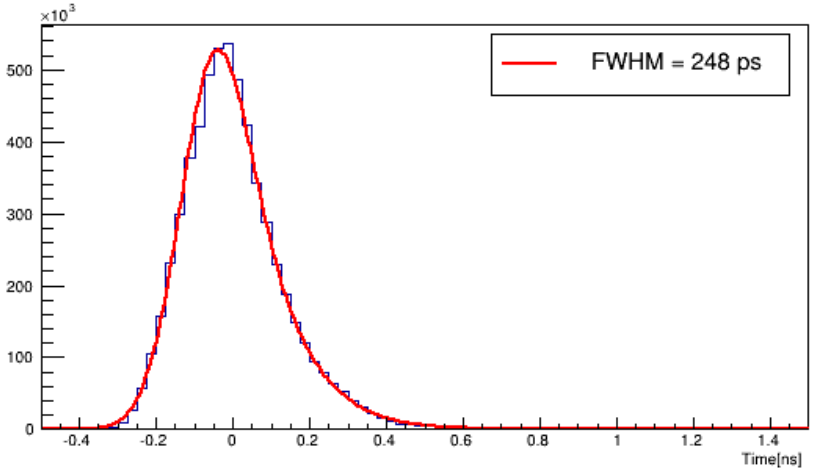
Charge Distribution



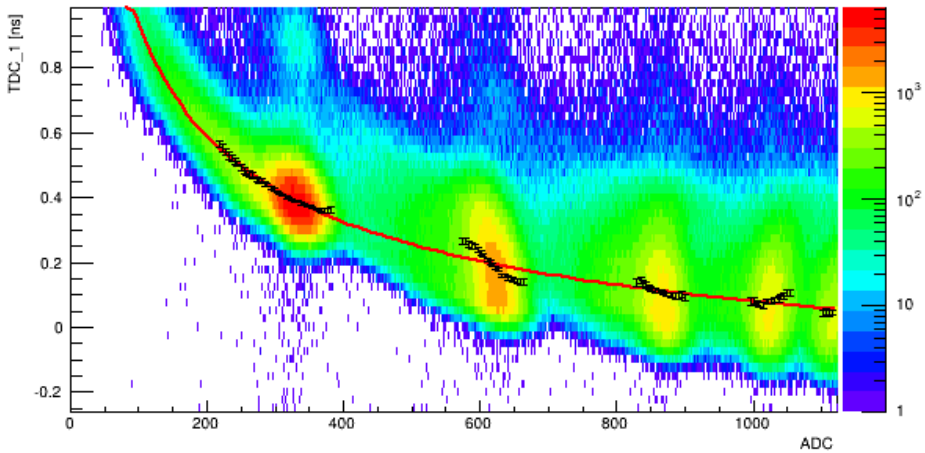
RAW Time Distribution



Corrected Time Distribution



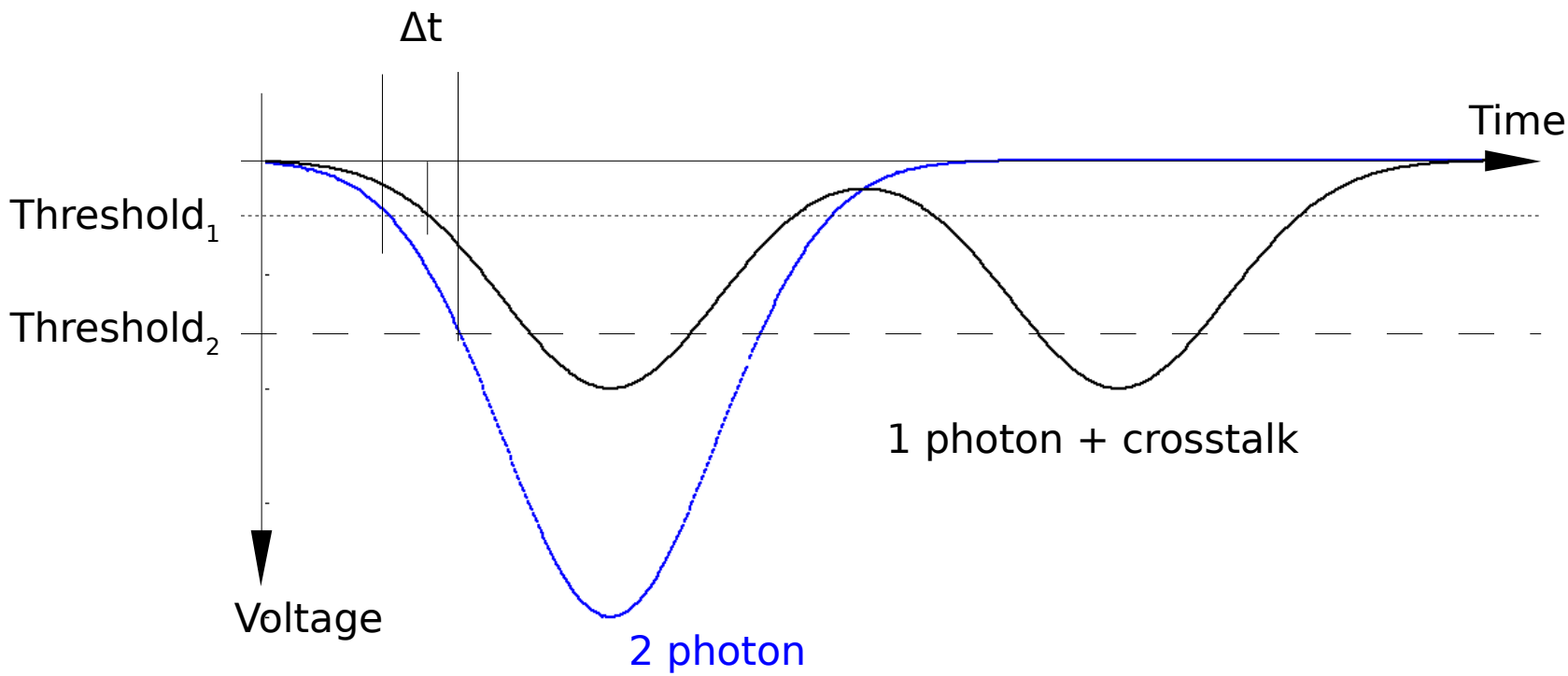
Time/Charge Correlation



- **248 ps FWHM** with
  - AdvanSiD, V_{ov}=6V, T=-25°C
  - laser defocused to illuminate whole surface

Improving Time Resolution

- main contributions to intrinsic SiPM time resolution:
  - individual micro cell time response
  - internal delays due to different signal pathlenths
  - crosstalk events lead to issues with time-walk correction (e.g. register at single m.c. time but double m.c. charge)
- attempt to correct the 3rd contribution:
  - separate time-walk correction for each m.c. signal height
  - Multi-Threshold measurement

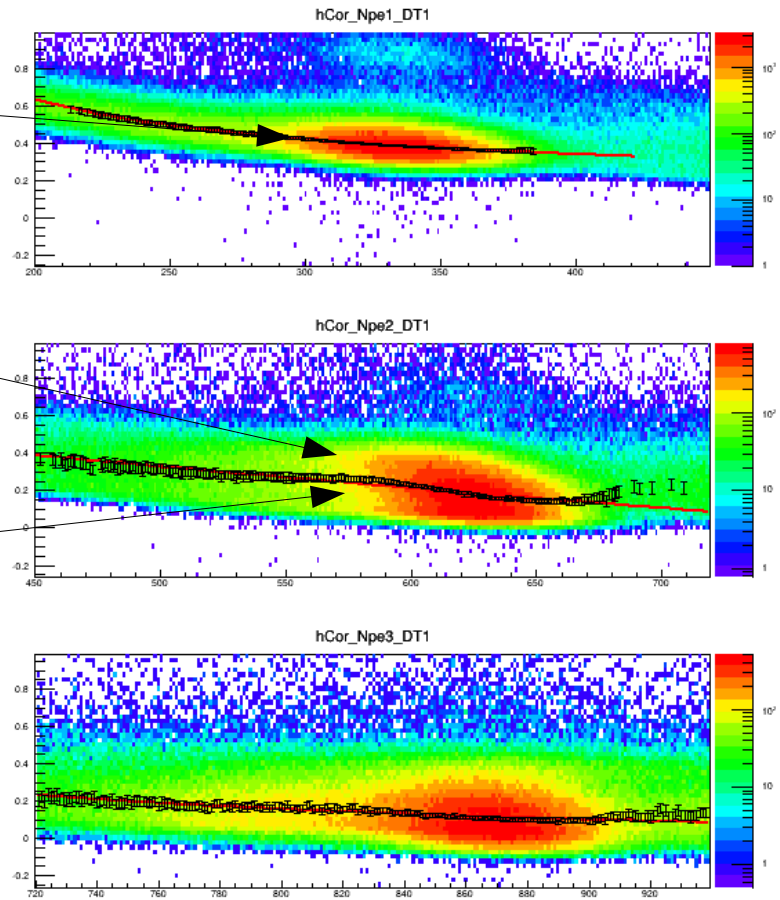


Time-walk correction for each m.c. height

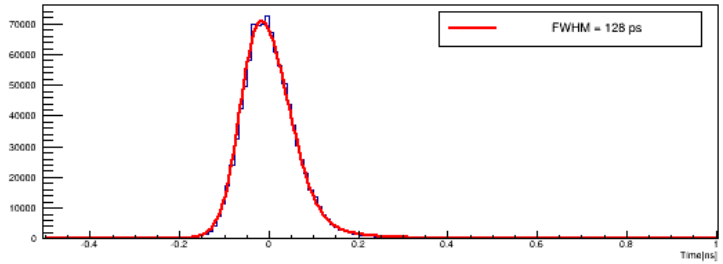
detection of 1 photon

delayed detection (crosstalk?)

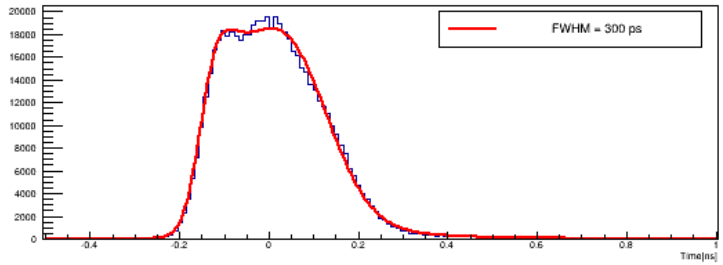
simultaneous detection of 2 photons



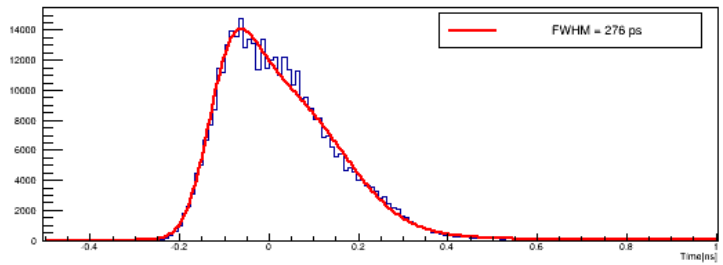
Corrected Time, **1 m.c.**



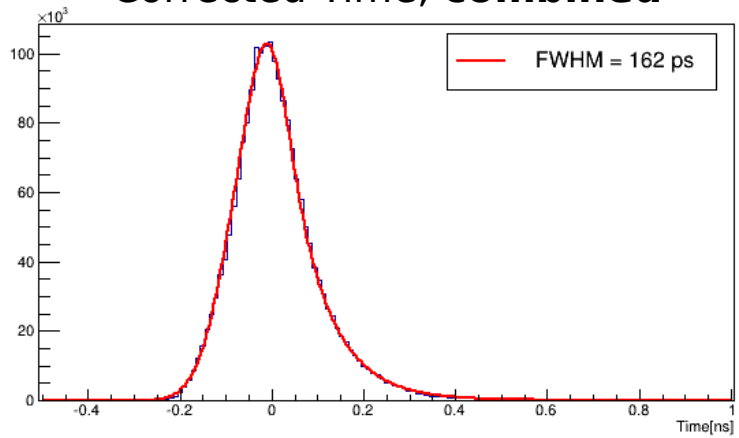
Corrected Time, **2 m.c.**



Corrected Time, **3 m.c.**



Corrected Time, **combined**

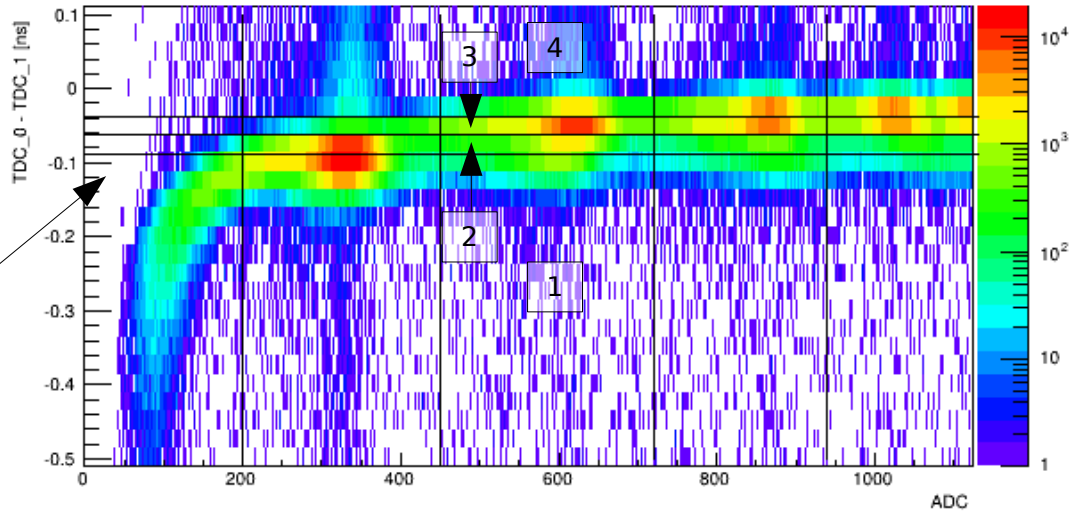


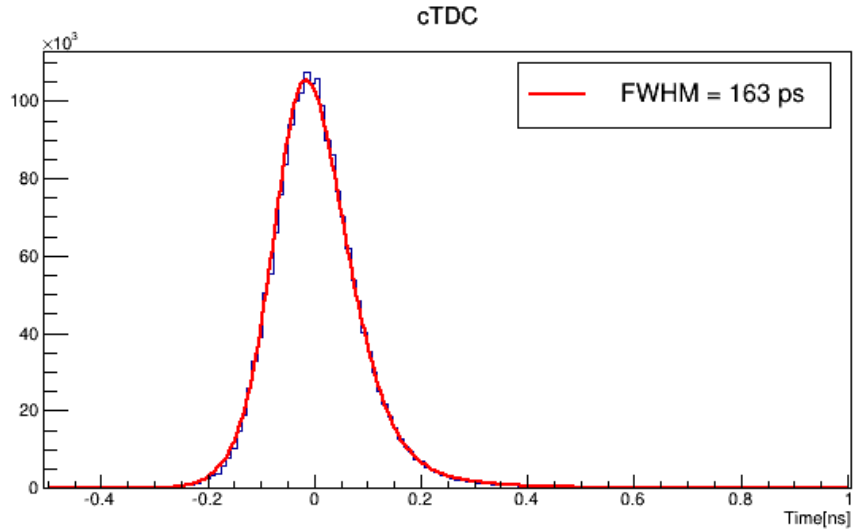
- **162 ps FWHM**
  - same measurement with AdvanSiD
  - laser defocused to illuminate whole surface

Multi-Threshold measurement

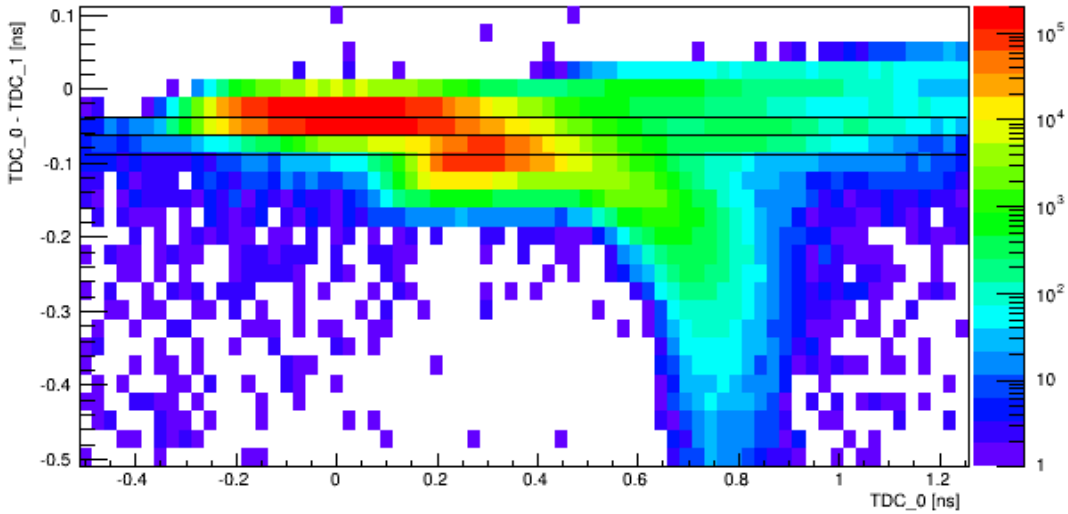
- SiPM signal additionally split after amplification
- two Discriminator and TDC channels:
  - threshold = 0.2 m.c.
  - threshold = 0.4 m.c.
- separate time-walk correction for each m.c., 4 regions in Δt
- **163 ps FWHM**

Δt/charge correlation



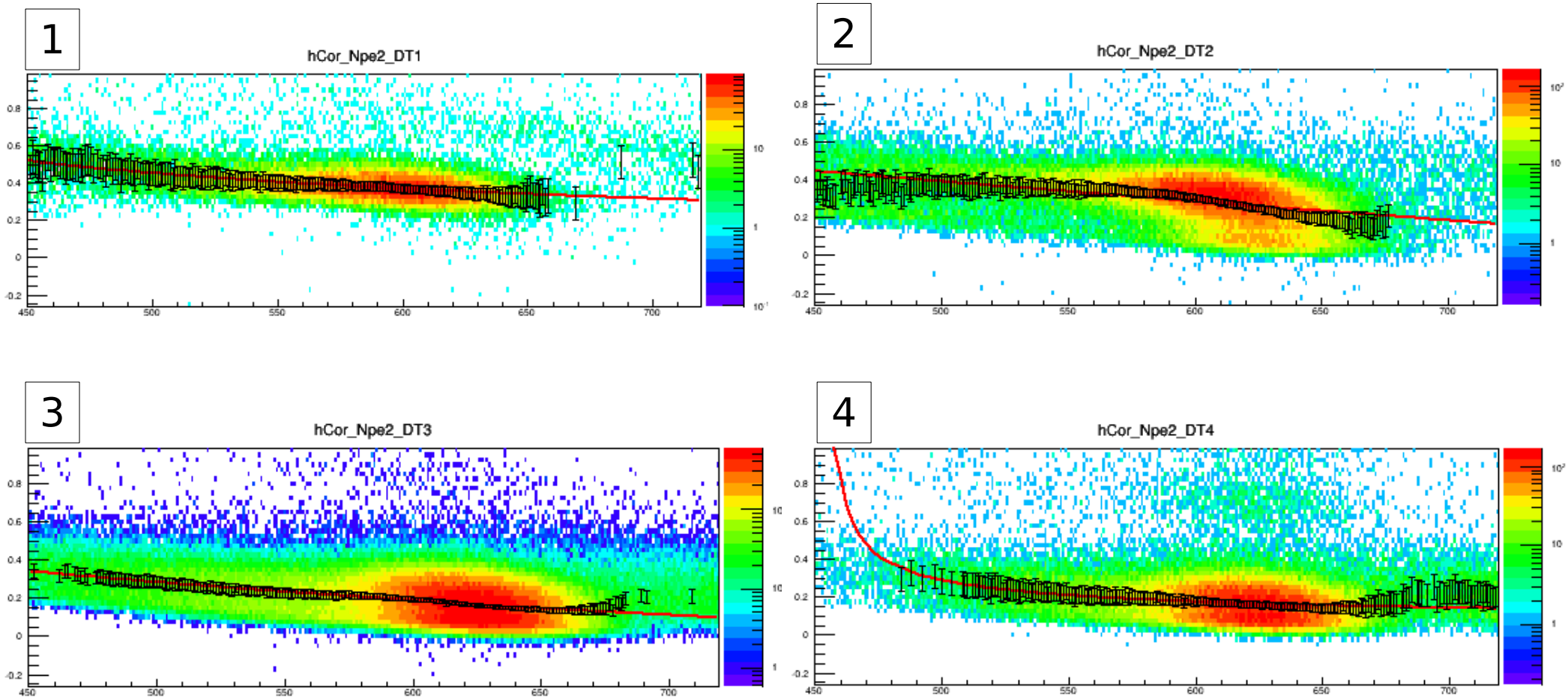


Δt/time correlation



Multi-Threshold measurement

- **2 m.c.** signal region for the **four regions in Δt**
  - some docoupling of the two contributions!



Summary of laser measurements

- Blue laser **defocused** to illuminate whole surface (timing in ps FWHM):

	simple t-w	individual m.c.	multi-threshold*	1 m.c.
AdvanSiD	248	162	163	128
KETEK 'new'	192	195	190	217
KETEK	457	(441)	-	414
Ham. S13360	178	178	173	200
SensL - J	221	185	191	197

- Blue laser **focused** on micro cell center (timing in ps FWHM):

	simple t-w	individual m.c.	multi-threshold*	1 m.c.
AdvanSiD	170	129	123	108
KETEK 'new'	162	158	153	151
KETEK	184	181	176	161
Ham. S13360	155	151	152	159
SensL - J	237	211	198	198

* variing success of decoupling of two peaks

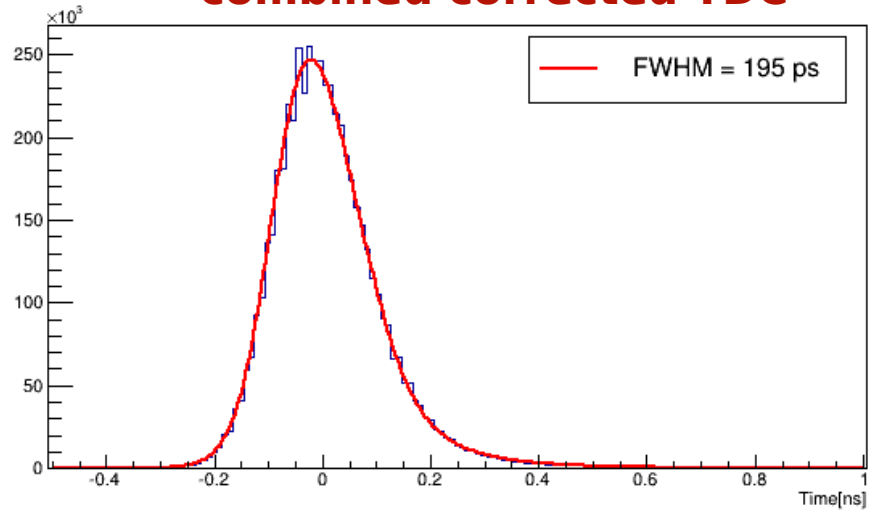
Conclusion

- Cherenkov TOF PET is a promising new method for PET
  - coincidence timing < 100 ps (with MCP PMTs)
  - efficiency competitive to scintillator PET (30% single side with SiPMs)
- SiPMs as photodetectors in Cherenkov TOF PET:
  - very good efficiency
  - high dark count rates → currently requires cooling
  - slightly limited timing
- Laser measurements:
  - importance of optimized path lengths for all micro cells
  - fraction of events registered with multiple m.c. charge come with some delay (SiPM crosstalk)
  - big improvement with time-walk on individual m.c. signal heights
  - multi-threshold measurement → some separation of two contributions demonstrated on 2 m.c. signals
  - significant improvement still seems possible (at leas 1 m.c. timing, if not 1/sqrt(N))

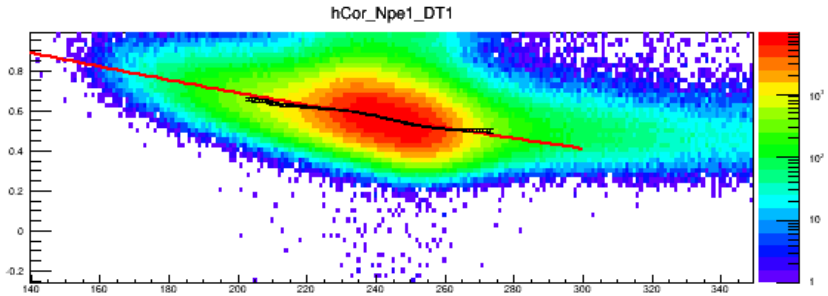
Backup slides

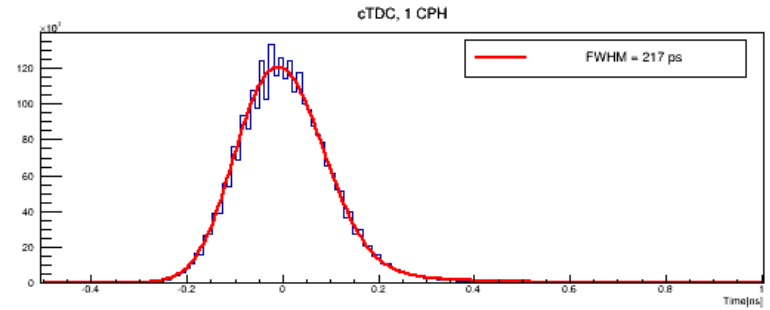
KETEK 'new', out of focus

combined corrected TDC

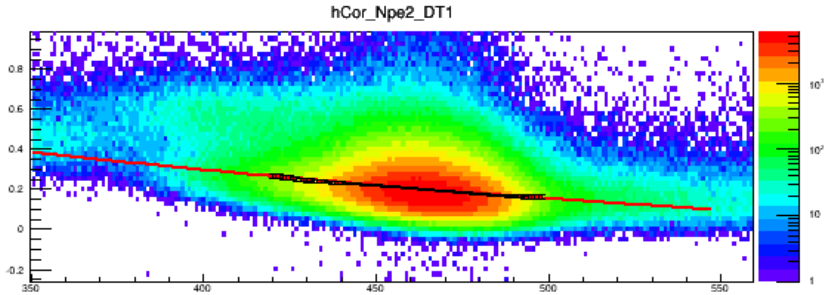


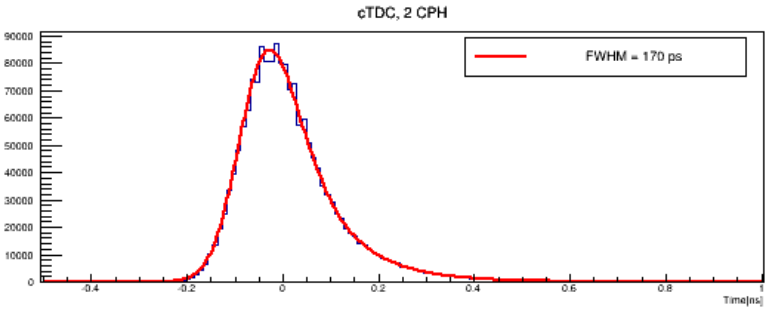
1 m.c. height



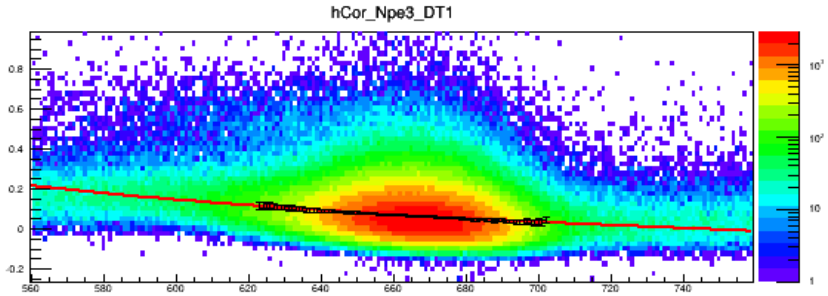


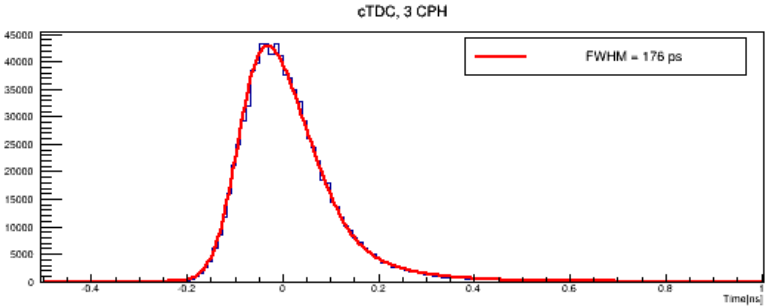
2 m.c. height





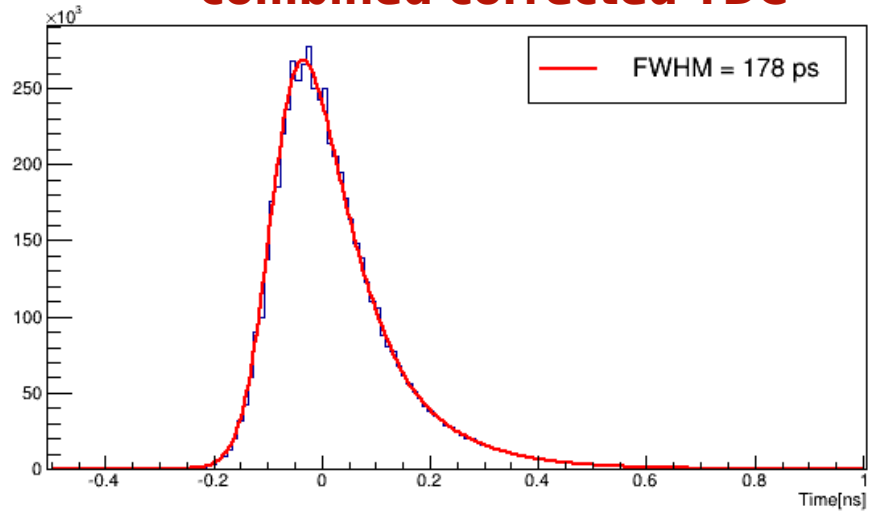
3 m.c. height



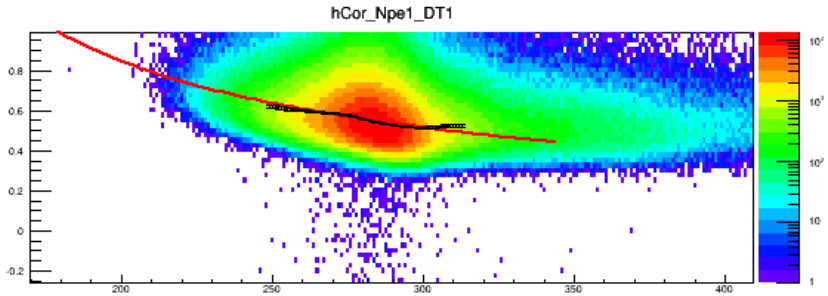


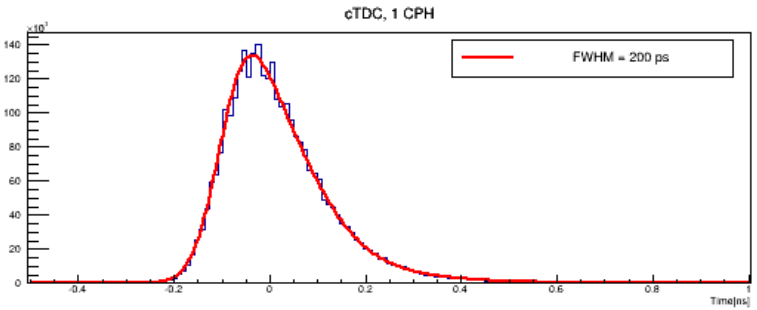
Hamamatsu S13360, out of focus

combined corrected TDC

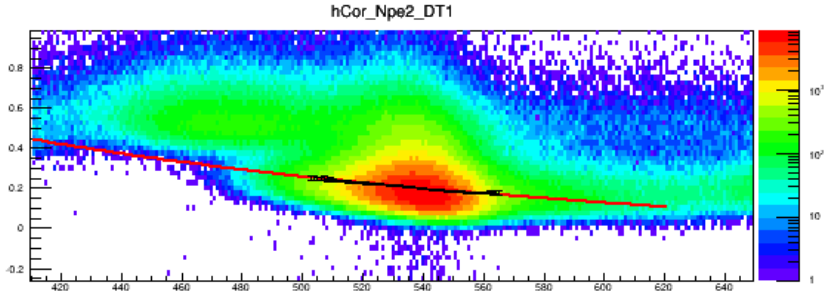


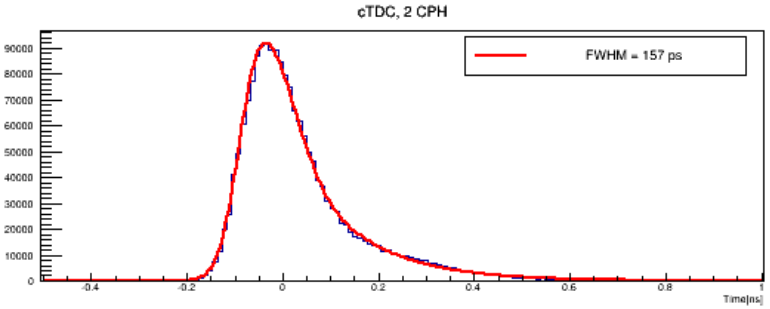
1 m.c. height



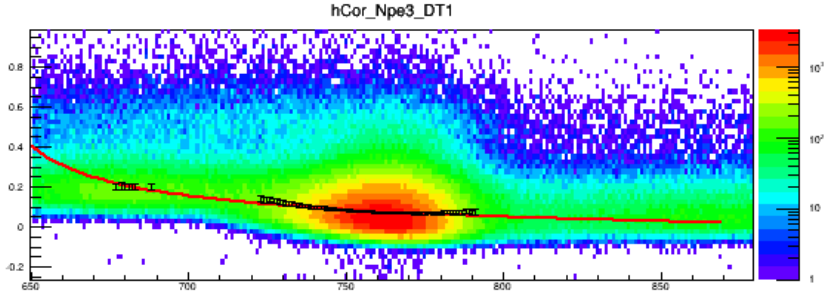


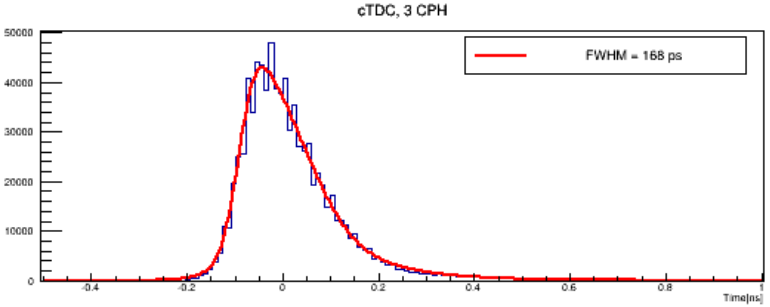
2 m.c. height





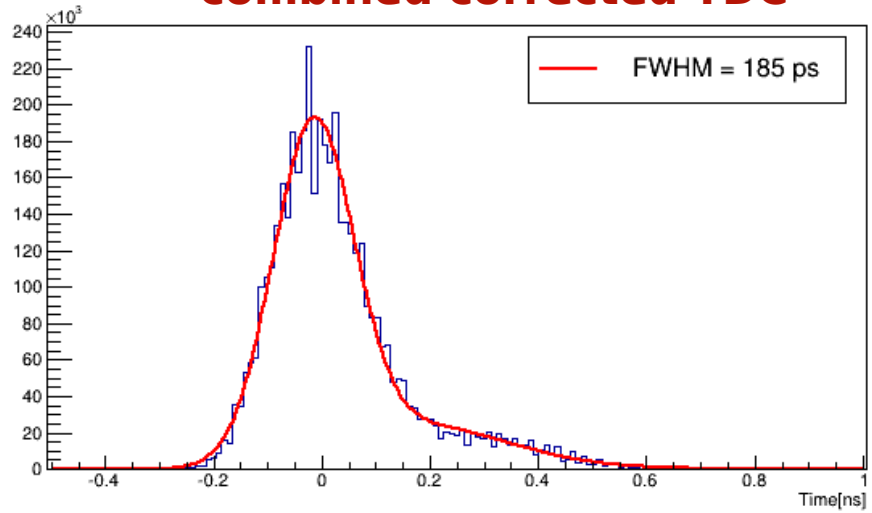
3 m.c. height



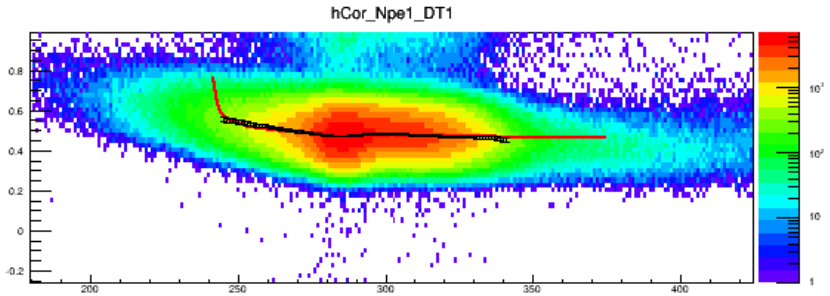


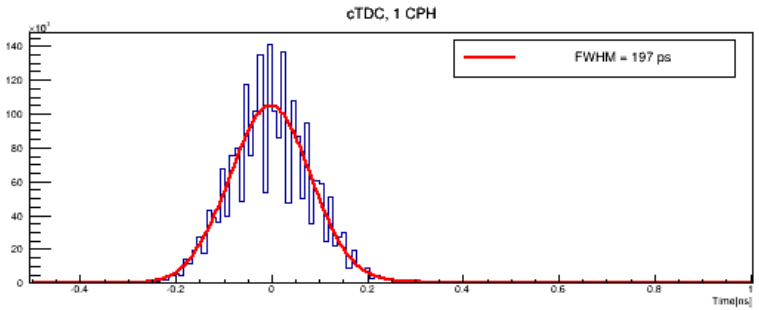
SensL - J, out of focus

combined corrected TDC

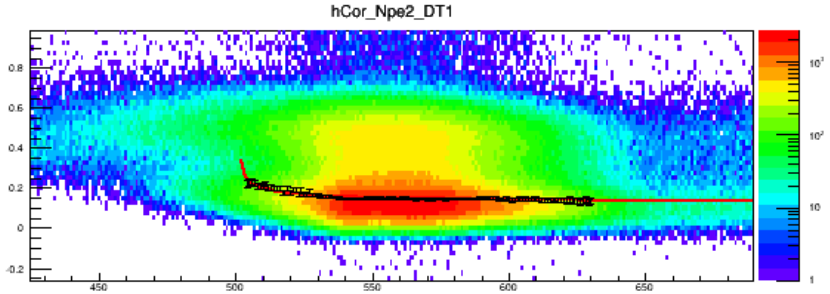


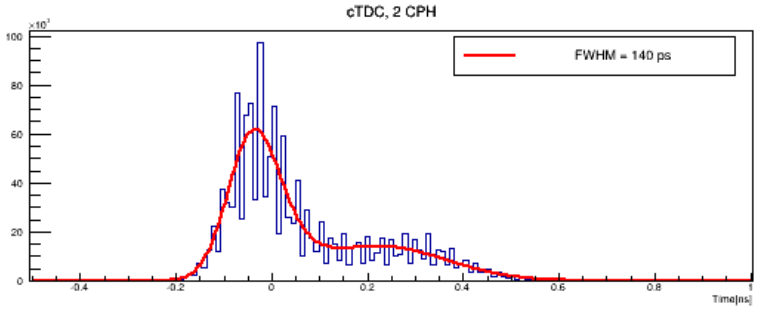
1 m.c. height



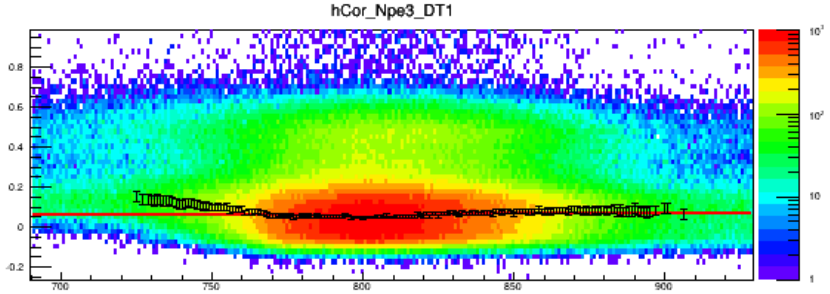


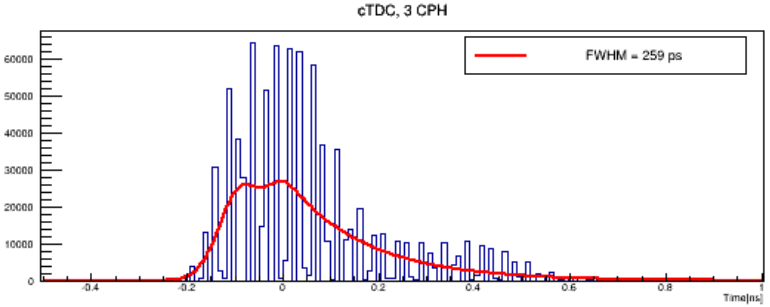
2 m.c. height





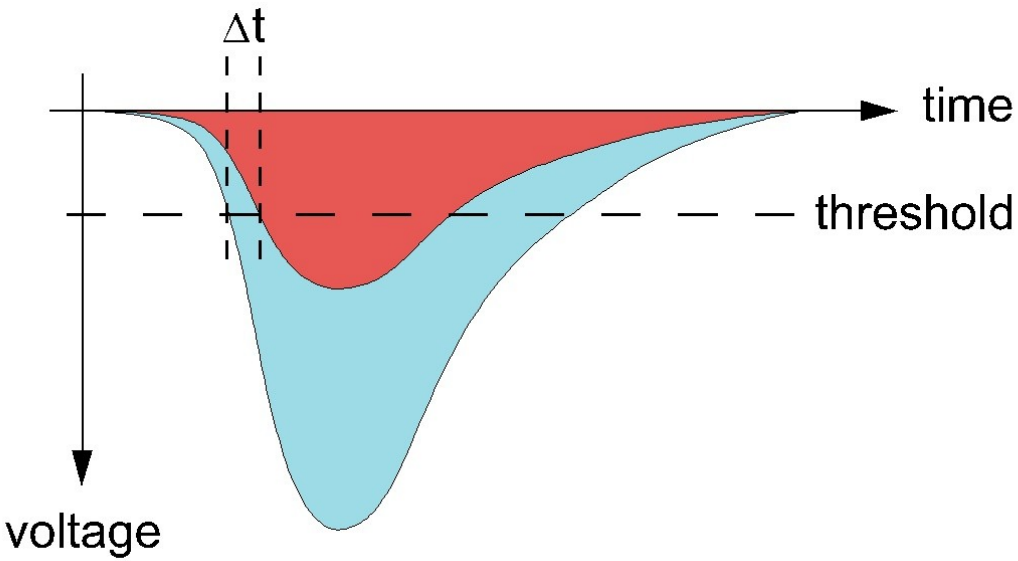
3 m.c. height

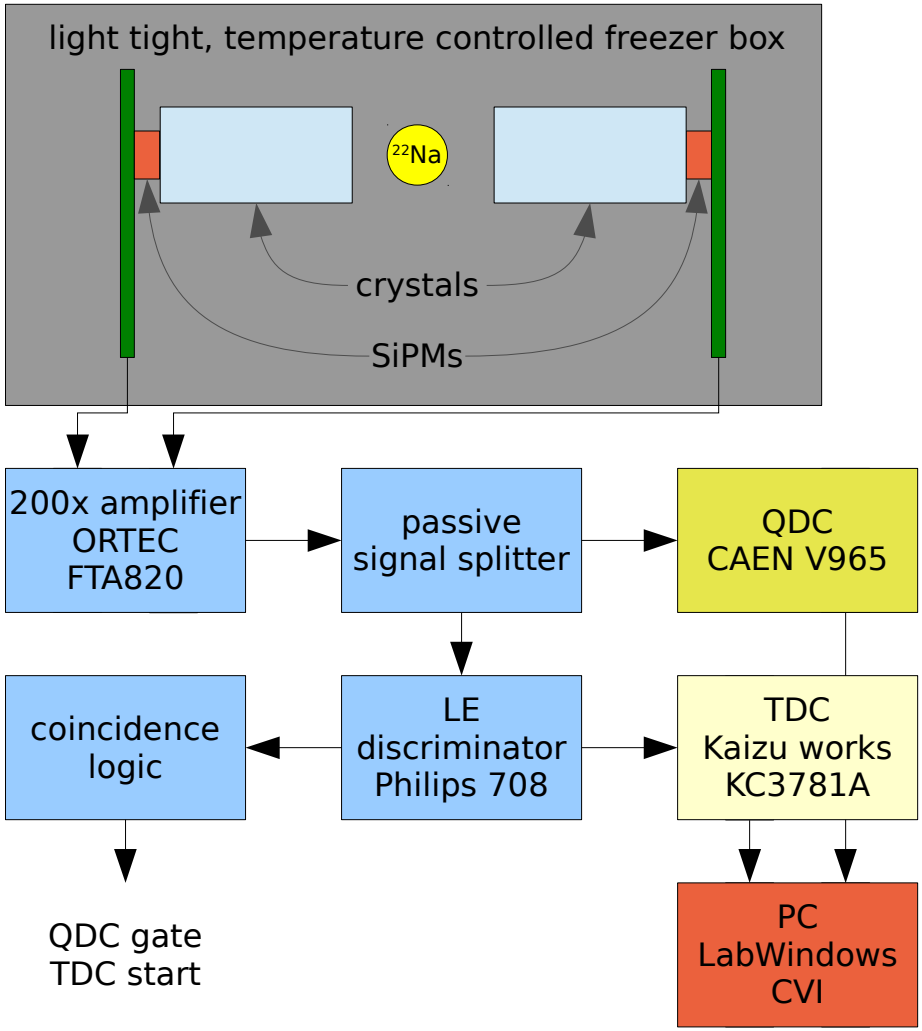




Experimental setup - readout

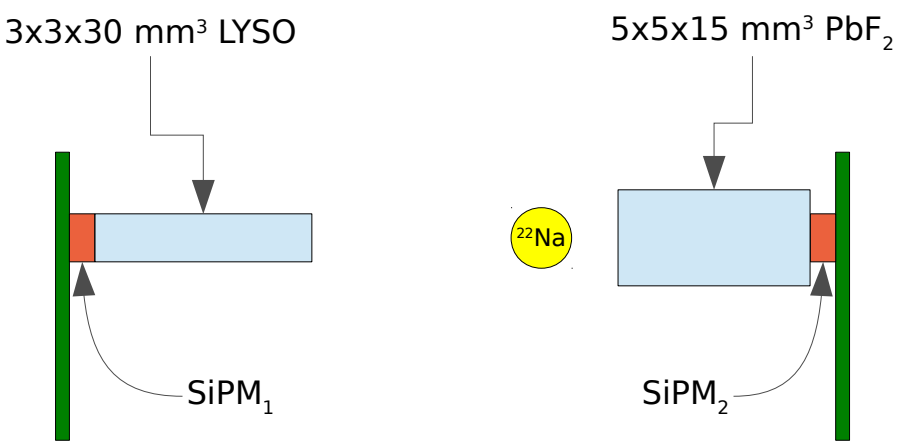
- custom electronics board with NEC uPC2710TB preamplifier
- ORTEC FTA820 amplifier
- Philips scientific mod.708 LE discriminat
- Kaizu works KC3781A TDC (25ps/bin)
- CAEN V965 QDC
- time-walk correction applied in analysis

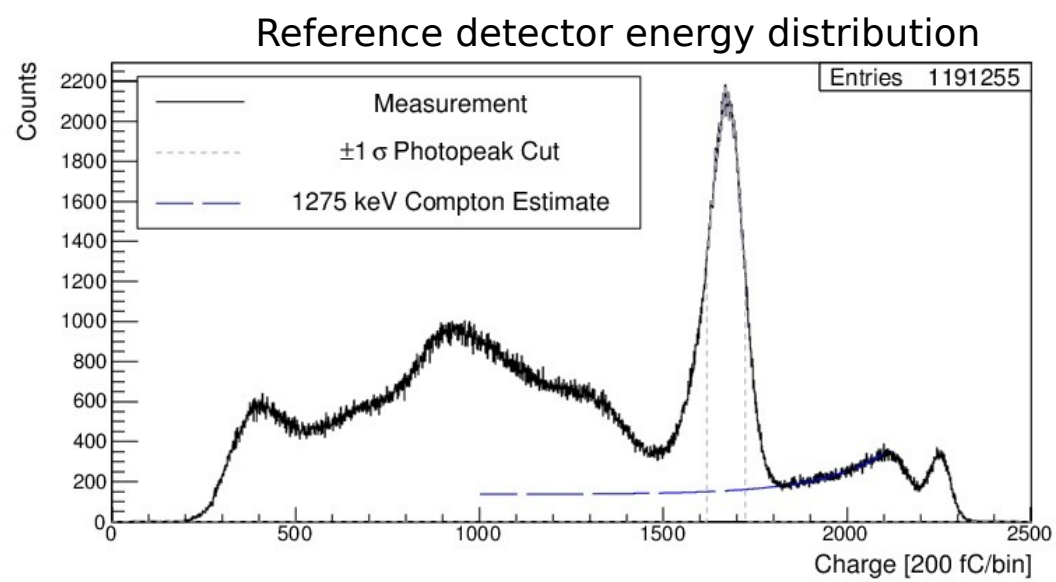




Efficiency measurements

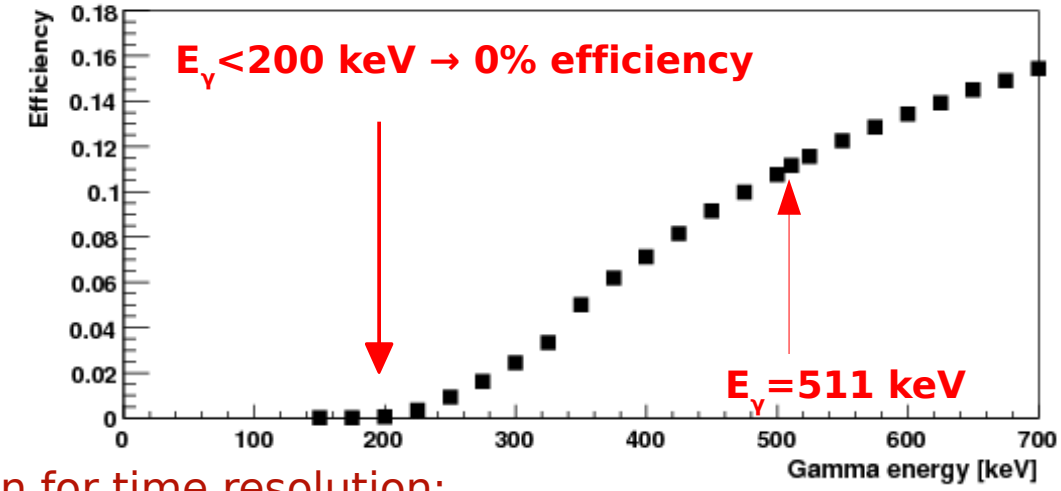
- one Cherenkov detector replaced with a reference scintillation detector
- tight collimation of coincidence gammas on Cherenkov detector
- photopeak cut on reference detector → single side detection efficiency on Cherenkov detector
- corrected for
  - SiPM dark count rate
  - Compton scatter of 1275 keV gammas from ^{22}Na





Cherenkov radiation in TOF PET

- 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, however there is an intrinsic Compton scatter suppression & less scattering in crystals (very high Z)



- New limitation for time resolution:
  - **optical photon travel time spread** in the crystal