Recent progress in Cherenkov based TOF PET

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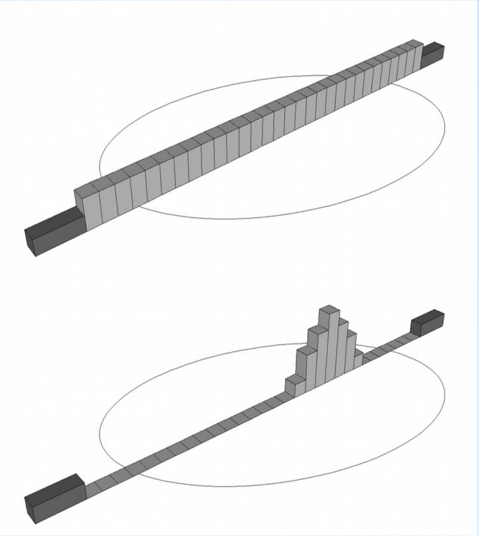
Outline:

- Introduction: Cherenkov TOF-PET
- MC study
- SiPM for Cherenkov TOF-PET:
  - Back-to-back measurements
  - Measurements with laser light
- Summary

Mediterranean
Thematic Workshops
in Advanced Molecular Imaging

TOF-PET with Cherenkov light

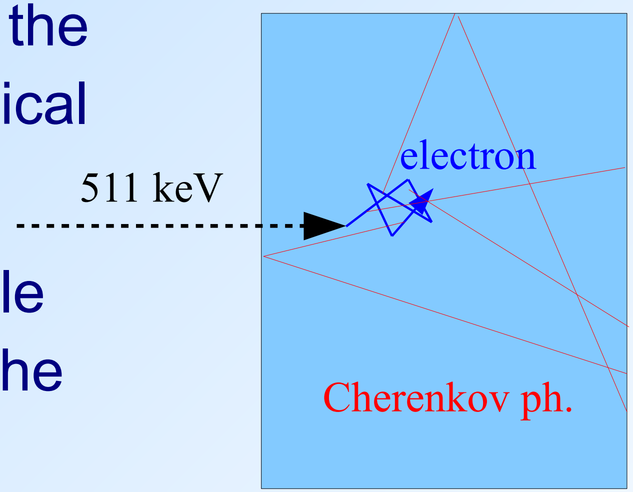


Time-of-Flight difference of annihilation gammas is used to improve the contrast of images obtained with PET.

- localization of source position on the line of response:

$\Delta t \sim 66\text{ps} \rightarrow \Delta x \sim 1\text{cm}$

Novel photon detectors – MCP-PMT and SiPM – have excellent timing resolution → TOF resolution limited by the spread in photon arrival time (scintillation process, optical path length ...)

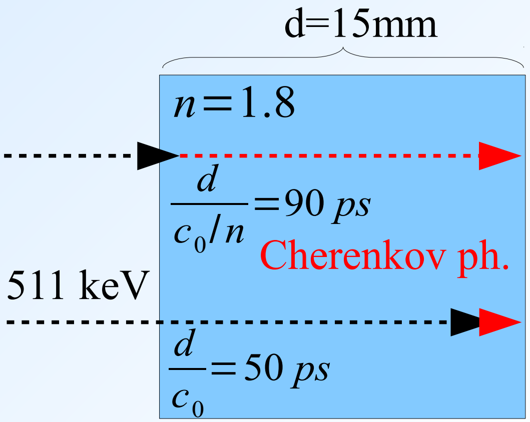


- Cherenkov light is promptly produced by charge particle traveling through the medium with velocity higher than the speed of light c_0/n.

- Disadvantage of Cherenkov light is the small number of Cherenkov photons produced per interaction

$$N \approx \frac{370}{eV\,cm}\cdot l\cdot\Delta E\cdot\sin^2\vartheta_C \approx 370\times0.01\times2\times0.75 \approx 8$$

→ detection at a single photon level!



Cherenkov radiator

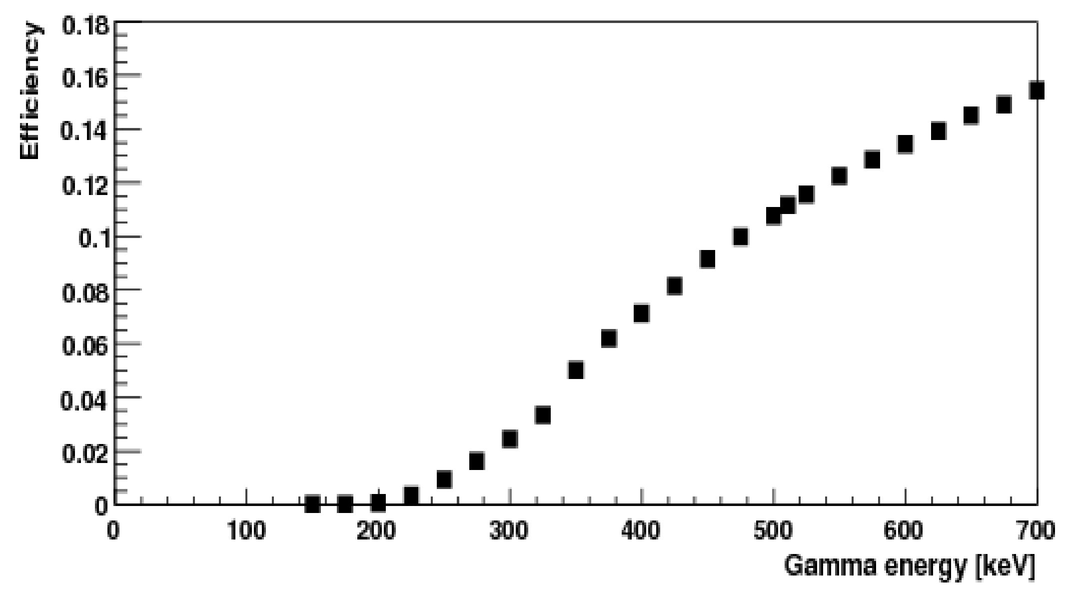
Cherenkov radiator PbF_2:

- high gamma stopping power
- high fraction of gamma interactions via photoeffect → electrons with maximal kinetic energy → more Cherenkov photons
- high transmission for visible and near UV Cherenkov photons

	ρ (g/cm^3)	n	e^- Cherenkov threshold (keV)	Cutoff wavelength (nm)	Attenuation length (cm)	Photofraction
PbF_2	**7.77**	**1.82**	**101**	**250**	**0.91**	**46%**
LYSO	7.4				1.14	32%

Traditional PET: large number of photons → gamma energy → rejection of scattered events

Cherenkov PET: a few photons detected → no energy information; efficiency drops with gamma energy → intrinsic suppression



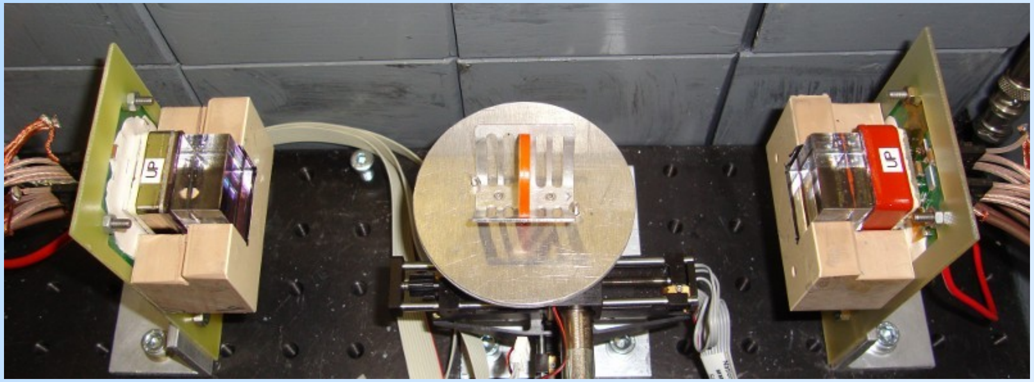
Excellent timing with MCP-PMT

Two detectors in a back-to-back configuration:

- Cherenkov radiators:

25x25x(5, 15) mm^3 PbF_2

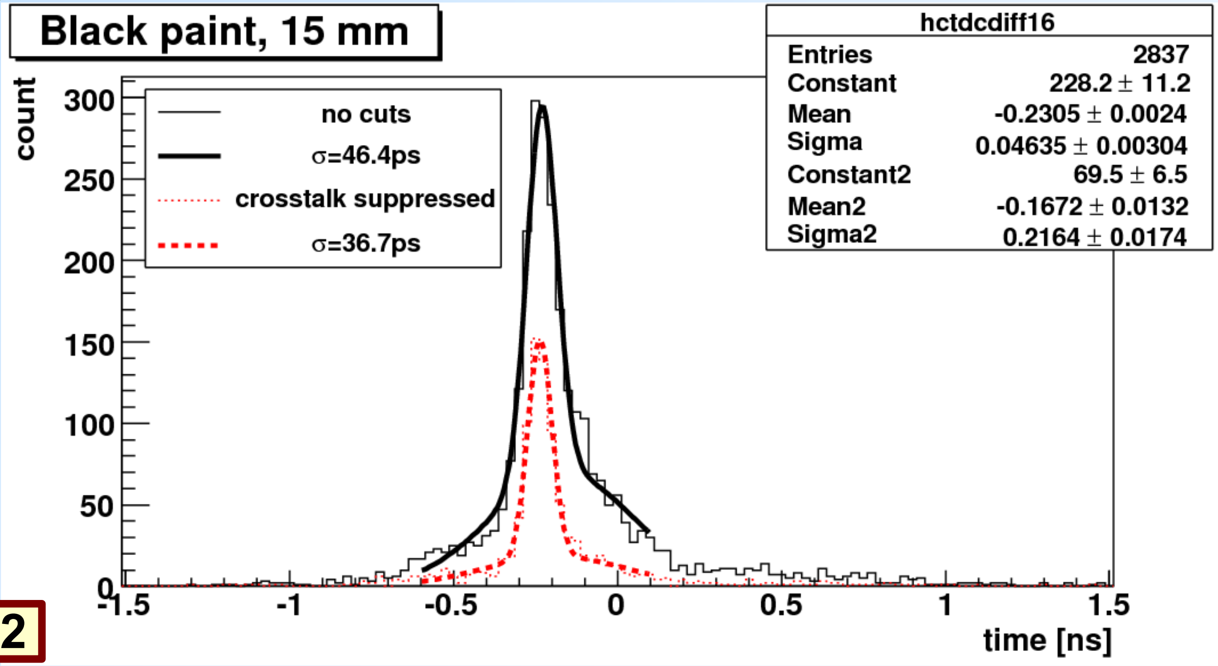
- MCP-PMT photodetectors:
  - single photon timing ~ 50 ps FWHM
  - active surface 22.5x22.5 mm^2



black painted, Teflon wraped, bare

- Timing resolution (black painted):
  - ~ 70 ps FWHM, 5mm crystal
  - ~100 ps FWHM 15mm crystal
- Efficiency (Teflon wrapped):
  - ~ 6%, single side

(~ 30% for LSO in ideal case)



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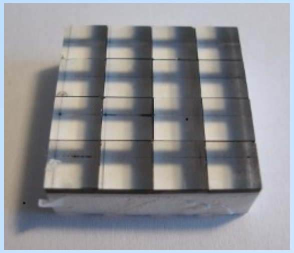
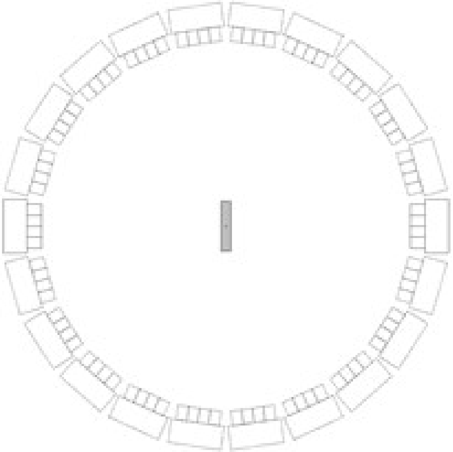
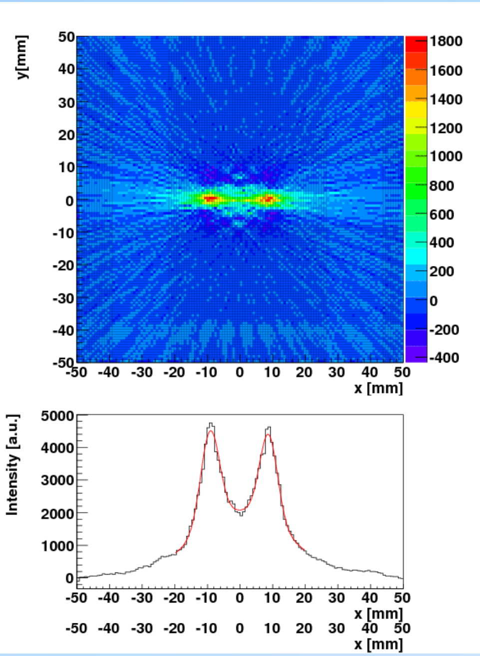
MCP-PMT: TOF PET reconstruction

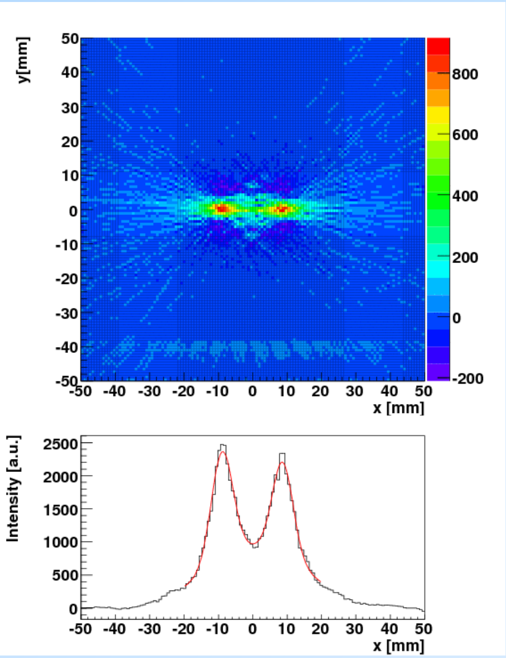




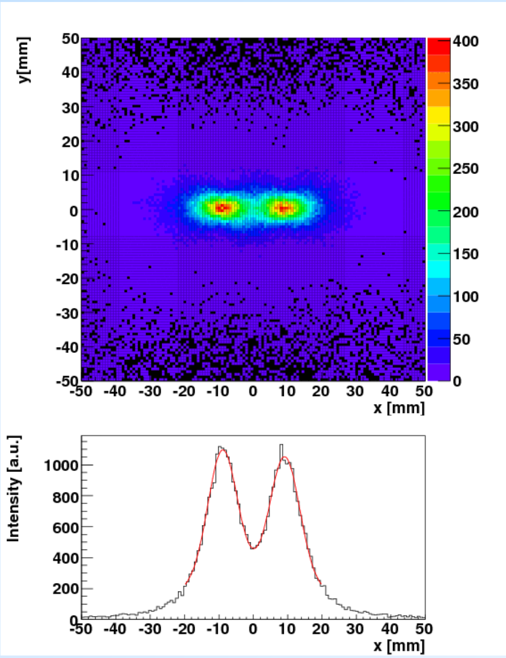
- ^{22}Na point sources at +10 mm and -10 mm
- 4x4 segmented, black painted PbF$_2$ radiators



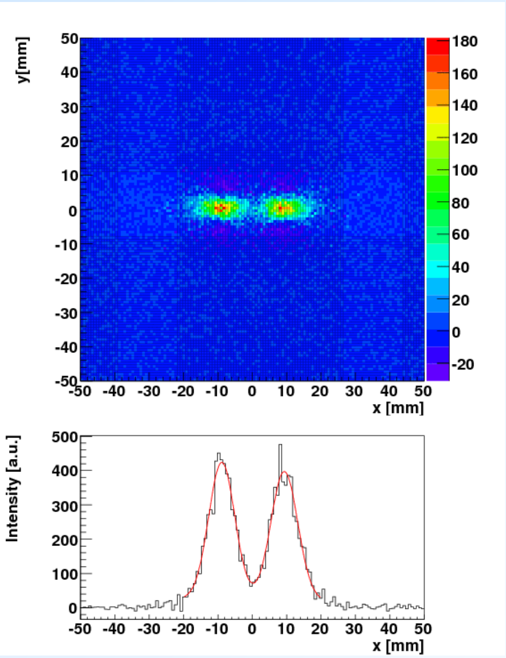
(non-TOF) FBP



TOF w/ FBP



MLP



Filtered MLP

- Simple and very fast MLP (Most Likely Position)

→ already a reasonable picture

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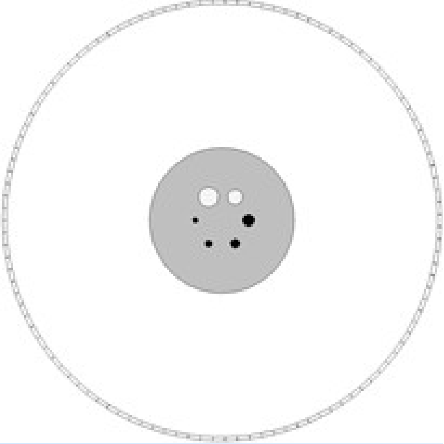
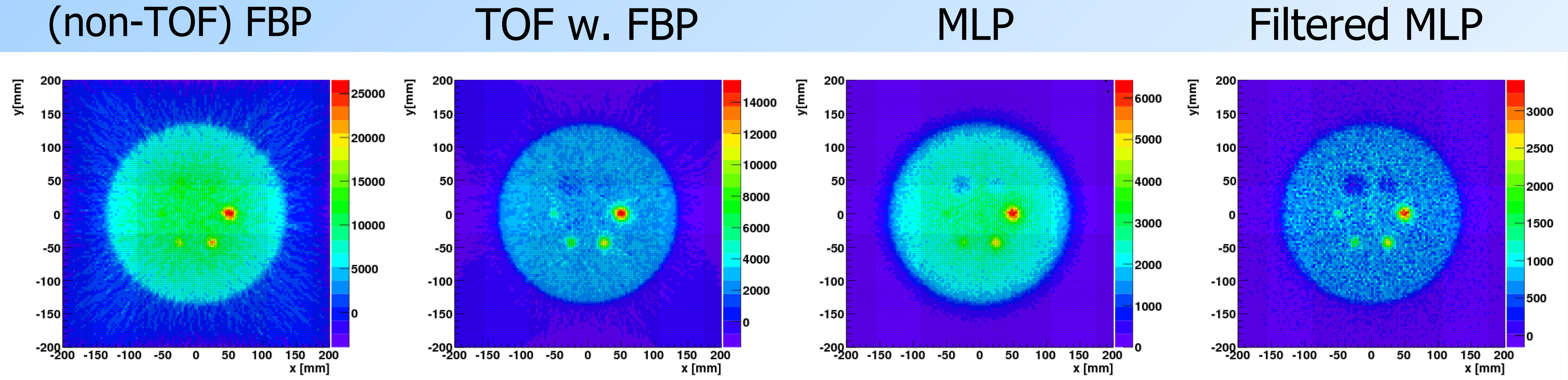
TOF PET reconstruction- simulation



- Hot spheres activity concentration: 3x phantom background
- Statistics equivalent to 163 s of PET examination
- 4x4 segmented, Teflon wrapped PbF_2 radiator
- 20 mm thick axial slices

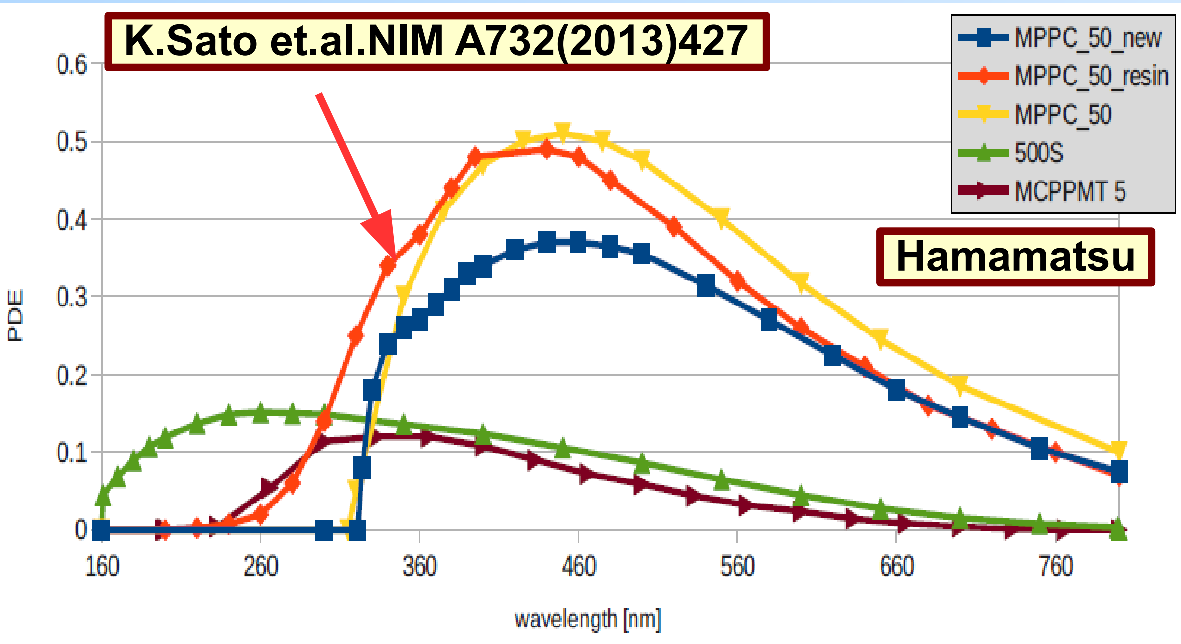


First tries, have to understand how the possible improvements in the detection efficiency will influence the performance:

- Black painted (better TOF resolution) → better contrast
- Teflon wrapped (higher statistics) → better contrast-to-noise ratio (despite the tails in timing distribution)

Efficiency simulation

- Cherenkov fotons in range 200nm – 800nm
- PbF_2 radiator – 15 mm
- perfect coupling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Hamamatsu

	C.Eff. [%]	C.T. [ps]	P(Nph>1) [%]	P(Nph>1)^2 [%]
QE100	**43.7**	**77**	**57.5**	**33**
MCPPMT_5	**3.6**	**135**	**3.5**	**0.12**
MCPPMT_500S	6.4	132	6.4	0.41
MPPC_50mum	18.7	93	21.6	4.7
MPPC_50mum_Resin →	**21.0**	**96**	**24.4**	**6.0**
MPPC_50mum_NEW	14.0	99	15.6	2.4
QE100	**32.4**	**72**	**42.9**	**18**
MCPPMT_5	**1.3**	**88**	**1.4**	**0.02**
MCPPMT_500S	2.5	91	2.8	0.08
MPPC_50mum	8.6	69	10.1	1.0
MPPC_50mum_Resin →	**10.1**	**73**	**11.9**	**1.4**
MPPC_50mum_NEW	6.0	70	6.8	0.5

Teflon wrapped

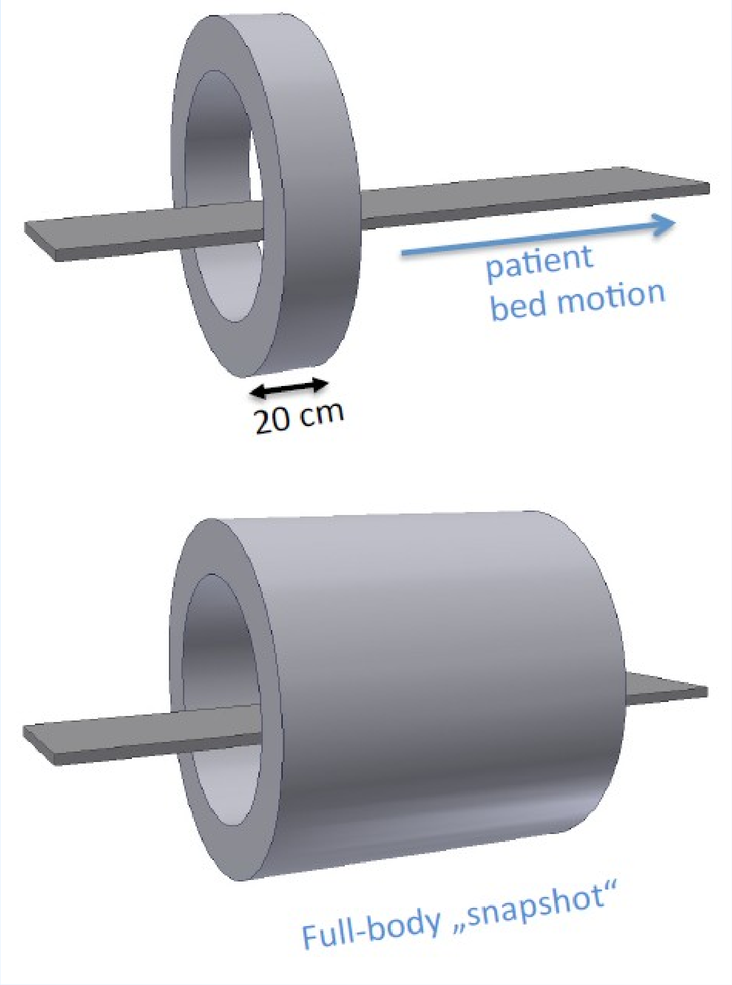
Black paint

Would Cherenkov based PET scanner be possible?

PbF_2 not a scintillator → considerably cheaper

Shorter attenuation length than LSO → smaller parallax error

→ Full body scanner



→ Join forces, groups led by:

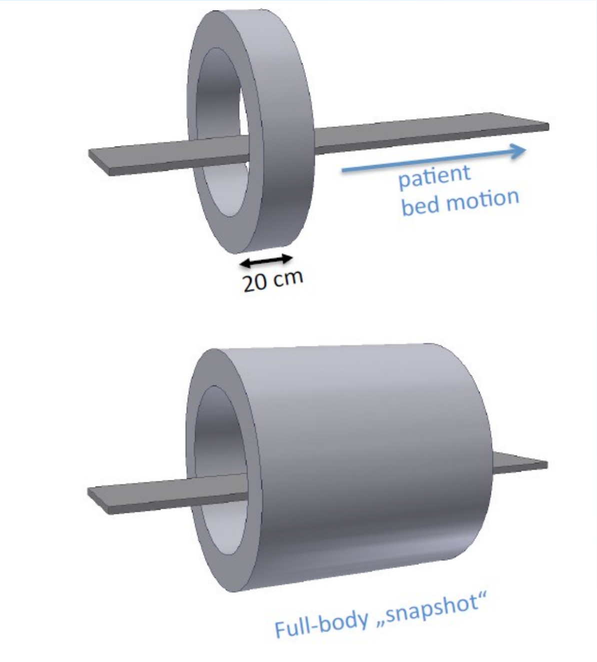
- Sibylle Ziegler, Technische Universität München
- Alberto Del Guerra, University of Pisa
- Peter Križan, J. Stefan Institute, Ljubljana
- Irene Buvat, IMIV, Orsay, CEA
- Edoardo Charbon, TU Delft
- Paul Lecoq, CERN
- Gabor Nemeth, Mediso
- Florian Wiest, KETEK
- Stefan Ritt, Paul Scherrer Institute

→ Carry out a feasibility study.

One of the outcomes → a preliminary MC simulation study →

Cherenkov based PET scanner – MC study

- Simulations were performed in order to estimate the performance of TOF PET scanner based on the Cherenkov method of gamma detection.
- The main building block of the simulated scanner was a gamma detector composed of a PbF_2 crystal ($4x4x15$ mm^3) and a SiPM as light sensor.
- The performance of a single gamma detector was first investigated in depth using GEANT4. The simulation was then transferred to GATE and a scanner was simulated.
- The performance of the scanner based on the Cherenkov method was compared to that of a state-of-the-art LSO ($4x4x20$ mm^3) scanner.

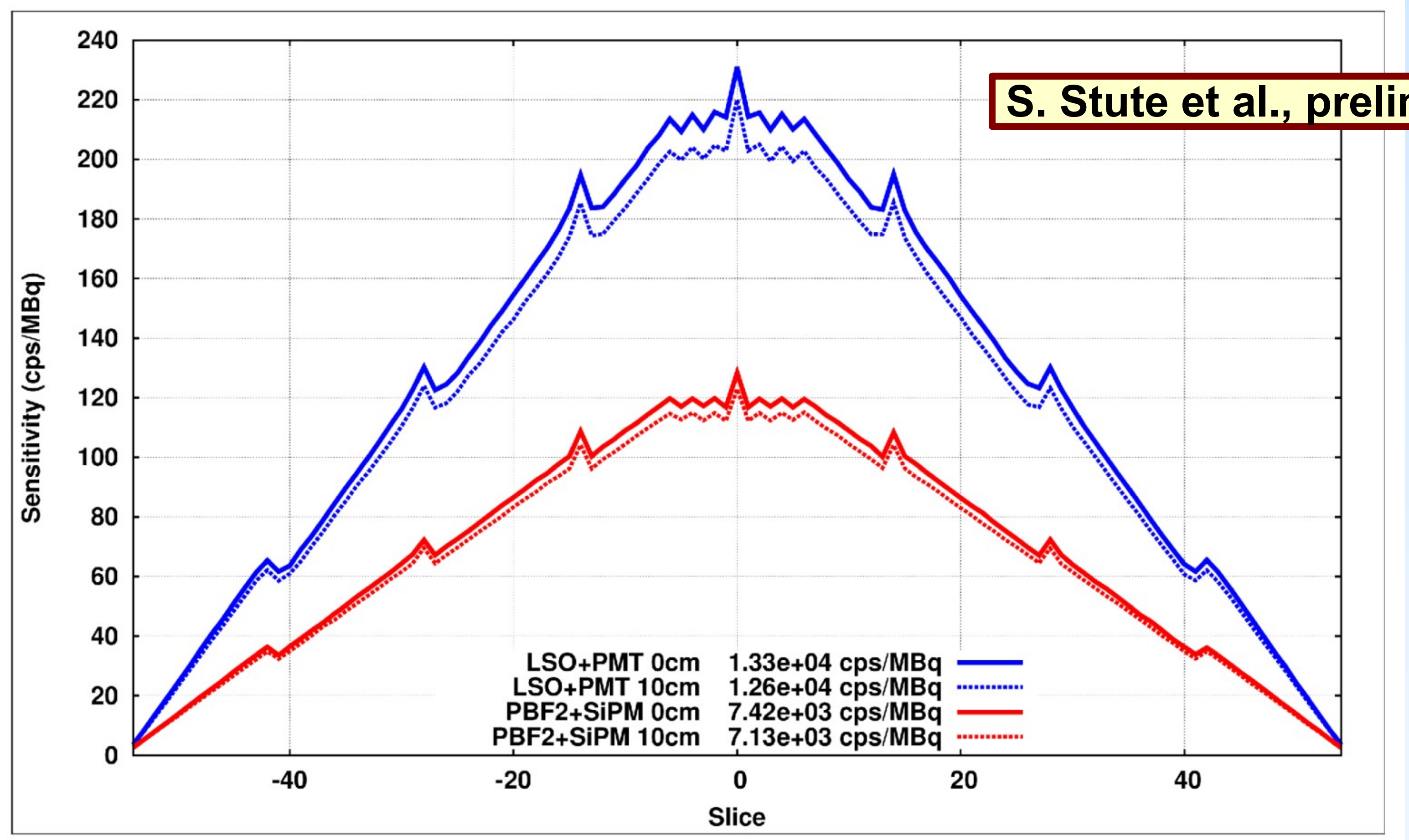


We studied:

- The standard axial length size scanner (axial extent 218 mm (4 blocks, sampled into 109 slices of 2 mm), diameter ~85 cm (crystal-to-crystal, front face).
- An axially extended 1m long scanner

Cherenkov based PET scanner – MC study

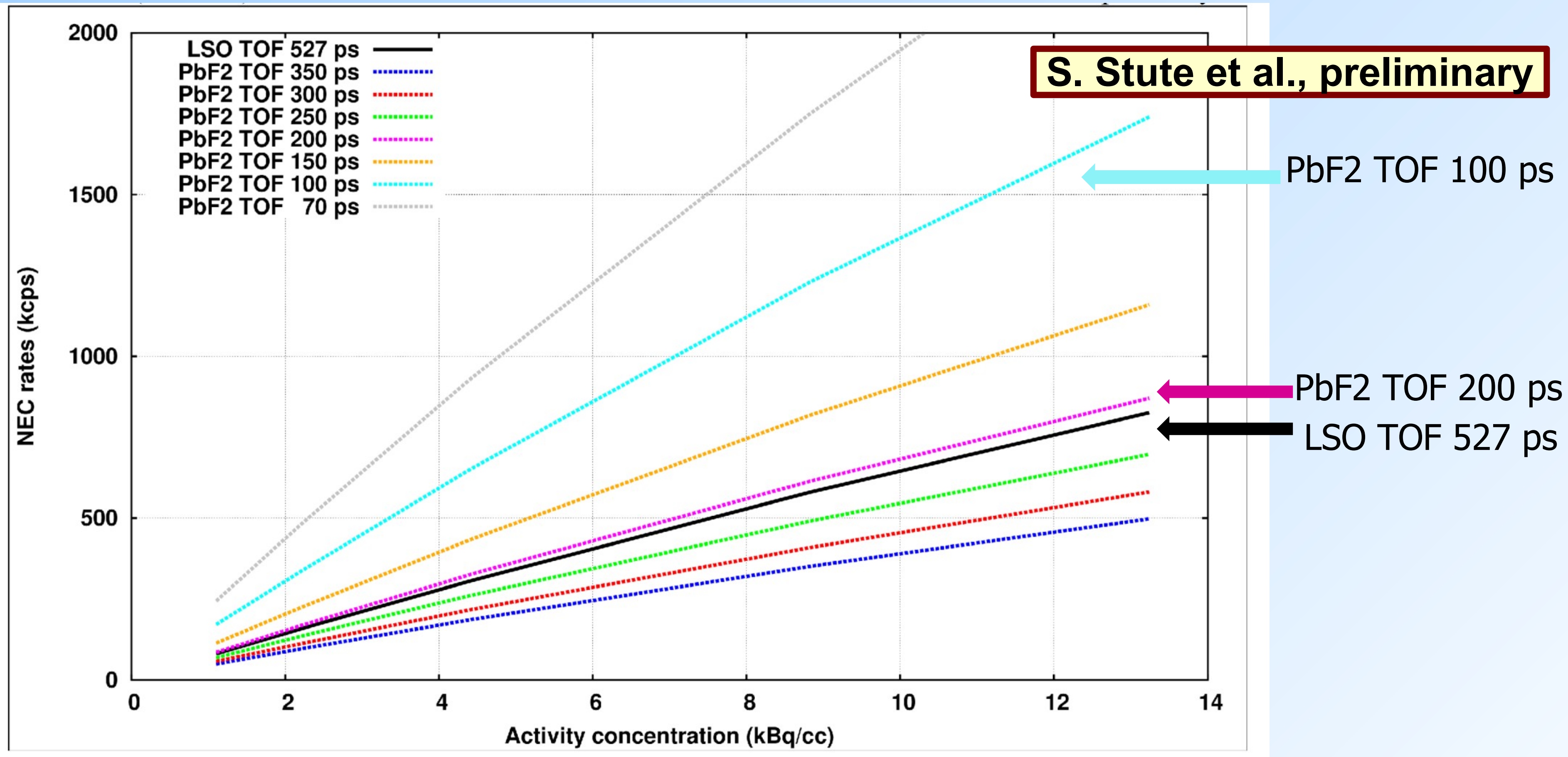
The sensitivity for a standard scanner geometry with the two technologies: the state-of-the art LSO+PMT combination has a higher sensitivity than Cherenkov-PbF2 because of a higher gamma detection efficiency.



Axial sensitivity profiles following the NEMA standards, for the two scanners and at radial offsets of 0 and 10 cm; global sensitivity (all slices combined).

Cherenkov based PET scanner – MC study

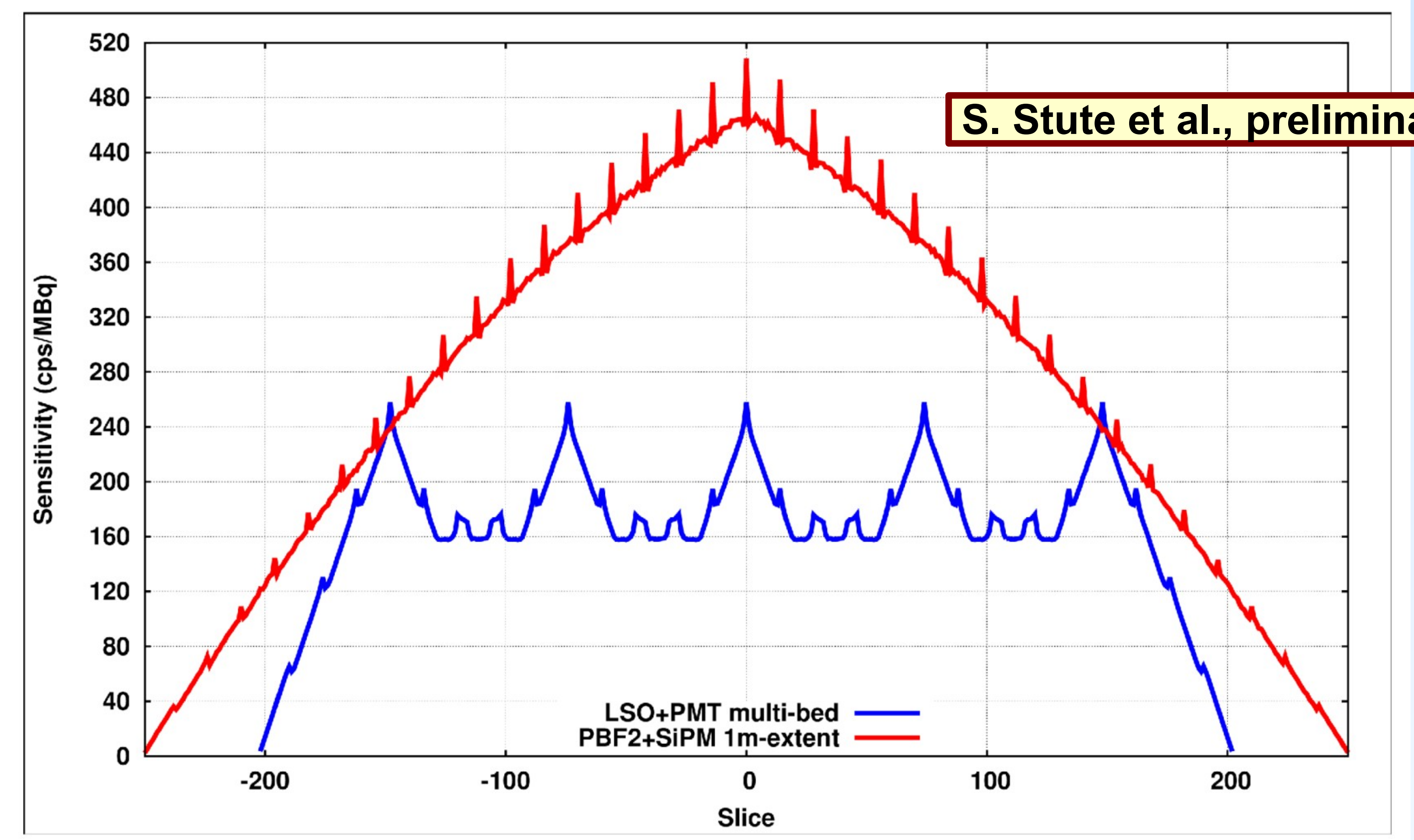
NEC rates: impact of improved TOF using the Cherenkov in PbF2 for a standard axial length scanner.



NEC rates for different activities and for the two scanners, following the Conti formula (with-TOF). Multiple TOF resolution are presented for the PbF_2-based scanner.

Cherenkov based PET scanner – MC study

Comparison of the 1-meter axial sensitivities for the two technologies – note that this is only the theoretical sensitivity without taking TOF into account.



Axial sensitivity profiles following the NEMA standards at the center of the FOV, for the 1meter axial extent PbF$_2$-based scanner and for a multi-bed LSO-based scanner.

Cherenkov based PET scanner – MC study summary

- First preliminary Monte Carlo simulation studies have shown that a Cherenkov-PET scanner using Lead fluoride with the same size of detector elements and the same ring geometry as a state-of-the-art LSO based PET scanner will have
- 20% improved spatial resolution, as is now achieved using one-to-one coupling.
- Sensitivity will be about one half, but noise equivalent count rate can be expected to be as good as or better than the standard PET scanner, if TOF resolution is 200 ps or better.

Back-to-back setup with SiPMs

Back-to-back with ^{22}Na source.

Cherenkov radiator (PbF_2):

- 5 x 5 x 15 mm^3 (SiPM),

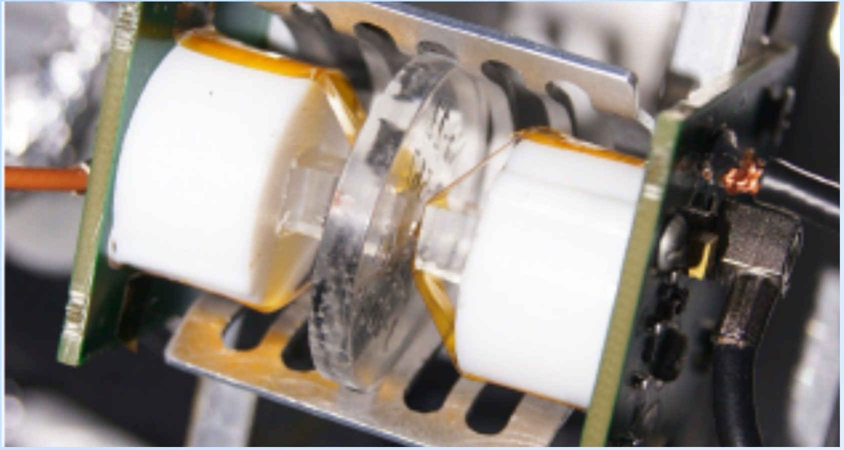
black painted, Teflon wrapped, bare

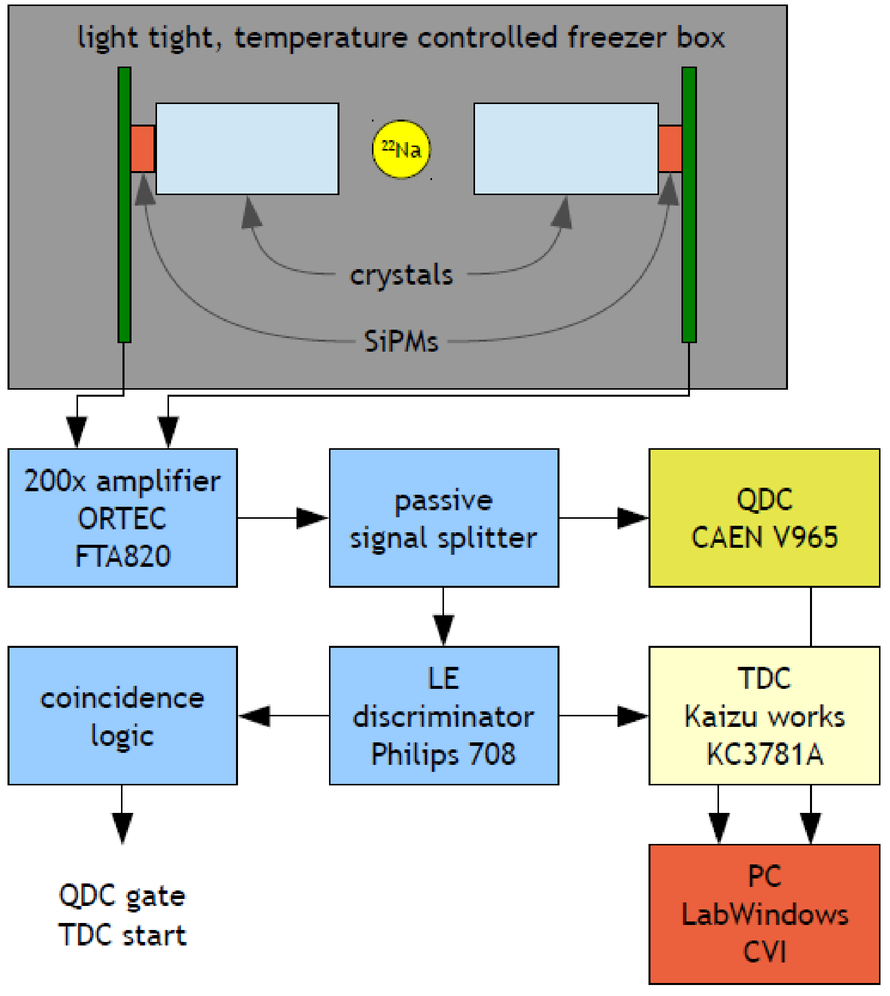
Readout: (timing ~25 ps FWHM)

- custom board with NEC μPC2710TB amp.
- amplifier: ORTEC FTA820
- discriminator: Philips sc. 708 LE
- TDC: Kaizu works KC3781A (25ps)
- QDC: CAEN V965

3x3 mm^2 SiPMs:

Producer	Model	Pixel pitch [μm]	Vbr [V]
Hamamatsu	S10931-050P, 'old'	50	69
Hamamatsu	S12641-PA050	50	65
AdvanSiD	ASD-NUV3S-P-40	40	26
KETEK	PM3350TP	50	25
SensL-J	MicroFC-30050-SMT-GP	50	25





light tight, temperature controlled freezer box

^{22}Na

crystals

SiPMs

200x amplifier ORTEC FTA820

passive signal splitter

QDC CAEN V965

coincidence logic

LE discriminator Philips 708

TDC Kaizu works KC3781A

PC LabWindows CVI

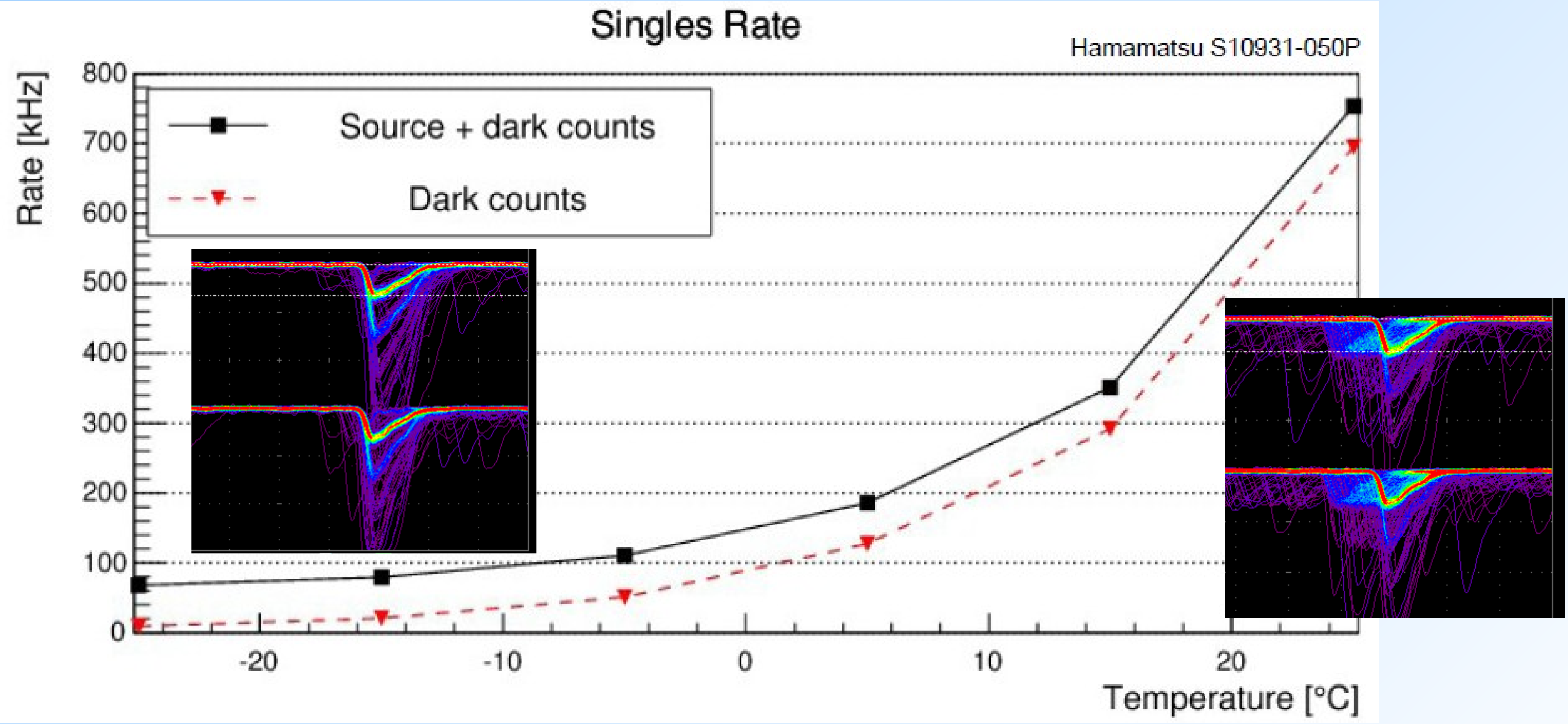
QDC gate
TDC start

Dark count rate vs. temparature

NIM A804(2015)127

Hamamatsu S10931-050P at constant gain (V_{ov} = 1.5V, recommended)

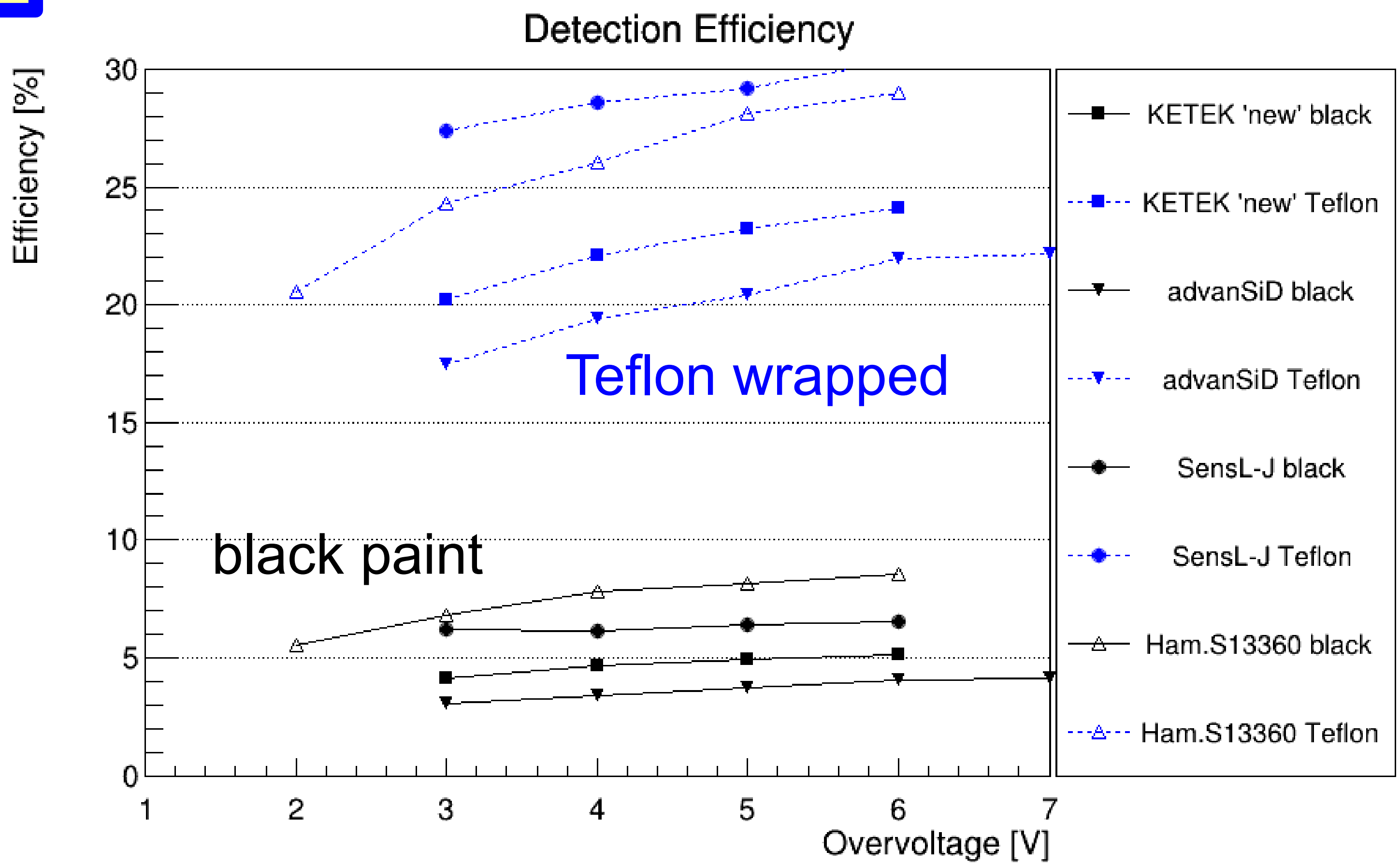
- dark noise reduces with temperature by ~ 2.4 x / 10°C



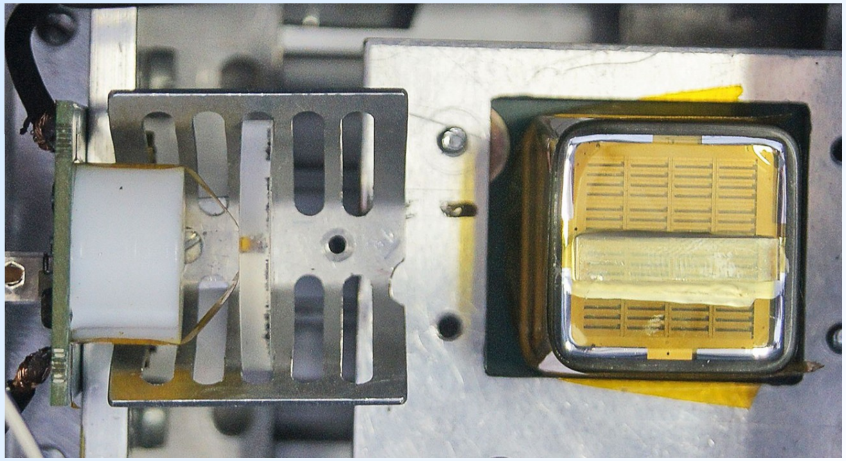
Single side efficiency

- best efficiency: ~30% with SensL SiPM and Teflon wrapped crystals
- T = -25°C

(note: 5x5mm^2 crystal on 3x3mm^2 SiPM!)



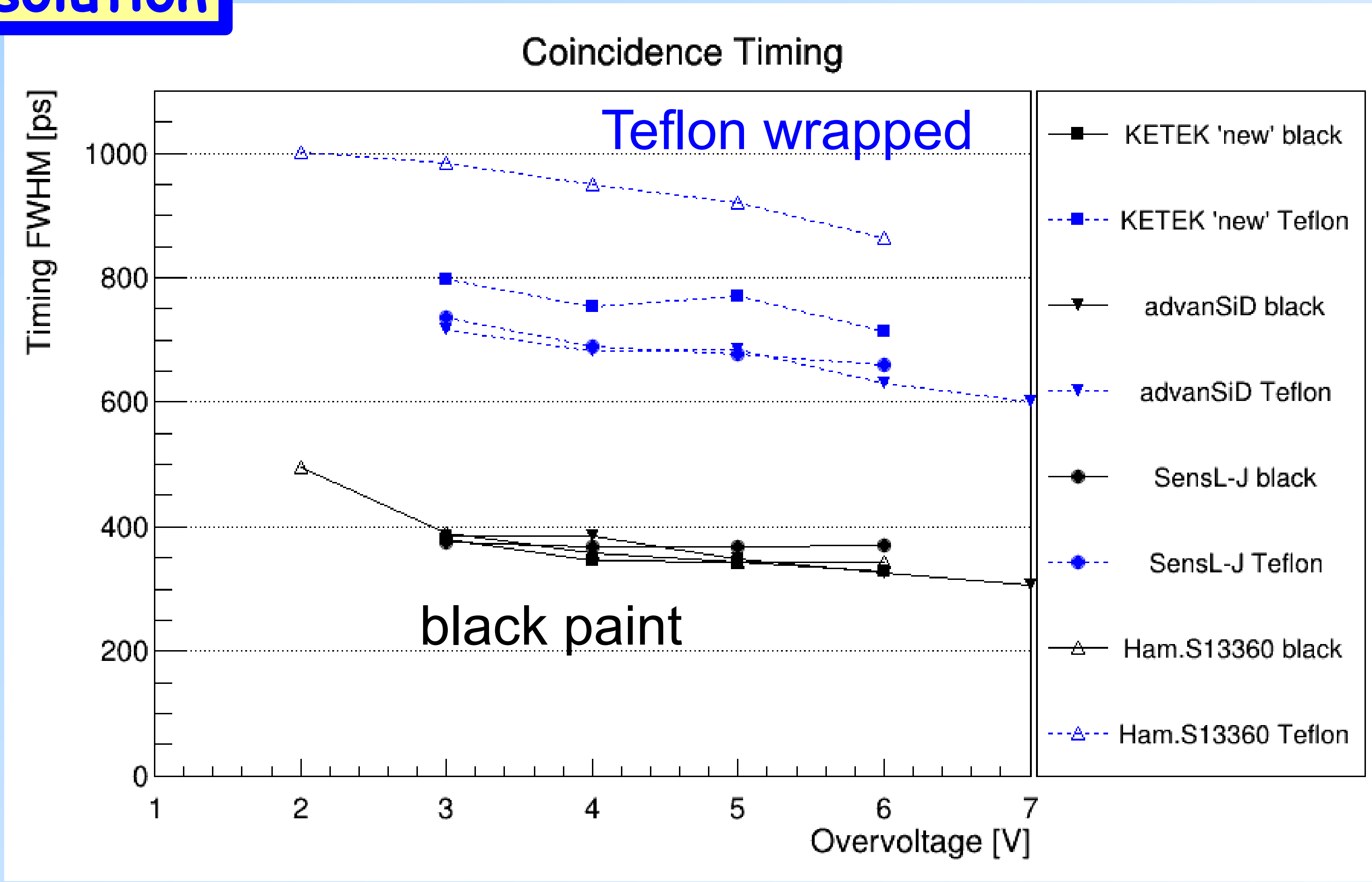
Producer	Model	Pixel pitch [μm]	Vbr [V]
Hamamatsu	S12641-PA050	50	65
AdvanSiD	ASD-NUV3S-P-40	40	26
KETEK	PM3350TP	50	25
SensL-J	MicroFC-30050-SMT-GP	50	25



Coincidence time resolution

- best timing: ~300 ps with AdvanSiD
- T = -25^{o}C

(note: 5x5mm^2 crystal on 3x3mm^2 SiPM!)



Producer	Model	Pixel pitch [μm]	Vbr [V]
Hamamatsu	S12641-PA050	50	65
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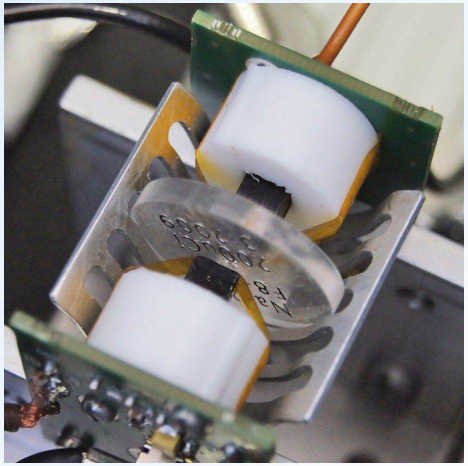
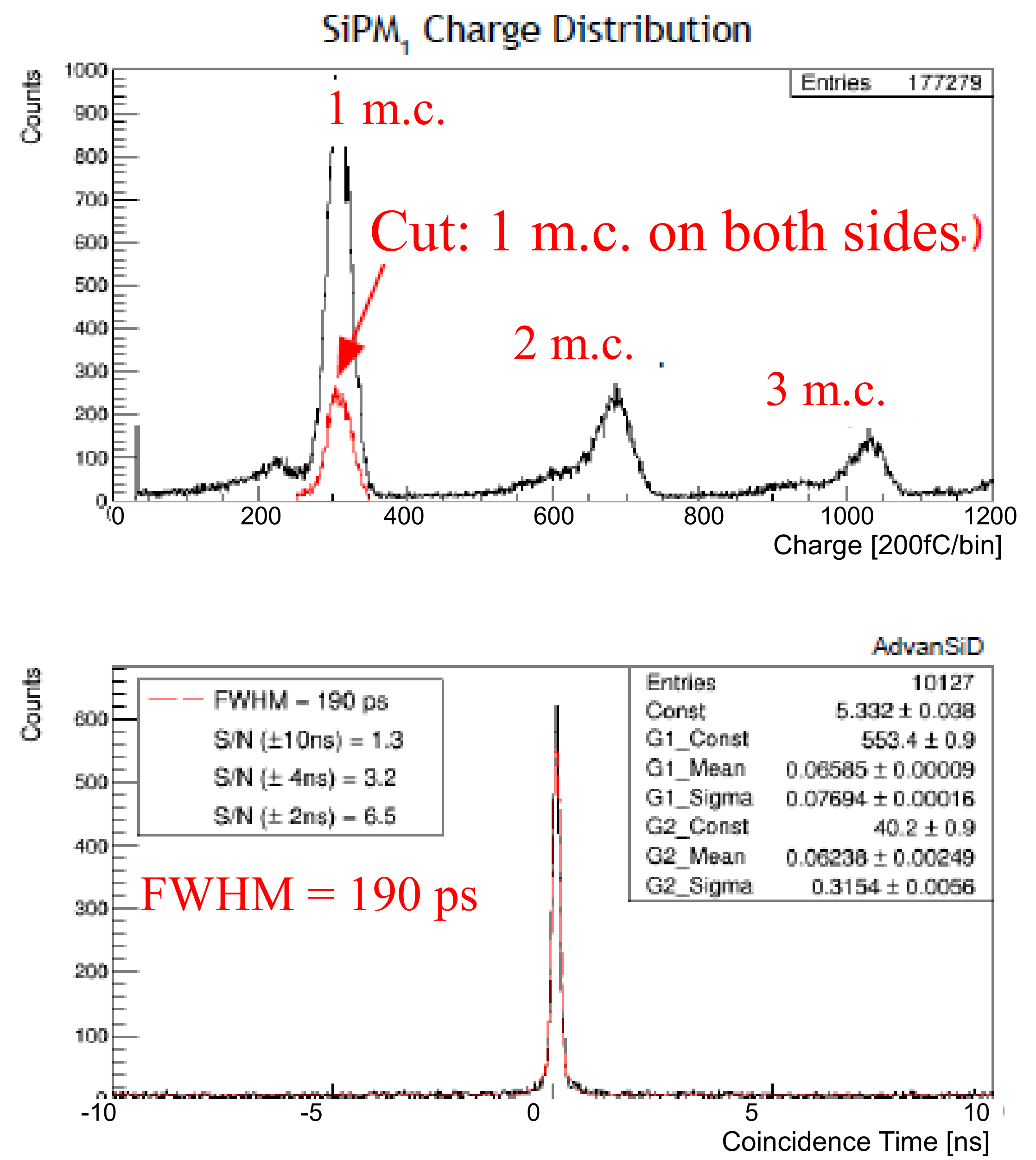


CRT using only single micro cell events

- Using only events with single micro cell signal on both sides: CRT= 190 ps FWHM (AdvanSiD, V_{OV}=7V, black-painted PbF_2, T=-25°C)

- To get the resolution below 200 ps we need to improve the resolution for the events with more than 1m.c. signal; stronger suppression of optical crosstalk?)

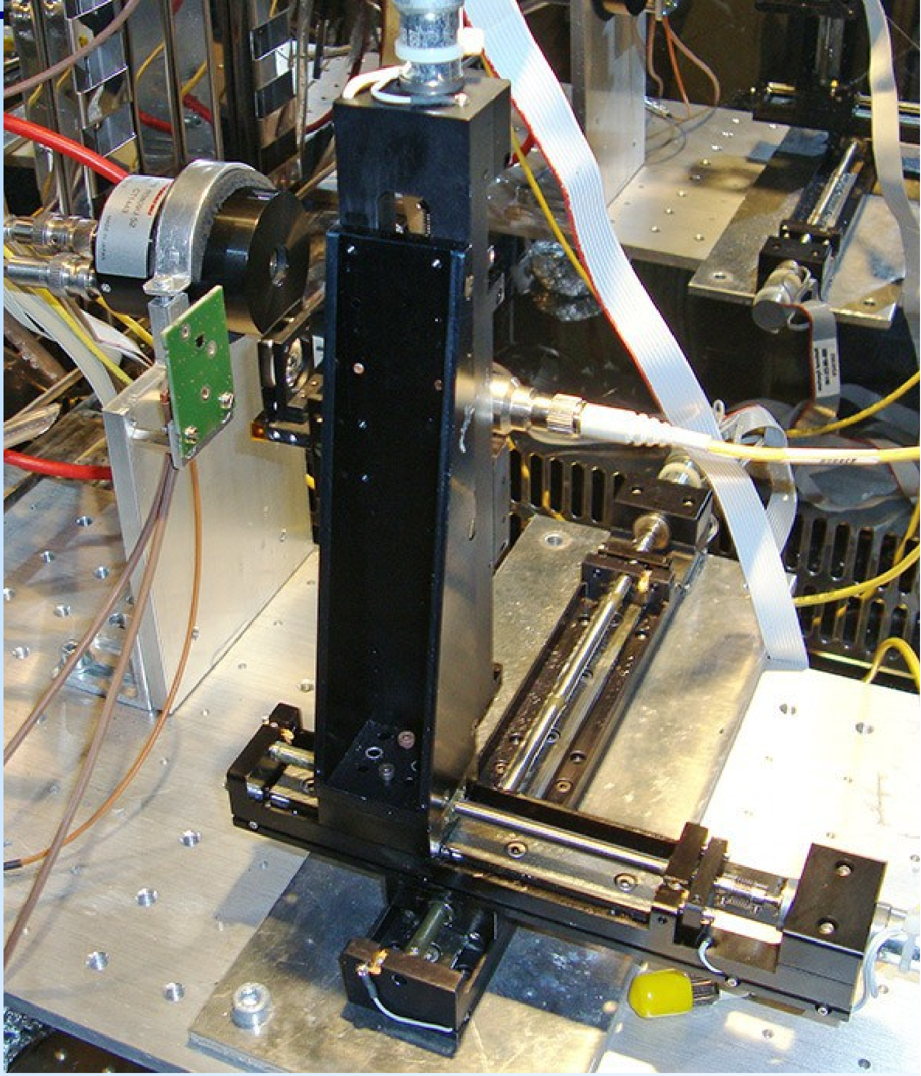


Laser setup with 3D stage

- PiLas diode laser system EIG1000D, 404nm and 635nm laser heads (ALS)
- ND filters (0.3%, 12.5%, 25%)
- optical fiber (single mode,~4μm core)
- focusing lens (min. spot size σ ~ 3μm)
- laser timing ~35 ps FWHM
- readout system the same as for CRT

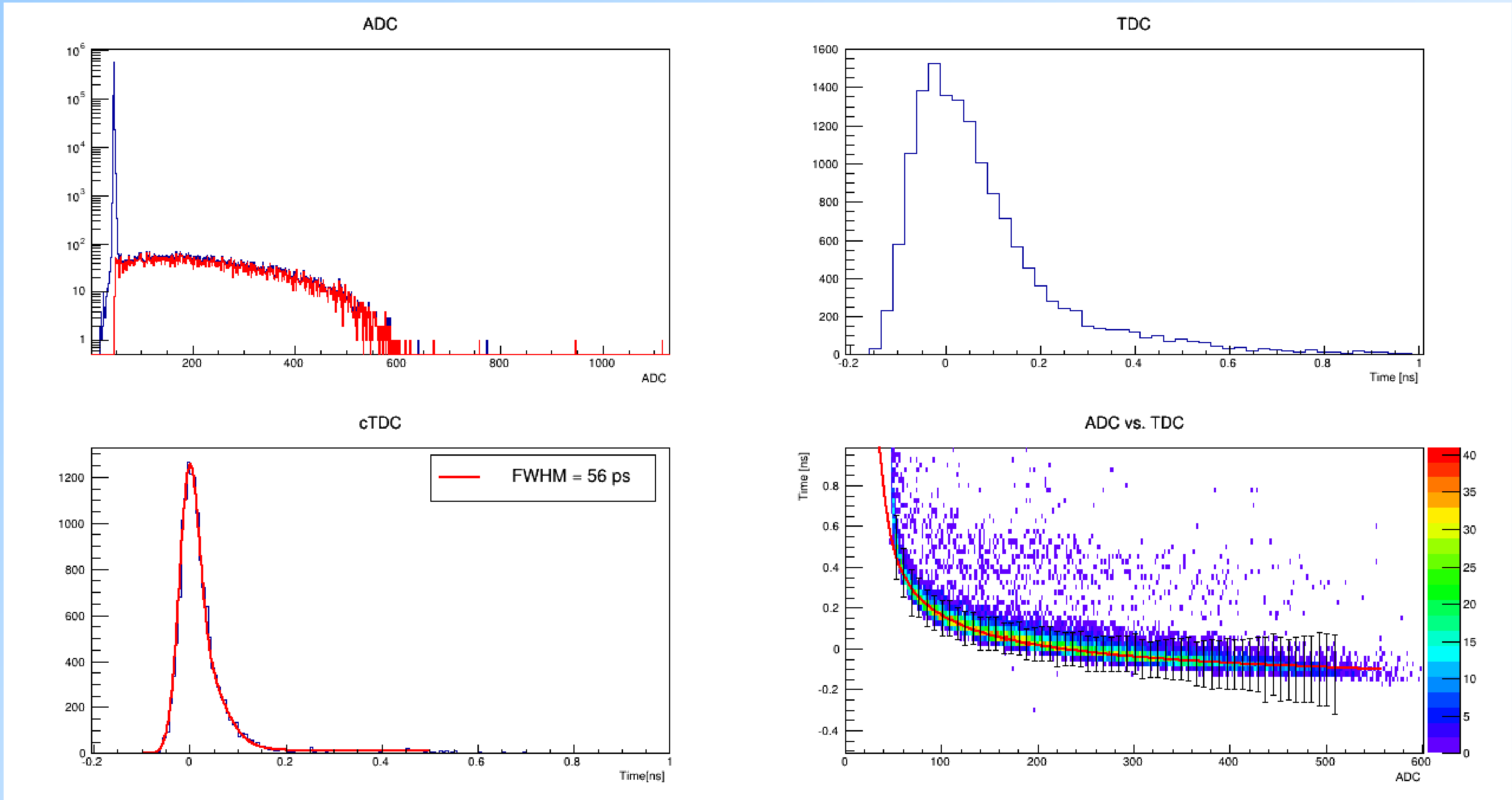
- Additional SiPM from KETEK with improved timing (@PhotoDet 2015)

Producer	Model	Pixel pitch [μm]	Vbr [V]
Hamamatsu	S12641-PA050	50	65
AdvanSiD	ASD-NUV3S-P-40	40	26
KETEK	PM3350TP	50	25
SensL-J	MicroFC-30050-SMT-GP	50	25



Reference sensor: MCP PMT

Hamamatsu MCP-PMT R3809U-52 (TTS ~ 25 ps FWHM)

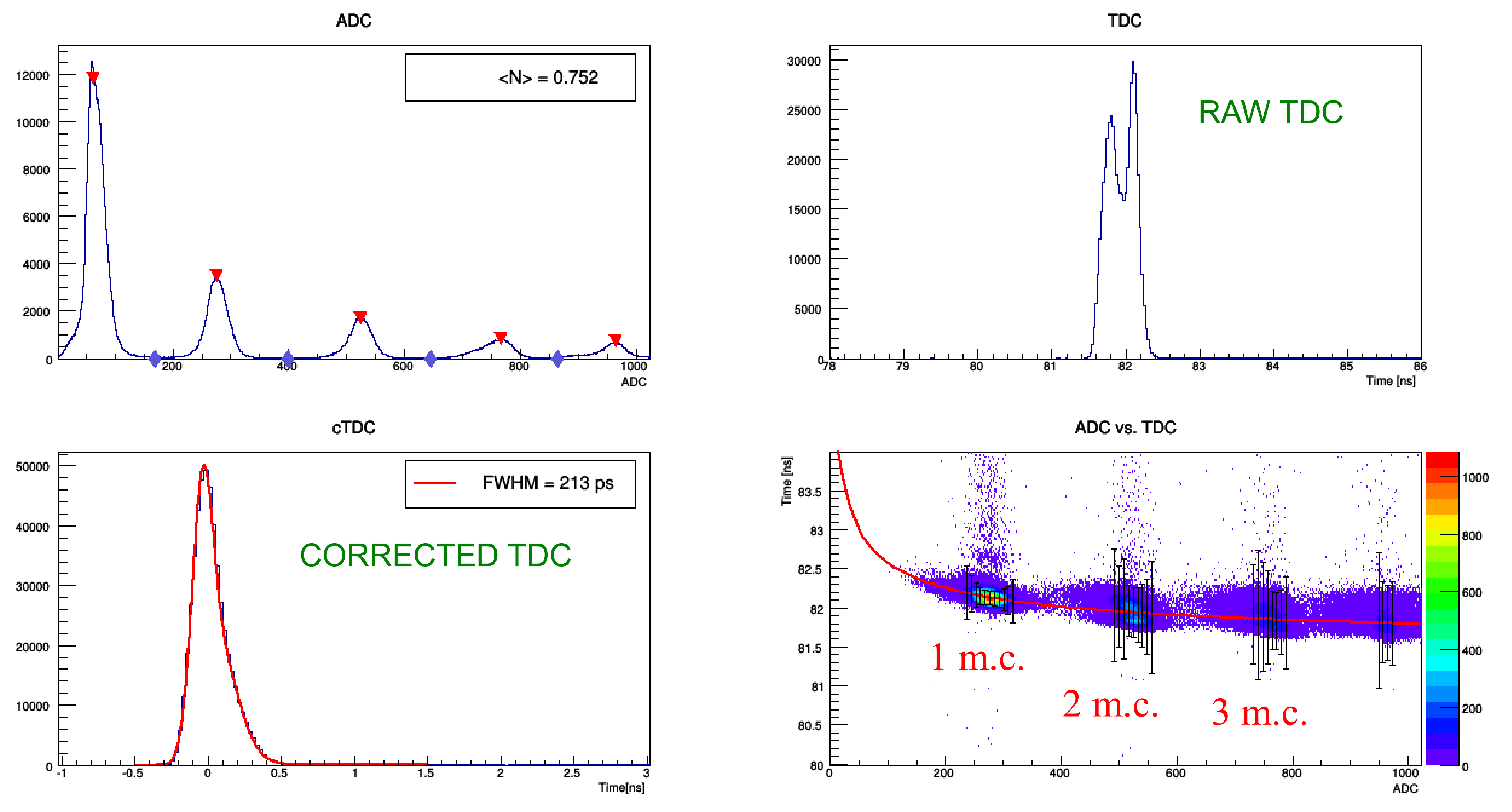


Red laser: 56 ps FWHM

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

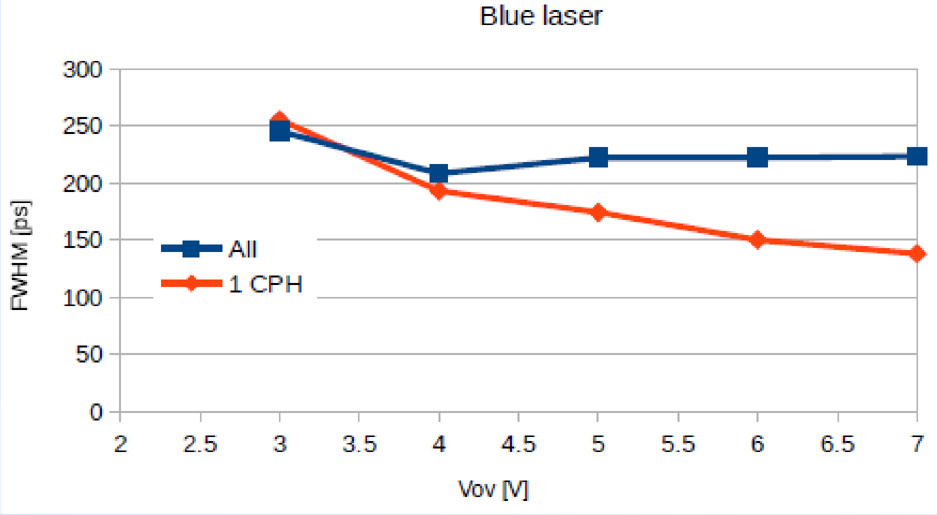
SiPM: Timing resolution with pico-second laser

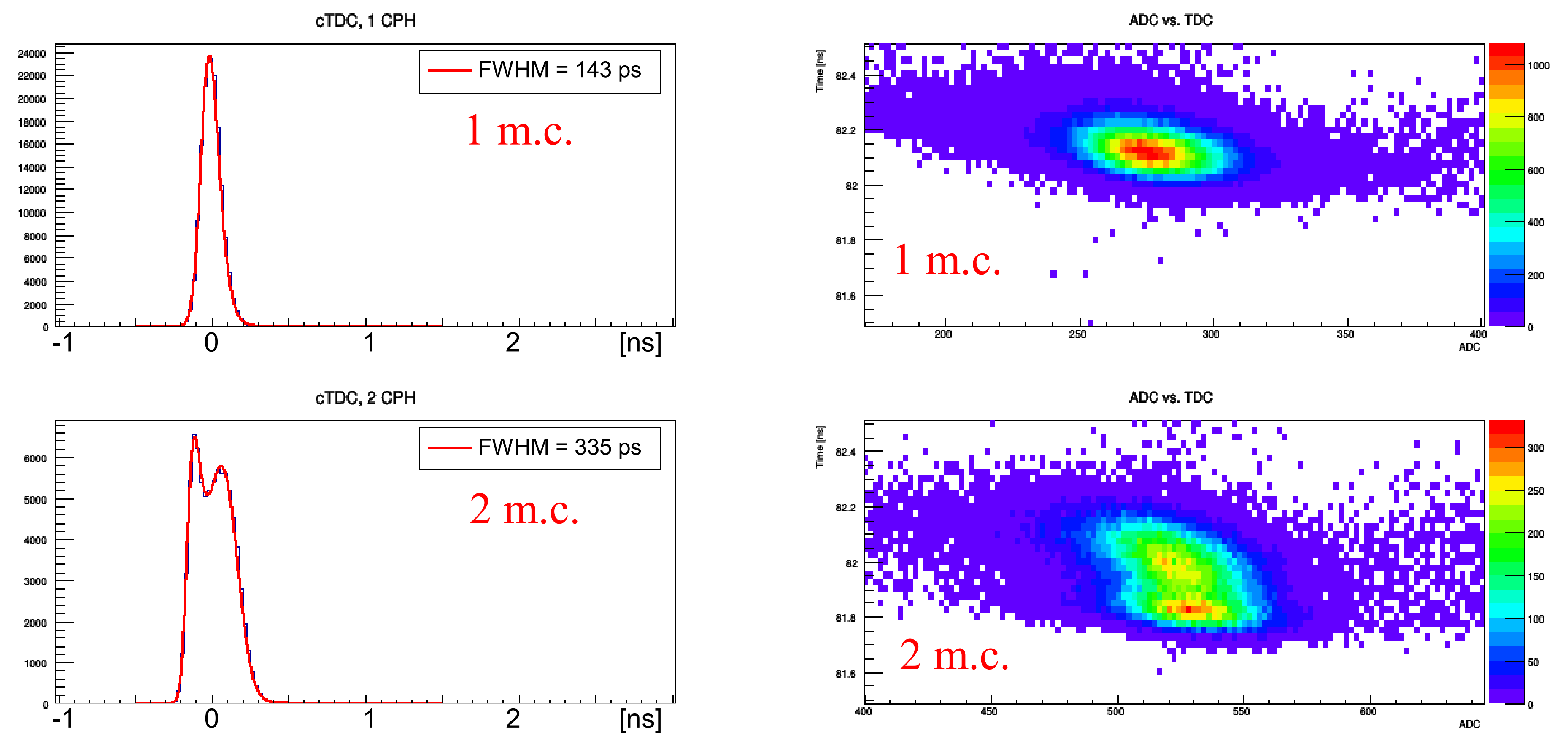
- AdvanSiD SiPM, V_{OV}=6V, T=-25°C
- blue laser λ=404nm



All vs. 1m.c. signal events

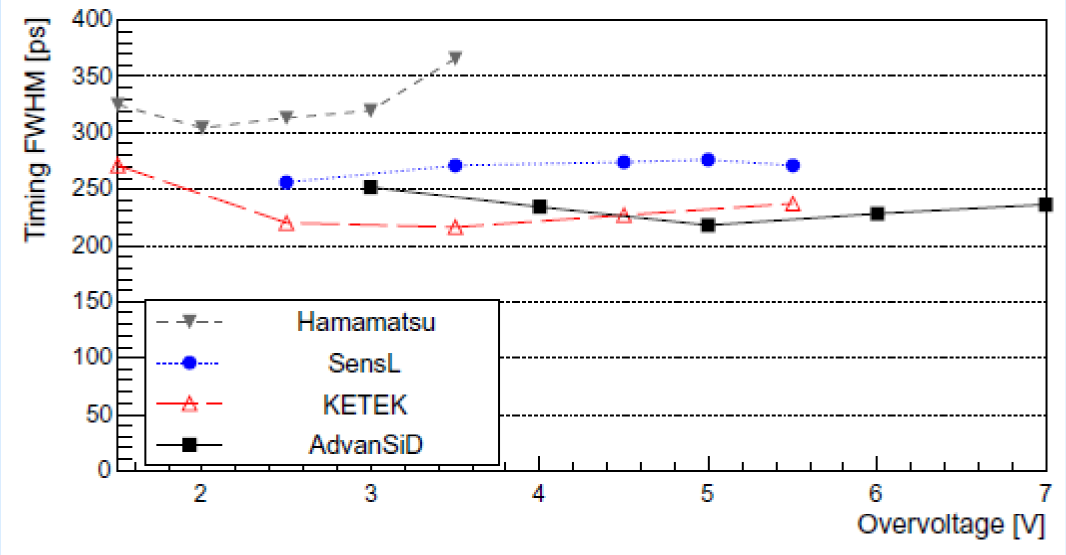
- AdvanSiD SiPM, V_{OV}=6V, T=-25°C
- blue laser λ=404nm
- events vith 2m.c. signal have two contributions: real double hit events with better resolution and optical crosstalk events

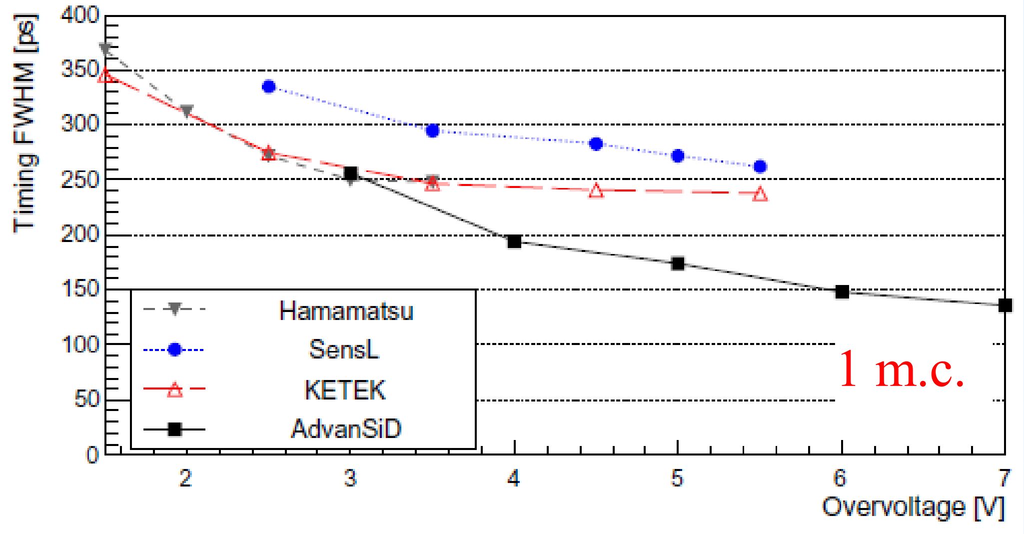


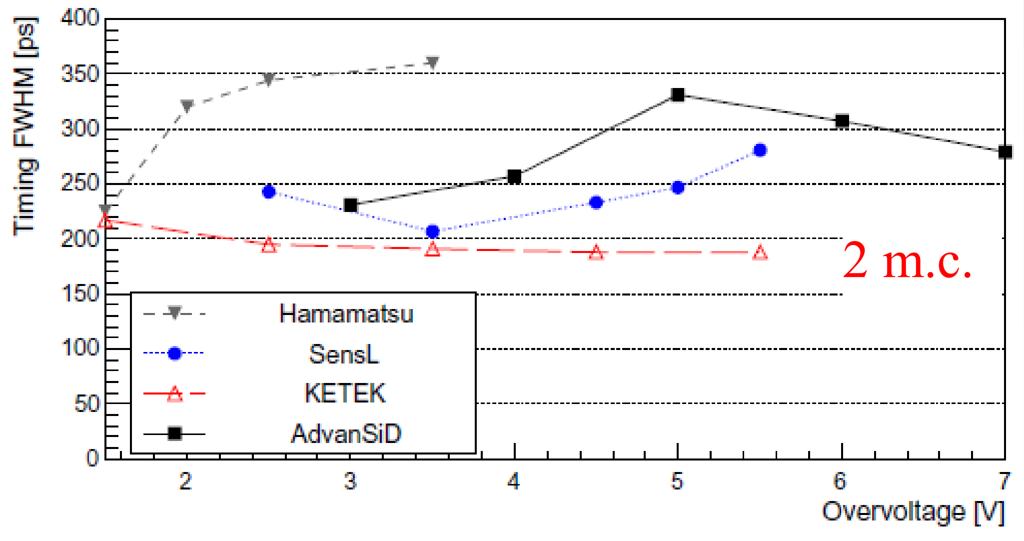


Timing resolution with laser pulses

- Uniform illumination of SiPMs, T=-25°C
- Timing for all events (left), and events with single and double micro cell signal (right)







Summary

- Cherenkov based TOF PET uses Cherenkov light produced in the radiator by the electron produced in the 511 keV gamma interacting with radiator
  - main advantage prompt emission
  - main disadvantage low number of photons
- Requires very fast single photon sensor with high PDE.

- Initial tests with MCP-PMT prototypes showed that CRT < 100 ps FWHM can be achieved but efficiency was low
- preliminary MC studies show that with SiPMs with higher PDE a competitive PET scanner may be possible
- We have studied several SiPMs from different producers to find the best candidate for the application → the best value for the efficiency reached 30% and the best CRT was ~300 ps (will improve with SiPM and crystal size matching).
- Performance of SiPMs is constantly improving and hopefully it will reach optimal performance → coincidence efficiency > 10% and timing < 200 ps FWHM

BACKUP SLIDES

Cherenkov radiator

Requirements for Cherenkov radiator:

- high gamma stopping power
- high fraction of gamma interactions via photoeffect → electrons with maximal kinetic energy → more Cherenkov photons
- high enough refractive index (needs to be optimized)
- High transmission for visible and near UV Cherenkov photons

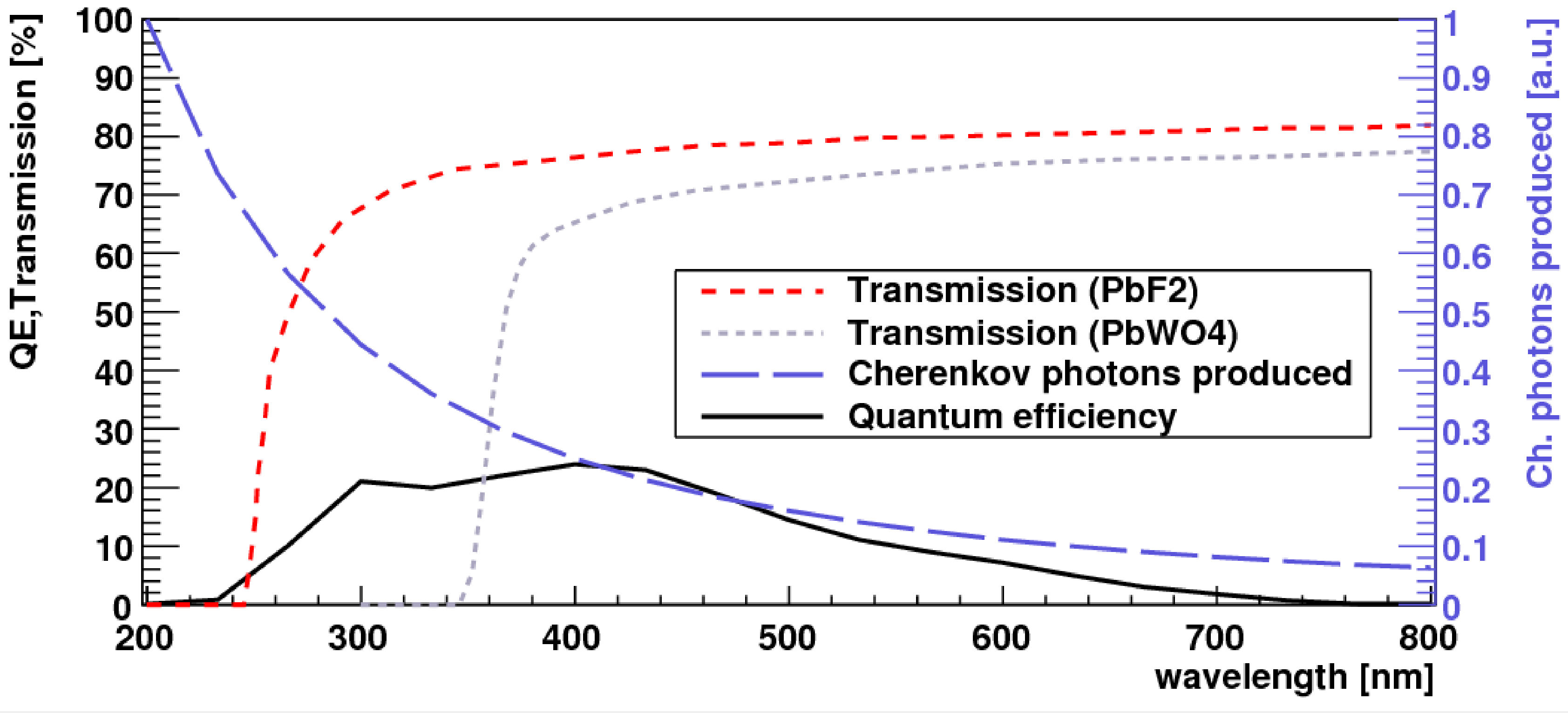
Promising candidates are PbF_2 and $PbWO_4$ (also scintillator)

	ρ (g/cm^3)	n	Cherenkov threshold (v/c$_0$)	e$^-$ Cherenkov threshold (keV)	Cutoff wavelength (nm)	Attenuation length (cm)
PbF_2	**7.77**	**1.82**	**0.55**	**101**	**250**	**0.91**
$PbWO_4$	**8.28**	**2.2**	**0.45**	**63**	**350**	**0.87**
LYSO	7.4					1.14
$LaBr_3$	5,07					2.23

- more Cherenkov photon produced in PbWO4
- more Cherenkov photons detected with PbF2, lower cut-off wavelength

Simulation: transmission and QE

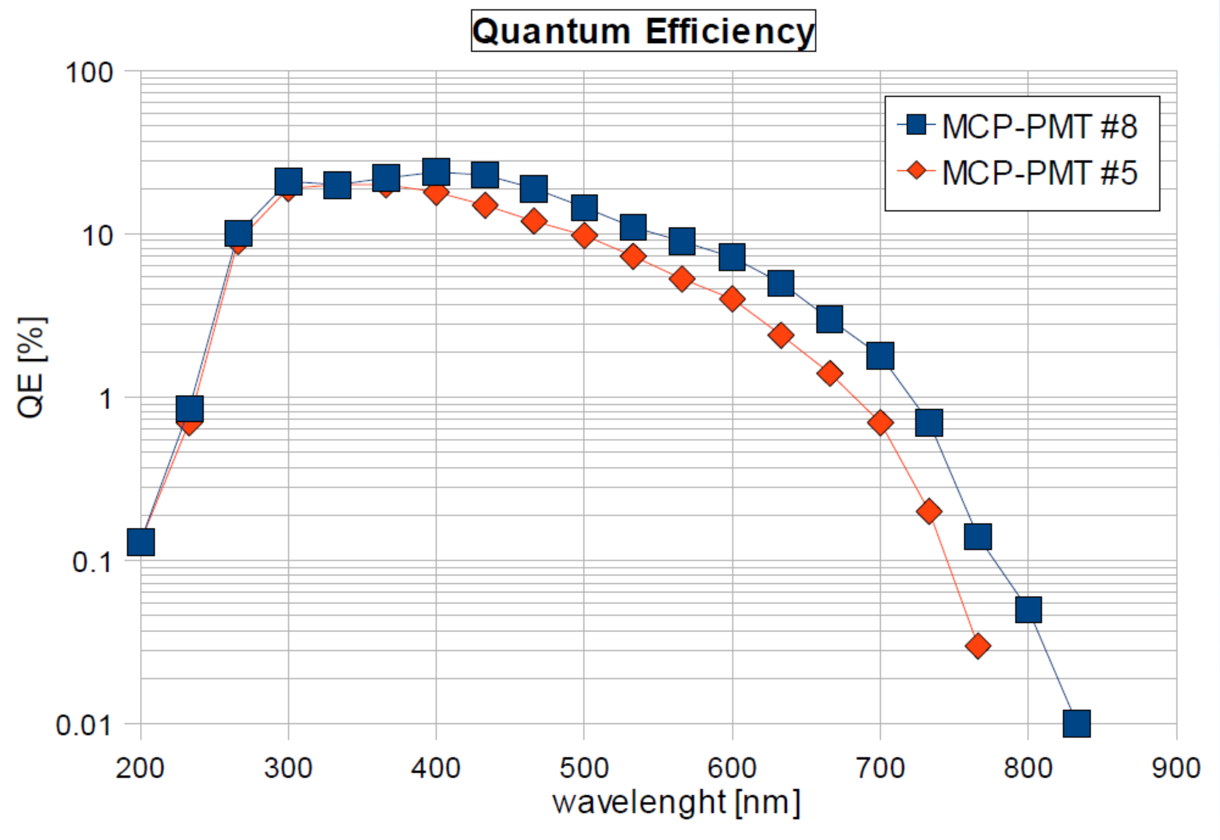
- Transmission of PbF_2 and $PbWO_4$ indicating the cut-off wavelength.
- QE used in simulation.

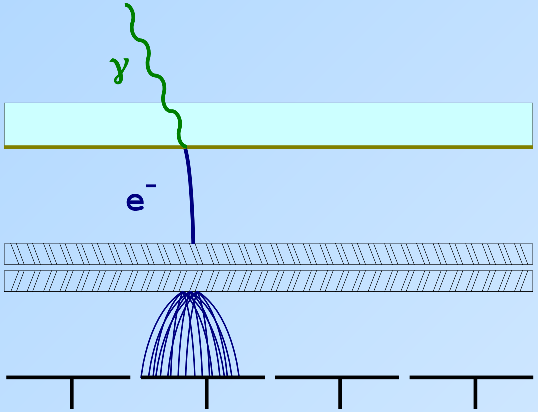


MCP-PMT properties

Hamamatsu MCP-PMT
(prototypes for Belle II TOP counter #5 and #8):

- multi-anode PMT with two MCP steps, 10 μm pores
- 16 (4x4) anode pads, pitch ~ 5.575mm, gap ~ 0.3mm
- box dimensions ~ 27.5 mm square
- excellent timing σ ~ 20ps for single ph.
- multi-alkali photocathode
- 1.5 mm borosilcate window
- gain > 10^6





window with photocathod

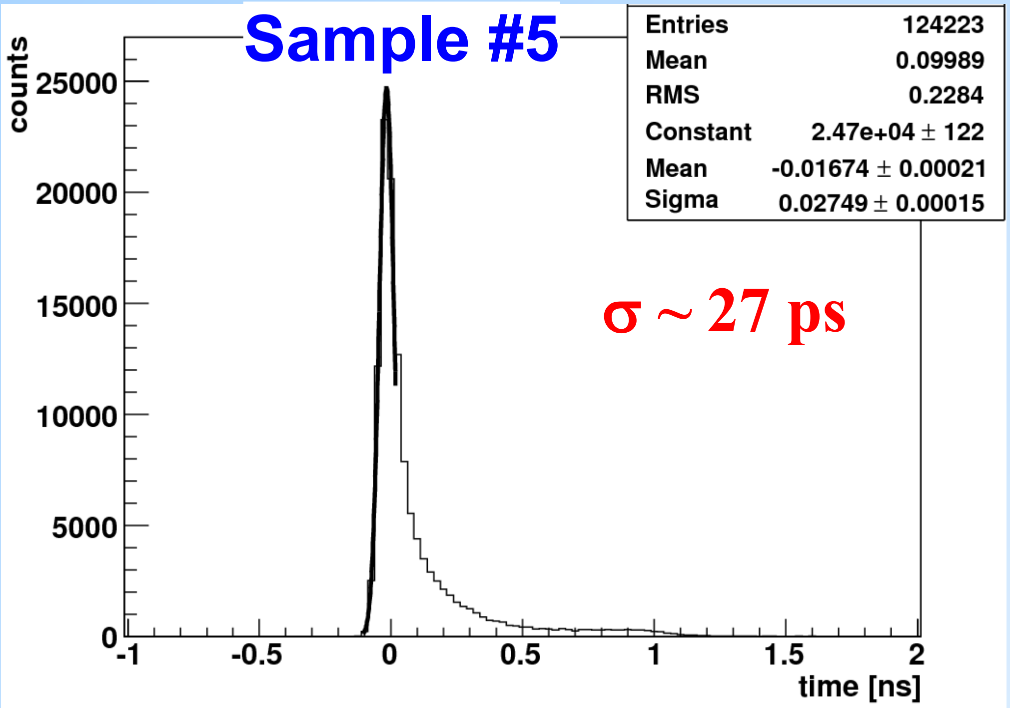
mocrochannel plate (two steps)

anods

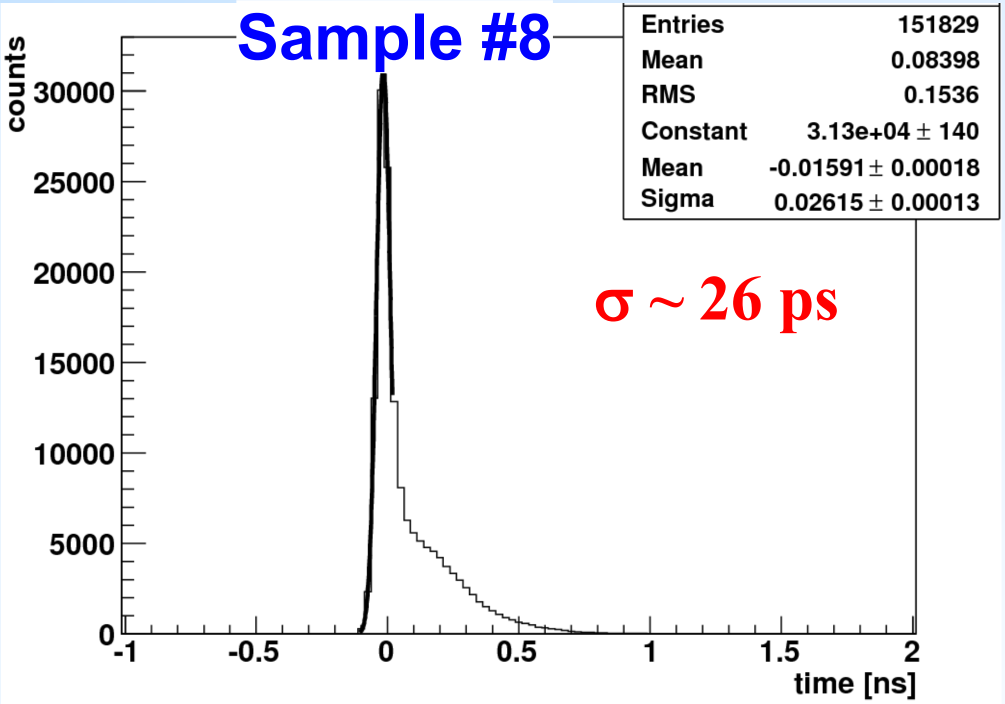
Tests with picosecond laser

Intrinsic resolution measured with pico-second PiLas laser, λ=406 nm, attenuated to single photon detection level:

- r.m.s. of prompt peak for both samples below 30 ps including contribution from laser ~15 ps and electronics ~11 ps
- intrinsic resolution ~ 20 ps


Sample #5

σ ~ 27 ps

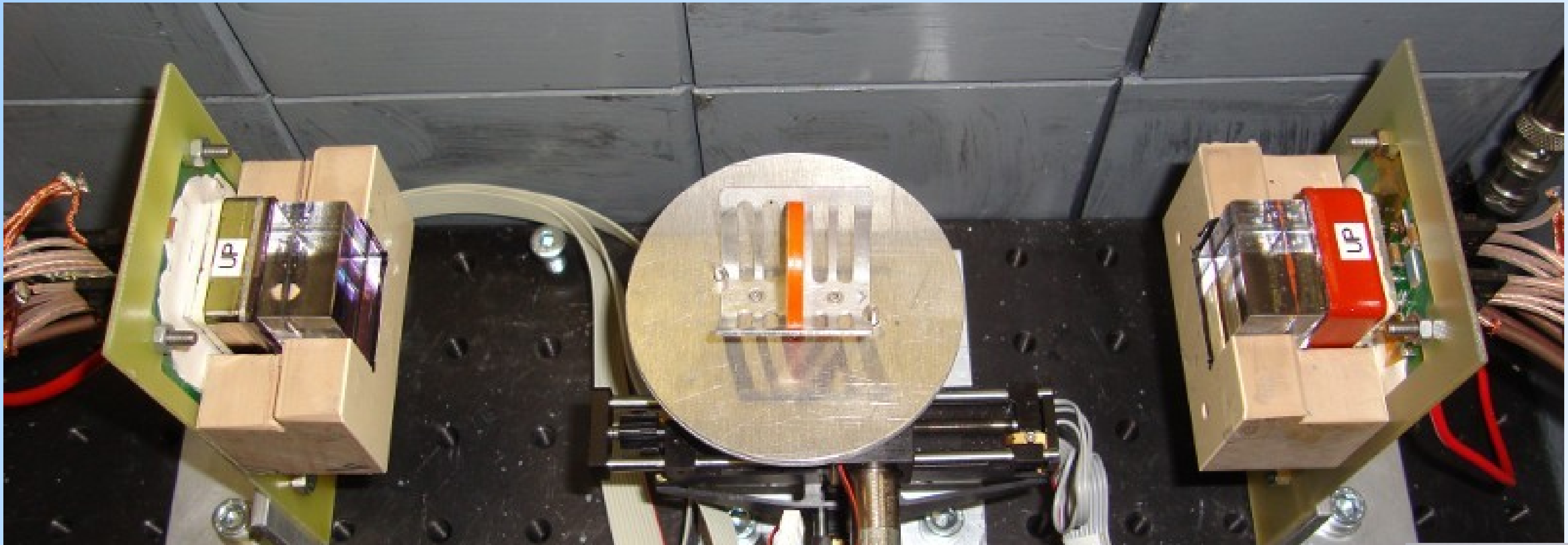

Sample #8

σ ~ 26 ps

- tails are mainly produced by photoelectron back-scattering events

Setup

Two detectors in back-to-back configuration with 25x25x15 mm^3 crystals coupled to MCP-PMT with optical grease.

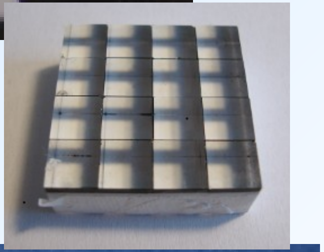


Cherenkov radiators:

-monolithic: 25 x 25 x 5,15 mm^3 (PbF_2, $PbWO_4$)

-4x4 segmented: 22.5x22.5x7.5 mm^3 (PbF_2)

-black painted, Teflon wrapped, bare



MCP-PMT: Back-to-back timing

Data taken with black painted PbF_2 crystals:

- 15 mm: r.m.s. ~ 37 ps
  FWHM ~ 95 ps

- 5 mm: r.m.s. ~ 30 ps
  FWHM ~ 70 ps

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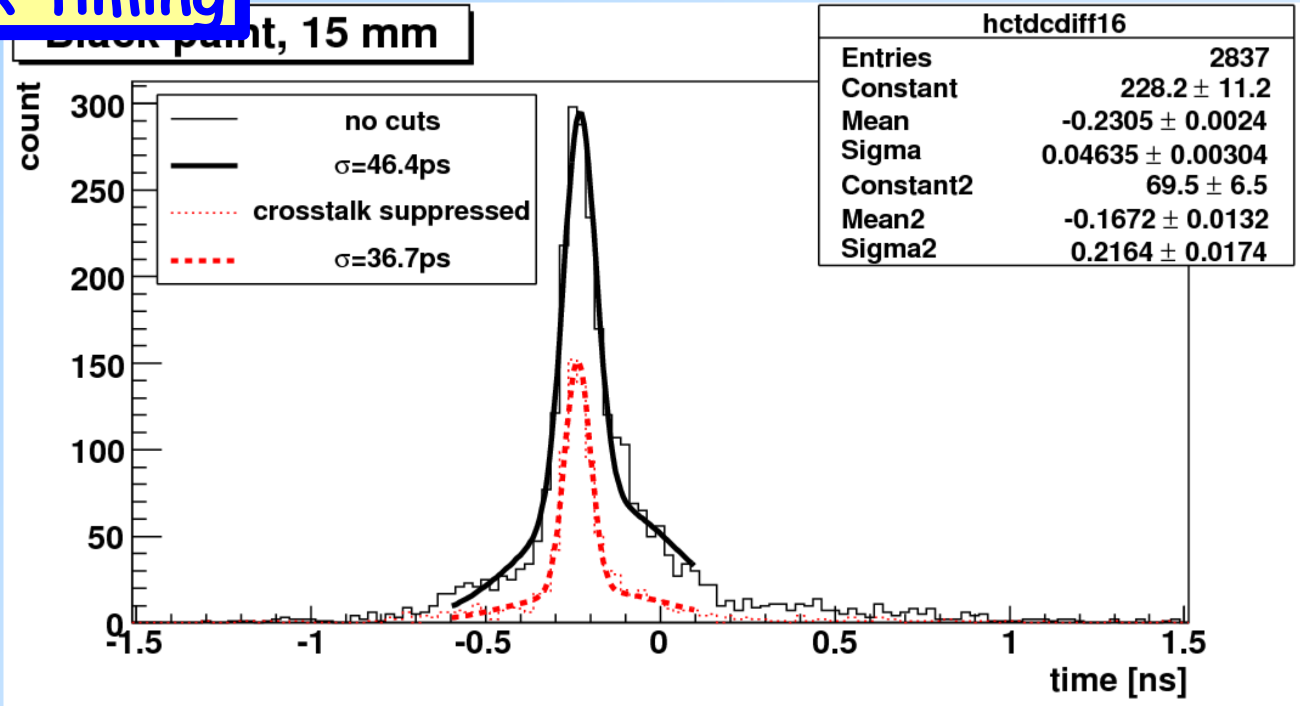
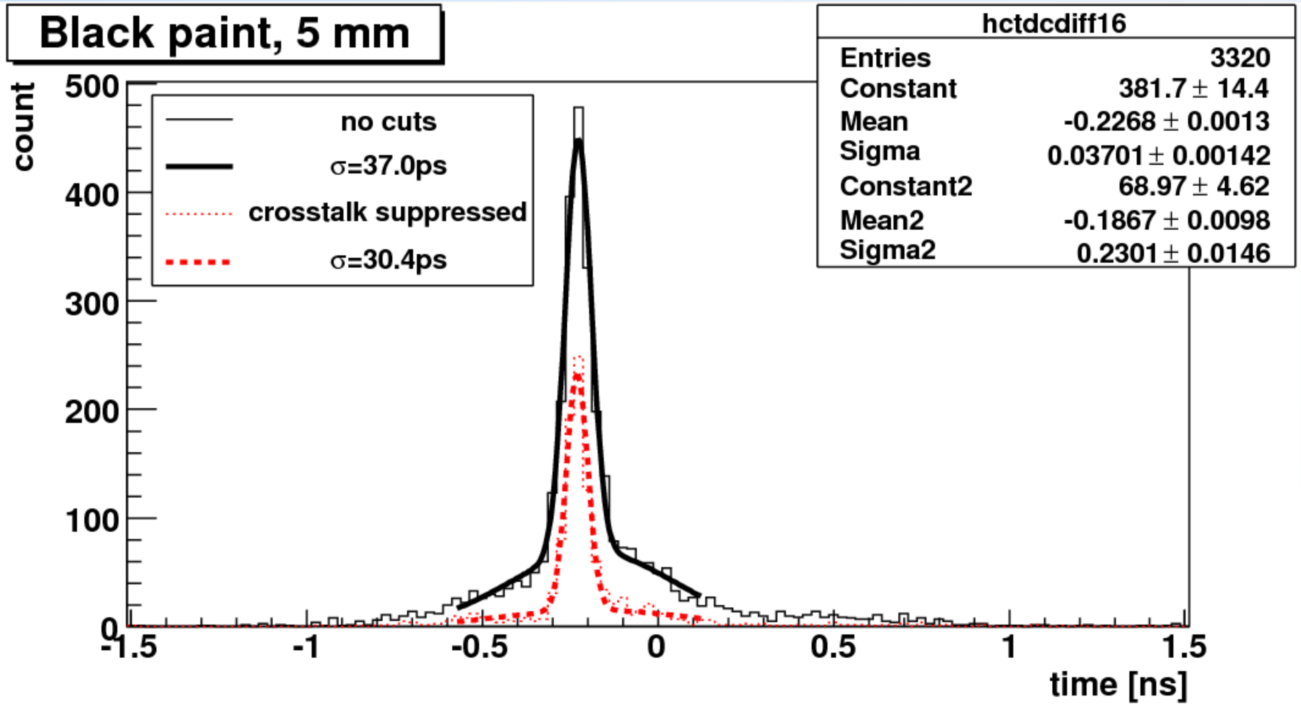


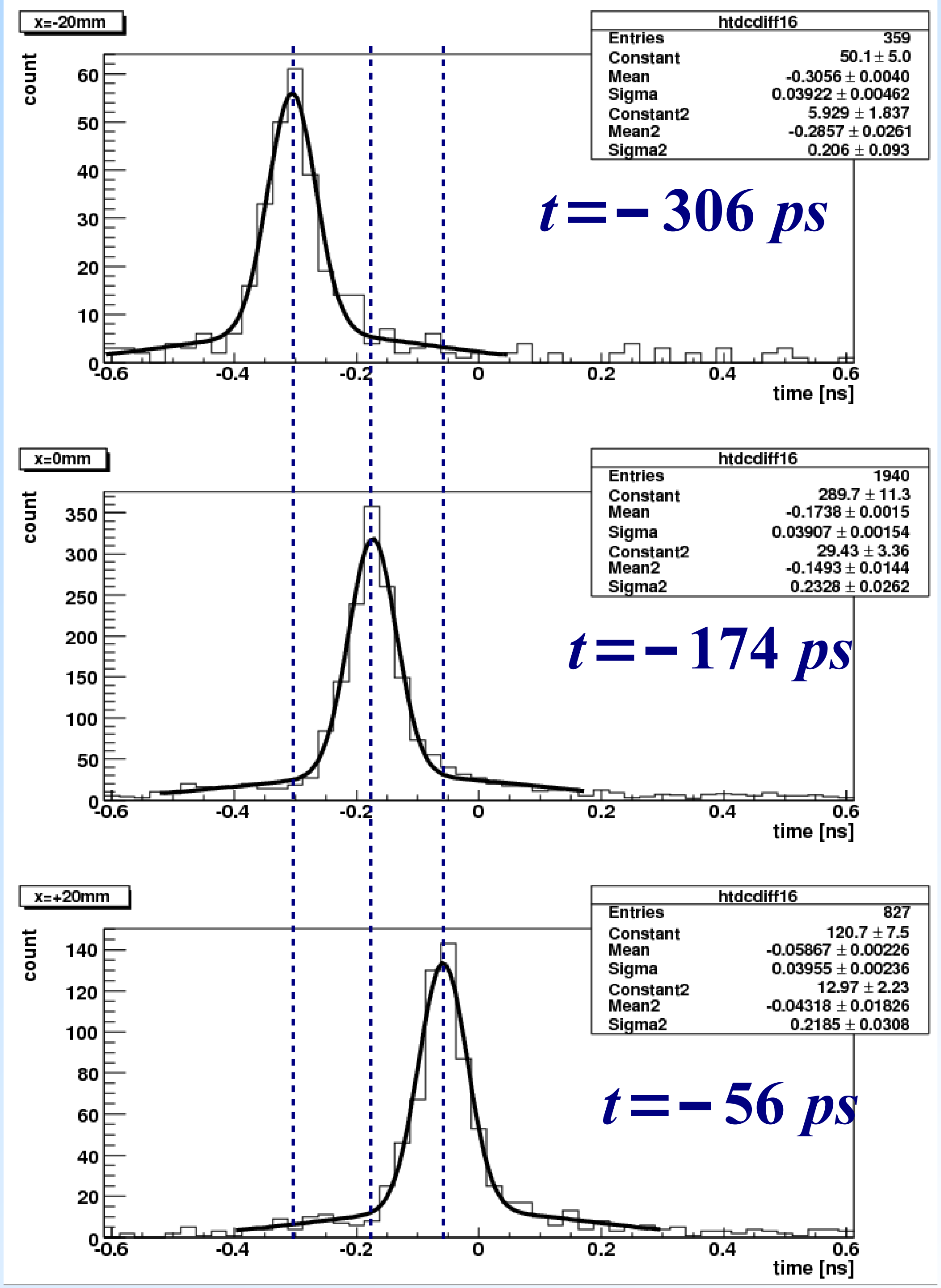


TOF PET position resolution

Data taken at three different point source positions spaced by 20 mm:

- average time shift 125 ps
- timing resolution ~ 40 ps,
  ~ 95 ps FWHM
- position resolution ~ 6 mm RMS,
  ~ 14 mm FWHM

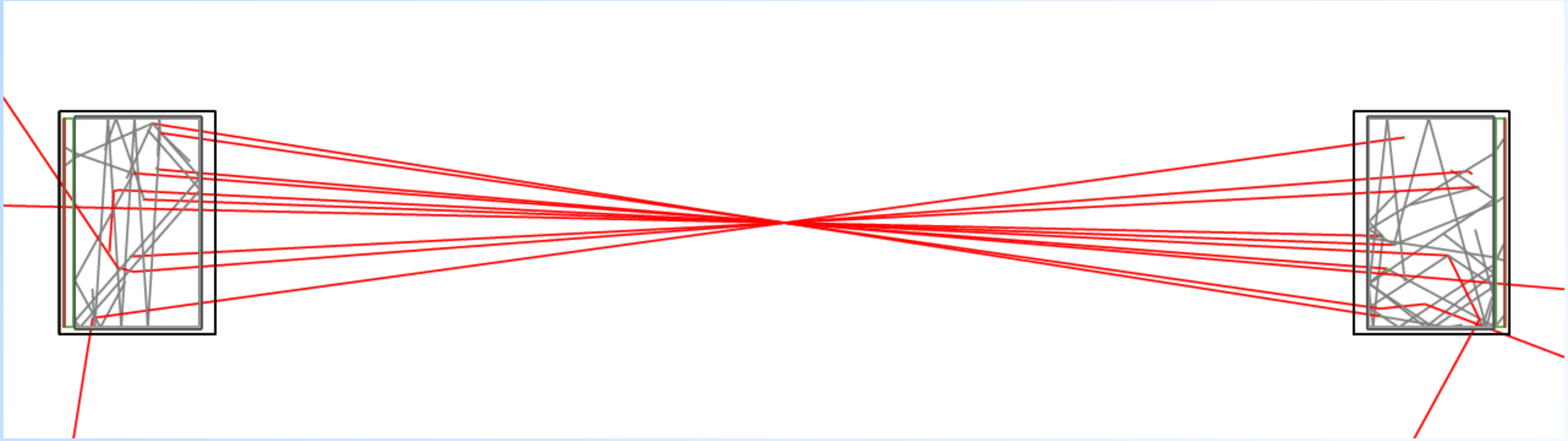
Black painted 15 mm PbF_2 crystals.



GEANT4 simulation

Interactions in a single crystal and full Back-to-back setup were simulated in GEANT4, taking into account:

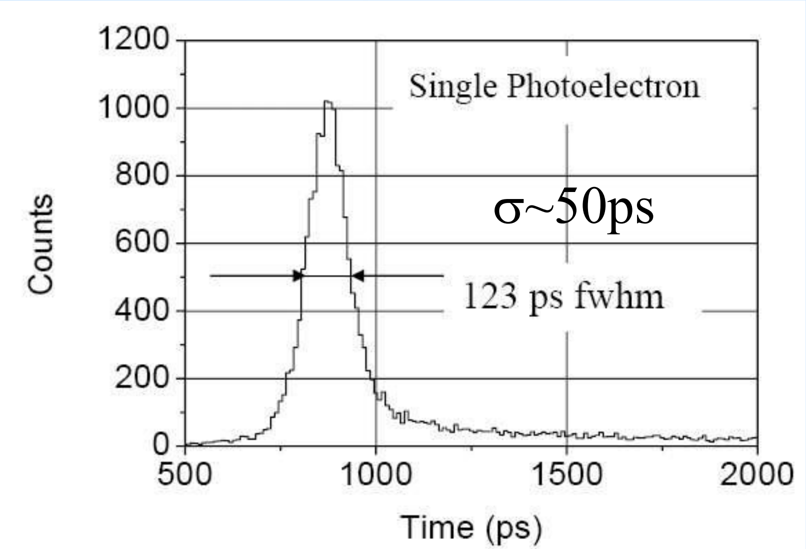
- gamma interactions with detector
- optical photons (Cherenkov and scintillation) produced between 200 nm – 800 nm (no scintillation assumed for PbF2)
- optical photon boundary processes (exit surface polished, other surfaces polished and wrapped in white reflector or black painted)
- photodetector window coupled with optical grease (n=1.5)
- photodetector QE (peak 24% @ 400nm)
- perfect photodetector timing – simulated timing resolution only includes photon travel time spread



SiPM for Cherenkov TOF PET?

Advantages:

- high PDE – more than 50% for recent samples
- flexible granularity
- low operation voltage
- operation in magnetic field
- affordable price (potentially)



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Disadvantages:

- high dark count rate (DCR) ~ 100kHz/mm^2 (cooling?)
- single photon timing resolution not yet below 100 ps FWHM (especially for large area devices)?

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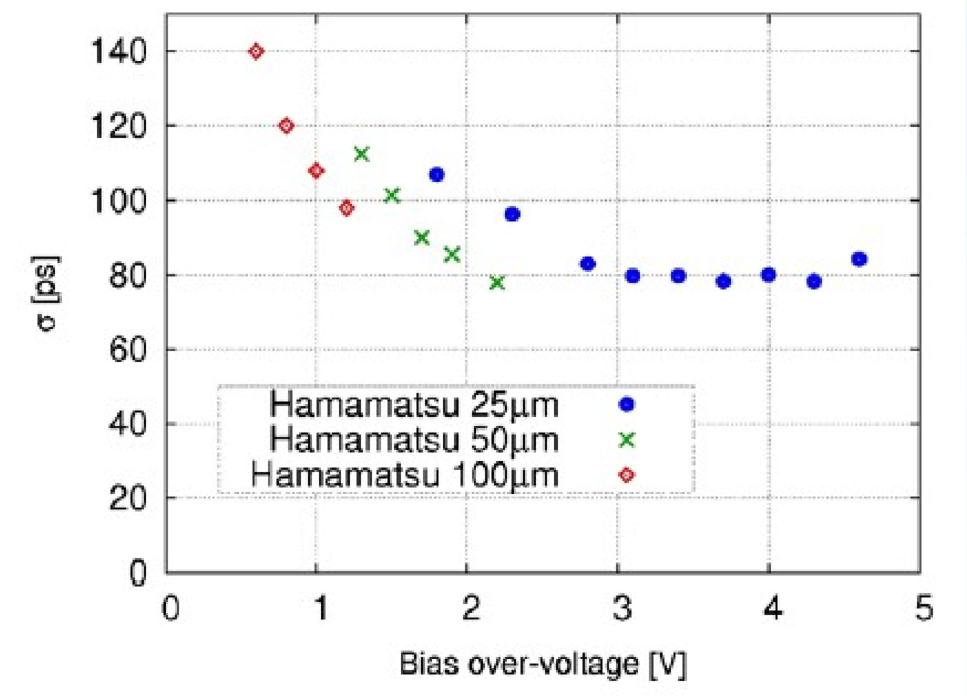
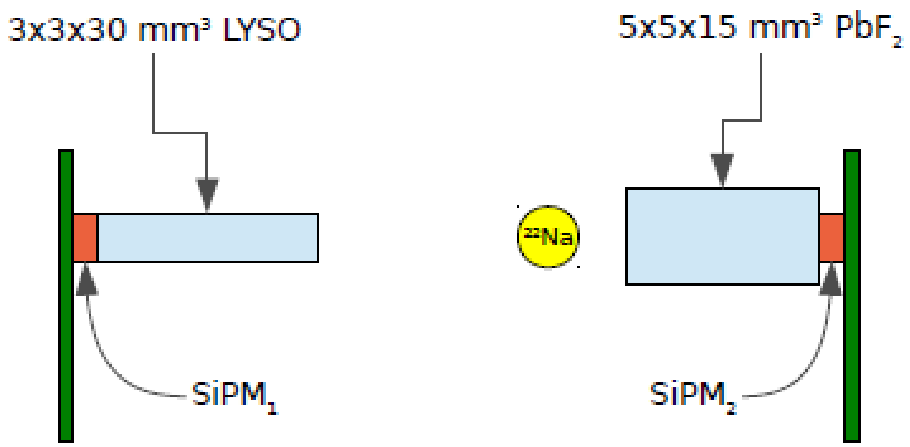
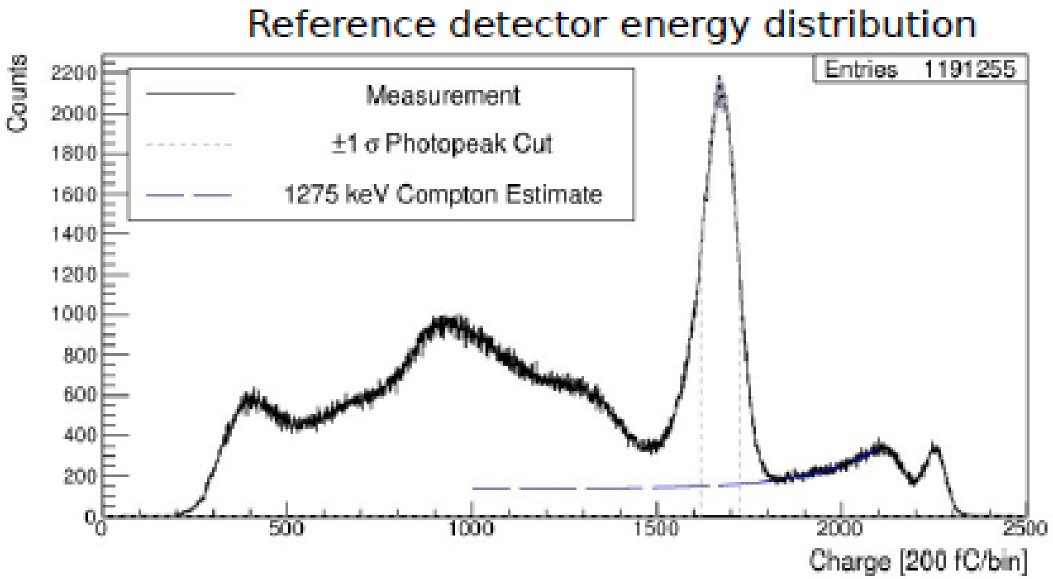


Efficiency measurements

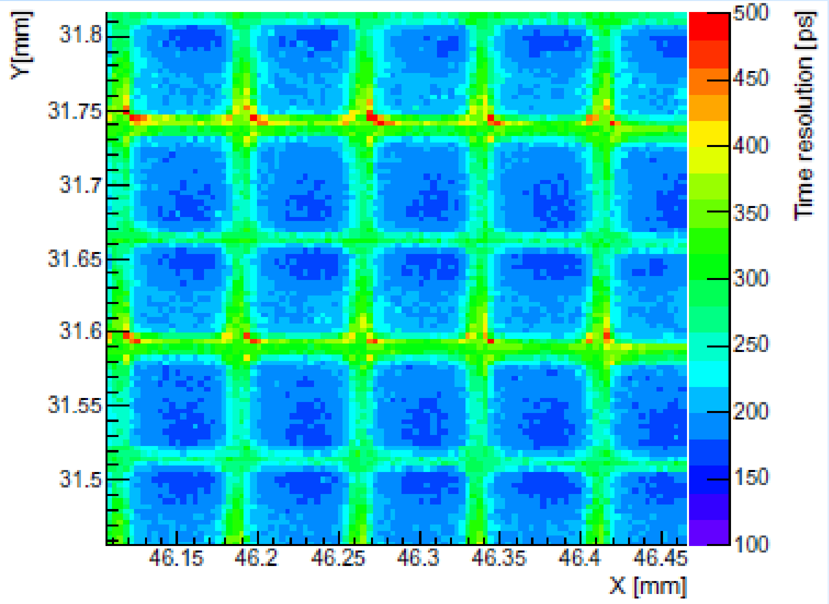
- one Cherenkov detector replaced with a reference scintillation detector
- tight collimation of coincidence gammas on Cherenkov detector
- photopeak cut on reference detector → single side detection efficiency on Cherenkov detector
- corrected for
  - SiPM dark count rate
  - Compton scatter of 1275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

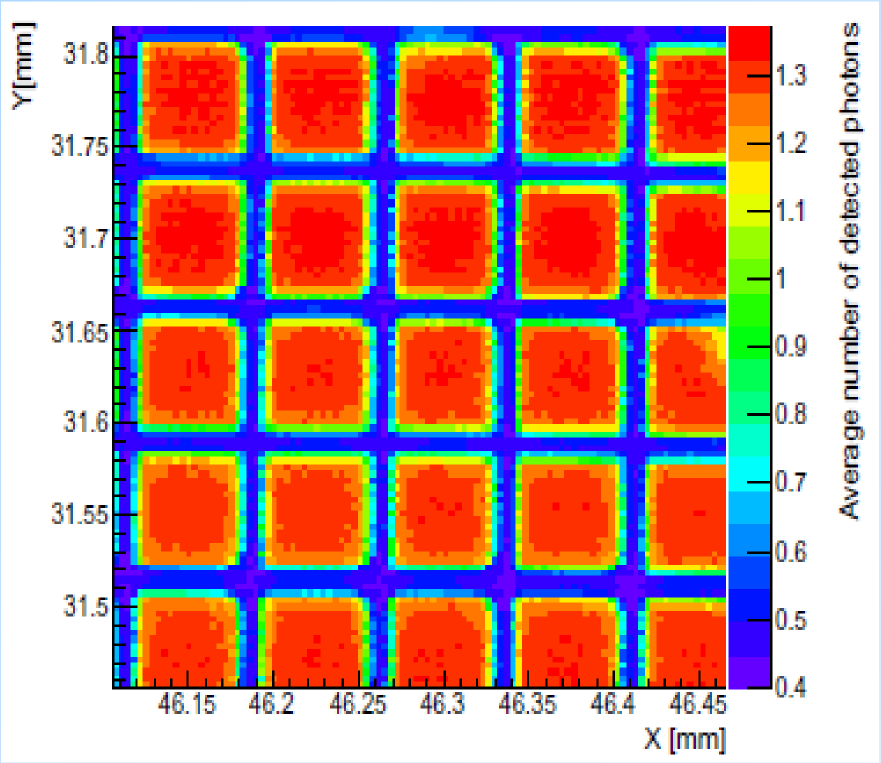


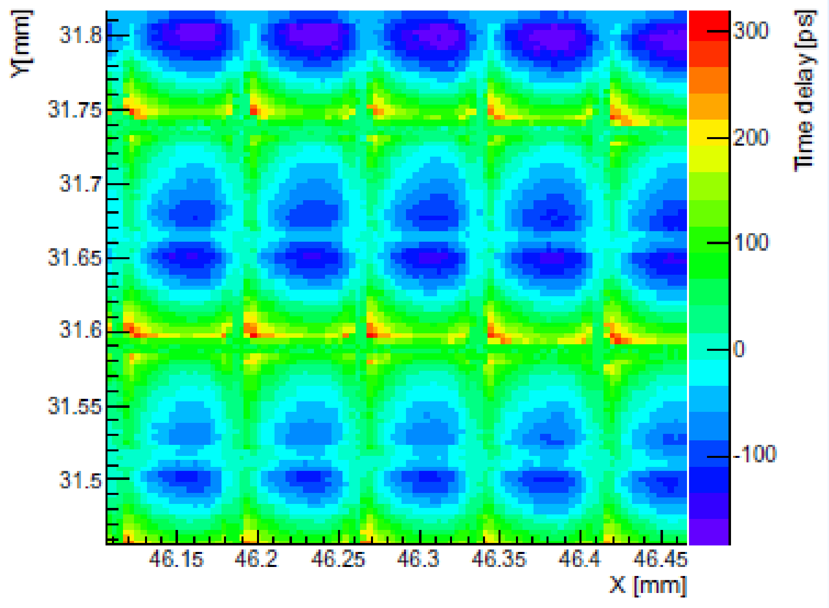


Timing resolution and delay vs. position - local

- Focused red laser ($\sigma \sim 3\mu m$), T=25°C, area ~250 x 250 μm^2
- Higher dark count rates and lover V_{OV}
- Timing resolution (right-top) and delay (right-bottom)[ps], vs. position
- Average number of detected photons (primary carriers) from P(0) (left)

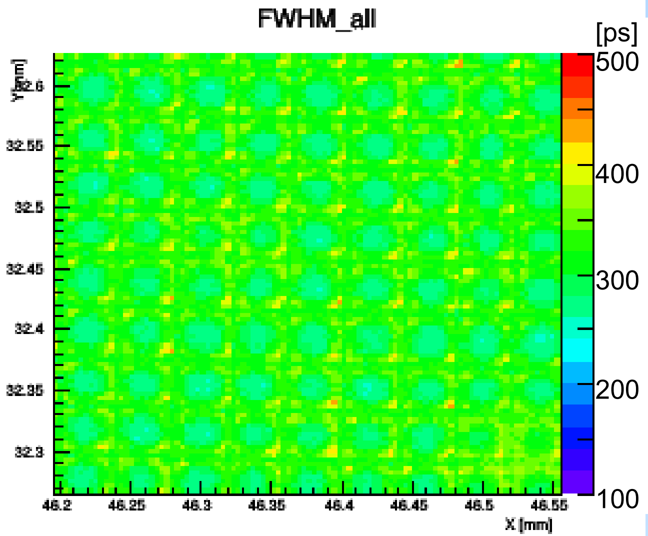




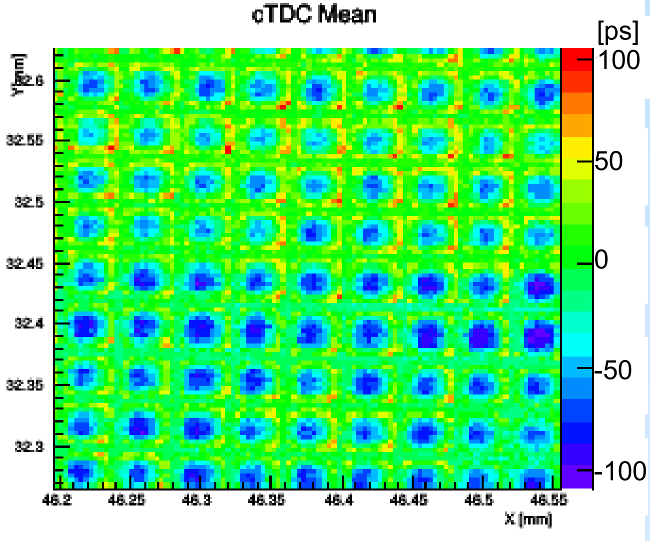


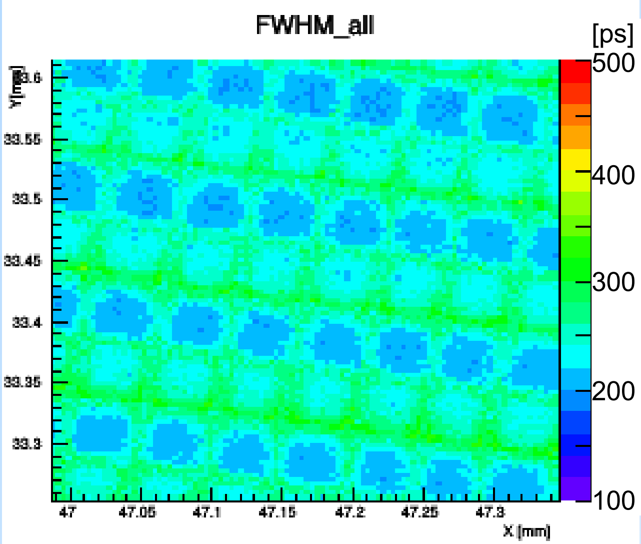
Timing resolution and delay vs. position - local

- Focused red laser ($\sigma \sim 3\mu m$), T=25°C, area ~250 x 250 μm^2
- Higher dark count rates and lover V_{OV}
- Timing resolution (top) and delay (bottom)[ps], vs. position

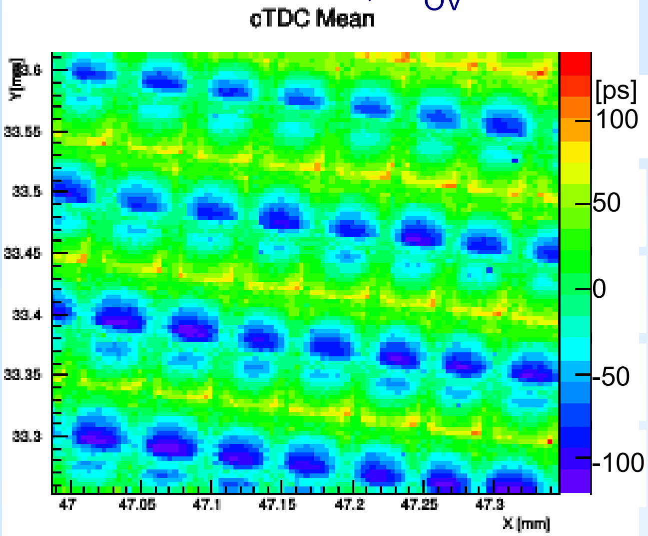


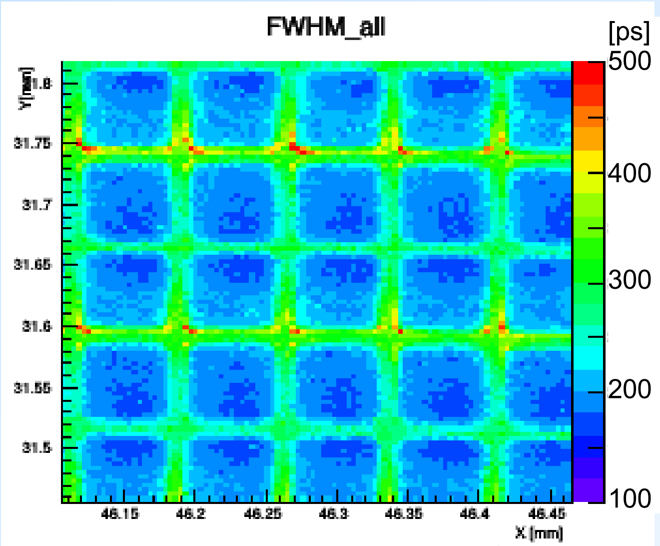
AdvanSiD, V_{OV}=2V



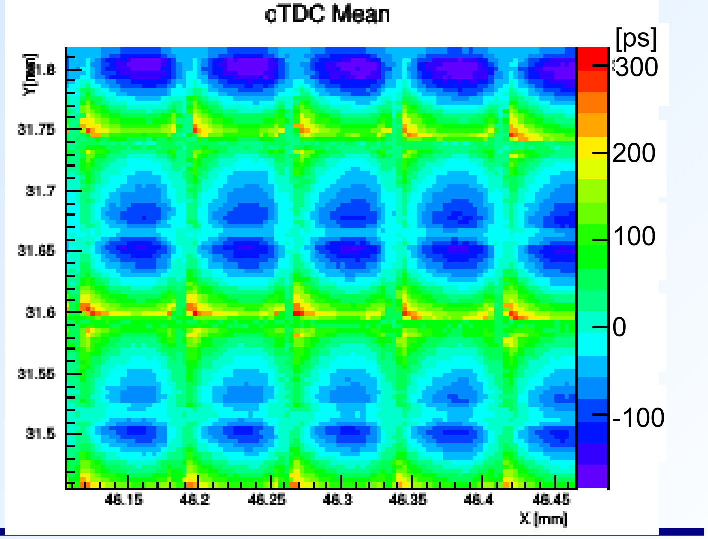


KETEK 'new', V_{OV}=2V



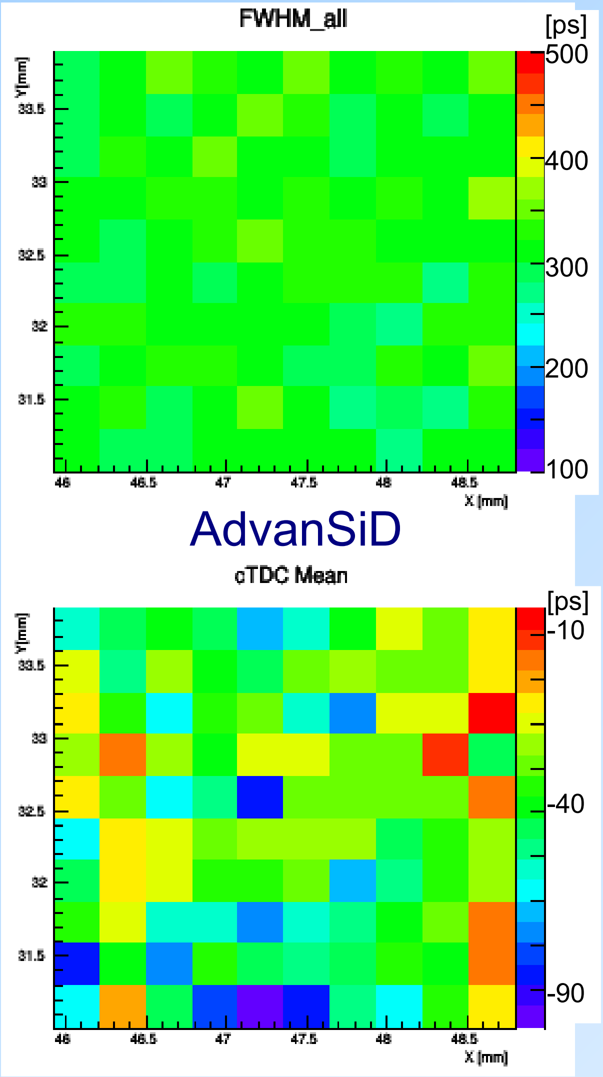


KETEK 'old', V_{OV}=2V

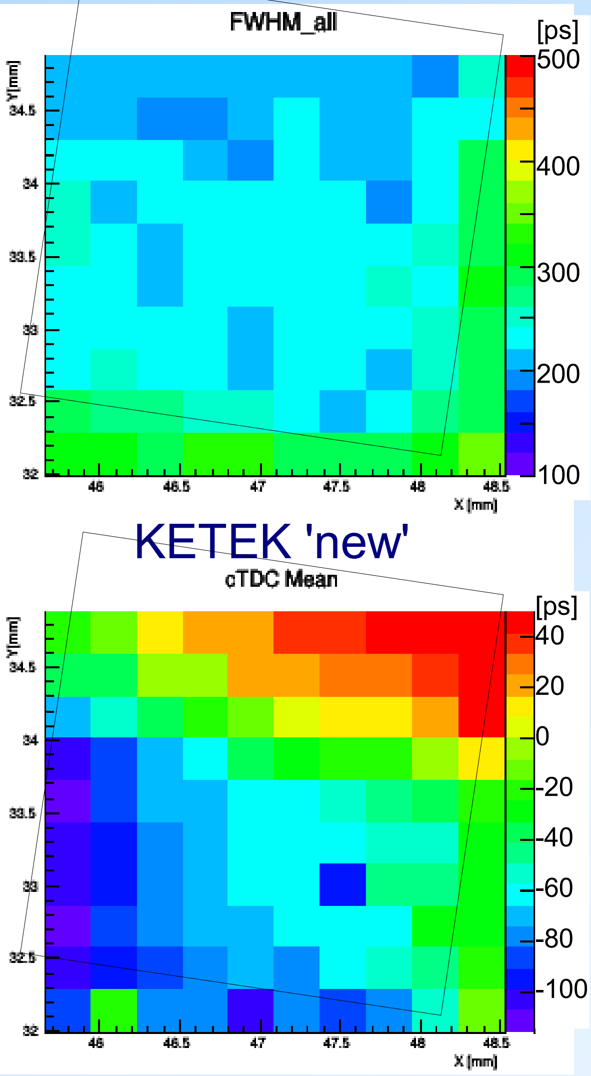


Timing resolution and delay vs. position

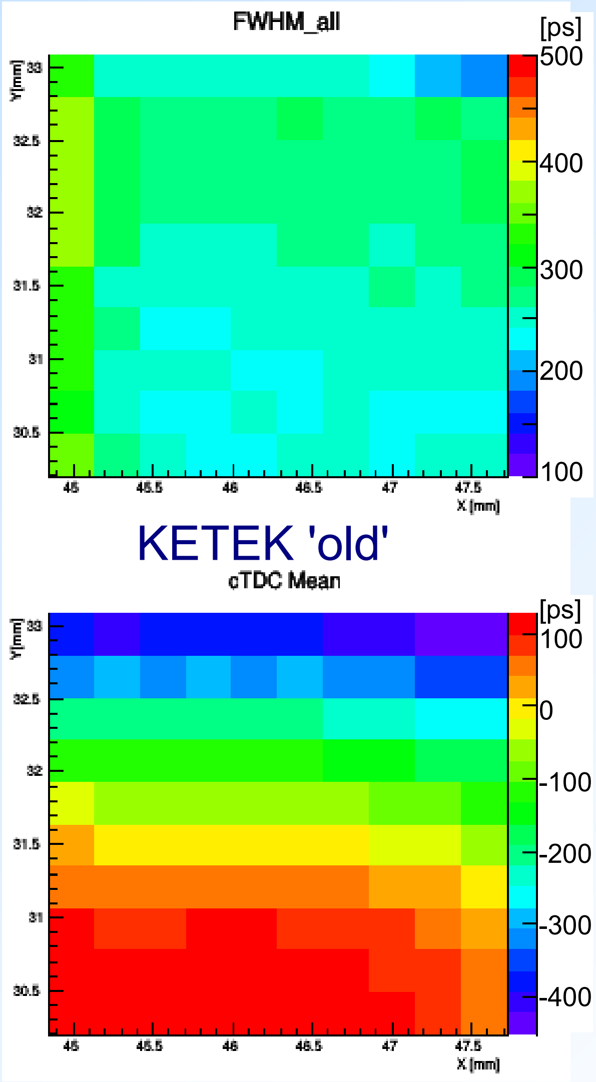
- Defocused red laser ($\sigma \sim 300\mu m$), $T=25^oC$, ~ 3 x 3 mm^2
- Higher dark count rates and lover V_{OV}
- Timing resolution (top) and delay (bottom) vs. position



AdvanSiD



KETEK 'new'



KETEK 'old'