Recent Detector Developments in the Context of Medical Applications

Peter Križan

University of Ljubljana and J. Stefan Institute

Contents

Interplay of detector R&D for particle physics and medical imaging

Traditionally excellent collaboration of the two research areas.

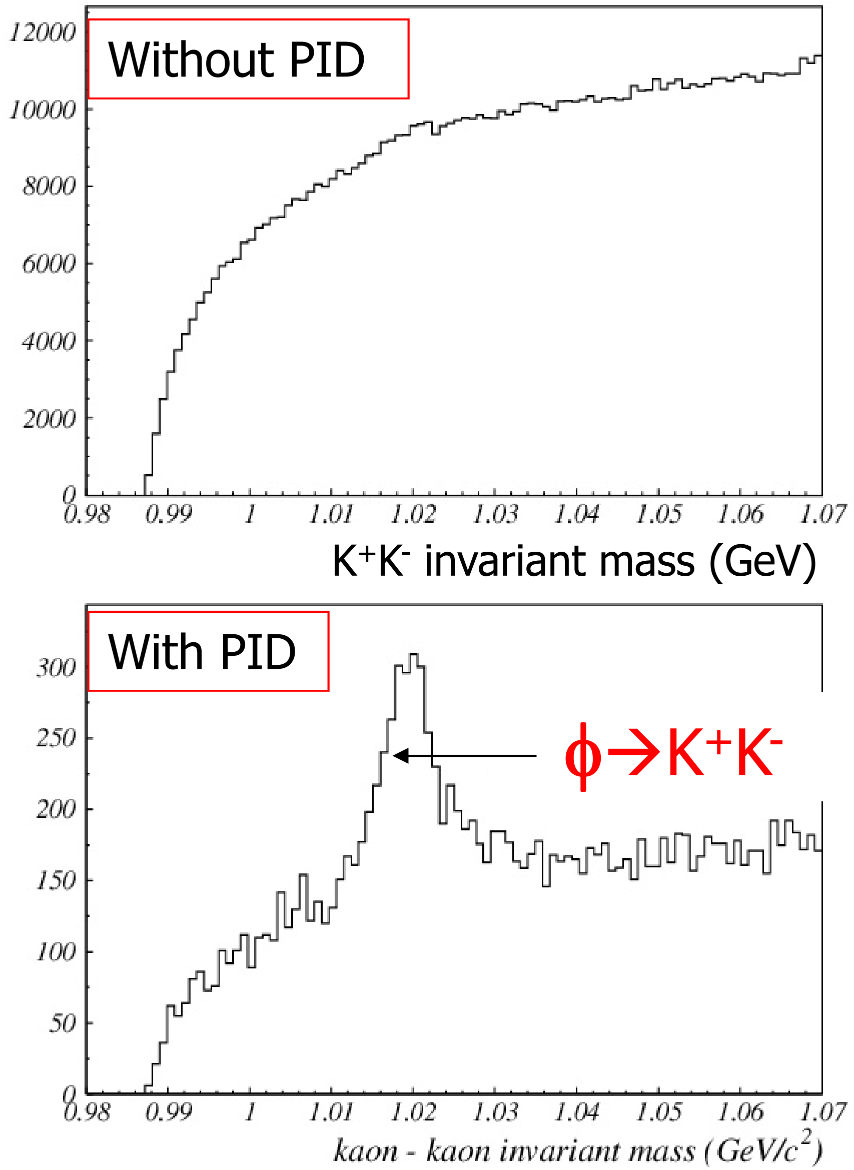
Novel detection techniques required in particle physics
→with modifications a potential application in medical physics

… and vice versa…

One of the recent examples: SiPMs as scintillation light sensors for

- Electromagnetic calorimeters
- PET scanners

Particle identification - which particles were produced in a reaction - one of the essential features of experiments



Very often the interesting reaction is burried in a large number other reactions (background).

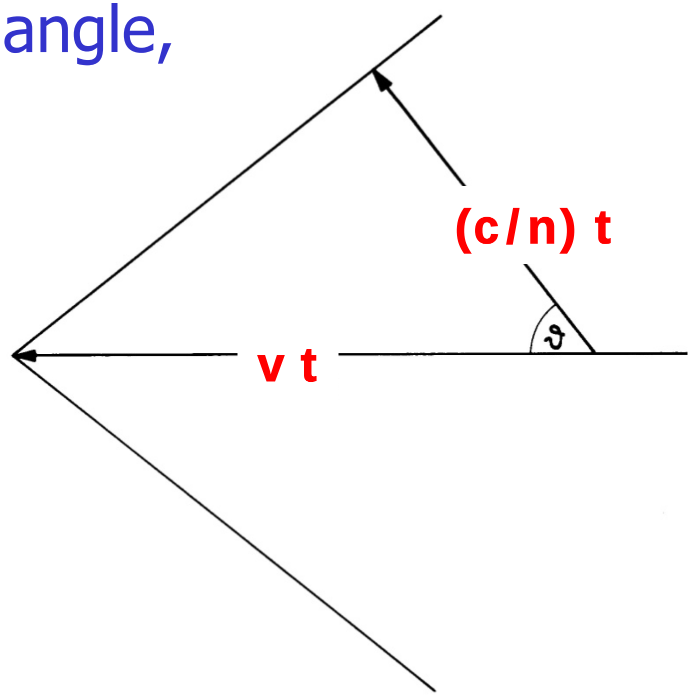
One important tool: select only reactions (events) with the right type of particles = identify each of them →particle identification (PID)

Example: the decay $\phi \rightarrow K^+K^-$ only becomes visible after particle identification is taken into account.

One of the important PID methods: use Cherenkov radiation

A charged track with velocity v=βc exceeding the speed of light c/n in a medium with refractive index n emits polarized light at a characteristic (Cherenkov) angle,

$$\cos\theta = c/nv = 1/\beta n$$

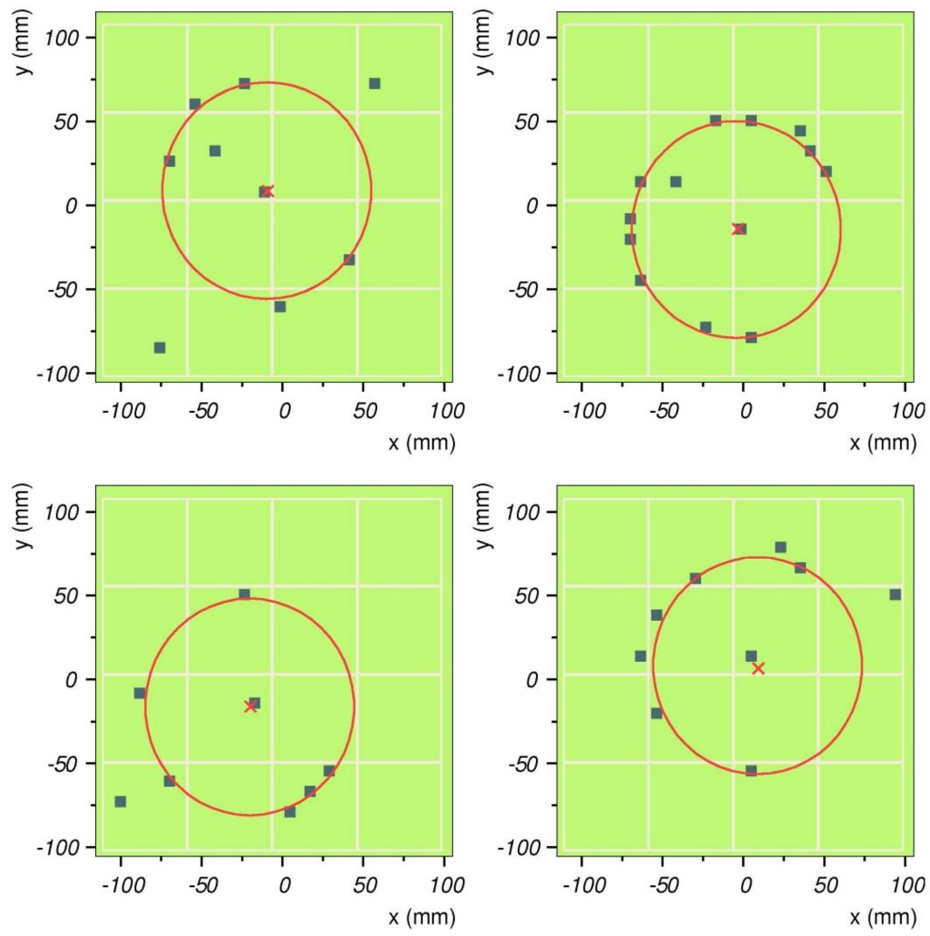


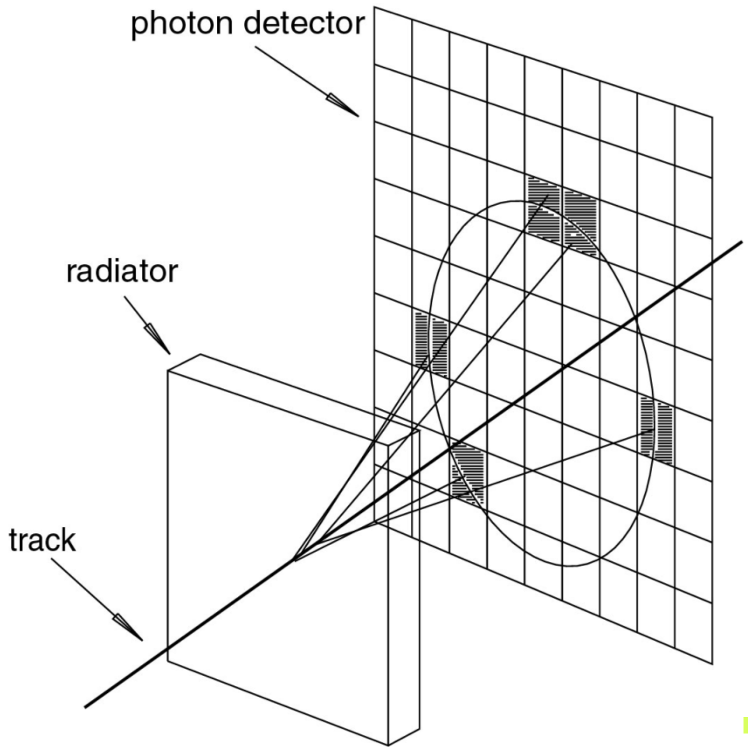
Excellent identification method, but very low light level = few detected photons

Measuring Cherenkov angle

Cherenkov photons detected on a plane: ring (Ring Imaging Cherenkov counter, RICH)

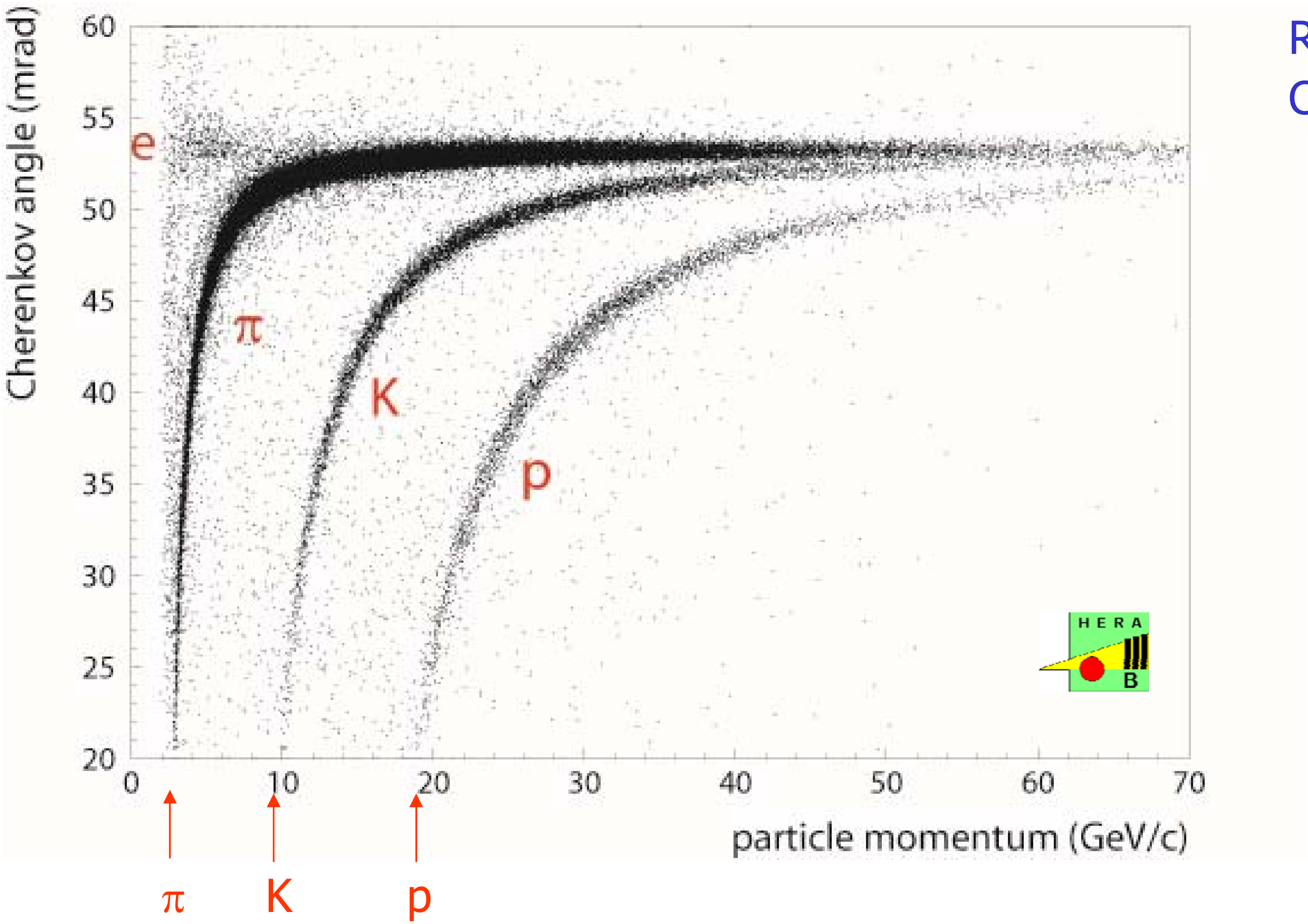
ring radius → Cherenkov angle





Need a fine granularity sensor for single photons with low noise

Measuring Cherenkov angle



thresholds

Radiator:
C_4F_{10} gas

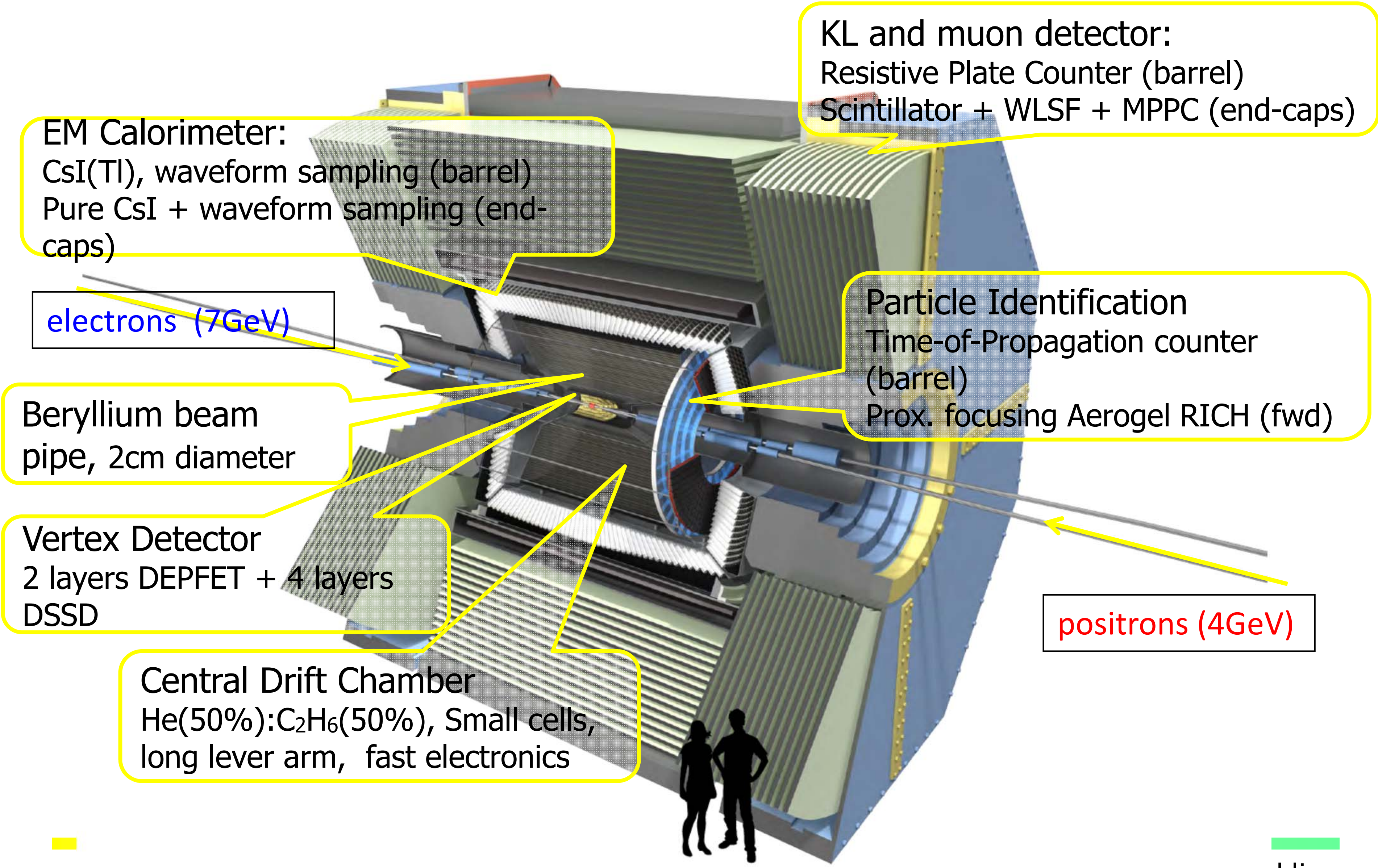
Recent trend: fast photon detection in Cherenkov detectors

New generation of RICH counters: precise time information needed to further improve performance:

- Reduce chromatic abberation (group velocity): Focusing DIRC
- Combine TOF and RICH techniques: TOP (Time-of-propagation counter), TORCH

→ Need photo sensors with excellent timing of <50ps (r.m.s.)

Belle II Detector



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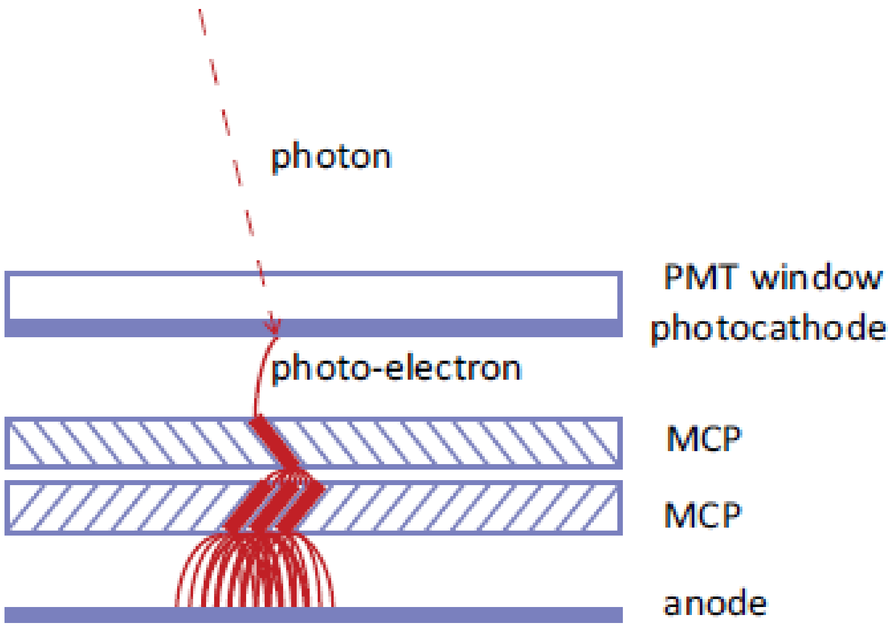
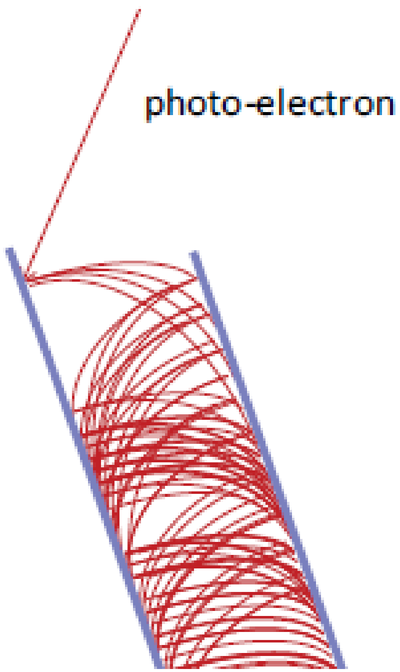
Very fast light sensor: micro-channel plate PMTs

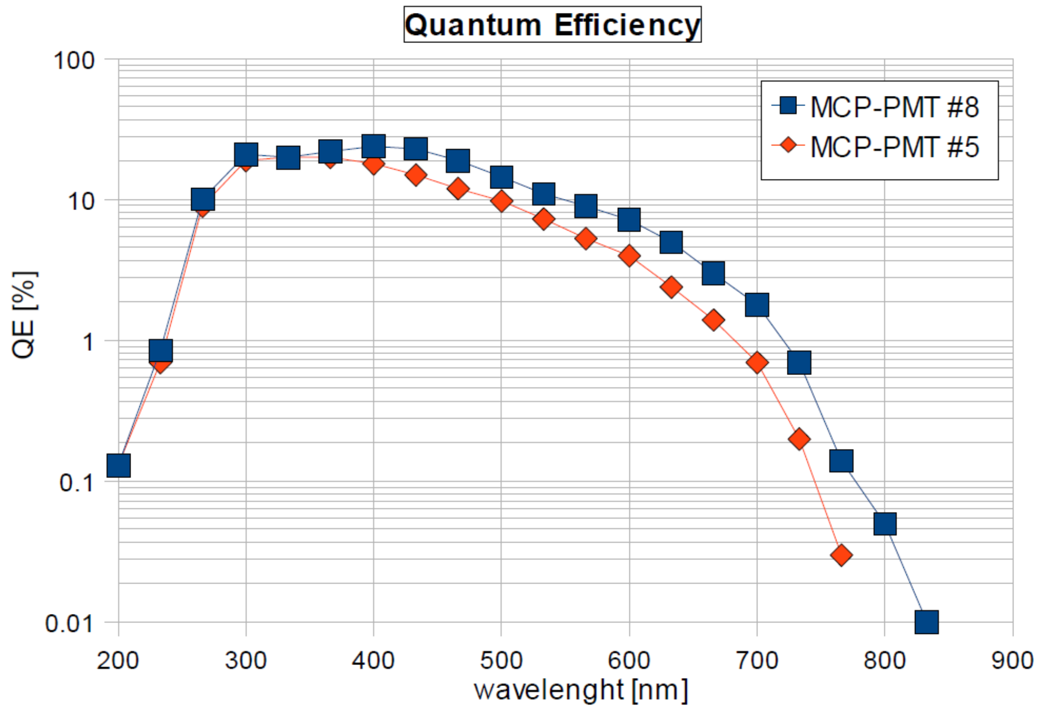




- Faster than PMTs
- Immune to an axial magnetic field

Photon detector: MCP-PMT

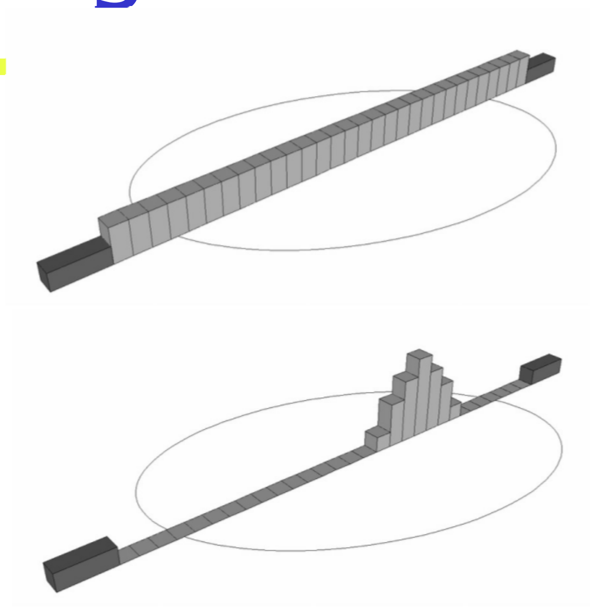
Example: Hamamatsu SL10 MCP-PM
- multi-anode PMT with two MCP steps, 10 mm pores
- 16 (4x4) anode pads, pitch ~ 5.6 mm, gap ~ 0.3 mm
- box dimensions ~ 27.5 mm square
- excellent timing **~ 20ps r.m.s.** for single photons
- multi-alkali photocathode
- 1.5 mm borosilicate window
- gain > 10^6



TOF-PET with Cherenkov light

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

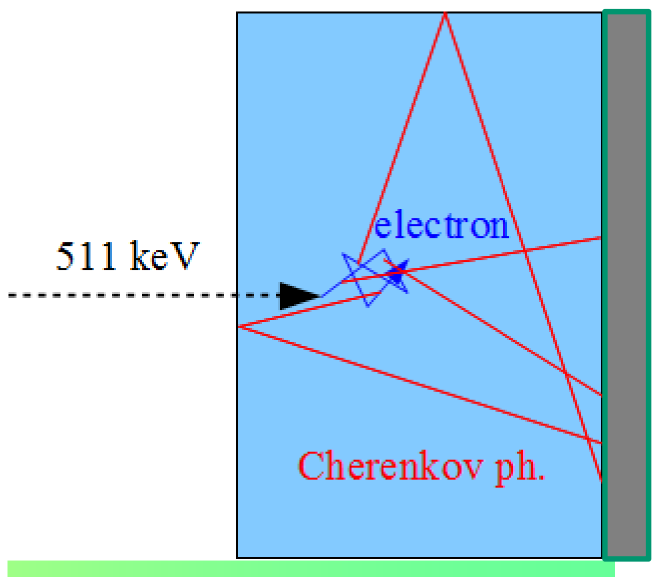
- localization of source position on the line of response
- reduction of coincidence background
- improvement of S/N



Novel photon detectors – MCP-PMT and SiPM – have excellent timing resolution → TOF resolution limited by the scintillation process

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

Disadvantage of Cherenkov light is a small number of Cherenkov photons produced per interaction → detection of single photons!



Cherenkov radiator for PET

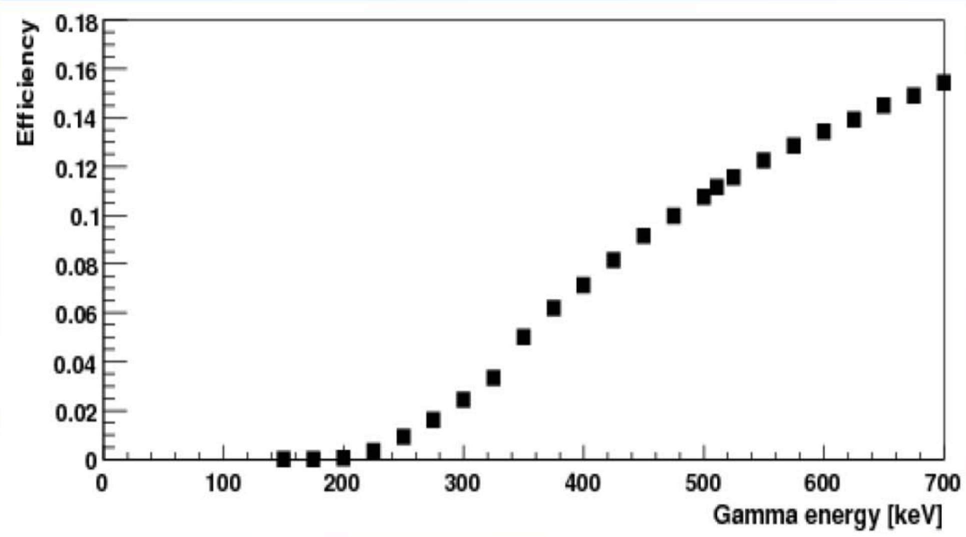
Cherenkov radiator PbF_2:

- 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/cm³)	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

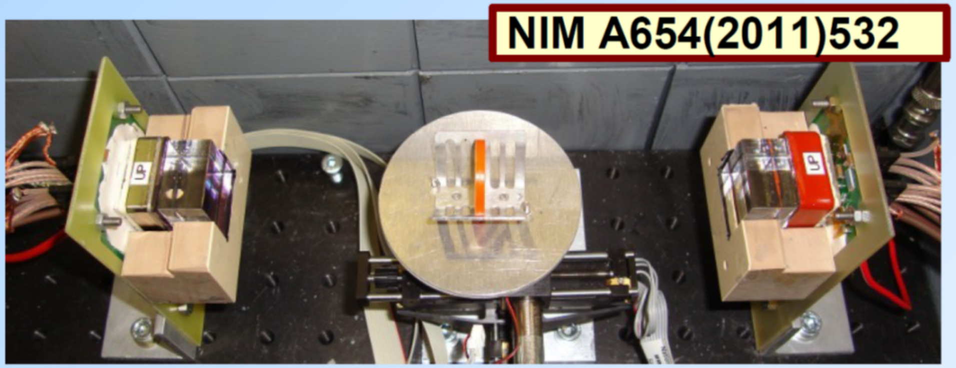


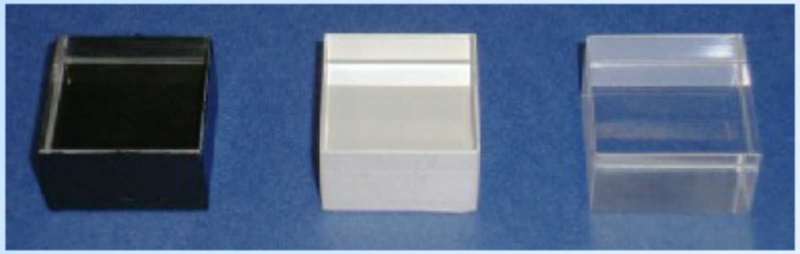
Excellent timing with MCP PMTs

- 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

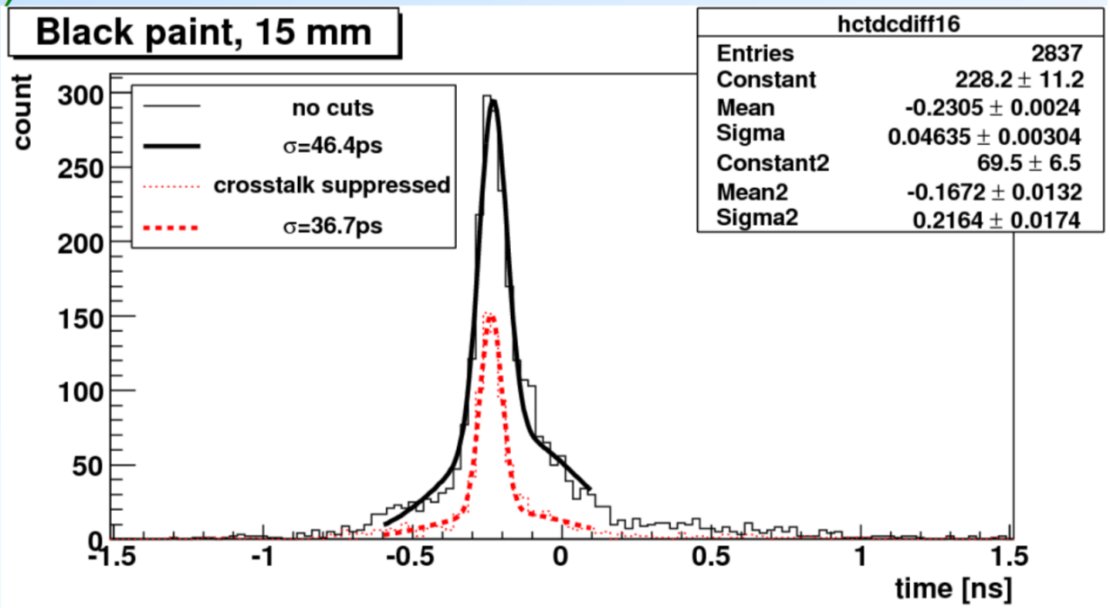




black painted, Teflon wraped, bare

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

(~ 30% for LSO in ideal case)



Point source position

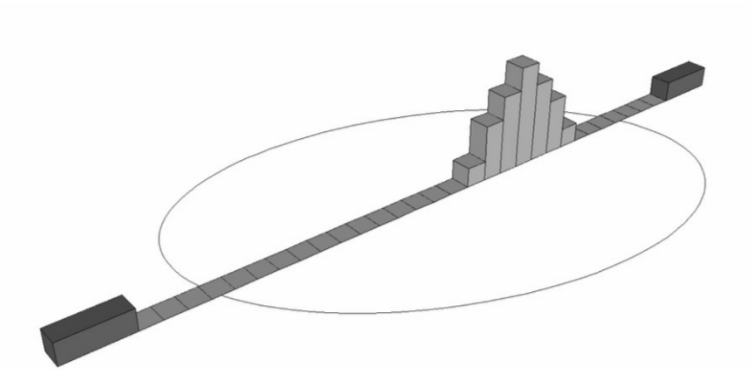
Data taken at three different point source positions spaced by 20 mm:

- average time shift 125 ps
- timing resolution ~ 40 ps rms,

  ~ 95 ps FWHM

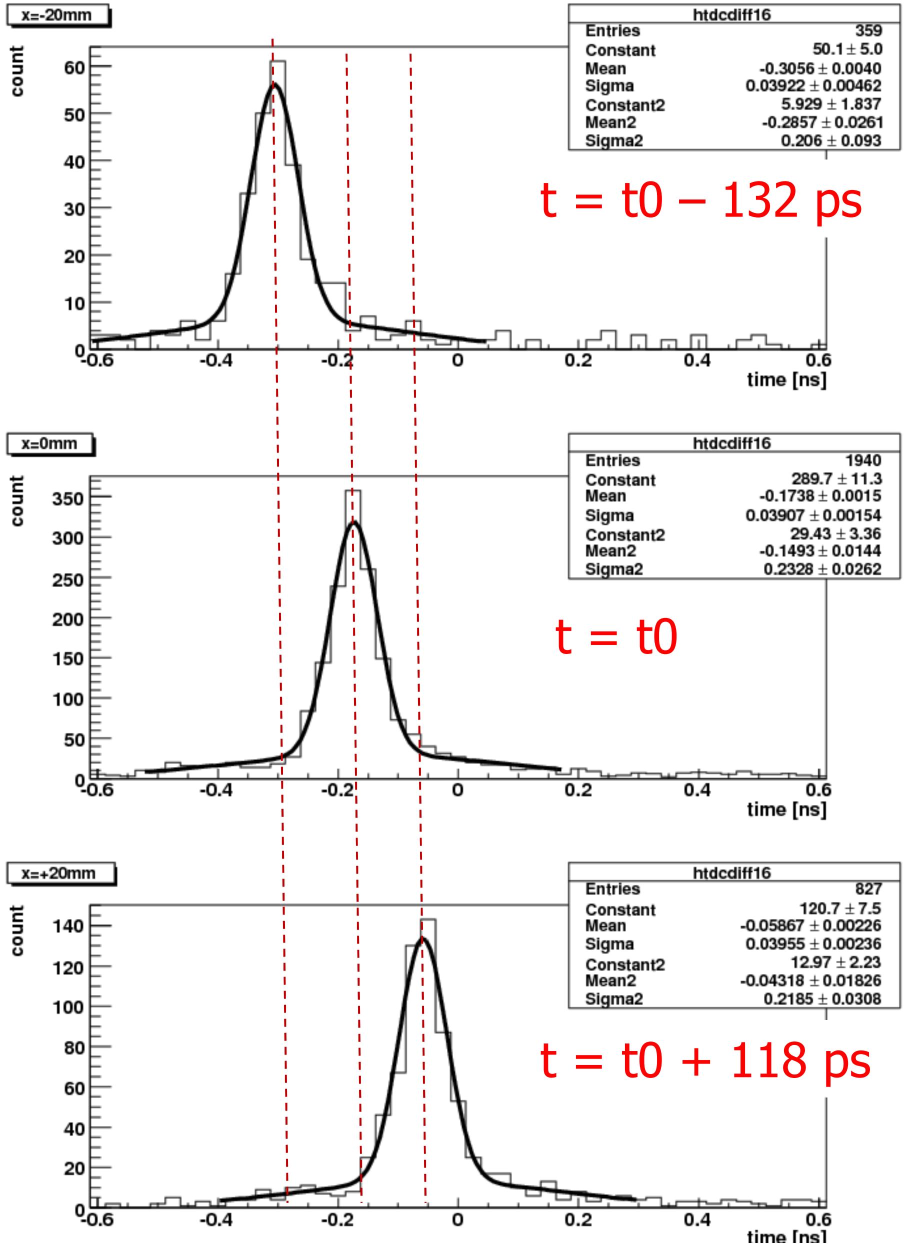
- position resolution along line of response ~ 6 mm rms,

  ~ 14 mm FWHM



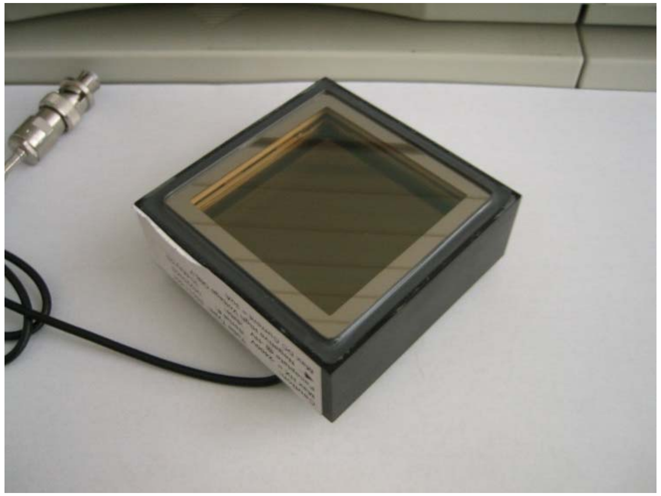
Black painted 15 mm PbF_2 crystals.

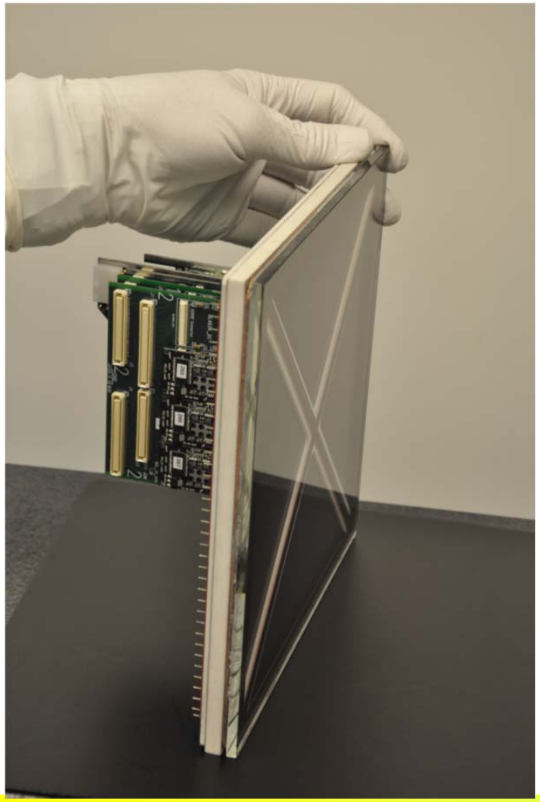
→ NIM A654(2011)532–538



Large system: use larger area MCP PMTs?

Hamamatsu SL10 1“
→Photonis Planacon 5cm x 5cm
→LAPPD 20cm x 20cm





The main problem of a MCP PMT in a Cherenkov based annihilation gamma detector: low quantum efficiency of a typical photocathode in a PMT

→ Detection efficiency: a few %

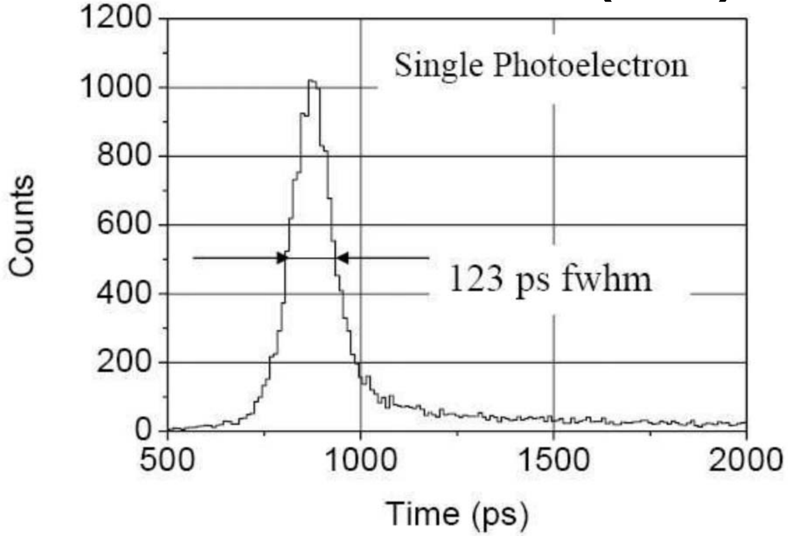
SiPM for Cherenkov TOF PET?

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

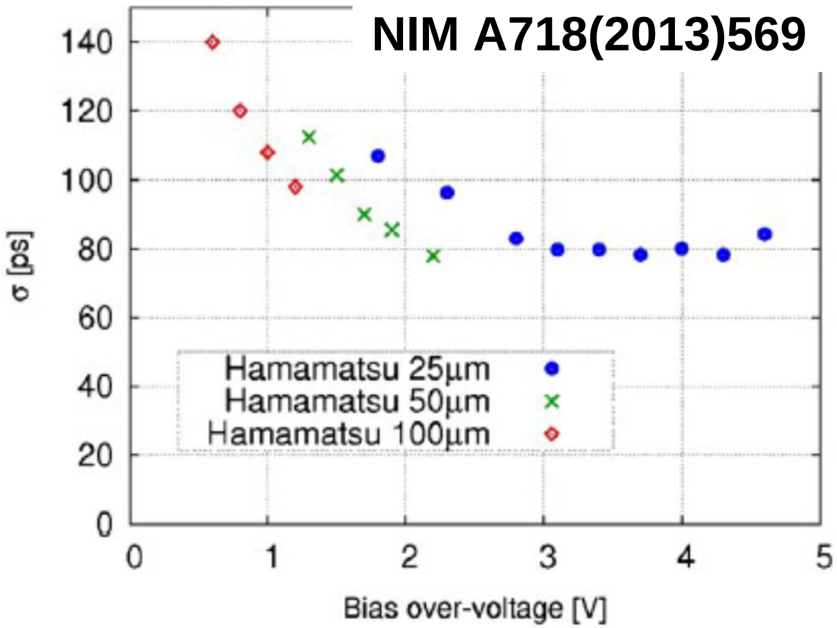
Disadvantages:
- high dark count rate (DCR) ~ 100kHz/mm^2 (cooling?)
- single photon timing resolution not yet below 100 ps FWHM (specially for large area devices)?

→ Explore new devices and test them

NIM A504 (2003) 48



S.Gundacker et.al. NIM A718(2013)569



SiPMs in a back-to-back configuration

Cherenkov radiator (PbF_2):

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

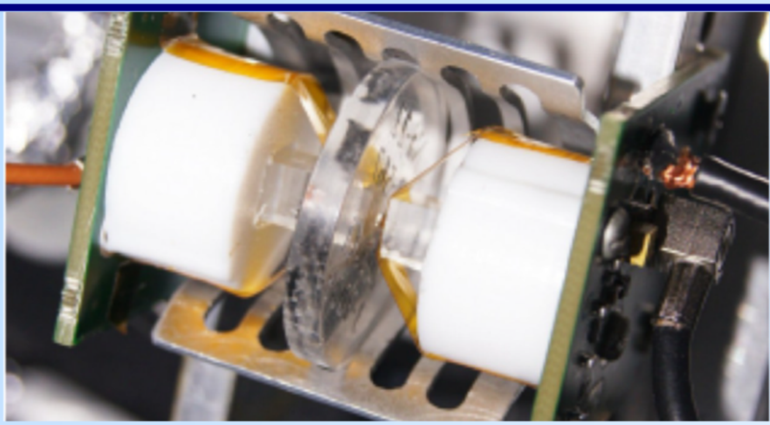
black painted, Teflon wrapped, bare

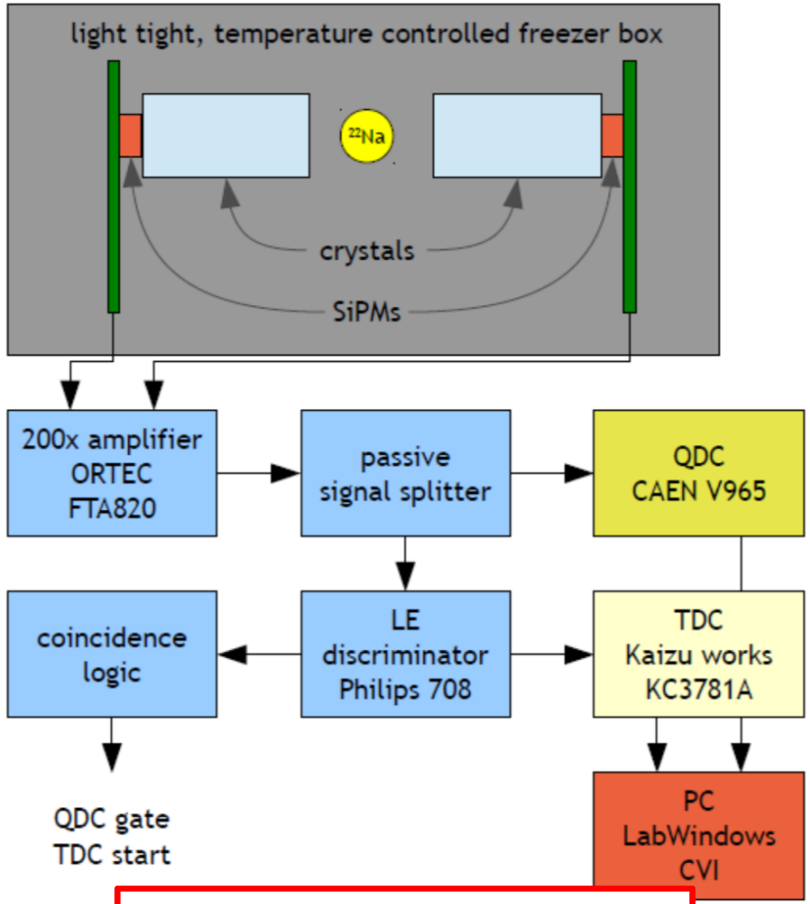
Readout: (timing ~25 ps FWHM)

- 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, 'new'	50	65
AdvanSiD	ASD-NUV3S-P-40	40	26
KETEK	PM3375TS-SBO, 'old'	75	25
SensL	MicroFC-30050-SMT-GP	50	25

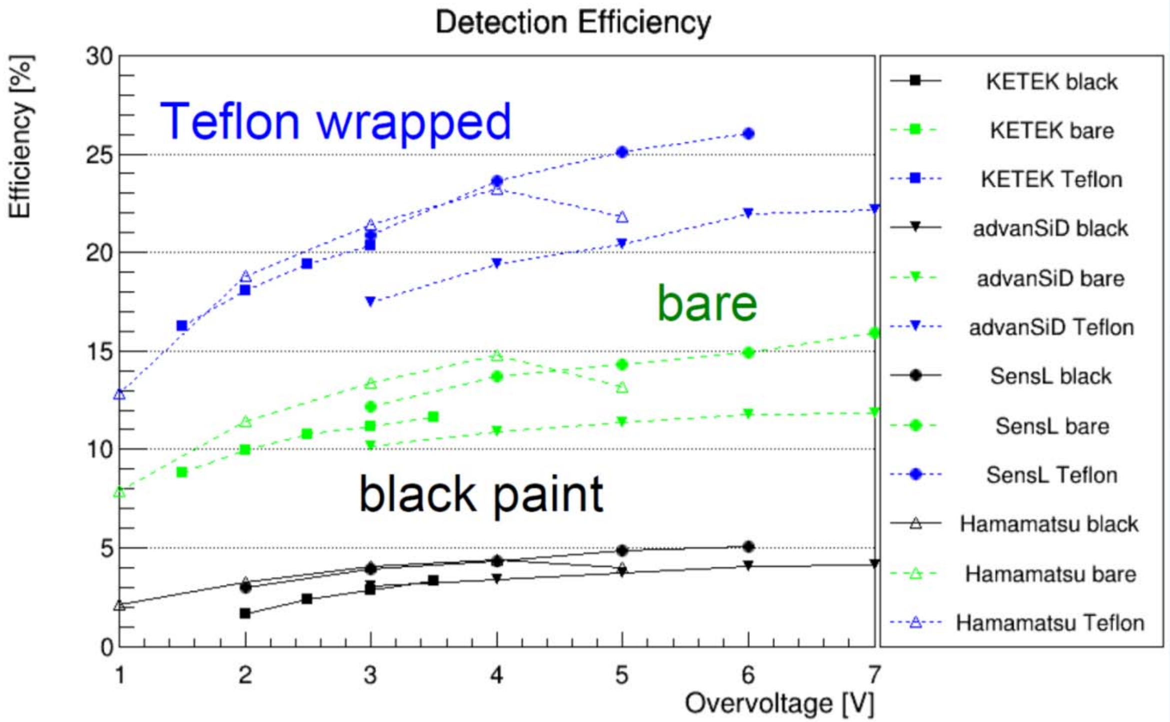




NIMA 804 (2015) 127

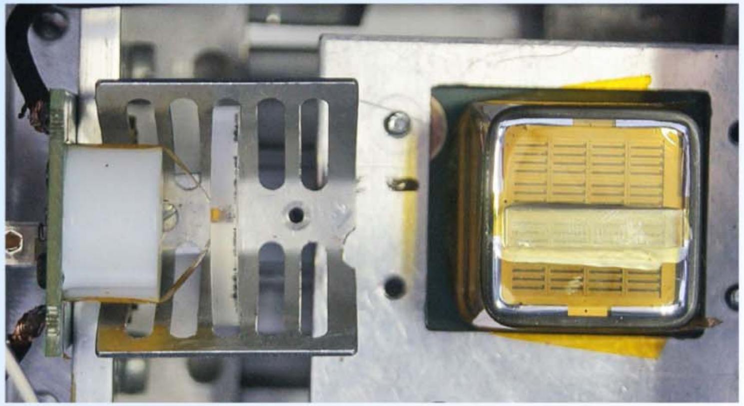
Single side detection efficiency

- best efficiency: 26% with SensL SiPM and Teflon wrapped crystals
- T = -25°C



(5x5mm² crystal on 3x3mm² SiPM)

Producer	Model	Pixel pitch [μm]	Vbr [V]
Hamamatsu	S12641-PA050	50	65
AdvanSiD	ASD-NUV3S-P-40	40	26
KETEK	PM3375TS-SBO	75	25
SensL	MicroFC-30050-SMT-GP	50	25

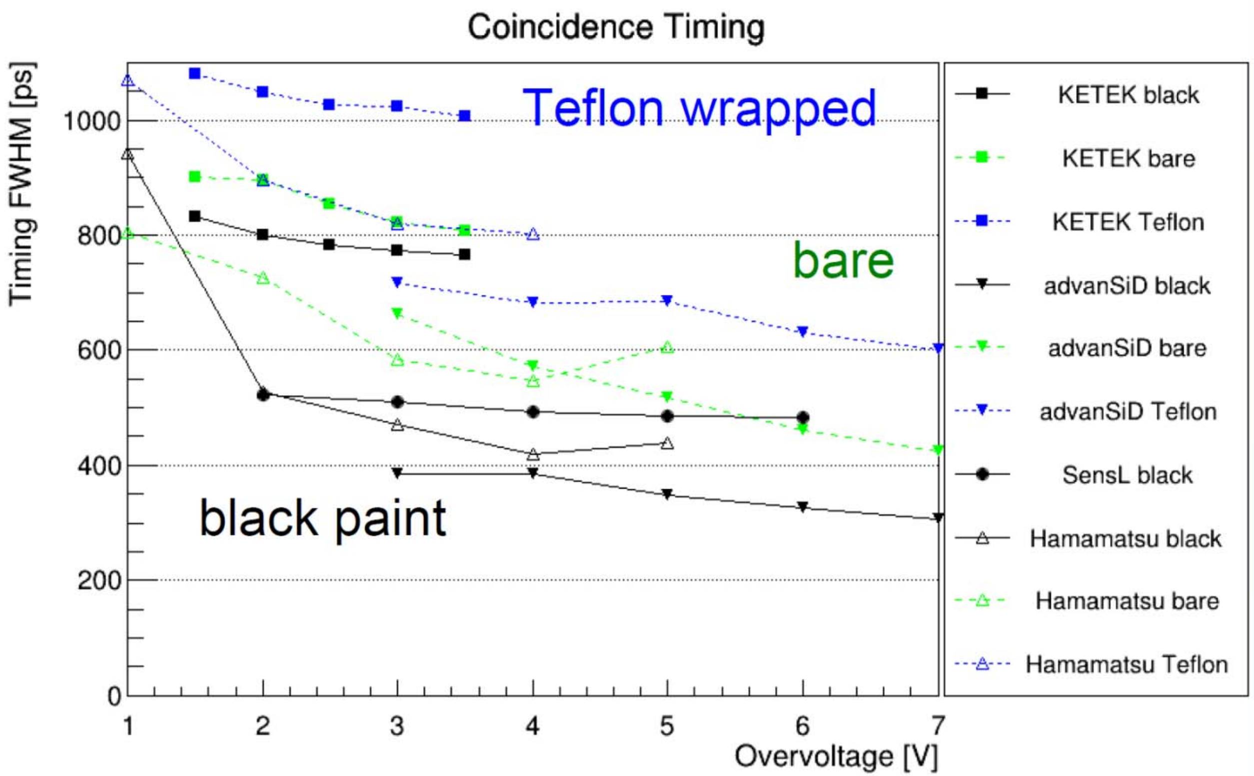


S. Korpar, IEEE/NSS 2015

Coincidence time resolution

- best timing: 309 ps with AdvanSiD
- T = -25°C

(5x5mm² crystal on 3x3mm² SiPM)



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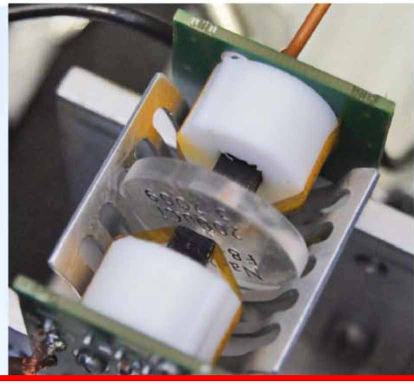


S. Korpar, IEEE/NSS 2015

Coincidence timing, continued

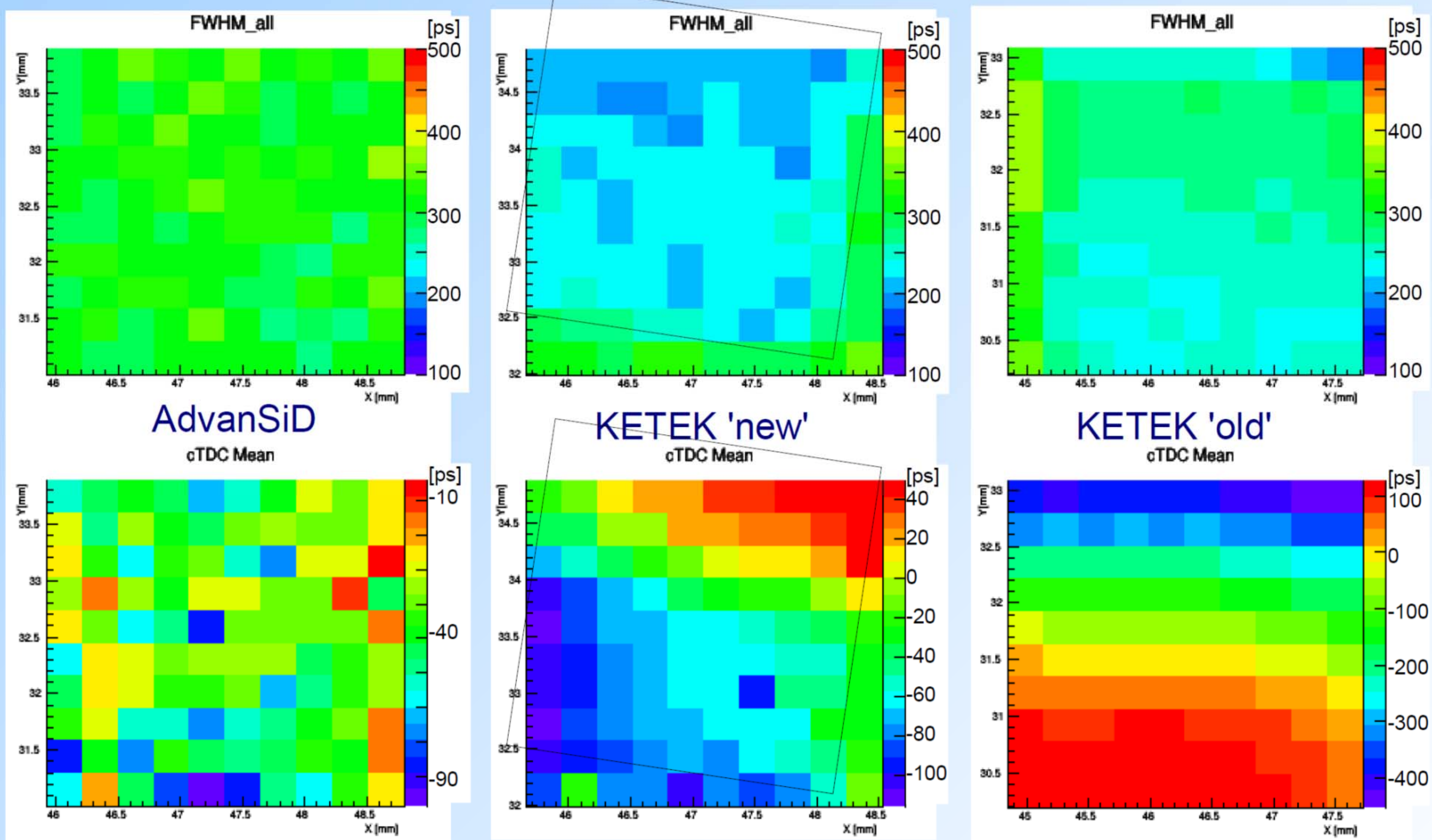
What is behind the best value of FWHM=300ps?

= Can we improve?

→ Perform picosecond laser scans

Timing resolution and delay vs position

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

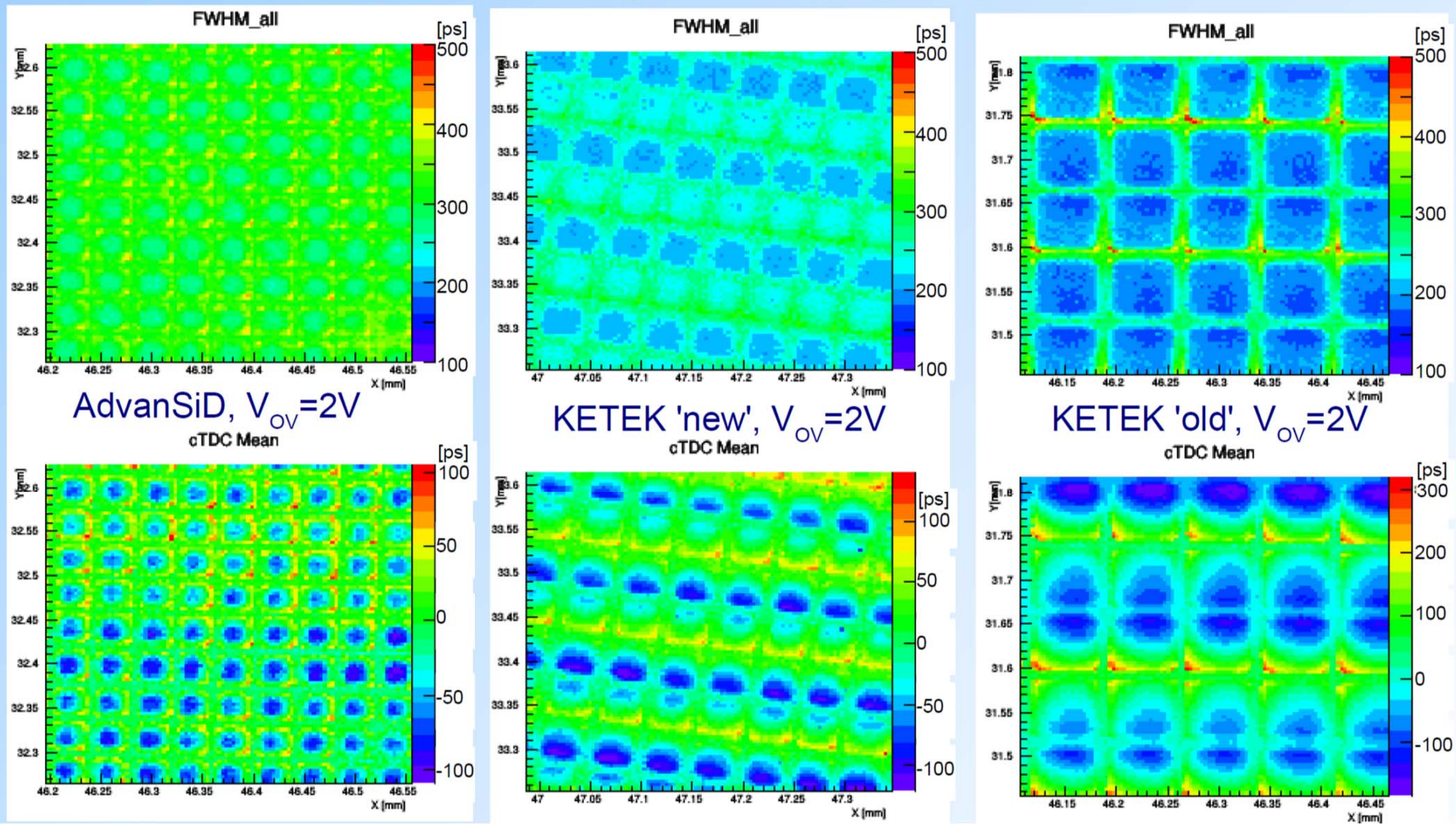


Recent Detector Developments

S. Korpar, IEEE/NSS 2015

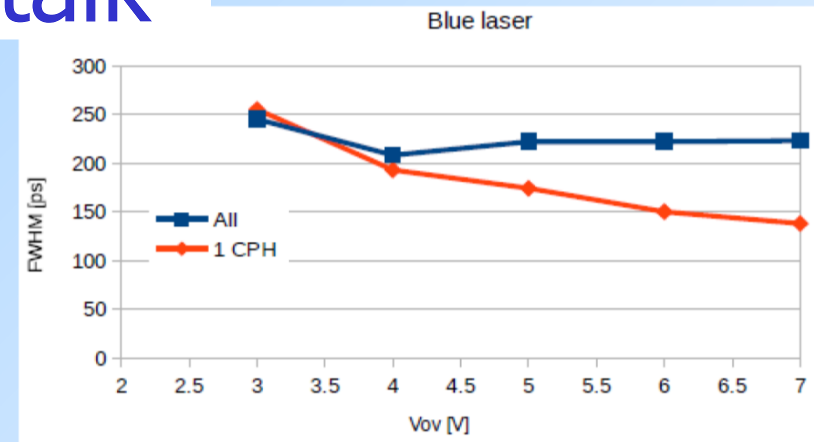
SiPM timing with a fine laser scan

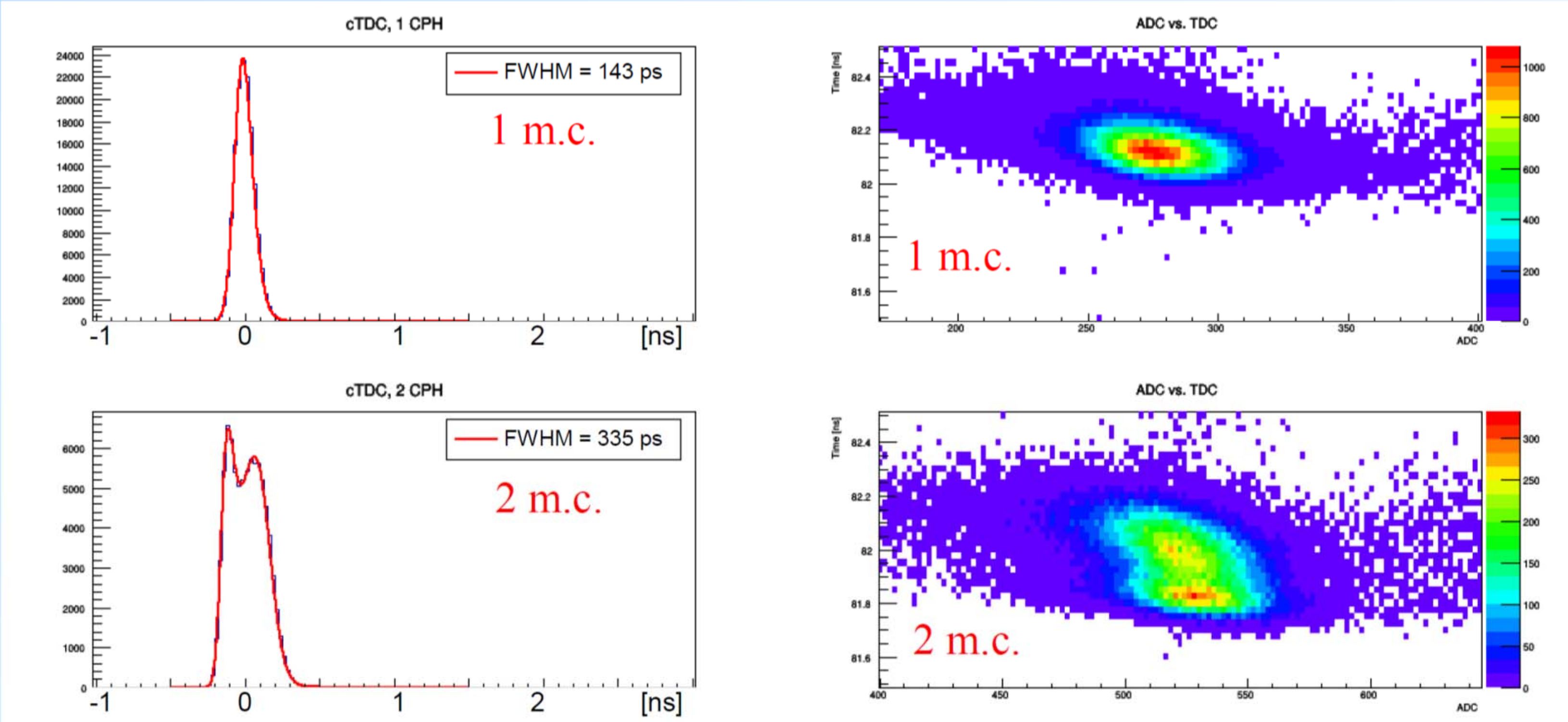
- Focused red laser (σ ~ 3μm), T=25°C, area ~250 x 250 μm^2
- Higher dark count rates and lover V_{OV}
- Timing resolution (top) and delay (bottom)[ps], vs. position



Impact of optical cross talk

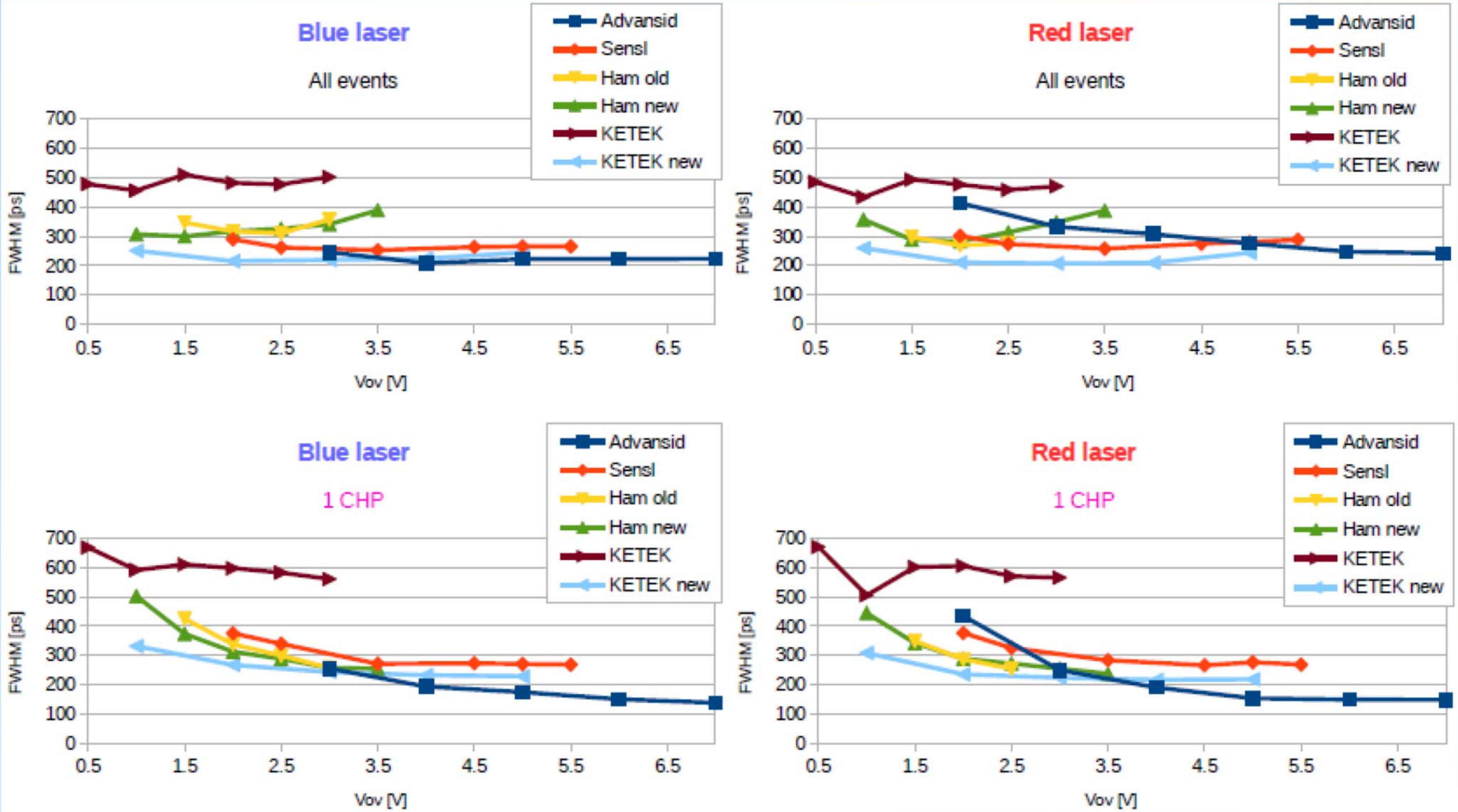
- AdvanSiD SiPM, V_{OV}=6V, T=-25°C
- blue laser λ=404nm
- events vith 2m.c. signal have two contributions: real double hit events with better resolution and optical crosstalk events





SiPM timing with uniform illumination

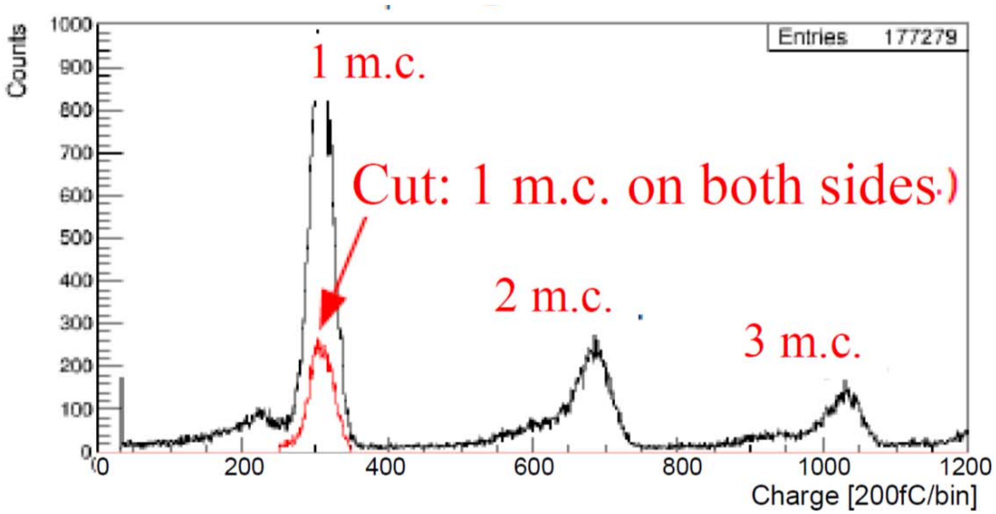
- Uniform illumination of SiPMs, T=-25°C
- Timing for all events (top) and events with single micro cell signal (bottom)

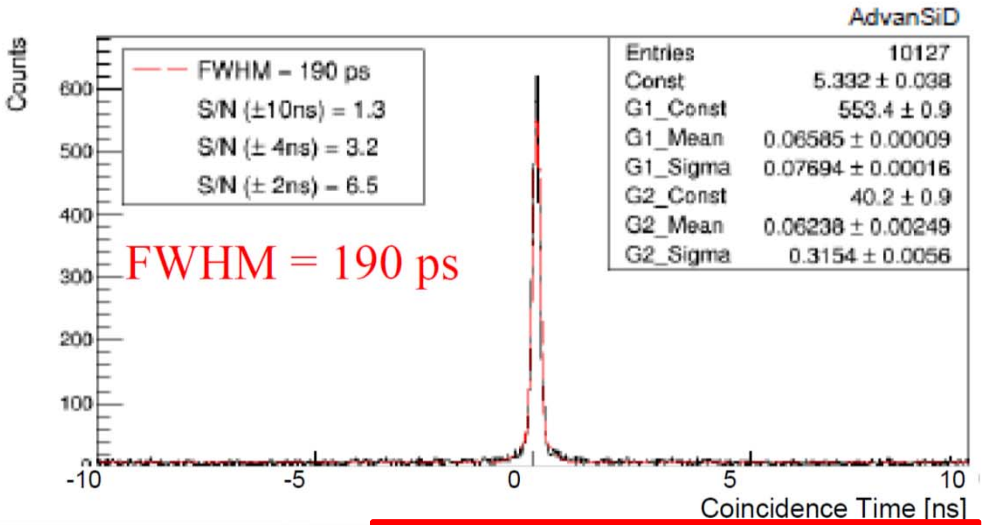


Coincidence time resolution with single cell events on both sides

- 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 and/or find the way to correct the timing (waveform sampling?)





S. Korpar, IEEE/NSS 2015

Cherenkov based TOF PET - summary

- main advantage prompt emission
- main disadvantage low number of photons
- requires very fast single photon sensor with high PDE.

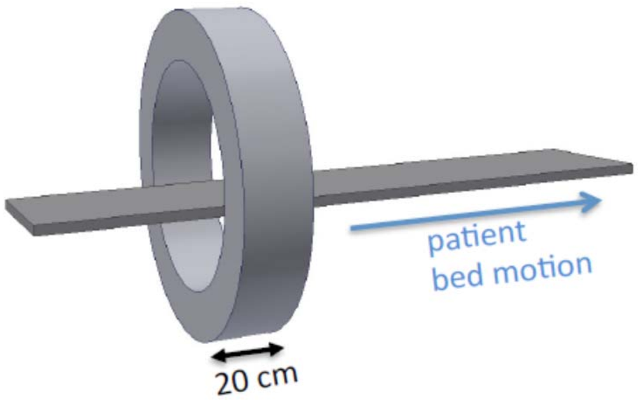
- We have studied several SiPMs from different producers to find the best candidate for the application → the best value for the efficiency reached 26% and the best CRT was ~300 ps (will improve with SiPM and crystal size matching).
- Performance of SiPMs is constantly improving and hopefully it will reach optimal performance → coincidence efficiency > 10% and timing < 200 ps FWHM

Cherenkov based PET scanner

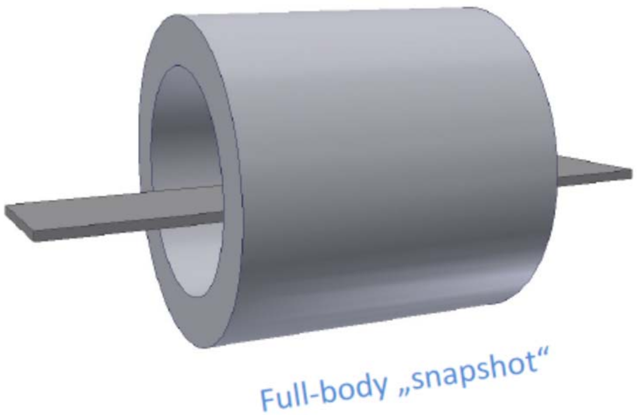
PbF2 not a scintillator → considerably cheaper!

Small attenuation length than LYSO – smaller parallax error

→ Cheaper normal scanner or



→ Full/half body device

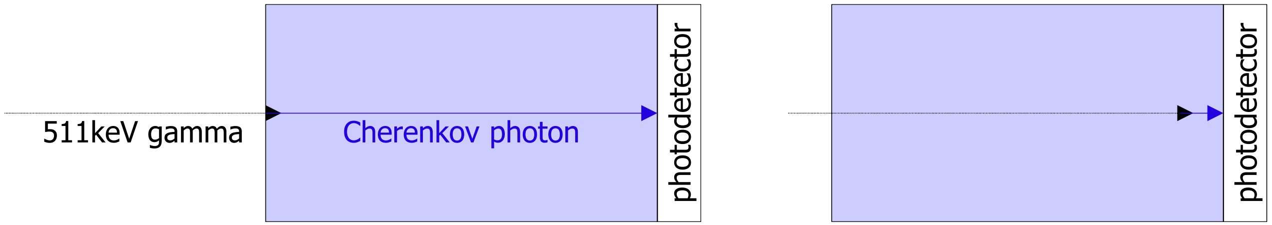


Limitations of Cherenkov photon timing

Cherenkov photons are produced promptly, but still need to reach the photodetector

Gamma rays travel faster than Cherenkov light!

Radiator dimensions, refractive index → intrinsic travel time spread due to different gamma interaction depths



d = 15 mm, n = 1.8: $t = d \cdot n / c_0 = 90$ ps $t = d / c_0 = 50$ ps → $\Delta t = 40$ ps

→ For a 15 mm long crystal the resulting FWHM contribution is ~40 ps

Can in principle be corrected for by

- a multi layer configuration with shorter crystals, or by
- measuring the depth of interaction (DOI)

N.B. This applies to all very fast light emission mechanisms.

DOI in Cherenkov based γ detectors

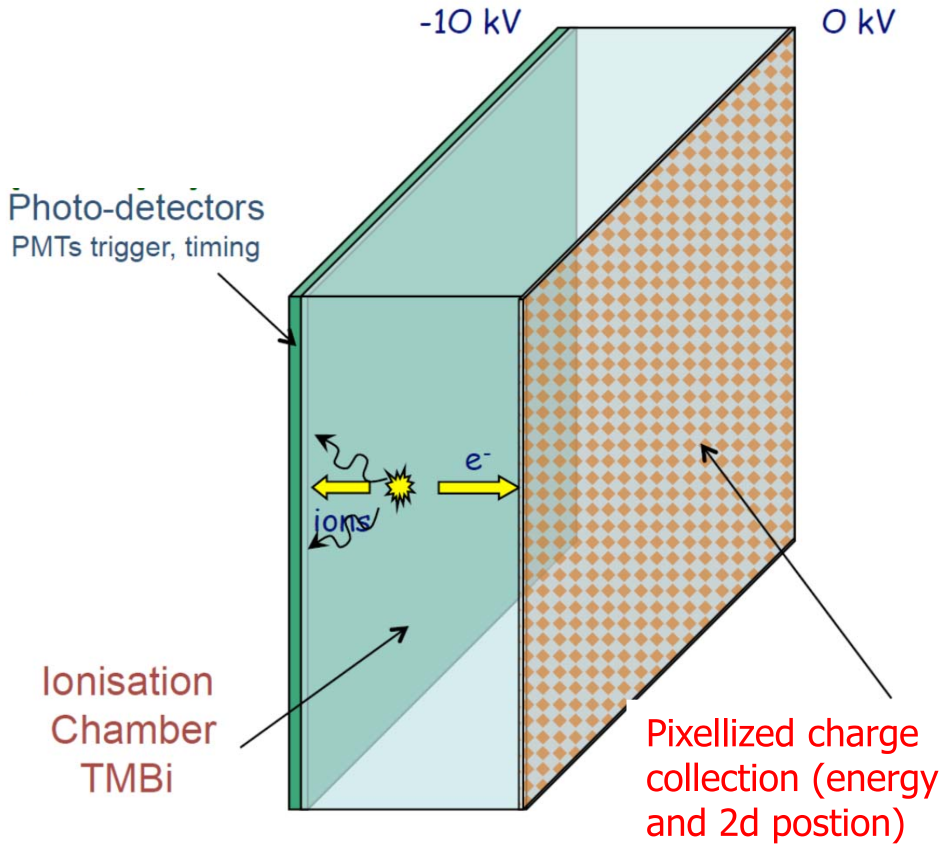
By measuring DOI we would

- Improve the timing
- Further mitigate the paralax error

A very interesting novel concept:
CaLIPSO (D. Yvon et al., CEA Saclay)

Use a heavy high Z liquid, TriMethyl Bismuth (TMBi), for gamma conversion and dual mode detection

- Cherenkov light for timing
- Ionisation for energy measurement and 3d gamma interaction point determination (2d pixels for charge collection and drift time)



D. Yvon et al., IEEE TNS, 61 (2014) 60.

N.B. Again a nice example of HEP → medical imaging

More ideas: Cherenkov++ …

Combine Cherenkov photons (time) and scintillator photons (efficiency): pioneered by P. Lecoq et al., S. Brunner et al.

More ideas around for multiple layer devices etc…

… stay tuned for more from the HEP comunity

Summary

Interplay of detector R&D for particle physics and medical imaging has a long history, and this will remain one of the sources of innovation in medical imaging

Cherenkov radiation based annihilation gamma detectors offer a promising method for very fast detection and potentially cheaper devices

A very active time for the development of very fast light sensors

MedAustron could provide an excellent place for testing and verification of novel techniques → a beam as soon as possible would be appreciated.

Close contact to the machine: new ideas on hadron therapy monitoring devices.

As a particle physicist with part time in R+D for medical imaging I am also looking forward to an interaction with the medical community around MedAustron.