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Study of a Cherenkov based TOF-PET module

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TOF-PET with Cherenkov light

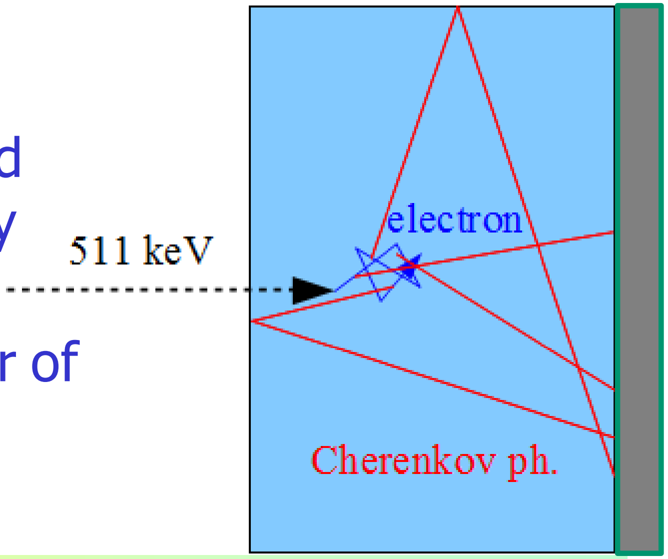
Time-of-Flight difference of annihilation gammas is used to improve the contrast of images obtained with PET:

- 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.

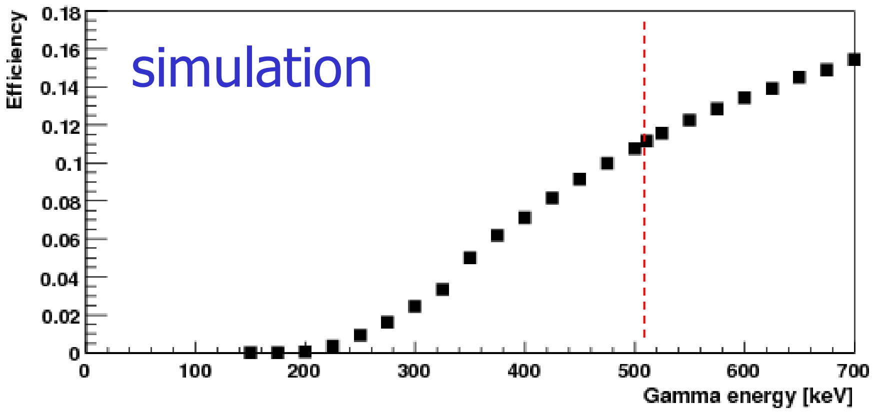
Disadvantage of Cherenkov light is a small number of Cherenkov photons produced per interaction → detection of single photons!



Intrinsic suppression of scattered events

Annihilation gammas scatter in patient or detector → unwanted background when scattered gamma is detected in coincidence

- Traditional PET
  - number of scintillation photons proportional to energy deposited
  - measurement of gamma energy → rejection of scattered (lower energy) events
- Cherenkov PET
  - at most a few photons detected → no energy information available
  - but: detection efficiency drops with gamma energy → intrinsic suppression



  - also: very high Z material, less Compton scattering in the radiator

Cherenkov radiator for gamma detection

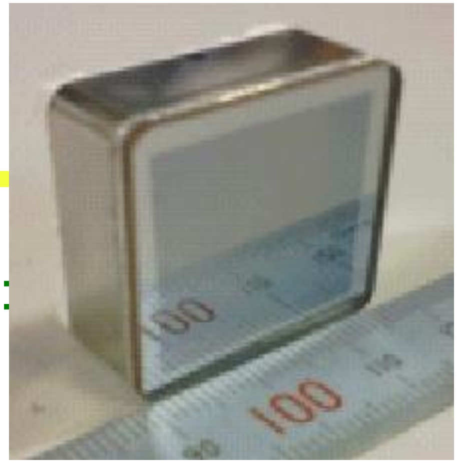
Requirements for the Cherenkov radiator for annihilation gammas:

- 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
- Studied: PbF_2 and $PbWO_4$

	ρ (g/cm³)	n	Cherenkov threshold (v/c_0)	e^- Cherenkov threshold (keV)	Cutoff wavelength (nm)	Radiation length (cm)
PbF_2	7.77	1.82	0.55	101	250	0.93
PWO	8.28	2.2	0.45	63	350	0.89

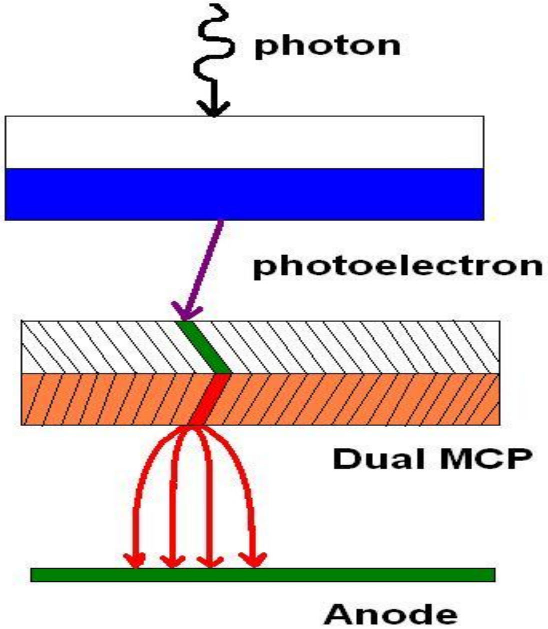
N.B. $PbWO_4$ is also a scintillator.

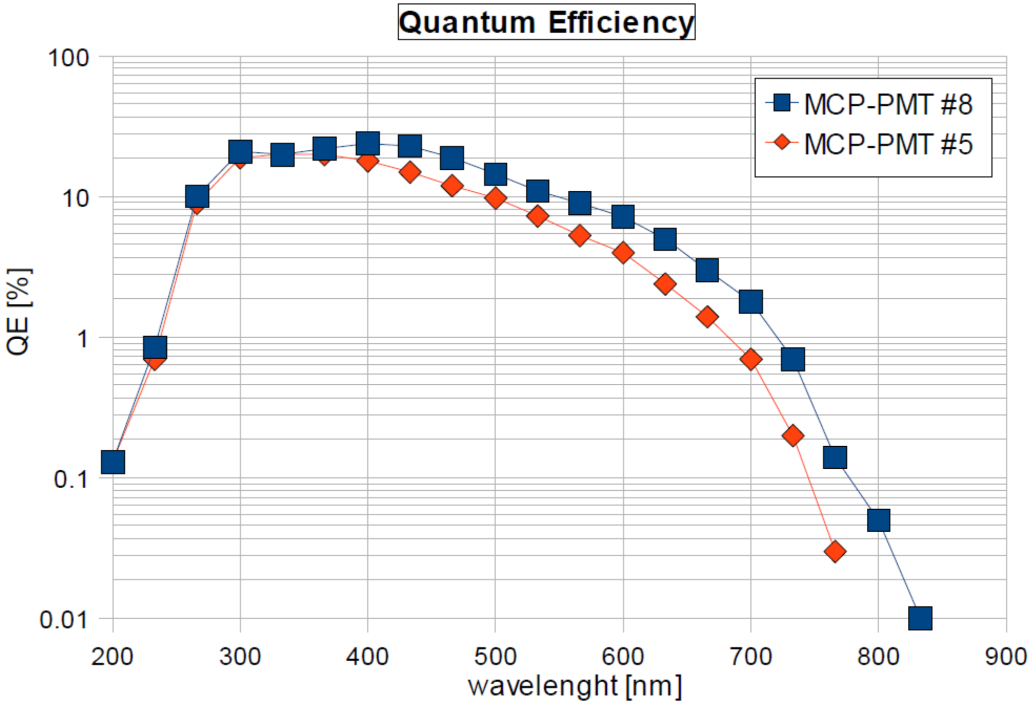
Photon detector: MCP-PMT



Hamamatsu SL10 MCP-PMT
(prototypes for Belle II TOP counter → talk by K. Matsuoka):

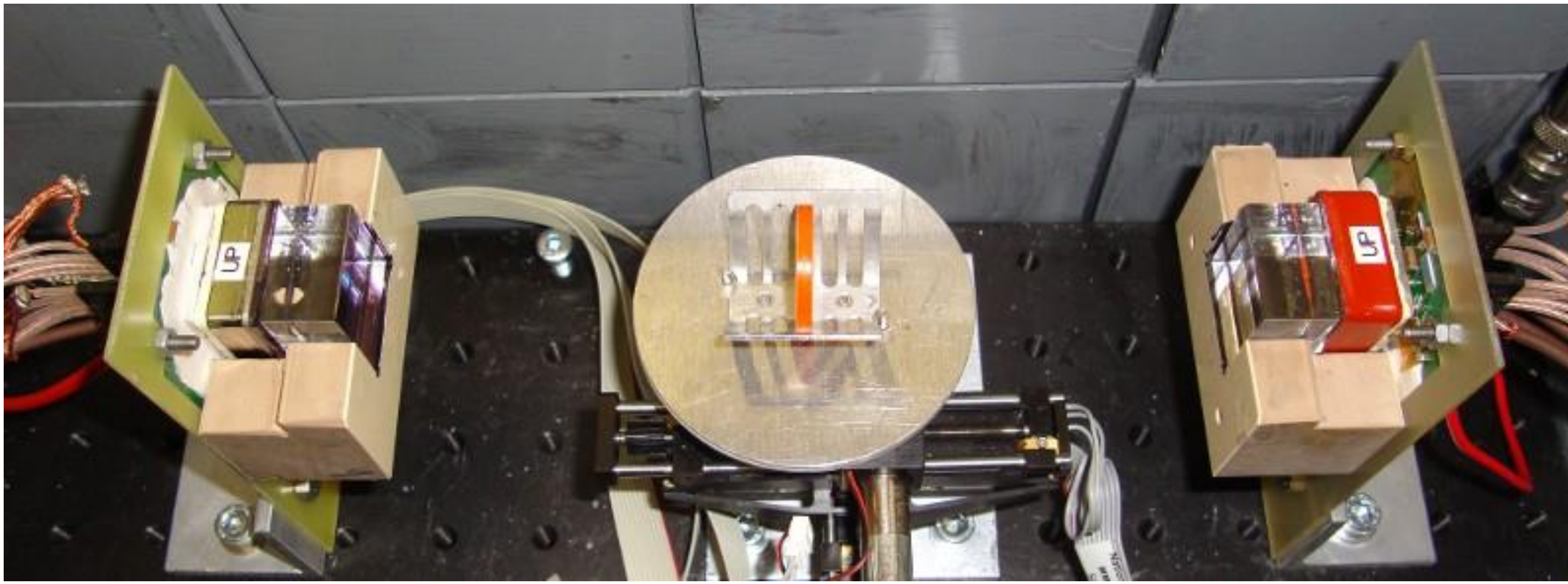
- multi-anode PMT with two MCP steps, 10 mm pores
- 16 (4x4) anode pads, pitch ~ 5.6 mm, gap ~ 0.3 mm
- box dimensions ~ 27.5 mm square
- excellent timing ~ 20ps for single photons
- multi-alkali photocathode
- 1.5 mm borosilicate window
- gain > 10^6





Experimental setup

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

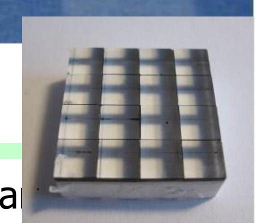


Cherenkov radiators:

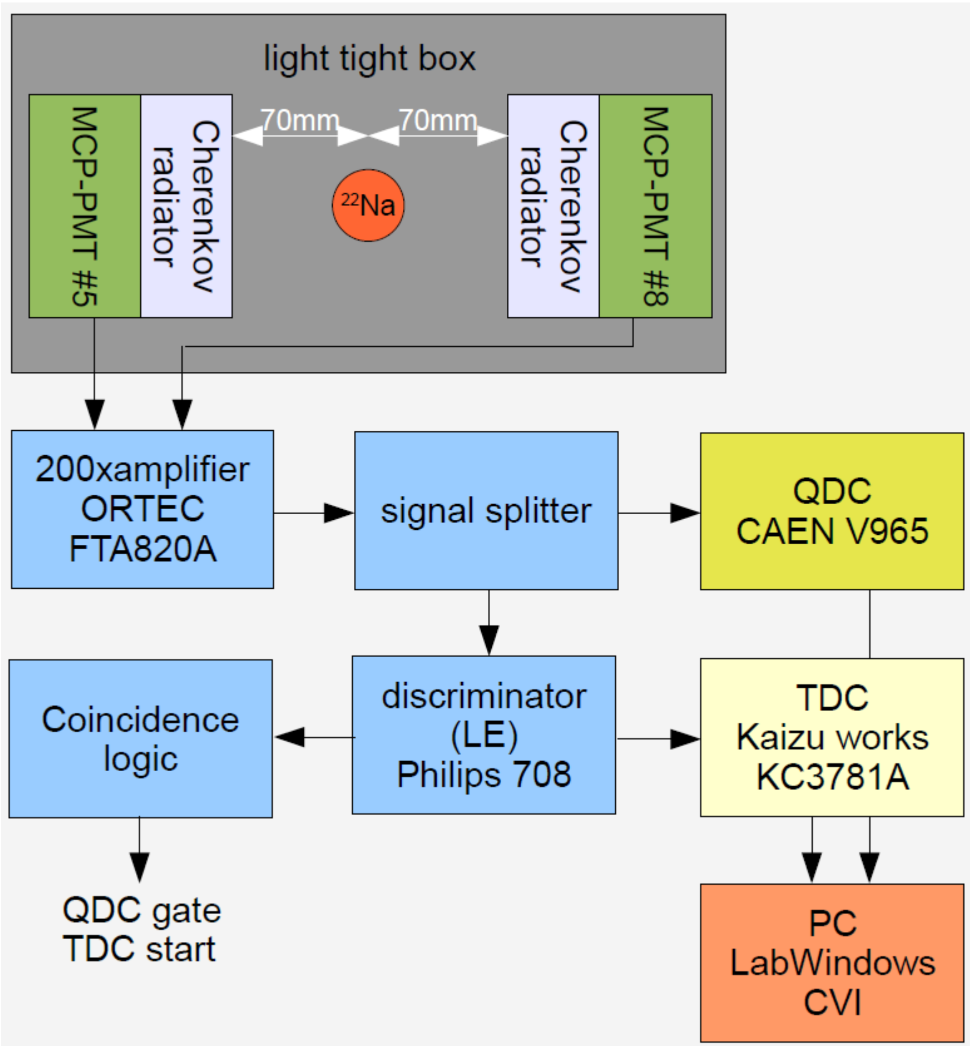
-monolithic: 25 x 25 x 5,15 mm^3 (PbF_2, $PbWO_4$)

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

-black painted, Teflon wrapped, bare



Experimental setup: read-out



Readout:

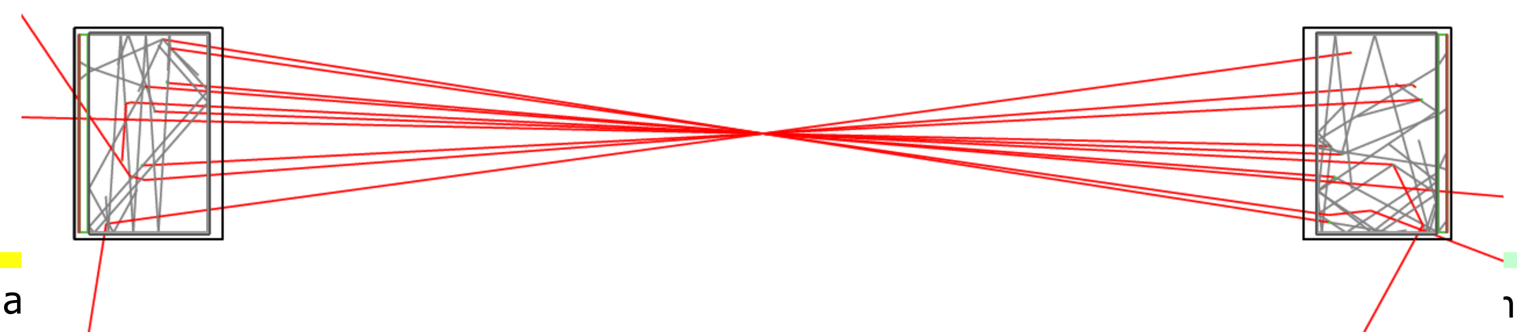
- amplifier: ORTEC FTA820
- discriminator: Philips sc. 708LE
- TDC: Kaizu works KC3781A
- QDC: CAEN V965

- Time-walk correction applied in the analysis step

Simulation: GEANT4

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

- gamma interactions with detector
- optical photons (Cherenkov and scintillation) produced between 250 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)
- photo-detector window coupled with optical grease (n=1.5)
- photo-detector QE (peak 24% @ 400nm)
- photo-detector intrinsic timing modeled according to the measured response function



Cherenkov photon production and detection

Simulation results for PbF_2 and $PbWO_4$ radiators

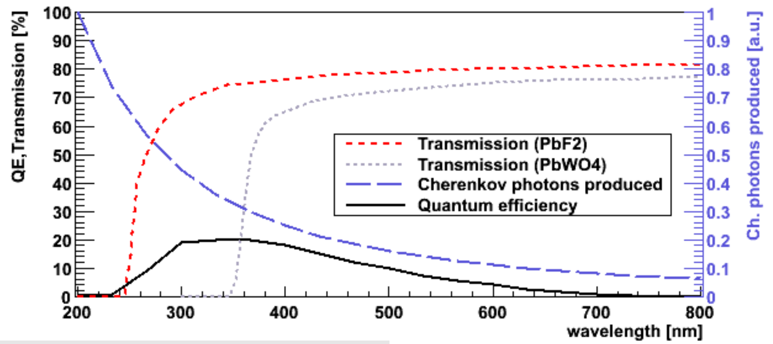
- 25x25x15 mm^3 crystal, black painted
- coupled to photo-detector with realistic PDE

	PbF_2	$PbWO_4$
Gammas interacting	79.7%	80.1%
Electrons produced	1.53	1.57
Ch. photons produced *	15.1	22.2
Ch.photons reaching photodetector	2.11	1.27
Detected Ch. photons	0.14	0.07
Detected scint. photons	-	0.47

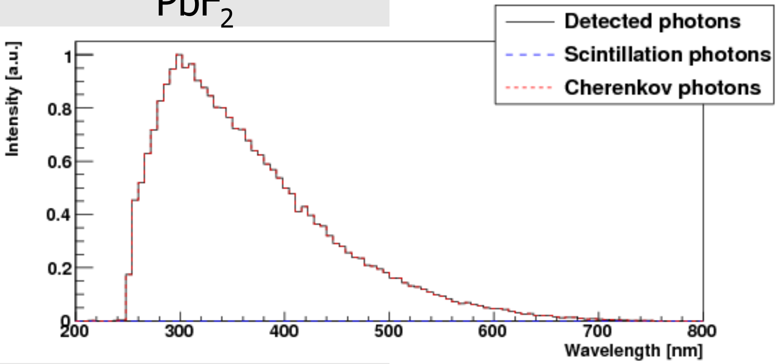
* in the 200 - 800 nm wavelength range

More Cherenkov photons produced in $PbWO_4$

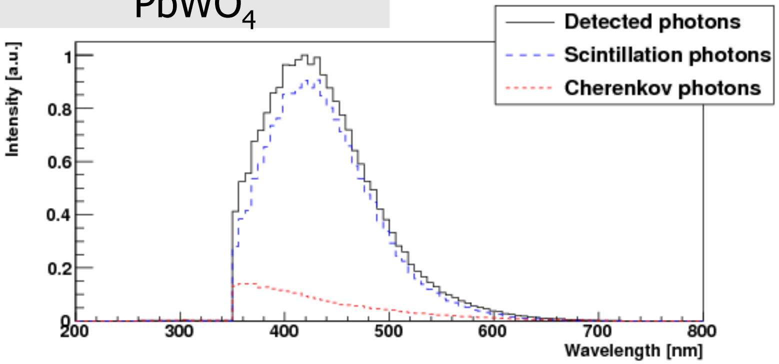
More are detected in PbF_2 due to a better optical transmission (lower λ_{cutoff})



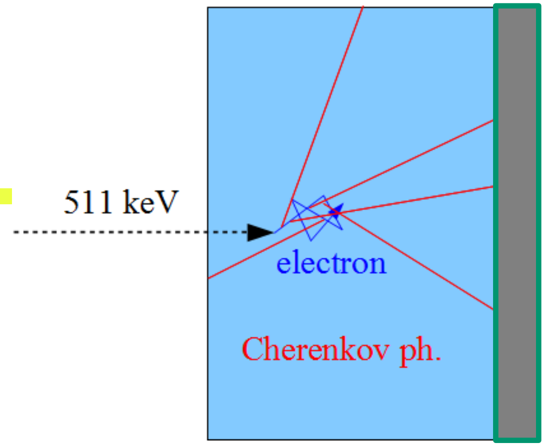
PbF_2



$PbWO_4$



Experimental results: Back-to-back time resolution

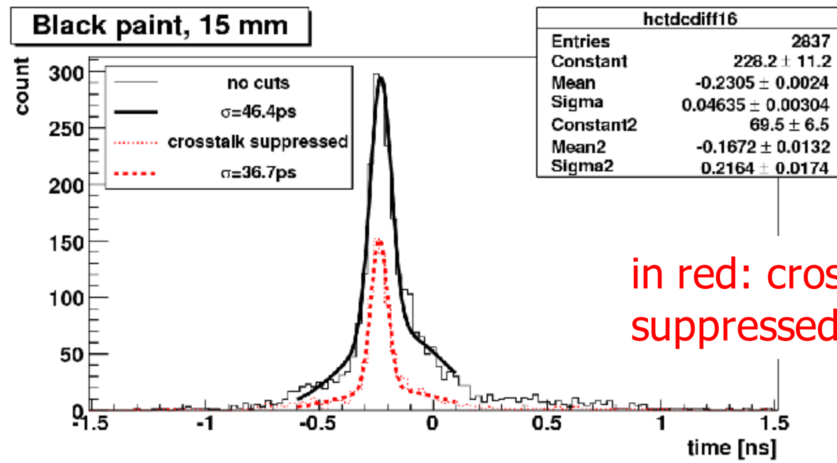


Best timing resolution: black painted PbF_2 crystals (Cherenkov light hitting the walls is absorbed - delayed Cherenkov photons suppressed → improved timing, reduced efficiency)

Data taken with :

- 15 mm long crystal:

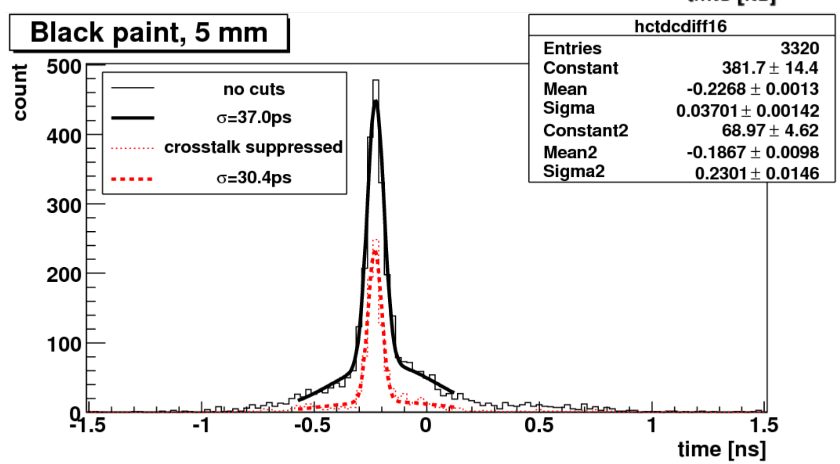
→ FWHM ~ 95 ps



in red: cross-talk suppressed

- 5 mm long crystal:

→ FWHM ~ 70 ps

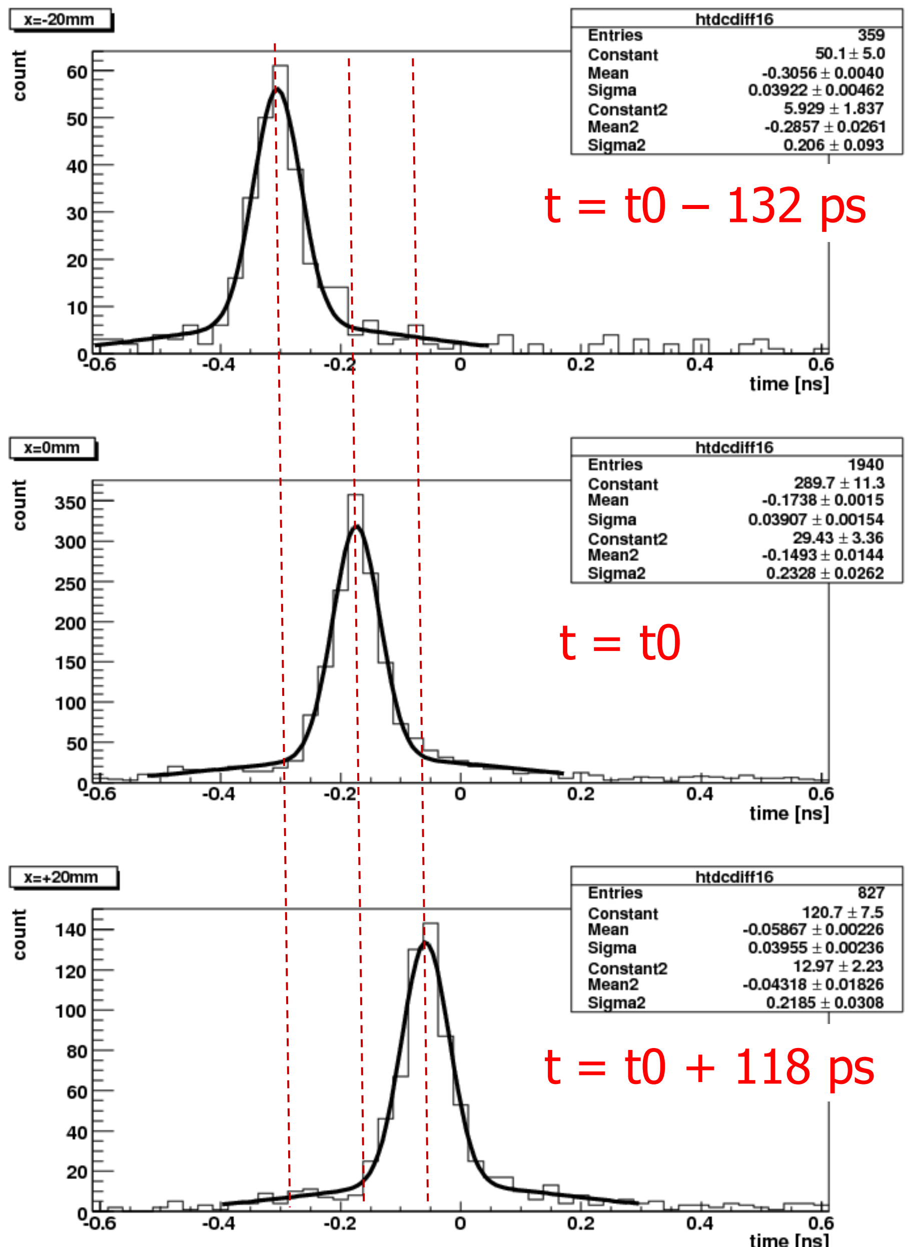


→ NIM A654(2011)532–538

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 ~ 6 mm rms,
  ~ 14 mm FWHM

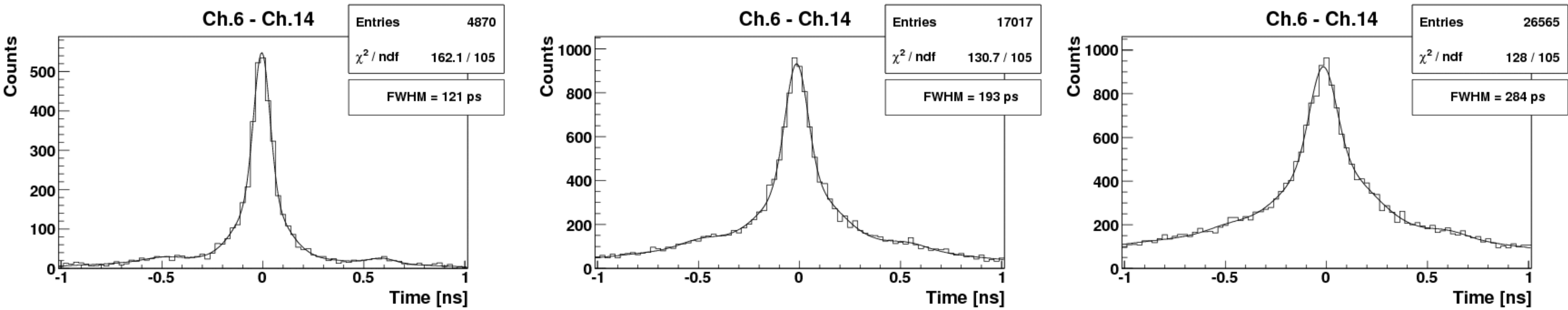


Black painted 15 mm PbF_2 crystals.

→ NIM A654(2011)532–538

Time resolution, PbF_2

TOF resolution for different radiator surfaces (15 mm thick PbF_2):
black painted: **121 ps** FWHM, bare: **193 ps** FWHM, Teflon wrapped: **284 ps** FWHM



Indirect photons (bare and Teflon wrapped crystals): adds a very wide component, FWHM increases faster than sigma of the peak

→ FWHM probably not the right quantity to compare

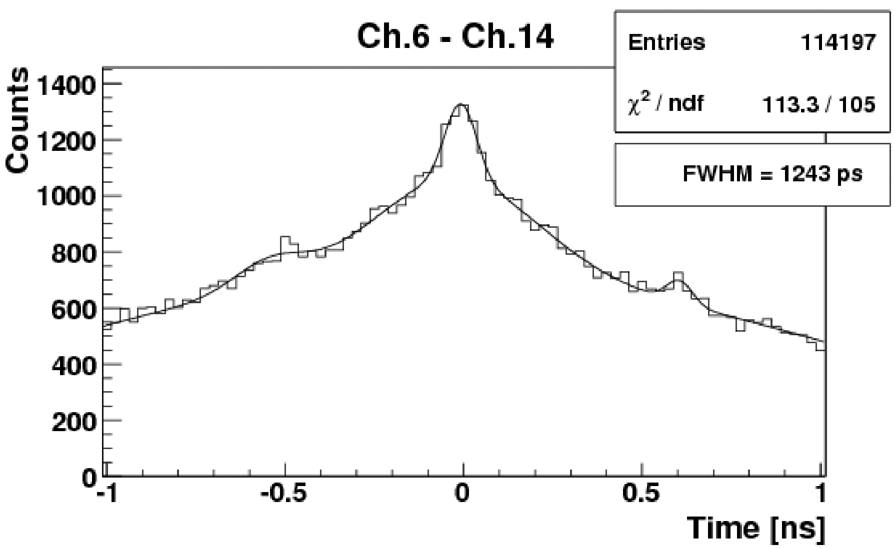
→ has to be checked on reconstructed images

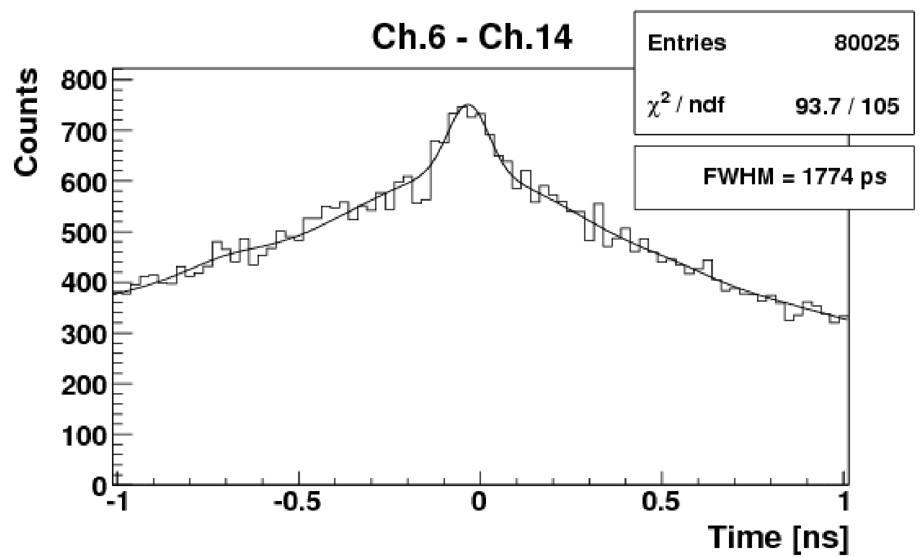
N.B. Somewhat worse timing performance than in the original set-up; now we have more channels, and not a perfect calibration.

Time resolution, $PbWO_4$

TOF resolution for $PbWO_4$ (black painted):

- time distributions dominated by scintillation background, with a small Cherenkov peak
- 5 mm thick: **1.2 ns** FWHM, 15 mm thick: **1.7 ns** FWHM



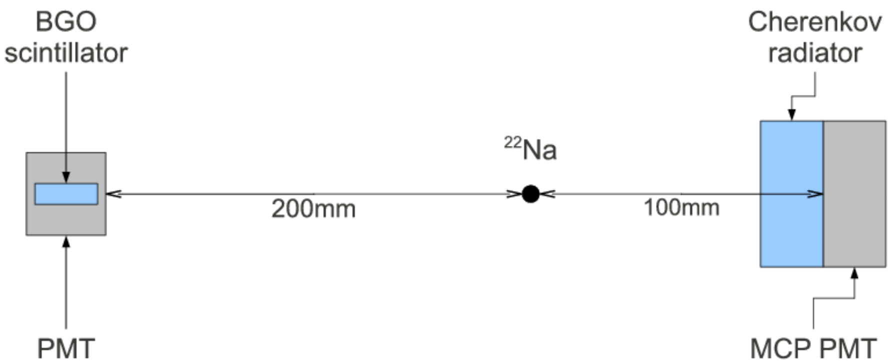


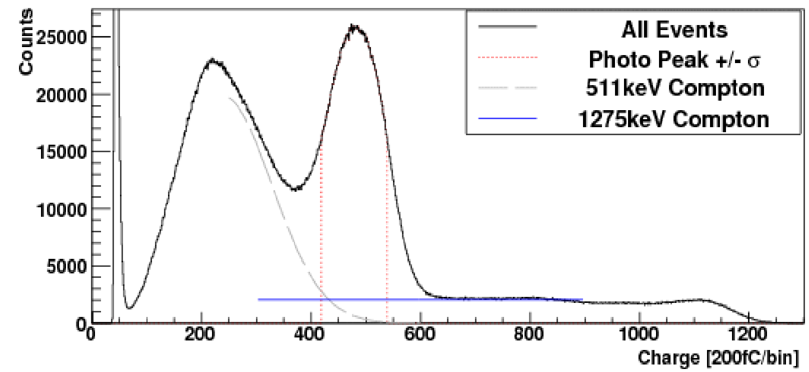
+ smaller number of Cherenkov photons

→ $PbWO_4$ does not look like a competitive Cherenkov detector for annihilation gammas

Detection efficiency

Triggered photons: on one side of the ^{22}Na source use a scintillation detector with energy measurement





Detection efficiency =

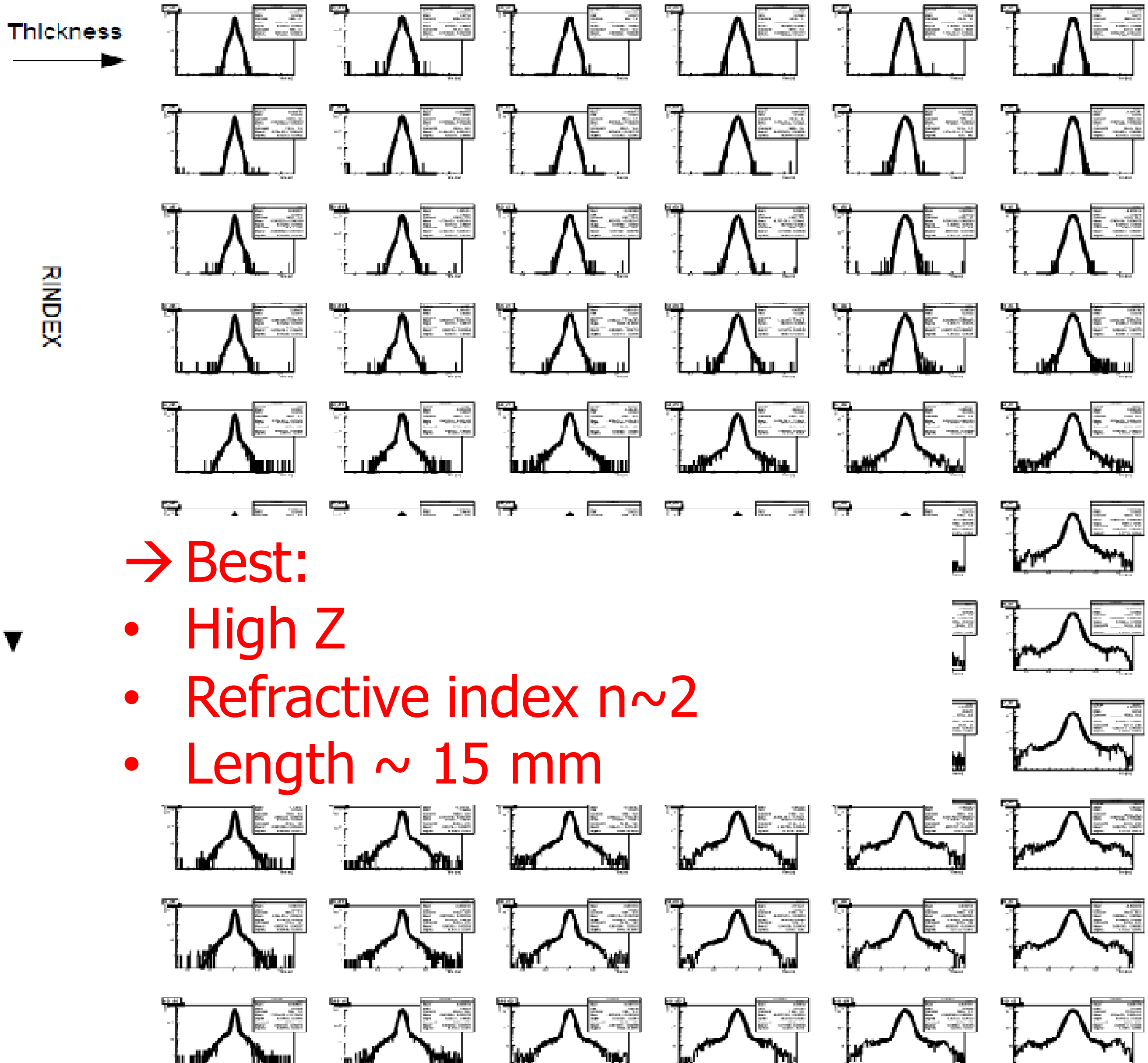
<u># events detected on Cherenkov detector with a 511 keV trigger</u>

events with 511 keV trigger

Corrected for events due to Compton scattering of 1275 kev gammas from ^{22}Na source

→ Results: from **4.3%** (5 mm thick, black painted PbF_2) up to **18%** (15 mm thick, Teflon wrapped PbF_2)

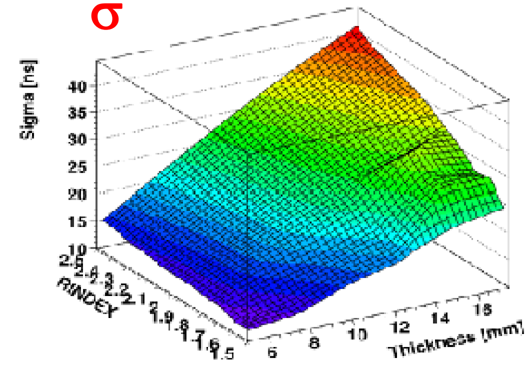
Simulation: search for optimum radiator parameters



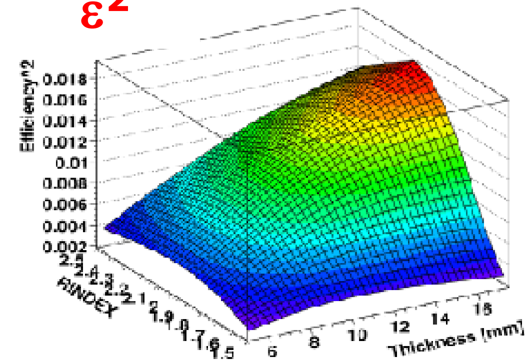
→ Best:

- High Z
- Refractive index n~2
- Length ~ 15 mm

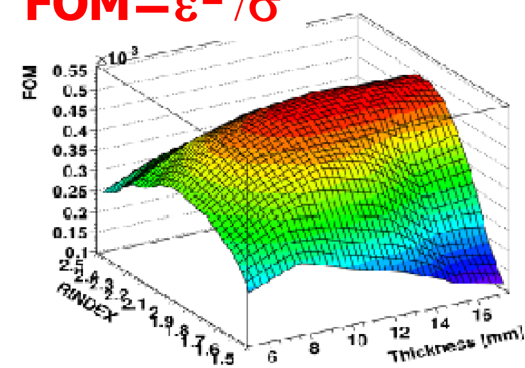
σ



ε^2



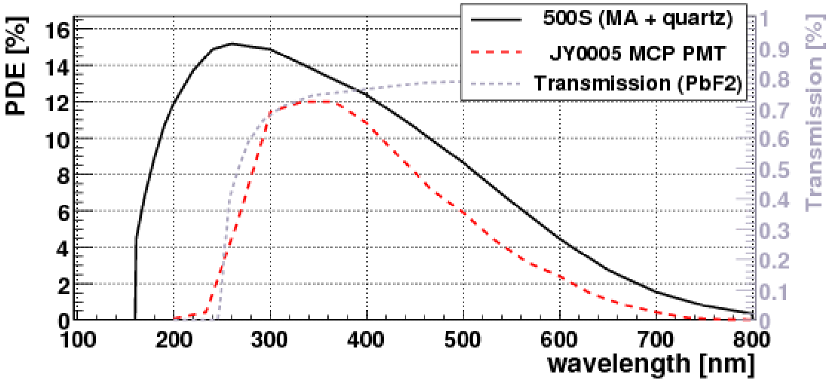
FOM=ε^2/σ



Efficiency improvements, MC estimates

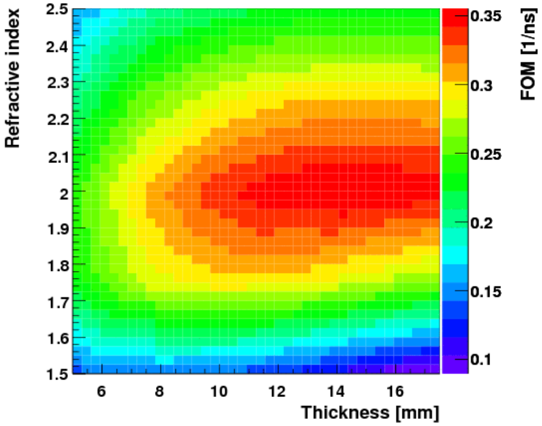
- **Photodetector**:
  - improved photon detection efficiency
    - photocathode with better QE
    - window, transparent to lower λ (quartz → 160 nm)
  - example: Hamamatsu 500S photocathode

  → **1.4x** detection efficiency (2x in FOM=ε^2/σ)



- **Transport of photons** from radiator to photo-detector:
  - optimal optical coupling of the radiator to the photon detector (at present radiator refractive index n=1.8, optical grease n=1.5, PMT window n=1.5) → ~**1.4x** efficiency (2x FOM)

- **Radiator optimization** with a hypothetical, PbF_2-like (using 500S photocathode):
  - With an optimized refractive index, thickness (n=2.0, d~14mm) → **1.5x** efficiency (3x FOM)
  - Improved optical transmission (λ_{cutoff} = 160 nm) → **2.4x** efficiency (6x FOM)

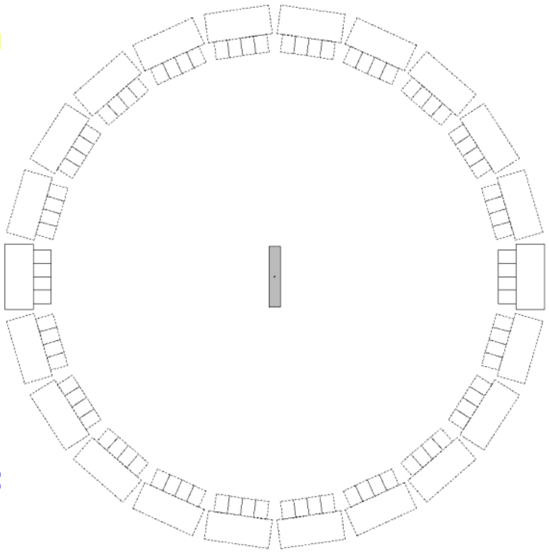


→ poster by S. Kurosawa et al, on $Gd_3Ga_5O_{12}$

Reconstruction

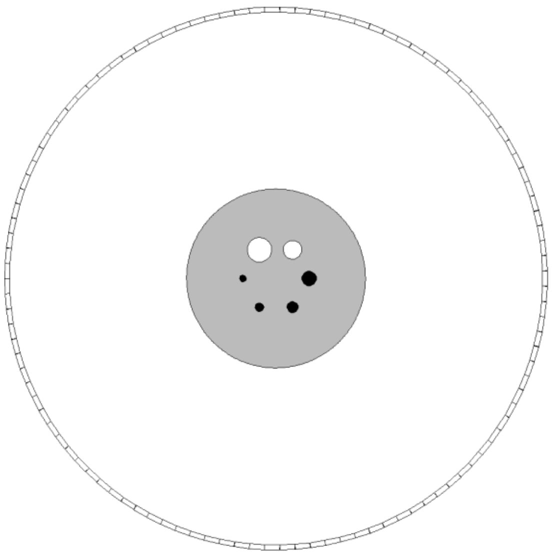
Cherenkov PET tested experimentally

- data equivalent to one PET ring obtained with only two detectors
- source rotated in discrete steps
- data collected at each step for the same amount of time
- D = 185 mm, H = 22.5 mm



Full body PET scanner simulated

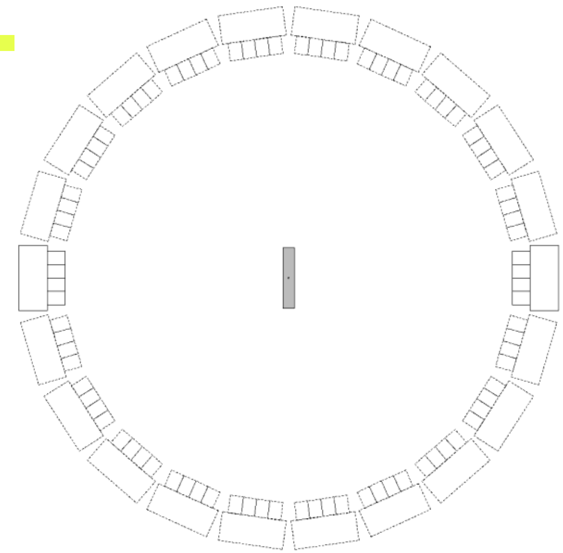
- D = 800 mm, 15 rings (H = 340 mm)
- phantom with d = 270 mm, 4 hot spheres (d: 10 - 22 mm) and 2 cold spheres (d = 28, 37mm)

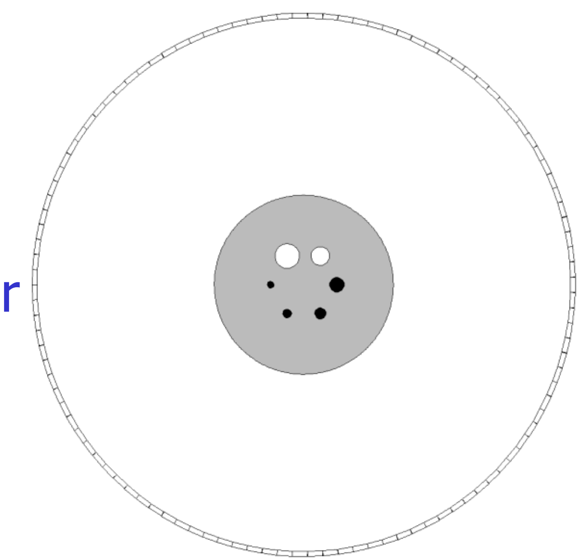


Reconstruction

Reconstruction algorithms:

- **Filtered backprojection (FBP):** basic non-TOF algorithm
- **TOF weighted FBP:** pixels along LOR incremented with TOF response defined weight
- **Most likely position (MLP):** point of decay on LOR calculated from TOF information
- **Filtered MLP:** MLP image deconvoluted for TOF response

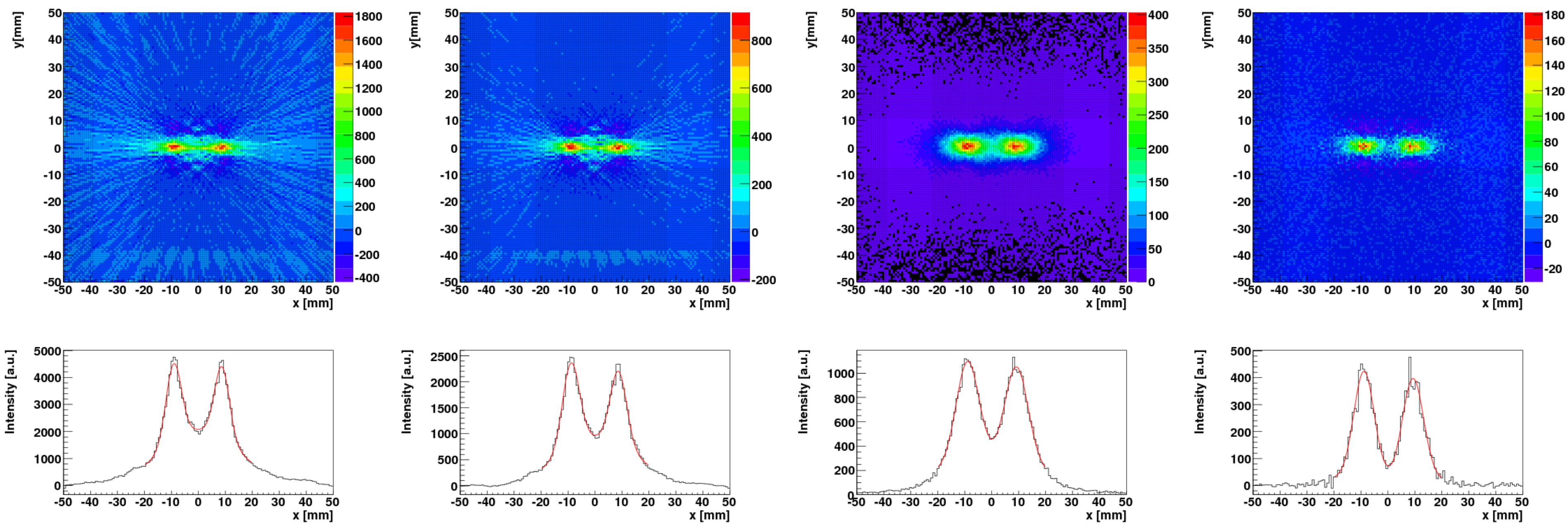




Reconstruction - experiment

- ^{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

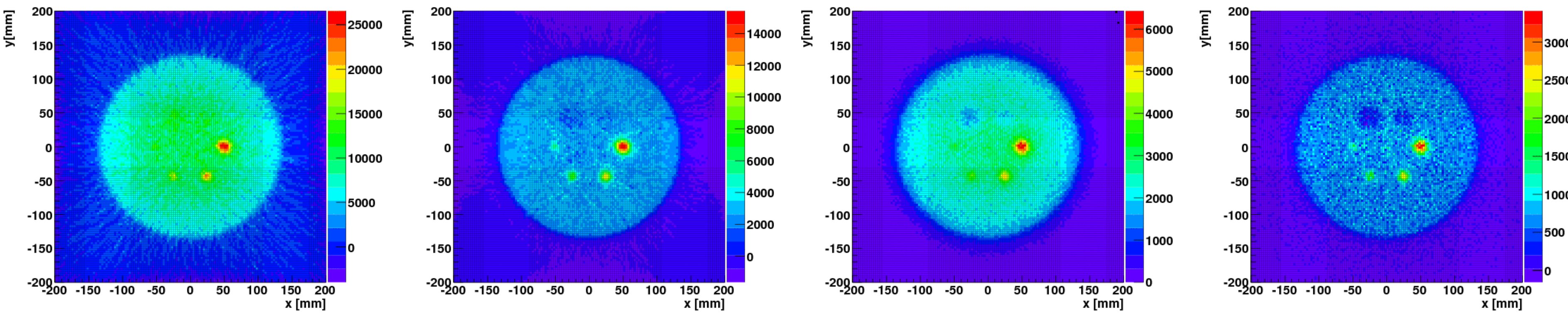


→ Simple, very fast Most-likely-point (MLP) method (~histograming of points) already gives a reasonable picture

Reconstruction - simulation

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

(non-TOF) FBP | TOF w. FBP | MLP | Filtered MLP



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

Summary

TOF PET with Cherenkov light

- Excellent time resolution: down to ~100 ps FWHM
- Intrinsic suppression of scattered events in spite of no energy measurement
- Low efficiency: 4 – 18% (per gamma)

Considerable improvements possible:

- With available technologies:

- photodetector QE
- better light extraction

- With an optimal Cherenkov radiator

TOF PET image reconstruction:

- faster, simpler reconstruction algorithms possible
- reflective radiator wrapping better contrast-to-noise ratio than black paint (preliminary – to be further studied)

Conclusions

TOF PET with Cherenkov light

- Promising method
- Challenge: improve efficiency, several options quite promising
- Fast and simple reconstruction possible – potentially interesting already with the present layout

With possible improvements in efficiency, Cherenkov TOF PET could become competitive (and potentially complementary because of fast reconstruction) with the traditional scintillator TOF PET

Back-up slides

TOF resolution, efficiency

Experimental results :

Radiator	ε [%]	ε^2 [%]	FWHM [ps]	FOM [%/ns]
5mm, black paint	**4.3**	0.18	**103**	1.8
15mm, black paint	**6.1**	0.37	**132**	2.8
15mm, bare	**12**	1.44	**186**	7.7
15 mm, Teflon	**18**	3.24	**271**	12.0
4x4, black paint	**4.3**	0.18	**116**	1.6
4x4, Teflon	**8.6**	0.74	**301**	2.5

Simulation results:

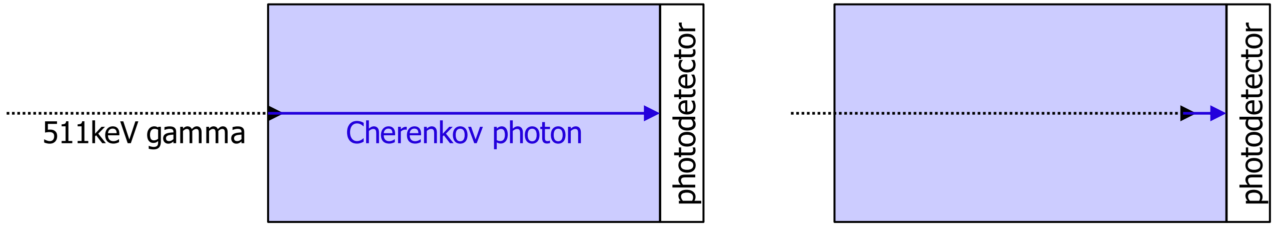
Radiator	ε [%]	ε^2 [%]	FWHM w/o photod. resp. [ps]	FWHM w/ photod. resp. [ps]	FOM [%/ns]
5mm, black paint	**6.2**	0.38	37.7	**84.4**	4.5
15mm, black paint	**11**	1.21	92.8	**148**	8.2
15mm, bare	**16**	2.56	118	**215**	11.9
15 mm, Teflon	**18**	3.24	130	**241**	13.4
4x4, black paint	**6.7**	0.45	45.7	**92.2**	4.9
4x4, Teflon	**12**	1.44	62.5	**154**	9.4

Note 1: Some discrepancies in the efficiency between data and MC could come from ageing of the MCP PMT photocathodes – was discovered after measurements were completed.

Note 2: FOM values: only informative, not Gaussian distributions

Cherenkov photon timing limitations

- Cherenkov photons are produced promptly, but still need to reach the photodetector
  - Radiator dimensions, refractive index → 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

  - Different photon emission angles
  - Reflections from radiator entry and side surfaces
    - total internal reflection (high refractive index)
    - reflective wrapping
- Black paint reduces total internal reflections and stops many photons
  - improved timing
  - reduced detection efficiency (but from photons with worse timing)

MCP PMT timing

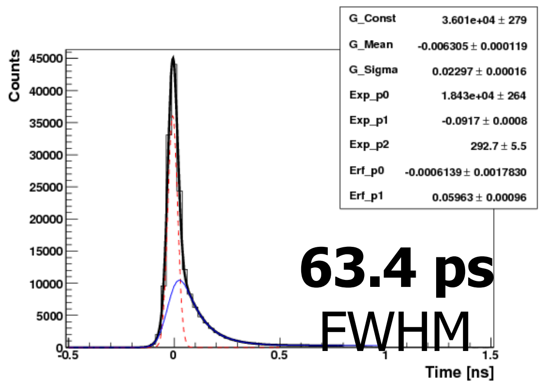
- Surfaces of MCP PMTs illuminated with very weak (single photon level) red (636 nm) and blue (404 nm) laser light pulses
- Time responses of 3 MCP PMT samples (incl. laser and electronics):

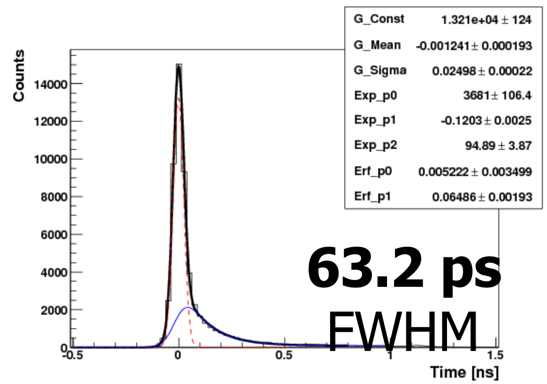
JY0002

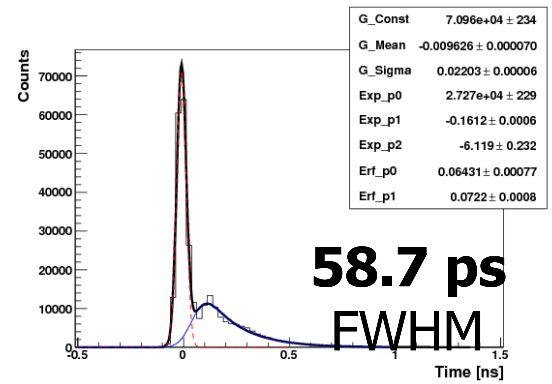
JY0005

JY0008

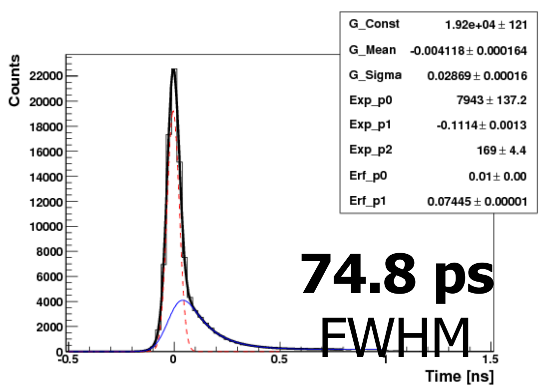
Red

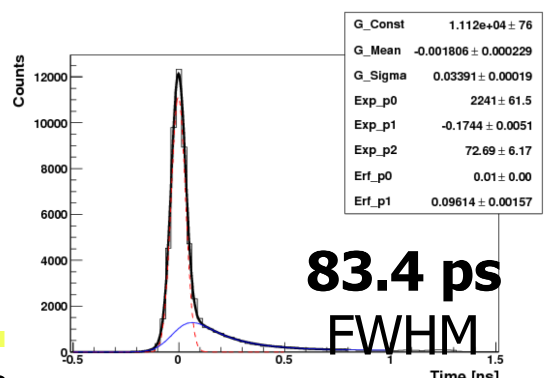






Blue

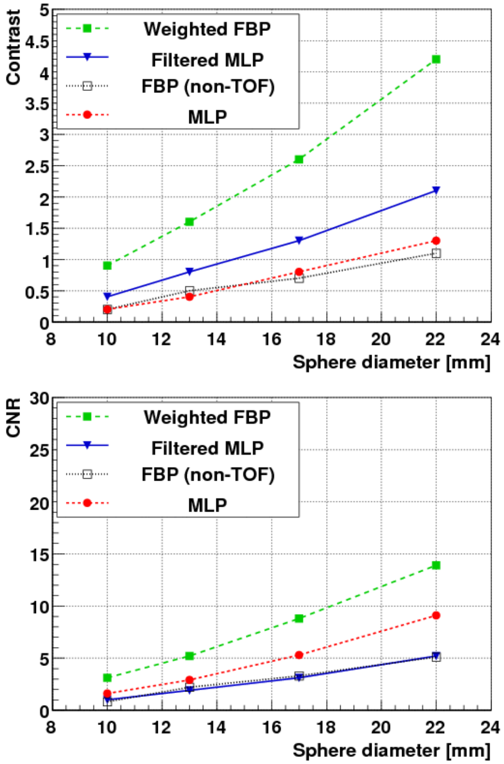




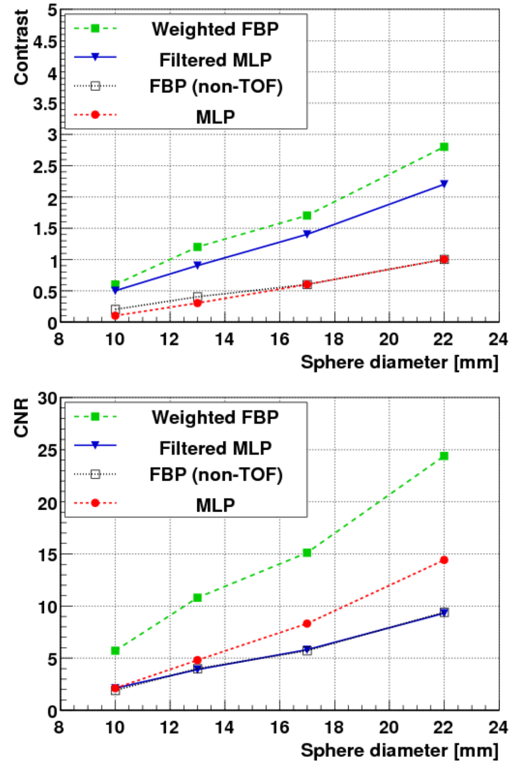
Reconstruction - simulation (2)

Contrast and contrast-to-noise ratios (CNR) of hot spheres (very preliminary!):

black painted



Teflon wrapped



- Black painted (better TOF resolution) → better contrast, Teflon wrapped (higher statistics) → better CNR (despite the tails in timing distributions)
- TOF information significantly improves CNR
- Simple, very fast MLP → very good CNR