Study of TOF PET using Cherenkov Light

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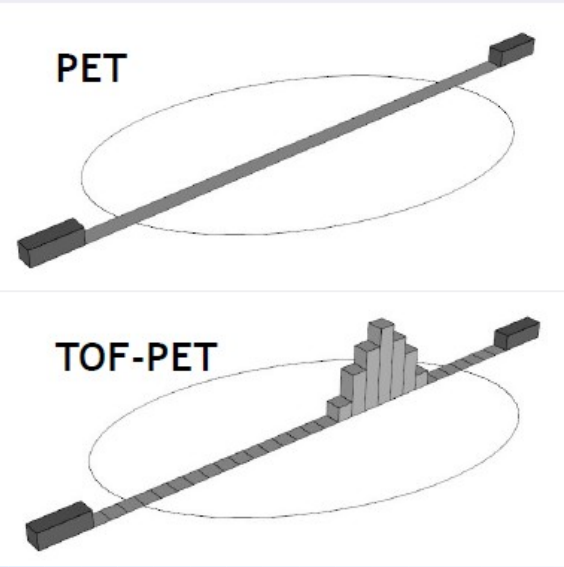

Outline:

- Cherenkov radiator for TOF-PET
- MCP-PMT & setup
- Back-to-back timing resolution
- Summary and plan

TOF-PET with Cherenkov light

Time-of-Flight difference of annihilation gammas is used to improve the contrast of images obtained wit 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 scintillation process

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 small number of Cherenkov photons produced per interaction → detection of single photons!

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Annihilation gammas and Cherenkov radiation

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)	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

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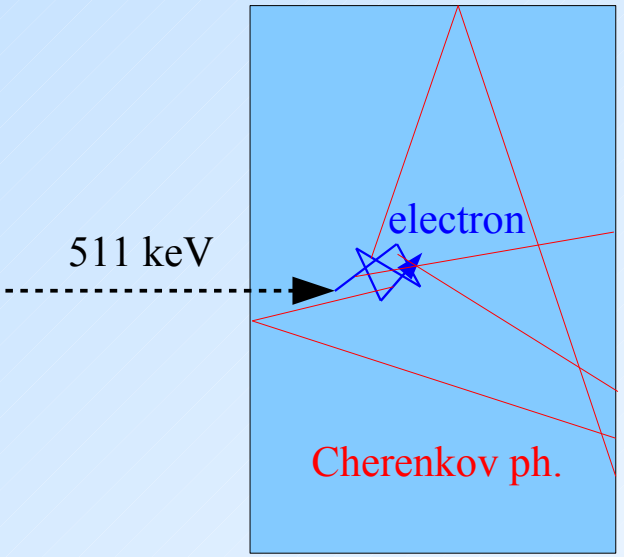
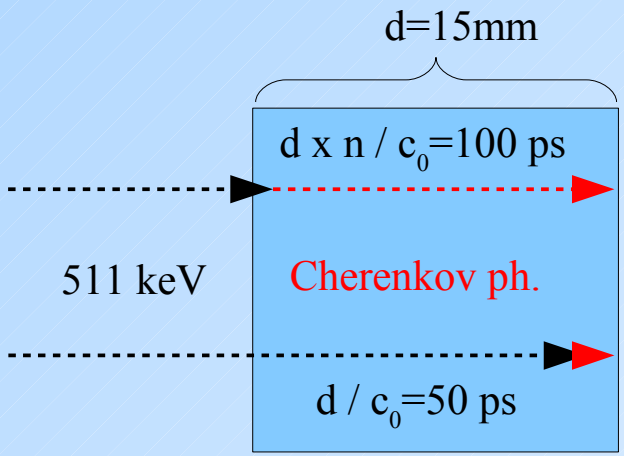
Time spread and number of photons

Estimates of expected number of Cherenkov photons produced and timing spread assuming n=2, electron path length 100 μm, Cherenkov photon energy interval 3 eV, 15 mm thick crystal.

$$N \approx \frac{370}{eV\,cm} \cdot l \cdot \Delta E \cdot \sin^2 \vartheta_C$$

$$N \approx 370 \times 0.01 \times 2 \times 0.75 \approx 8$$





Even for Cherenkov photons going strait to the photodetector the time spread of 50 ps results from depth of interaction.

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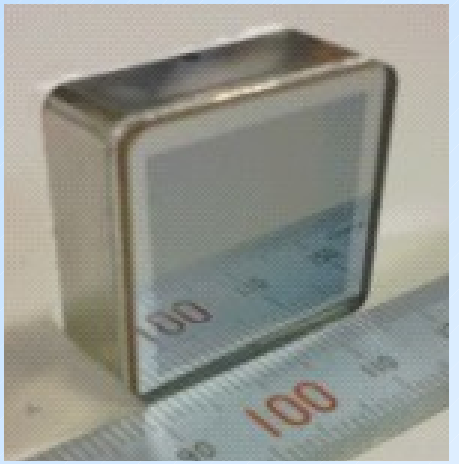
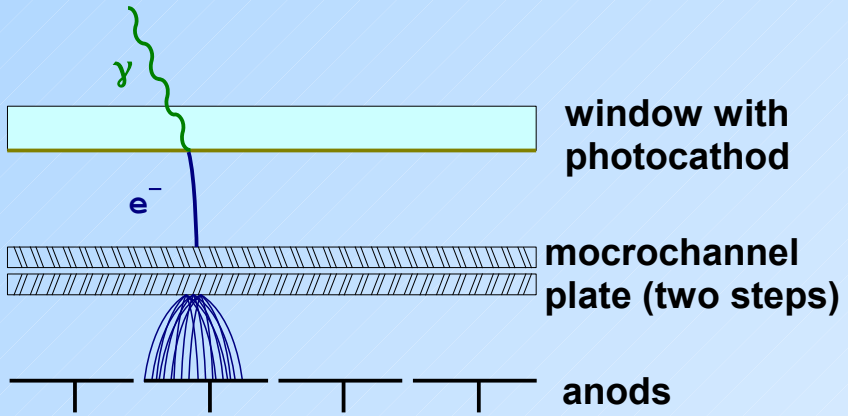
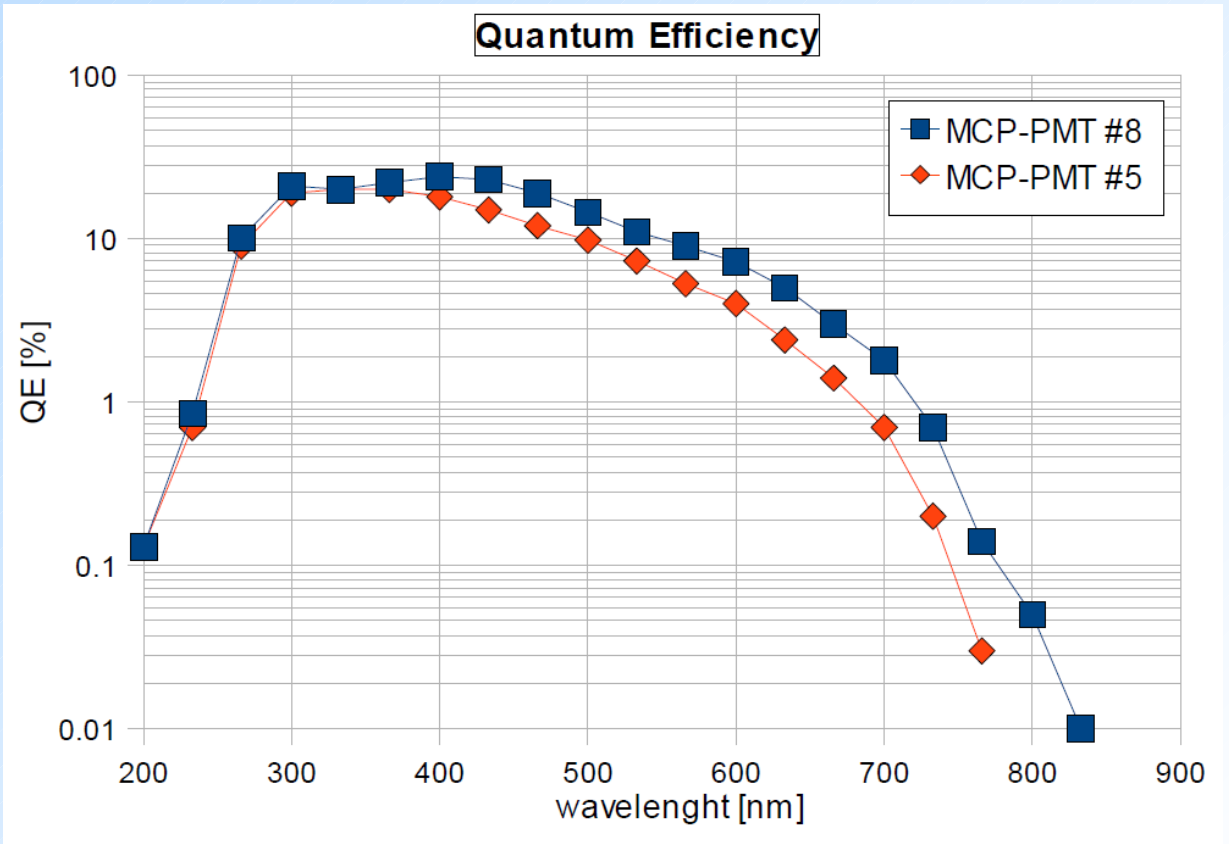
MCP-PMT properties



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 ~ 20ps for single ph.
- multi-alkali photocathode
- 1.5 mm borosilcate window
- gain > 10^6





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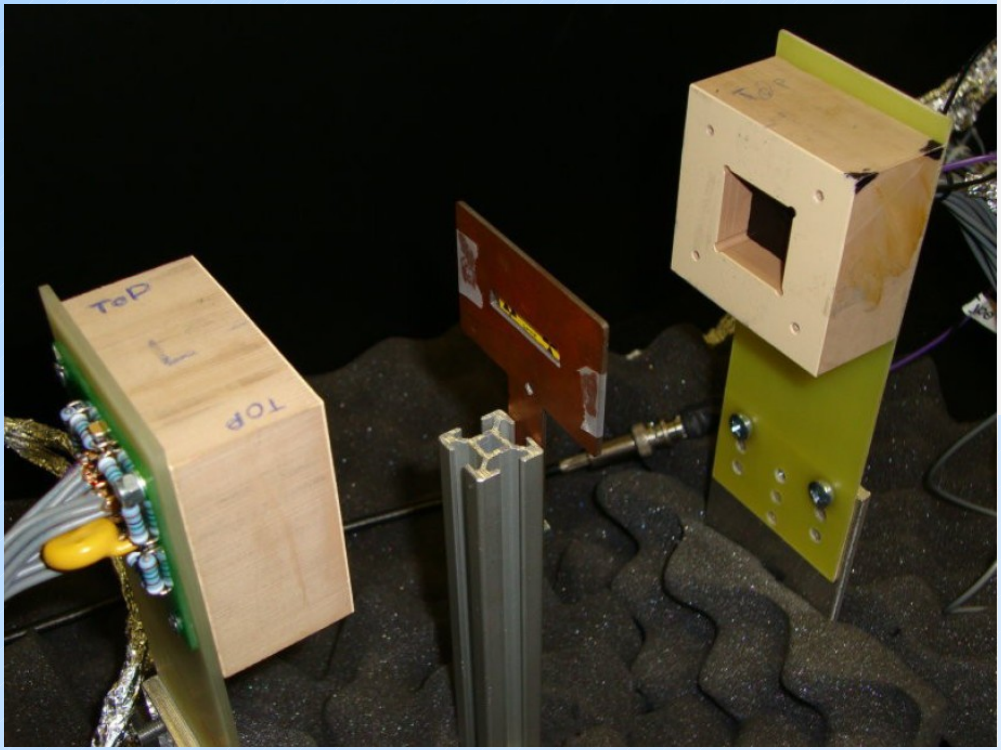
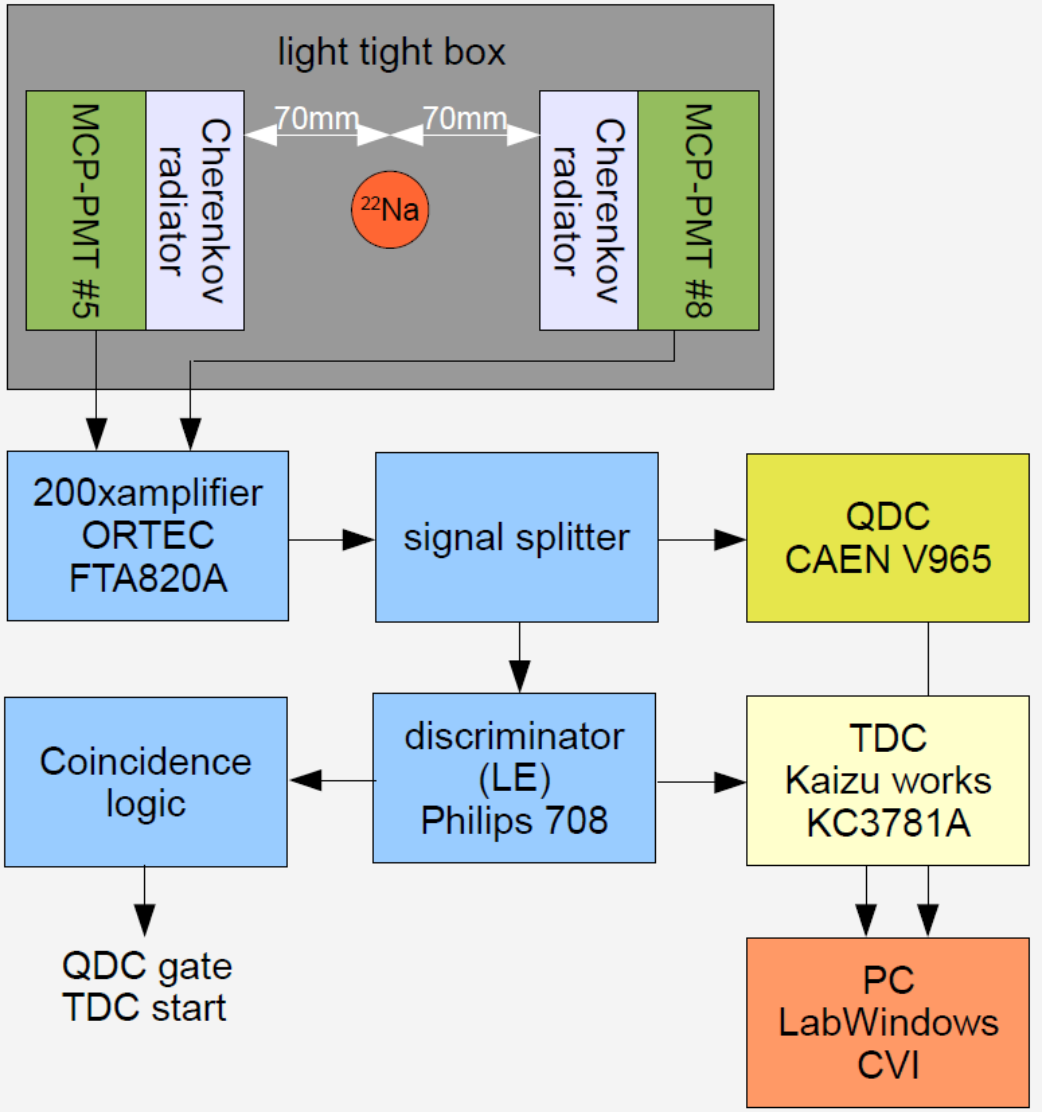
Setup

Readout:

- ORTEC FTA820 amplifier
- Philips sc. 708 LE discriminator
- Kaizu works KC3781A TDC (25ps)
- CAEN V965 QDC

Time-walk correction applied in anlysis





Two detectors in back-to-back configuration with 25x25x15(5) mm^3 crystals coupled to MCP-PMT with optical grease.

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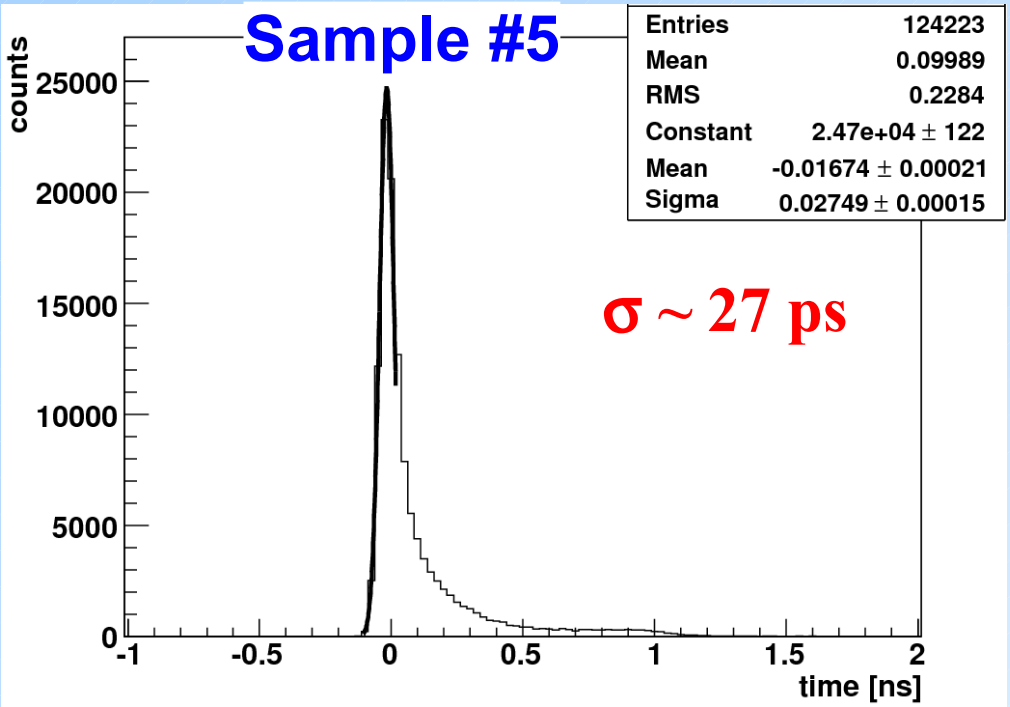
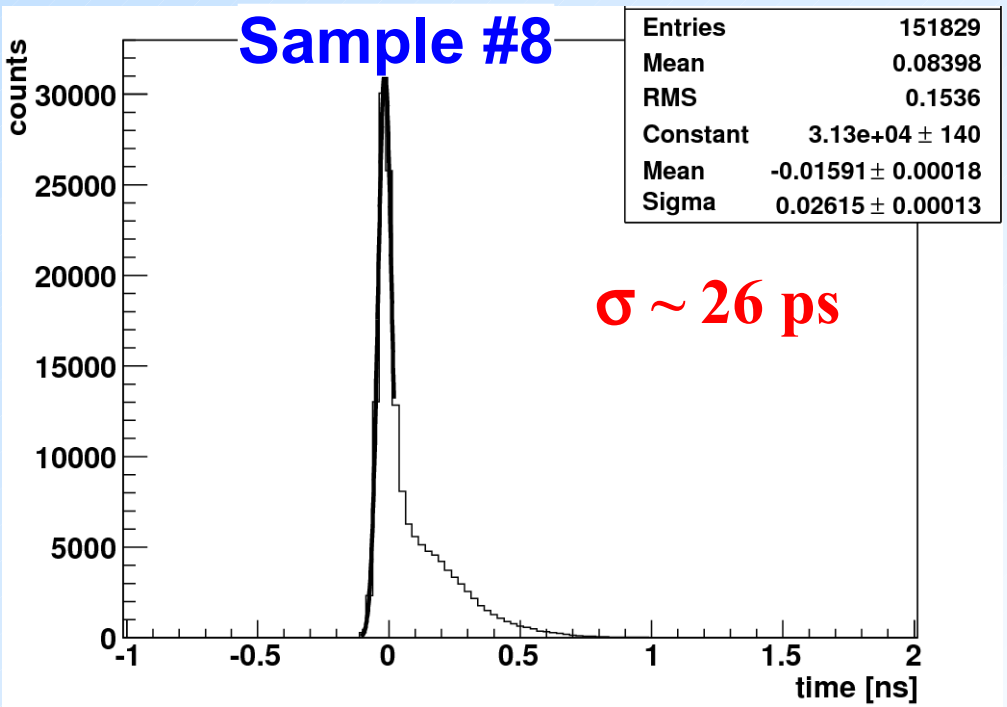
Tests with picosecond laser

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





- tails are mainly produced by photoelectron back-scattering events

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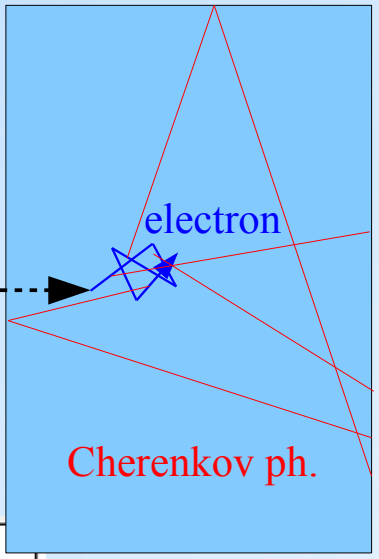
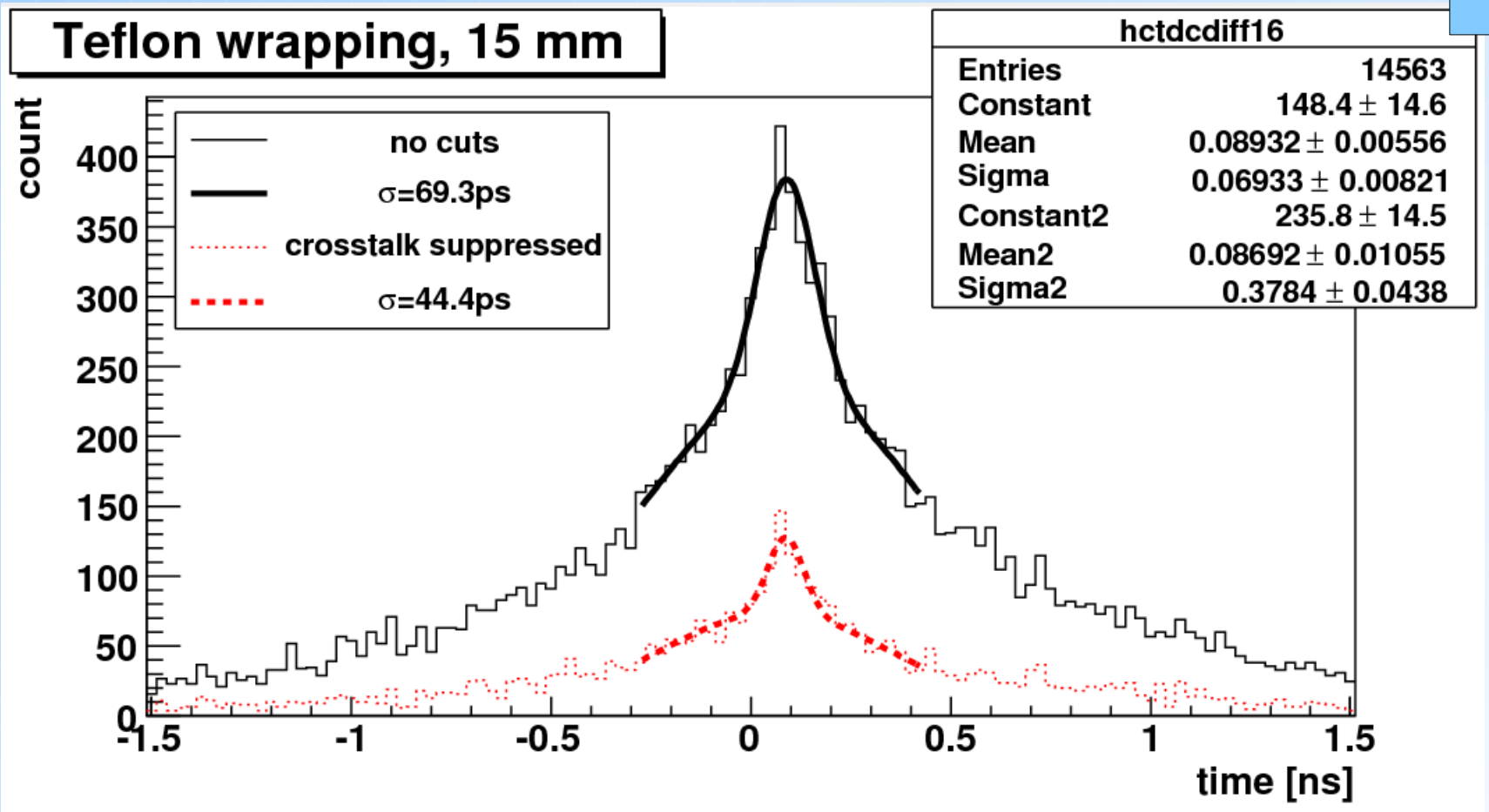
Back-to-back timing

First attempt with Teflon tape wrapped around the 15 mm thick PbF_2 crystal to increase detection efficiency.

Reflected photons are detected with considerable delay and produce rather long tails.





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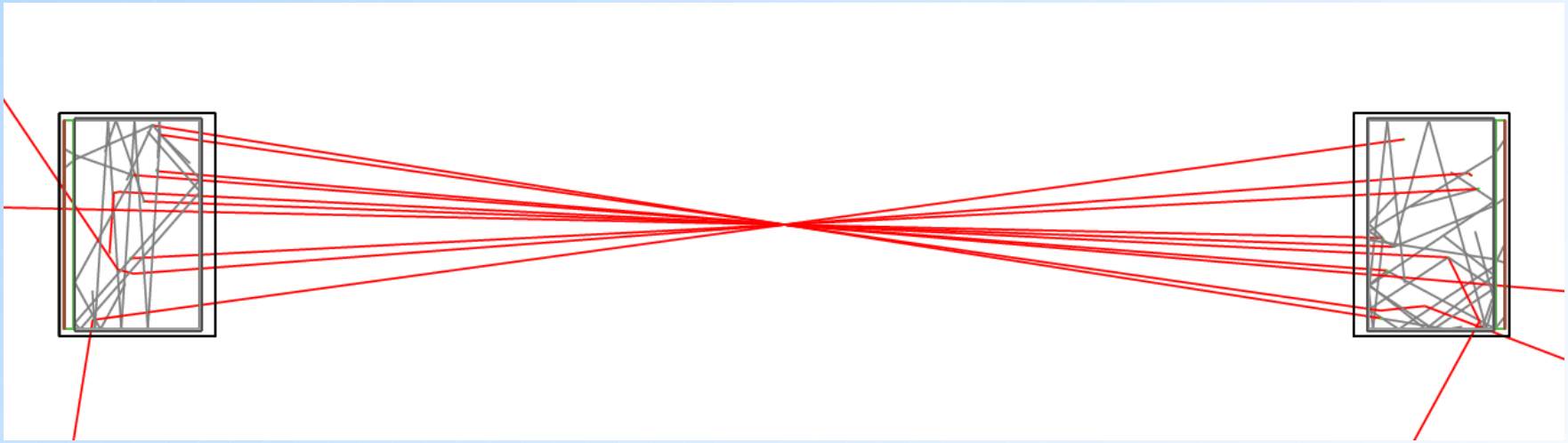
GEANT4 simulation

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 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)
- 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



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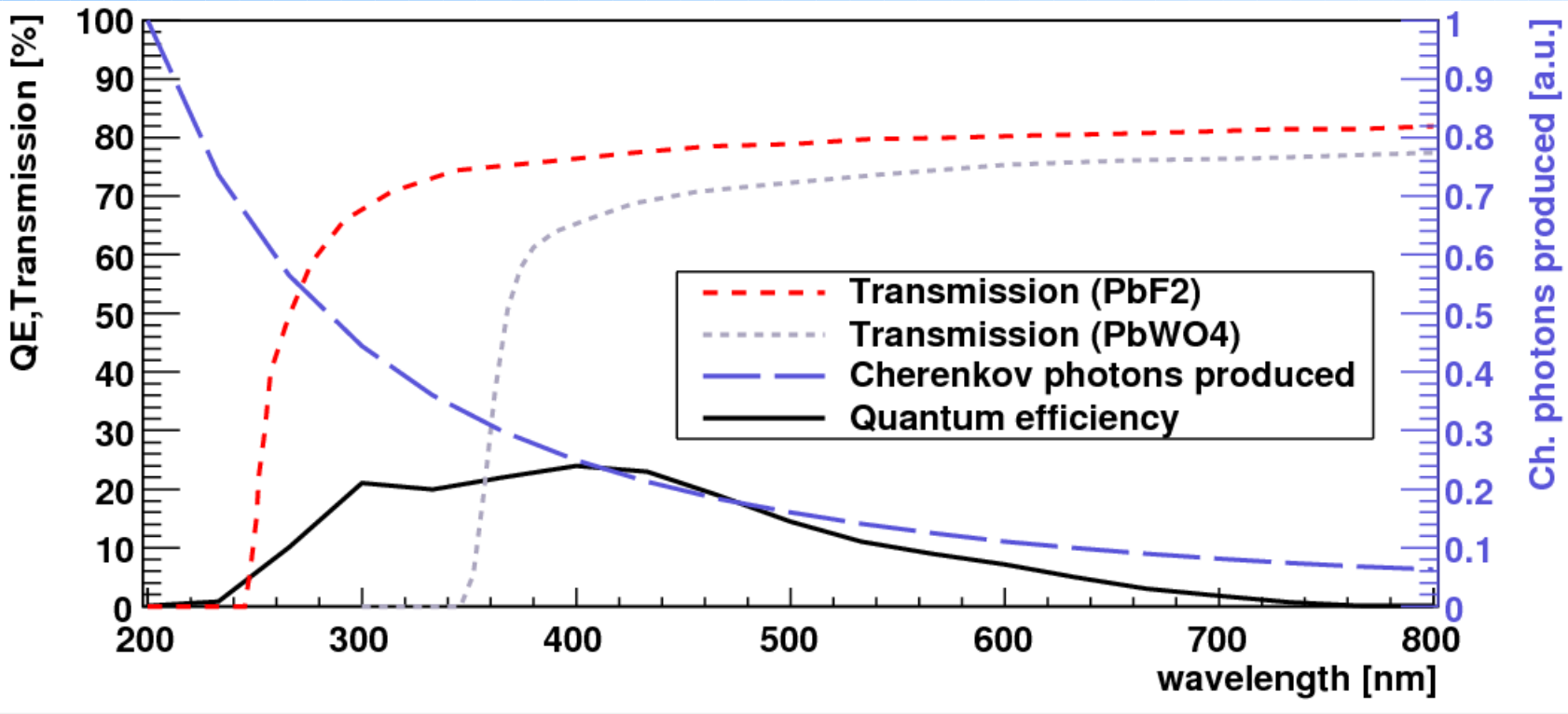
Simulation: transmission and QE

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



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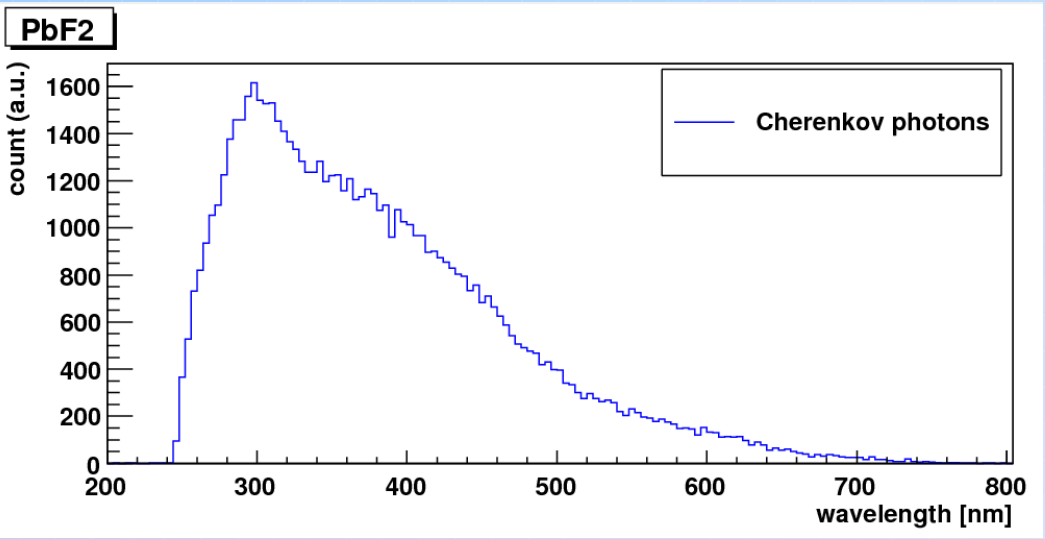
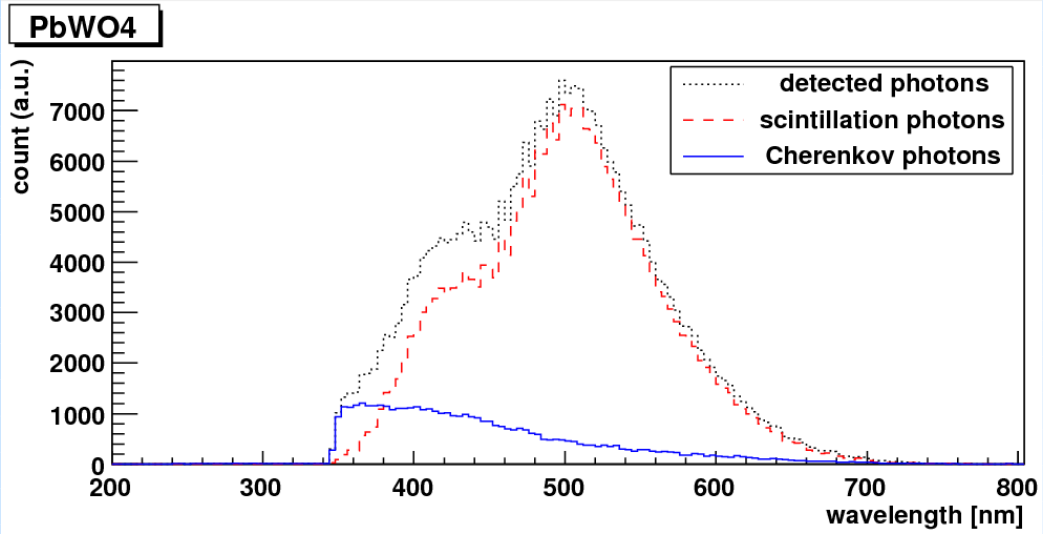
Simulation: Cherenkov photon production

Cherenkov photon production in 15 mm crystals and average number of detected Cherenkov photons per detected gamma.





	PbF_2	$PbWO_4$
Fraction of e^- above Cherenkov threshold	0.77	0.88
Ch. photons produced / γ	10.2	15.8
Ch. photons detected / γ (white reflector)	0.11	0.068
Ch. photons detected / γ (black paint)	0.070	0.044

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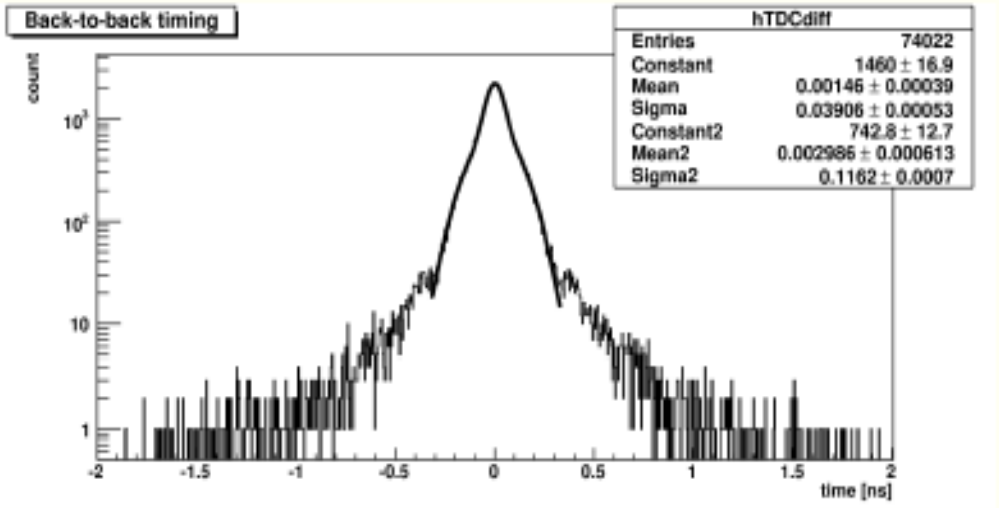
Simulation: back-to-back timing

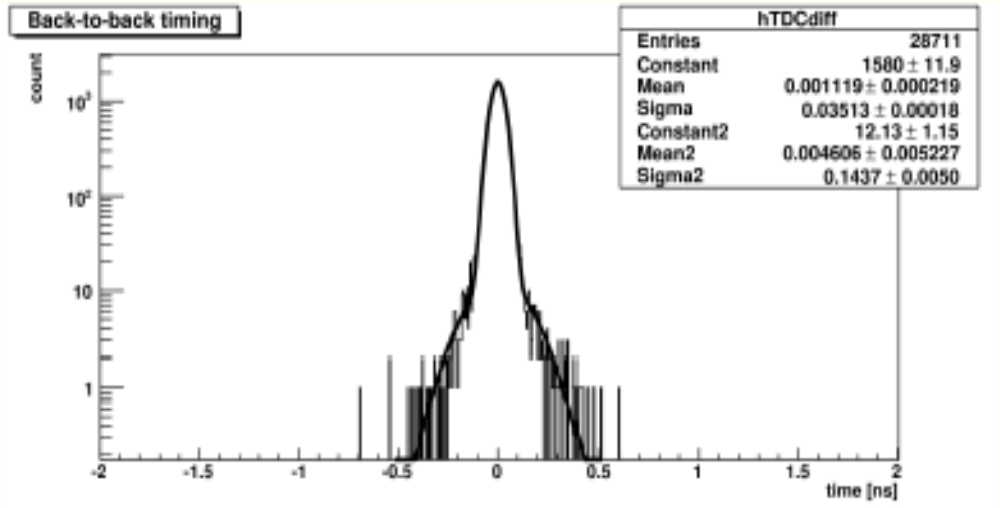
Time of arrival difference of the first photon on each photo-detector

Timing resolution is improved by replacing the reflective wrapping by black paint to absorb non-direct photons but the efficiency is reduced.



Teflon wrapping

σ = 39ps, efficiency = 7.4%



Black painted

σ = 35ps, efficiency = 2.9%

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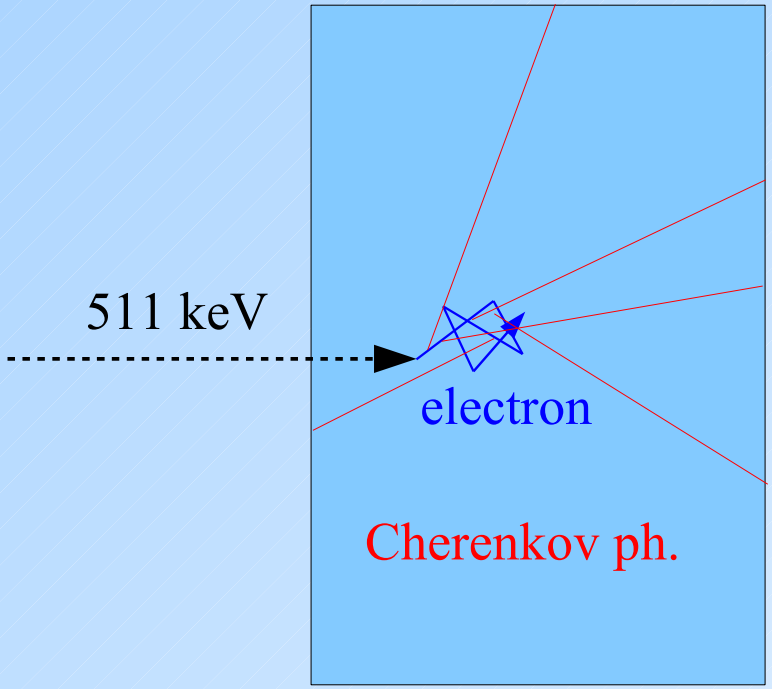
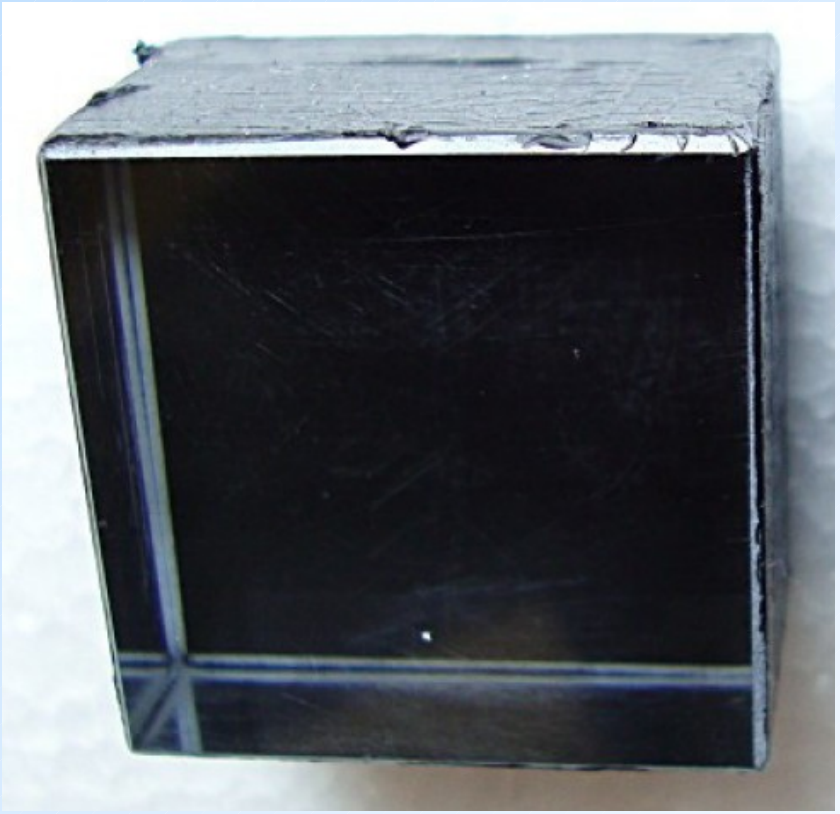
Painted crystals

PbF_2 crystals with black painted surfaces. Most of the Cherenkov light hitting the walls is absorbed - delayed Cherenkov photons suppressed:

→ improved timing

→ reduced efficiency





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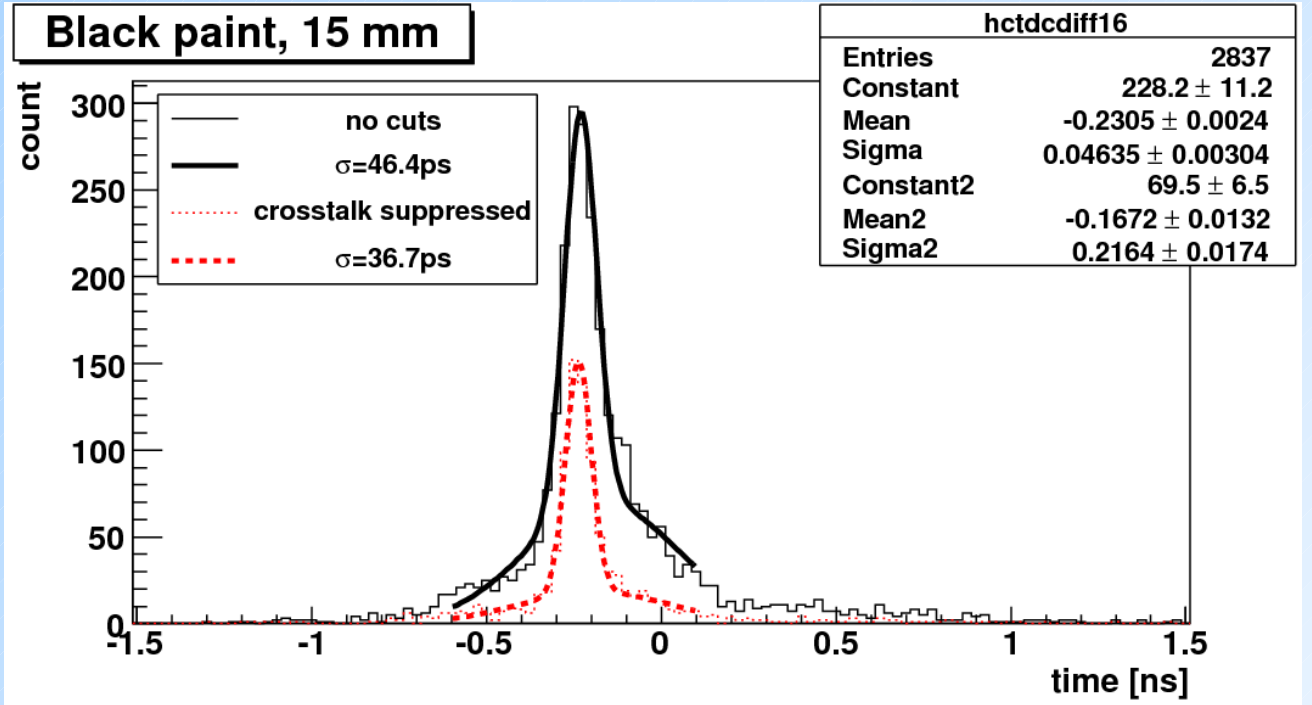
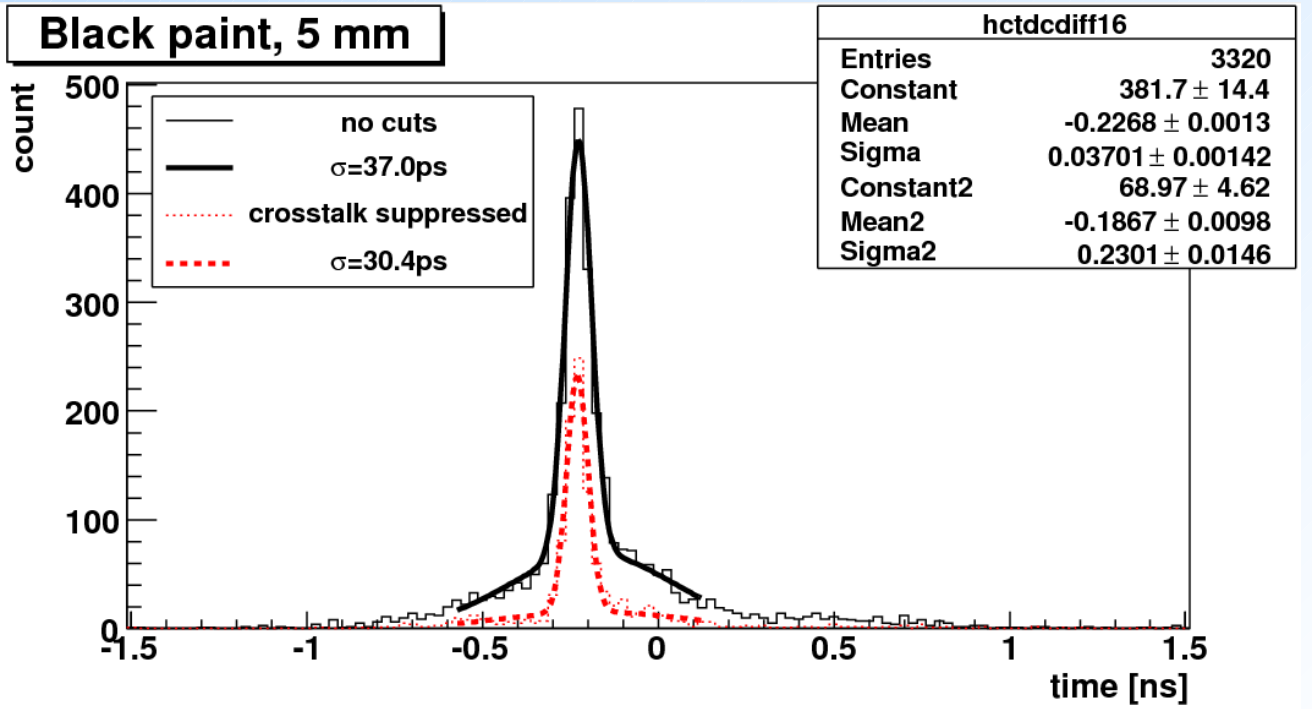
Back-to-back timing

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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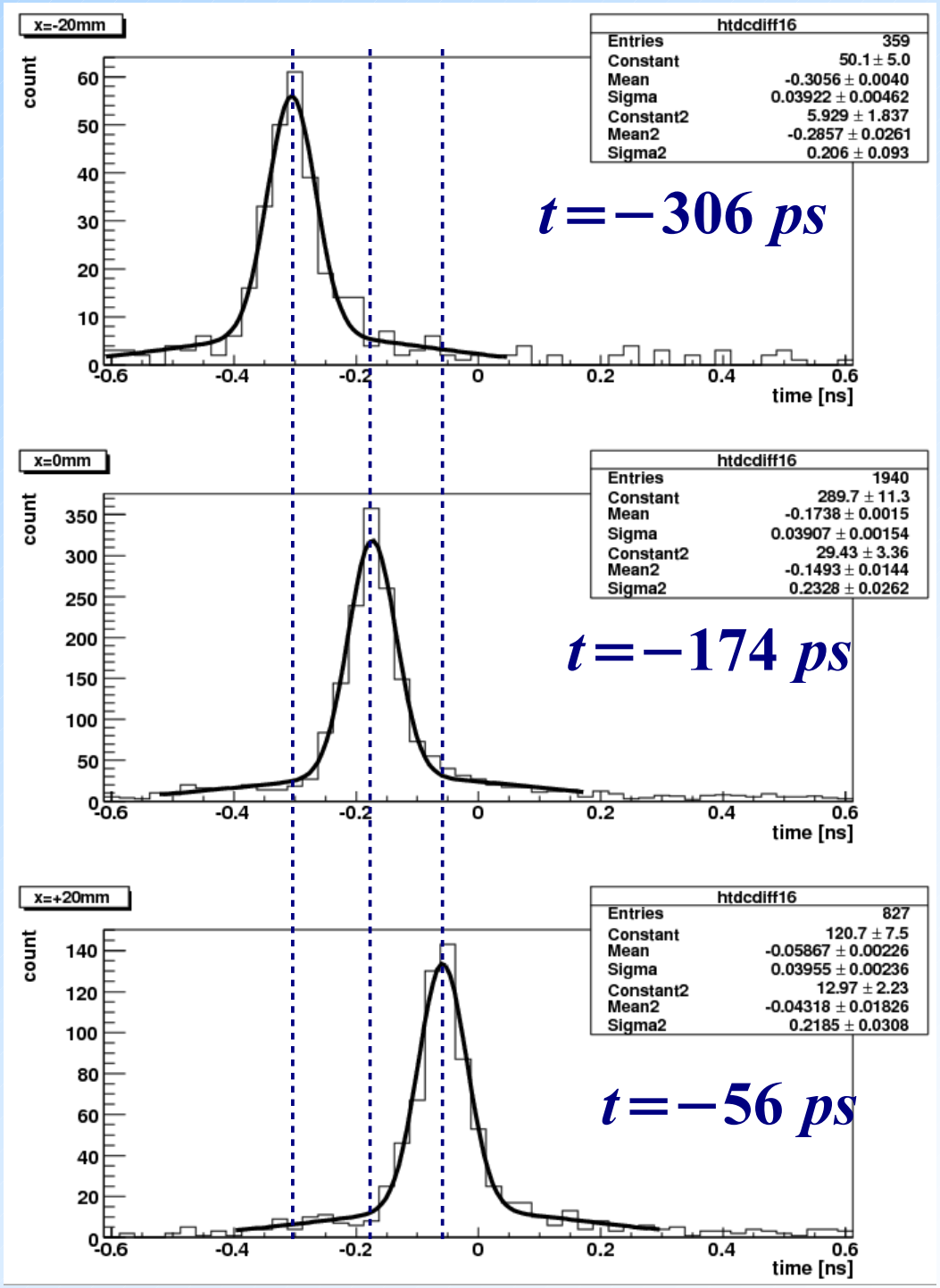
Point source position

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

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

Black painted 15 mm PbF_2 crystals.



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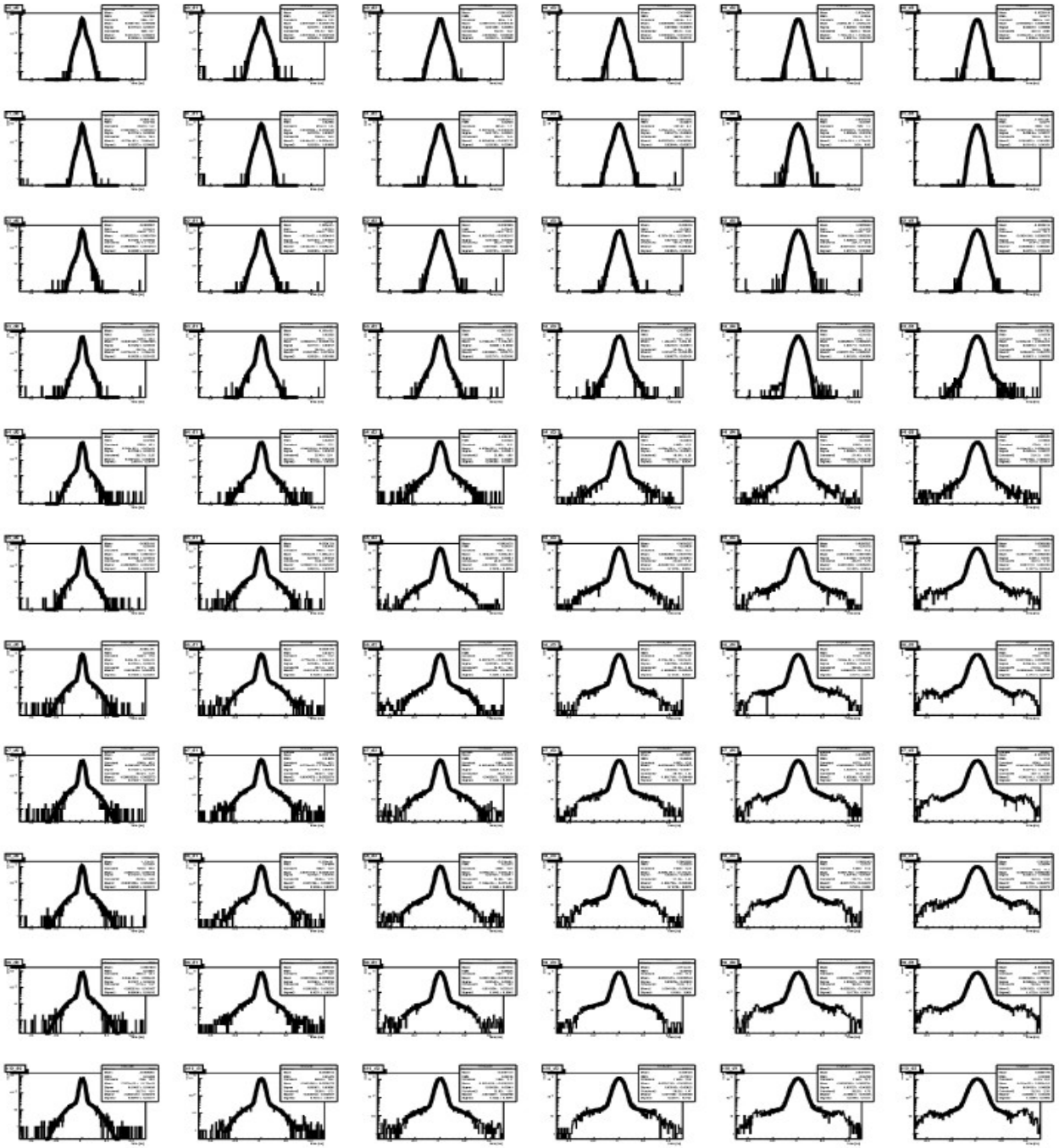
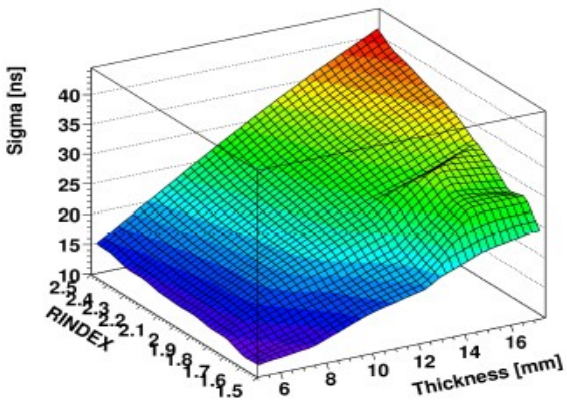
Simulation: search for optimum radiator parameters

Thickness

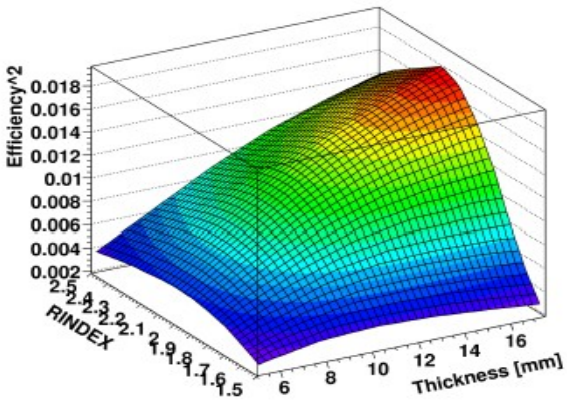
RINDEX



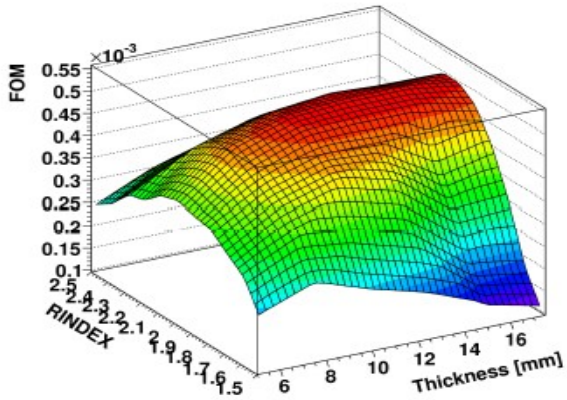
Sigma



Efficiency^2



FOM=Efficiency^2/Sigma



Summary and plan

- We have studied back-to-back timing of 511 keV anihilation gammas using Cherenkov radiator coupled to MCP-PMT with TTS ~ 20 ps.
- With such a fast photodetector the propagation time spread of Cherenkov photons in the crystal becomes the limiting factor.
- Measured resolution for 5 mm crystal is ~70ps FWHM (~30ps r.m.s.) and for 15 mm crystal ~95ps FWHM (~40 ps r.m.s.)
- Measured spatial resolution along the LOR is ~14mm FWHM (~6mm r.m.s.) for 15 mm crystal
- Efficiency to detect the coincidence event is rather low – at percent level.

Plan:

- Instrument all 32 channels
- Improve the simulation
- Study the performance of the large scale system with optimized reconstruction software
- Efficiency improvements: SBA photocathode, quartz window, search for possible new radiators with extended UV transmission ...

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BACKUP SLIDES

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Setup - readout configuration

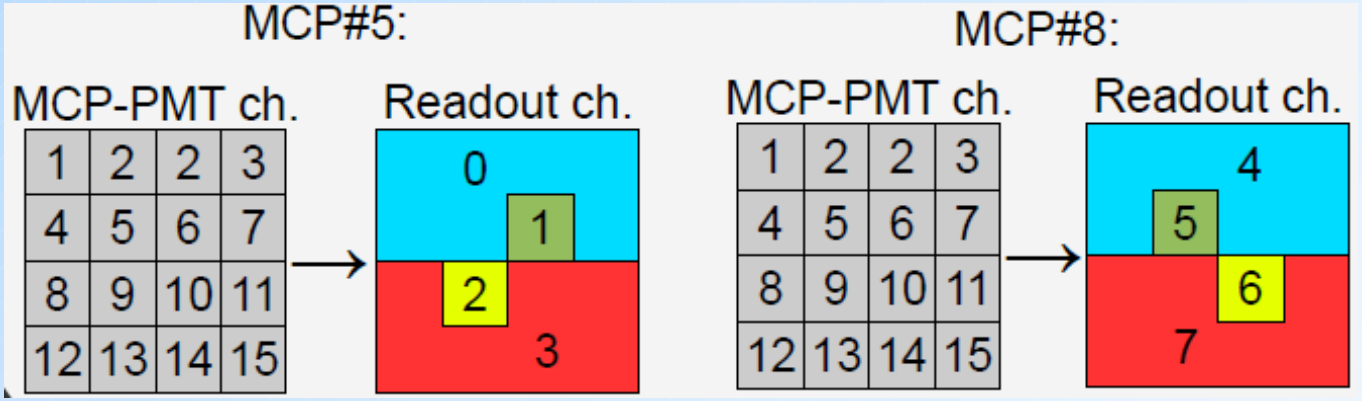
Limited number of electronic channels – 4 per MCP-PMT:

- 2 middle channels instrumented
- Remaining channels combined in groups of 7

Signal from single photon can be detected on more than one channel due to charge sharing, cross-talk …

Directly hit channel will most probably have the largest signal.

Plots labeled 'crosstalk suppressed' use only the channel with the largest signal.



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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 ~15ps and electronics ~11ps
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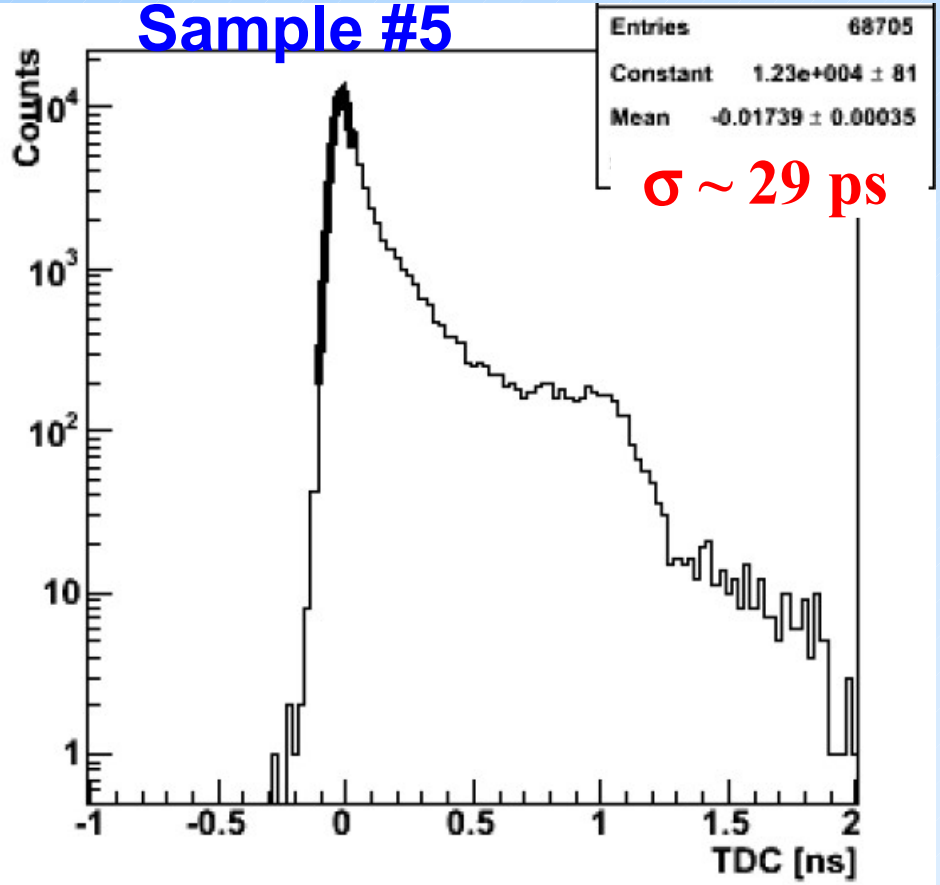

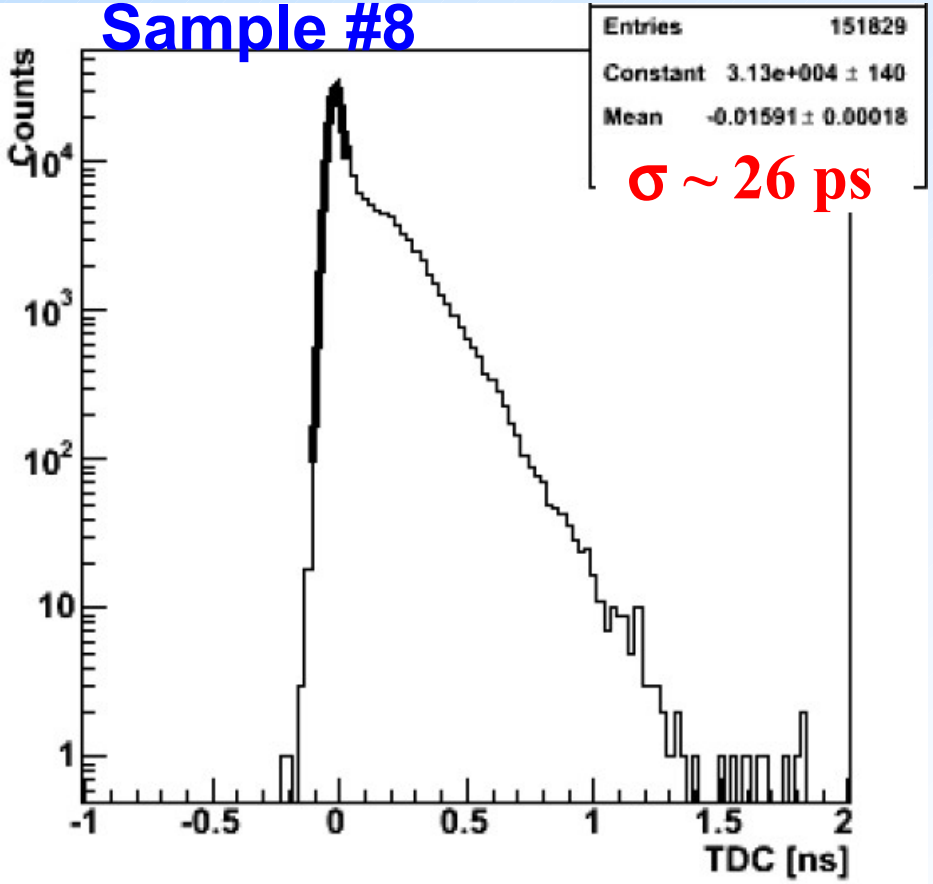

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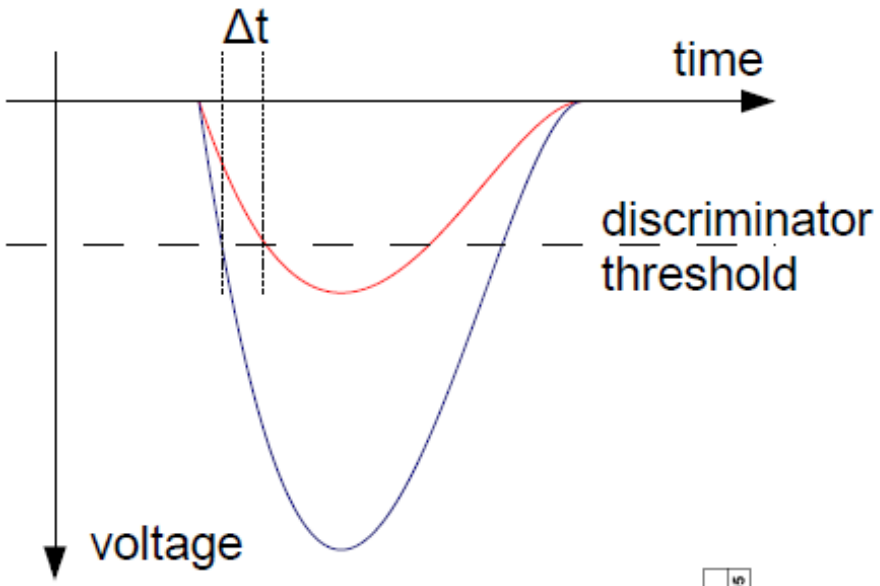
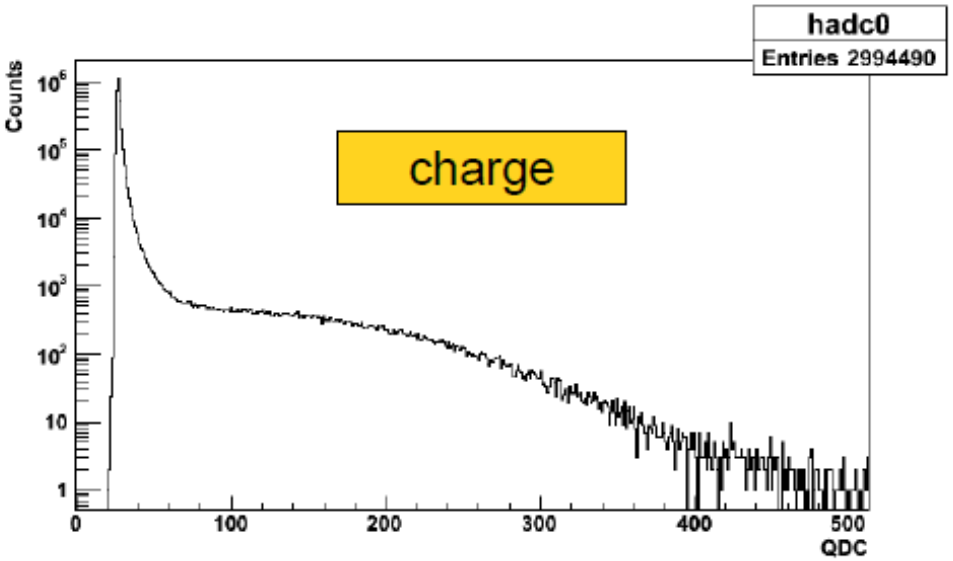
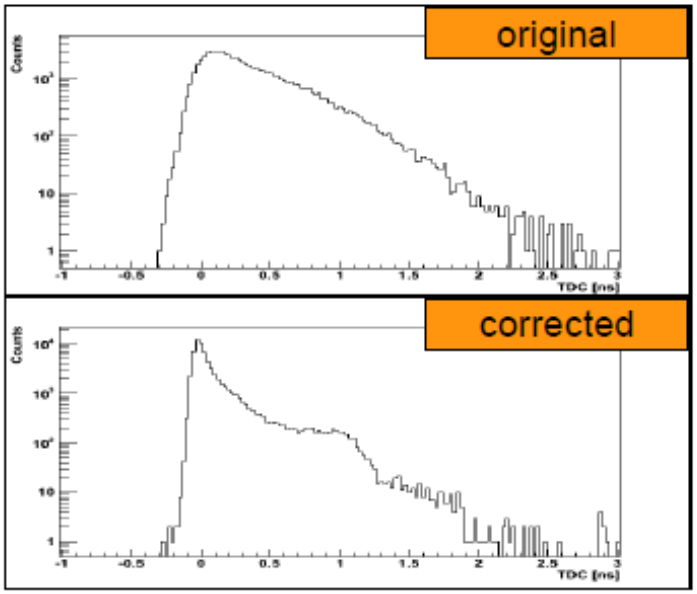
Time-walk correction

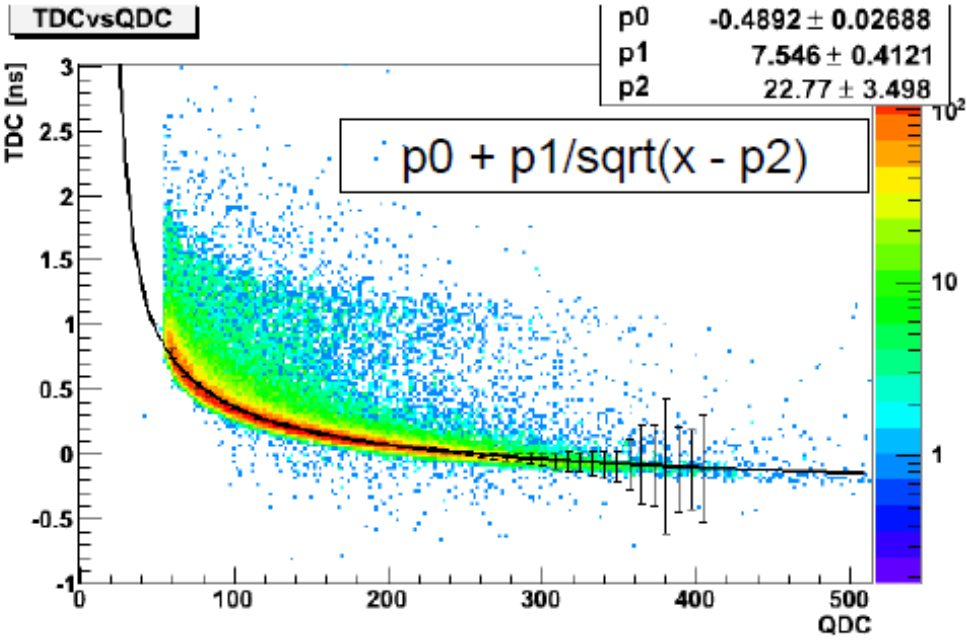
- Leading Edge discriminator – triggers at set signal voltage level
  → smaller pulses register at later time







time



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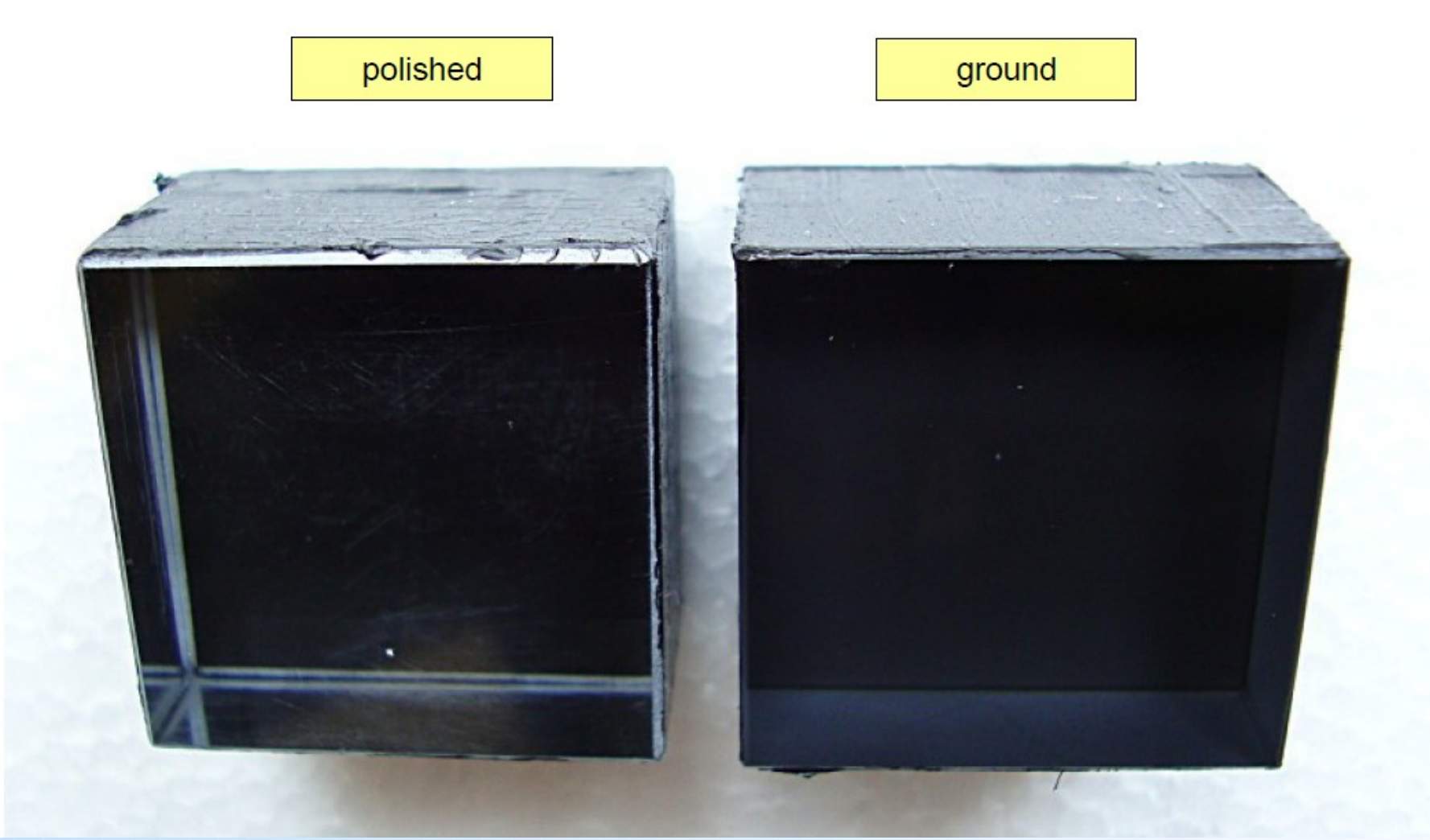
Painted crystals

PbF_2 crystals with black painted surfaces for polished and ground finish.

Painted ground sample gave slightly worse timing resolution than polished one. Some light is still reflected from the side walls.



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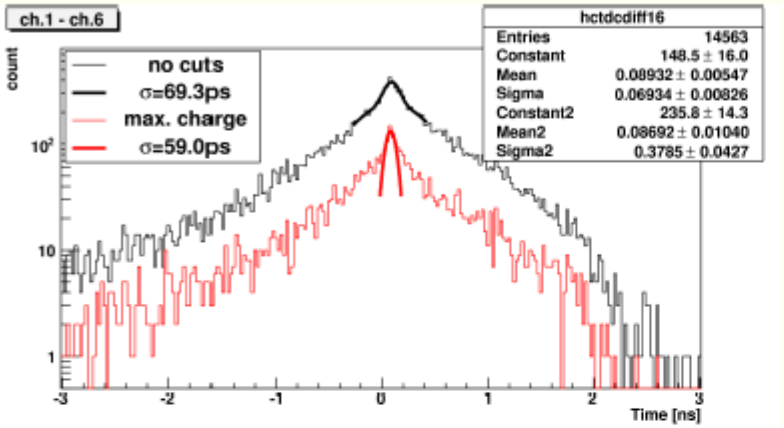
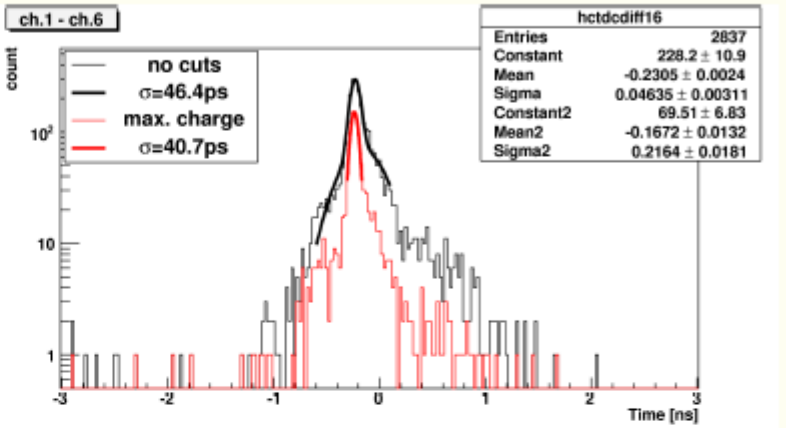
Back-to-back timing

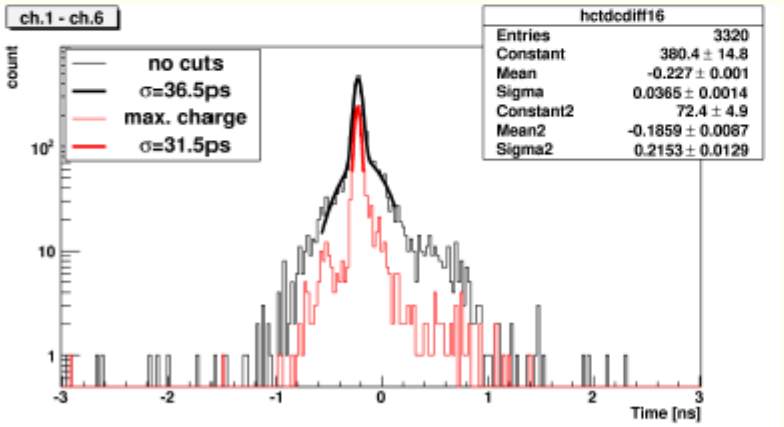
Back-to-back timing between two selected individually connected channels, obtained from time-walk corrected TDCs (black histogram, fitted with sum of two Gaussians). To reduce background due to crosstalk, only events, where both channels had maximum charge on their MCP-PMT, were selected (red histogram, fitted with single Gaussian).



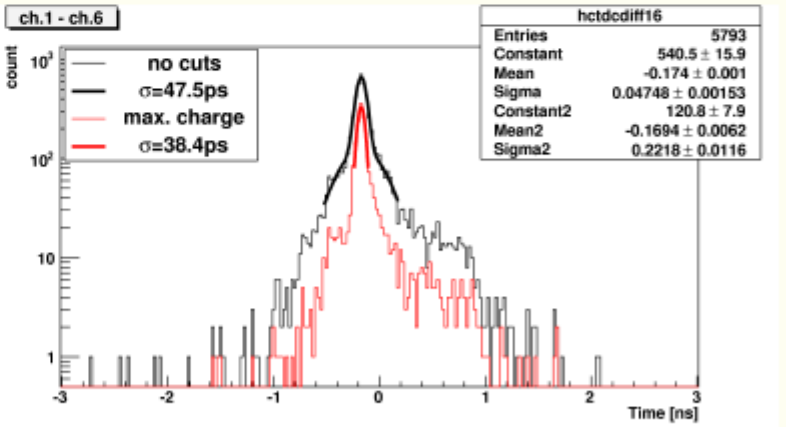
Teflon wrapped 15mm thick PbF_2: σ (narrow peak) = **69ps**



Black painted 15mm thick PbF_2: σ (narrow peak) = **46ps**



Black painted **5mm** thick PbF_2: σ (narrow peak) = **37ps**



Black painted 15mm thick **PWO**: σ (narrow peak) = **48ps**

- High refractive index → lower photon speed, more total internal reflections
- Reflected photons travel longer to the photocathode → degrade timing resolution
- For best timing resolution reflections have to be suppressed → paint black all but exit surface

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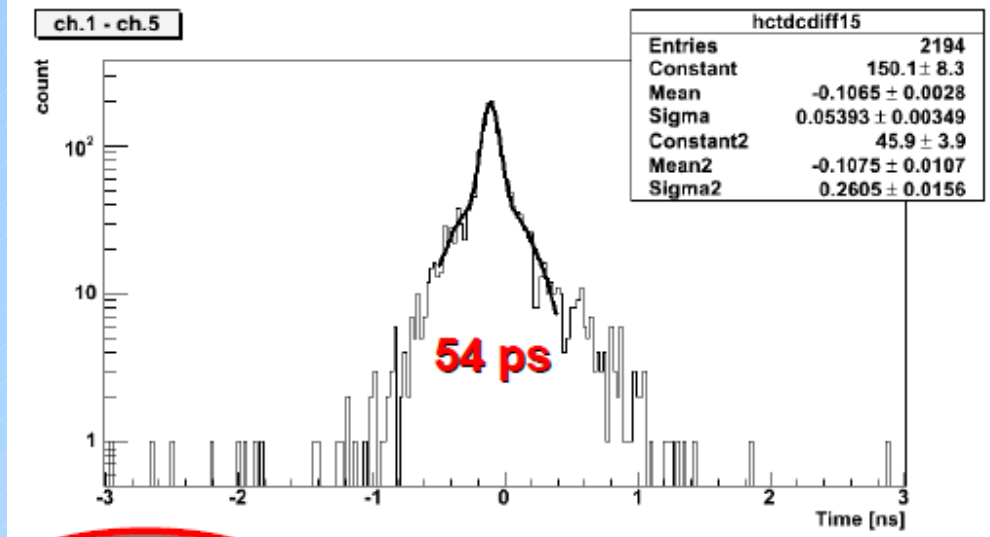
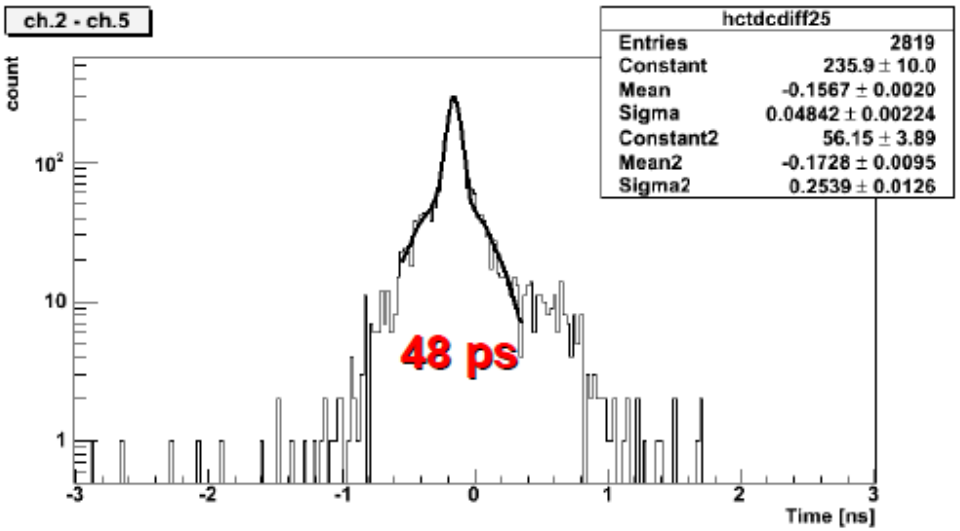
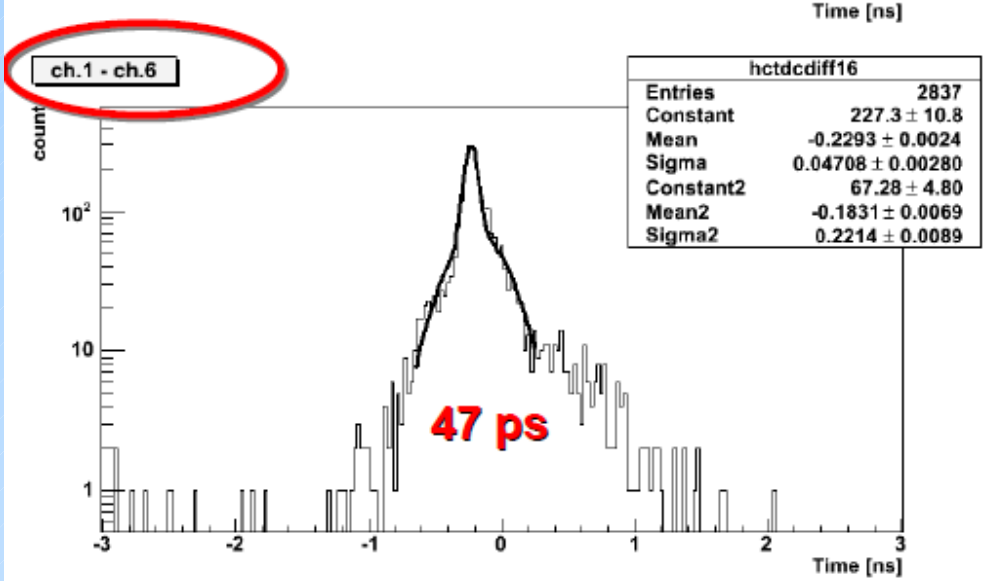
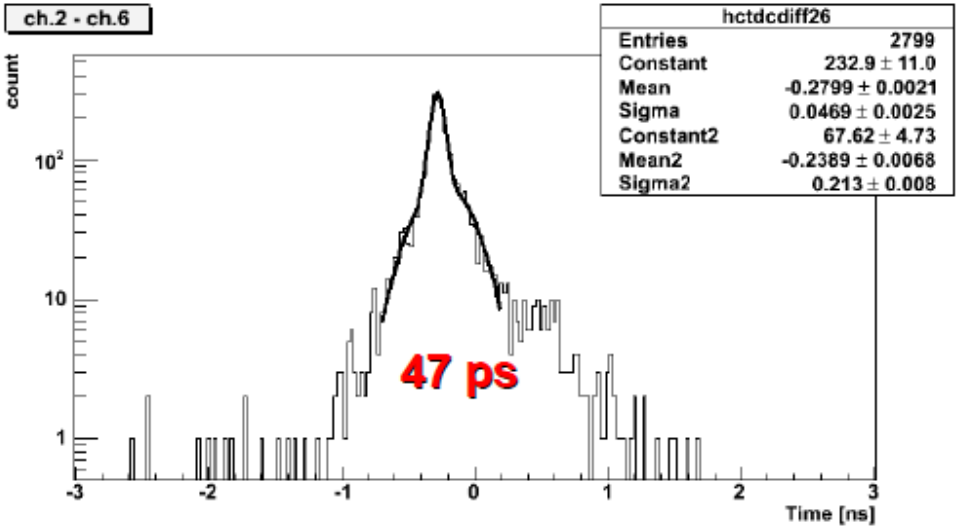
B2B timing - 15mm PbF_2, black

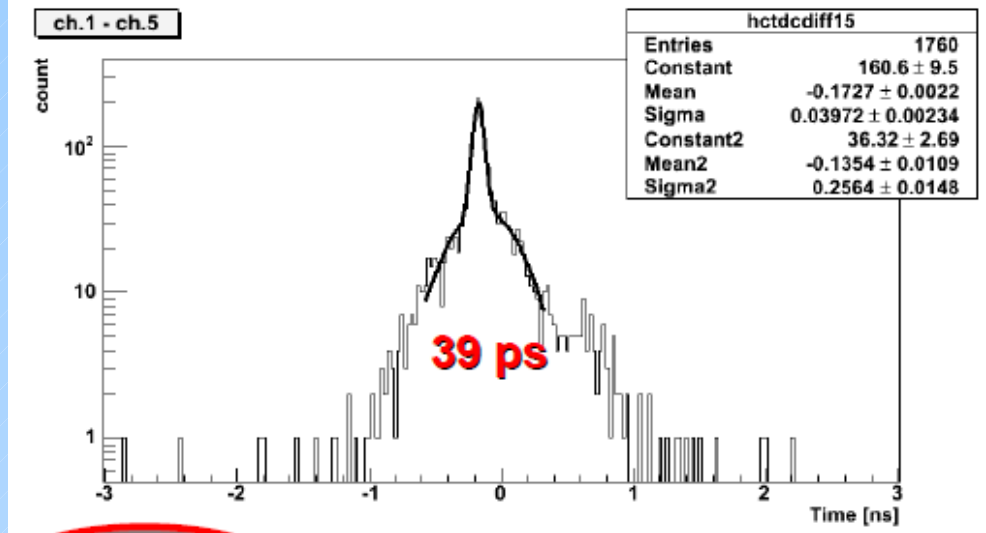


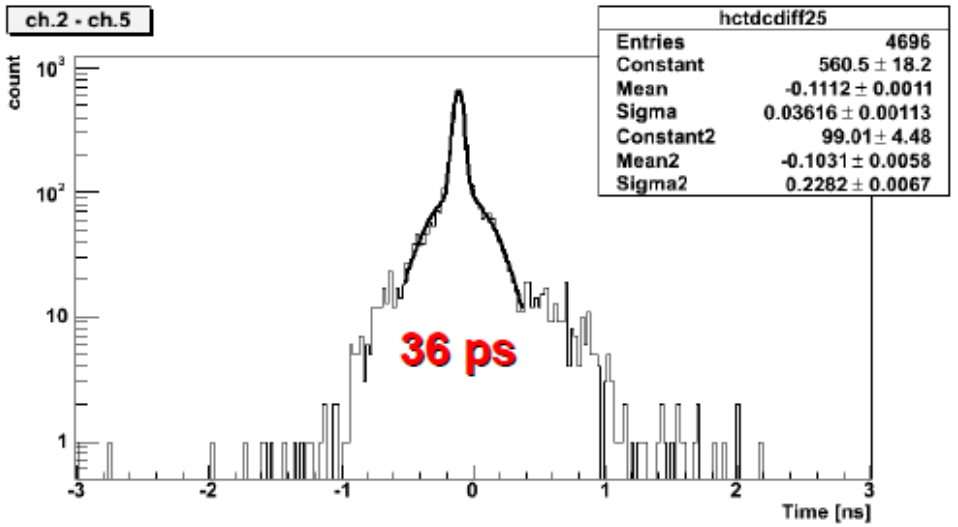


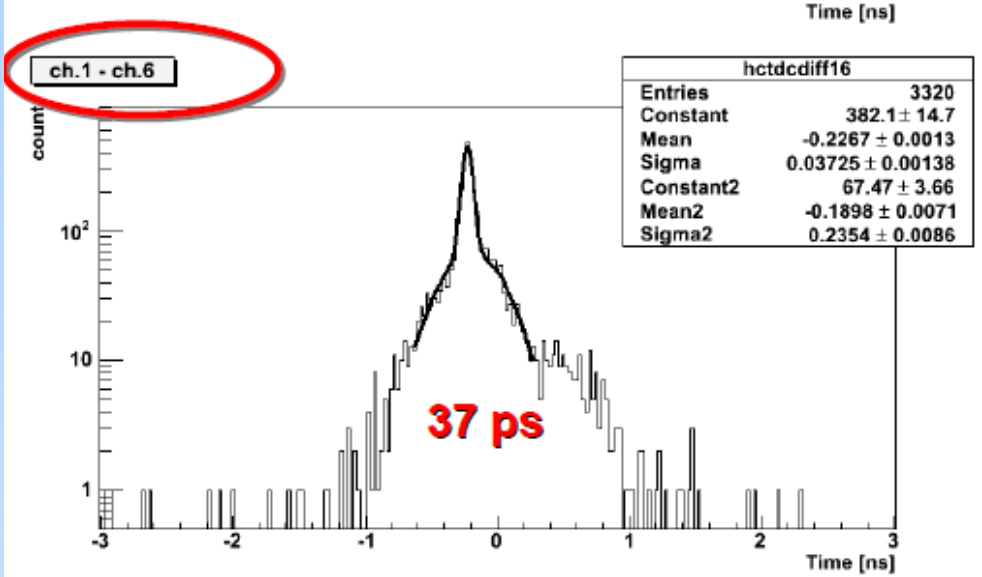


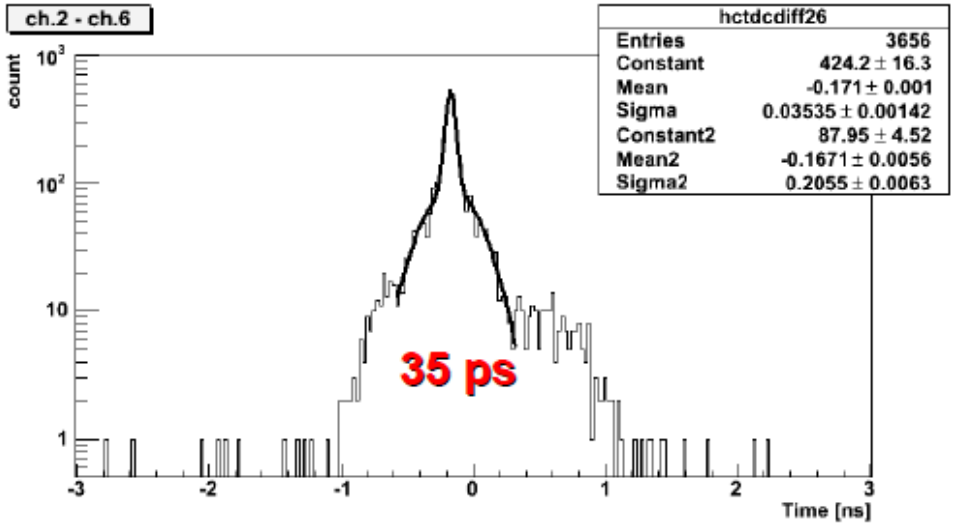


B2B timing - 5mm PbF_2, black

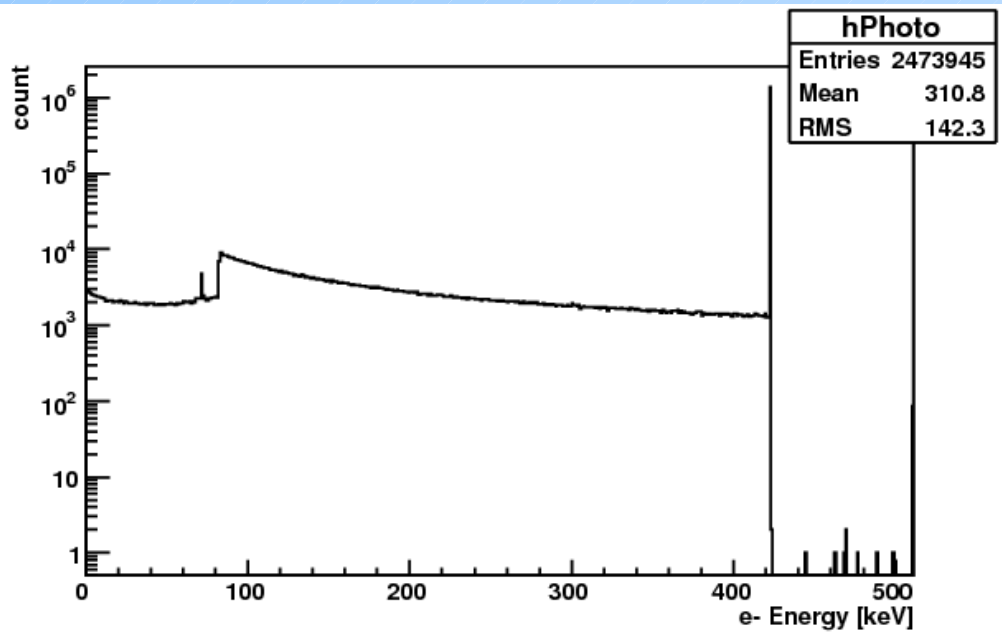


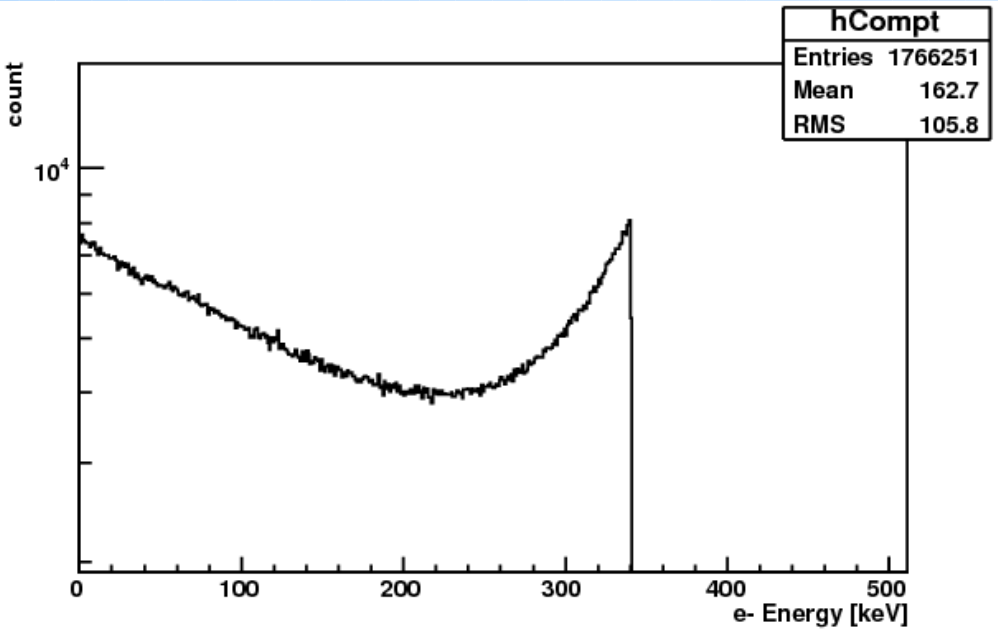


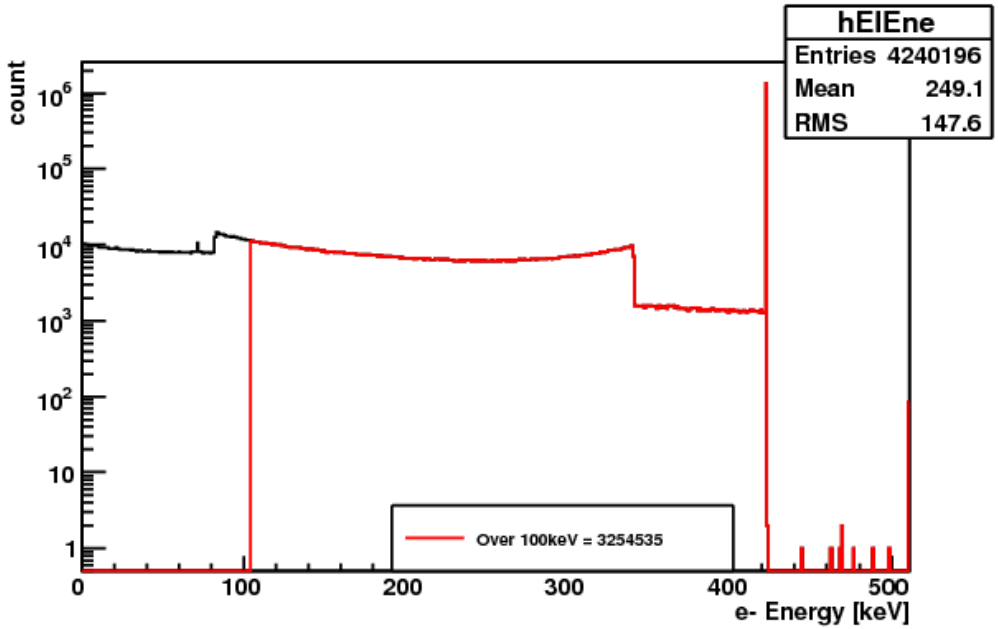


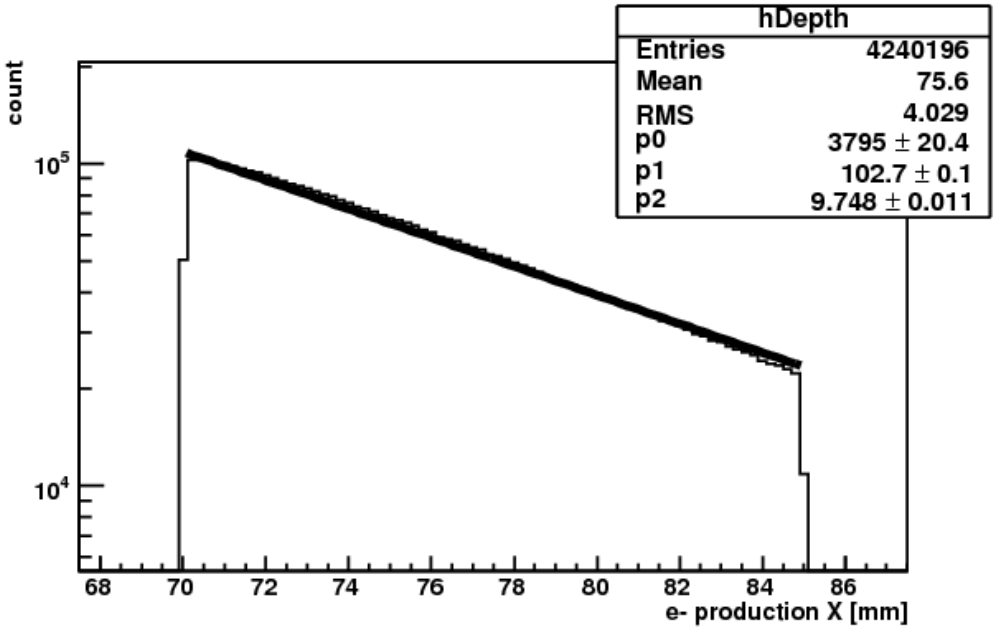


Simulation: electron production









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