Time-of-Flight PET using Cherenkov Photons Produced in PbF_2 Crystals

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Outline:

- detection method & Cherenkov radiator
- MCP PMT & experimental setup
- simulations
- back-to-back timing resolution
- summary

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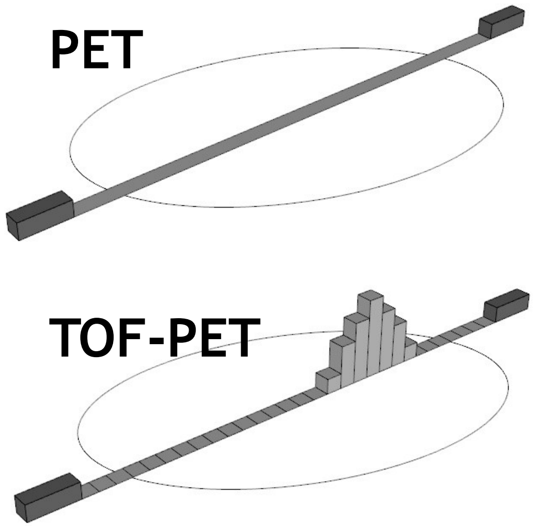
TOF PET using Cherenkov photons

- Contrast of images obtained with positron emission tomography (PET) can be improved by measuring time-of-flight (TOF) difference of annihilation gammas
  - localizes source position on line of response (LOR)
  - reduces number of background sources on LOR contributing to random coincidences
  - improves S/N ratio



- Novel photon detectors (SiPM, MCP-PMT) have excellent timing resolution → time-of-flight resolution is limited by scintillation decay time.

- Charged particles passing trough matter at a speed higher than the speed of light ($v_{Thr} > c_0/n$) produce prompt Cherenkov photons.
- However, at low energies (e^- from 511 keV annihilation γ), only a small number of Cherenkov photons is produced → single photon detection.

Cherenkov radiators

- To obtain Cherenkov photons from 511 keV annihilation gammas, they must transfer their energy to an electron in a suitable Cherenkov radiator:
  - high 511 keV γ stopping power → high ρ/Z
  - high fraction of γ interactions via photoeffect – electron receives more energy than via Compton scattering → high Z
  - high enough index of refraction – more electrons produced above Cherenkov threshold v_{Thr}
  - good optical properties – transmission for visible & near UV Cherenkov photons

- Most promising available crystals: PbF_2 and $PbWO_4$ (PWO)

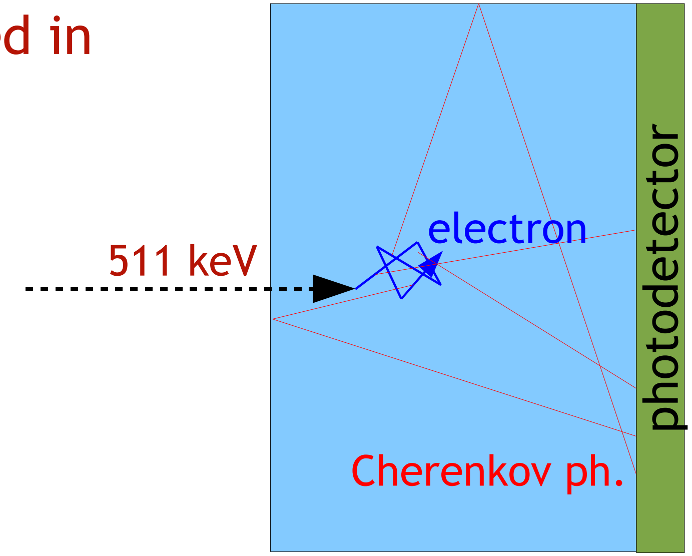
	ρ (g/cm^3)	n (λ=400nm)	E_{Thr} (keV) for e^-	Optical transmission λ_{Cutoff} (nm)	Light yield (ph/MeV)	Decay time (ns)	Emission peak (nm)
PbF_2	7.77	1.8	104	250	-	-	-
$PbWO_4$	8.28	2.3	56	350	200	6 / 30	440 /530

Cherenkov photon production

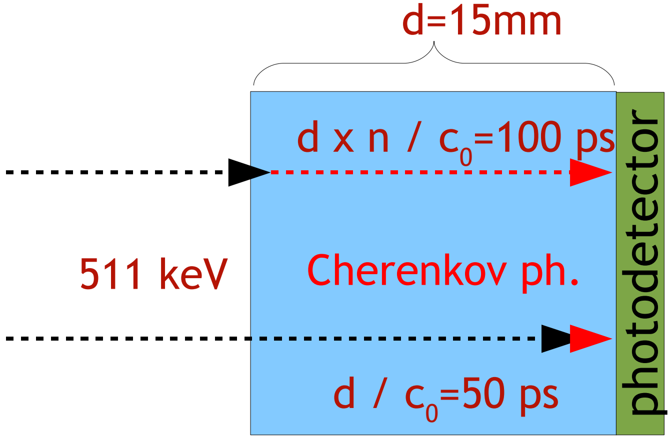
- Estimated number of Cherenkov photons produced in 15mm thick crystal with n=2.0, assuming e^- path length of l=100μm and Cherenkov photon energy inteval of 3eV (~ 250 – 700nm):

$$N \approx 370\ (eV^{-1}\ cm^{-1}) \cdot l \cdot \Delta E \cdot \sin^2\theta_c$$

$$N \approx 370 \cdot 0.01 \cdot 3 \cdot 0.75 \approx \mathbf{8}$$

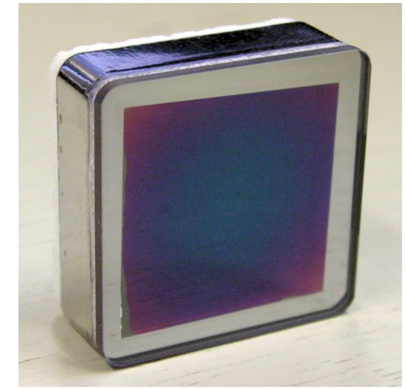


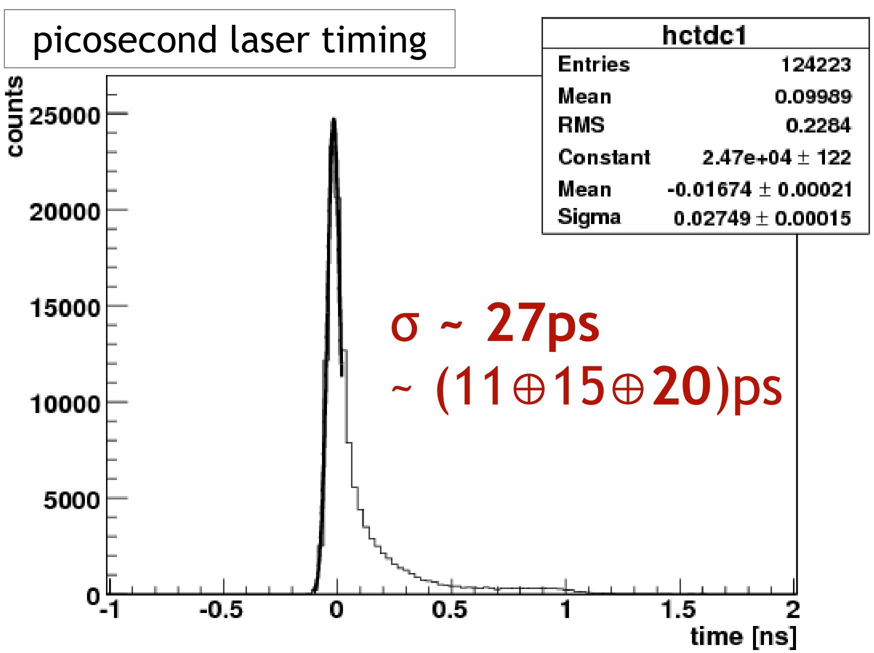
- optical photon travel time in the crystal a significant contribution to the timing resolution
  - even for Cherenkov photons going strait to the photodetector the time spread of 50 ps results from depth of interaction
  - additional variations due to initial path direction, reflections

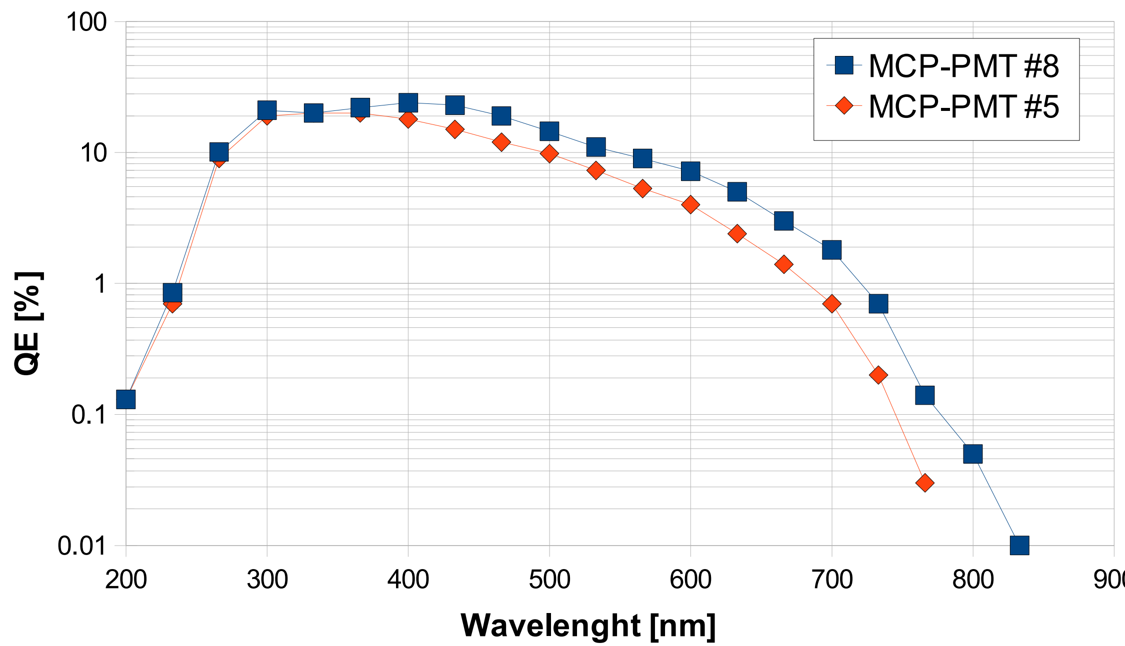


Microchannel plate photomultipliers

- two Hamamatsu MCP PMTs (prototypes for Belle II TOP counter), #5 and #8
  - PMT with two MCP steps, 10μm pores
  - multi-anode, 16 (4x4) pads, pitch ~ 5.575mm
  - active surface 22.5x22.5mm^2
  - multi-alkali photocathode, 1.5mm thick borosilicate window
  - excellent timing <u>σ~20ps</u> for single photons

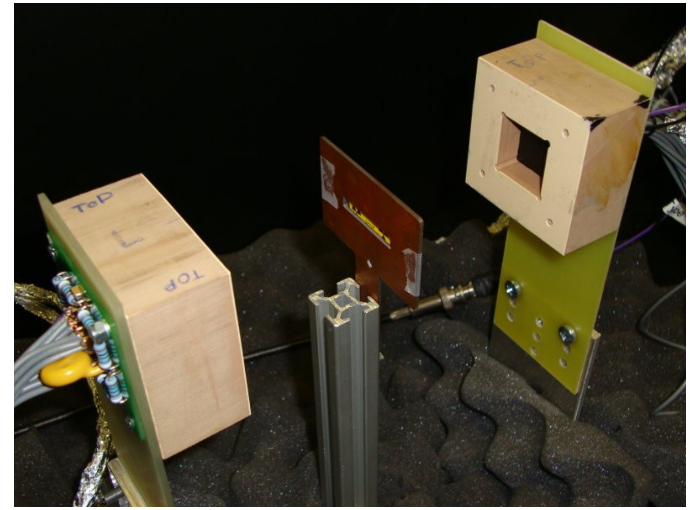




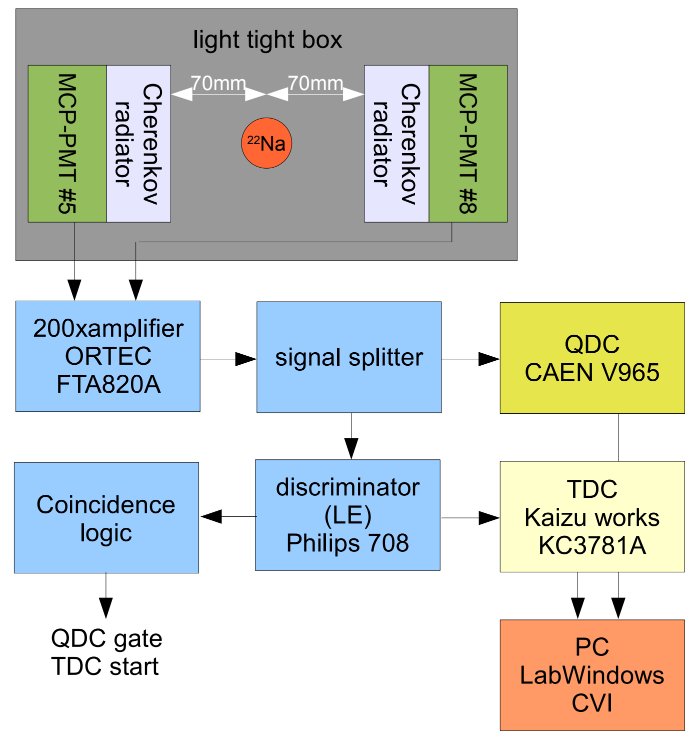


Experimental setup

- Two detectors in back-to-back configuration
  - 25x25x15 (5) mm^3 PbF_2 or $PbWO_4$ crystals, coupled to MCP-PMT with optical grease
  - ^{22}Na point source

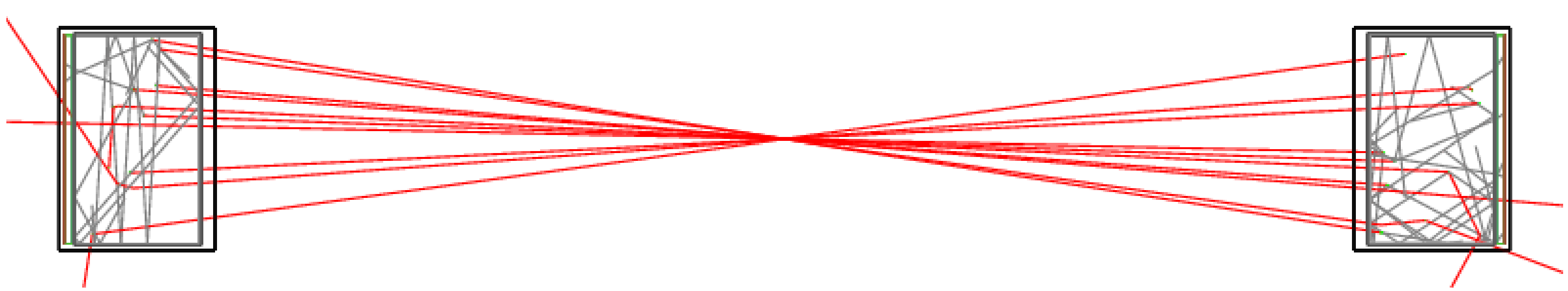


- Readout
  - amplifier (ORTEC FTA820)
  - LE discriminator (Philips sc. 708)
  - TDC (25ps/bin Kaizu works KC3781A)
  - QDC (CAEN V965)
  - time-walk correction applied in analysis



Simulation

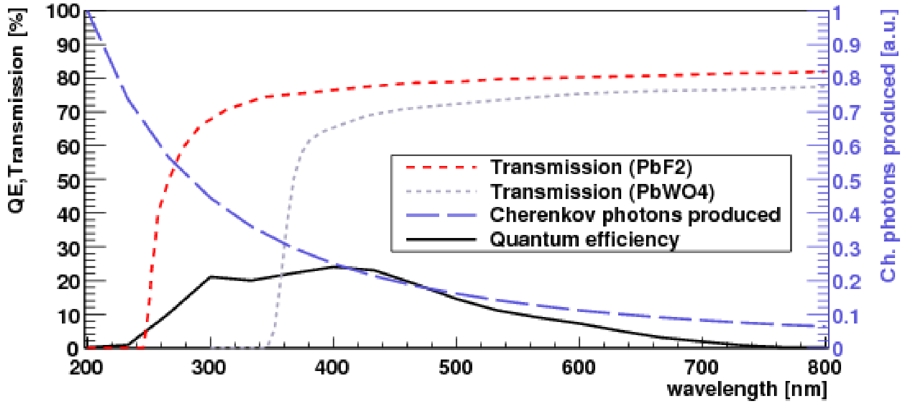
- experimental back-to-back configuration was simulated in GEANT4, taking into account:
  - 511keV gamma pairs interacting with the crystals
  - optical photons produced between 250nm – 800nm by Cherenkov process (and scintillation in case of $PbWO_4$)
  - optical photon boundary processes (exit surface polished, other surfaces polished and wrapped in diffuse reflector - Teflon or painted black)
  - 1.5mm borosilicate photodetector window, coupled with optical grease (n=1.5)
  - photodetector QE
  - perfect photodetector timing – simulated timing resolution only includes photon travel time spread

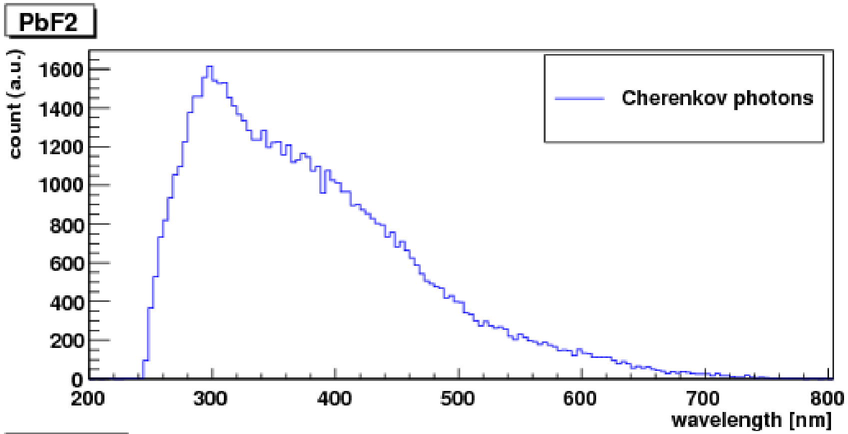


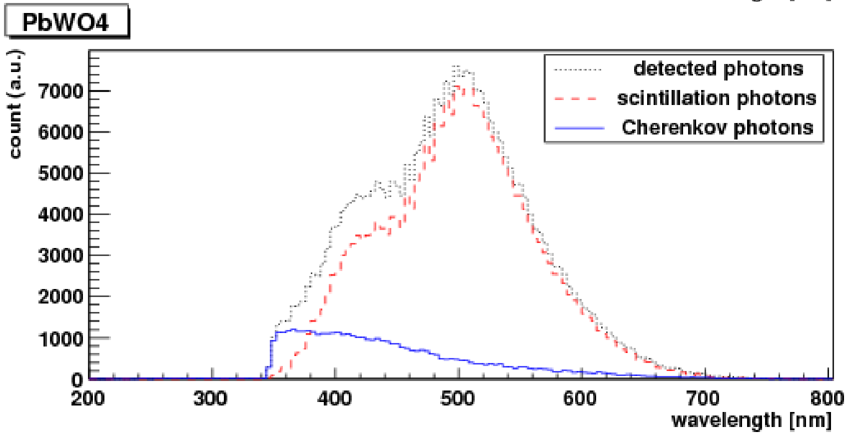
Simulation - Optical photon production

- wavelength distributions for number of Cherenkov photons produced, QE and optical transmissions
- wavelength distributions of first detected photon (Cherenkov or scintillation)
- more Cherenkov photons produced in $PbWO_4$, however due to worse transmission less are detected than in PbF_2

	PbF_2	$PbWO_4$
e^- above E_{Thr}	77%	88%
Ch.ph. produced / γ	10.2	15.8
Ch.ph. detected / γ (reflector)	0.11	0.68
Ch.ph. detected / γ (black paint)	0.070	0.044



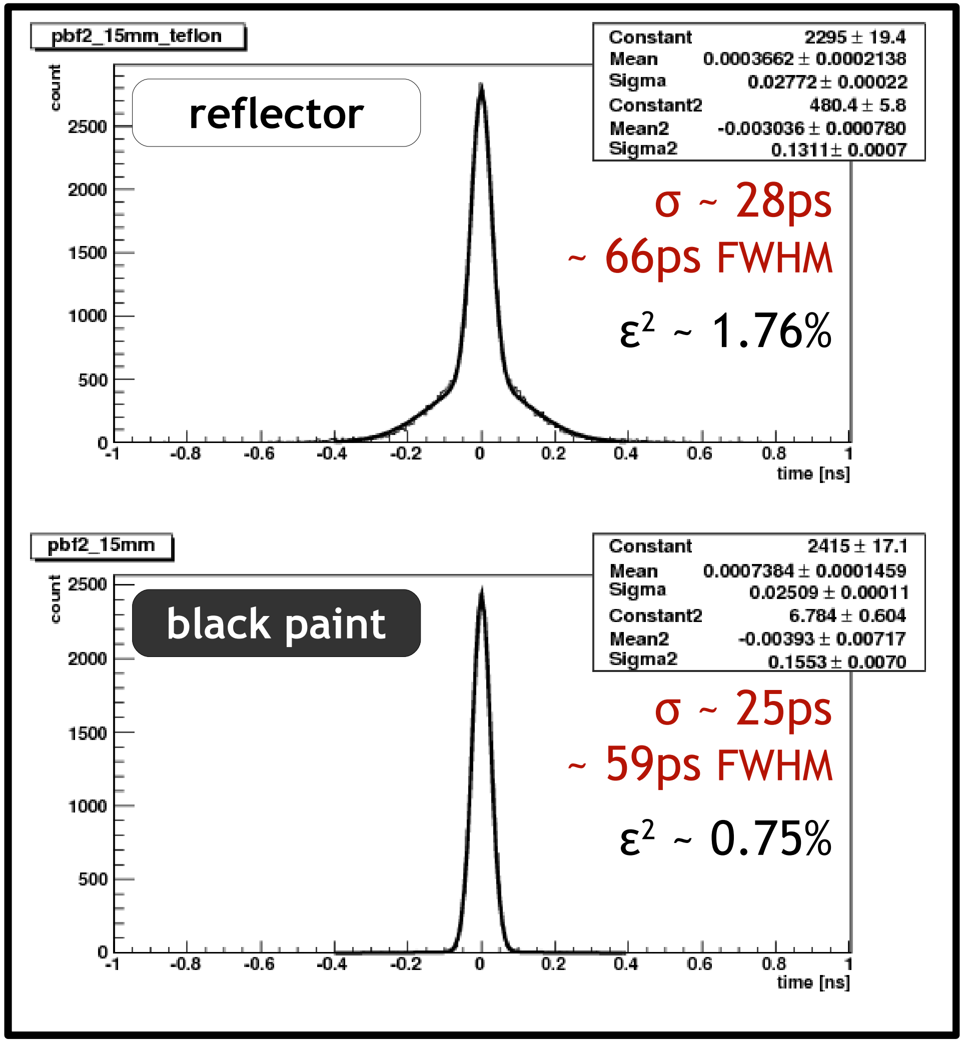




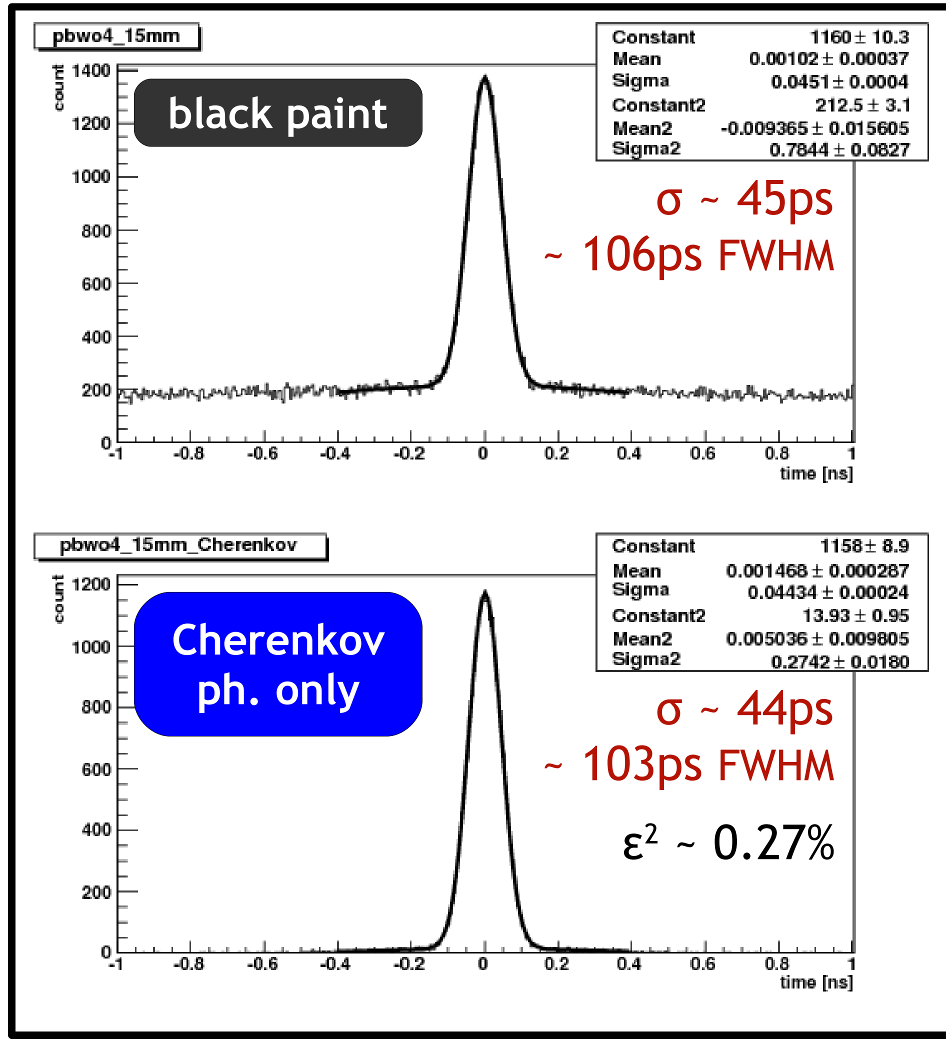
Simulation - coincidence timing resolution and efficiency (ε^2)

- time difference between first optical photons reaching each photodetector

PbF_2



$PbWO_4$

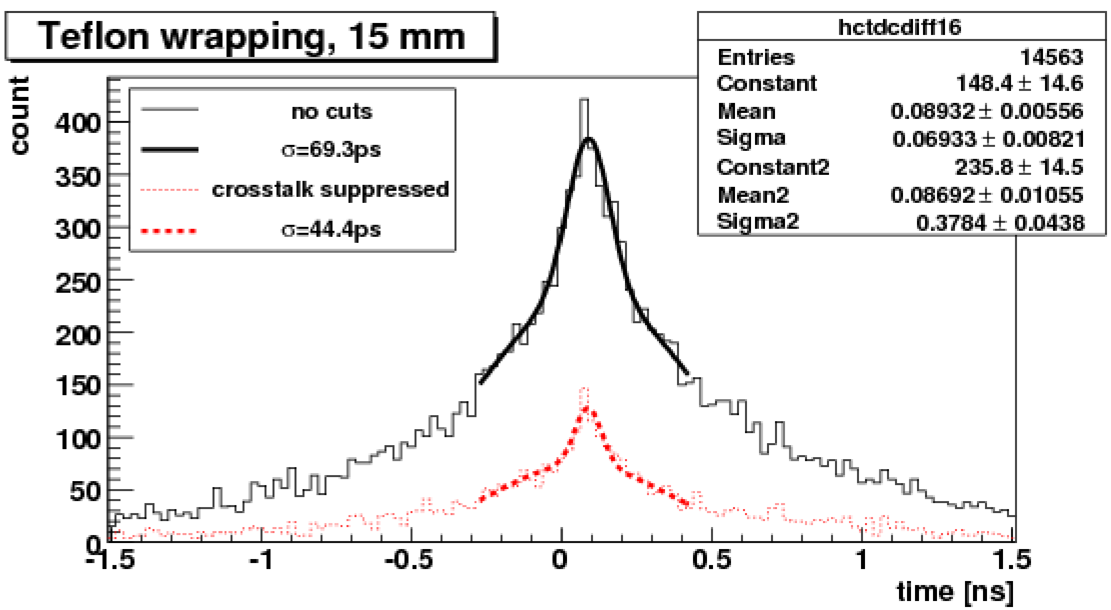


Simulation - summary

- detection of single photons & QE - very low coincidence efficiency (~ 1%)
- black paint stops most reflections at crystal surfaces
  - improves timing
  - reduces efficiency (but mostly at the expense of photons with bad timing)
- PbF_2
  - expected coincidence resolution $\sigma \sim (25 \oplus 2*20)$ps ~ 40ps (15mm thick, black painted crystals)
- $PbWO_4$
  - higher $\rho \rightarrow$ gamma stopping power
  - higher n and Z → more e^- above Ch. threshold → more Ch. photons
  - optical transmission $\lambda_{Cutoff} \rightarrow$ less Cherenkov photons detected
  - higher n → slower optical photons → worse timing resolution
  - scintillation background

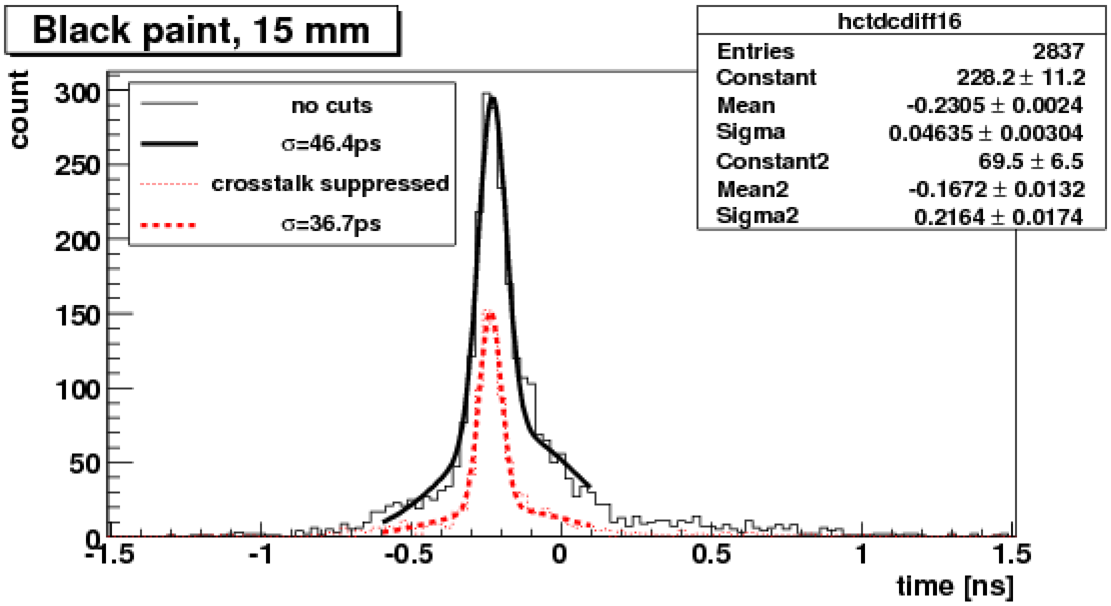
Experimental results – coincidence timing resolution

- time-walk corrected time difference between two selected channels, located near the center of MCP PMT
- crosstalk suppressed events – only events, where the selected channels had maximum charge on their MCP PMT
- 15mm thick PbF_2 crystals, wrapped in Teflon: **σ ~ 44ps (103ps FWHM)**
  - reflected photons are significantly delayed and produce long tails

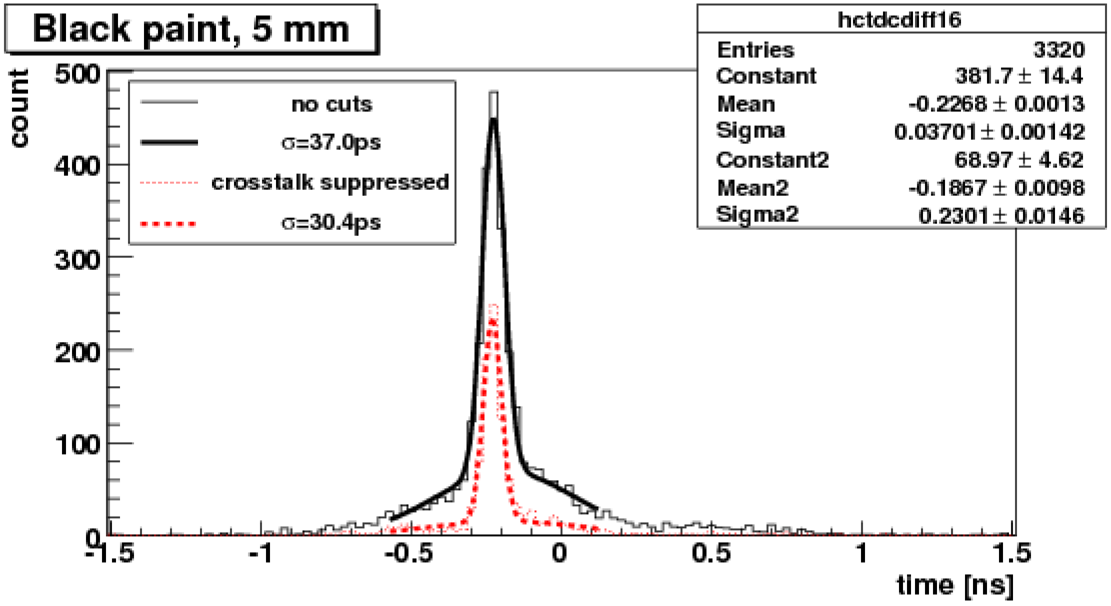


Experimental results – coincidence timing resolution

- black painted, 15mm thick PbF_2 crystals: **σ ~ 37ps (87ps FWHM)**



- black painted, 5mm thick PbF_2 crystals: **σ ~ 30ps (71ps FWHM)**

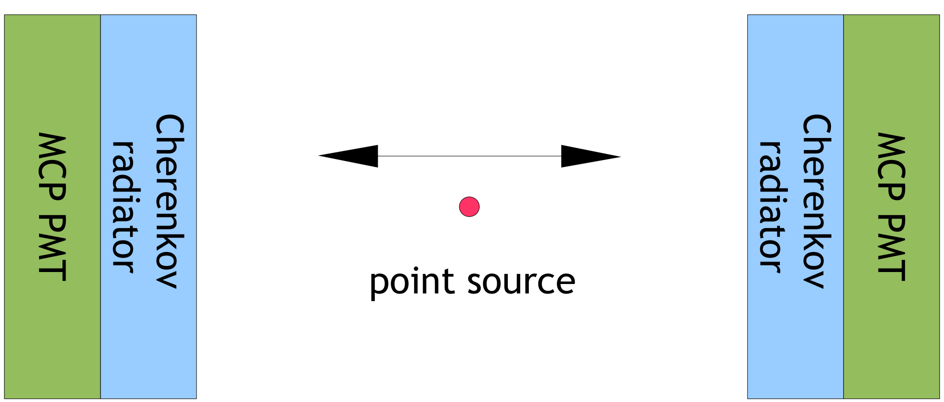


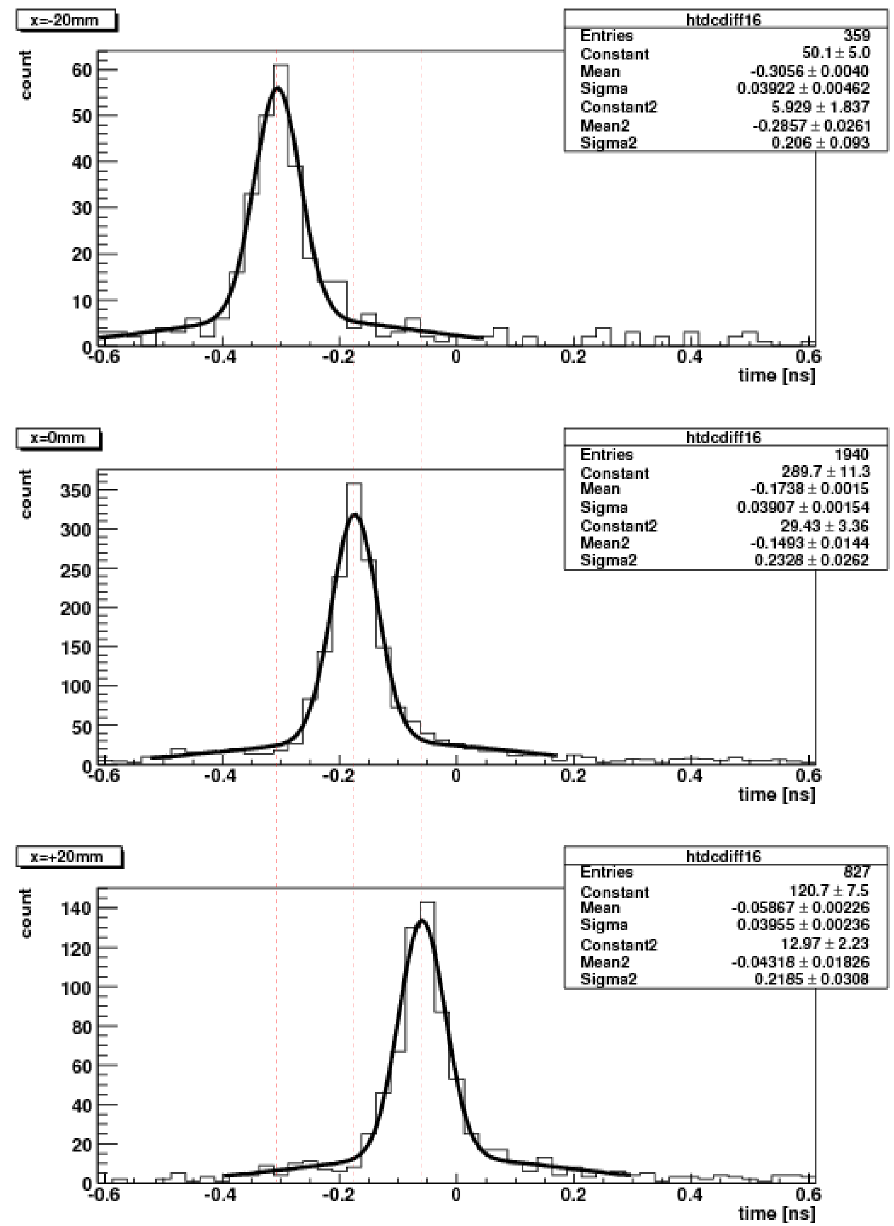
Experimental results - point source position

- black painted, 15mm thick PbF_2 crystals
- point source moved in 20mm steps along LOR
  - average time shift ~ 125ps (→ 19mm)
  - timing resolution σ ~ 40ps

  → position resolution σ ~ 6mm (14mm FWHM)

$$\Delta x = \frac{c_0 \Delta t}{2}$$

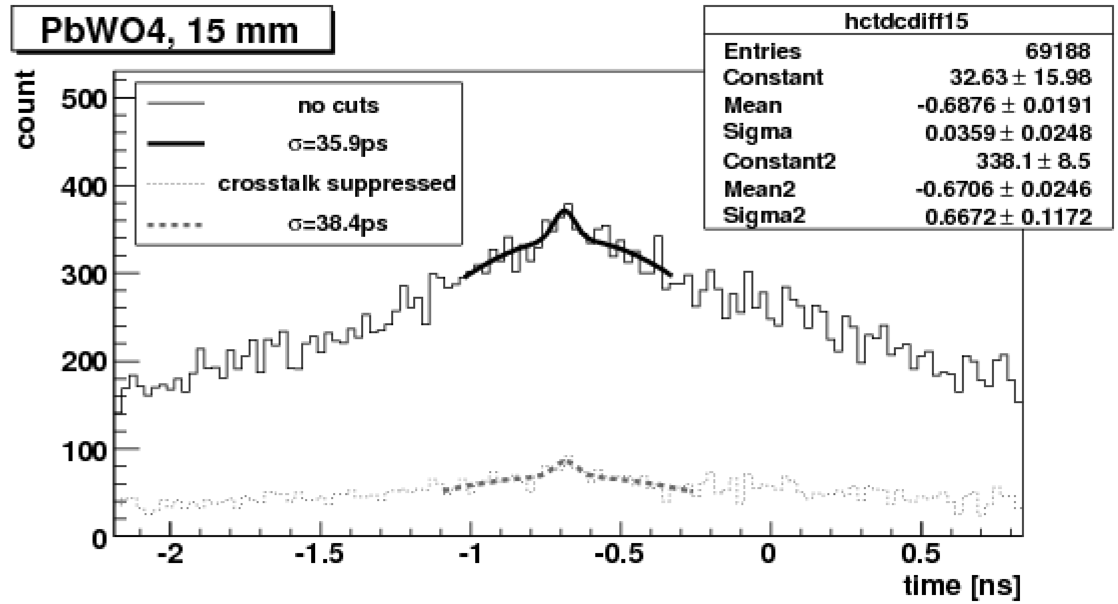


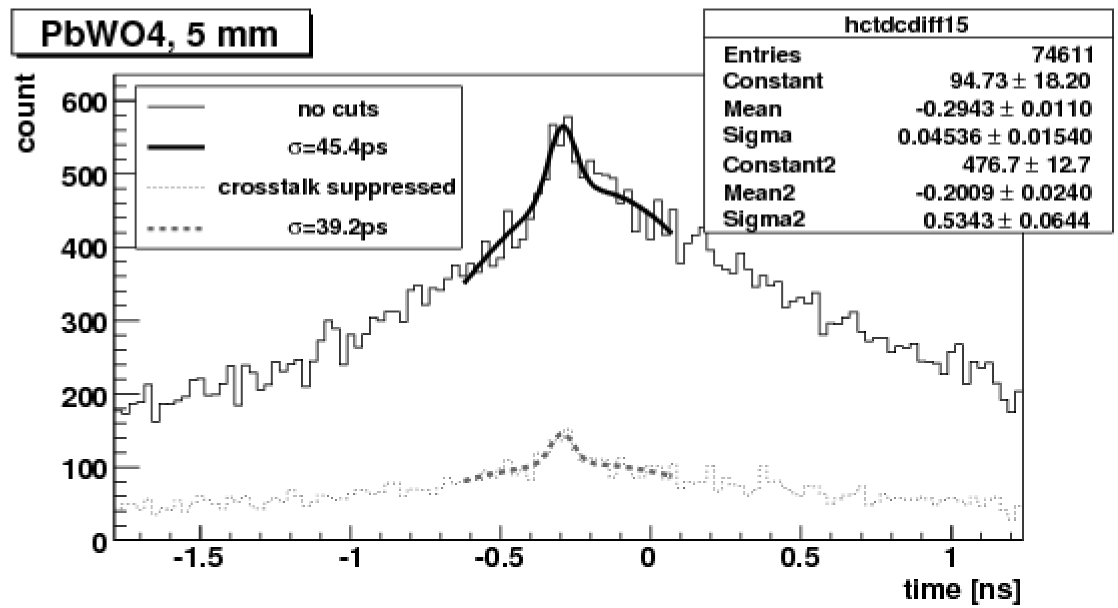


Experimental results - $PbWO_4$

- black painted, 15mm & 5mm thick $PbWO_4$ crystals
- narrow (Cherenkov) peak barely visible, even at 5mm
- 15mm: σ ~ (38 ± 18)ps
- 5mm: σ ~ (39 ± 10)ps

- majority of events produced by single photon detection
- coincidence rate ~30x the rate with PbF_2 crystal (15mm thickness) → majority of events produced by scintillation





Summary

- Scintillation decay limits the TOF resolution
- Prompt Cherenkov photons in combination with very fast photodetectors can be used to measure TOF for 511keV annihilation gammas
- The limiting factor becomes the propagation time spread of Cherenkov photons in the crystal
- Measured coincidence time resolution for
  - 5mm thick PbF_2 crystal σ ~ 30ps (71ps FWHM)
  - 15mm thick PbF_2 crystal σ ~ 37ps (87ps FWHM)
- Measured position resolution along LOR σ ~ 6mm (14mm FWHM)
- With $PbWO_4$ crystal the scintillations present a challenge
- Efficiency of this method is rather low (~1%)
  - improvements possible with SBA photocathode, quartz PMT window and possible new Cherenkov radiators (transmission in UV)
  - such excellent time resolution may enable modified reconstruction methods, maybe possible with lower statistics

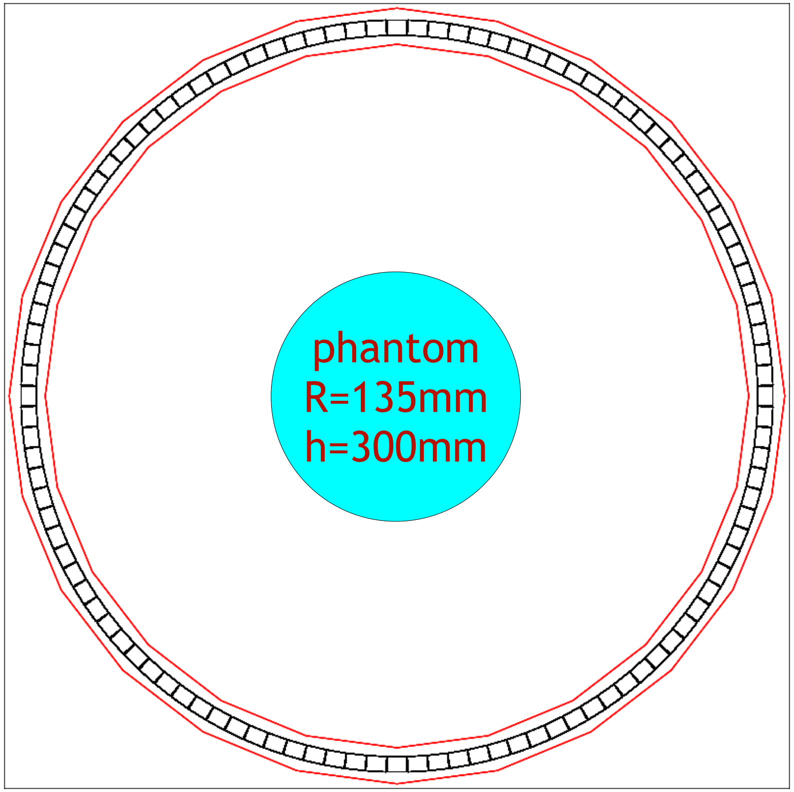
Backup slides

Reconstruction - first attempt

- simulated full body scanner:
  - 16 rings (~370mm axial coverage)
  - ring R=400mm, 112 detectors/ring
  - detector: 15mm thick, black painted PbF_2, segmented into 4x4 (~5.5mm pitch)
  - MCP PMT time response included
- phantom R=135mm, h=300mm
- 2 point (R=0.3mm) sources
  - at (-5,-5,-5) mm and (5,5,5) mm
- Most Likely Position reconstruction method
  - point on LOR defined by TOF information

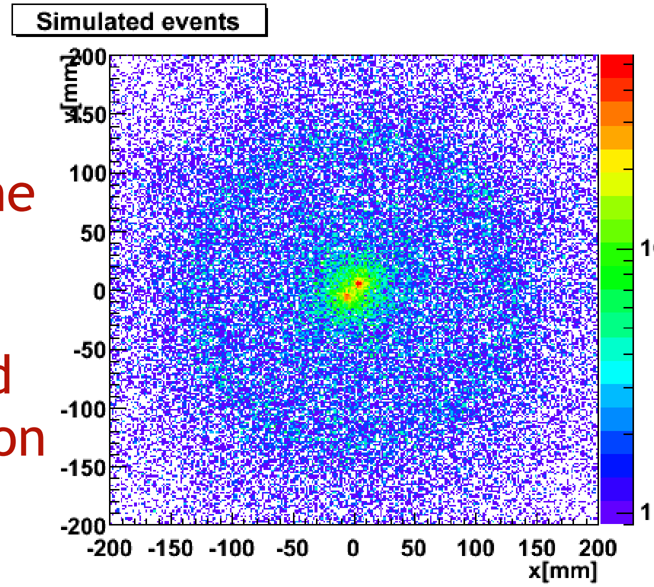
$$r = \frac{(r_1 + r_2)}{2} - \frac{c_0 \Delta t}{d_{LOR}} \frac{(r_2 - r_1)}{2}$$

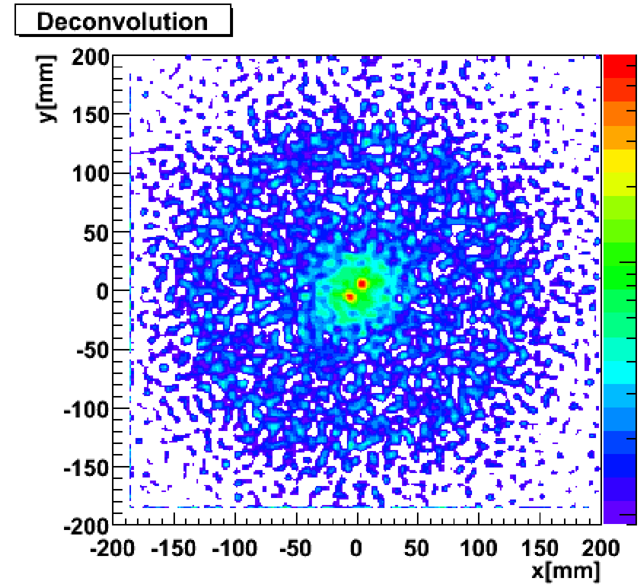
  - deconvoluted by Gaussian response function (σ = 20ps → 3mm)



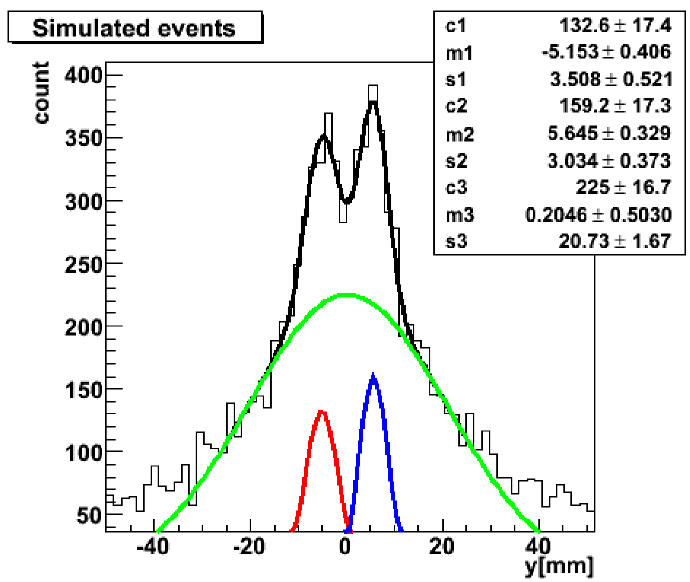
Reconstruction - MLP method

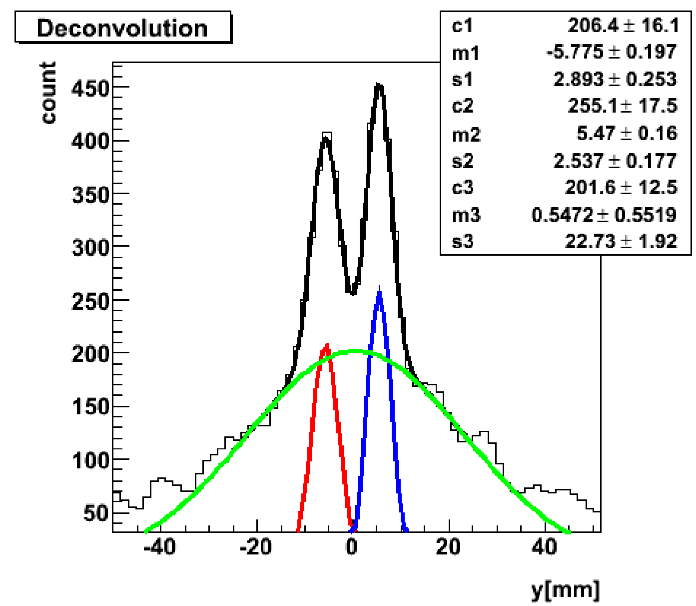
- transverse projection
- all coincidences, including all crossplane
- phantom visible
- two sources separated by ~14mm in projection





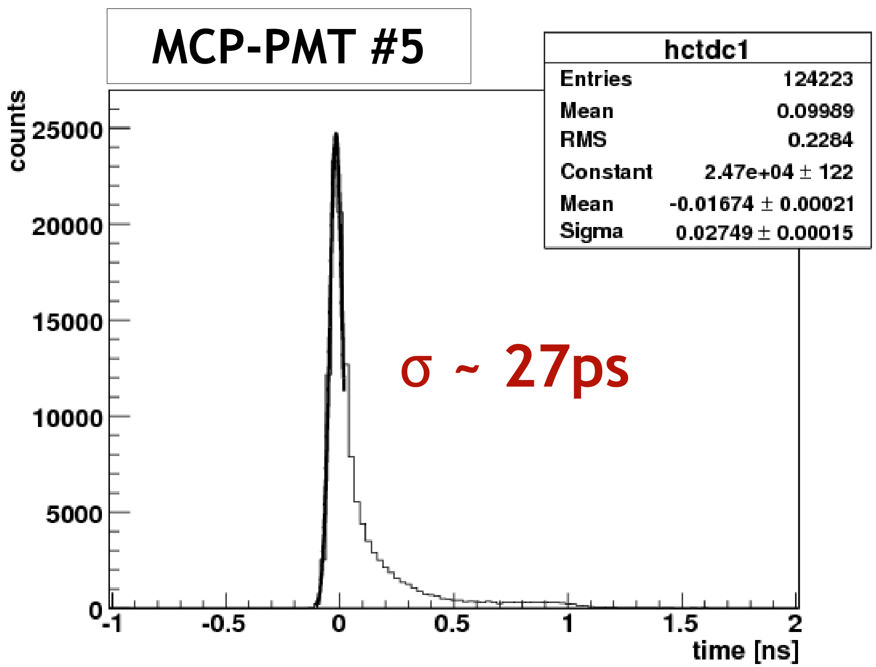
- 1D projection along Y
  - σ ~ 3.5mm
- after deconvolution
  - σ ~ 2.9mm

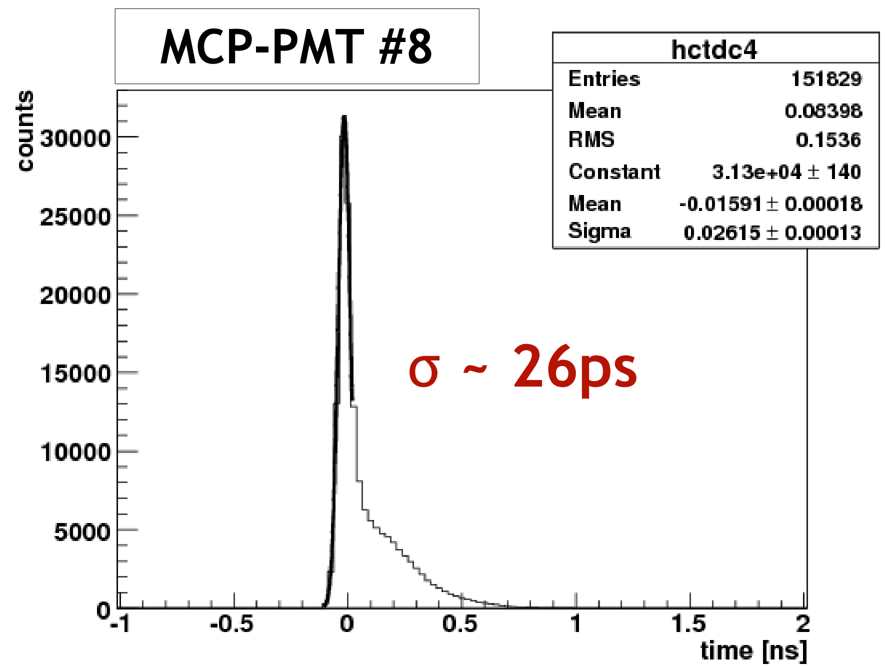




MCP PMT intrinsic timing resolution

- measured with PiLas pico-second laser (λ=406nm), attenuated to single photon detection level
- r.m.s. of prompt peak for both samples below 30ps, including contributions from laser (~15ps) and electronics (~11ps)
- intrinsic timing resolution for single photons ~ 20ps
- about ~ 1ns long tails, mainly due to photoelectron backscattering from front MCP surface

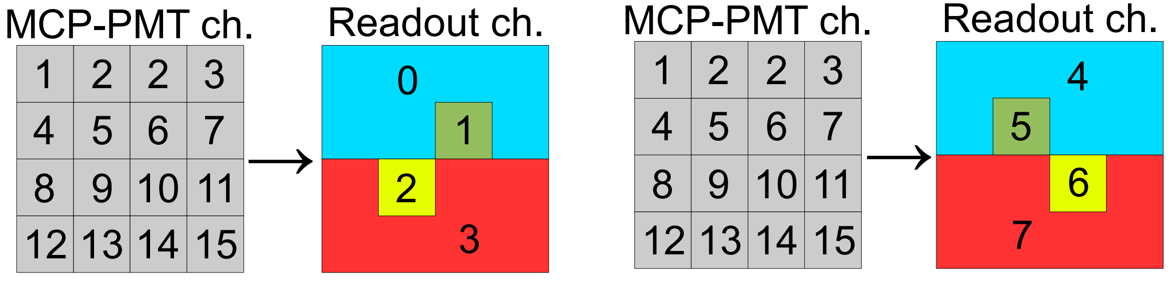




Setup - redout configuration

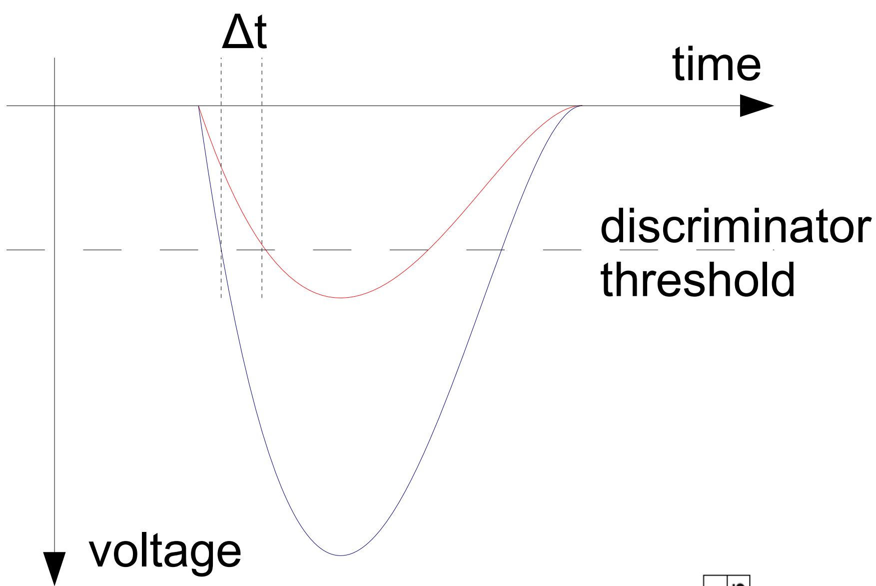
- Limited number of electronic channels – 4 per MCP-PMT:
- 2 channels near the center instrumented individually
- Remaining channels combined in groups of 7

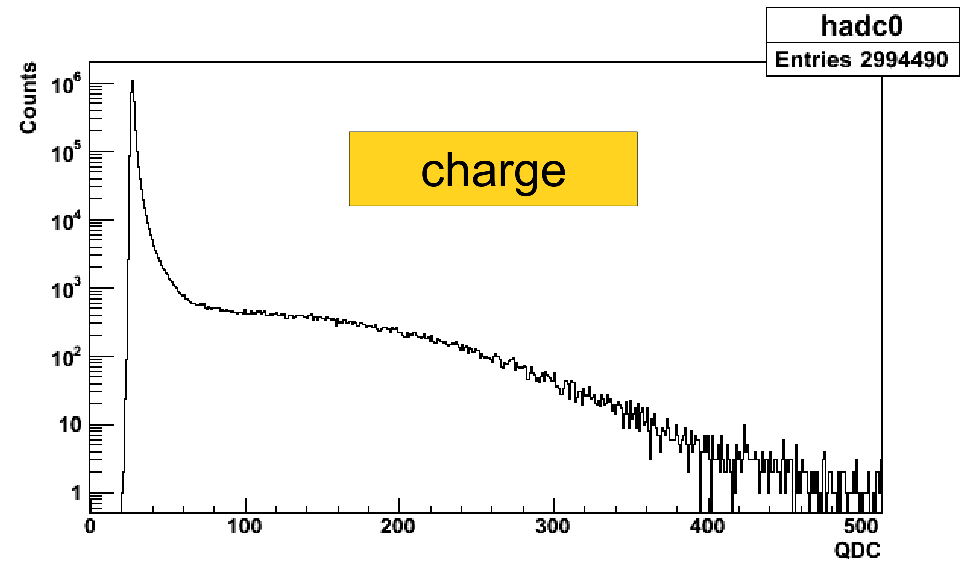
- Signal from single photon can be detected on more than one channel due to charge sharing, cross-talk …
- Directly hit channel will most probably have the largest signal.
- Plots labeled 'crosstalk suppressed' use only the channel with the largest signal.

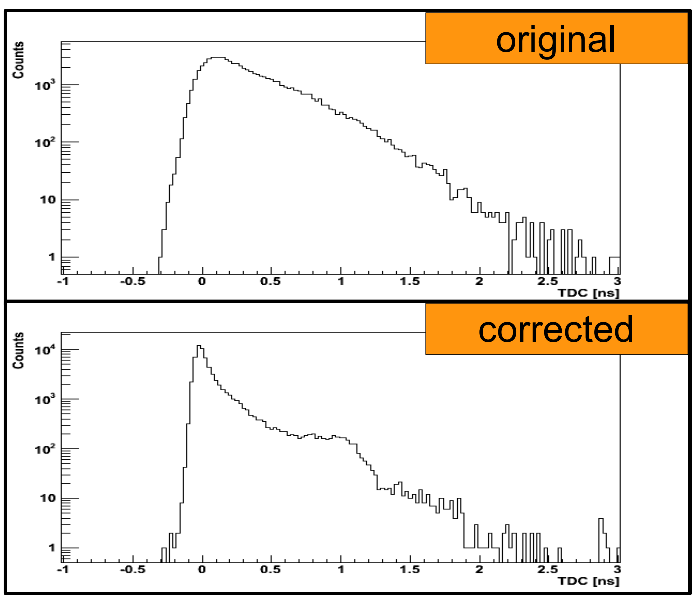


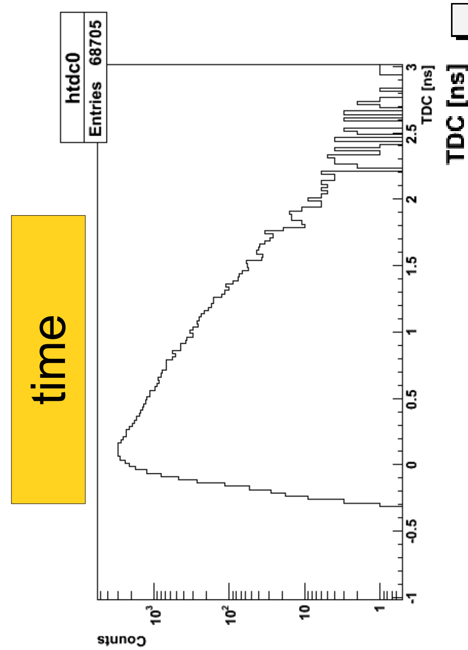
Time-walk correction

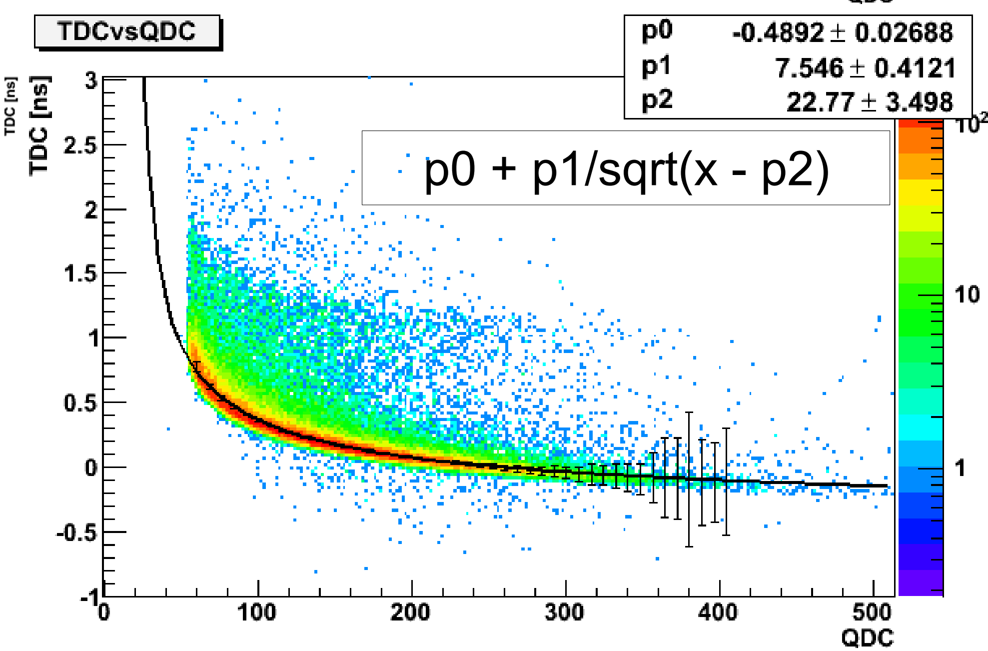
- Leading Edge discriminator – triggers at set signal voltage level → smaller pulses register at later time









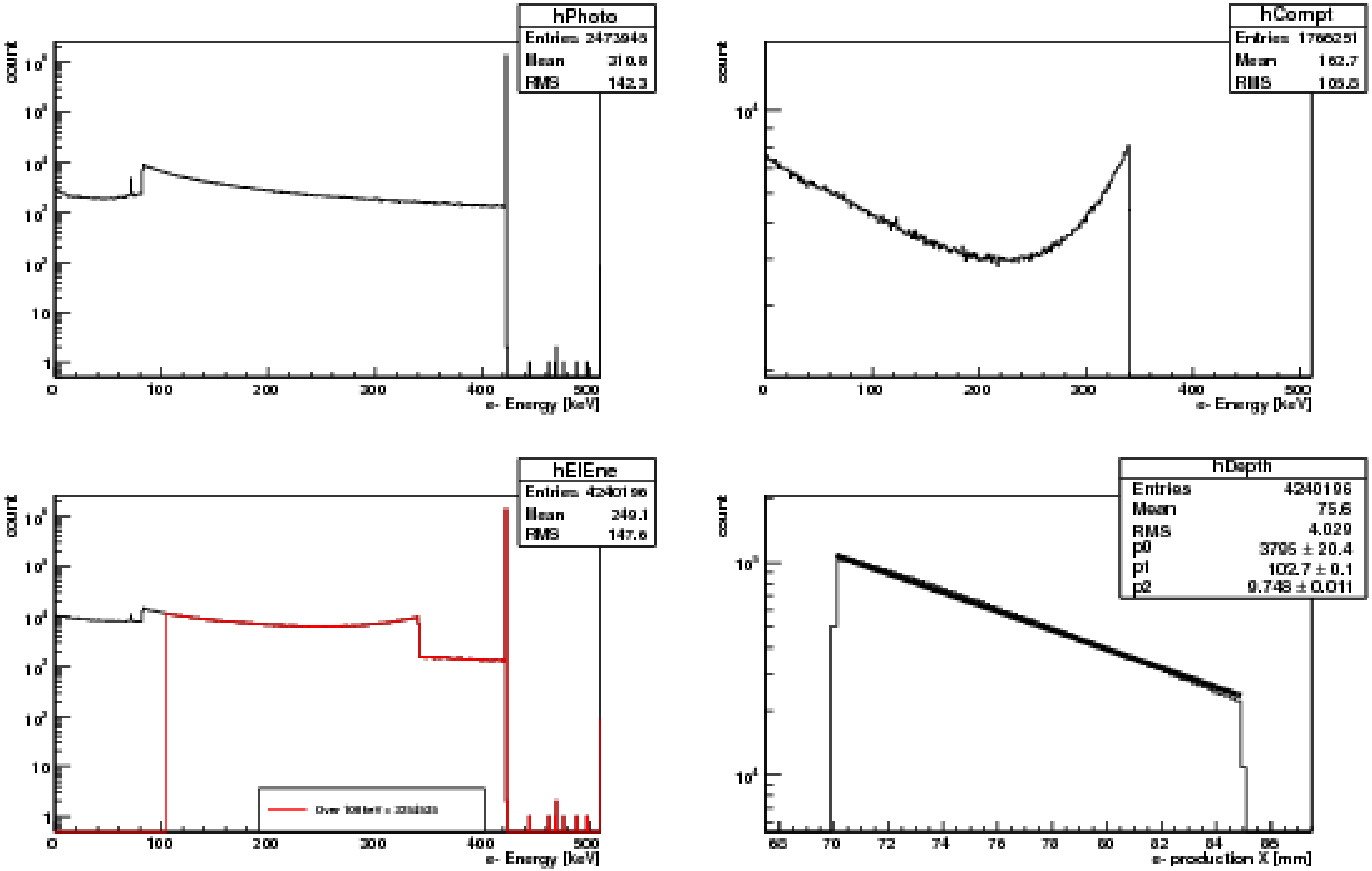


Black paint (PbF_2)

Polished

Ground

Simulation - electron production



Photon interaction with matter

- Compton scattering: γ scatters on electrons, loosing part of its energy
  - cross section ∝ Z/E_γ
- photoelectric absorption: γ is absorbed, giving most of its energy to electron
  - cross section ∝ Z^n/E_γ^3, n~4