Development of the Fast and Efficient Gamma Detector Using Cherenkov Light for TOF-PET

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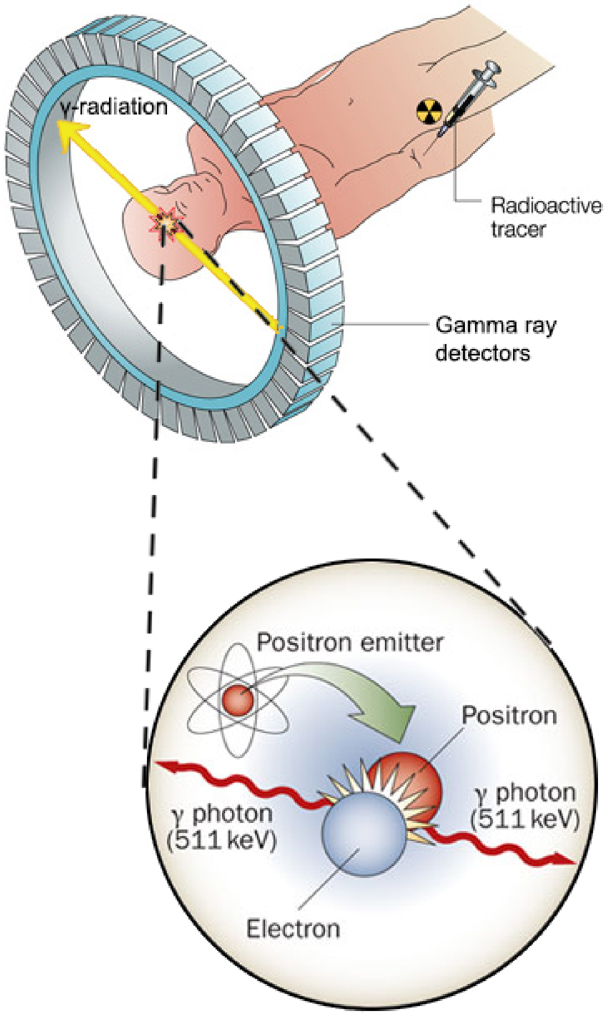
Positron Emission Tomography (PET)

- Functional 3-D imaging technique in nuclear medicine
  - **Oncology** : small tumors and metastases imaging
  - **Neurology** : exams of neurodegenerative diseases (Alzheimer, Parkinson)
  - …
- **Principle :**
  - **Radioactive tracer** (ex : FDG) is injected in the patient body and then chemically bounded in tissue
  - **β+ decay** : emission of a **positron**
  - **Annihilation** with an electron of tissue : **two 511 keV γ** are emitted back-to-back
  - Detection in **coincidence**
  - **Image reconstruction**
- Important characteristics of PET detector
  - **Efficiency**
  - **Time resolution**
  - **Spatial resolution**



Time of Flight Technique

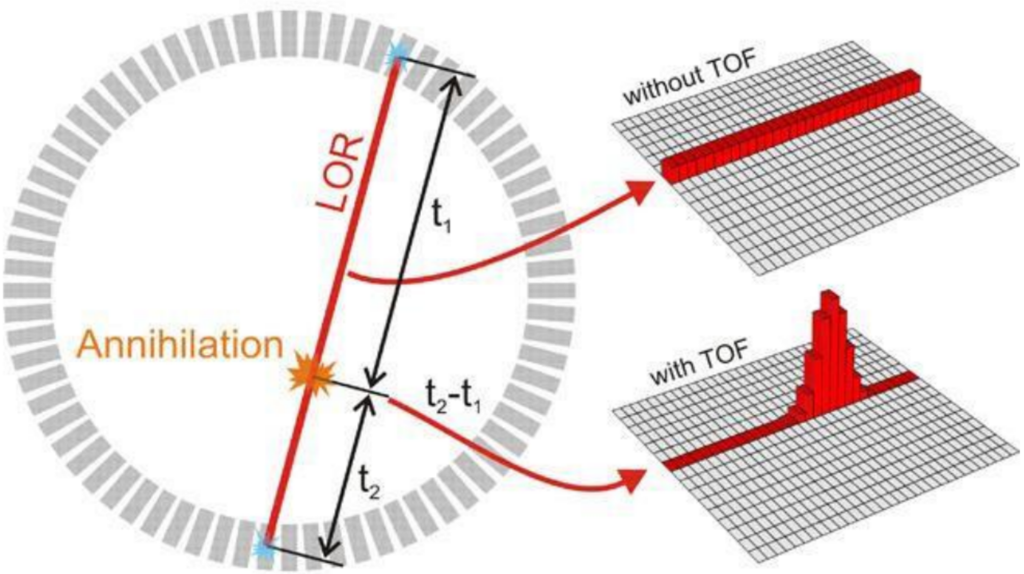
Provides information on the localisation of the annihilation vertex on the Line-Of-Response (LOR).

Goal : achieve time resolution of 100 ps (FWHM)

→ localisation of 3 cm on the LOR

→ Improvement of the image **signal-to-noise ratio**

$$\text{gain} = \sqrt{\frac{2 \cdot D}{c \cdot \delta t}}$$



For example,
*With * D = 20 cm (organ size)*
* * δt = 100 ps,*
gain in constrast is 3.6

Time of Flight Technique

Improvement of **the signal-to-noise ratio :**

→ reducing of the radiation dose received by the patient while keeping the same image quality,

→ or, alternatively, improvement of the image quality without increasing the received dose.

Current PET-scan uses scintillation

~ 10 to 50 ns

To improve the TOF : using of **Cherenkov radiation**

fast :~ 10 ps

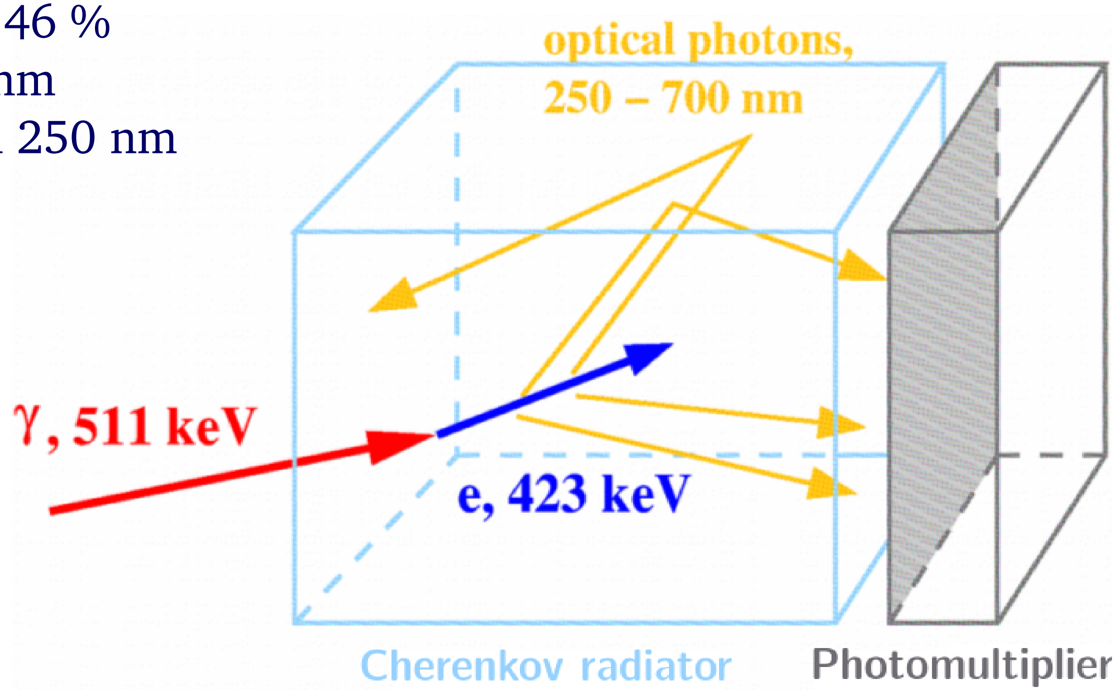
but low yield

→ development of 2 twin projects : **CaLIPSO** and **PECHE**

→ Construct a Cherenkov detector with high detection efficiency and time resolution

→ PbF_2 crystal (10 mm) :
* very fast with Cherenkov radiation
* one of the highest photoelectric fraction : 46 %
* optical refractive index : 1.82 for λ=400 nm
* near perfect optical transparency between 250 nm and infrared wavelengths
* large density : 7.66 g/cm^3

KORPAR, S. et al., NIM A, vol. 654, 2011
KORPAR, S. et al., NIM A, vol. 732, 2013



→ Optical gel (OCF 452) :
* refractive index : 1,55 (400 nm)
* transparent up to 300 nm

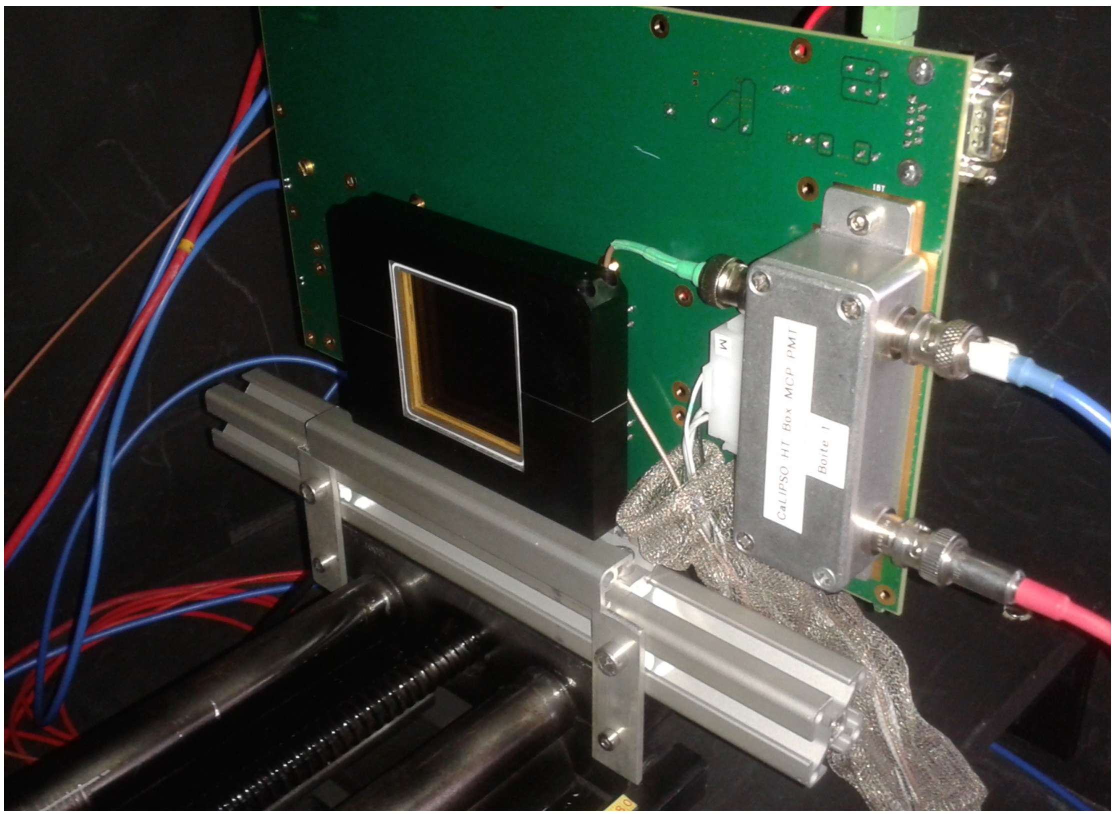
→ MicroChannel Plate-PMT (Photonis)

→ Preamplifiers 2.5 GHz bandwidth, 30 dB, ZKL-2R5+

→ SAMPIC module : Time and Waveform Digital Converter (TWDC) chip

MicroChannel Plate – PhotoMultiplier Tube

MCP-PMT Photonis
XP85012 Planacon



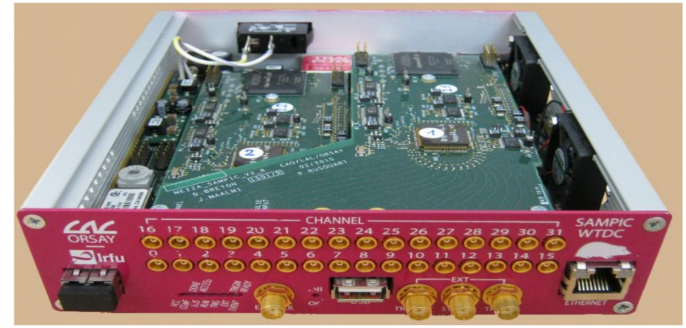
* **Low Dark Count Rate**
  $\simeq$ 100 Hz/cm^2
* **Fast :**
  TTS $\lesssim$ 100 ps (FWHM)
* **Good quantum efficiency**
  up to 25 %

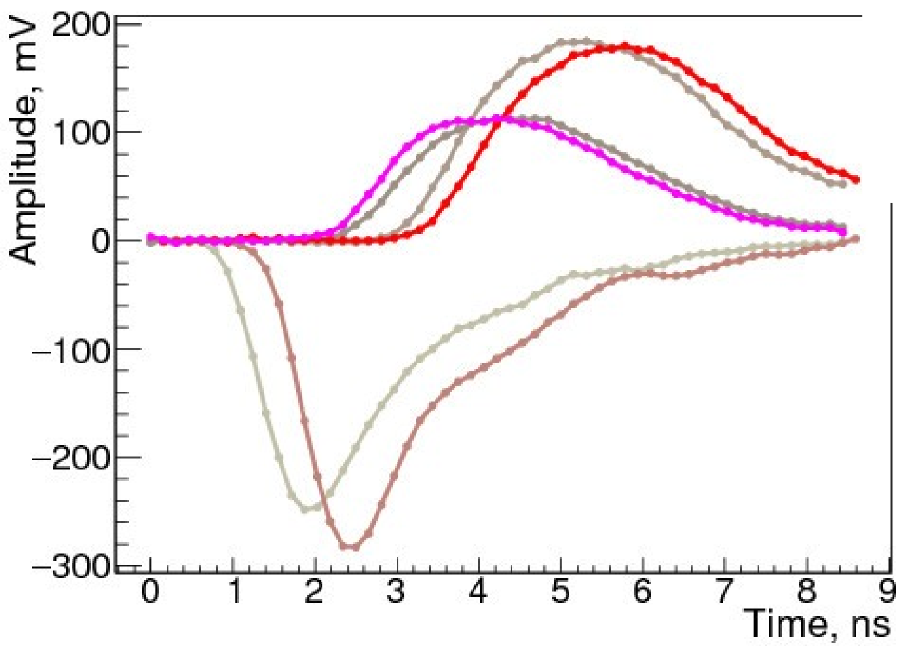
* Active surface 53 mm x 53 mm
* Windows material : sapphire
* 8 x 8 anodes
* 25 μm pore diameter

The SAMPIC module

Signals numerisation with the **SAMPIC** module:

A 32-channel, 10-GSPS Time and Waveform Digital Converter module, developped by **IRFU** and **LAL.**





Typical signal with 6.4 GS/s

* provides digitized waveform with 64 samples, 1.6 GS/s to 10 GS/s

* extremely good resolution in time :
< 5 ps (σ)

* allows to use on-line the configurable Constant Fraction Discriminator (CFD) algorithms

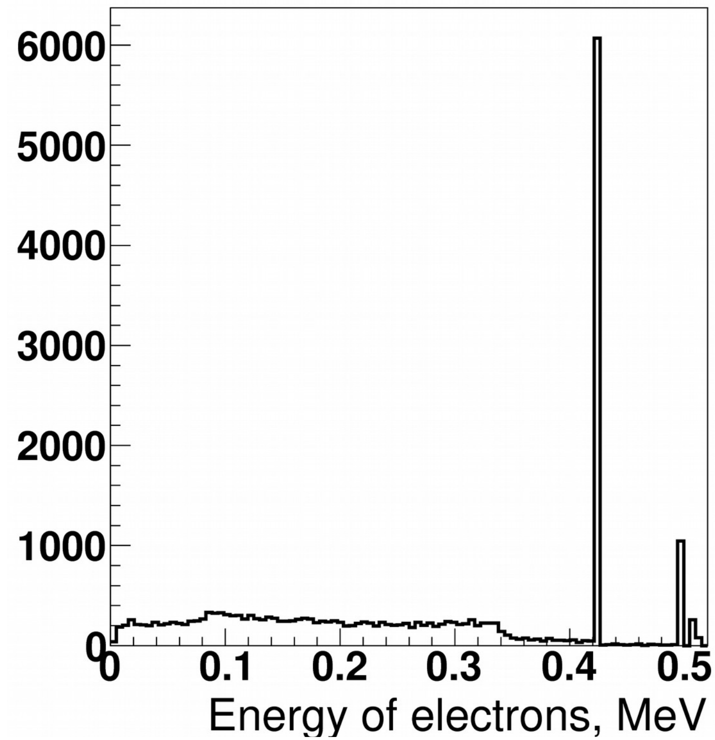
* acquisition of waveform and/or CFD time

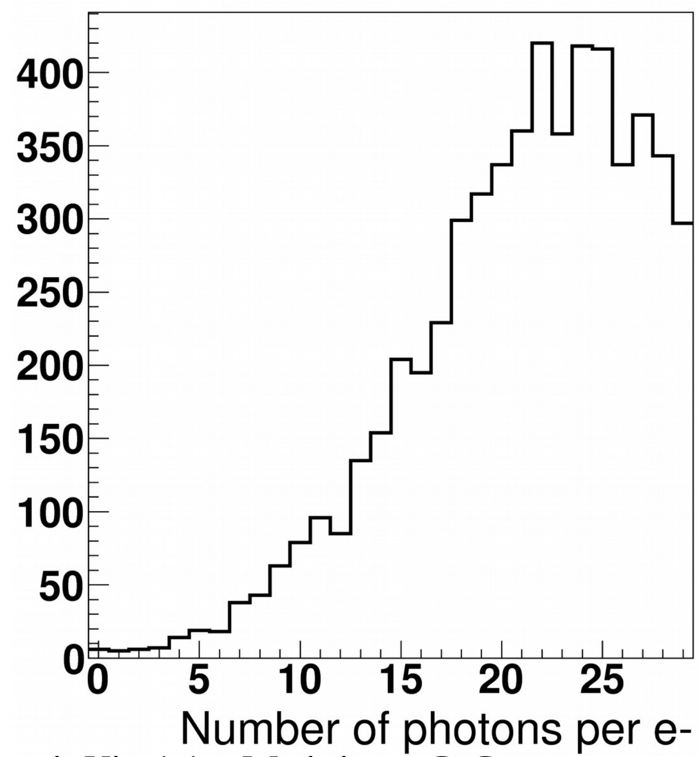
BRETON, D. NIM, A 835, 51-60, 2016
DELAGNES, E. NIM, A. 245, 2015

Detector Efficiency Model

→ A 511 keV gamma enters the crystal, what probability do I have to detect it ?

* gamma-conversion efficiency : 67 % for 10 mm crystal
* photoelectric conversion in PbF_2 : 46 %
* optical coupling from crystal to PMT
* quantum efficiency of photocathode : up to 25 %





Simulation gives an efficiency of about 30 %

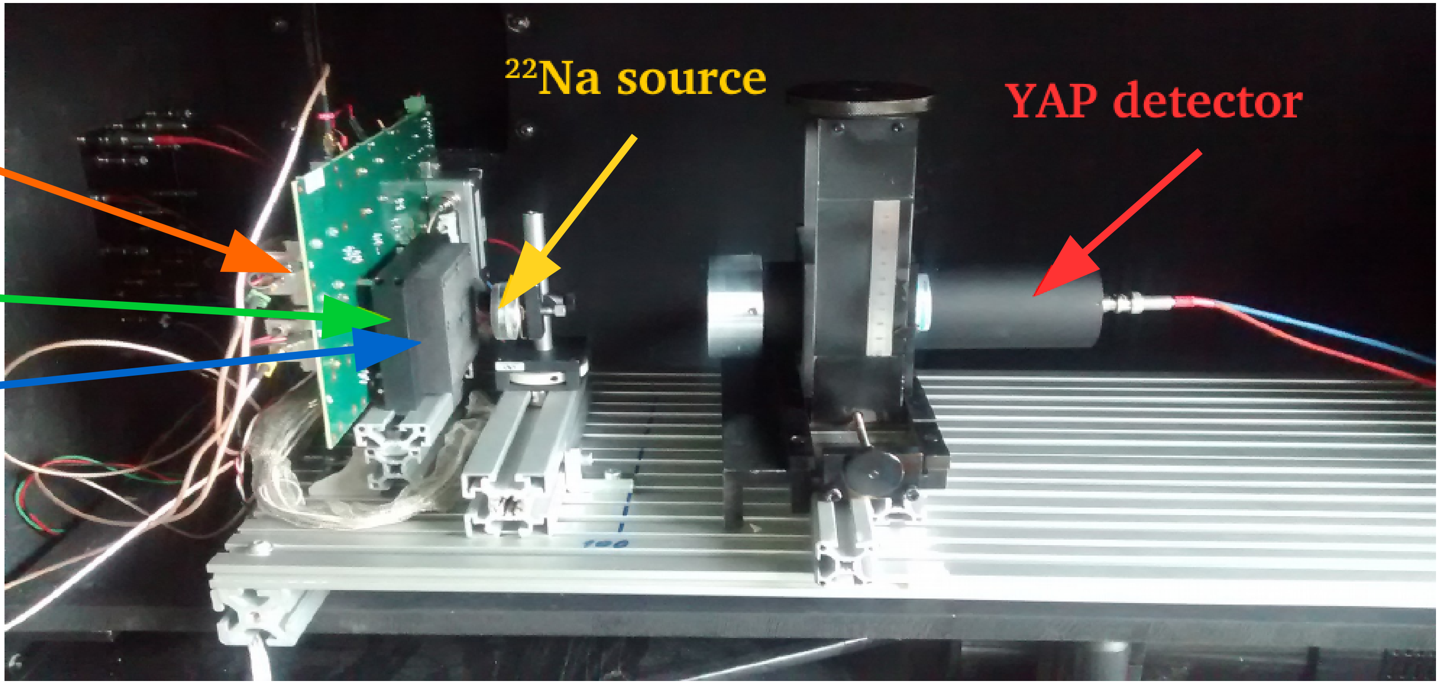
Efficiency Measurement Setup

→ **Measured with reference YAP detector with « Tag & Probe » method**

Pre-amplifiers

MCP-PMT

PbF_2 crystal :
59 mm x 59 mm x 10 mm



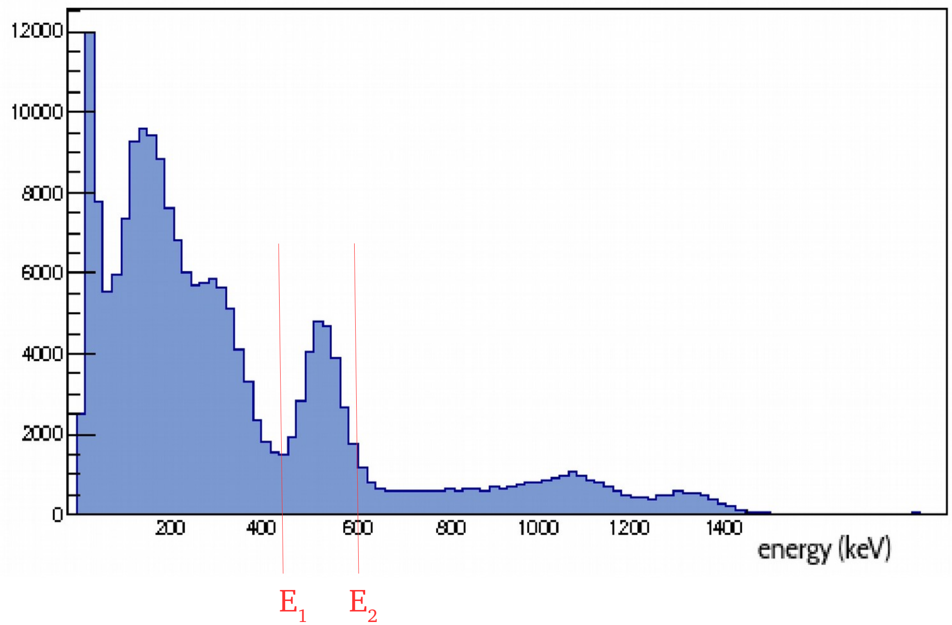
Efficiency Measurement Results

In order to know when a 511 keV gamma entered on the detector

→ selection of the 511 keV events in the YAP

→ look at the coincidence events in the PbF_2

YAP energy spectrum



$$Eff = \frac{N\ (PbF_2)}{N_{YAP}\ (E>E_1,\ E<E_2)}$$

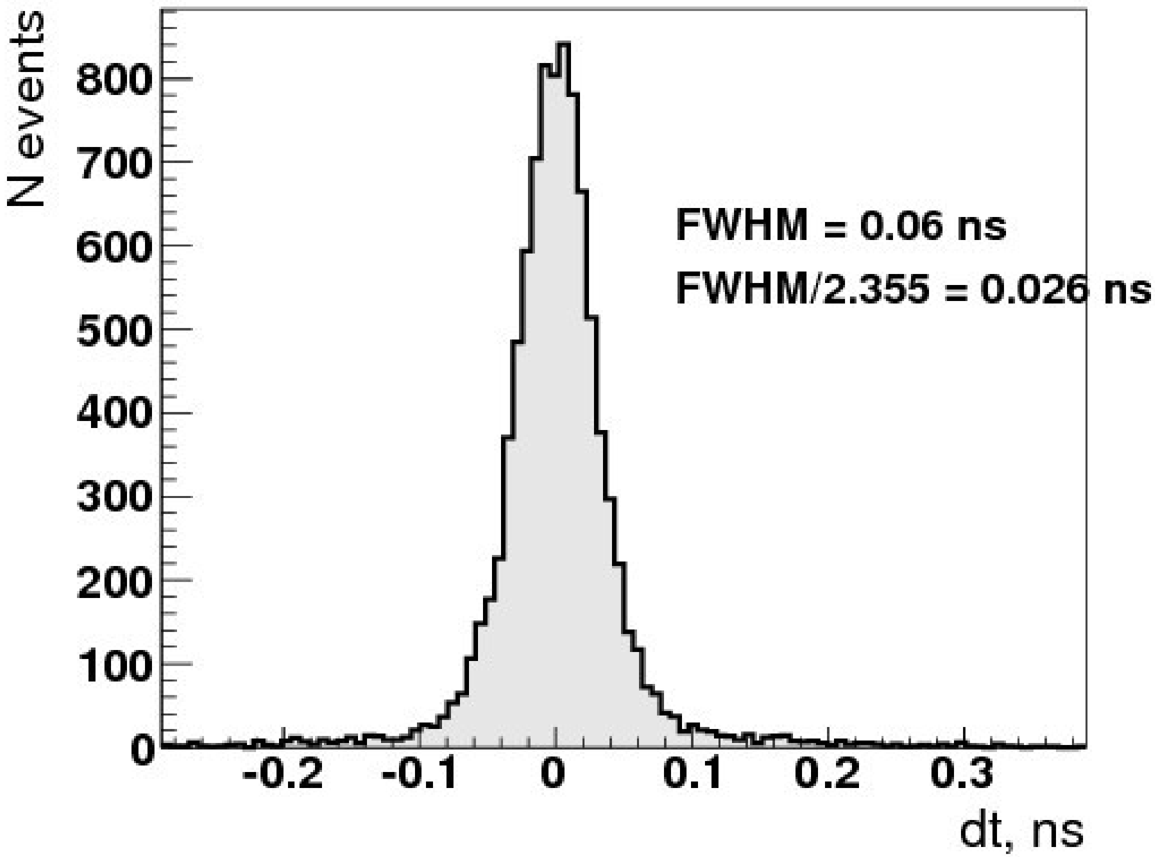
Eff ~ 28 % *(preliminary)*

Systematic effects taken into account :

overestimation of the N_{YAP}, due to the presence of Compton scattering from 1.3 MeV Compton

Detector Time Resolution
Optical Dispersion only

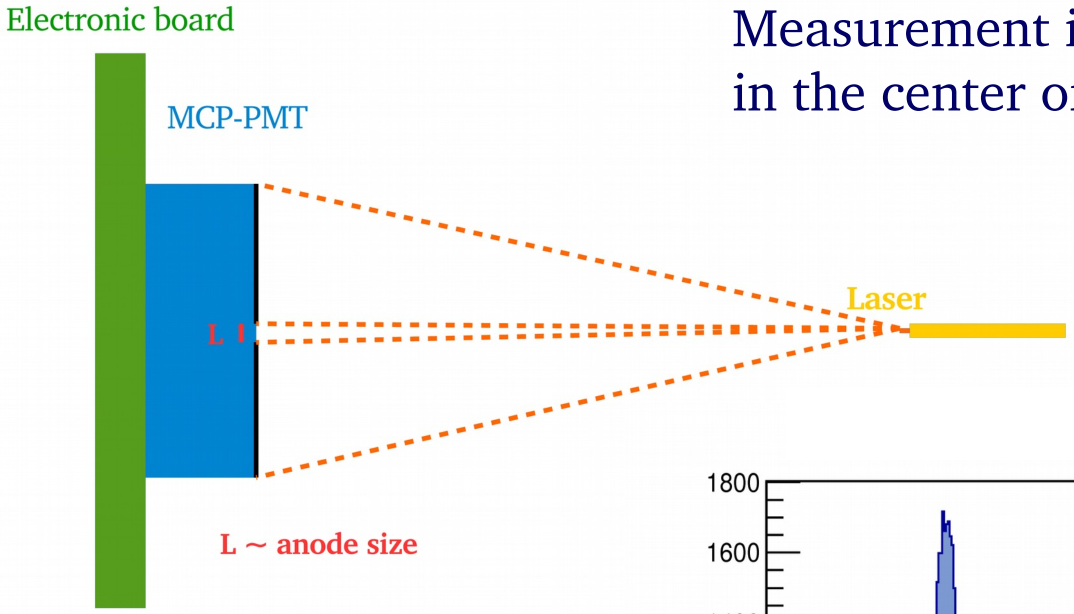
Simulation of intrinsic dispersion of the optical paths in the crystal



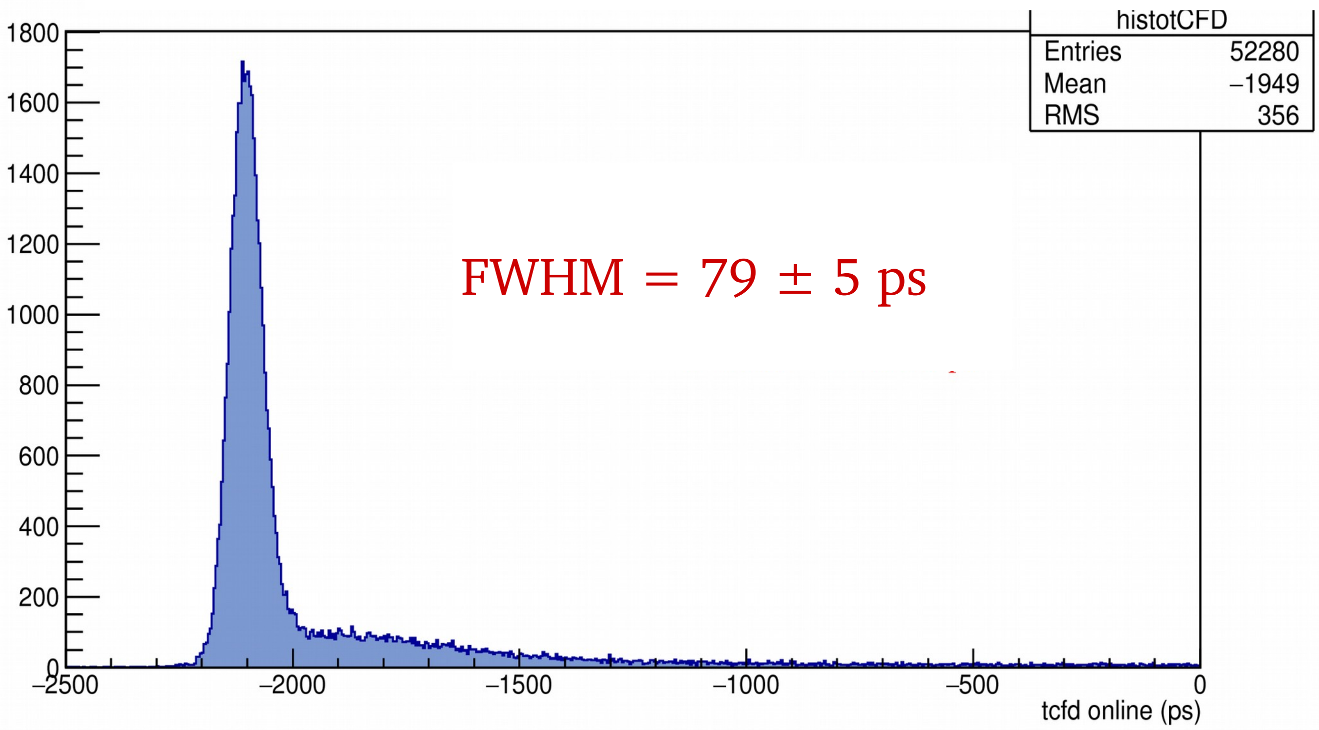
10 mm thick

For a single detector : **FWHM ~ 40 ps**

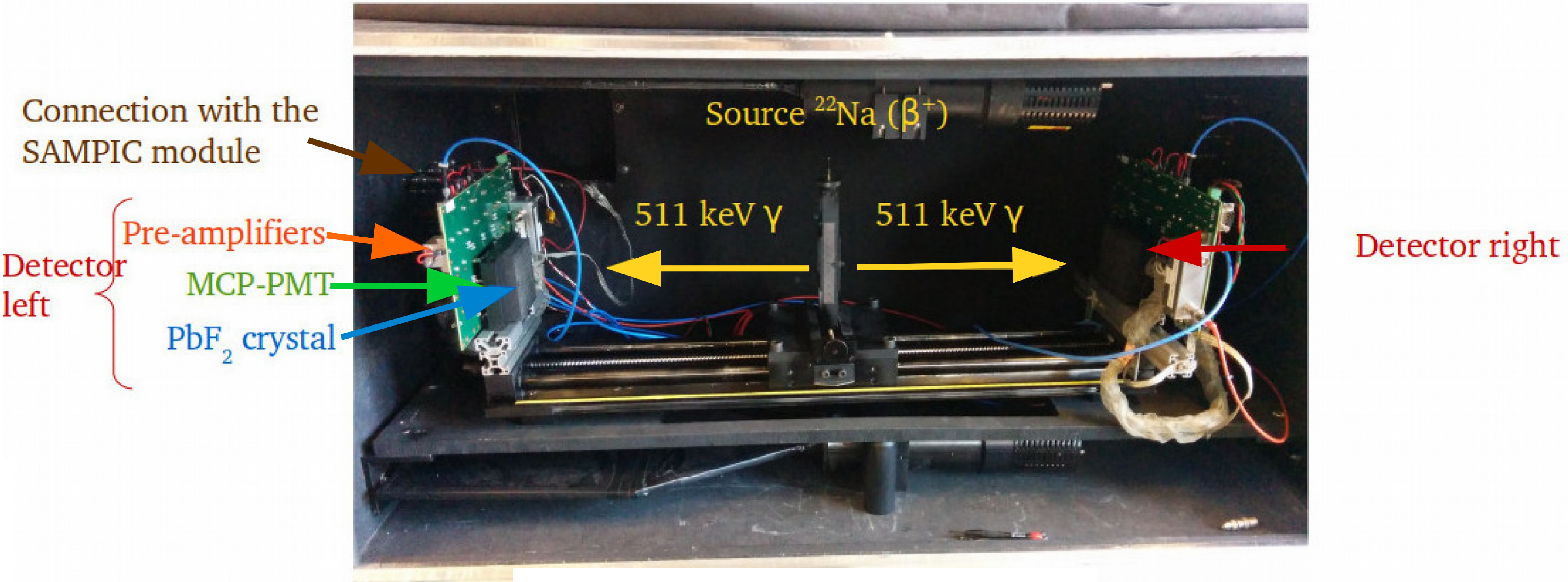
MCP-PMT Time Resolution Measurement

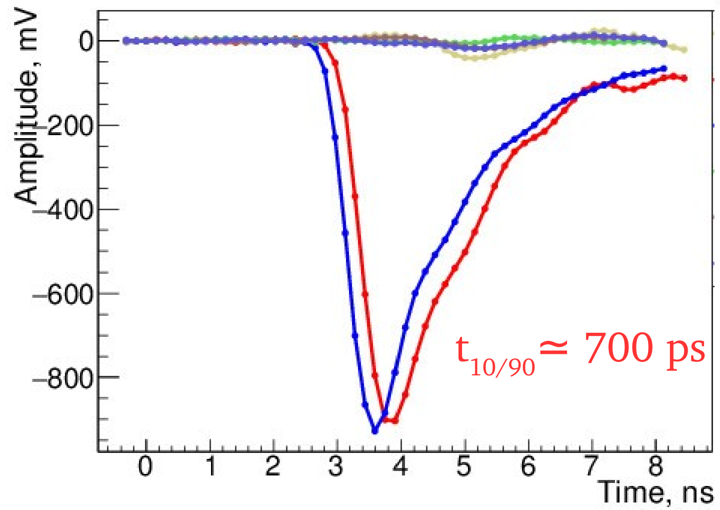


Measurement in a single photon mode,
in the center of MCP-PMT, laser beam width ~ 25 ps

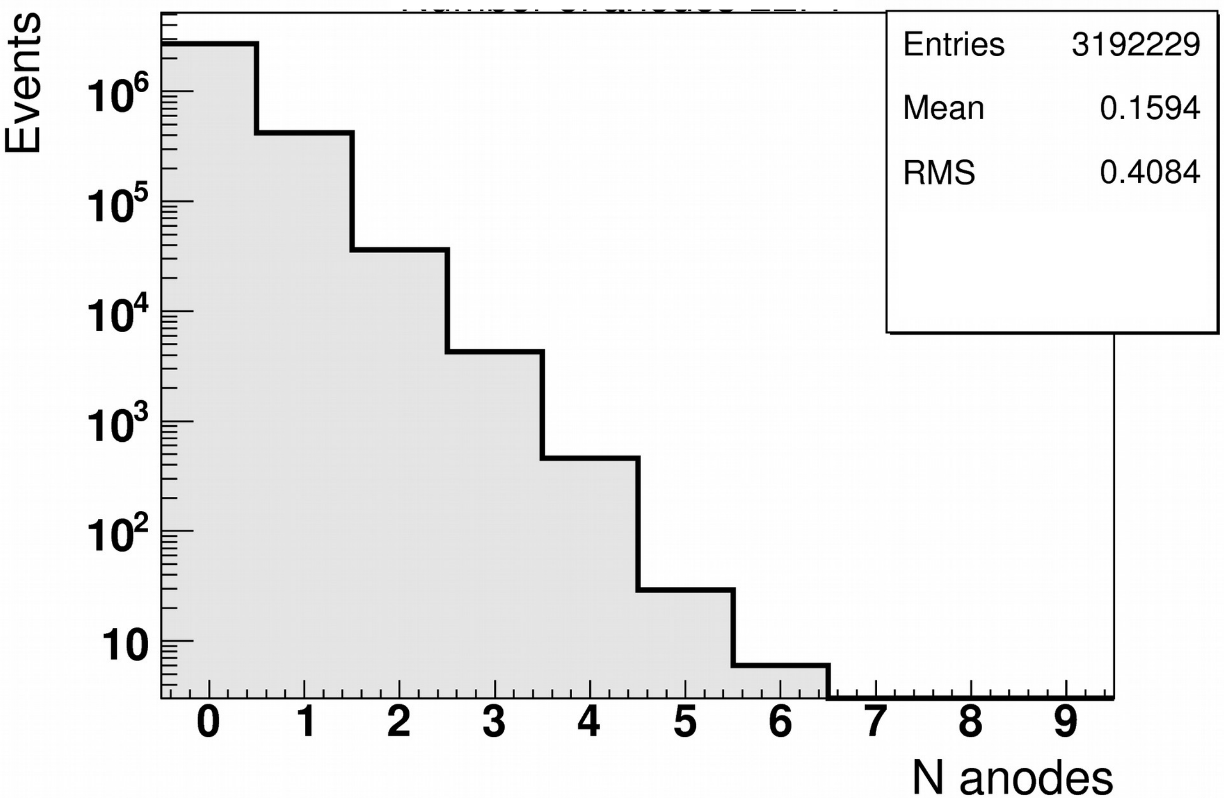


Detector Time Resolution Setup



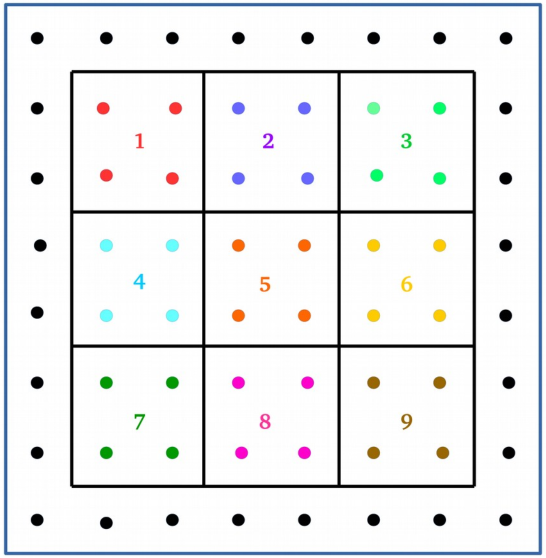


Towards full-size Detector



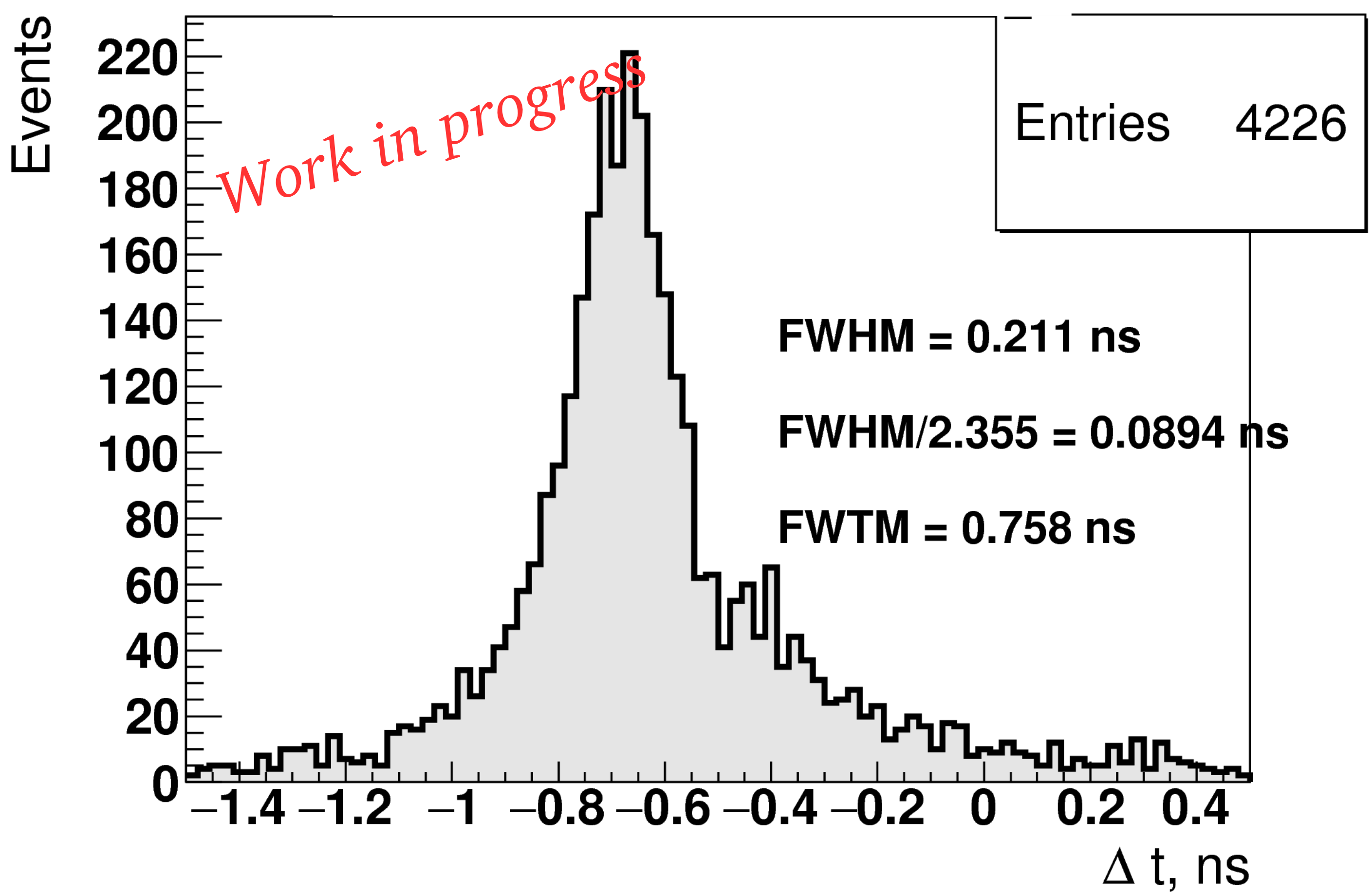
SIMULATION : Number of anode hits per PMT

* MCP-PMT = 64 anodes
* grouping anodes by 4
* reading the 9 central anodes



Towards full-size Detector Measurement

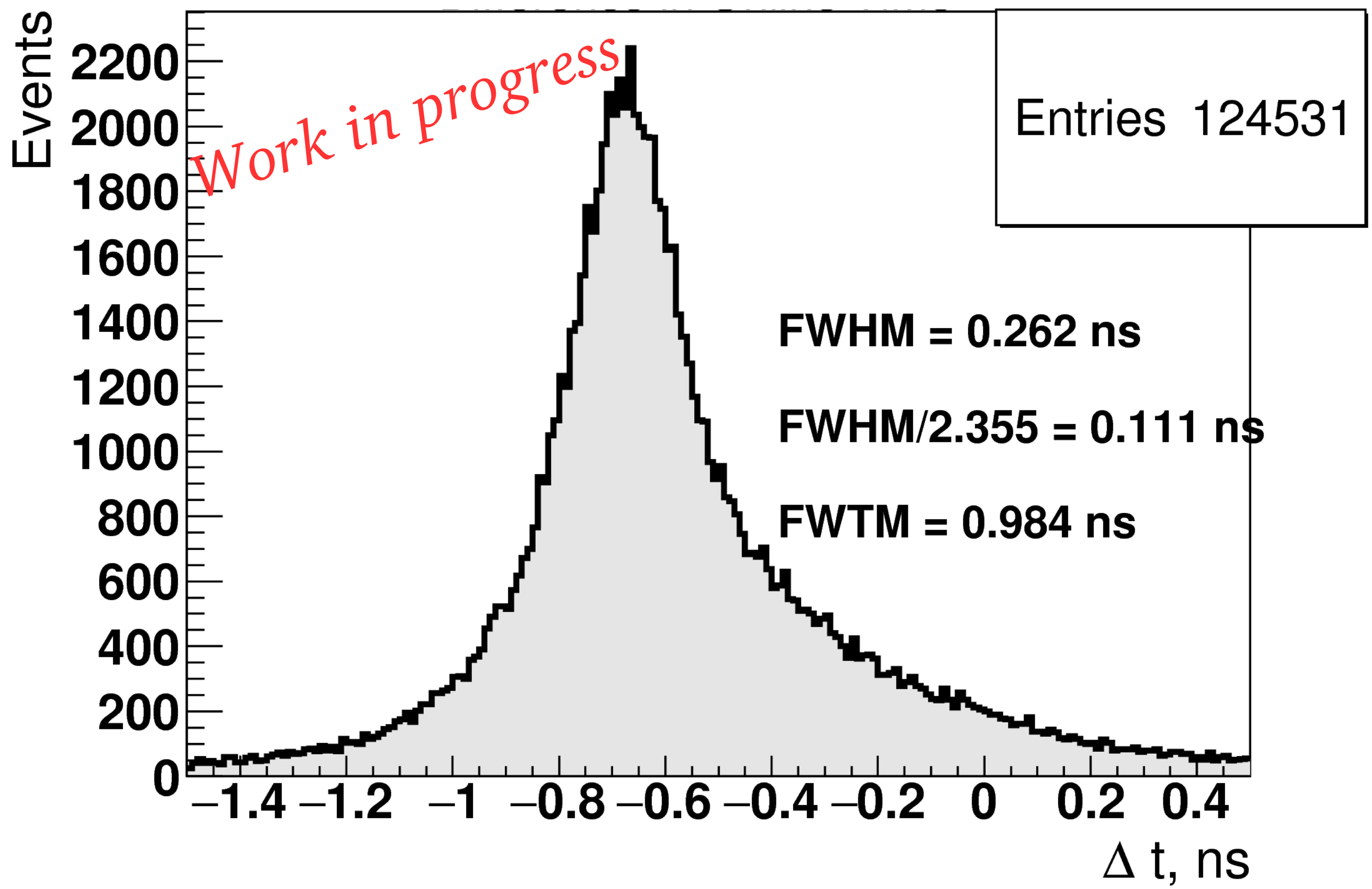
Time Difference between the two detectors
in the MCP-PMT center



For a single detector : **FWHM = (150 ± 10) ps**

Towards full-size Detector Measurement

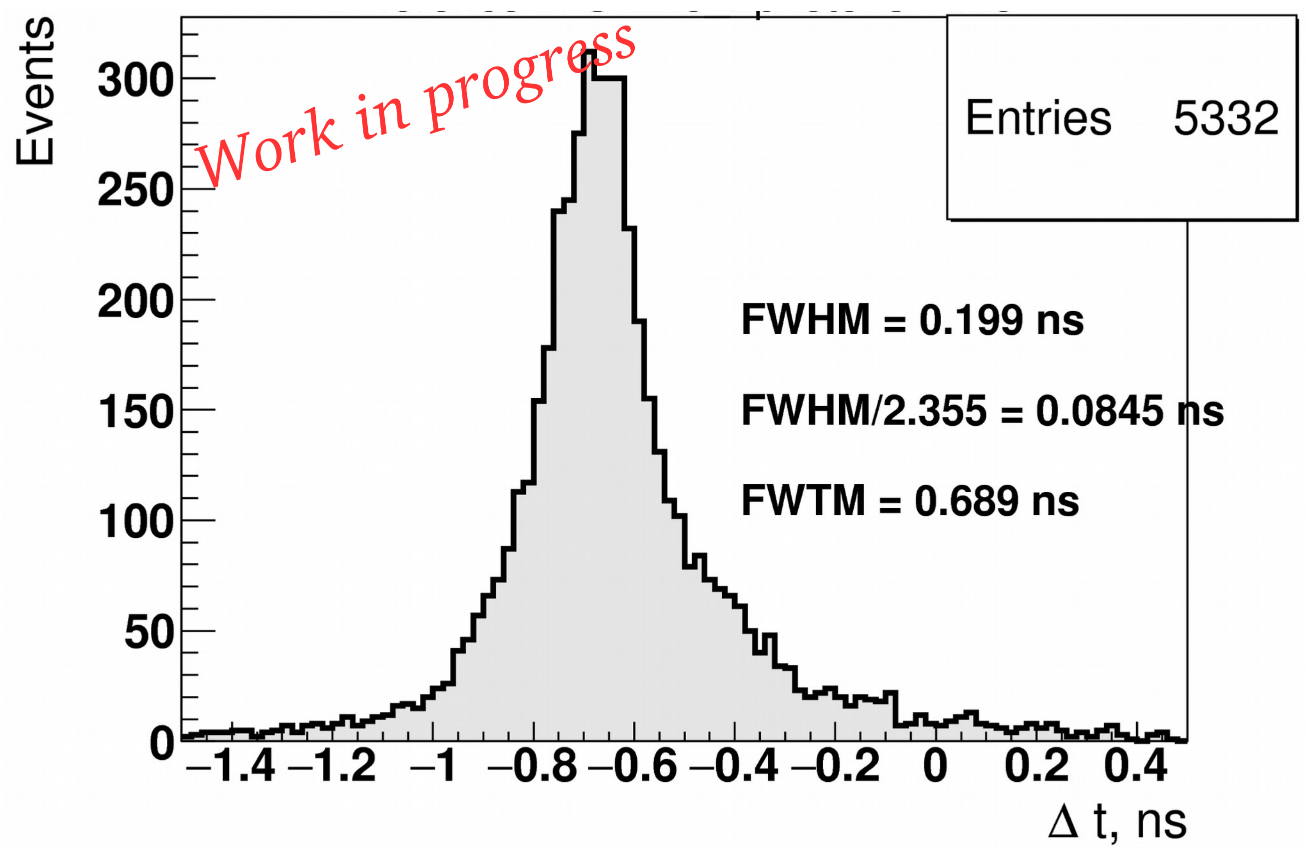
Time Difference between the two detectors in the full MCP-PMT



For a single detector : **FWHM = (180 ± 10) ps**

Detector Time Resolution Measurement

Time Difference between the detectors with a better light collection : 2 photons per MCP-PMT



For a single detector : **FWHM = (138 ± 10) ps**

PECHE Summary & Perspectives

→ First test with PbF_2 crystal Cherenkov detector allows us to reach an efficiency of **28 %** in rough agreement with simulations. Main degradation factor is the optical interface between crystal and windows MCP-PMT. We are working on improving it.

→ In time resolution, we measure for a single detector:
  * in the center of the detector **150 ps**.
  * in all the readable surface **180 ps**, after a first work calibration.

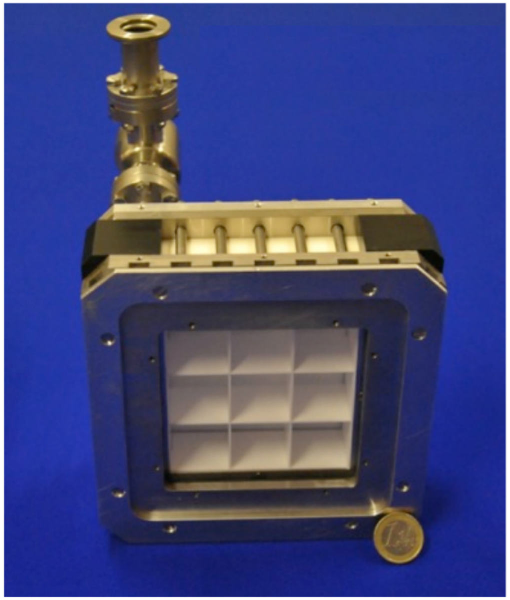
We are now working on the optimization on read-out electronics.

CaLIPSO liquid Cherenkov radiator

→ Twin to PECHE

→ TMBi used as liquid Cherenkov radiator

→ Previous demonstrator:
Time Resolution of (592 ± 18) ps (FWHM)
Efficiency of 34.5 %

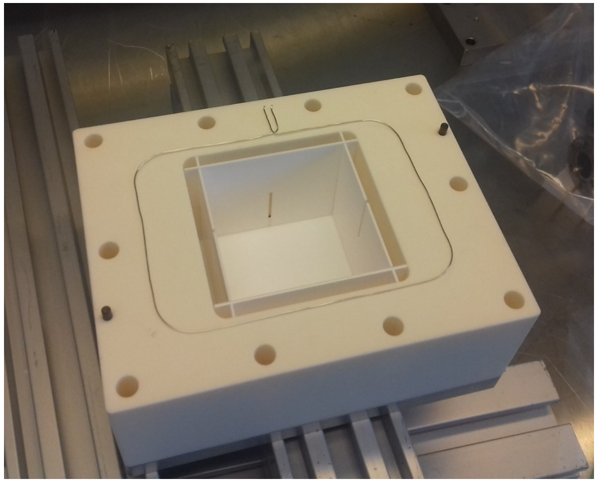


Previous demonstrator

E. Ramos et al., « Efficient, Fast, 511-keV γ detection through Cherenkov radiation : the CaLIPSO optical detector », Vol.11 (2016) p11008

→ We now focus on Time Resolution, in order to reach 150 ps (FWHM)

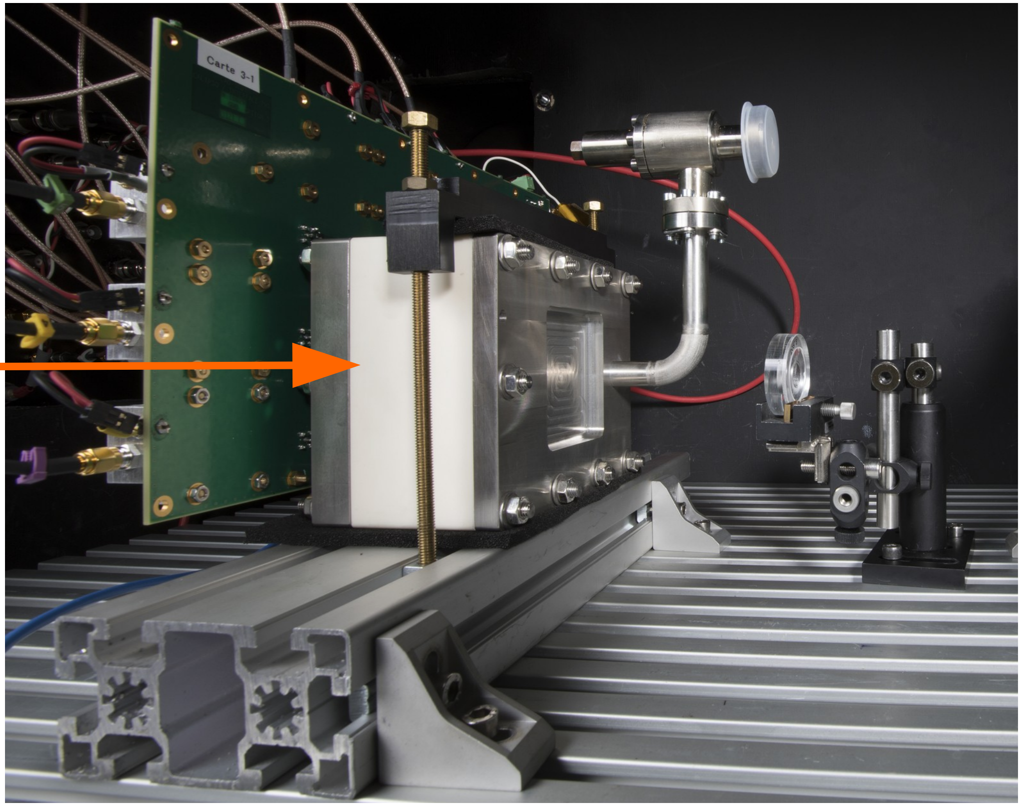
Optical Demonstrator CaLIPSO assembly and filling



→ Efficiency measurement as previously : ~ 23 %

→ Time resolution in progress

CaLIPSO Optical Demonstrator



Thank you for your attention !

Back-Up

Clinical size performance : NECR calculation

NECR = noise equivalent count rate, estimated with GATE-based simulation