Using new digital SiPM from Philips with AX-PET a new geometrical concept for PET

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On behalf of the AX-PET collaboration

https://twiki.cern.ch/twiki/bin/view/AXIALPET

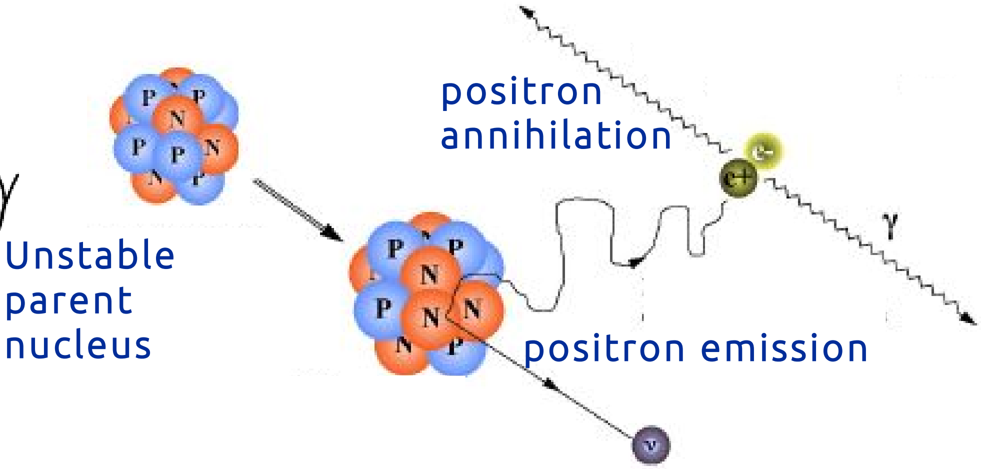
Workshop on Digital Counting Photosensors
For Extreme Low Light Level
19-20th April 2012, Lisboa

Outline

- Introduction to Positron Emission Tomography
- AX-PET
  - The AX-PET concept
  - Detector components
  - Module characterisation
  - Results of tomographic reconstructions
- AX-PET as an application of digital SiPM from Philips
  - Energy resolution
  - Time resolution
  - Future

Positron Emission Tomography

- basis of the PET system **Positron Emission :** $p \rightarrow n + e^{+} + \nu_e$
- β^{+} decay of different radionuclides
- **Positron Annihilation :** $e^{+}e^{-} \rightarrow \gamma\gamma$
  2 photons emitted "back - to - back"
  $E\gamma$ = 511 keV



γ interact with matter :

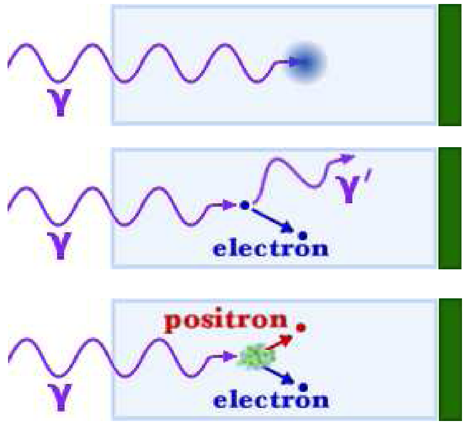
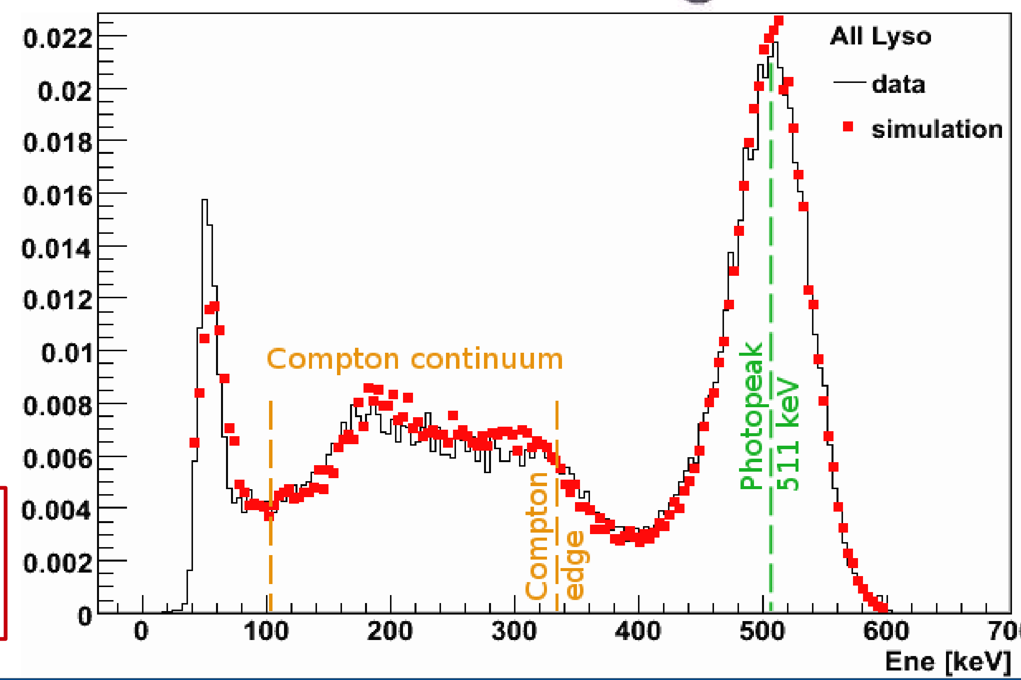


Photo-electric effect

Compton scattering

Pair production

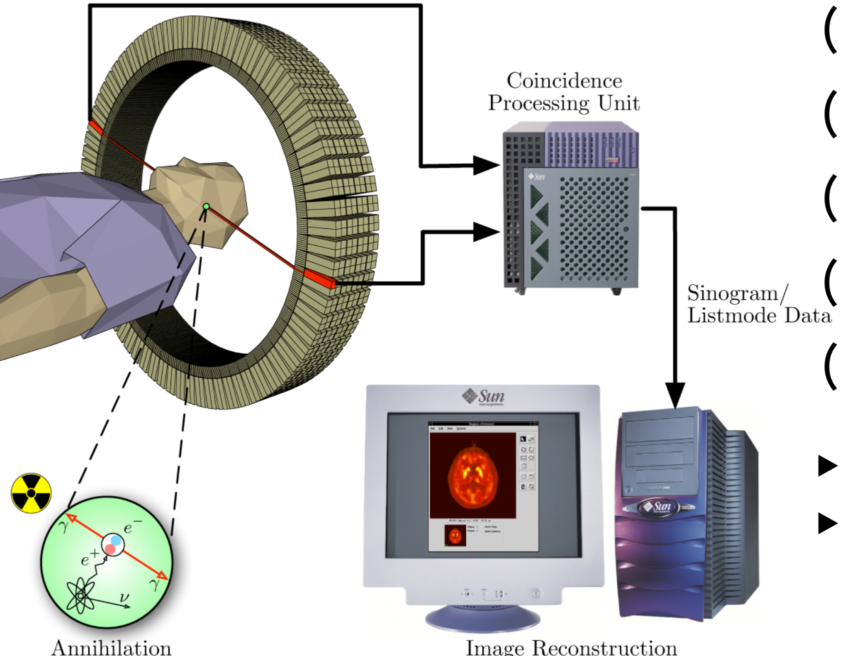


To measure the positron emitter distribution :
Measure the γ pair → build line of response (LOR)

Positron Emission Tomography

PET detector principle :

coincidence of 2 photons of defined energy (511 keV) and emitted on the same line



(1) Inject the **radiotracer into the body**

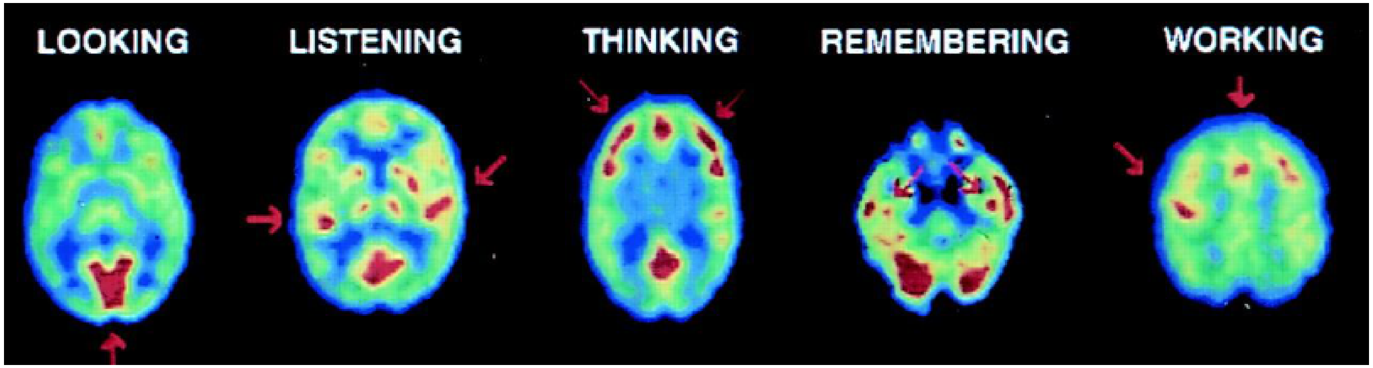
(2) Wait for uptaking period

(3) Start the acquisition (i.e. **detection of coinc. events**)

(4) Feed the data into the reconstruction algorithms

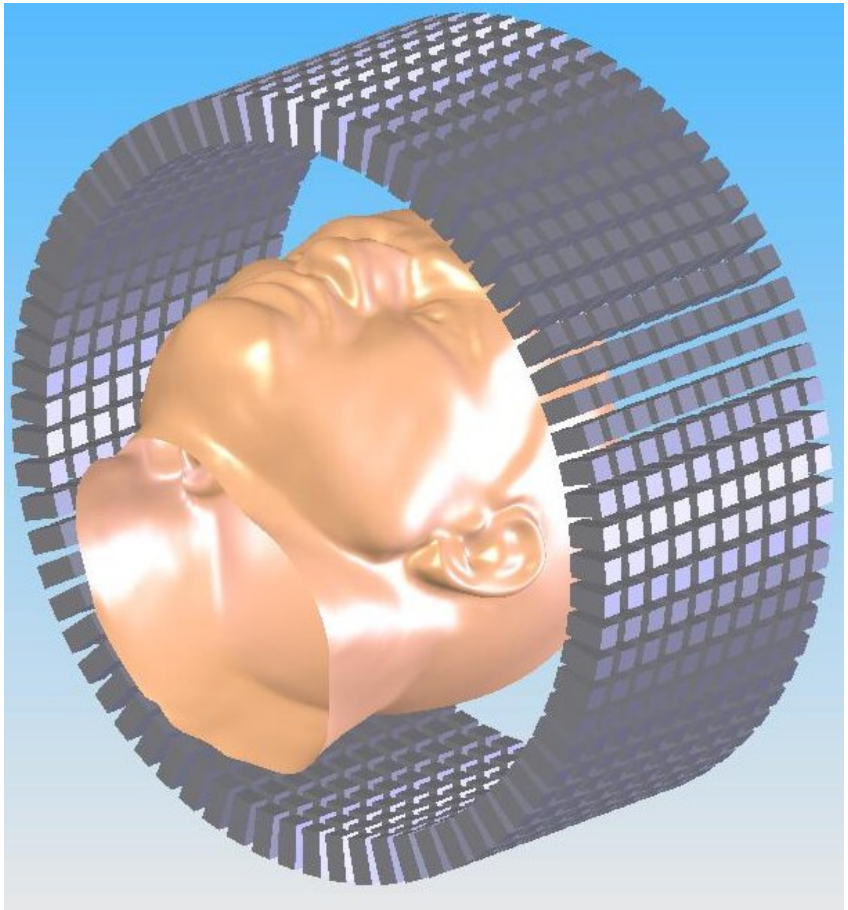
(5) **image** of the **activity concentration**

- PET : **"in-vivo" functional imaging** technique
- get a (quantitative) image of the radio-tracer concentration

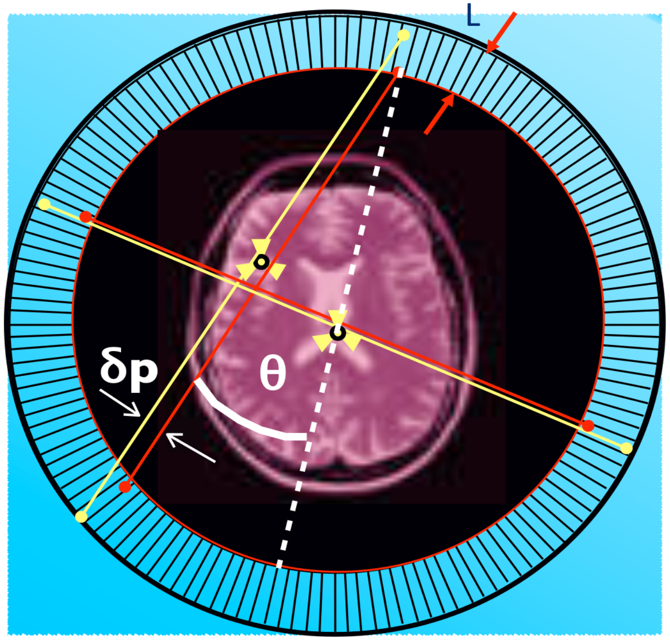


The AX-PET concept

Standard PET scanners



Short crystals radially oriented
Block readout



$$\epsilon = 1 - e^{-\mu \cdot L}$$

Max. interaction efficiency
→ **long L**

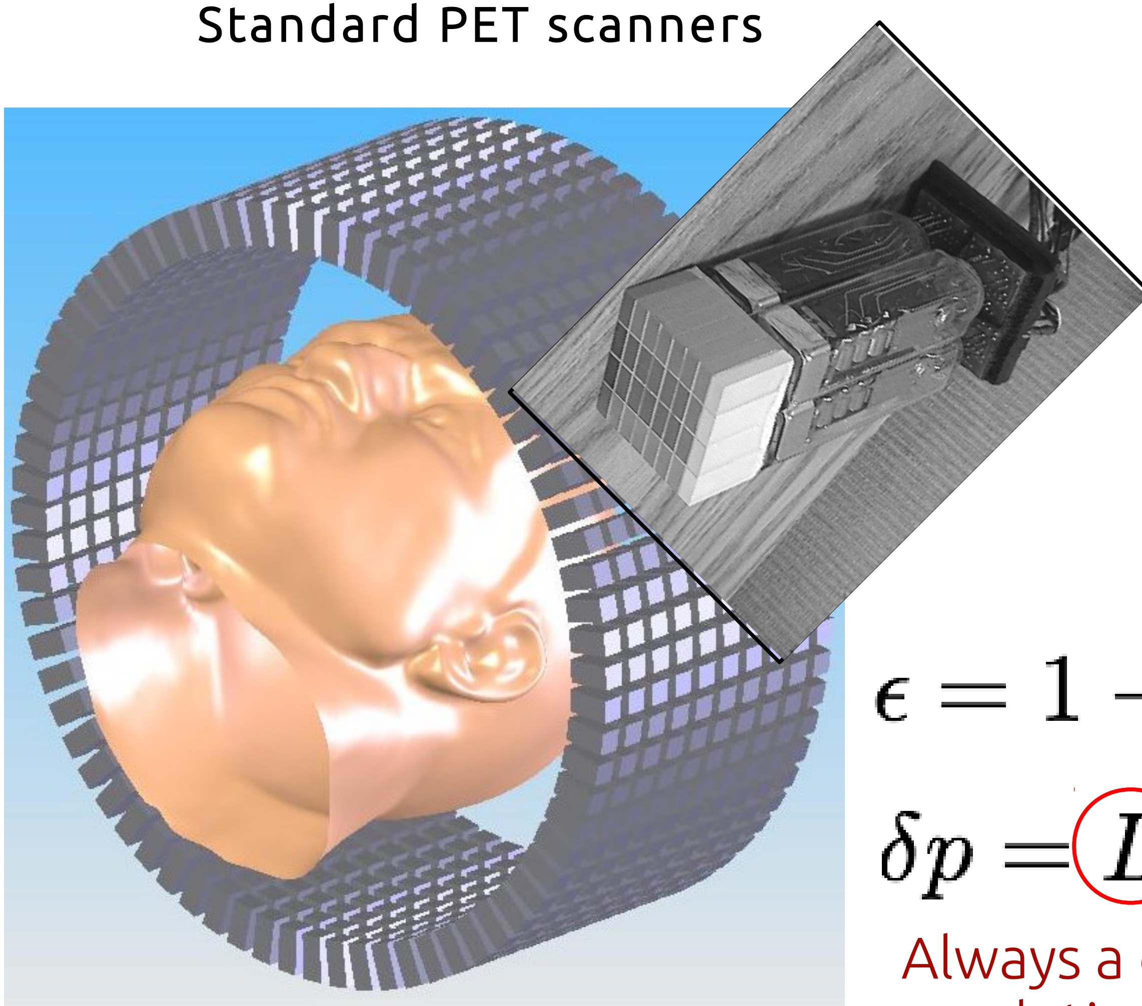
$$\delta p = L \cdot sin\theta$$

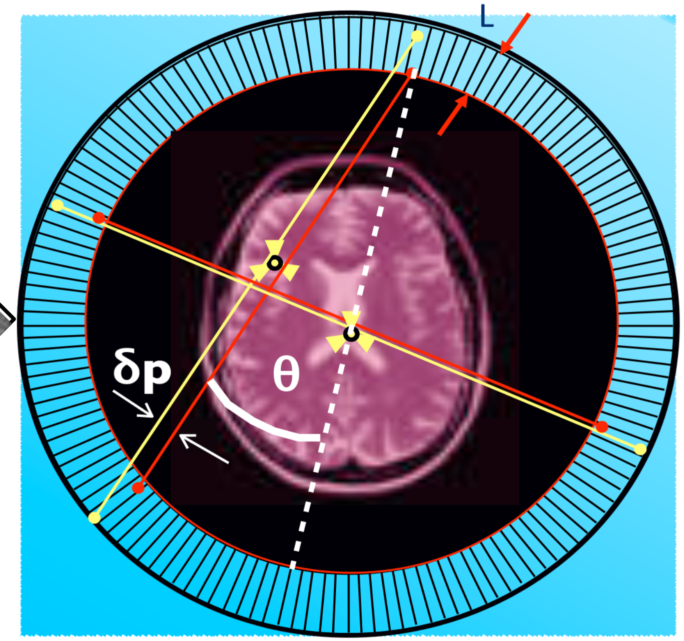
Min. parallax error
→ **short L**

Always a compromise between spatial resolution and sensitivity :
<u>solution</u> : add depth of interaction information

The AX-PET concept

Standard PET scanners





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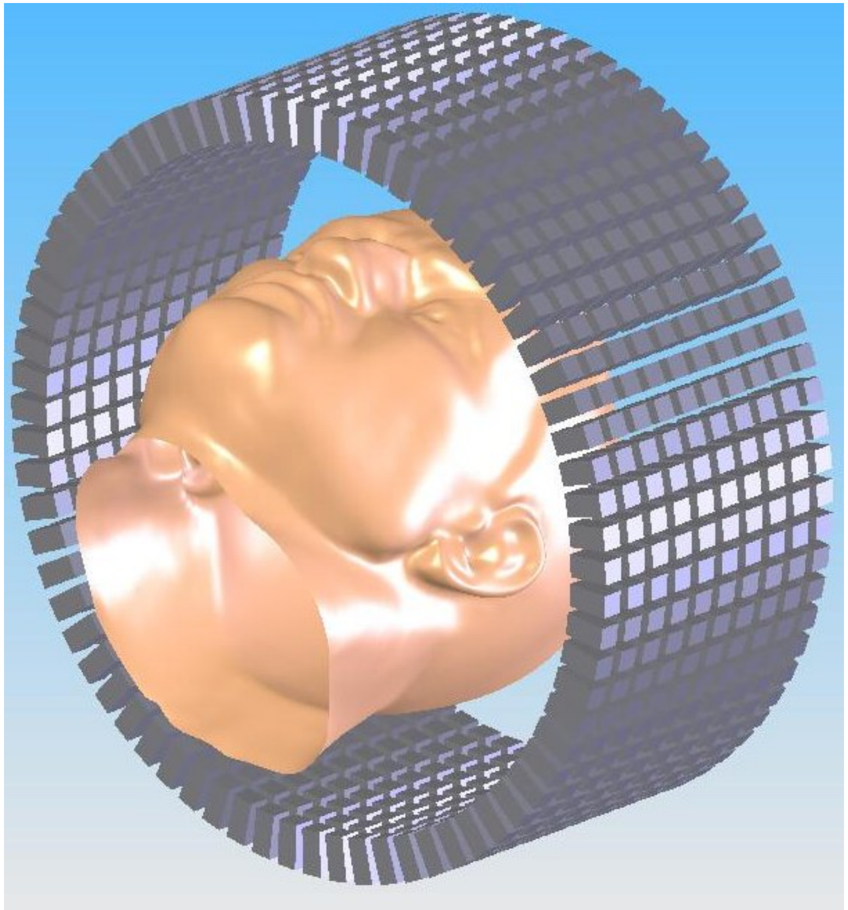
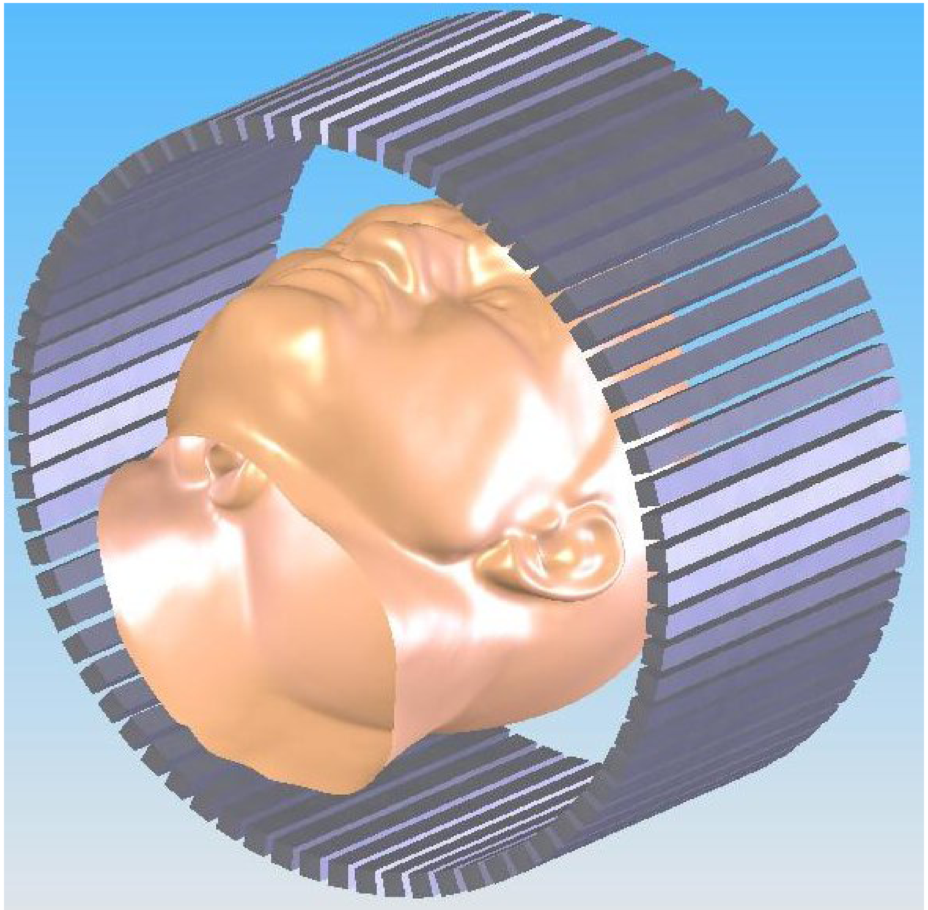


Short crystals radially oriented
Block readout

AX-PET geometry proposal

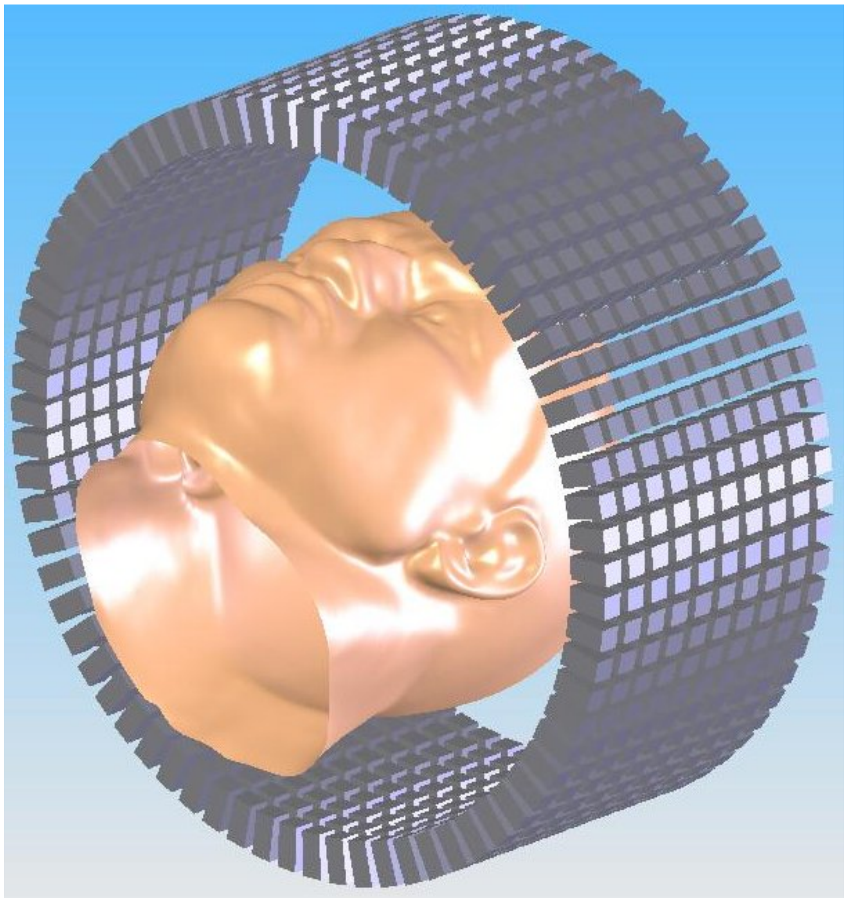


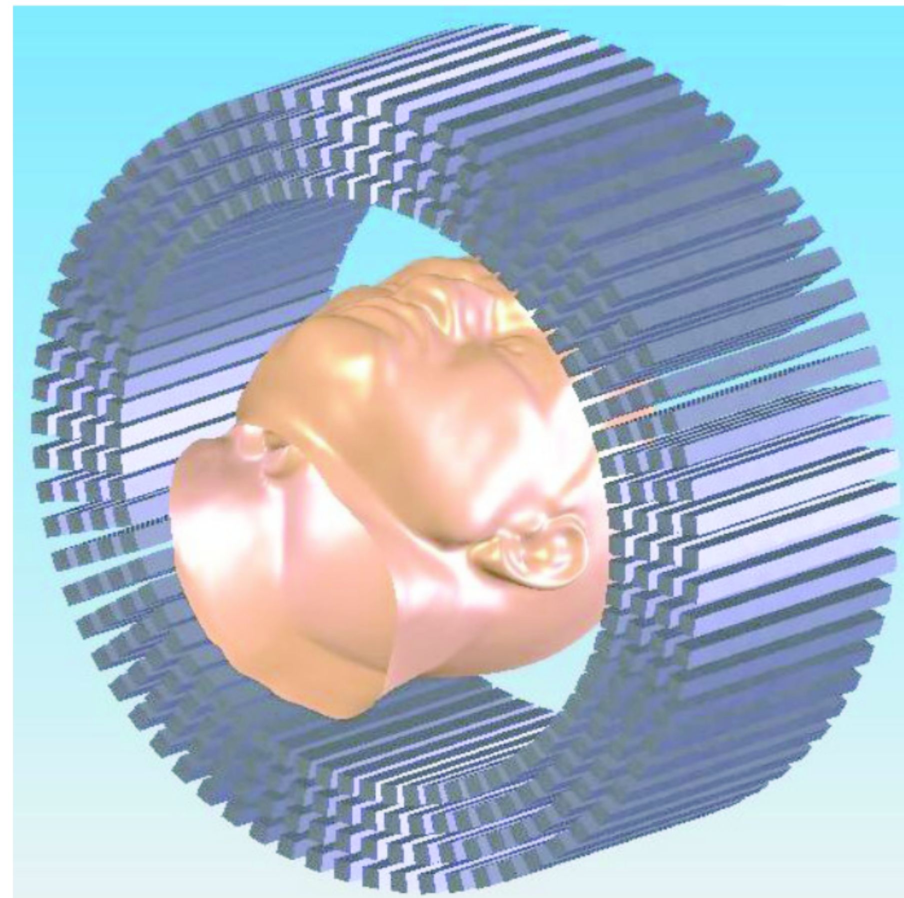
Long crystals axially oriented
Single crystal readout

The AX-PET concept

Standard PET scanners

AX-PET geometry proposal





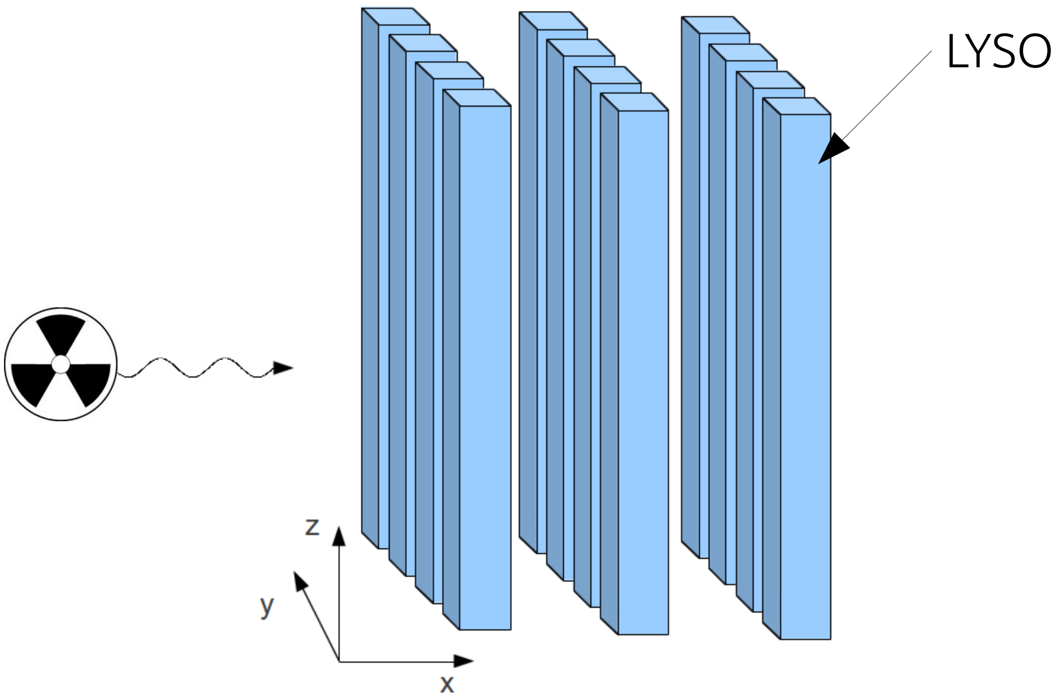
Short crystals radially oriented
Block readout

Long crystals axially oriented
Single crystal readout

The AX-PET concept

3D measurement of the photon interaction point

- Transaxial coordinate and energy measurement with thin elongated scintillator LYSO crystals
  - The hit crystals gives the transaxial coordinate (x, y)



The AX-PET concept

3D measurement of the photon interaction point

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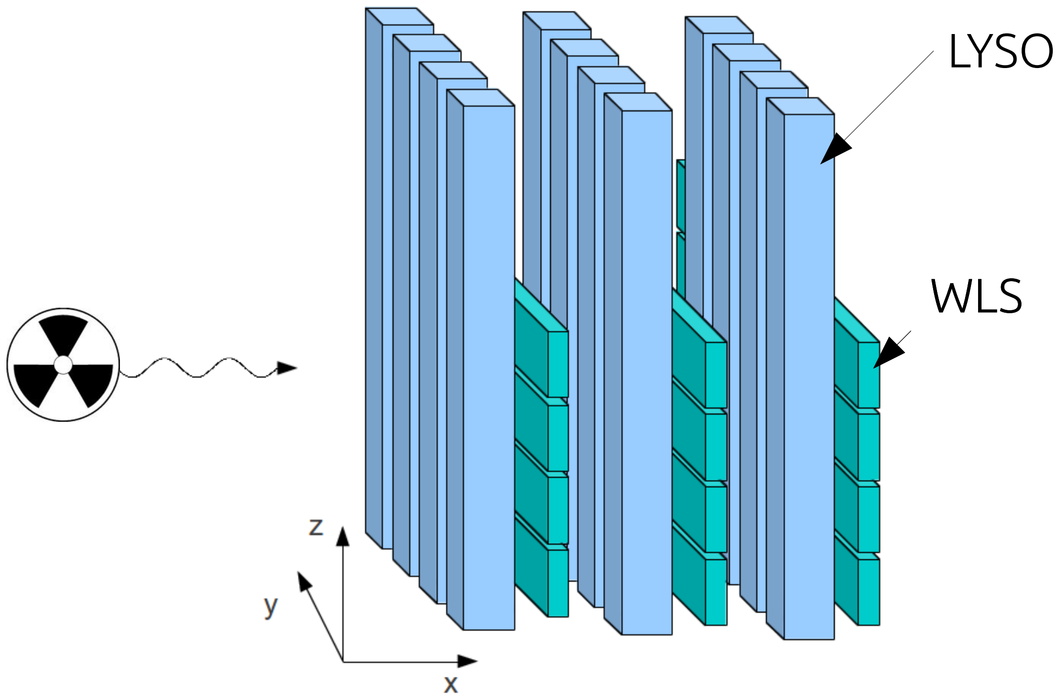
- Axial coordinates measured with Wave Length Shifter (WLS) strips



The AX-PET concept

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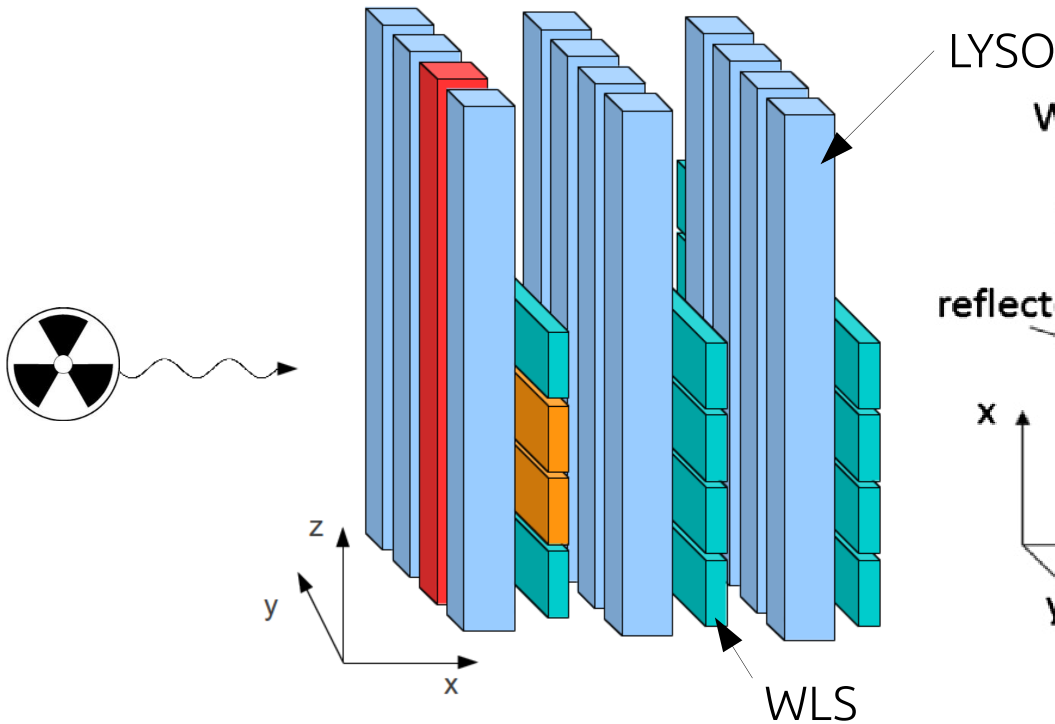
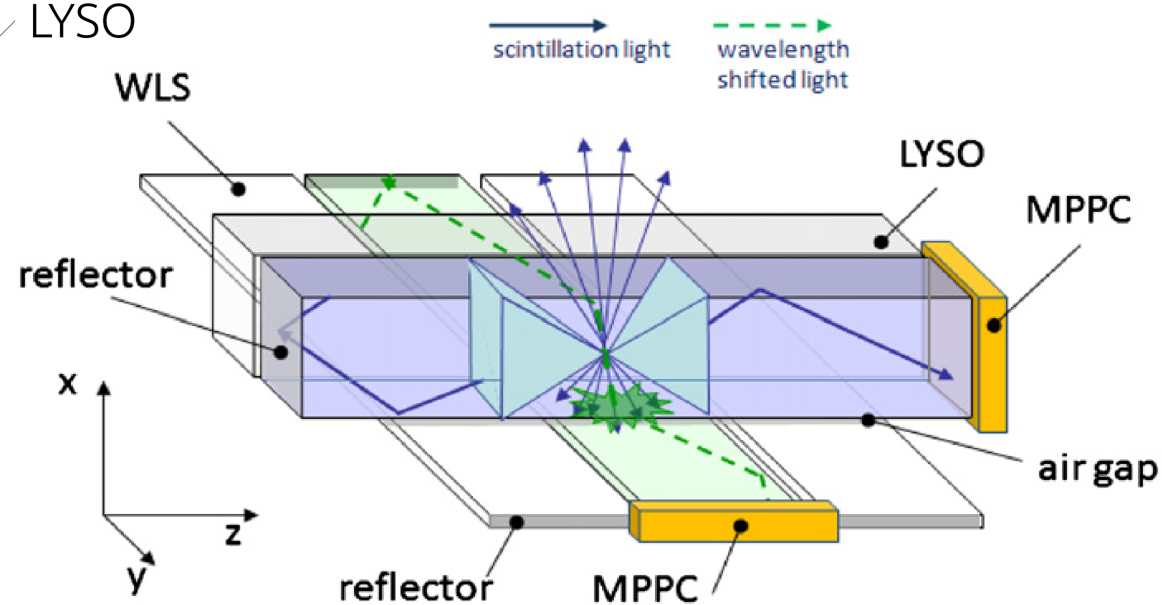
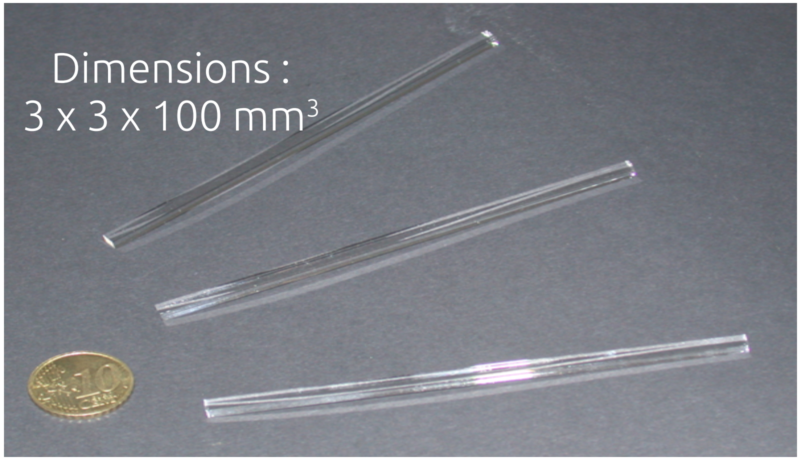




Detector components

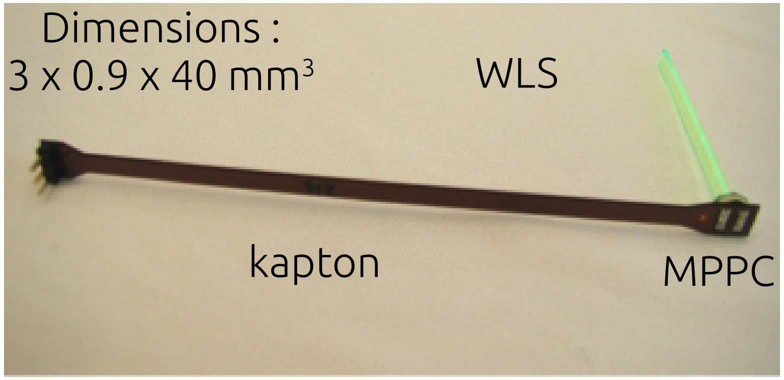
Scintillator crystals and WLS strips

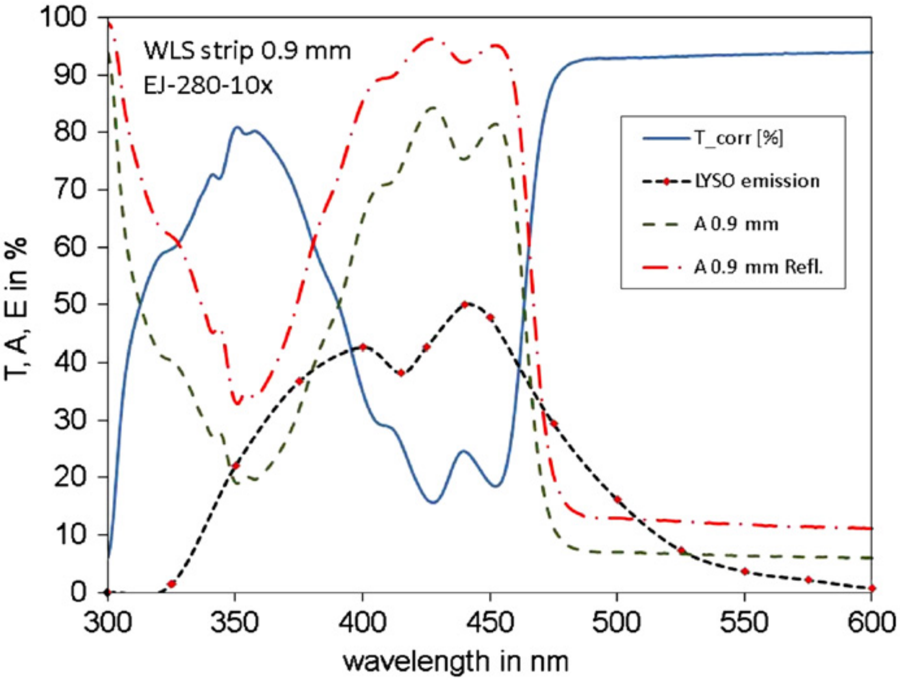
- LYSO ($Lu_{1.8}Y_{0.2}SiO_5$:Ce), Prelude 420 from Saint Gobain



- Light Yield LY=32 photons/keV
- High density : 7.1 g.cm^{-3}
- Attenuation length λ_{511}=12 mm @ 511keV
- Intrinsic energy resolution : 8.3 ± 0.5% (FWHM) @ 511keV

- WLS strips, Type EJ-280-10x, from Eljen Technologies



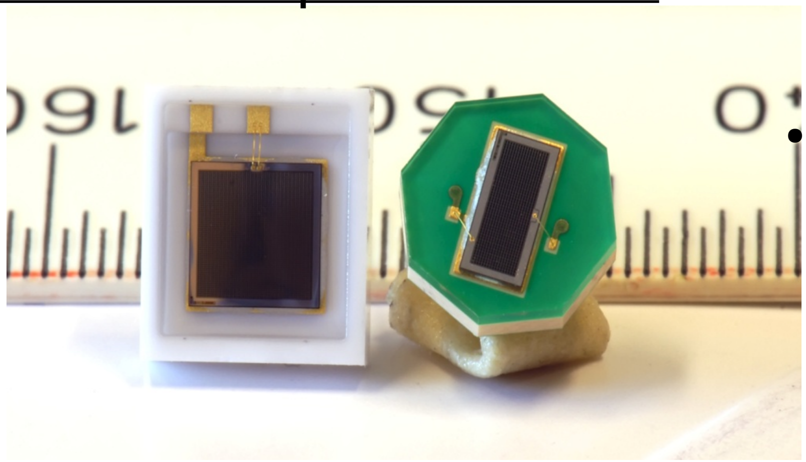


Detector components

<u>Arrays of Geiger-Avalanche photo-diode</u> : MPPC – Hamamatsu

- LYSO readout :

  Type S10362-33-050C



- WLS strips readout :

  OCTAGON-SMD

Expected LYSO light output for 511 keV event : ~ 1000 photons

- 3 x 3 mm^2 area, 3600 cells 50 x 50 um^2
- PDE ~ 40%
- Gain : 5.7 10^5
- Bias voltage ~ 70 V

Expected WLS light output : ~ 50 photons

- 3. 22 x 1.19 mm^2 area, 782 cells of 70 x 70 um^2
- PDE ~ 40%
- Gain : 4 10^5
- Bias voltage ~ 70 V

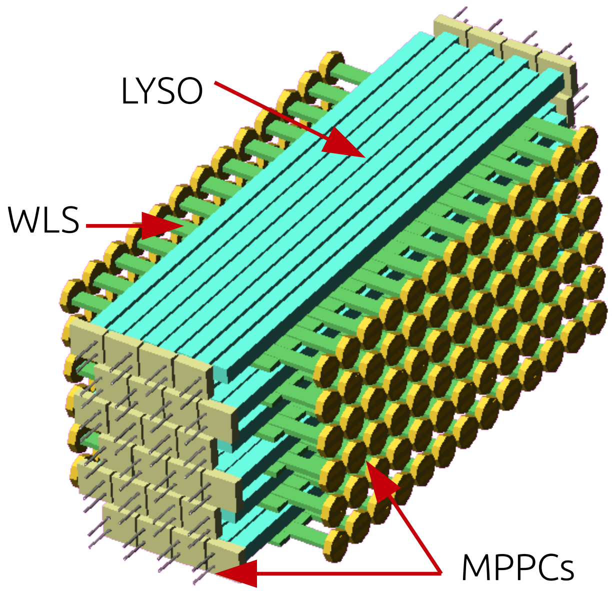
Advantages of a Si sensor :

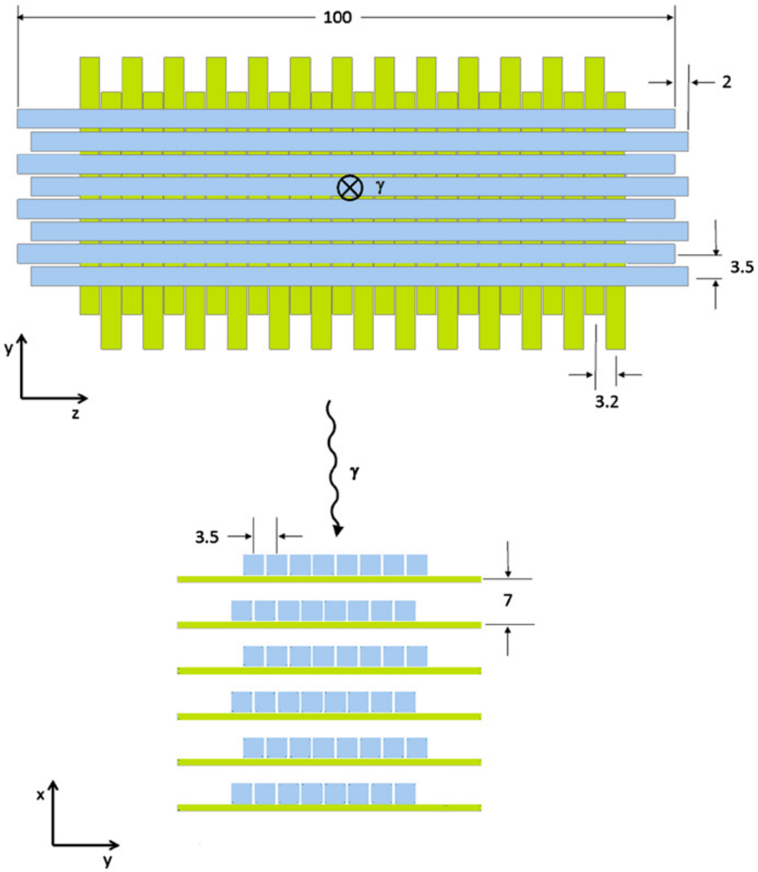
- high QE
- compactness
- insensitive to magnetic field (MRI comb.)

Drawbacks of a Si sensor:

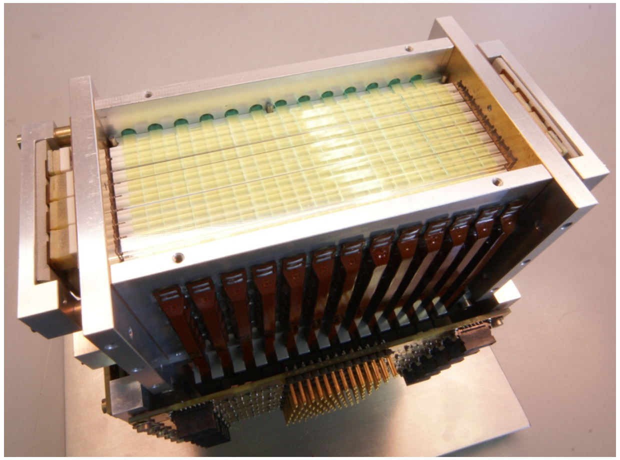
- temperature dependent
- dark rate (~ 1 MHz @ thr = 0.5 pe)

Module assembly

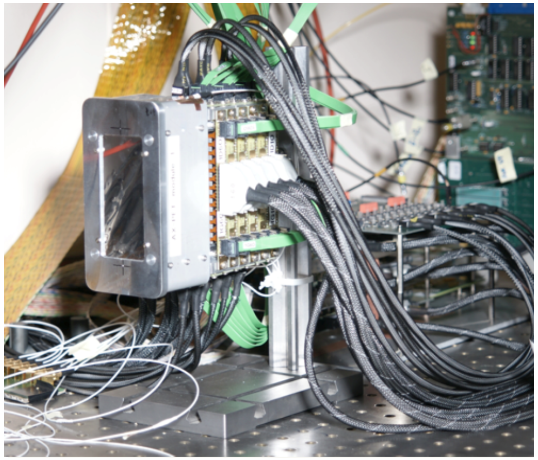




- Each module is composed by six layers
- Each layer is made of 8 LYSOs and 26 WLS both staggered to enable the readout
  - 204 channels per module individually biased
- All layers are optically decoupled



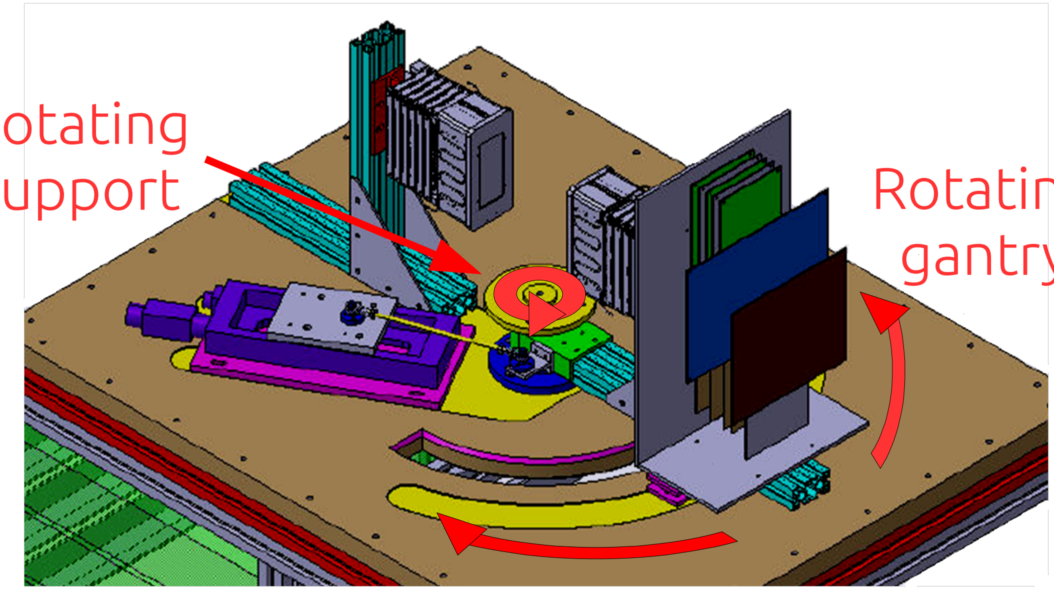
Assembled module

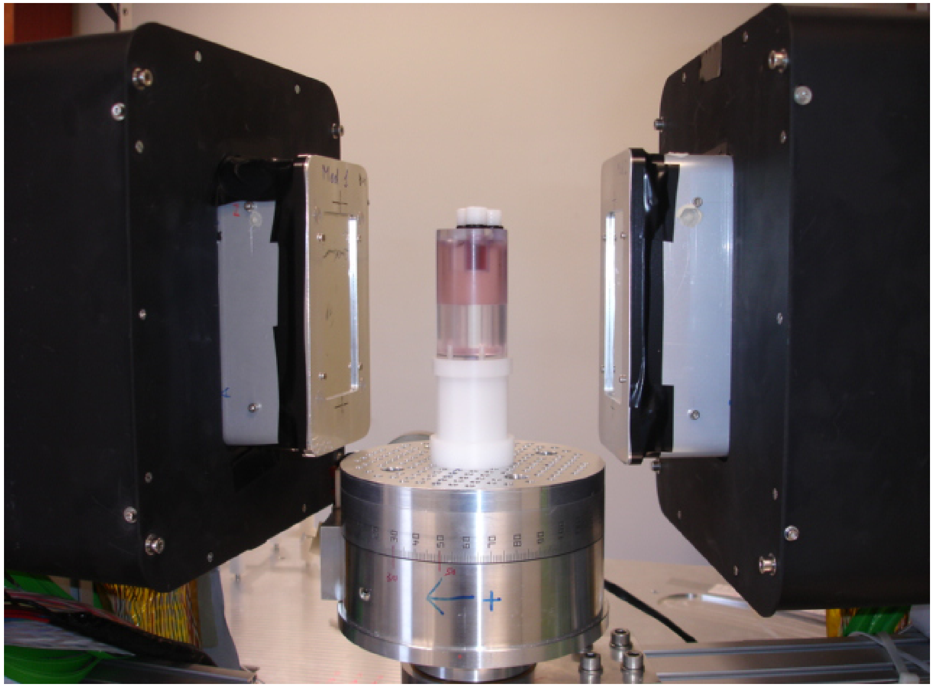


Module housing and services

Test bench for tomographic reconstruction

- The two modules are mounted on top of a portable platform, which houses also the electronics, power supply, etc...
- A rotating motor can move the source or phantom positioned in the field of view
- One of the modules can rotate wrt 180° position by ±60°

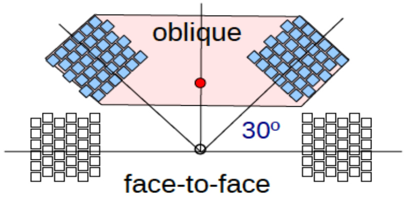




Demonstrator performance

For more explanations see publication : doi:10.1016/j.nima.2011.06.059

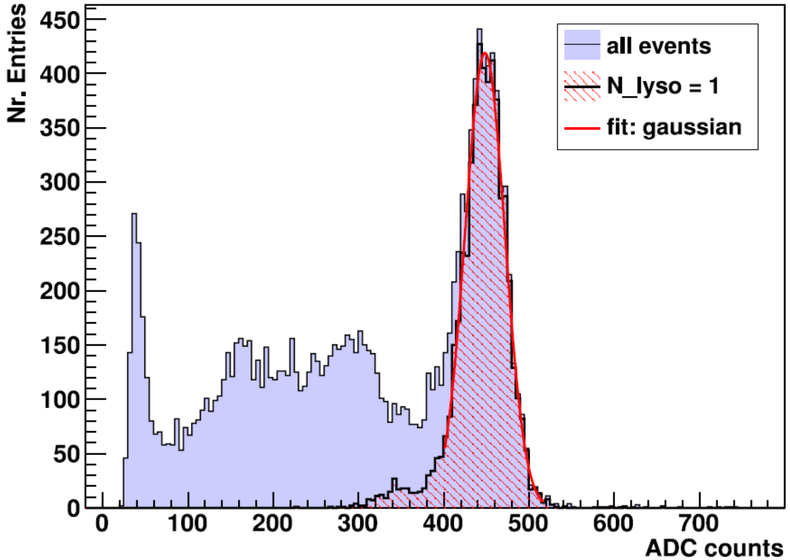
- **Energy resolution :**
  - Average value of the energy resolution of all the LYSO crystals for both modules is 11.8% FWHM at 511 keV

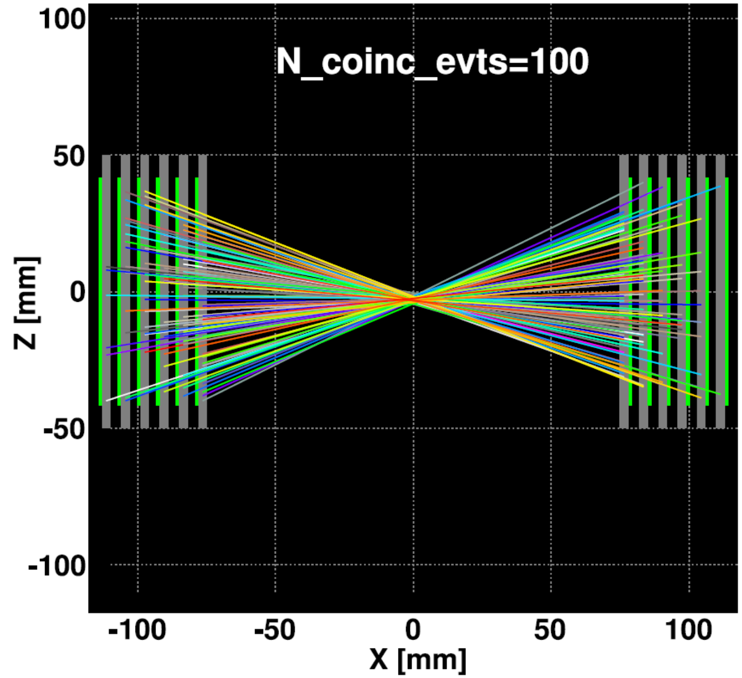


- **Spatial resolution**
  - Axial :
    - Single module
      - Module 1 : 1.75 mm FWHM
      - Module 2 : 1.83 mm FWHM
    - Module in coincidences
      - F2F, OBL : 1.35mm FWHM
  - Transaxial
    - F2F, OBL : 2 mm FWHM

- **Efficency/Sensitivity :**
  - Can always be improved by increasing the number of layers

- **Time resolution :** 1.9 ns FWHM

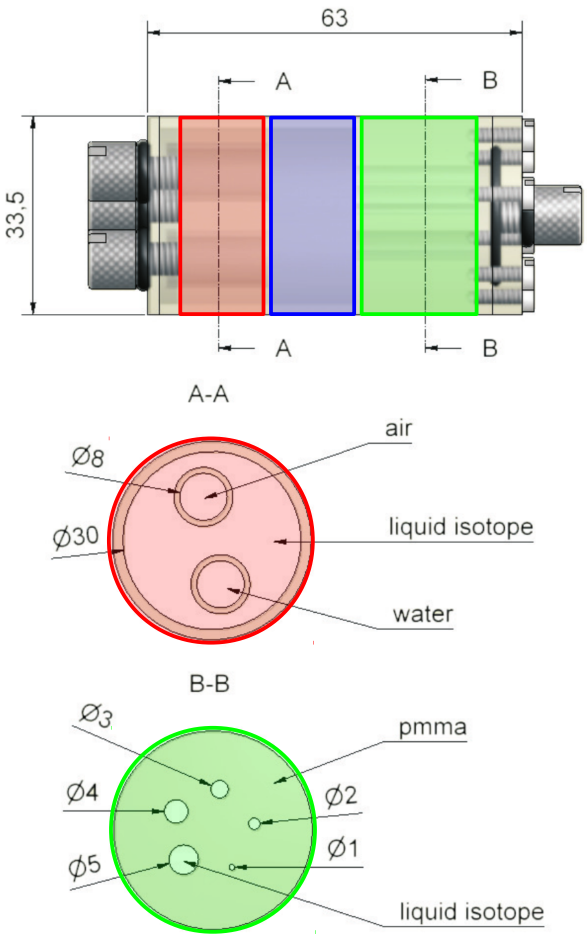


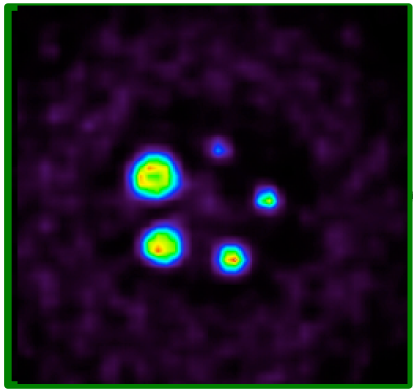


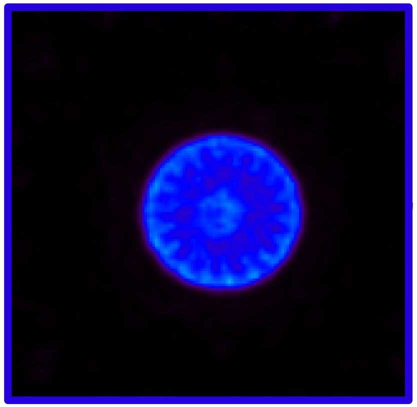
Results from tomographic reconstruction

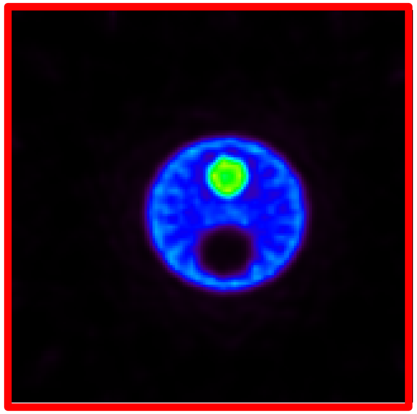
NEMA NU4

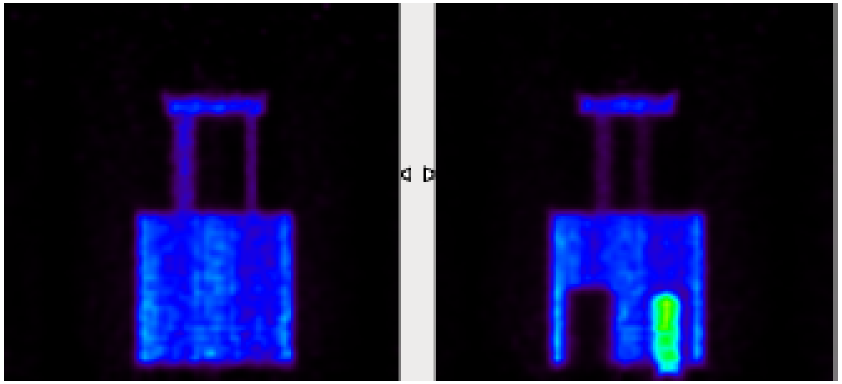
Image Quality
Mouse Phantom

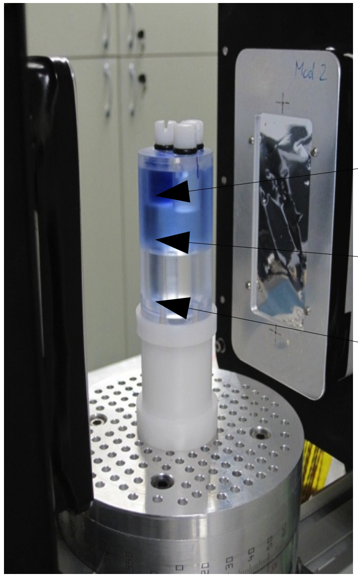










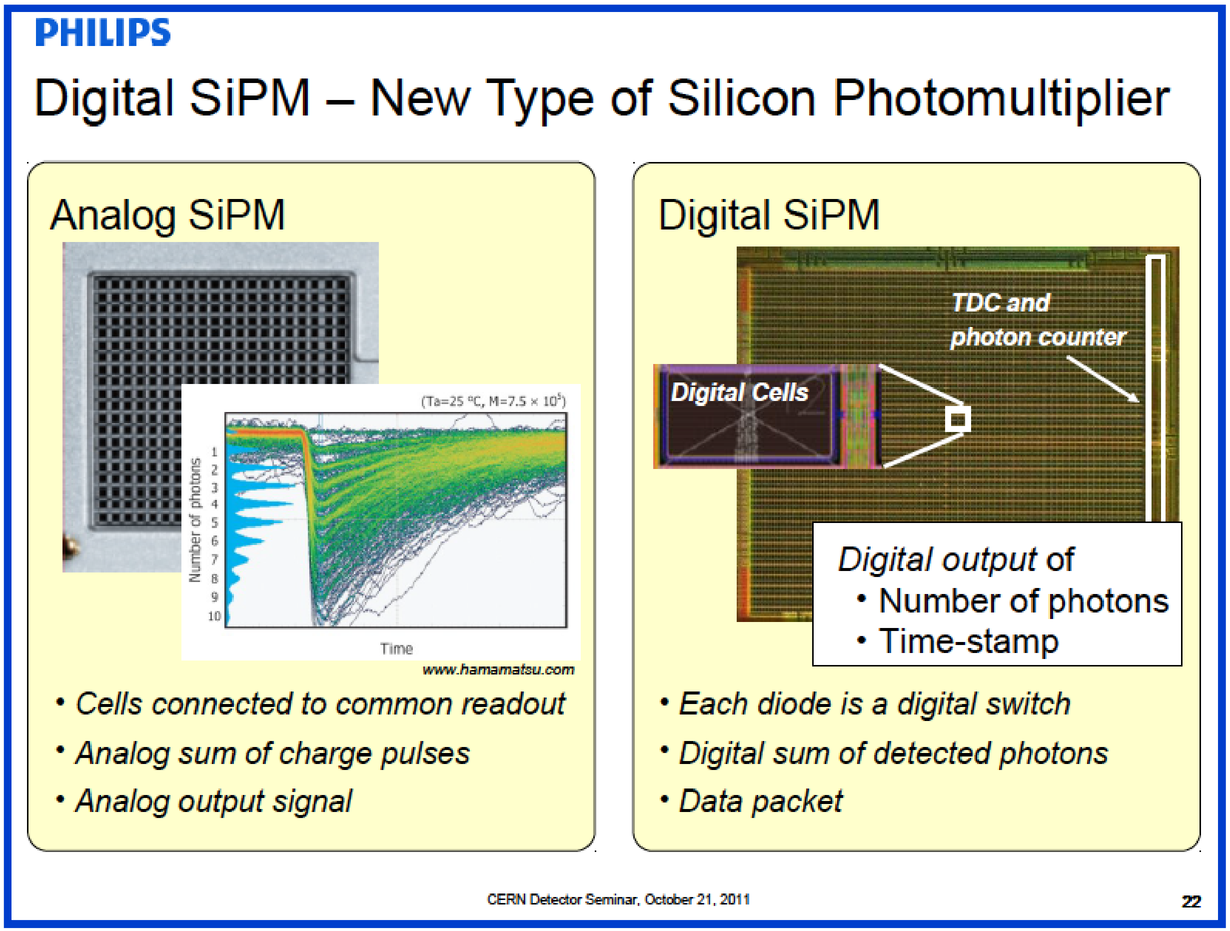


- Contrast region
- Homogenous region
- Spatial resolution region

Resolve 1 mm rod with 1.6 mm FWHM

Using Philips digital SiPM as alternative photodetectors

Web site : http://www.research.philips.com/initiatives/digitalphotoncounting/



- **Sensitivity**
  - Lower dark count level compared to analog devices
- **Speed**
  - Excellent timing resolution → Time Of Flight PET
- **Robustness**
  - Against electromagnetic interference (Compatibility with MRI scanner)
  - Low sensitivity to temperature variations
- **High production yield** due to the possibility of disabling individual cells

Why going from analog to digital SiPM

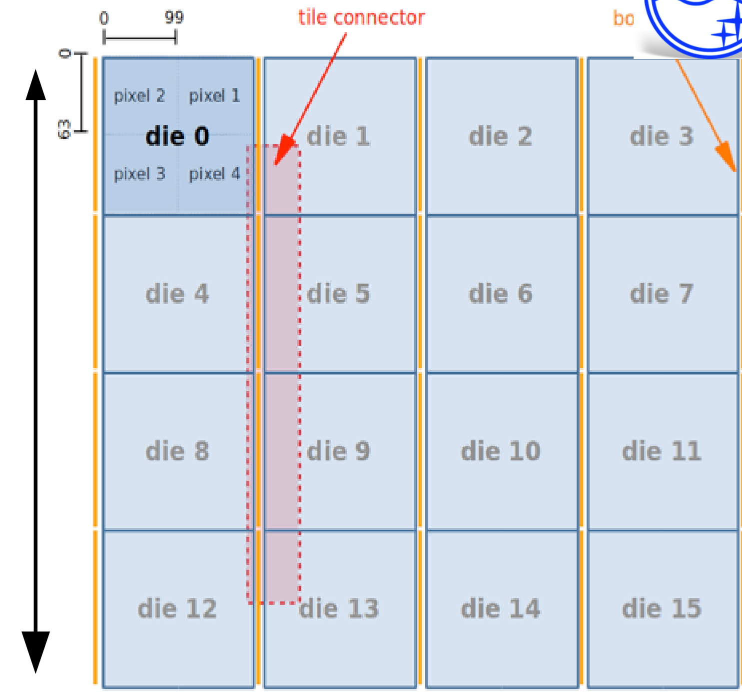
Characteristic	dSiPM	aSiPM	APD	PMT
Sensitivity (PDE)	Max. ~70 % tbp	Max ~ 70% tbp	~ 70%	~ 35%
Intrinsic timing res.	~ 50 ps	> 150 ps	~ 1 ns	~ 400 ps
CRT on system level (depends also on scintillator)	Pot. ~ 150 ps 250 ps proven	~ 500 ps in literature	> 1 ns	~ 500 ps
voltage	35 V	35-70V	Up to 1500V	400-800V

- Advantages of dSiPM wrt aSiPM
  - Lower DCR
  - Better CRT (triggering on the first photon) → TOF PET
  - Afterpulses does not affect the digital sum thanks to active quenching
  - No custom electronics needed

Technical Evaluation Kit

- Our evaluation kit is made of :
  - 2 DLS 3200 sensor with 3200 cells per pixel
  - 2 DLS 6400 sensor with 6400 cells per pixel
  - 4 kapton cables
  - One base to connect the tiles
  - One power supply
  - One computer for detector configuration and data acquisition

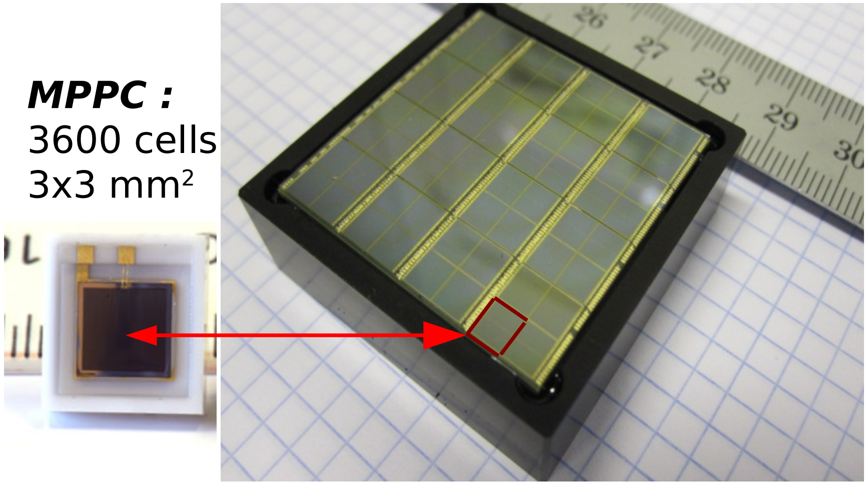
32 mm



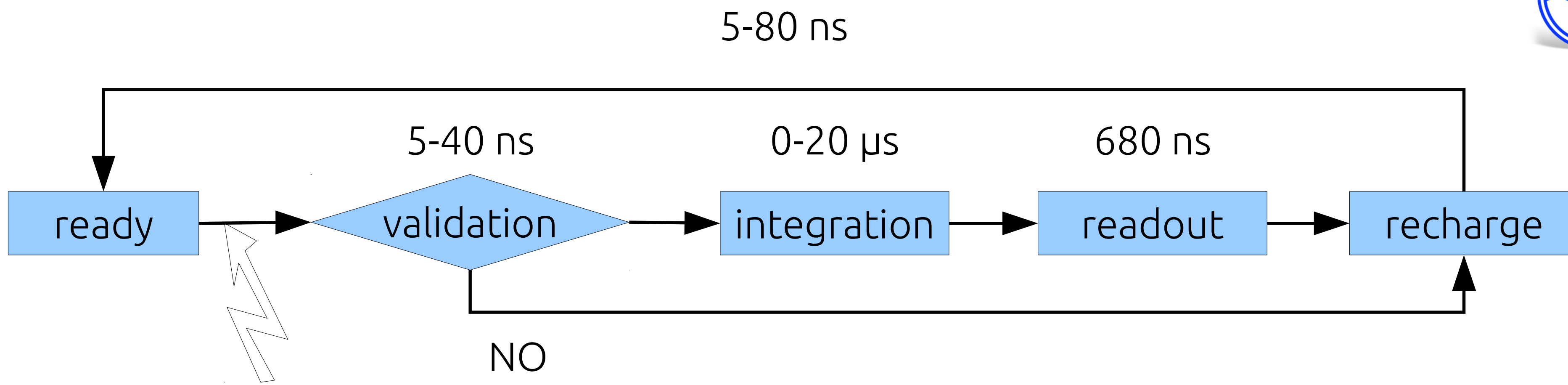
Seen from top (glass position)

Few characteristics	DLS 6400	DLS3200
Cell size [μm²]	30 x 50	59.4 x 64
Fill factor [%]	54	78 (→ 84)
PDE [%] @ 420 nm	30	43 (→ 47)
DCR [MHz/pixel] @20°C	<5	<10
Op. voltage [V]	< 35	
Temp. dep of PDE [% / K]	- 0.33	

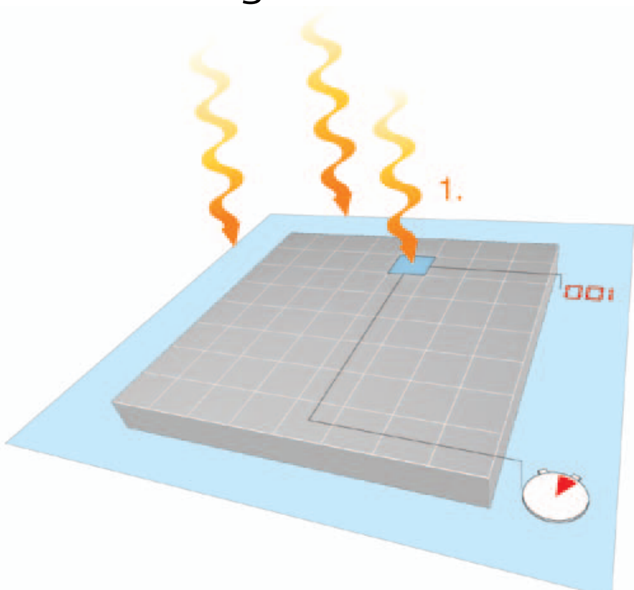
MPPC :
3600 cells
3x3 mm²

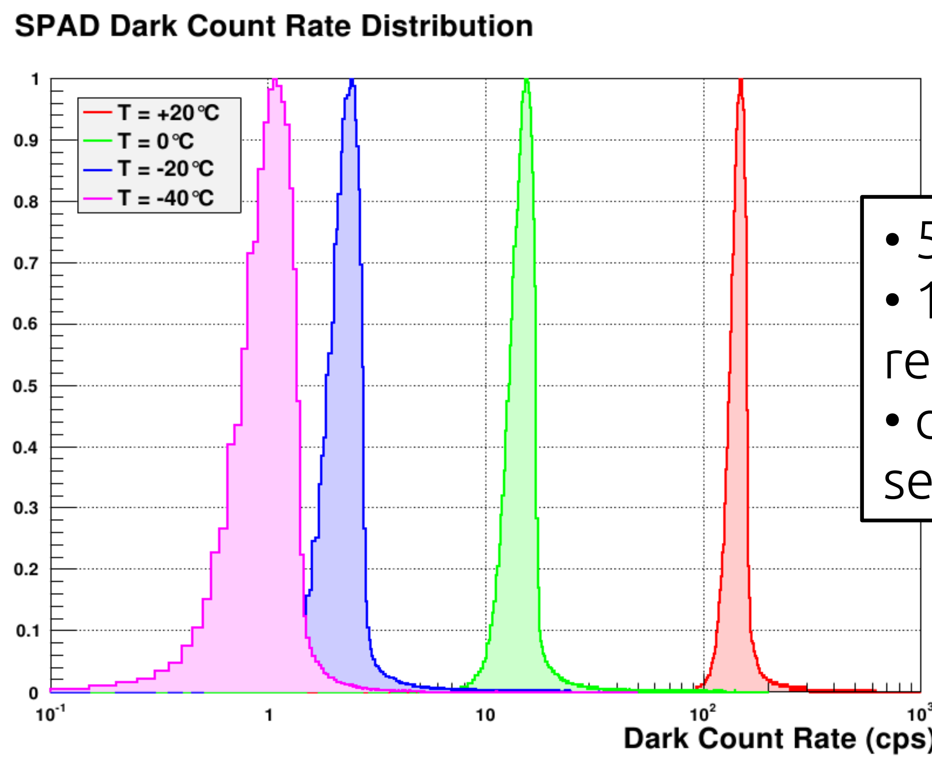


DSiPM state machine



Trigger generated by the 1st, 2nd, 3rd or 4th photon arriving, this latter gives the time stamp

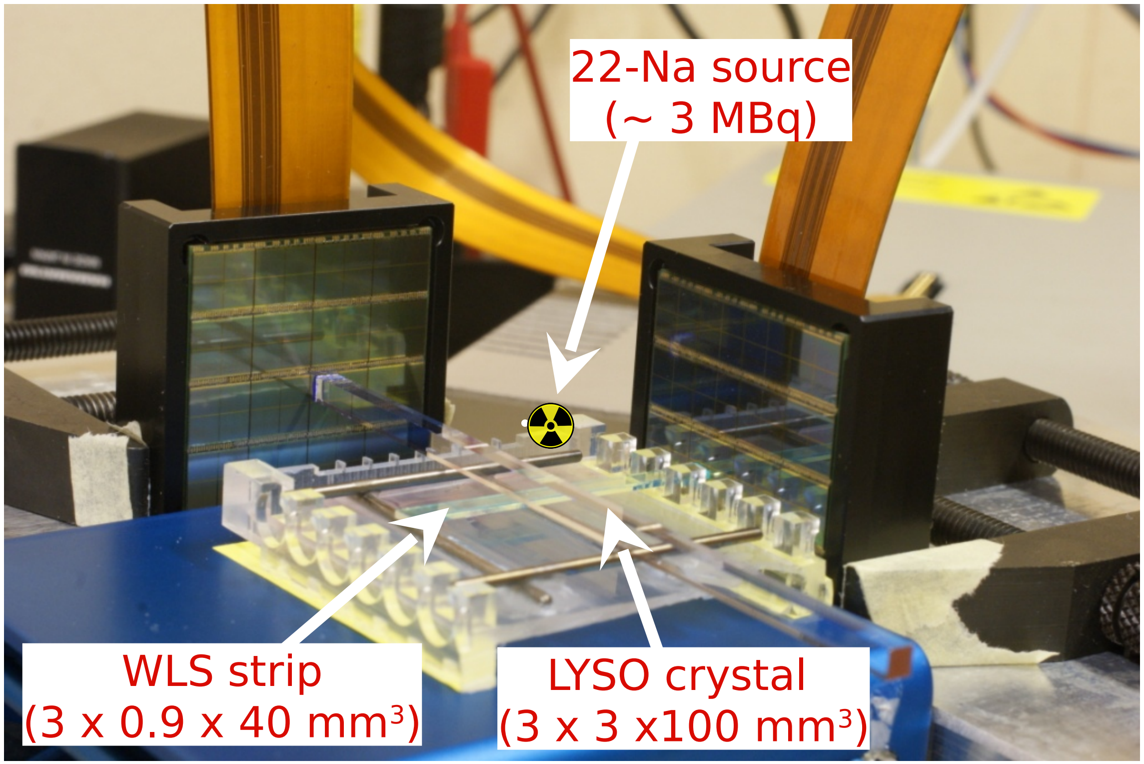


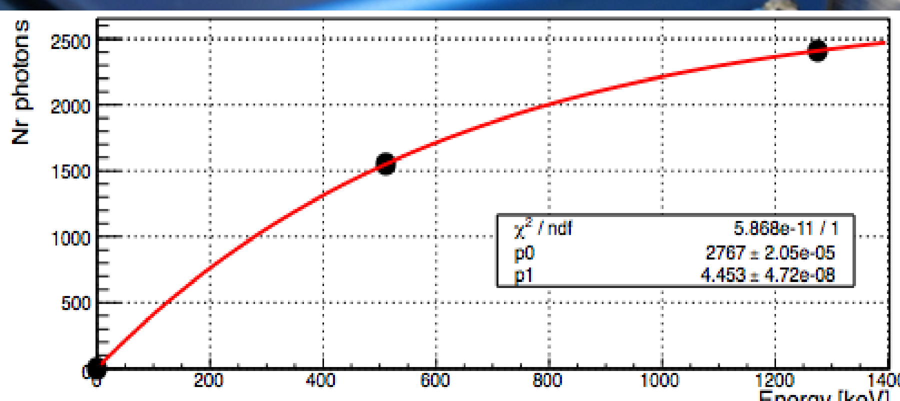


- 5ns system clock
- 15ns dark count recovery
- dark counts → sensor deadtime

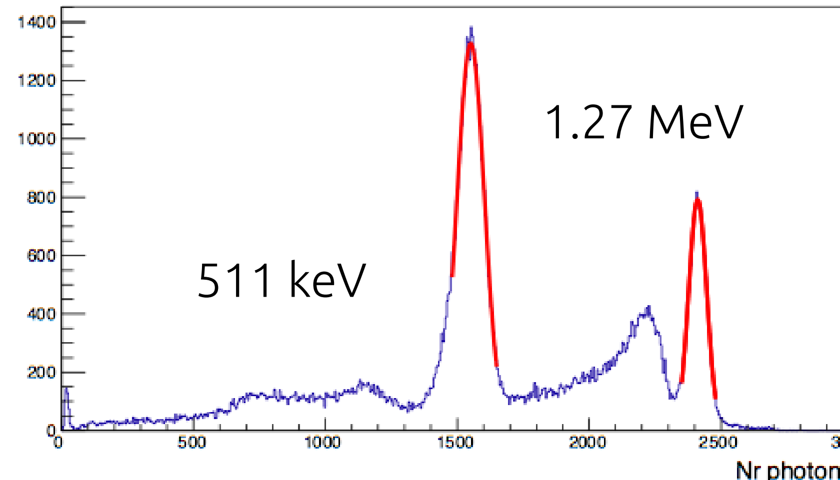
Energy resolution with the DLS 3200

Minimal AX-PET like set-up



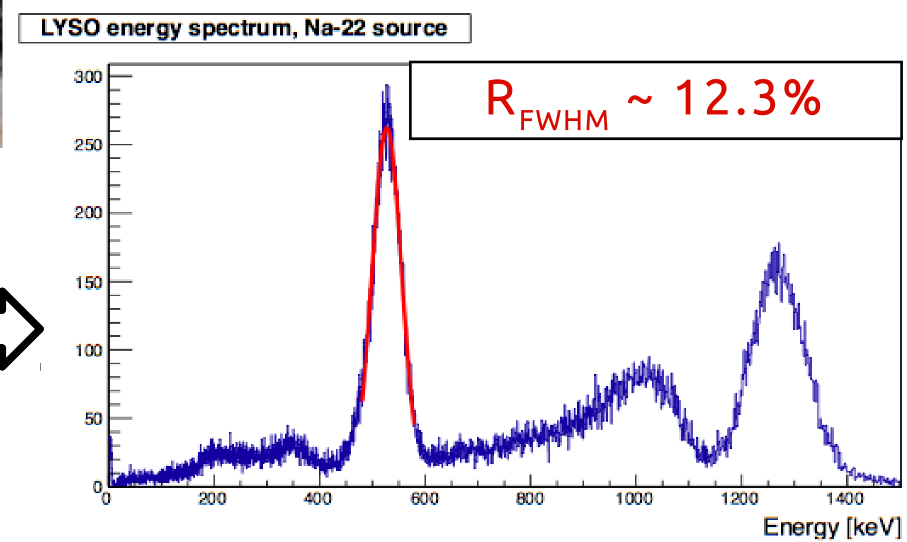


Raw spectrum

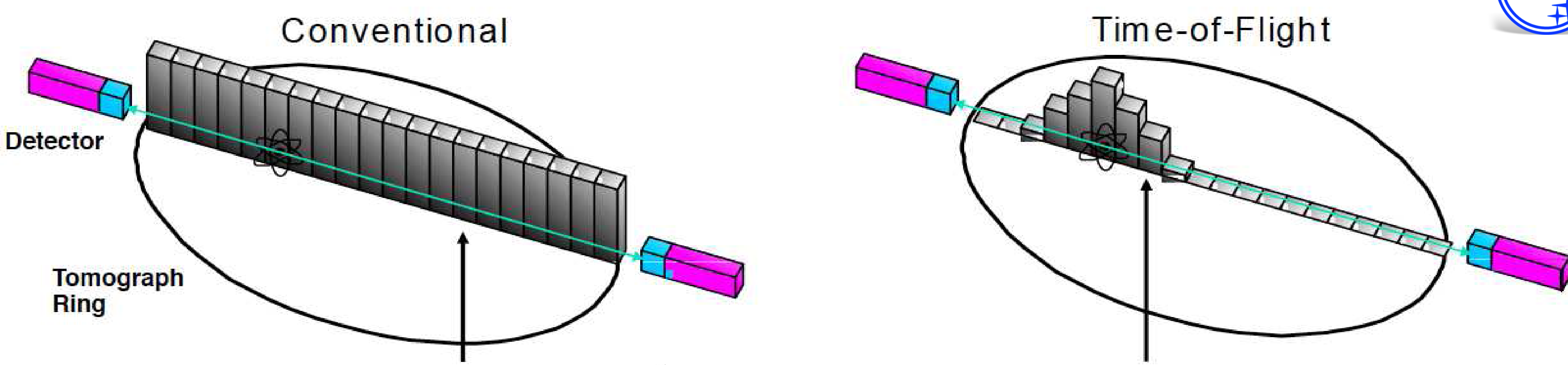


Energy spectrum

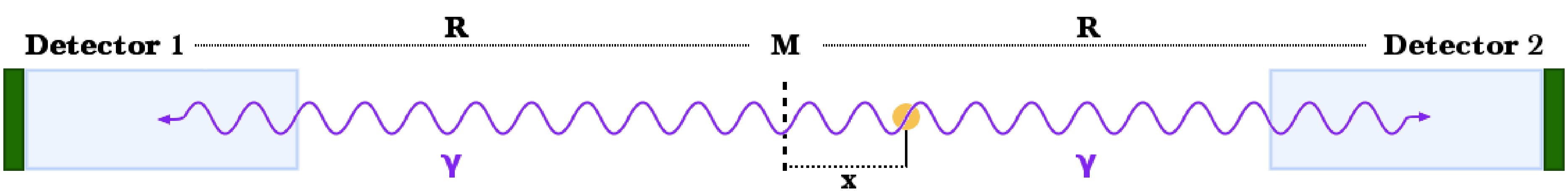
(calibrated, i.e corrected for saturation)



Towards Time Of Flight PET

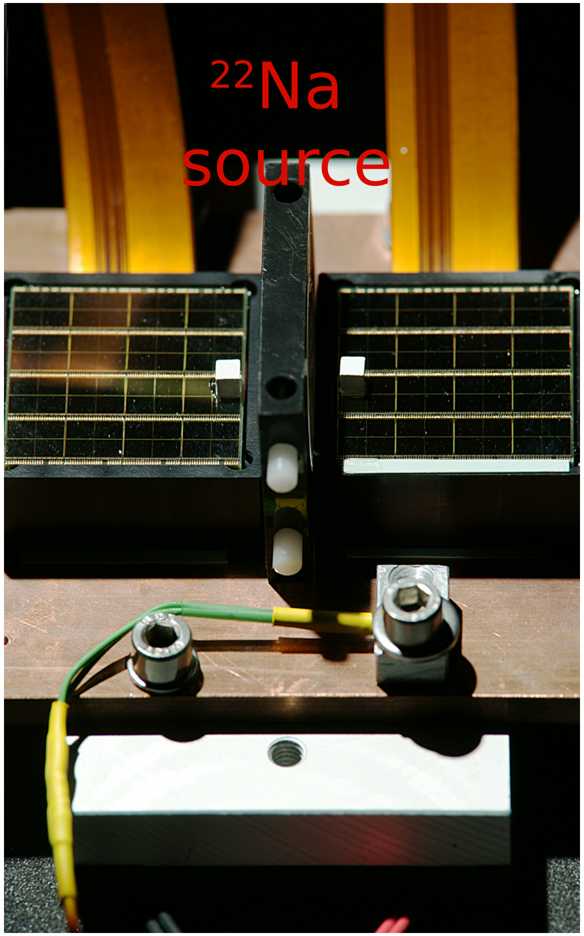


Height represents weight assigned to each voxel by reconstruction algorithm

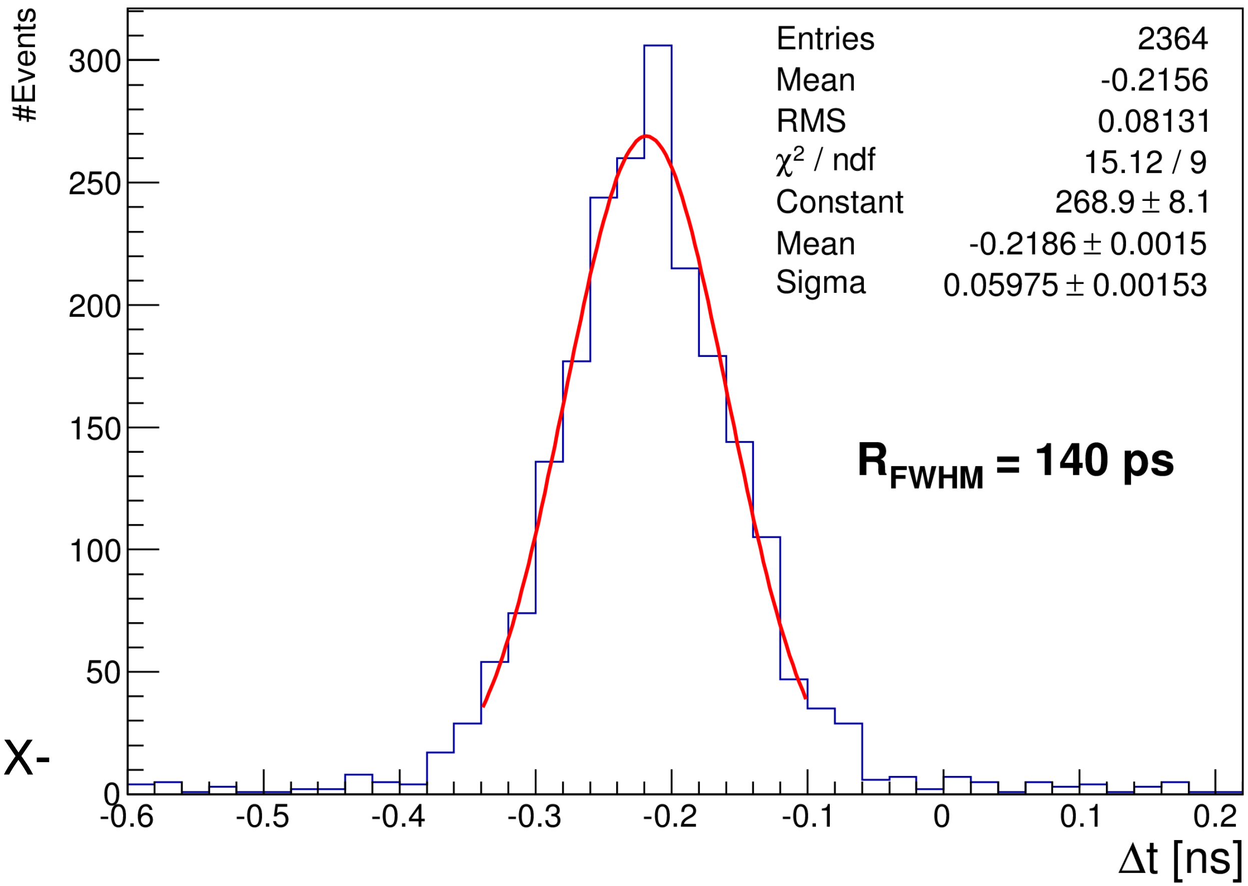


$$x = \frac{\Delta t \cdot c}{2} \quad \Rightarrow \quad \sigma_x = \frac{\sigma_t \cdot c}{2} \quad \Rightarrow \quad \sigma_x = 1\ \text{cm} \rightarrow \sigma_t = 65\ \text{ps}$$

Time resolution with the DLS 3200



time difference between the two tiles
for photopeak coincident events
(coincidence window = 5 ns, Peltier cooling @ 10˚C)

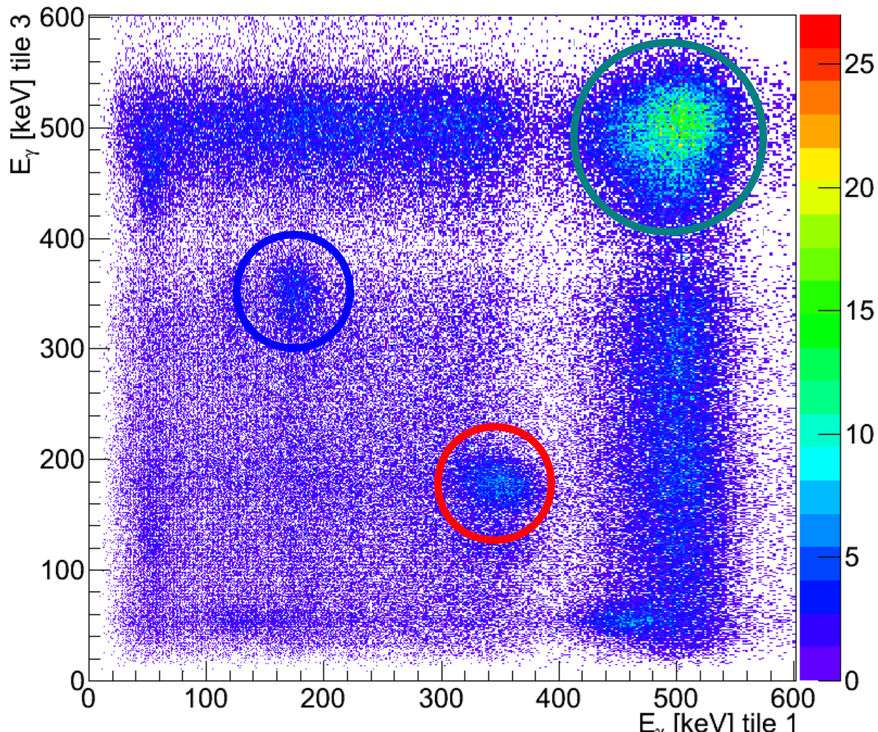


- 2 LYSO scintillator crystals **non AX-PET standard** (3x3x3) mm^3
- Reflective white paint
- coupling done with optical grease

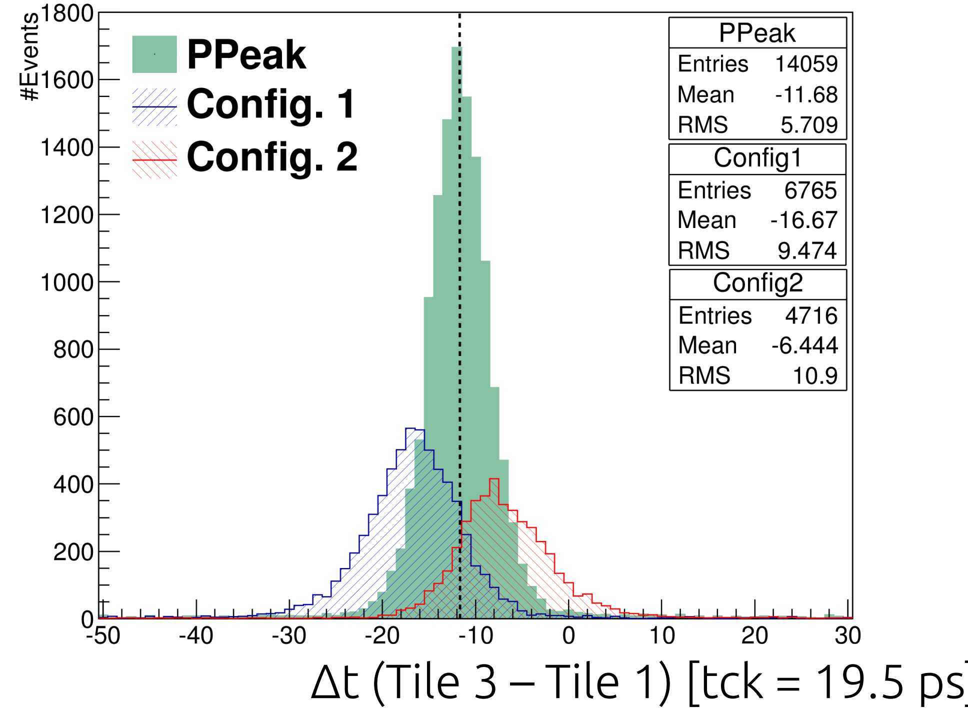
R_t FWHM = 140 ps → R_x FWHM = 2 cm

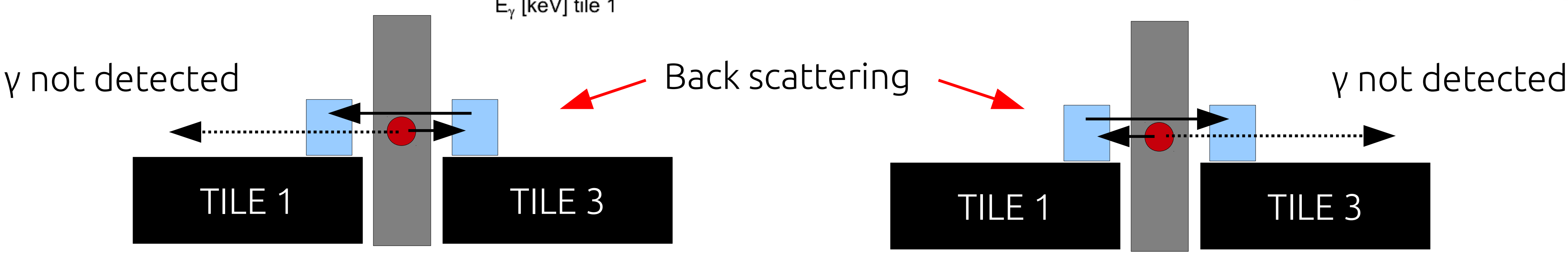
Use of the DSiPM timing performance

Energy spectrum correlation



Time difference





Config 1 → $\Delta t = t_3 - t_1 < 0$

Config 2 → $\Delta t = t_3 - t_1 > 0$

AX-PET future activities using Philips DSiPM

- **AX-PET performance demonstration with dSiPM**

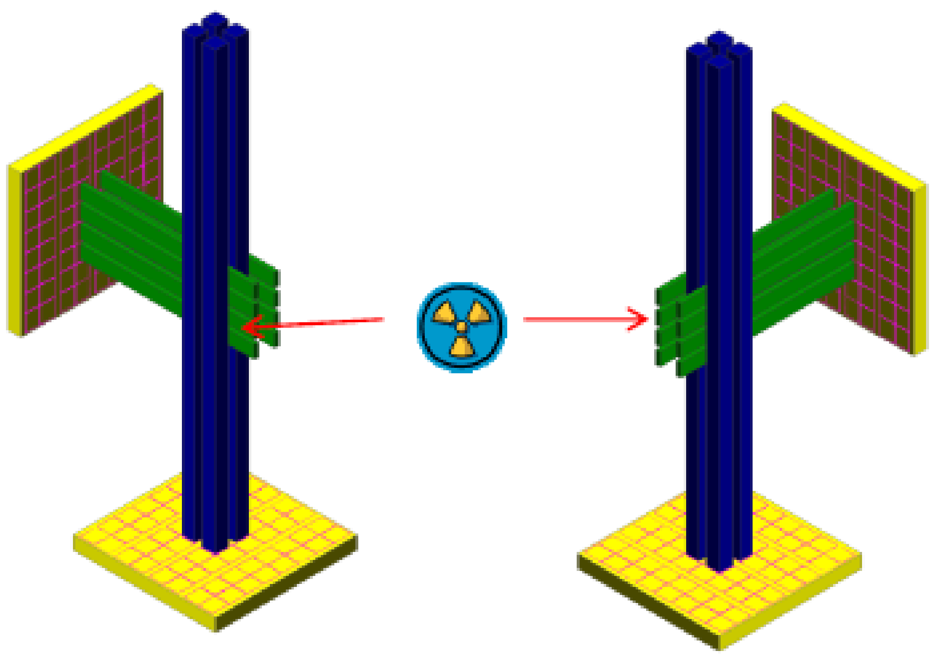
light yield and ΔE/E from LYSO crystals ?

axial coordinate reconstruction: does it work ?

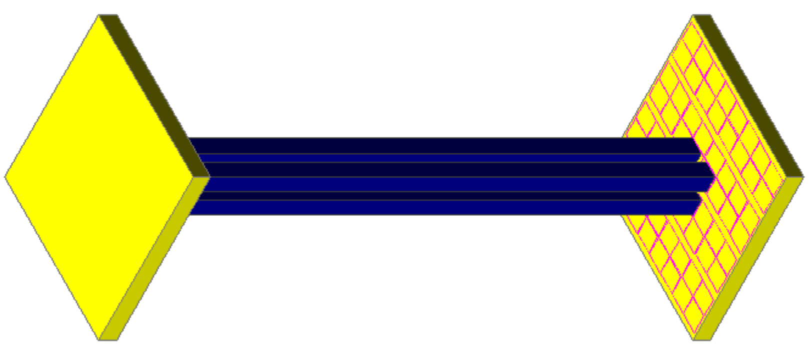
axial resolution through WLS readout ?

time resolution (long crystals) ?

<u>Mini AX-PET setup</u>



<u>Double side readout setup</u>



Thanks for your attention
The AX-PET collaboration

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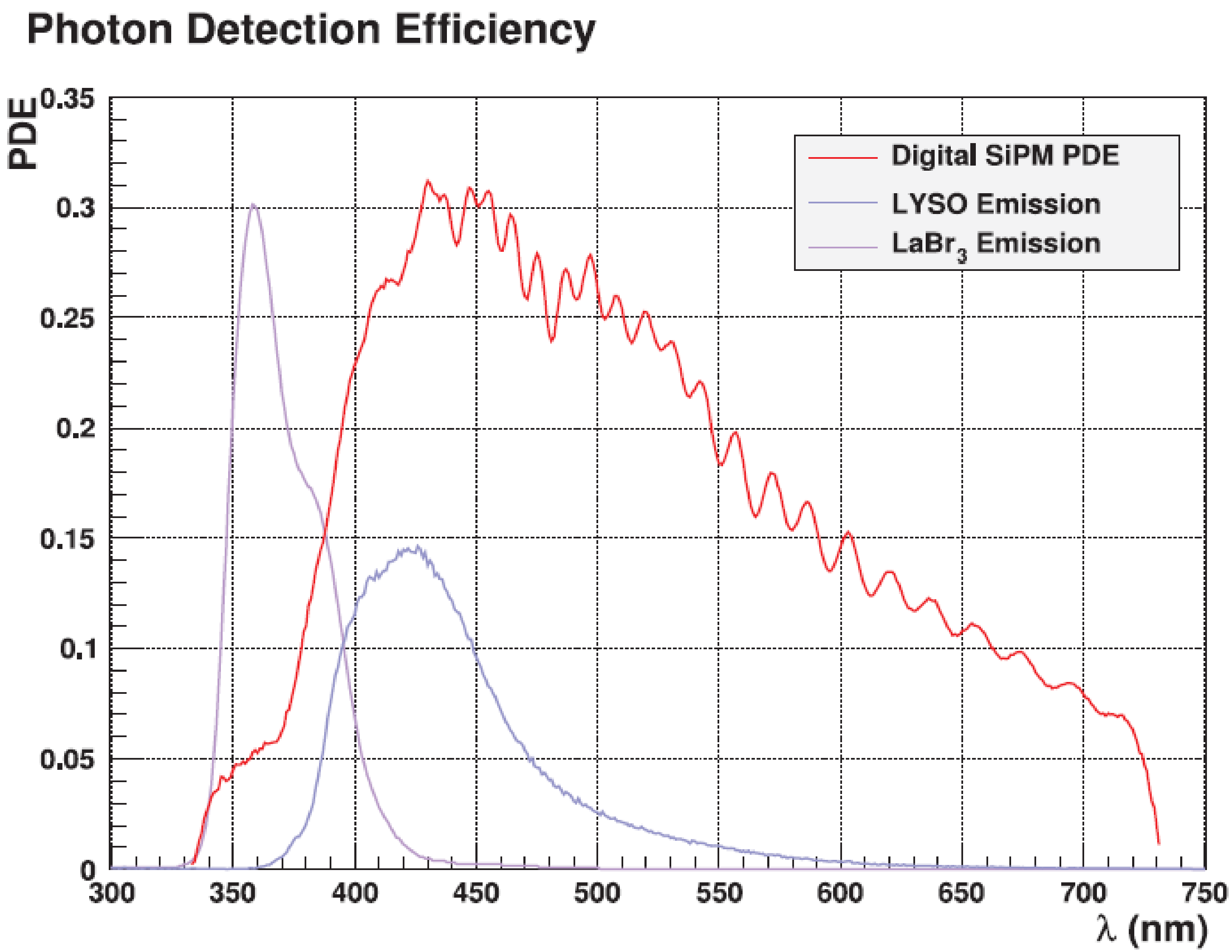
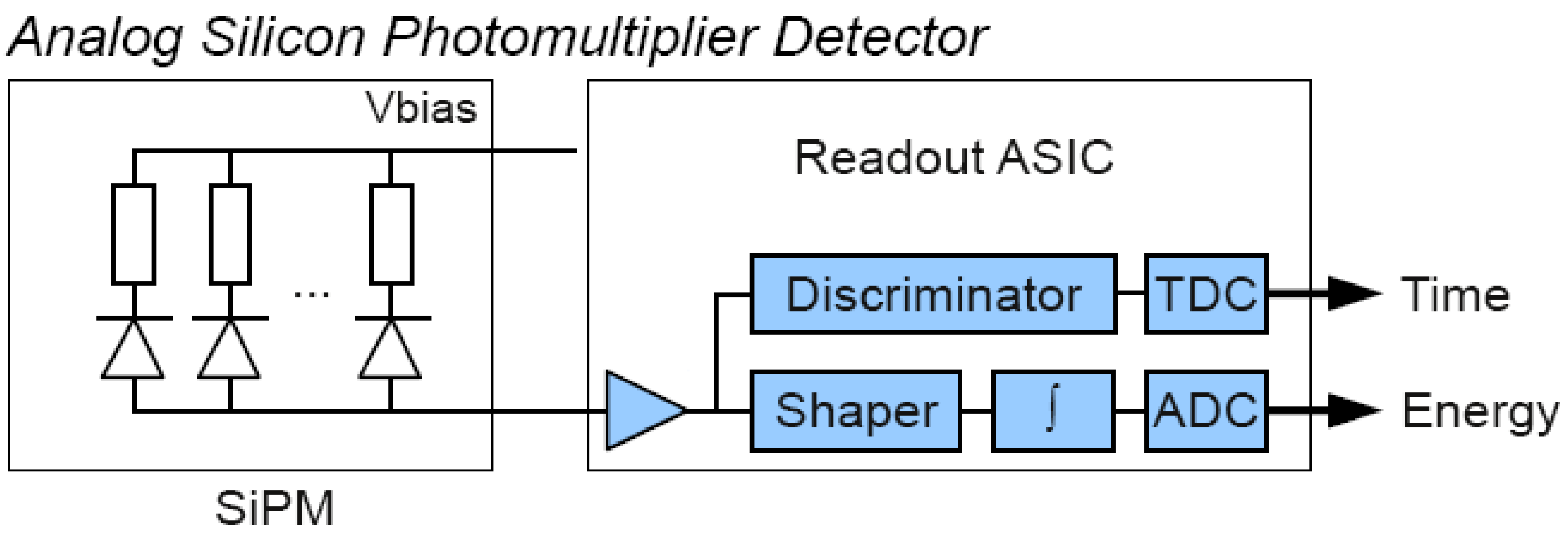
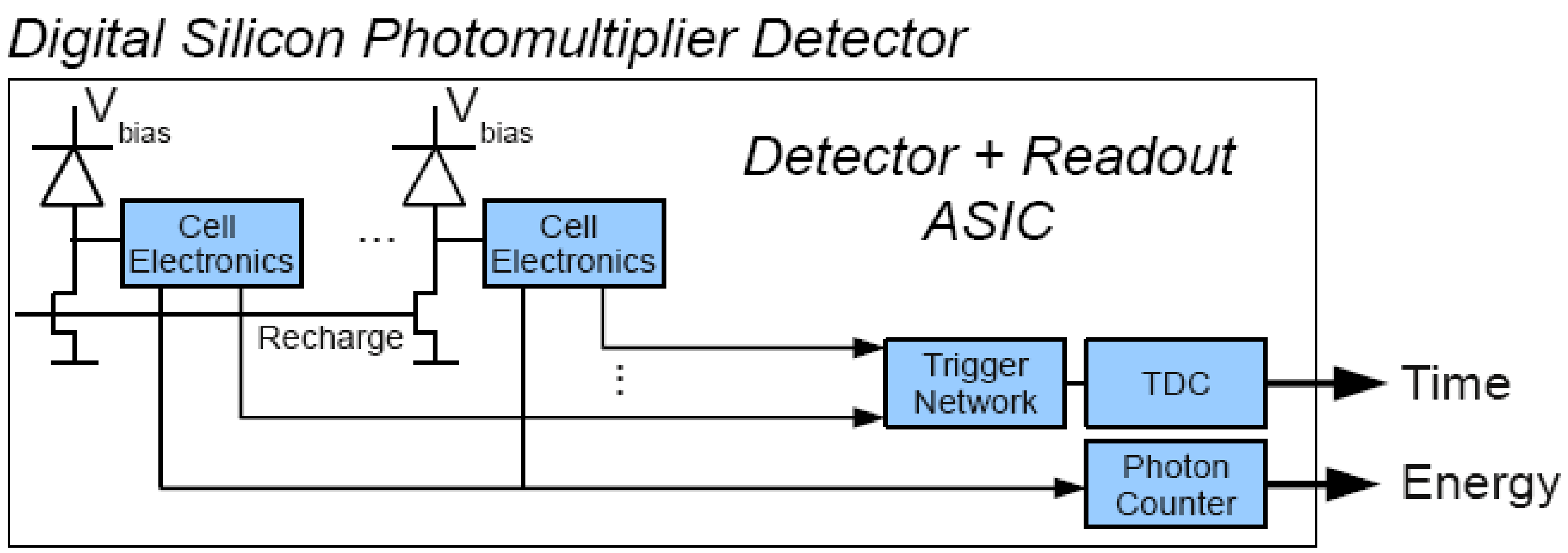
dSiPM Photon detection efficiency

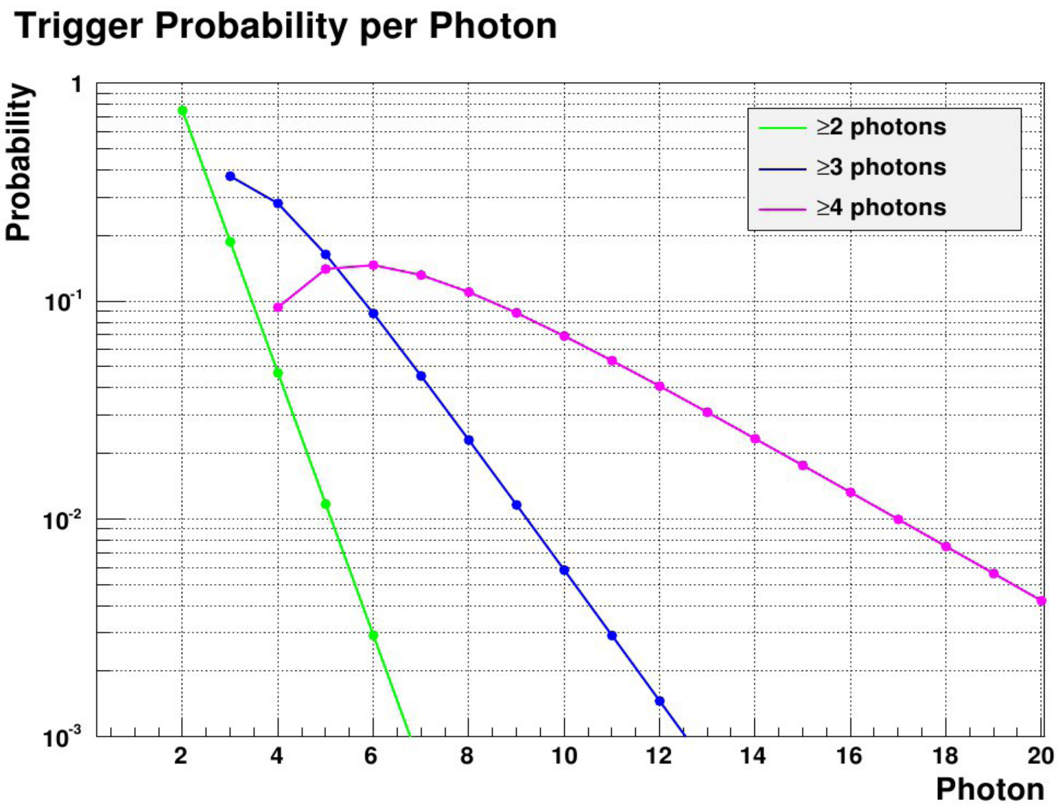


Analog vs. Digital SiPM concept

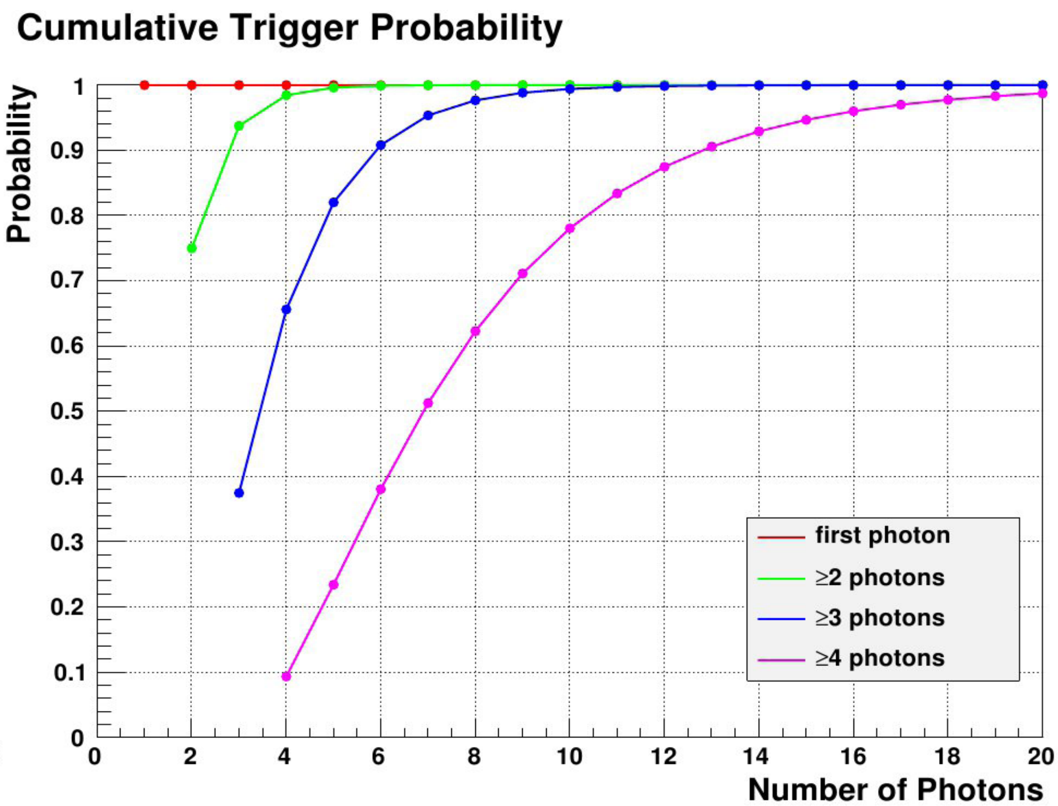




dSiPM Trigger probability

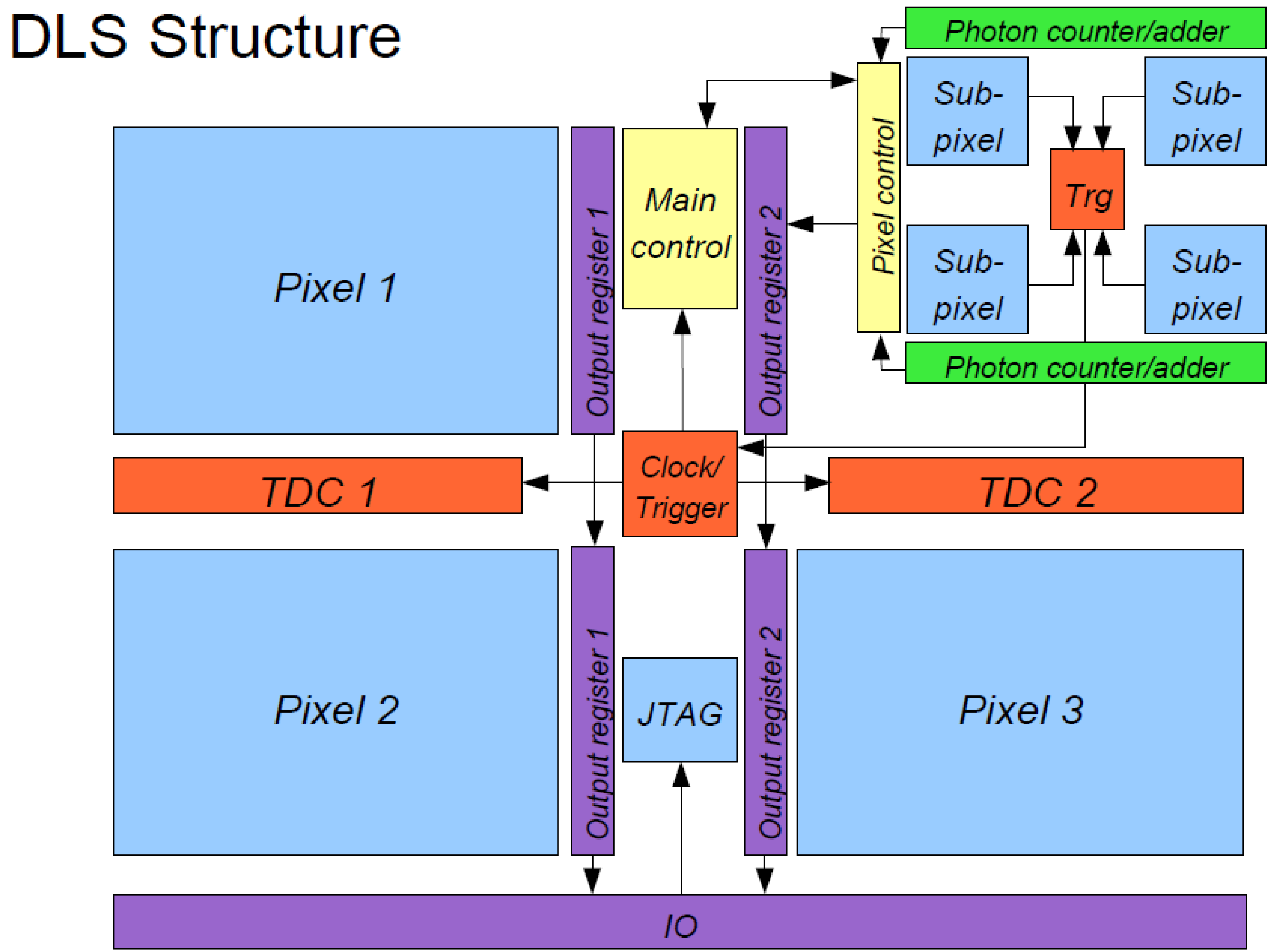


Probability for the nth photon to provide the trigger

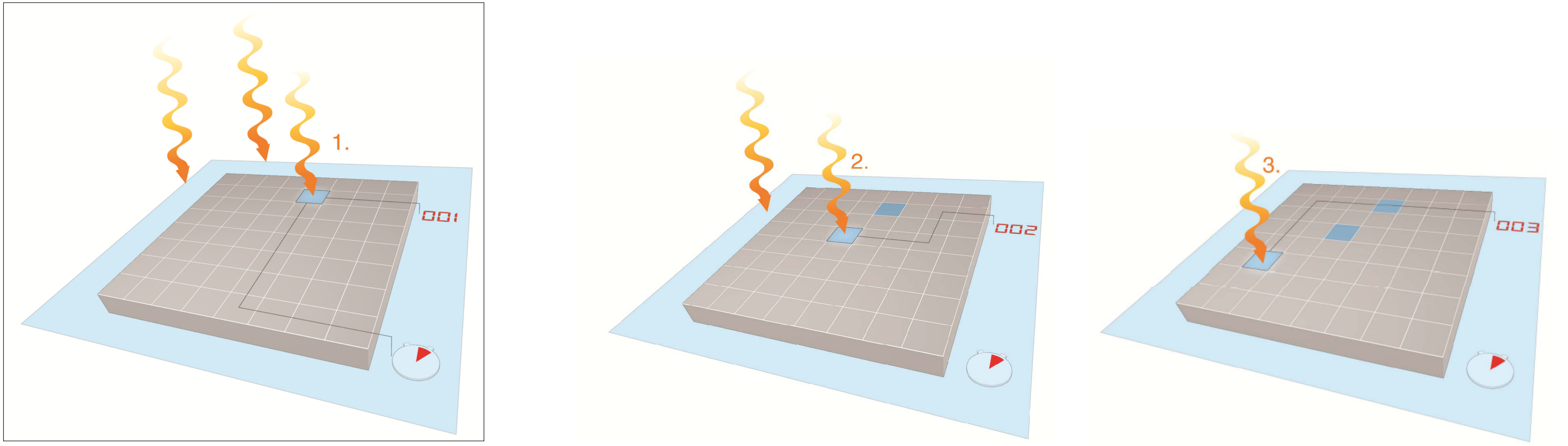


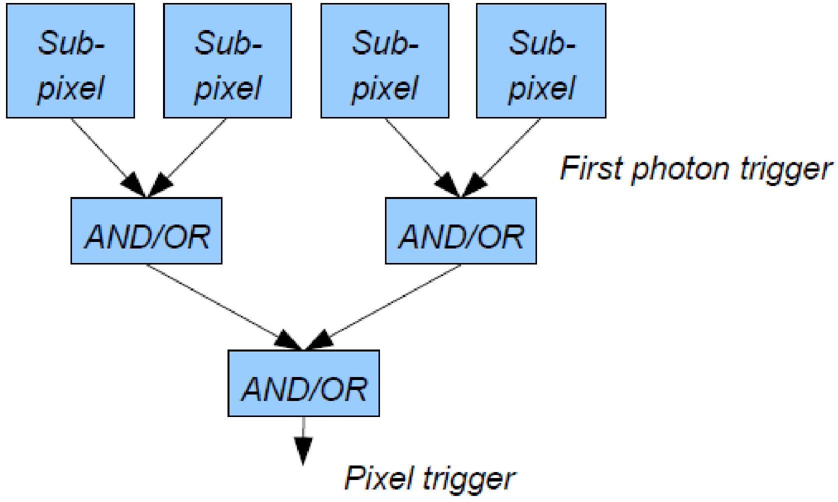
Probability to trigger as function of the amount of inpinging photons

dSiPM Trigger logic

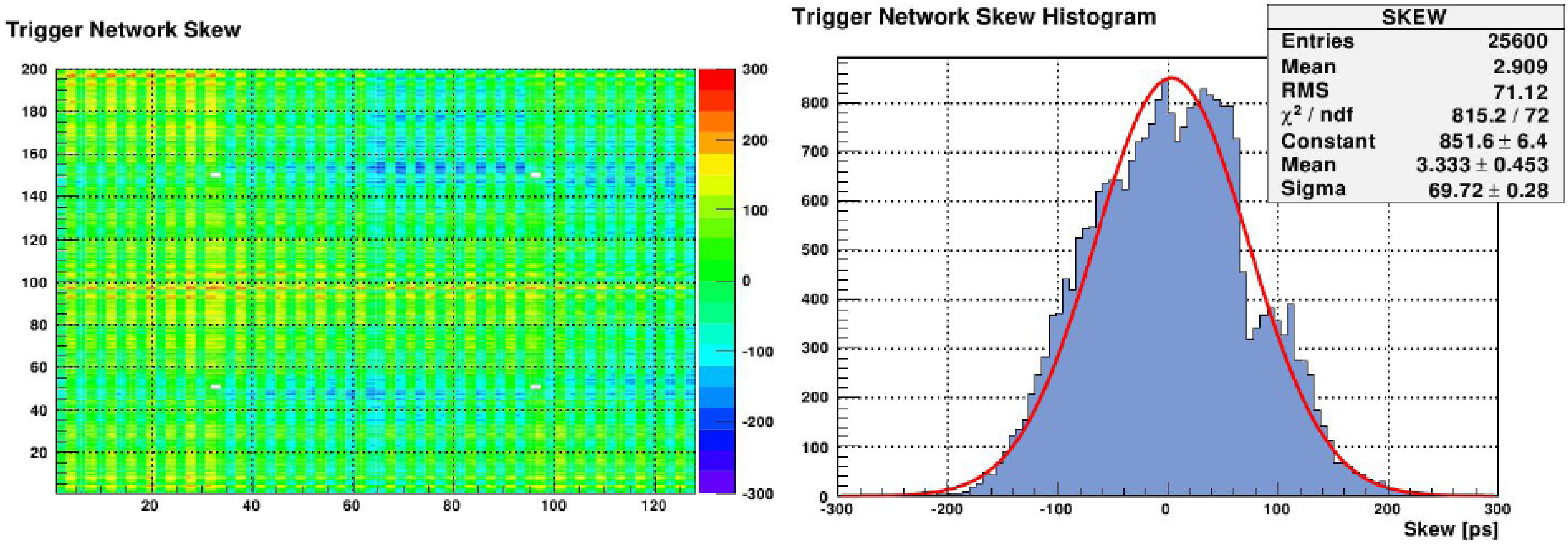


dSiPM Trigger logic

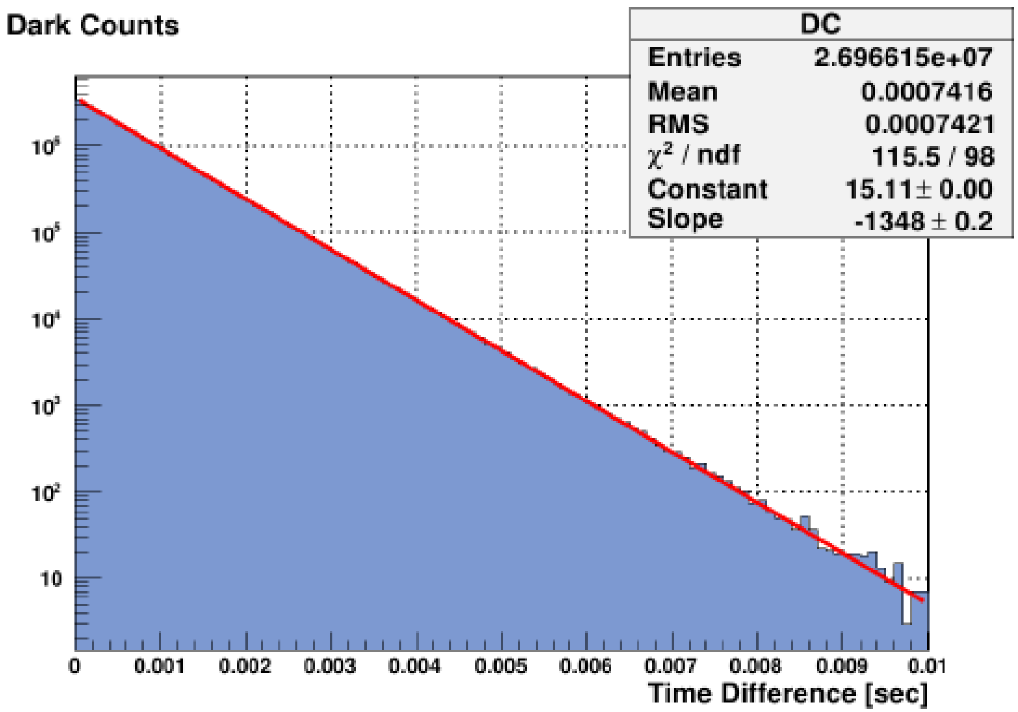


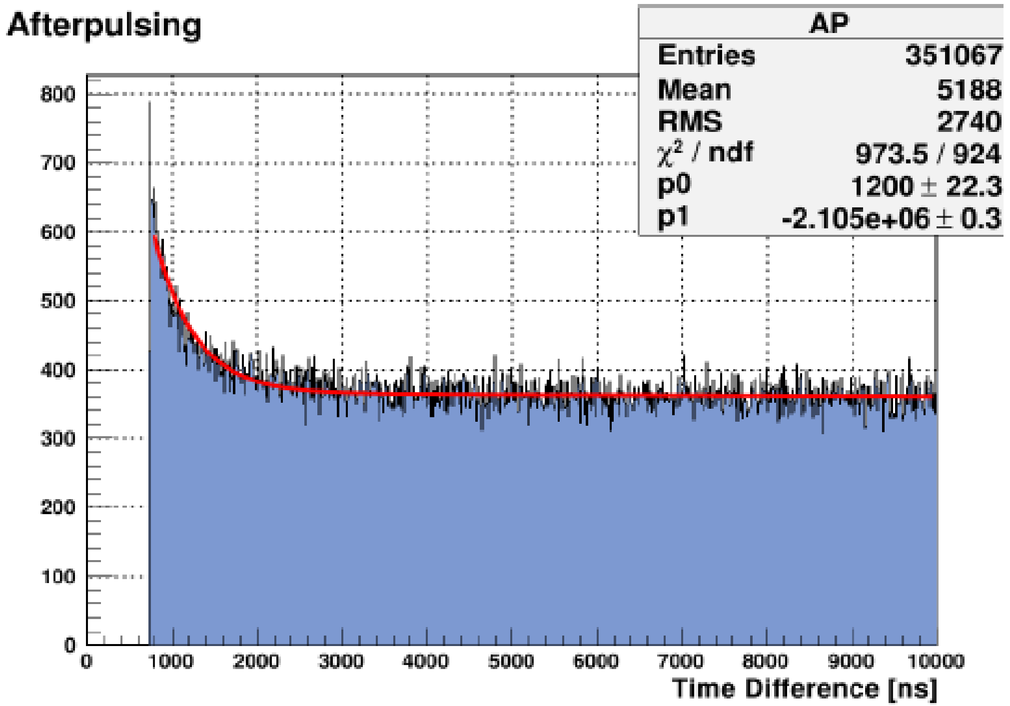


dSiPM Trigger logic



dSiPM DC and afterpulse





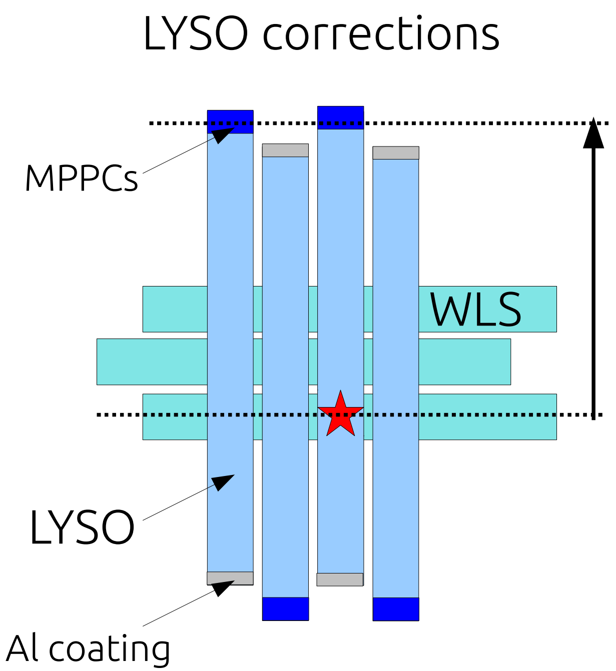
Time differences of two consecutive dark counts in a single diode.

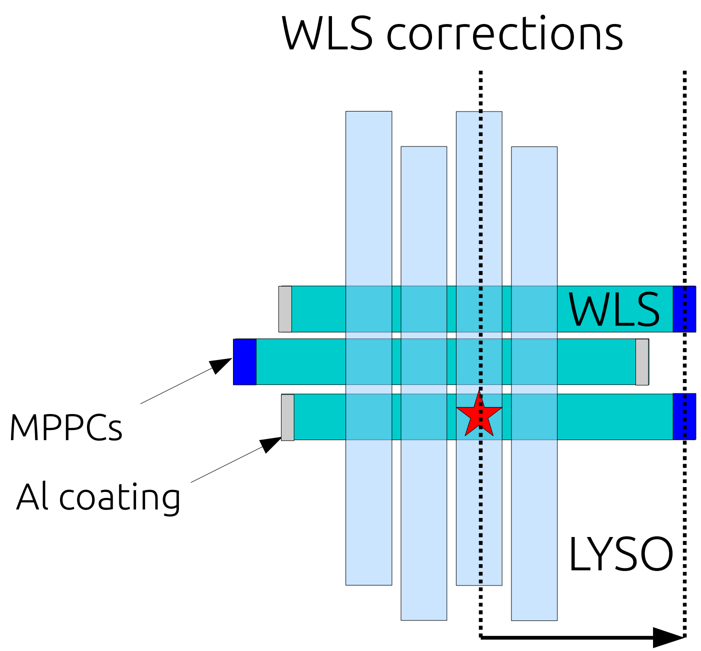
Afterpulsing: deviation from the Poisson distribution in the first few µs.

Many diodes show afterpulsing probabilities of less than 0.1%, few are in the 2-3% range.

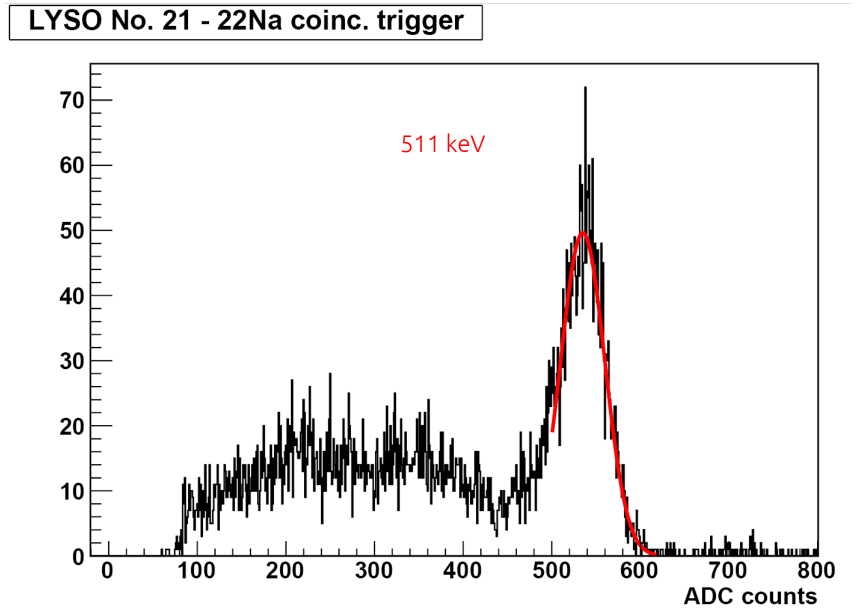
Measurement corrections

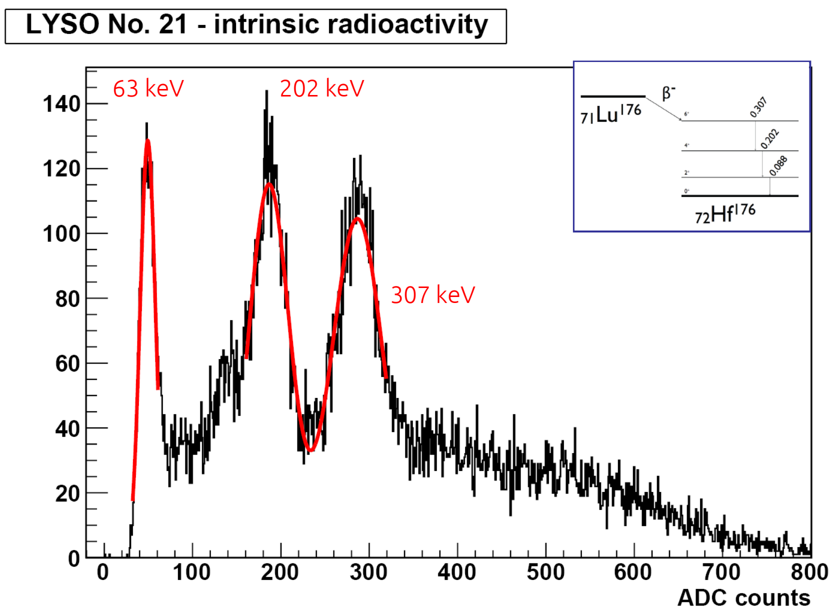
- The variation of the MPPC gain with the temperature is corrected to uniformize the response of all the LYSO and WLS
- WLS and LYSO are read out on one side, the other extremity being covered with a Al coating. Thus the light collected by the MPPCs depends on the position of the photoelectric interaction : Attenuation and reflexions
- This can be corrected using the spatial information from the WLS and LYSO

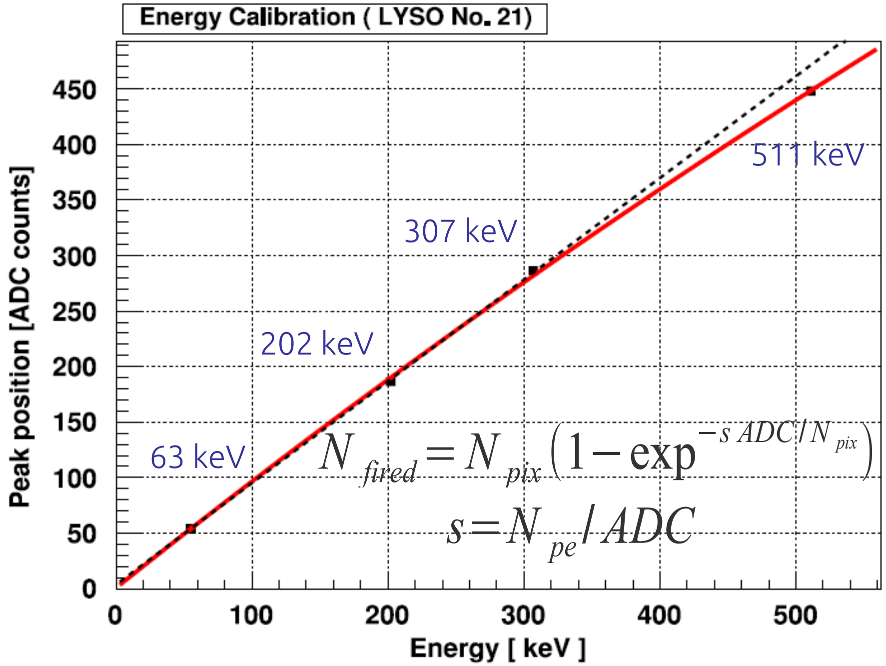




MPPC saturation correction and Energy calibration



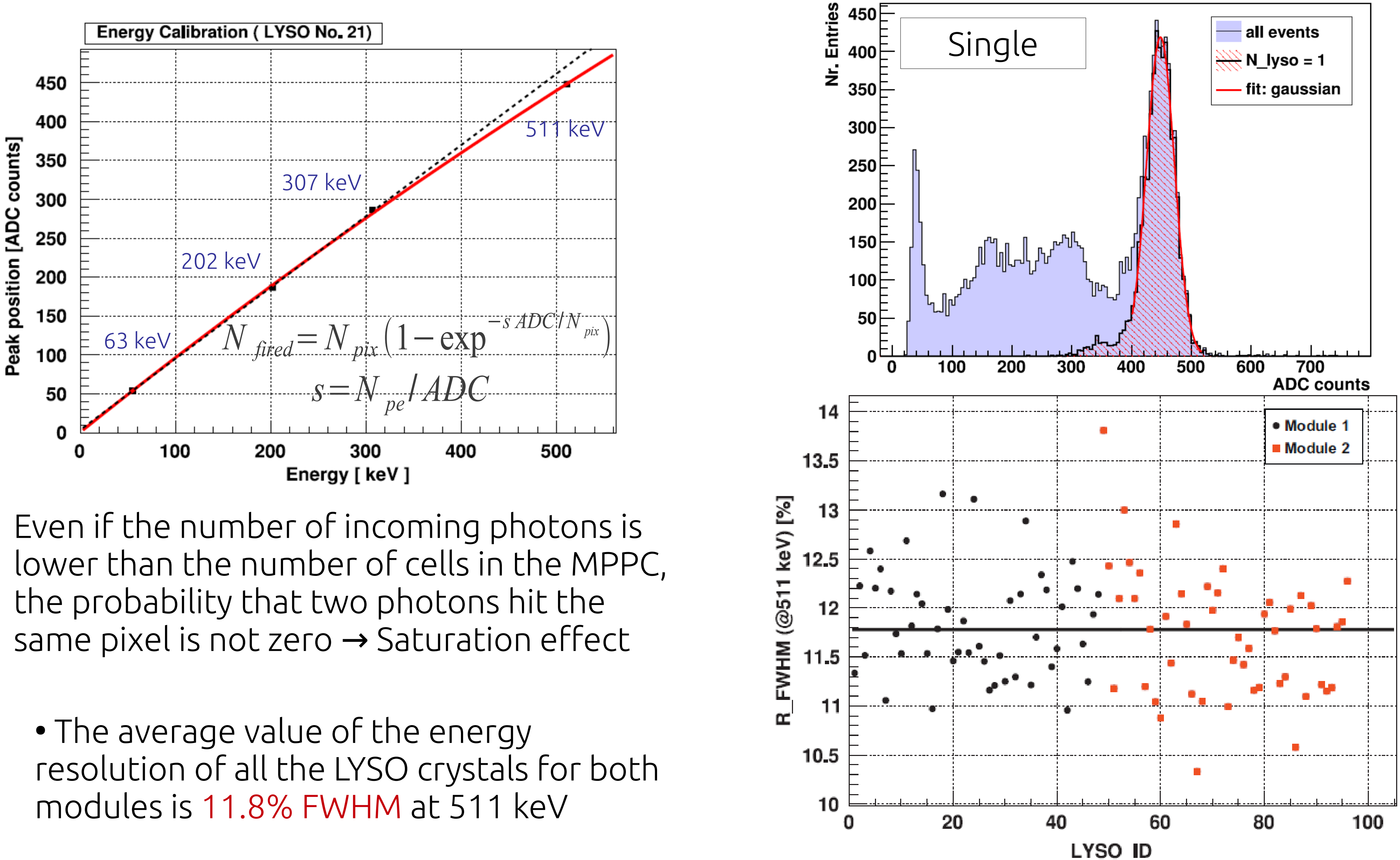




- In order to correct the MPPC saturation, two calibration sets are needed :
  - Photoelectric peak at 511 keV, acquired with the ^{22}Na source
  - "Integrated calibration source" : Two of the peaks of the ^{176}Lu decay spectrum at 202 and 307 keV (natural radioactivity of LYSO) and the Lutetium K_{α} escape line at 63 keV

- The four data points are fitted to take into account the saturation effect in the MPPCs

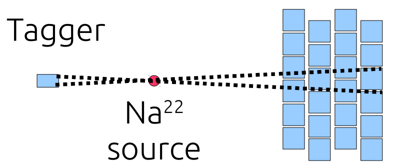
Energy Calibration and Resolution



Even if the number of incoming photons is lower than the number of cells in the MPPC, the probability that two photons hit the same pixel is not zero → Saturation effect

- The average value of the energy resolution of all the LYSO crystals for both modules is 11.8% FWHM at 511 keV

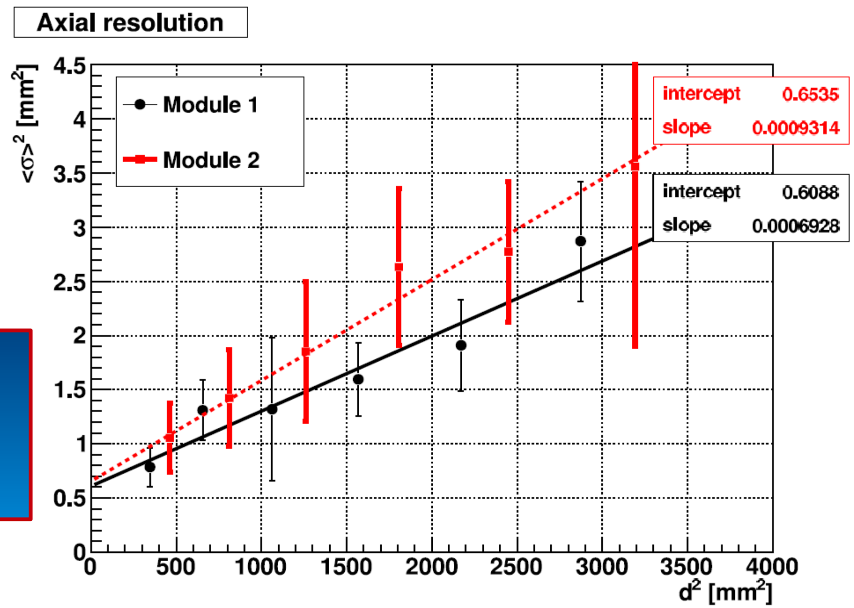
Spatial resolution with point-like source



Collimated beam for precision scan

<u>Taken into account :</u>

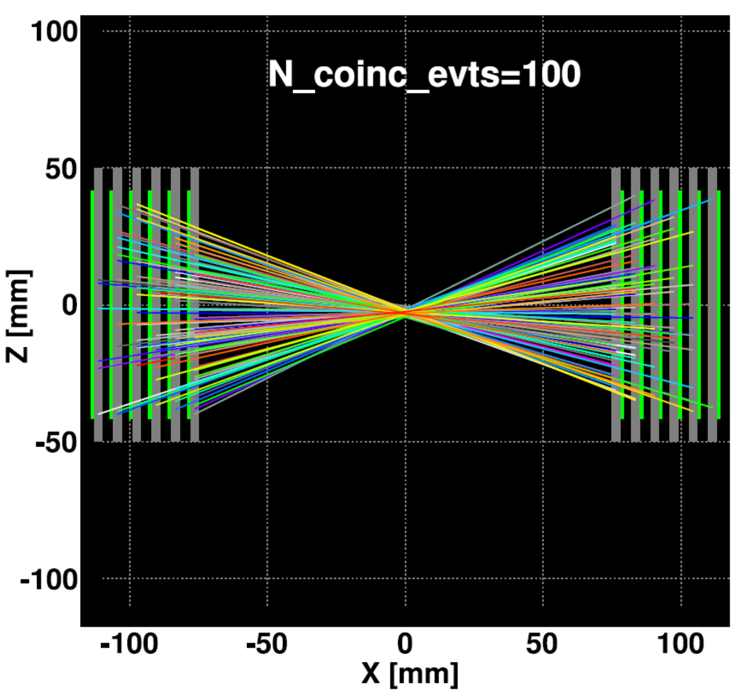
- positron range : ρ ~ 0.54mm
- non-collinearity : ~ 0.0022 x D ~ 0.33mm
- source dimensions : ø=250µm
- Beam divergence

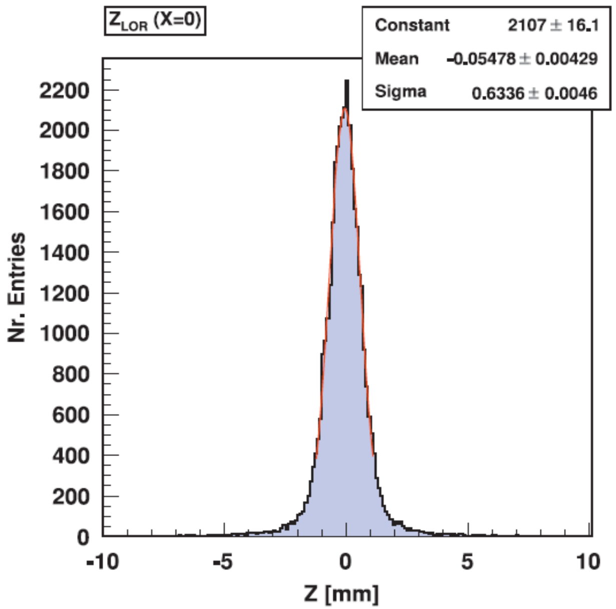


Axial resolutions

- Module 1 : 1.75 mm FWHM
- Module 2 : 1.83 mm FWHM

side view

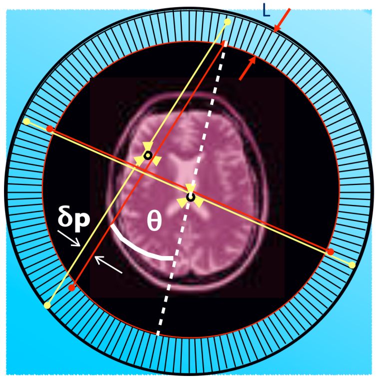




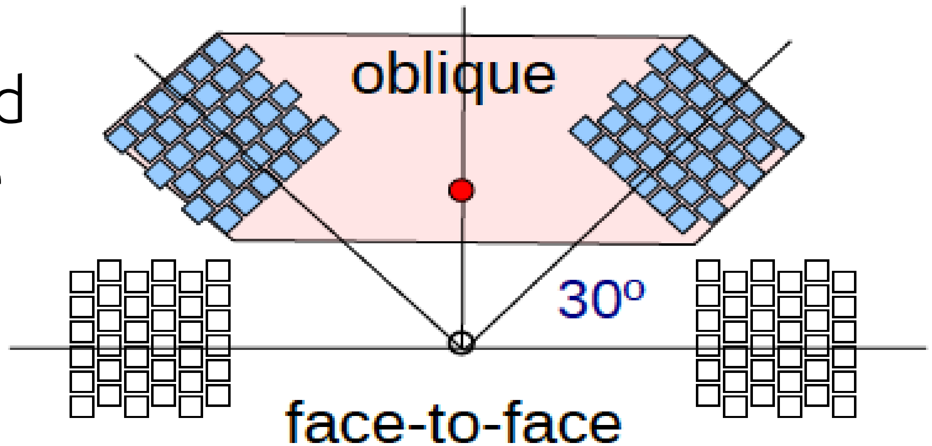
Axial resolution

- LOR of 100 coincidences in the axial plane. Intersection with plane x=0 gives R = 1.35 mm FWHM

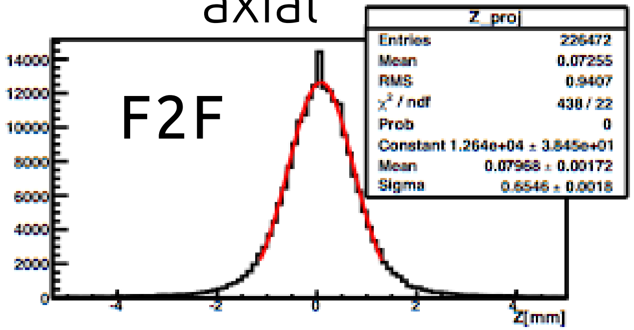
Spatial resolution with point-like source

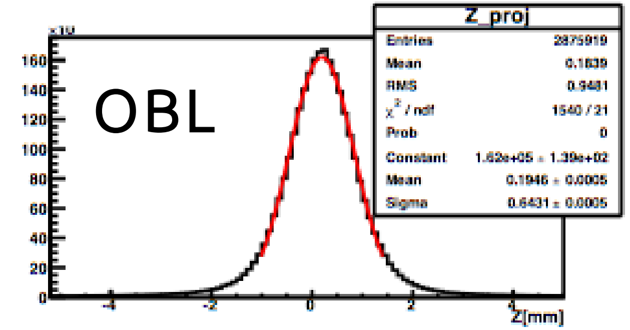


parallax error is more and more important outside the center of the FOV

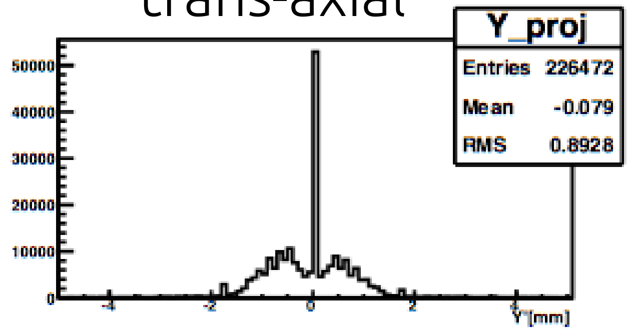


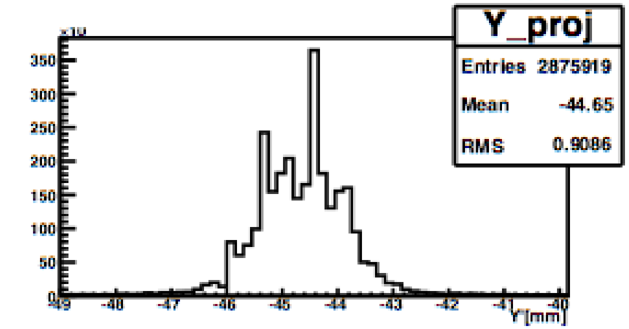
axial





trans-axial

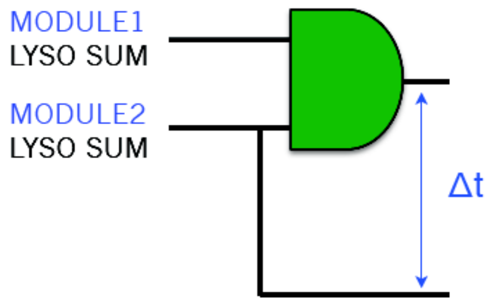


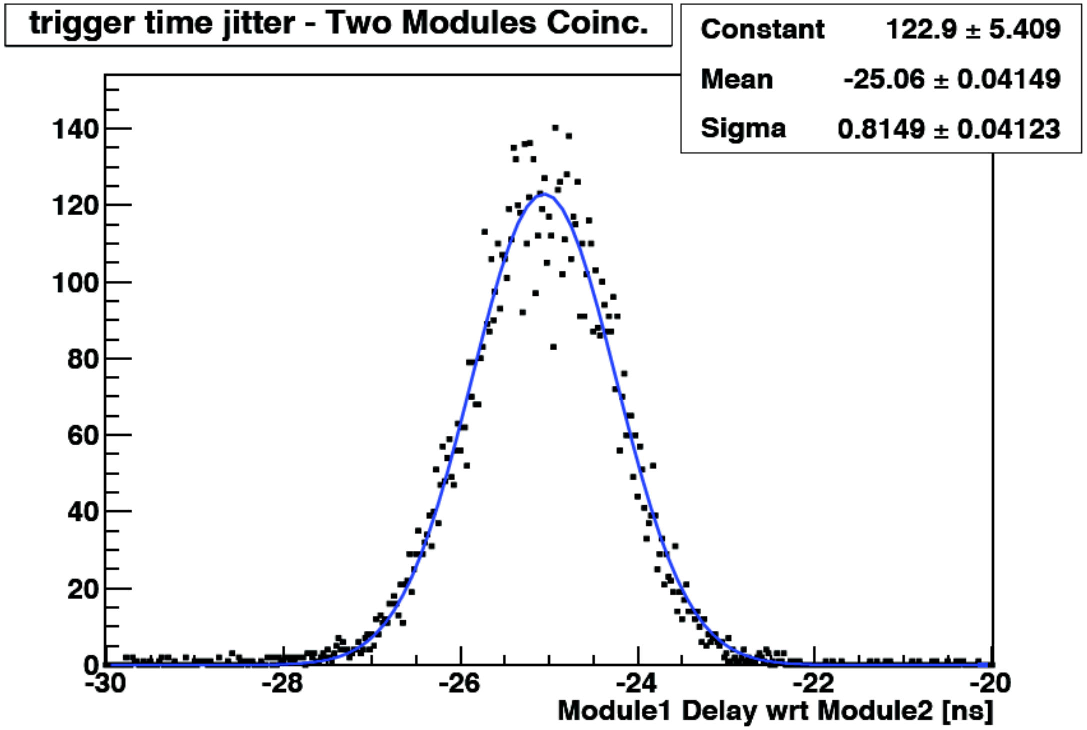


	Axial	Transaxial
F2F	σ=0.655	RMS=0.893
OBL	σ=0.643	RMS=0.909

Time resolution

- measure delay of coincidence wrt Mod2
- measurement from the scope [Lecroy Waverunner LT584 L 1GHz]





Measured time resolution : FWHM ~1.9 ns