# Development of Detector Modules and the Associated Electronics for Time-of-Flight Positron Emission Tomography

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*On behalf of TagusLIP group*

# Positron Emission Tomography (PET)

PETsys Electronics

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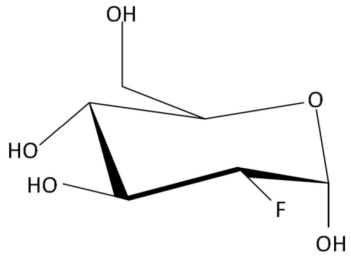
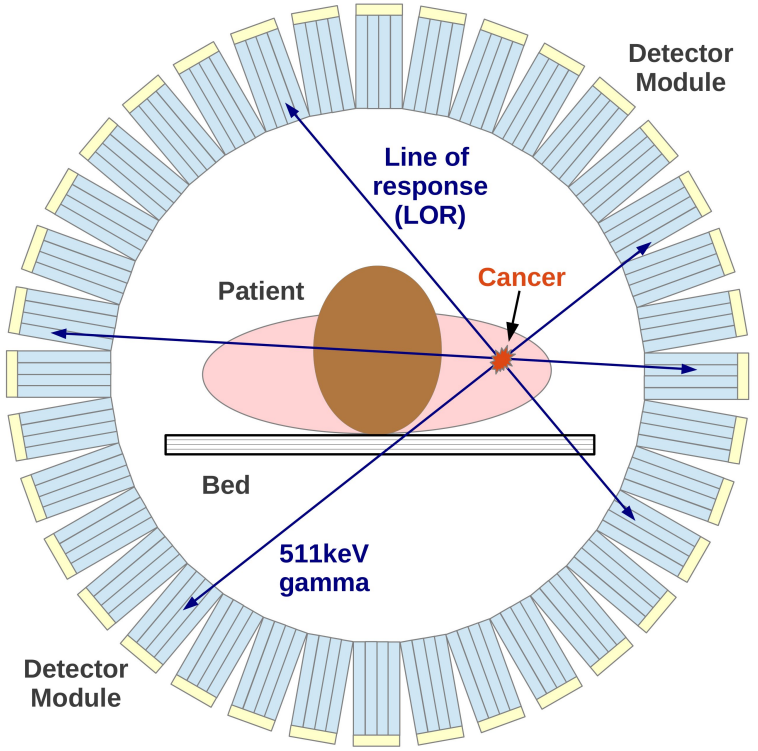
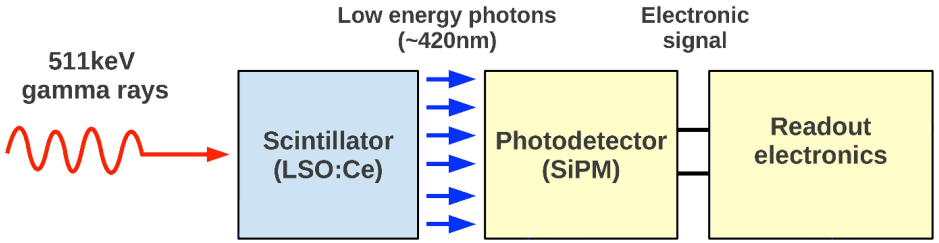
→ Noninvasive imaging technique that provides a functional or **metabolic** assessment of tissue

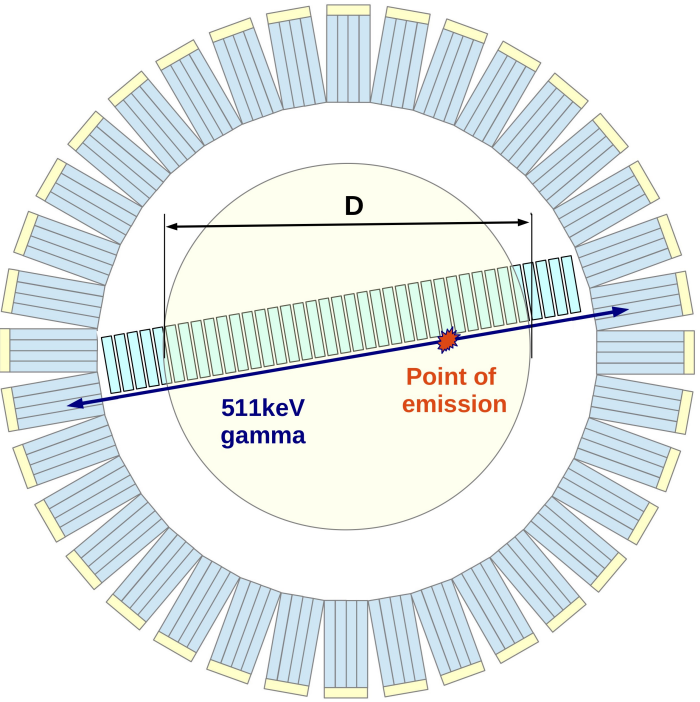
→ In $^{18}$F-Fluorodeoxyglucose (FDG) the radioisotope Fluorine ($^{18}$F) emits a positron.



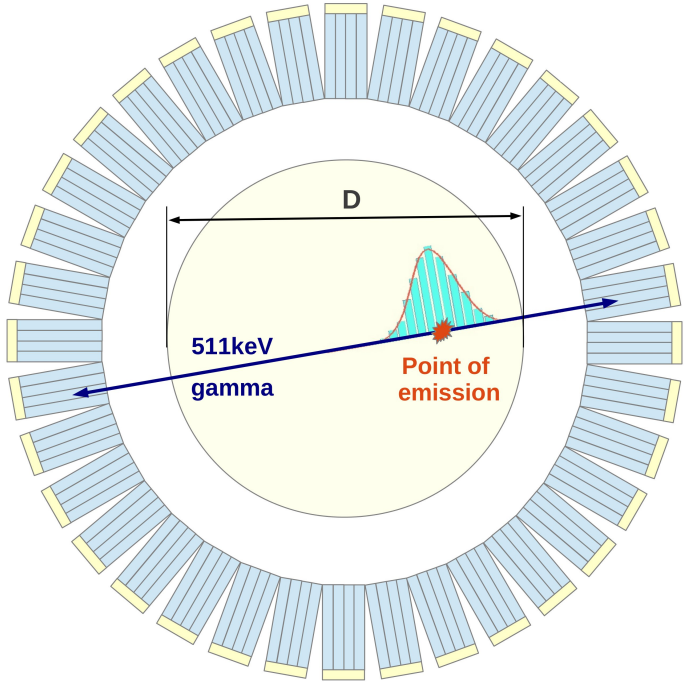



# Time-of-Flight PET (TOF-PET)

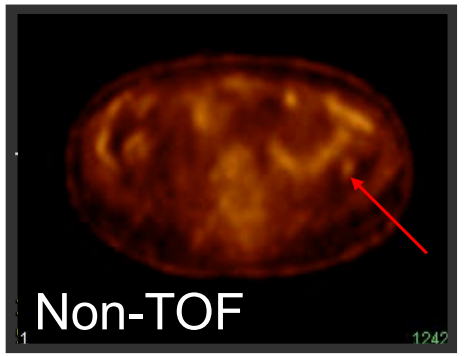


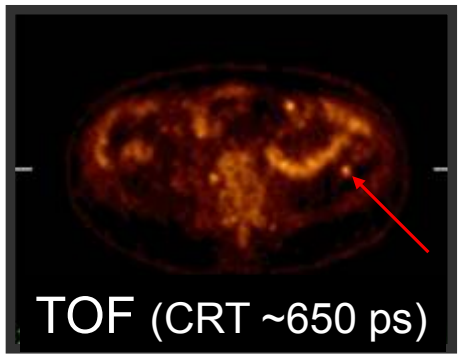

→ Without timing the positron emission could have happened anywhere along the line of response (LOR).




→ Time of flight can effectively confine the positron emission point.

→ Timing is determined by the full width at half maximum (FWHM) of the coincidence time resolution (CTR).





Colon cancer, left upper quadrant peritoneal node
13.4 mCi; 2 hr post-injection

$$G = \frac{SNR_{TOF}}{SNR_{non\,TOF}} = \sqrt{\frac{2*D}{c*CTR}}$$

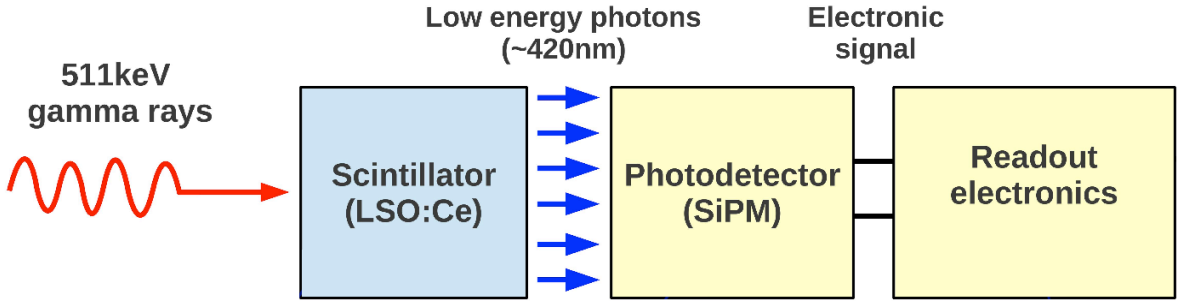
# Factors affecting Coincidence Timing Resolution (CTR)

→ Readout electronics

→ Photodetector type

→ Crystal type

→ Crystal geometry



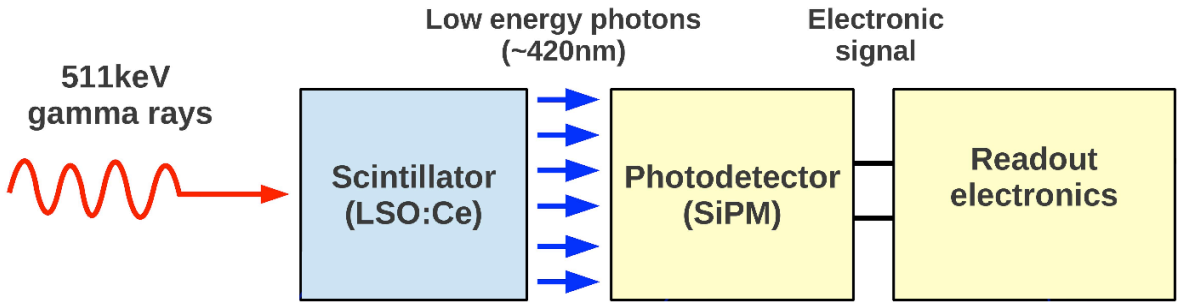

# Factors affecting Coincidence Timing Resolution (CTR)

→ Readout electronics: TOFPET2 ASIC

→ Photodetector type: SiPM

→ Crystal type: LYSO

→ Crystal geometry



# ASIC for TOF applications timeline

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| | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|---|---|
| **TOFPET1** (PET and HEP) | Design and prototyping | | Evaluation | | | | | |
| | | | | Design and evaluation of a TOF-PET demonstrator | | | | |
| **TOFPET2** (PET and HEP) | | | | Design and prototyping | | | Evaluation | |
| | | | | | | | Production | |
| **TOFEE** (HEP: CT-PPS) | | | | | | D & P | Evaluation | |
| **TIGER** (HEP: BES III) | | | | | | | Design | Production |
| **TOFHiR** (HEP: CMS BTL) | | | | | | | | Design and prototyping |

# TOFPET1 ASIC: TOFPET demonstrator

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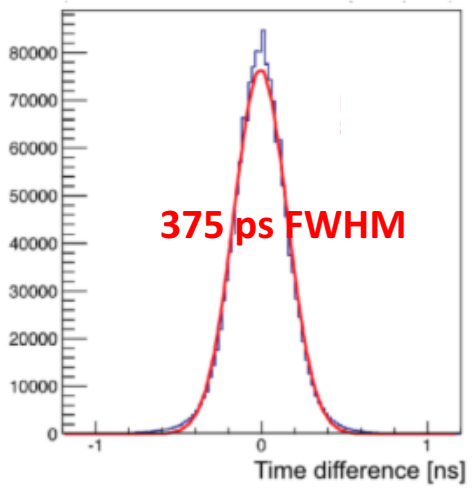
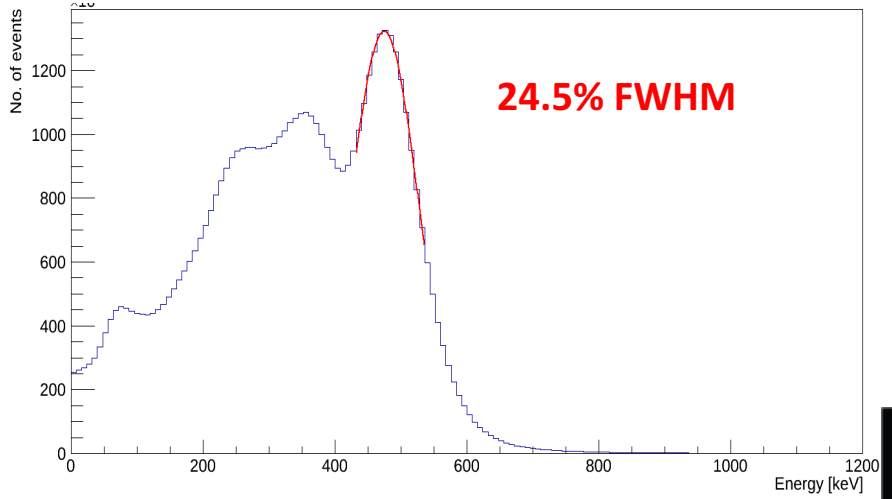
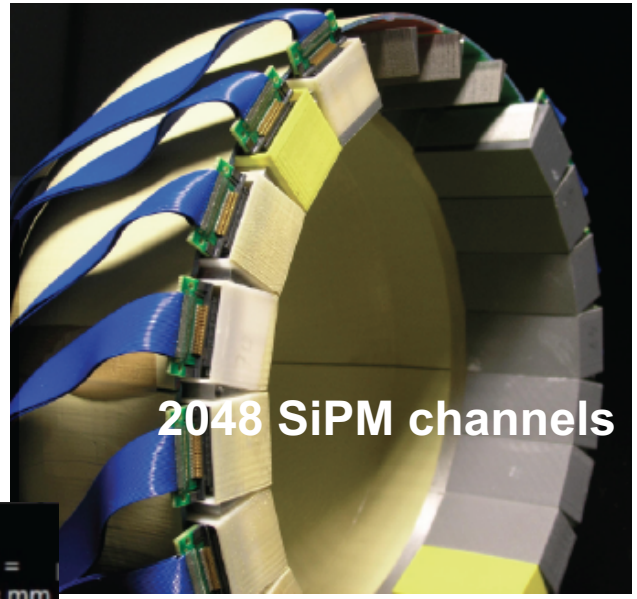
CTR
(All events in photopeak)

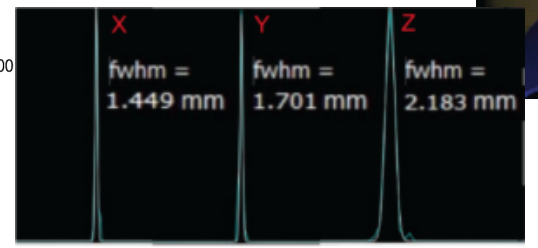



Ge-68 energy spectrum of coincidence events

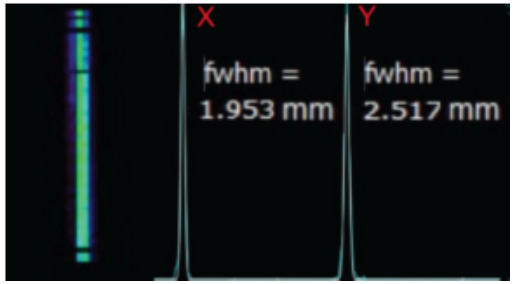


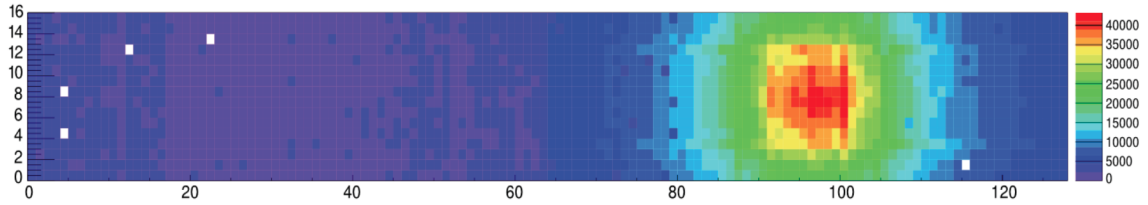

Point source




Line source




Flood map with Na22 point source off-center (# events in Photopeak)



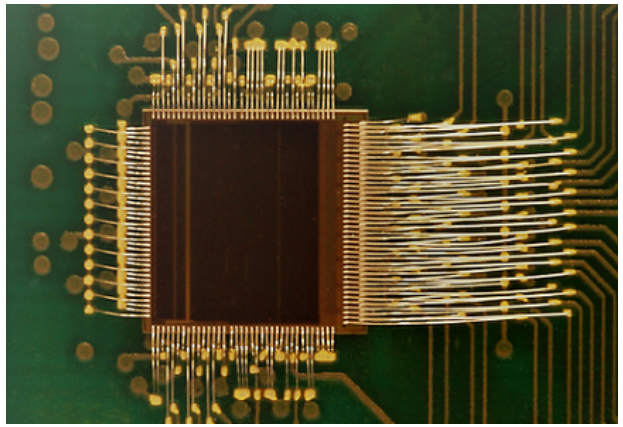
Each detector module is an array of 4x4:

- LYSO (3x3x15 $mm^3$)
- SiPM (3x3 $mm^2$)
- One-to-one coupling

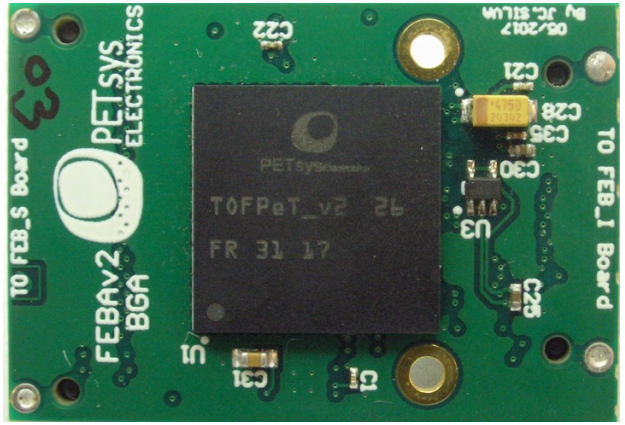
## Analog frontend to digital interface

- 64 independent channels in 5x5 $mm^2$
- Standard CMOS 110 nm
- Positive or negative signal polarity
- Dynamic range 100 fC - 1500 pC
- Noise 1.5 mV (1 p.e. ~ 30 mV)
- Charge integration ADC 10 bit
- TDC time binning 30 ps
- Low power: 5-8 mW/Ch
- Event rate: up to 480 kHz per channel*
- On-chip calibration circuitry

* 600 kHz in next chip iteration



TOFPET2 chip-on-board

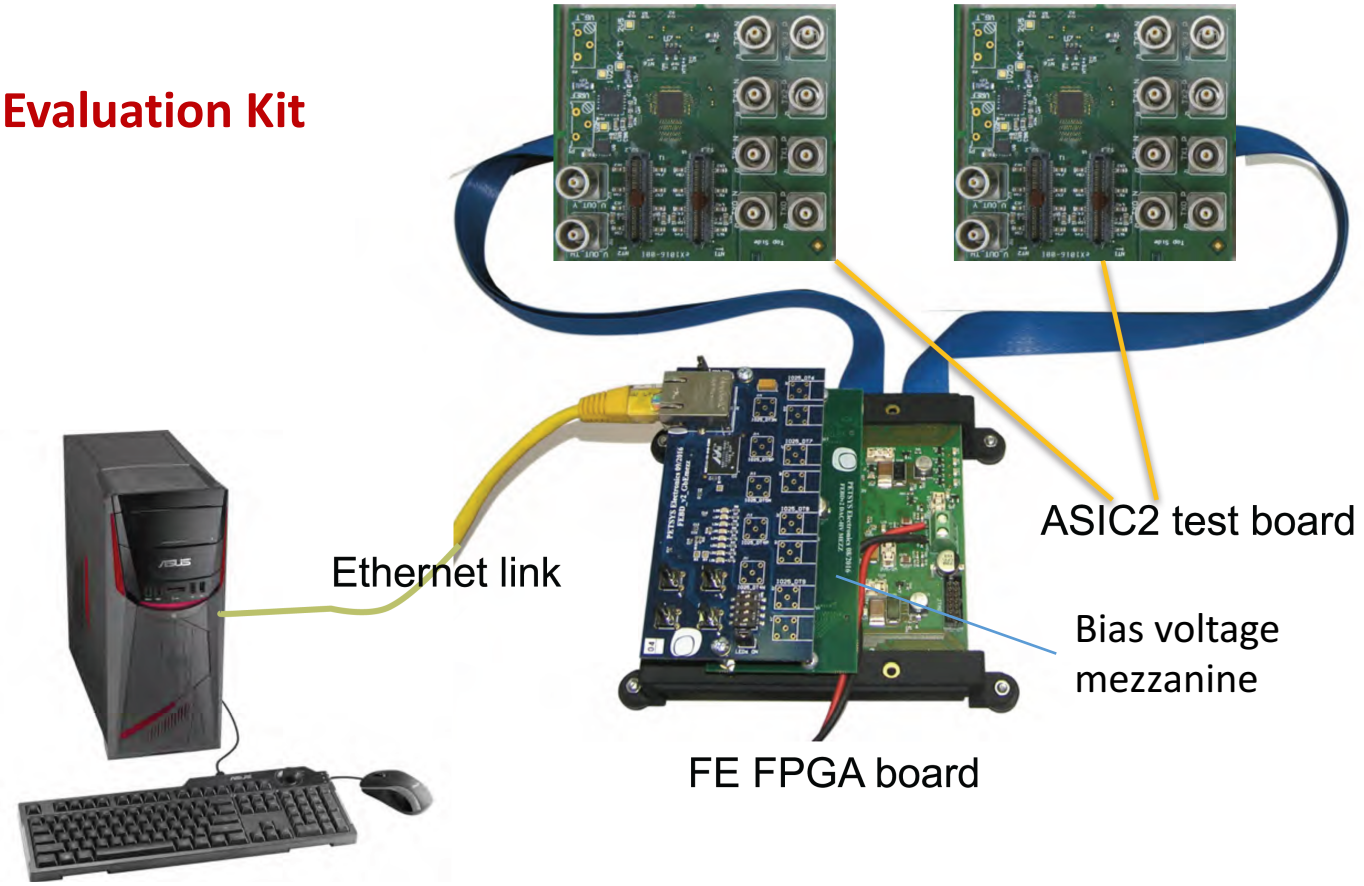



TOFPET2 BGA

# Test setup

- ASIC test boards and SiPMs/LYSO thermally stabilized at 18°C

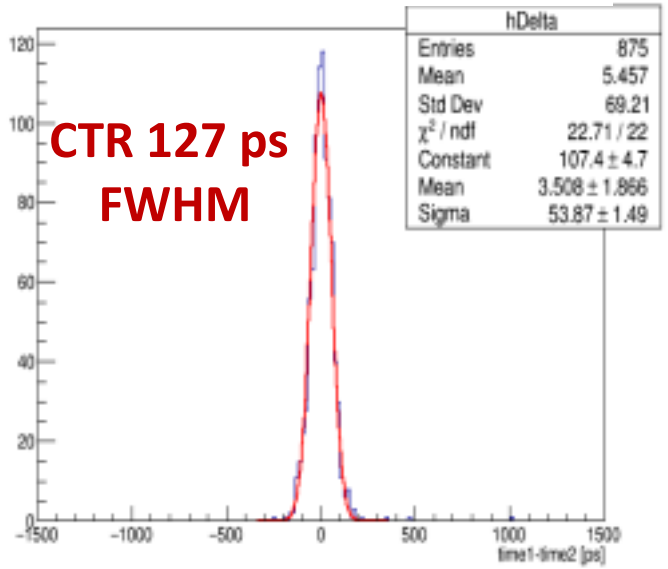
**PETsys Evaluation Kit**



# TOFPET2 coincidence time resolution with LYSO

- CTR with Na22 point source
  - LYSO: 2x2x3 mm3 ;
  - SiPM array from Broadcom AFBR-S4N44P163;
- The events selected have the energy of both photons within +/- 1 sigma window centered on the 511 keV photopeak, as measured by the ASIC ADCs.

AC coupling SiPM - ASIC
8.5 V overvoltage




- Other CTR measurements with several SiPM producers (performed with individual LYSO crystals of 3x3x5 $mm^3$ glued to SiPMs 3x3$mm^2$)
- One-to-one crystal-SiPM coupling with the same area

| SiPM type | SiPM area (mm2) | Over-voltage (V) | CTR FWHM (ps) |
|---|---|---|---|
| KETEK-PM3325-WB | 3x3 | 4 | 229 |
| HPK MPPC S13361-3050AE-04 | 3x3 | 5.5 | 215 |
| SensL ArrayJ-30035-64P-PCB | 3x3 | 5 | 228 |

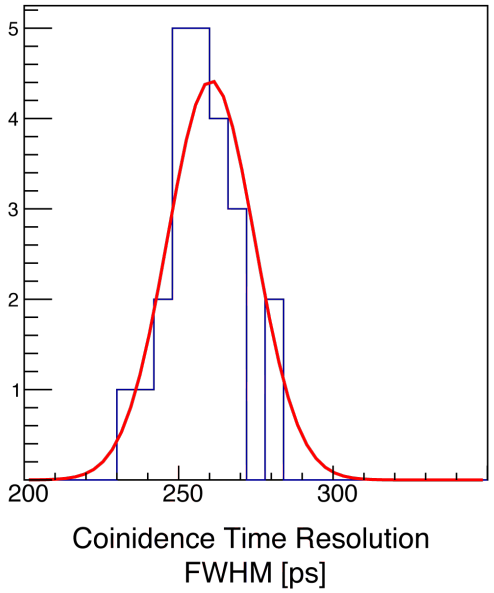
# CTR with realistic PET detector modules

4x4 LYSO arrays, LYSO pixels 15 mm long, Vikuiti foils 70 µm

HPK S13361-3050AE-04 MPPC 4x4 arrays matching one-to-one LYSO pixels 3.13x3.13x15 $mm^3$

DC coupling SiPM - ASIC

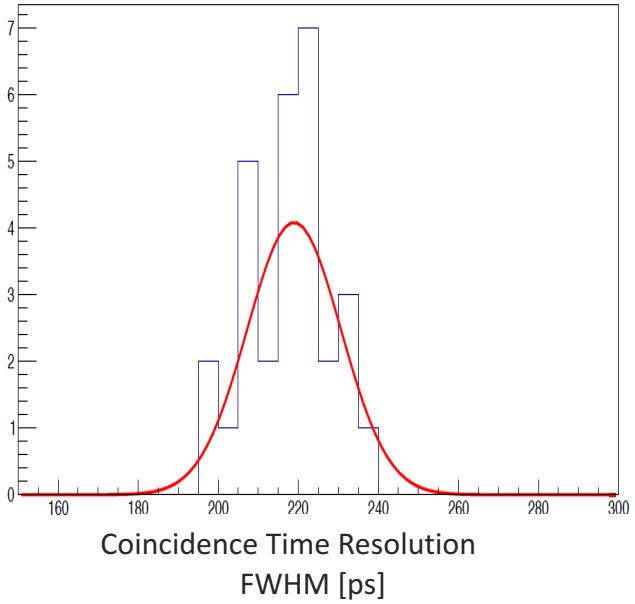
Average CTR = 260 ps FWHM




Broadcom AFBR-S4N44P163 SiPM 4x4 arrays matching one-to-one LYSO pixels 3.86x3.86x15 $mm^3$

AC coupling SiPM - ASIC

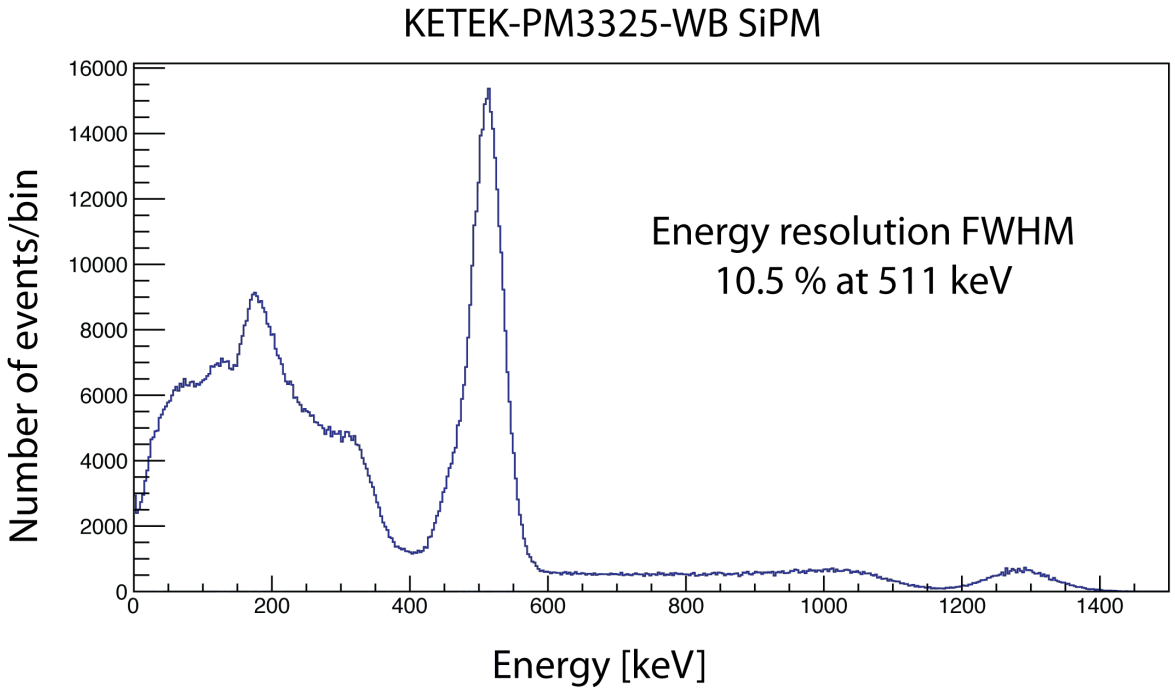
Average CTR = 218 ps FWHM



# Energy resolution with LYSO and TOFPET2

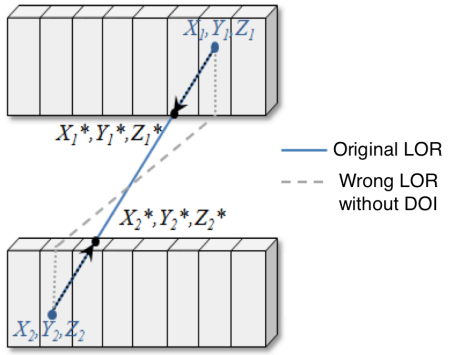
**With Na22 point source** (511 keV photons)

Crystal pixel: 3 x 3 x 5 $mm^3$;
SiPM KETEK PM3325-WB, 13408 cells
4 V over-voltage; temperature 20° C.
After correction for SiPM non-linearity and energy calibration.



# Detector module with DOI capability

→Gamma Depth of Interaction: Parallax error



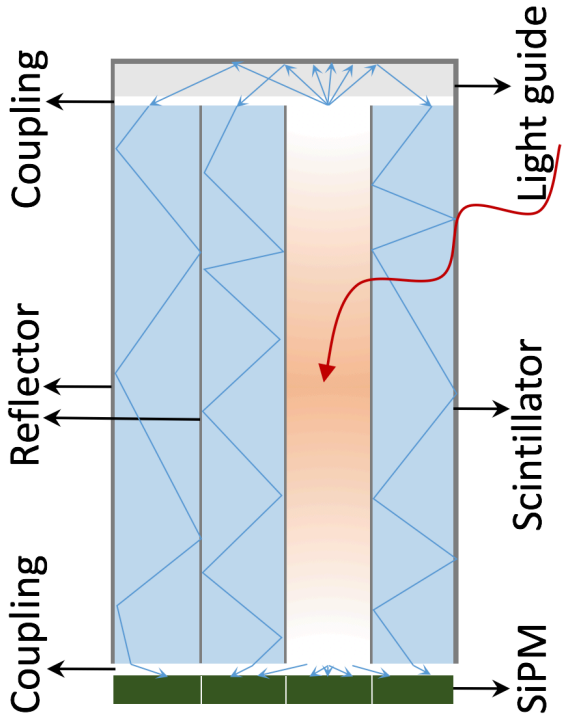

- Common method: Double-sided readout
- New method developed at LIP: Single-sided readout

→ Only one side readout

→ A light guide is placed on the top of the module (same dimension of the matrix).

→ The reflector recirculates the light and redirects it to the MPPC array.

→ Optical treatment of the lateral surfaces of the crystals: depolished

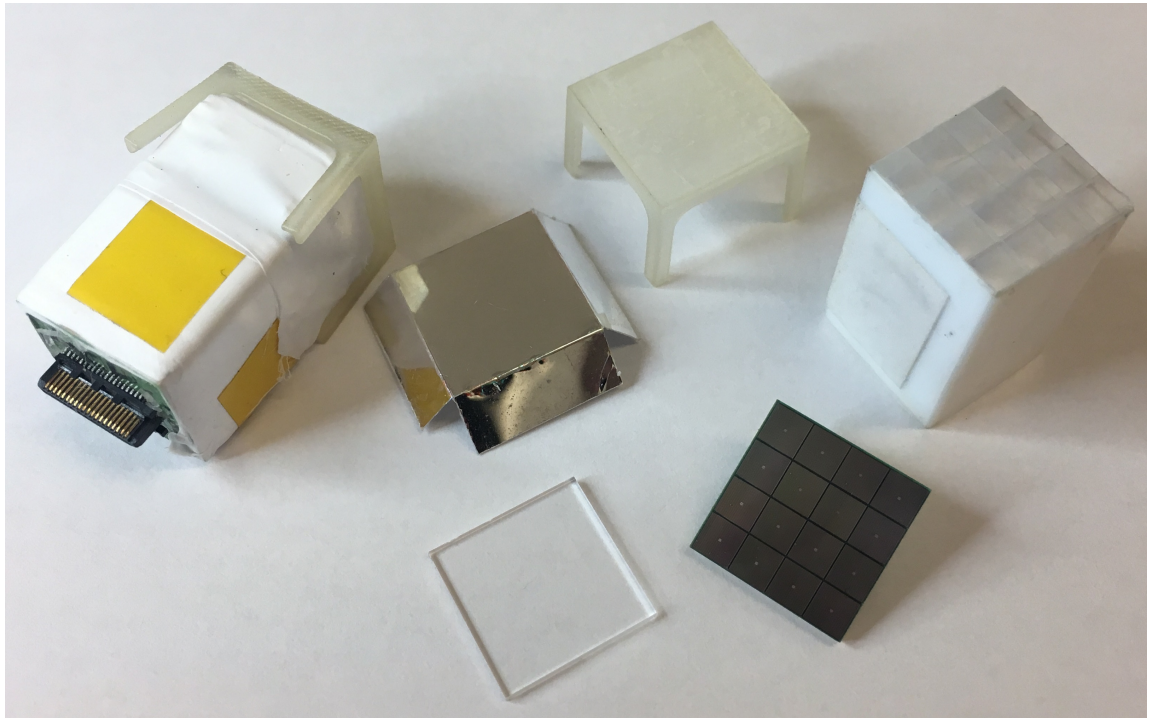



**Patent PCT EP2015/074462**

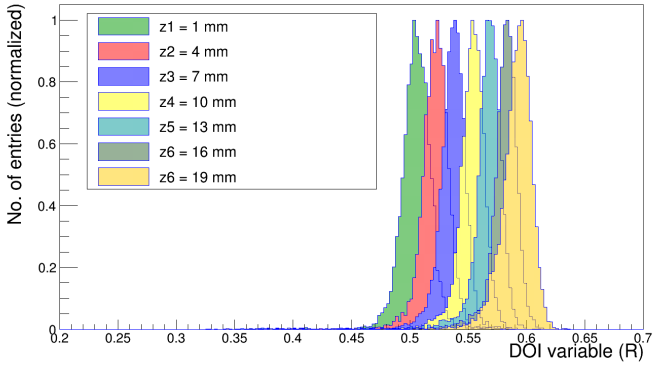
# Detector module characterization

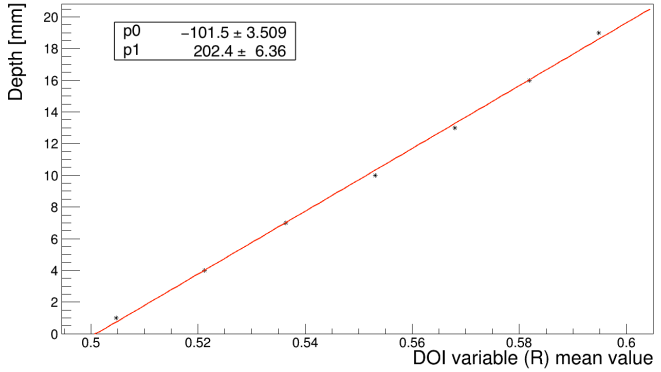
## →Module components

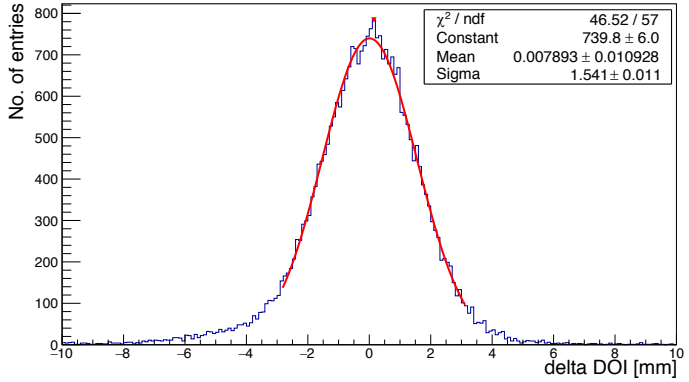
- Array of LYSO
  - $4\times4$ crystal pixels
  - $3.13\times3.13\times20\ mm^3$ each
  - Lateral surfaces depolished
  - Separated by Vikuiti foils
- MPPC from Hamamatsu (S13361−3050AE−04)
  - $4\times4$ channels
  - Channels active area $3\times3\ mm^2$
  - Operated at 55.8 V (OV=3.5 V)
- $1\ mm$ Glass on top
- Optical grease for coupling
- TOFPET2 ASIC
  - Timing information
  - Energy information
- Temperature $18^oC$

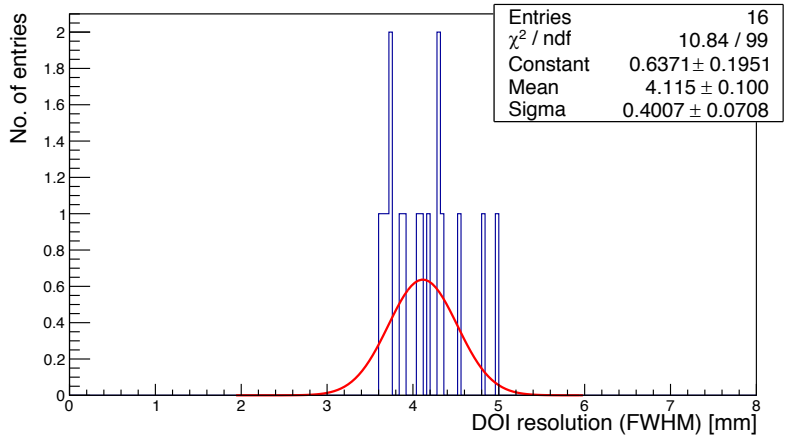


# DOI resolution

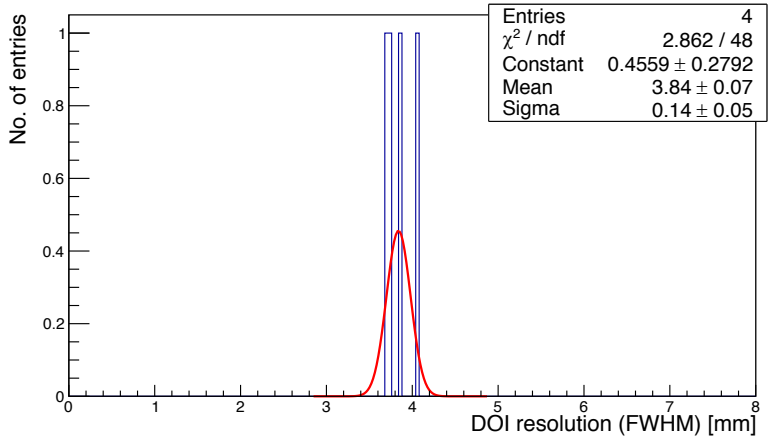


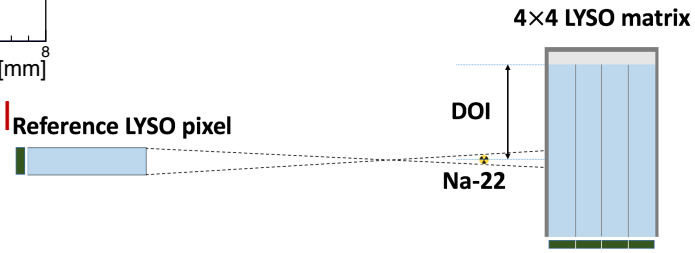




Average DOI resolution over 16 channels = 4.1 mm FWHM




Average DOI resolution over central channels = 3.8 mm FWHM



# Factors affecting Coincidence Timing Resolution (CTR)

→ Readout electronics

→ Photodetector type

→ Crystal type

→ Crystal geometry: Light transport

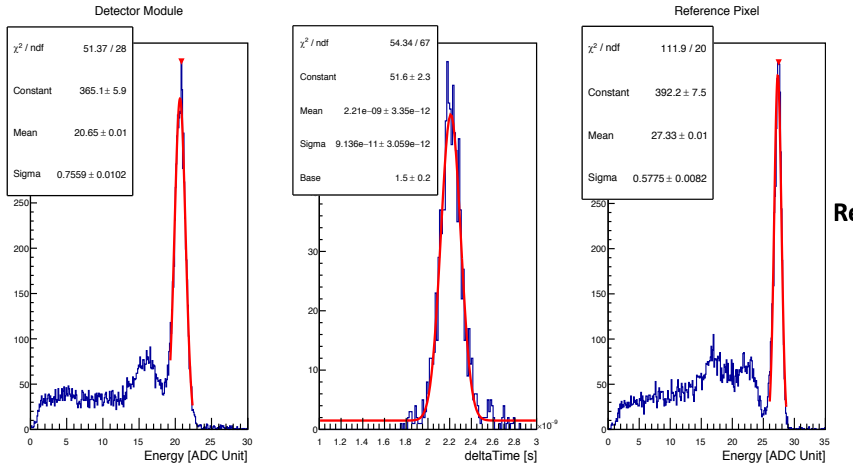


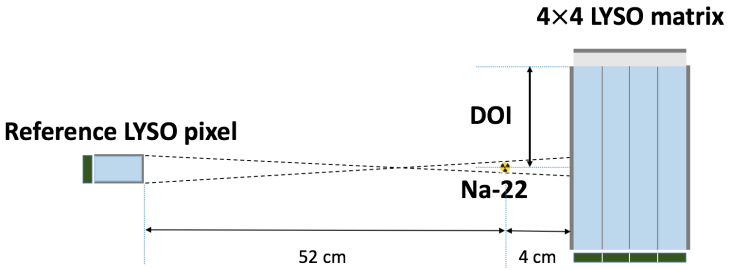


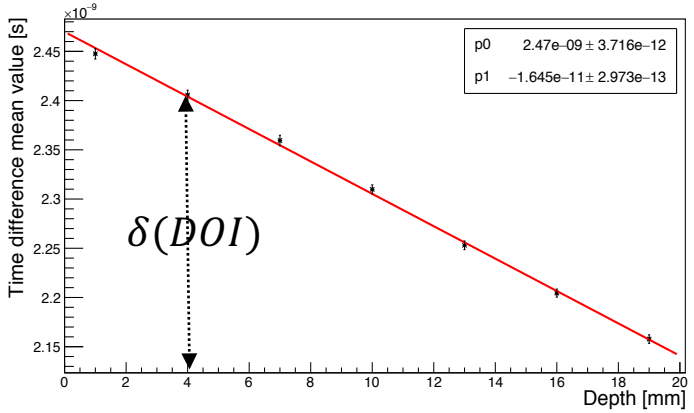
- ❖ Delay in propagation time of photons
- ❖ Time walk
- ❖ Light sharing: $CTR \propto {}^{1}/_{\sqrt{N_{ph}}}$

# DOI correction for time measurement

- → Plot delta time spectrum for coincidence events in each depth
- → Events are within $\pm\sigma$
- → Fit Gaussian and extract mean and sigma
- → Calculate the delay in arrival time of the photon



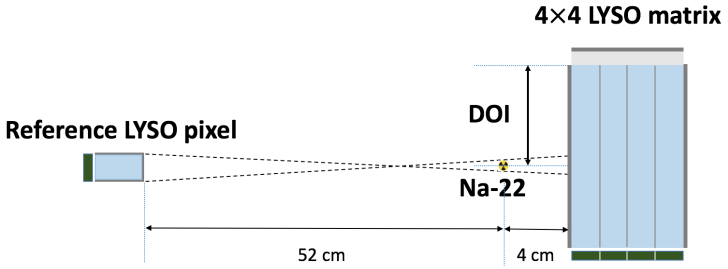

Initial time stamp

$$t_i^{'} = t_i - \delta(DOI)$$

Corrected time stamp

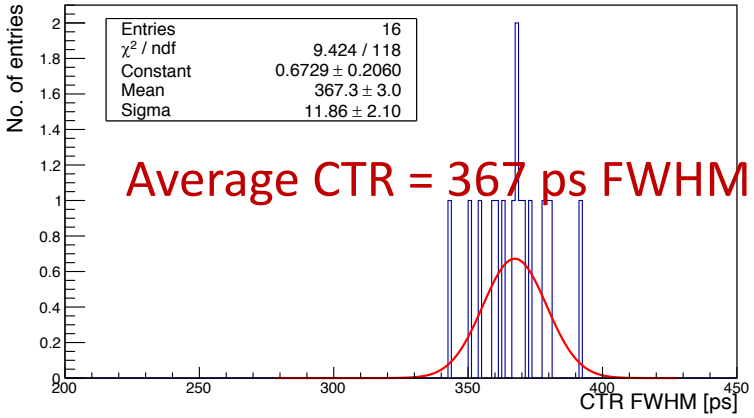
Timing correction as a function of DOI

# DOI correction for time measurement

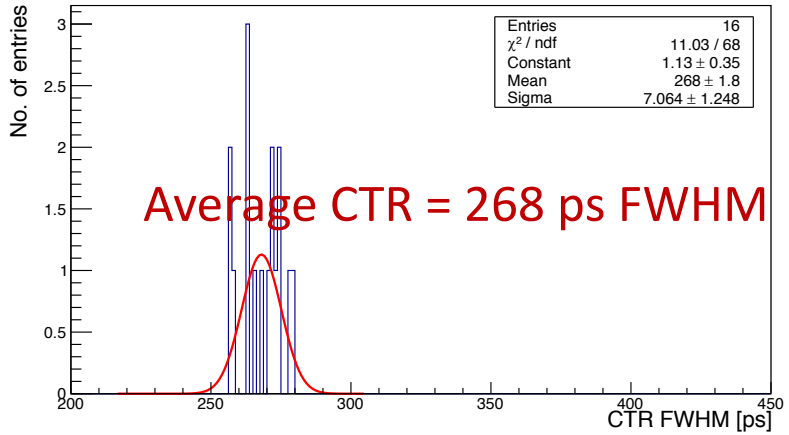



$$\sigma^2 = \sigma^2_{module} + \sigma^2_{ref}$$

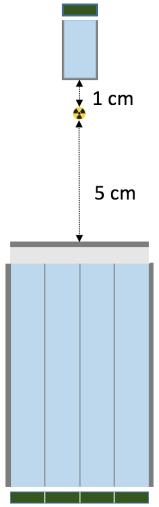
**Before correction**

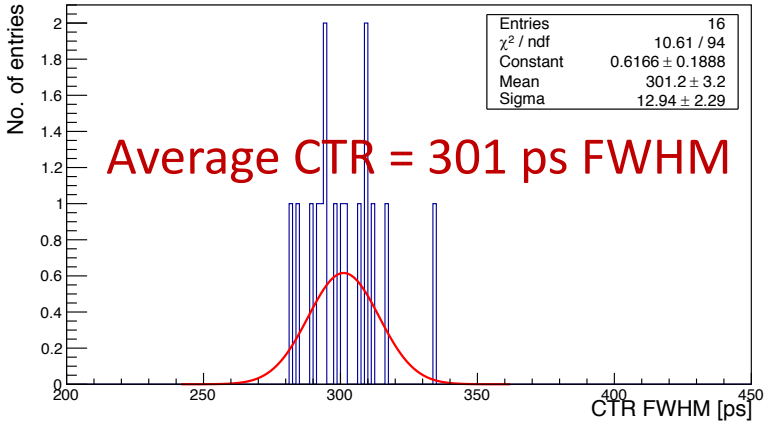


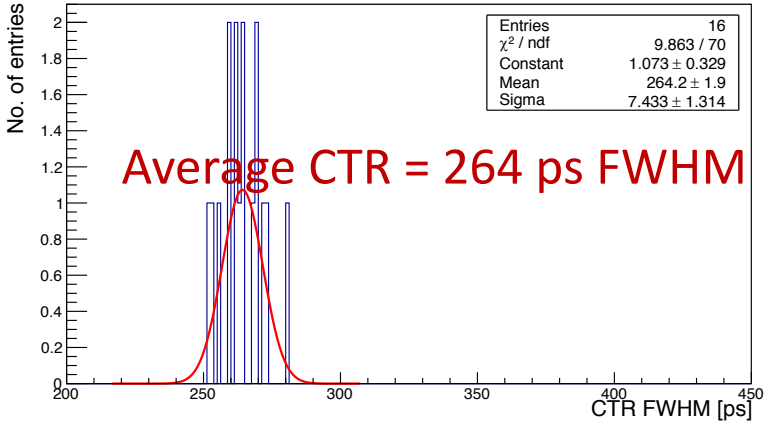

**After correction**




→ CTR of two identical modules sided by side is estimated to be improved from ~472 ps FWHM and ~312 ps FWHM




→ CTR of two identical modules face-to-face is estimated to be improved from ~368ps ps FWHM and ~306 ps FWHM

# Summary and remarks

PETsys Electronics

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- Remarkable set of measurements with TOFPET2, a 64-channel ASIC for SiPM readout and digitization in TOF applications:
  - CTR 127 ps FWHM (w/ LYSO 2x2x3 $mm^3$ ; SiPM array from Broadcom AFBR-S4N44P163)
  - Energy resolution 511 keV = 10.5% (w/ LYSO; SiPM KETEK PM3325)
- Detector module with DOI capability and improved timing resolution
  - DOI resolution 3.8 mm FWHM
  - CTR 306 ps FWHM (w/ 4x4 array of LYSO pixels each 3.13x3.13x20 $mm^3$; 4x4 array of SiPM from Hamamatsu)
- More than 50 groups are using our electronics (PET and HEP applications)
- 2 groups built a real scanner with TOFPET1 ASIC, now upgrading to TOFPET2 (Bruker and TUM)

# Achievements (2016-2018)

- ✓ **2 Patents**
- ✓ **7 published peer-reviewed papers + 1 under review**
- ✓ **International conferences:**
  - **~ 25 talks**
  - **7 posters**

PETsys Electronics

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# Thank you for your attention