A method for time calibration of PET systems using fixed beta-plus radioactive source

KAMIL DULSKI

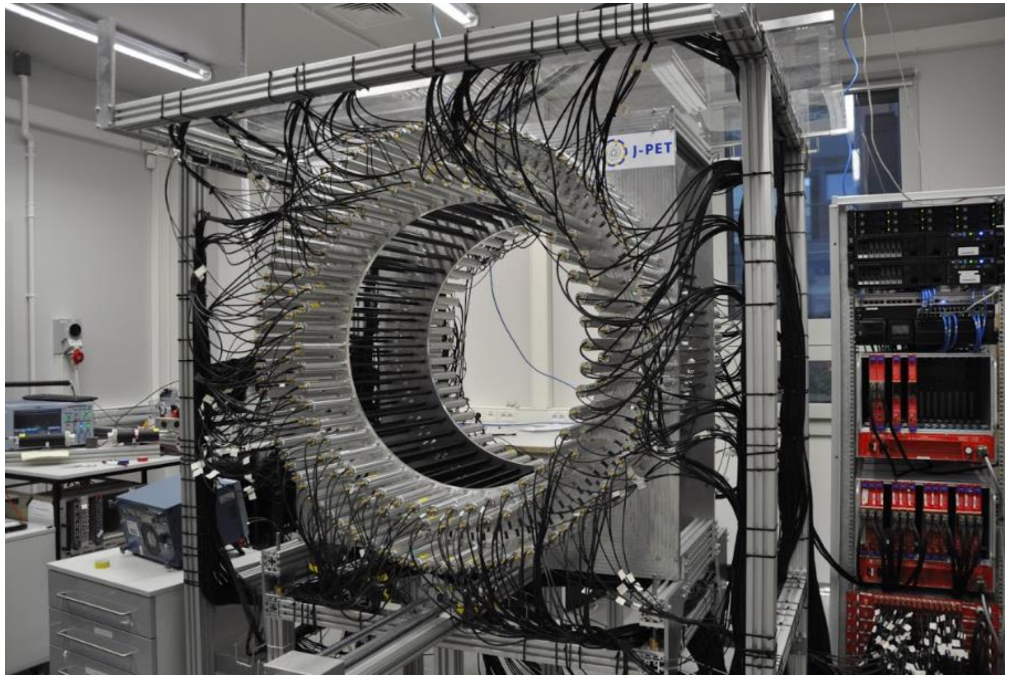
ON BEHALF OF THE J-PET COLLABORATION

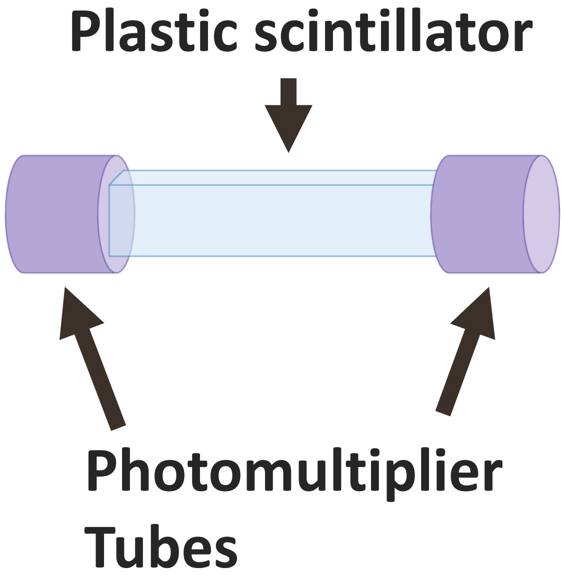
3RD JAGIELLONIAN SYMPOSIUM ON FUNDAMENTAL AND APPLIED SUBATOMIC PHYSICS

Outline

1. J-PET – TOF-PET system
2. Calibration of TOF-PET systems – established methods
3. Calibration of a single module of J-PET
4. Calibration between modules

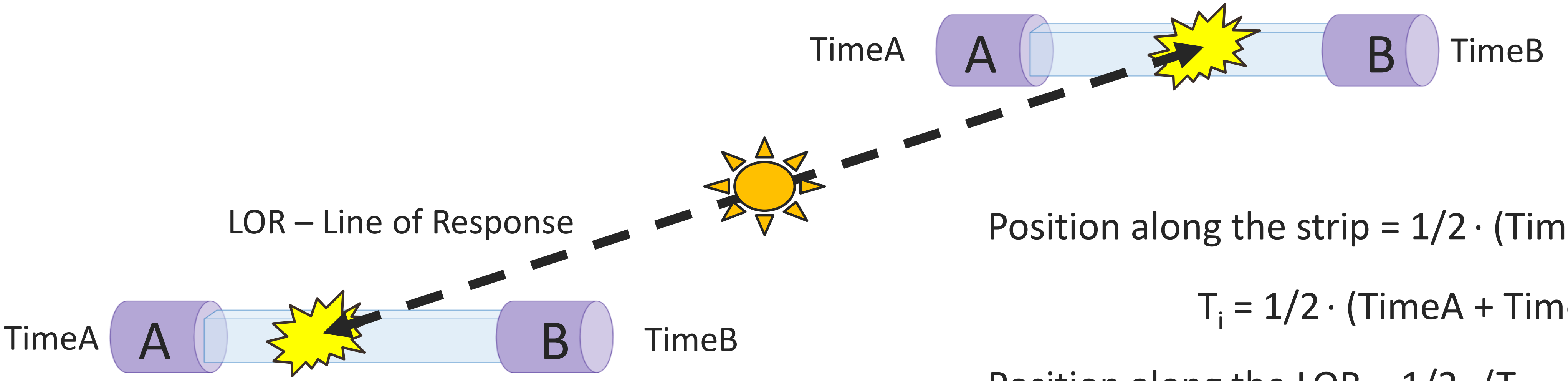
J-PET – (Time-Of-Flight) TOF-PET system





192 x Plastic scintillator → **384 x Photomultiplier Tubes**

Principle of position reconstruction



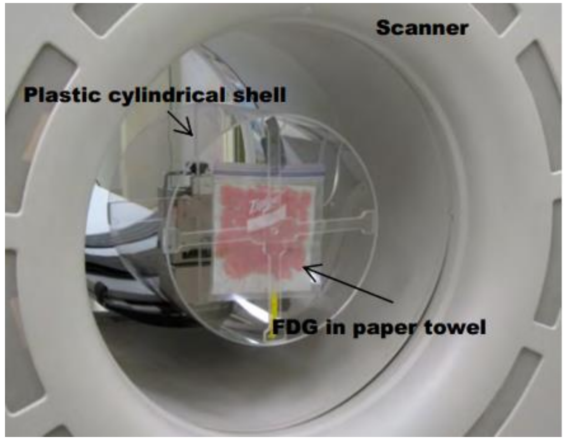
Position along the strip = $1/2 \cdot (\text{TimeA} - \text{TimeB}) \cdot V_{scint}$

$T_i = 1/2 \cdot (\text{TimeA} + \text{TimeB})$

Position along the LOR = $1/2 \cdot (T_1 - T_2) \cdot c$

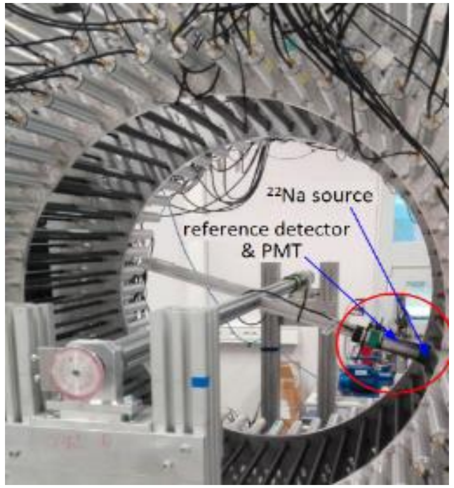
Reconstruction of position of the hit based on the time difference between signals → **384 modules to calibrate with each other**

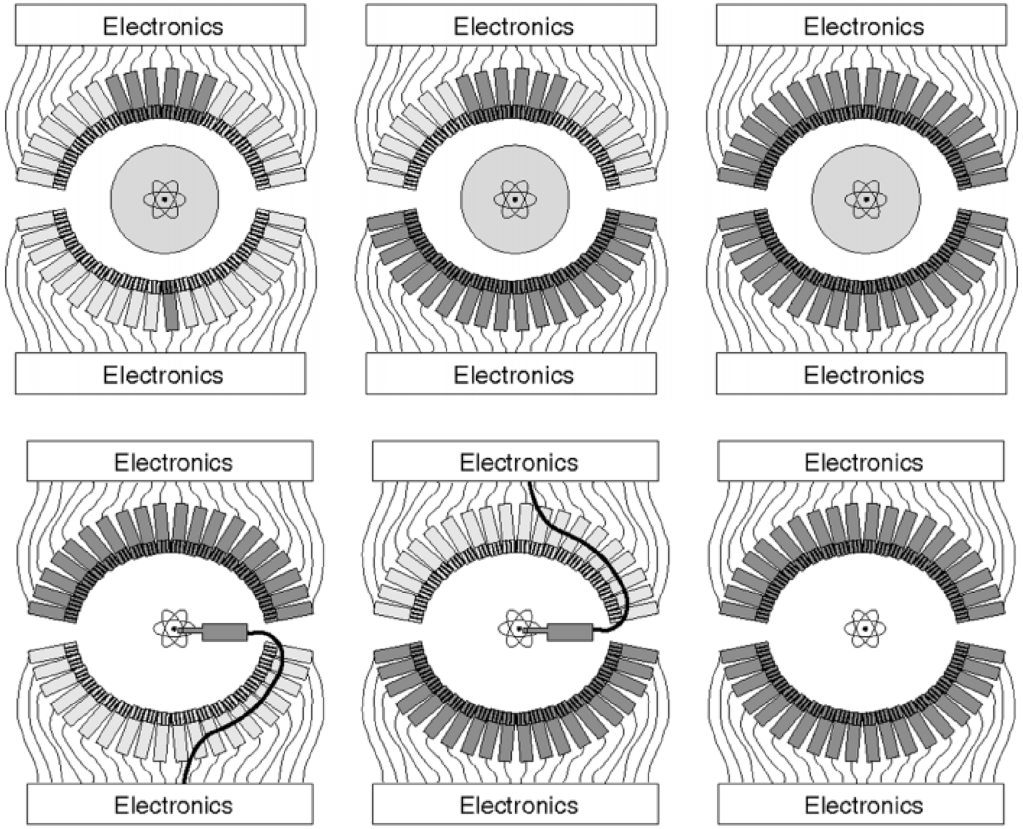
Calibration of TOF-PET systems - established methods



Large phantom:
Needs additional measurement,
with large phantom
to cover many LORs

Reference rotating system:
Needs additional measurement,
that scans over all detectors

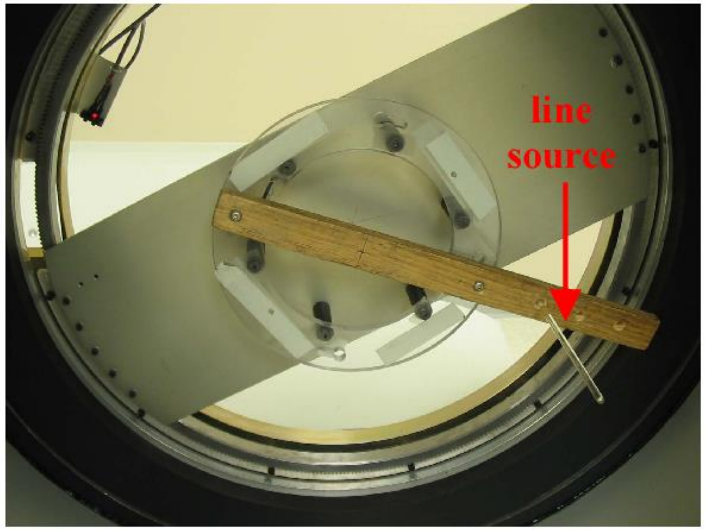


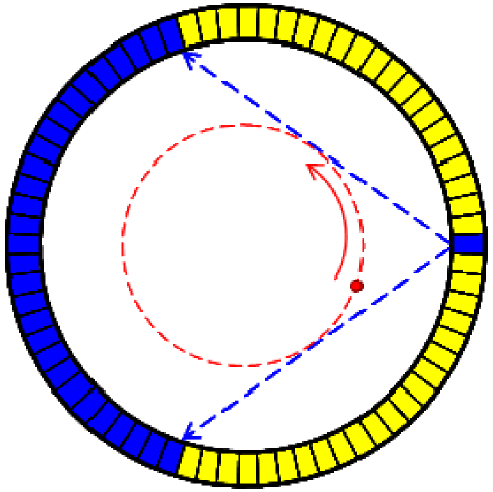


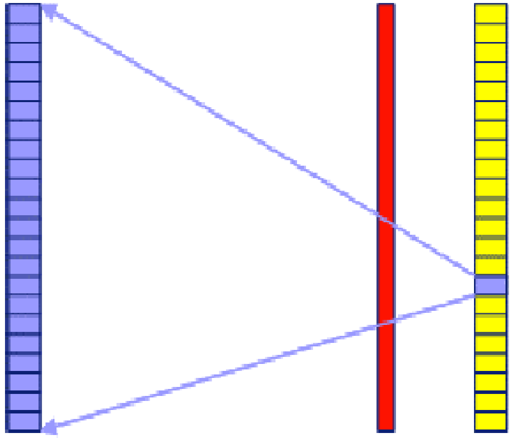
Xiaoli Li et al., IEEE Transactions on Nuclear Science 63, 3 (2016)
W. W. Moses and C. J. Thompson, IEEE Transactions on Nuclear Science 53, 5 (2006)
M. Skurzok et al., Acta Phys. Polon. A 132, 5 (2017)

Calibration of TOF-PET systems - established methods

Rotating radioactive rod:
Needs additional measurement, that scans over all LORs







A. E. Perkins, M. Werner, et al., IEEE Nucl. Sci. Symp. Conf. Rec., pp. 2488-2491, 2005

Performed measurement

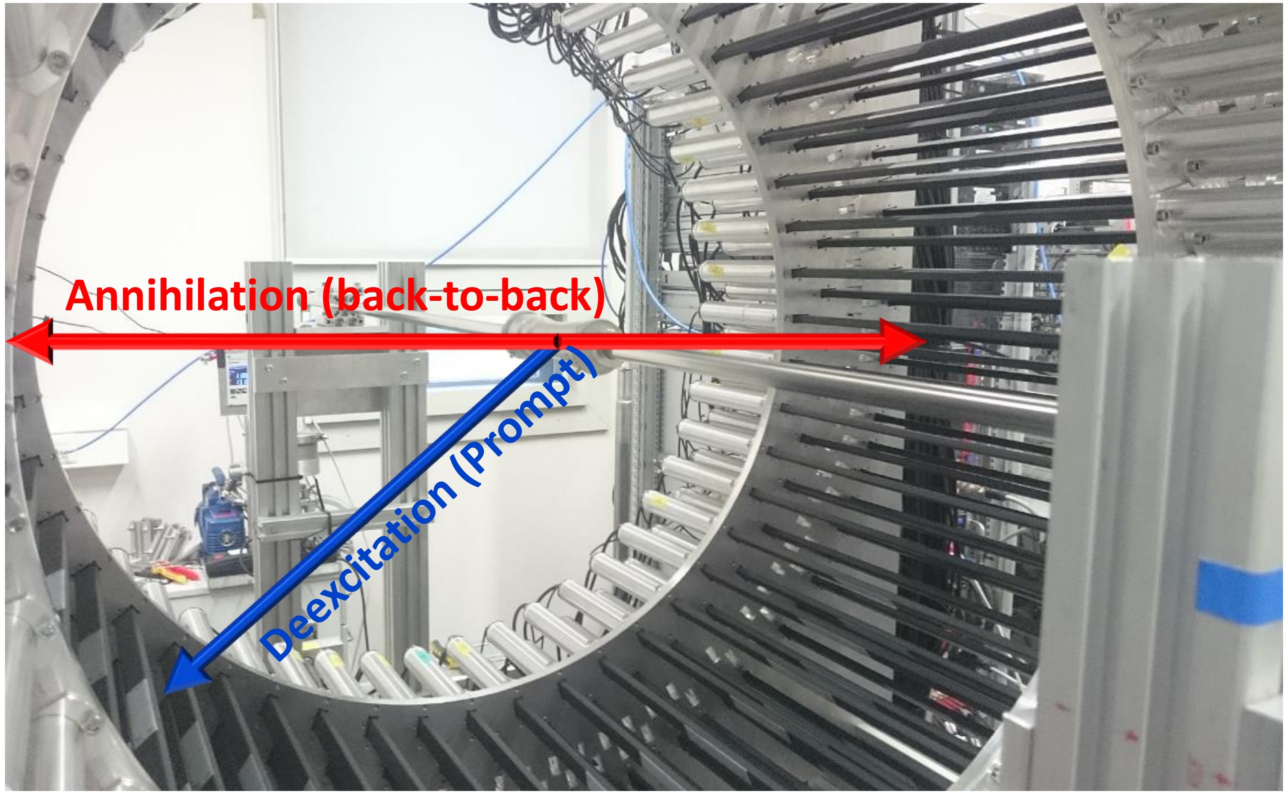
^{22}Na source (1 MBq acitivity) in Kapton foil was placed between two layers of XAD4[1] (porous polymer) and inserted inside aluminum chamber. Chamber was placed inside J-PET, in the center of the detector. Measurement done to study Positronium Annihilation in XAD4.

Calibration measurement details:

- Fixed source in the center
- Calibration based on prompt + annihilation quanta

[1] https://www.sigmaaldrich.com/content/dam/sigma-aldrich/docs/Sigma/Product_Information_Sheet/1/xad4pis.pdf

Performed measurement



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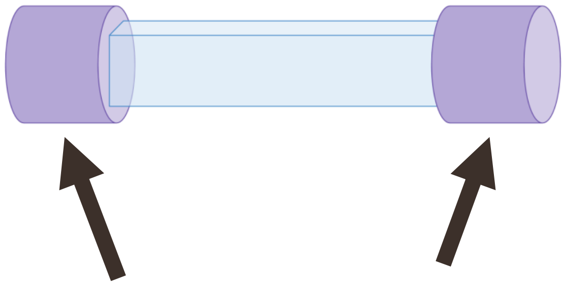
Calibration procedure

1st step:
Calibrating Photomultipliers tubes, connected to one scintillator with each other

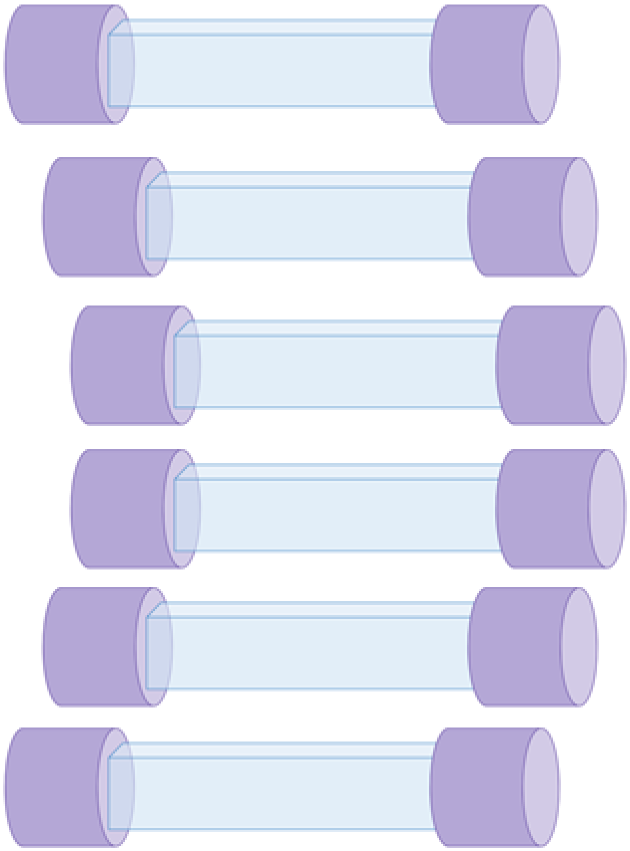
Modules calibrated



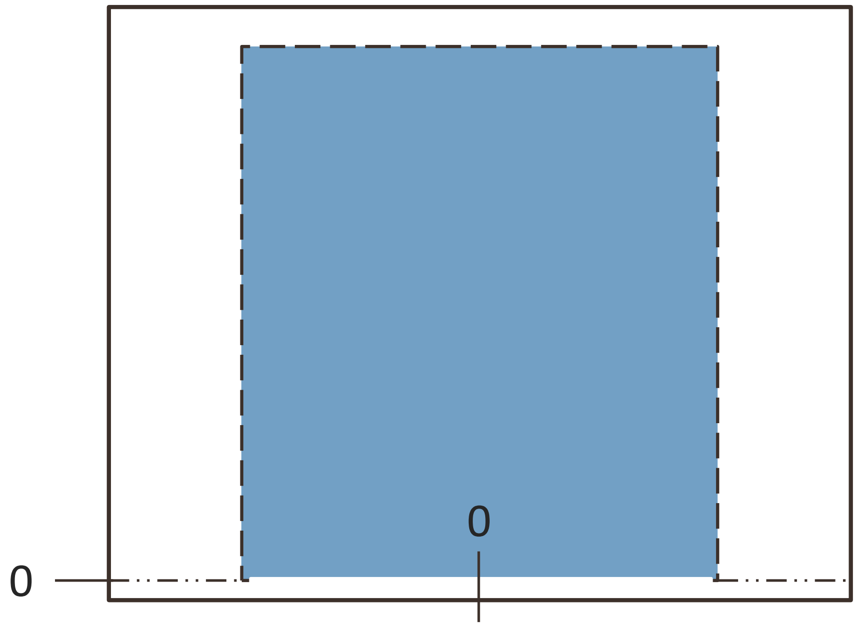
Photomultiplier Tubes

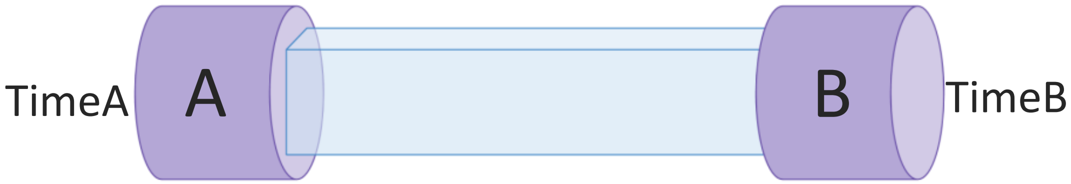
2nd step:
Calibrating all modules with each other at once

Detector calibrated



Calibration of a single module of J-PET



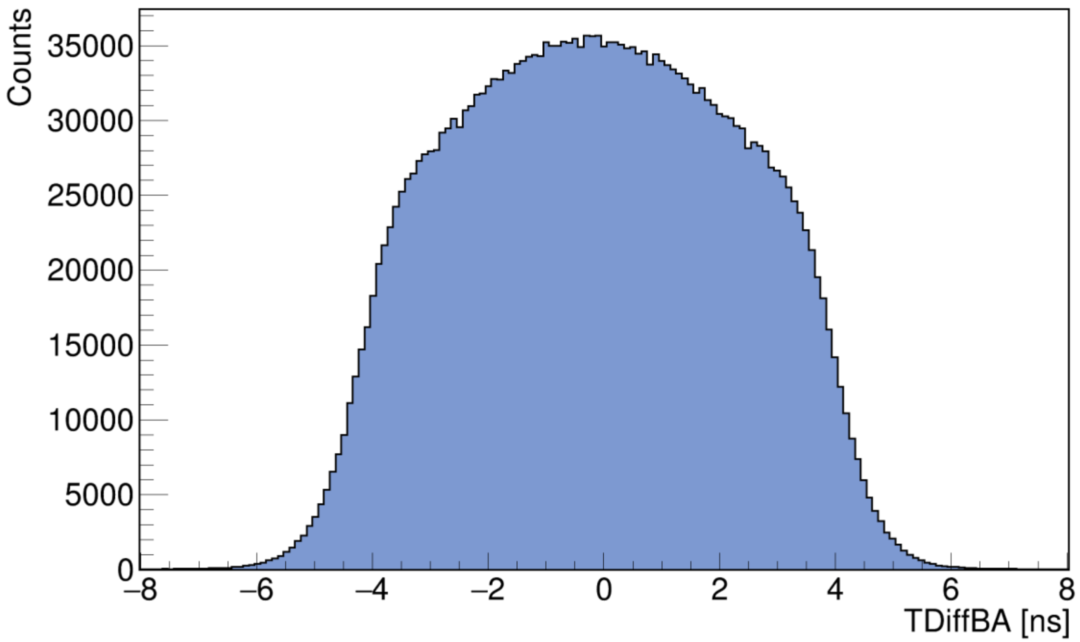


Perfect situation:
- Perfect time resolution
- Uniform irradiation of the strip

Rectangular distribution of Time differences

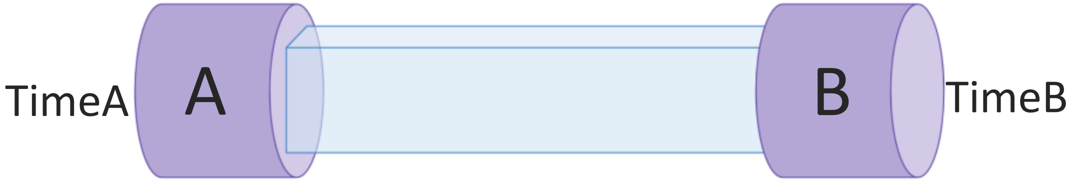
TDiffBA = TimeA - TimeB

Calibration of a single module of J-PET

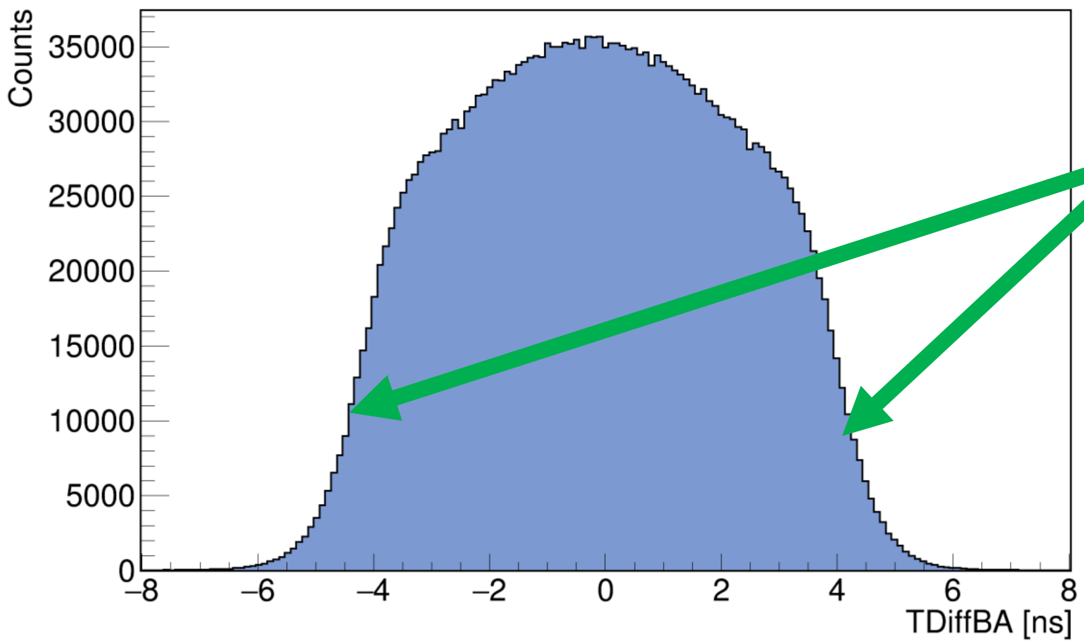


Real situation:
- Gauss-like smearing of photomultiplier
- Cosine squared distribution of irradiation for source in the center of the detector

TDiffBA = TimeA - TimeB

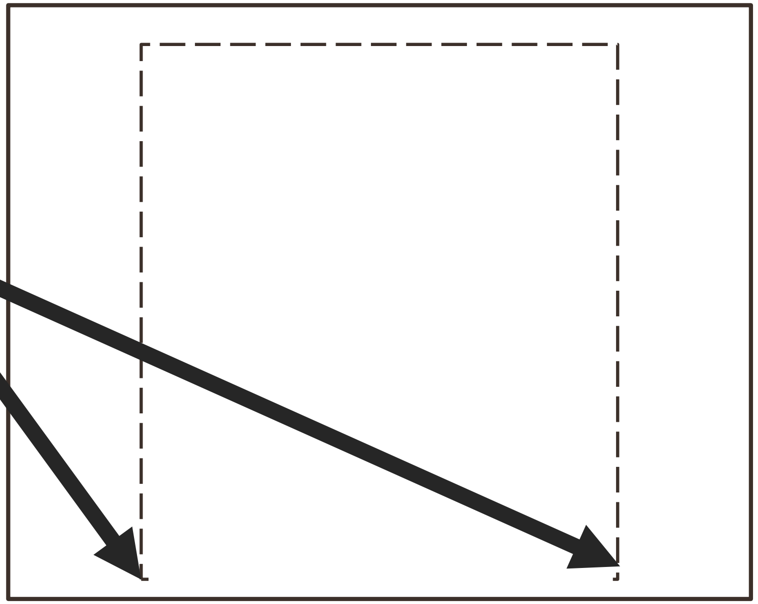


Calibration of a single module of J-PET



MiddleEdgeLeft **MiddleEdgeRight**

Taking the middles of these edges as the estimates of real edges



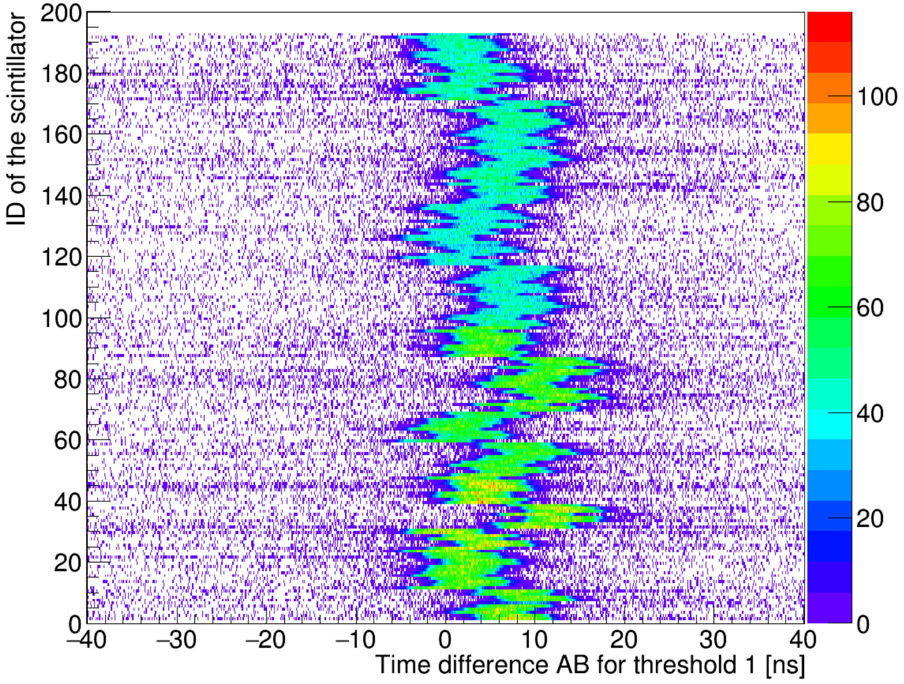
1 module (scintillator + 2 Photomultipliers) are treated as calibrated if

MiddleEdgeRight + MiddleEdgeLeft = 0

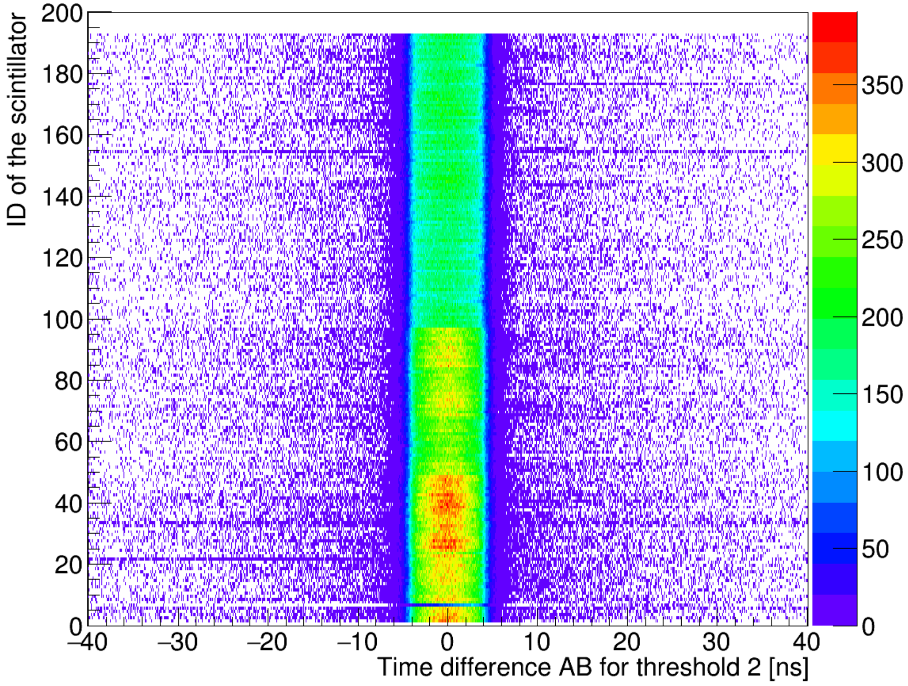
Middle calculated as a zero of a second derivative (point of inflection)

Calibration of a single module

No calibration



After calibration



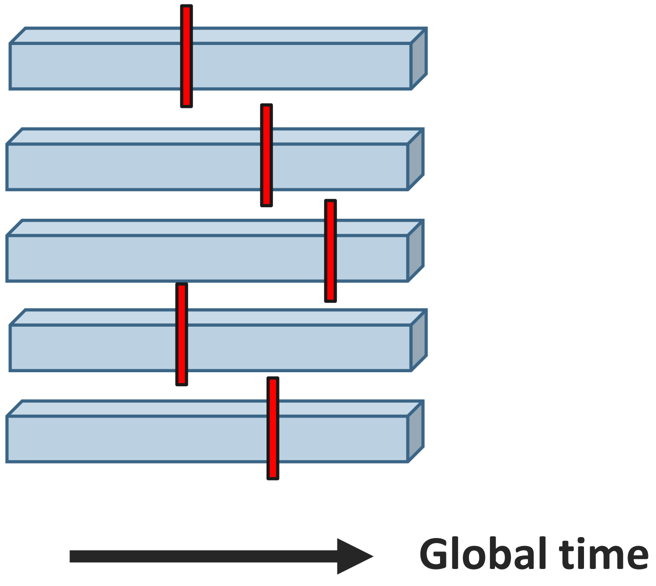
$TimeA_{new}$ = $TimeA_{old}$ – (MiddleEdgeRight – MiddleEdgeLeft)/2

$TimeB_{new}$ = $TimeB_{old}$

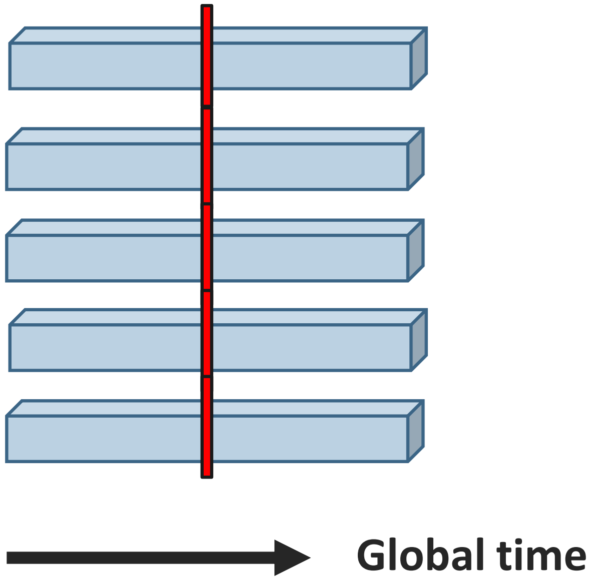
TDiffAB = TimeA - TimeB

Intermediate status

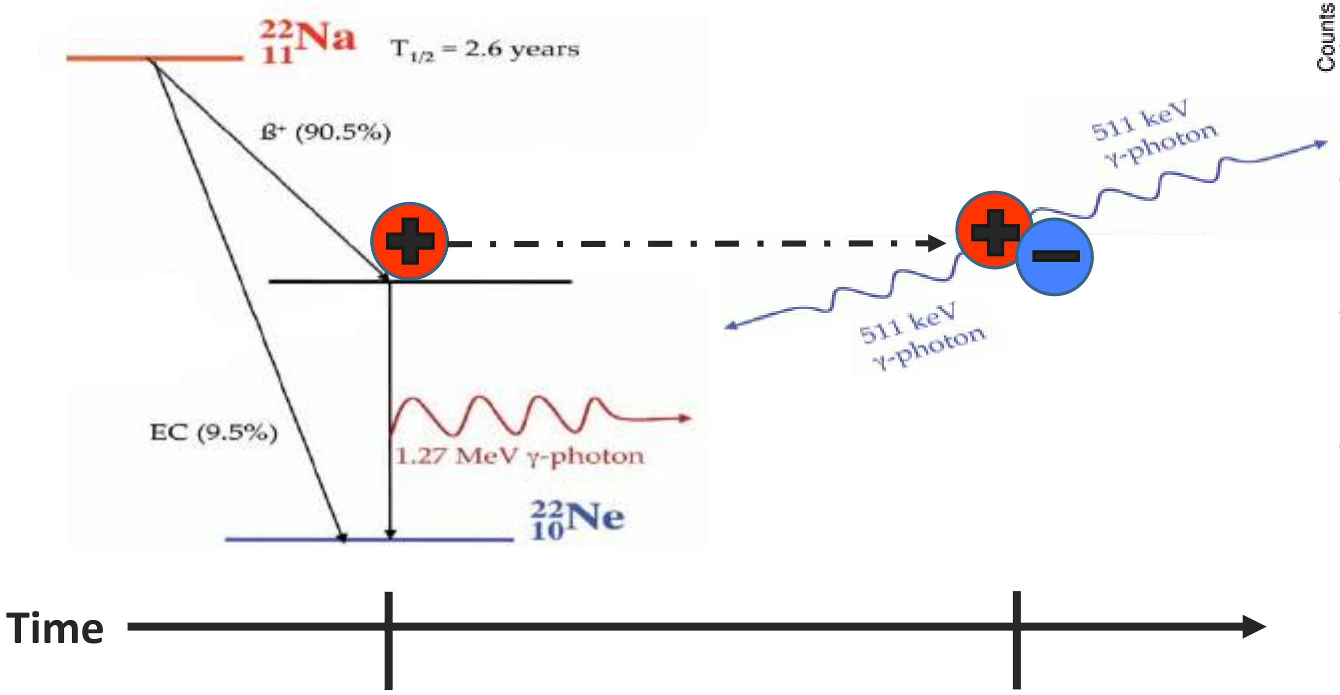
Each module working in their own domain



All modules working in one domain

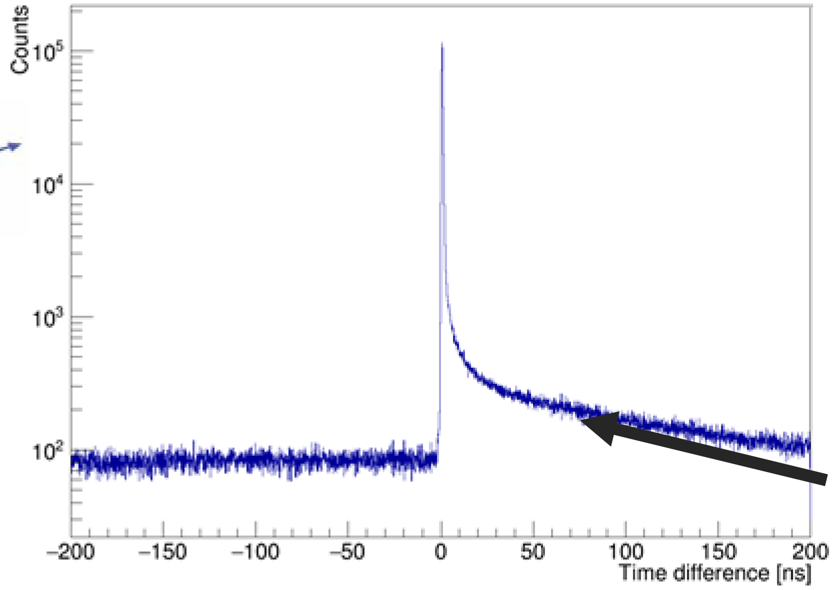


^{22}Na decay + Positronium



Time of deexcitation
= T_{Deex}

Time of annihilation
= T_{Anni}

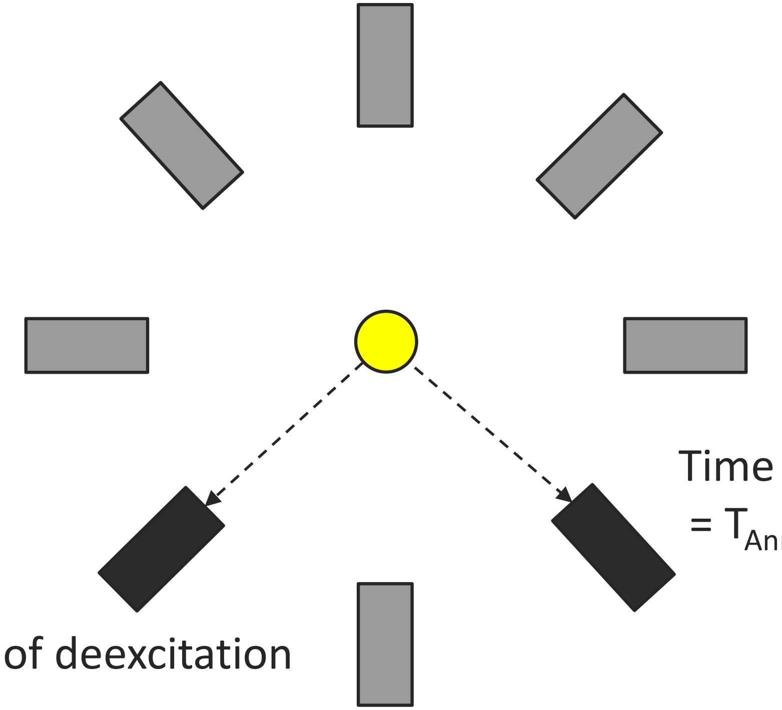


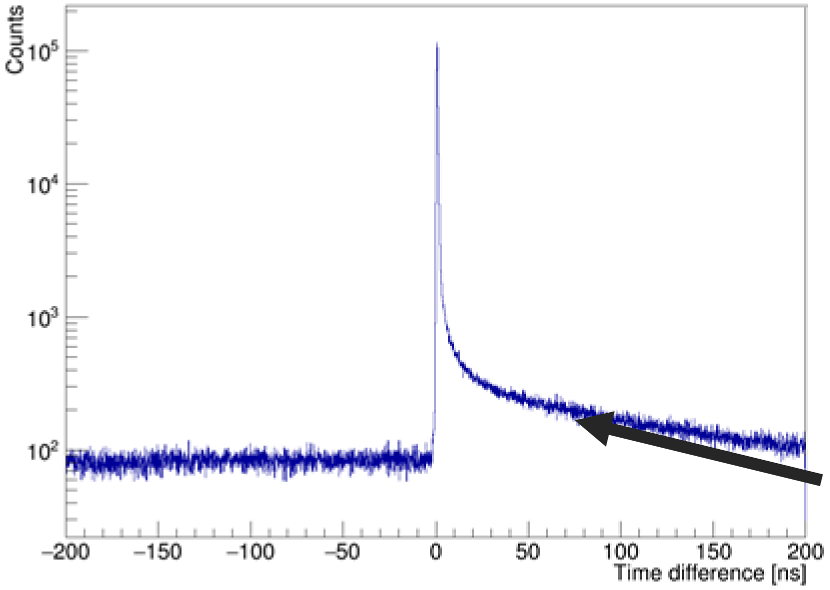
Calibration scan made for ^{22}Na source in Kapton foil with XAD4.

Mean Lifetime of Positronium in XAD4 ≈ 90 ns

Estimate of the lifetime of positronium
Time difference = T_{anni} - T_{Deex}

^{22}Na decay + Positronium





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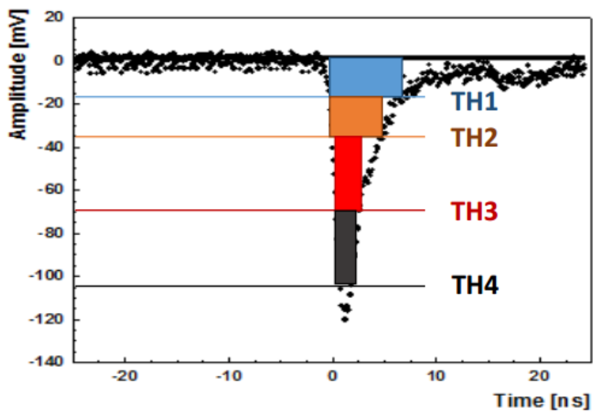
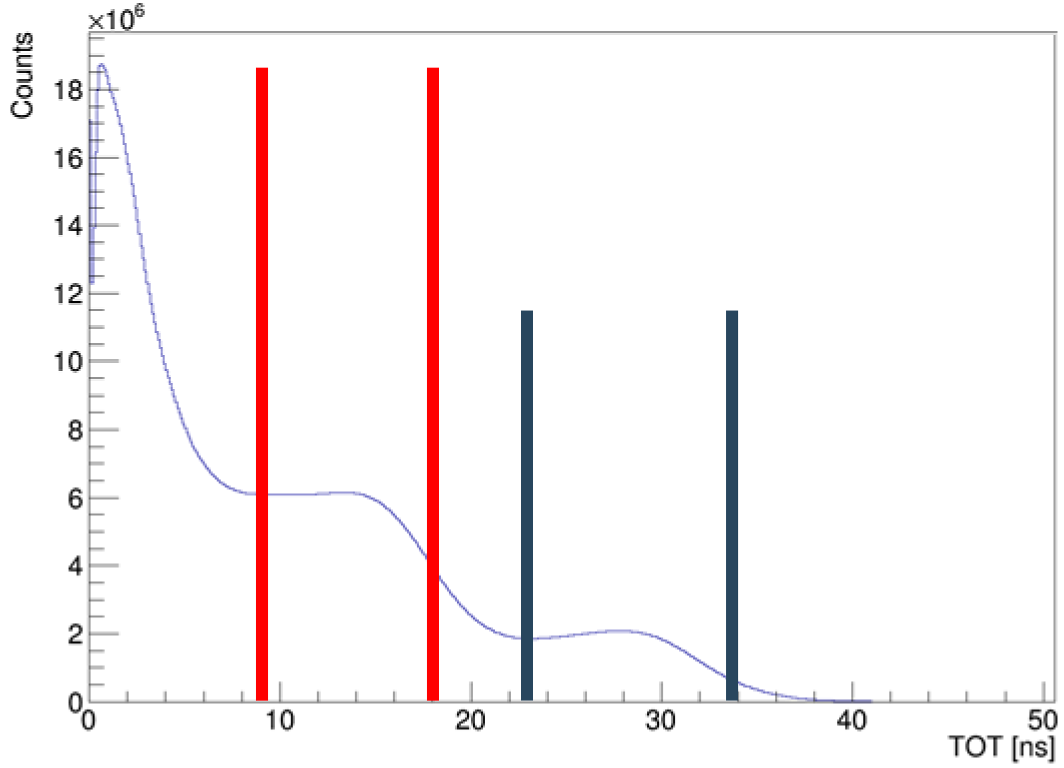
^{22}Na decay + Positronium

Condition to fulfill:
- 1 **Deexcitation** gamma quantum
- 1 **Annihilation** gamma quanta

Proceeding:
- Distinction of the origin of the registered gamma quantum



Area under signal depends on the deposited energy

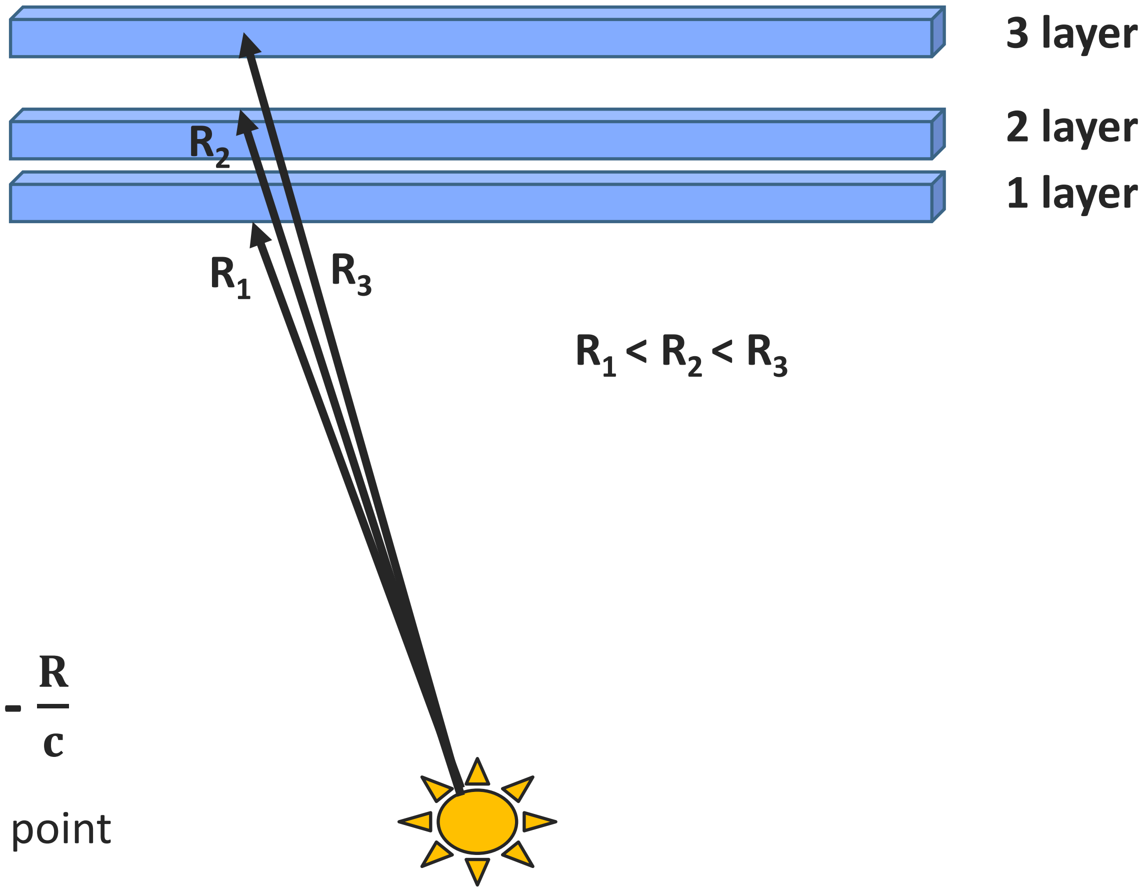


TOT (Time over Threshold) – Sum of widths of signal on 4 thresholds

Correction on Time-of-Flight (TOF)

Condition to fulfill:
- 1 **Deexcitation** gamma quantum
- 1 **Annihilation** gamma quanta

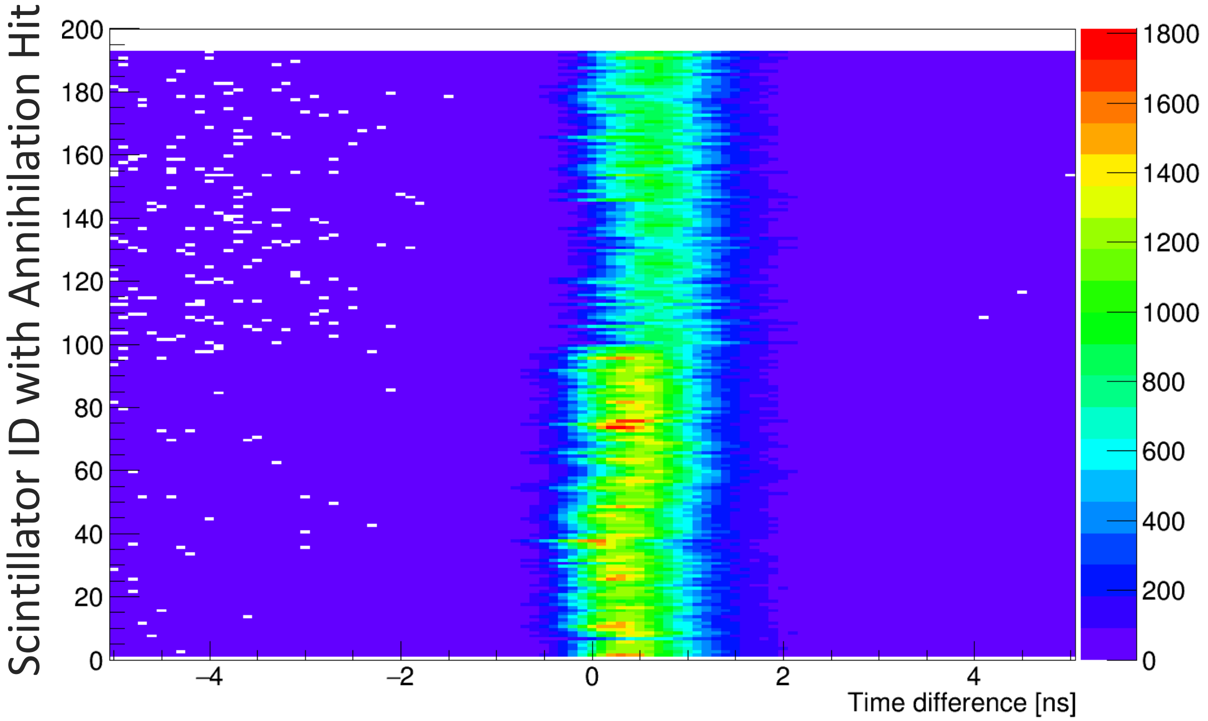
Proceeding:
- Distinction of the origin of the registered gamma quantum
- 1 Annihilation + 1 Deexcitation
- Times of the Hits corrected on Time-Of-Flight

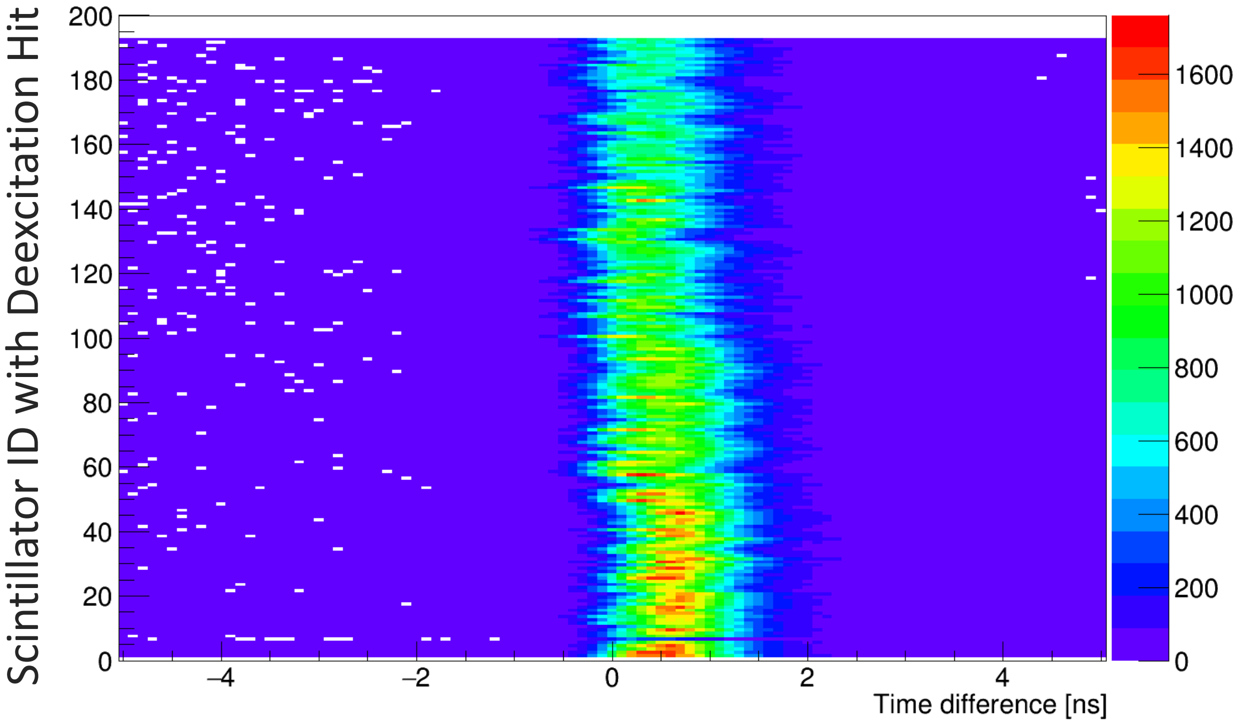


$$\mathbf{Time_{new} = (Time_{sideA} + Time_{sideB})/2 - \frac{R}{c}}$$

R – Distance from the position of the source and the registration point
c – speed of light in vaccum

Calibration between modules

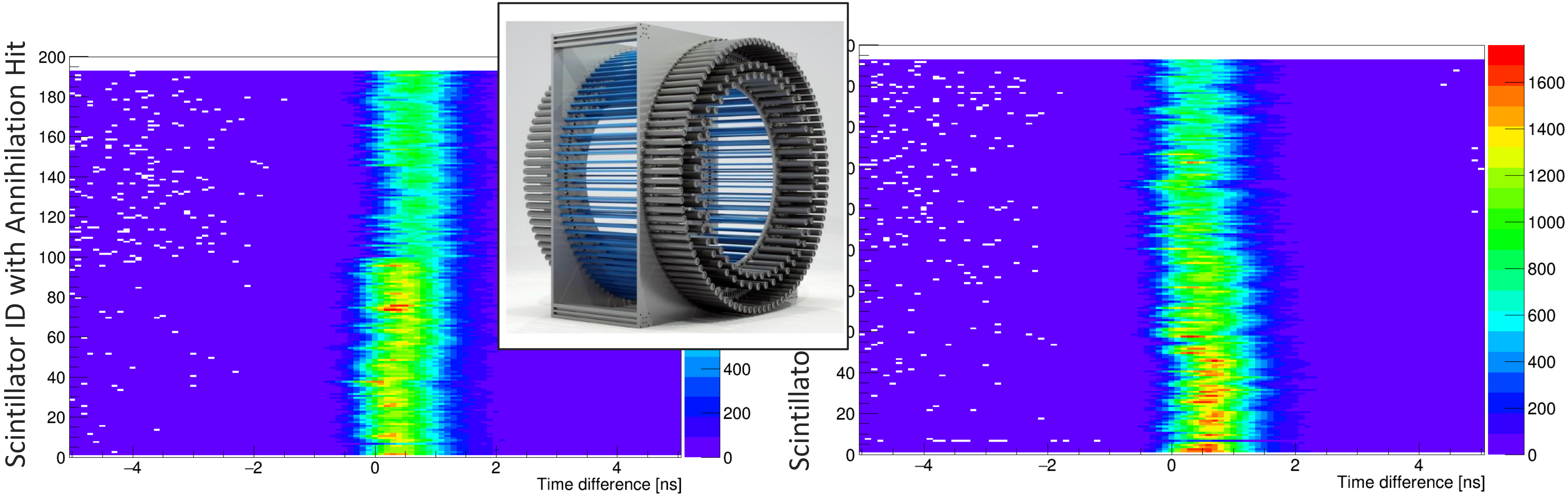




Positronium Lifetime spectrum should not depend on the pair of modules that were hit (if all are calibrated)

And most important which scintillator Annihilation/Deexcitation gamma quantum hit

Calibration between modules

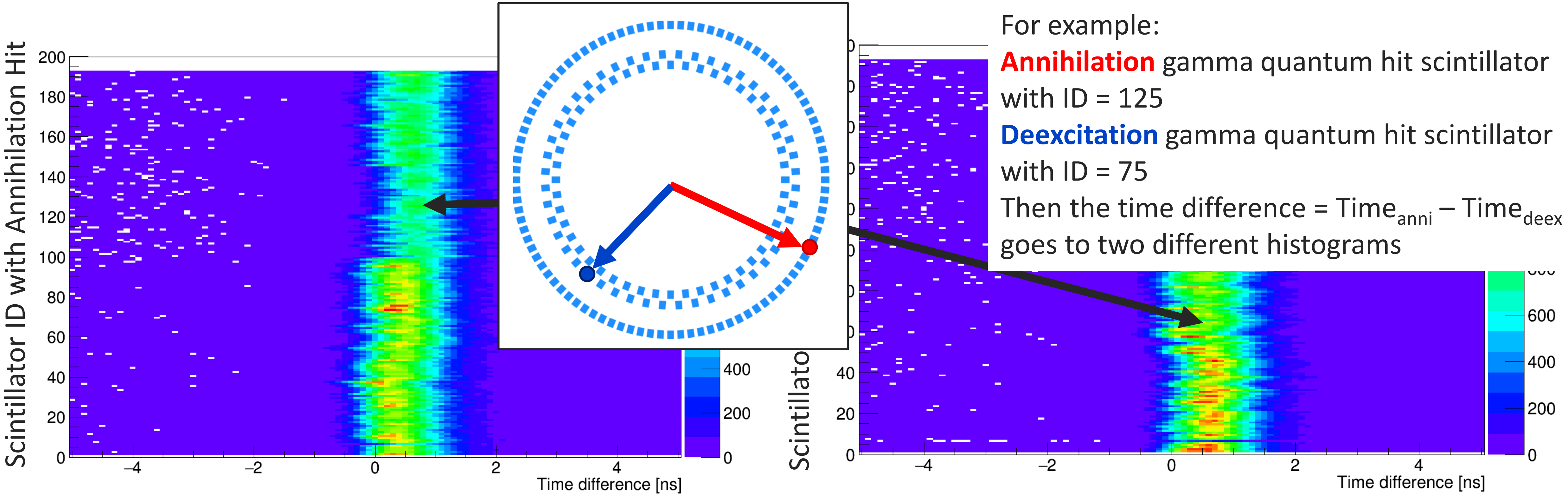


Positronium Lifetime spectrum should not depend on the pair of modules that were hit (if all are calibrated)

And most important which scintillator Annihilation/Deexcitation gamma quantum hit

Calibration between modules

For example:
Annihilation gamma quantum hit scintillator with ID = 125
Deexcitation gamma quantum hit scintillator with ID = 75
Then the time difference = $Time_{anni} - Time_{deex}$ goes to two different histograms



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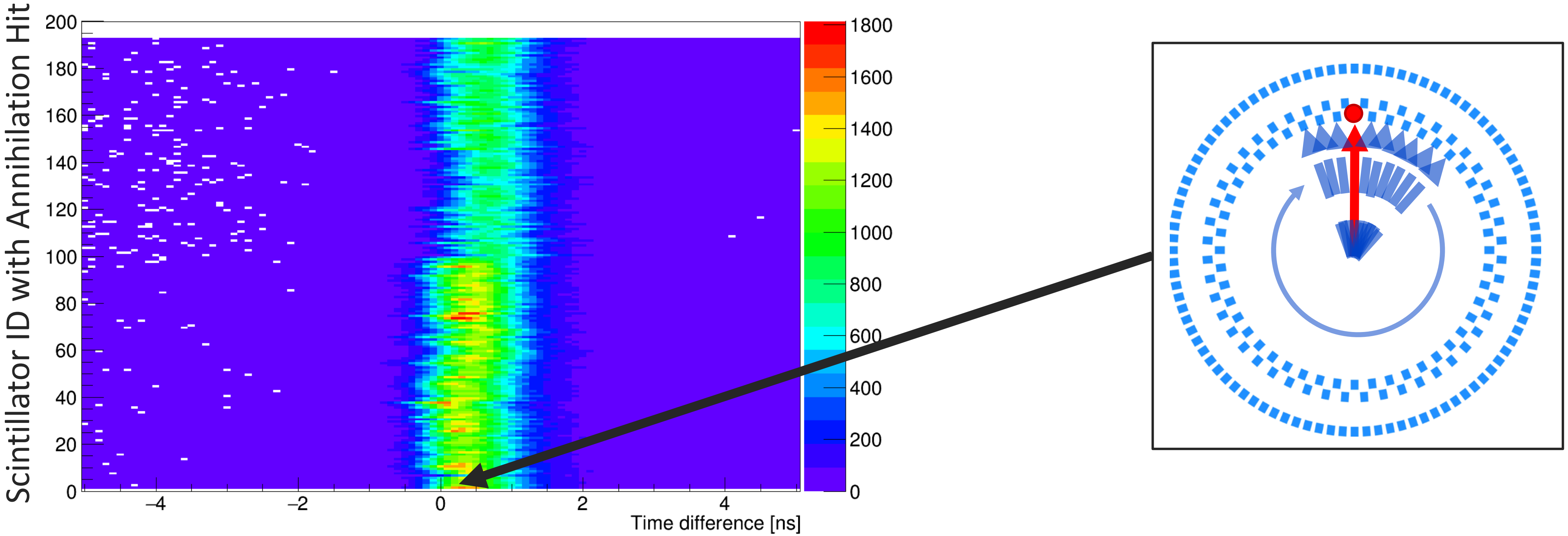
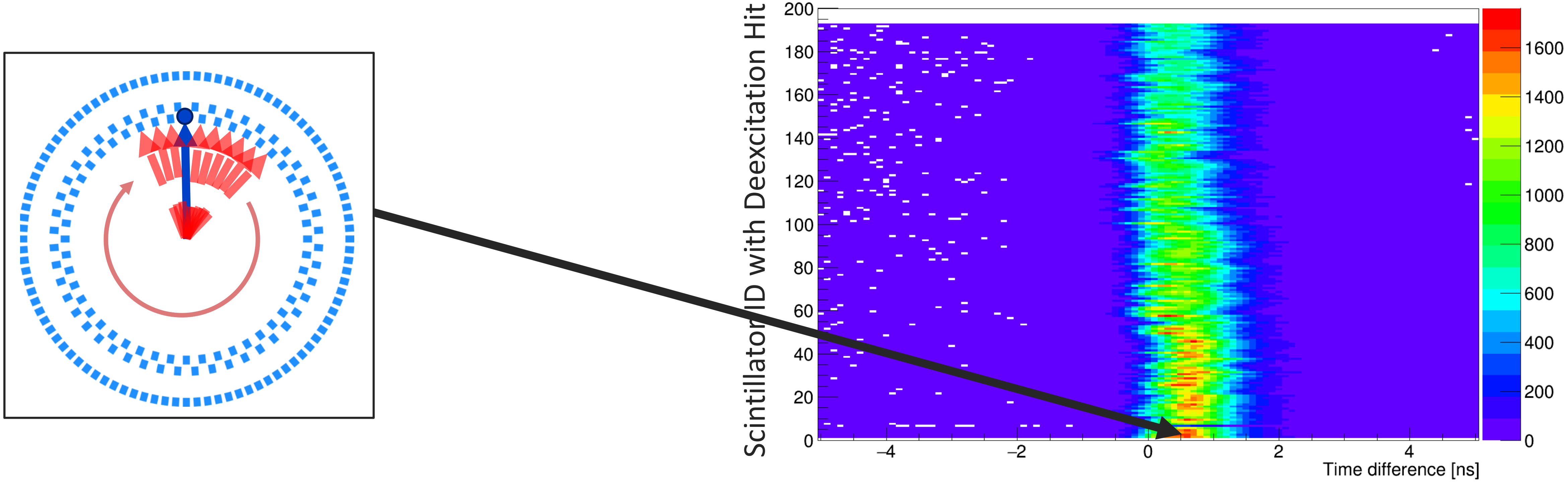
Calibration between modules



Focusing attention on one ID = 1.

Every event in which Annihilation gamma quantum hit scintillator with ID = 1

Calibration between modules

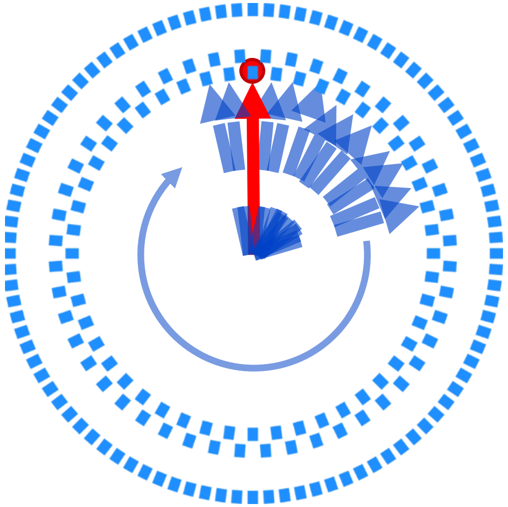


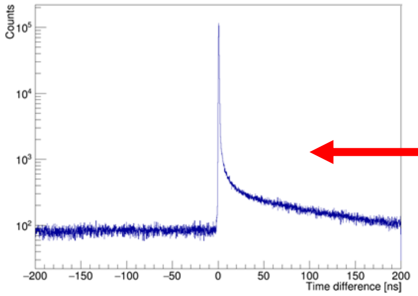
Focusing attention on one ID = 1.

Every event in which Deexcitation gamma quantum hit scintillator with ID = 1

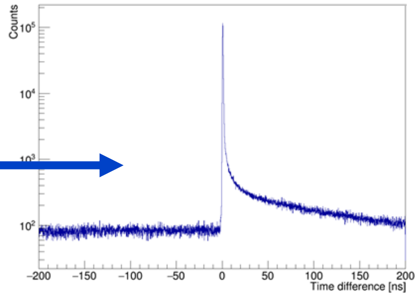
Calibration between modules

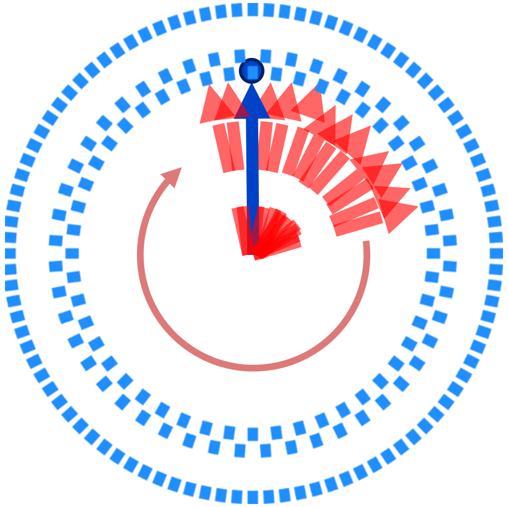
For one given ID of the scintillator we will have two histograms for consideration





In perfect situation **these** will be the same





For given Annihilation ID:

For given Deexcitation ID:

$(Time_{Anni} + CalibConstant_{ID}) - (Time_{Deex} + MeanCalibConstant) =$ **Time difference** $= (Time_{Anni} + MeanCalibConstant) - (Time_{Deex} + CalibConstant_{ID})$

Calibration between modules

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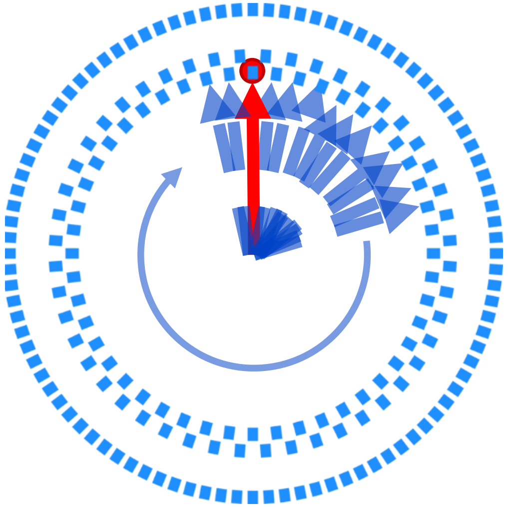
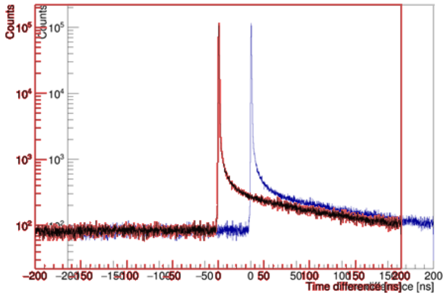
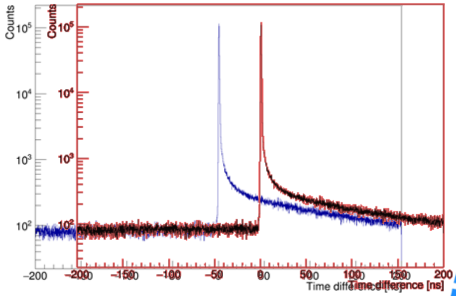
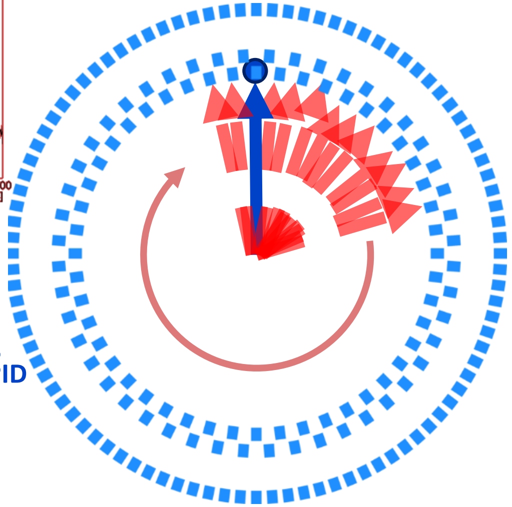




If there is some miscalibration **spectra** will be **shifted**





$CalibConstant_{ID}$ - MeanCalibConstant

MeanCalibConstant - $CalibConstant_{ID}$

For given Annihilation ID:

For given Deexcitation ID:

$(Time_{Anni} + CalibConstant_{ID}) - (Time_{Deex} + MeanCalibConstant) =$ **Time difference** $= (Time_{Anni} + MeanCalibConstant) - (Time_{Deex} + CalibConstant_{ID})$

Calibration between modules

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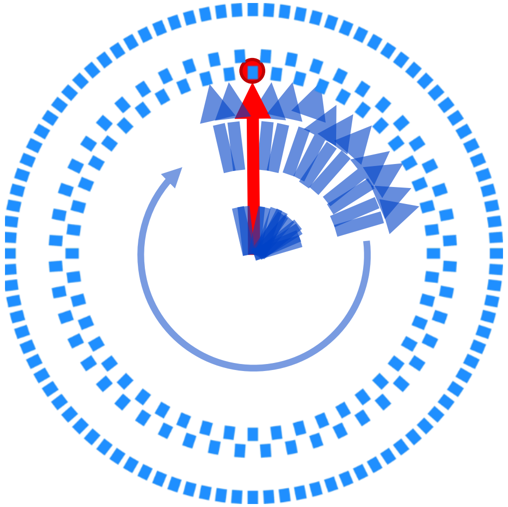

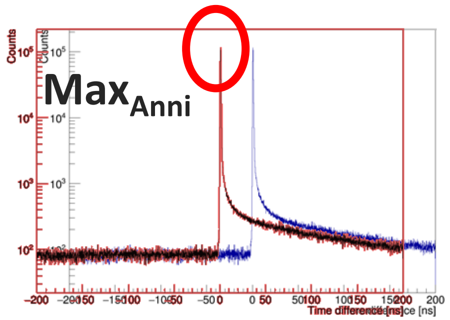

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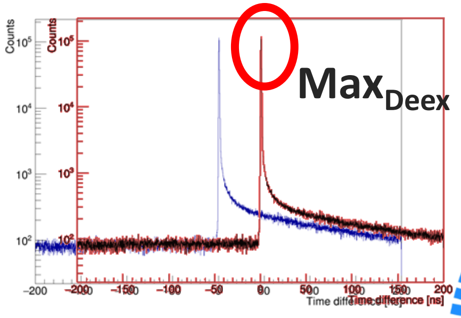
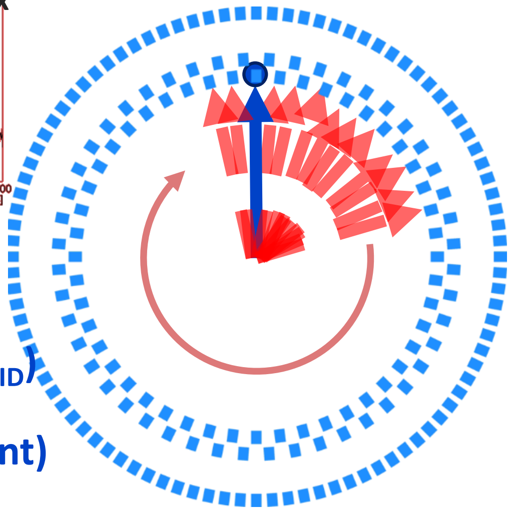




($CalibConstant_{ID}$ – MeanCalibConstant)

(MeanCalibConstant – $CalibConstant_{ID}$)

=

- ($CalibConstant_{ID}$ – MeanCalibConstant)

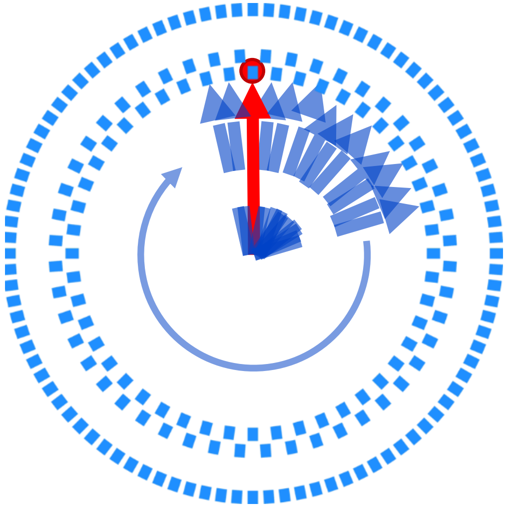
For given Annihilation ID:

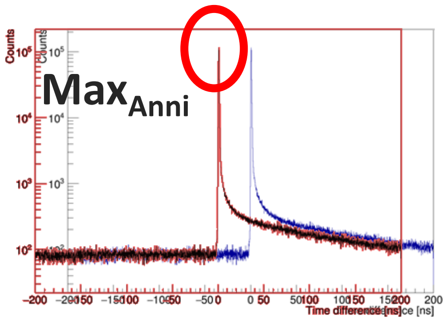
For given Deexcitation ID:

$(Time_{Anni} + CalibConstant_{ID}) - (Time_{Deex} + MeanCalibConstant) =$ **Time difference** $= (Time_{Anni} + MeanCalibConstant) - (Time_{Deex} + CalibConstant_{ID})$

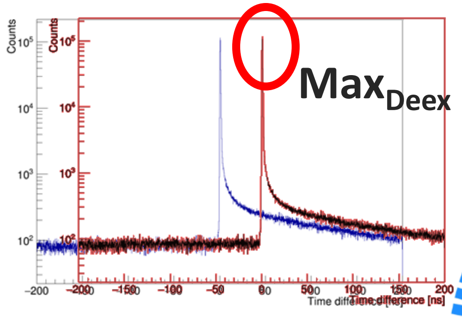
Calibration between modules

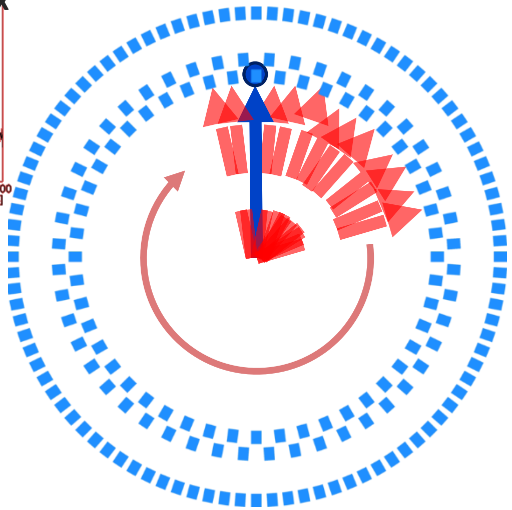
For one given ID of the scintillator we will have two histograms for consideration





If there is some miscalibration **these** will differ by





$$Max_{Anni} - Max_{Deex} =$$
$$2 \cdot CalibConstant_{ID} - 2 \cdot MeanCalibConstant$$
$$= 2 \cdot Constant_{Corr}$$

For given Annihilation ID:

$(Time_{Anni} + CalibConstant_{ID}) - (Time_{Deex} + MeanCalibConstant) =$ **Time difference** $= (Time_{Anni} + MeanCalibConstant) - (Time_{Deex} + CalibConstant_{ID})$

For given Deexcitation ID:

Calibration between modules

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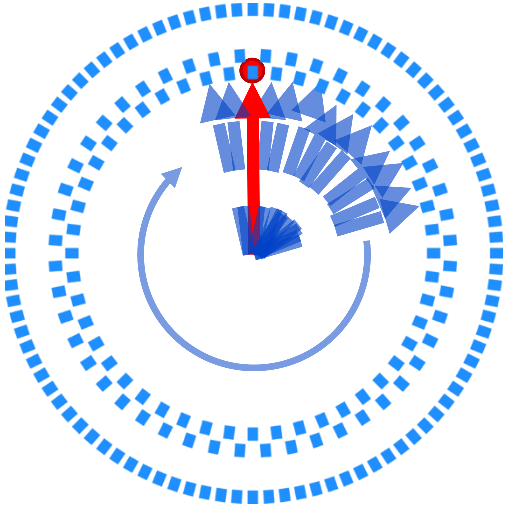
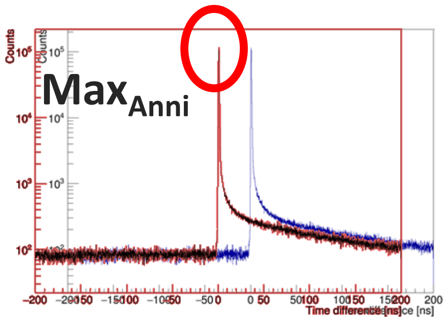
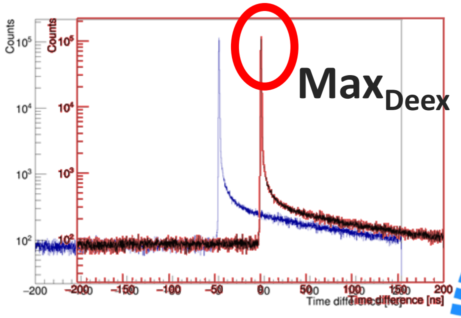
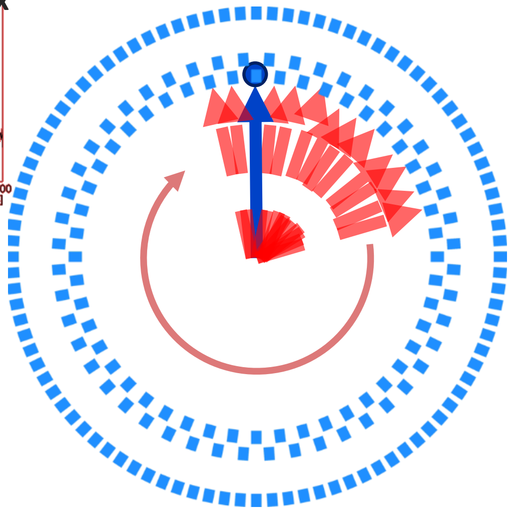




If there is some miscalibration **these** will differ by





$$Max_{Anni} - Max_{Deex} = 2 \cdot CalibConstant_{ID} - 2 \cdot MeanCalibConstant = 2 \cdot Constant_{Corr}$$

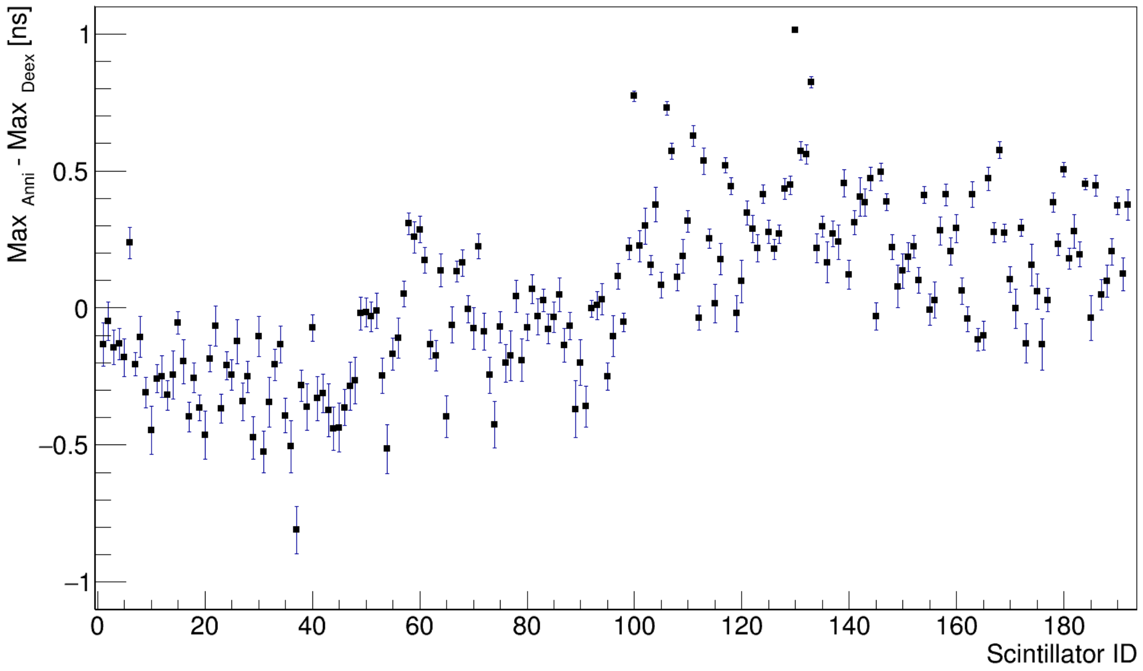
Correction for Scintillator:
$(Max_{Anni} - Max_{Deex})/2$

Maximum of distribution calculated as zero of 1st derivative

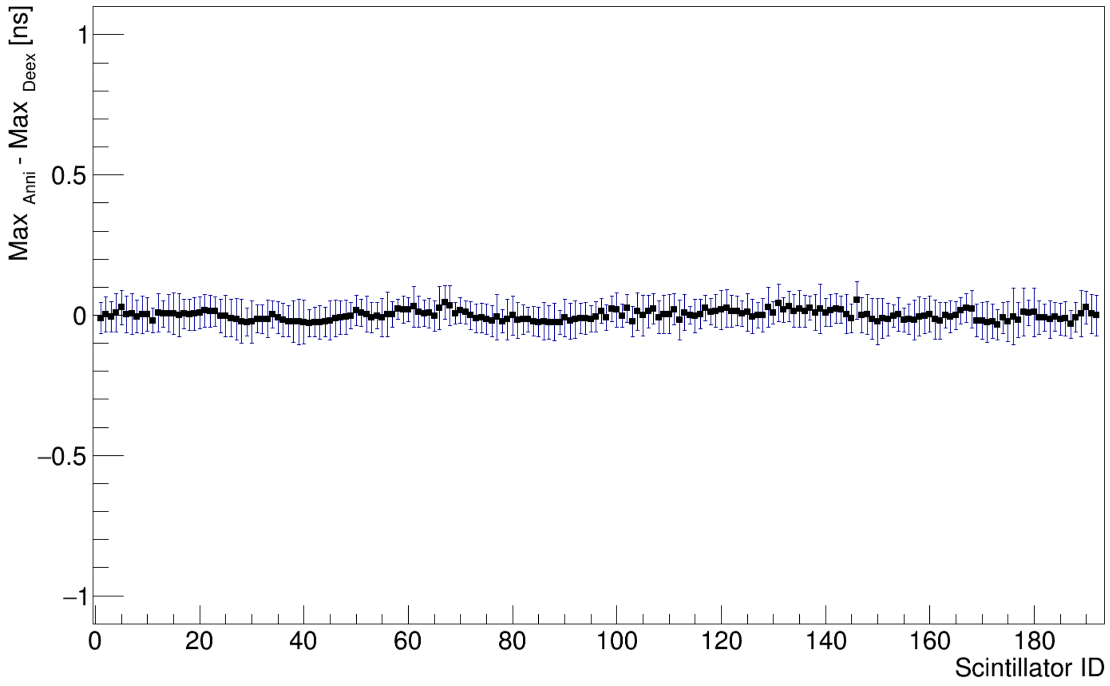
Correction for each side of module:
Correction for scintillator

Calibration between modules

Before Calibration (0 iteration)



After Calibration (3rd iteration)



Conclusions

New Iterative Time Calibration procedure was developed for the J-PET. As a first calibration method of TOF-PET systems, it uses point-like source that emits prompt gamma quantum for calibration. Calibration was performed for ^{22}Na source in Kapton foil with XAD4 (porous polymer) around it.

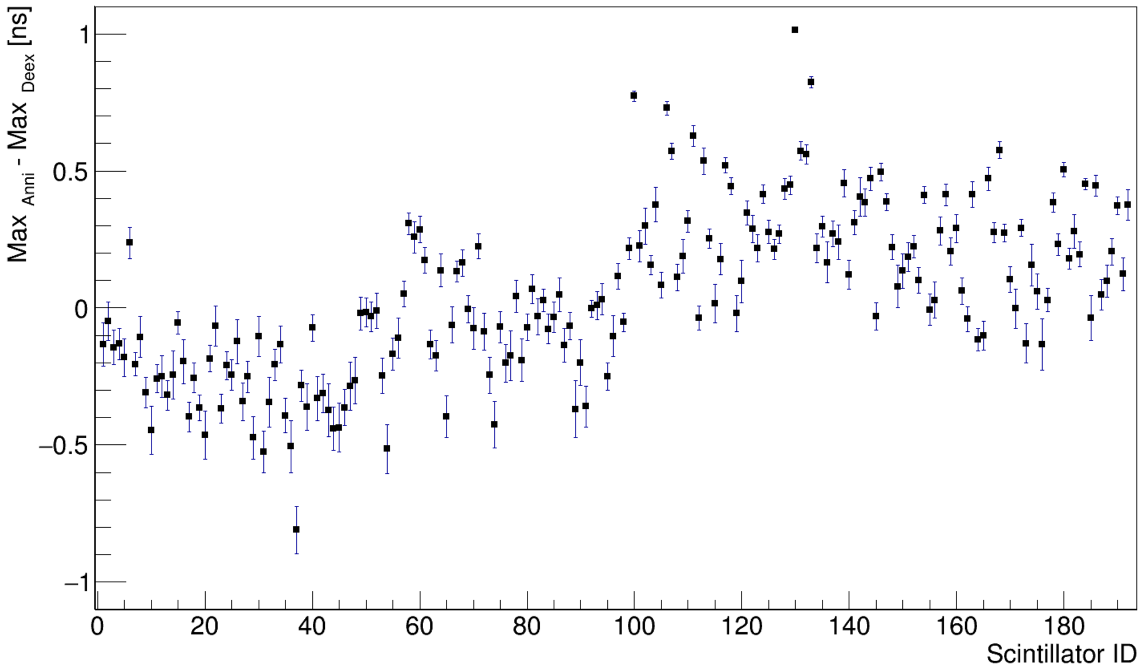
Compared to other methods, there is no need to mount complicated setup for calibration in TOF-PET detector. Every possible pair of detector is calibrated at once.

Additionally, because the measure of the miscalibration is the difference in the positions of the maxima, calibration does not depend much on the material that is around radioactive source.

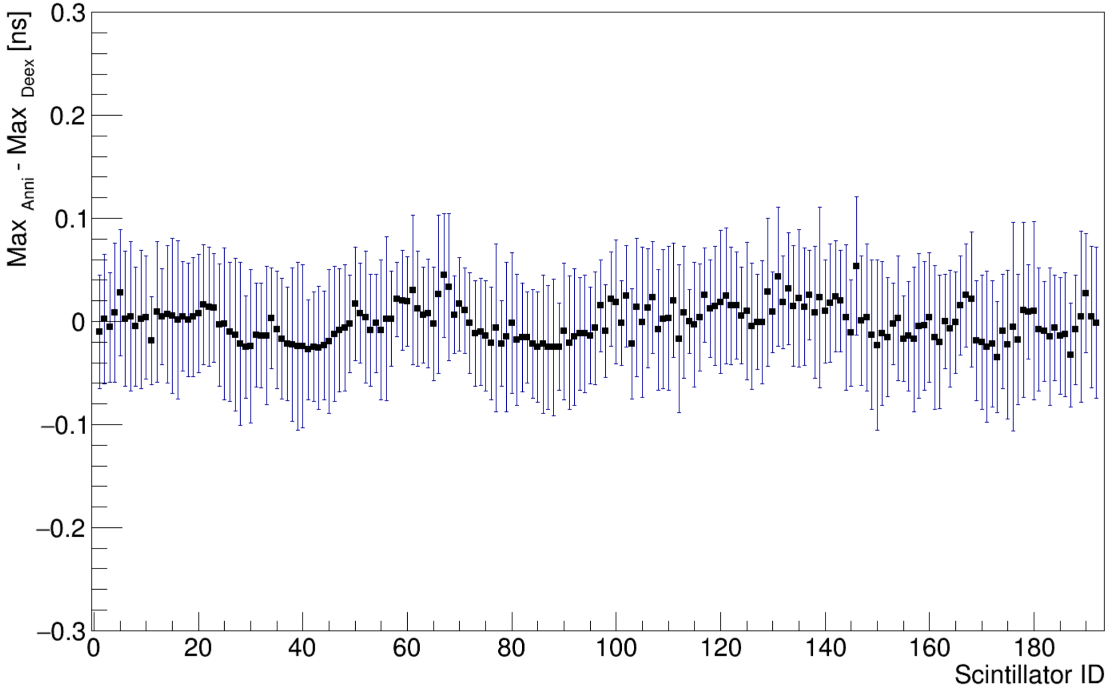
Thank You for Your attention

Calibration between modules

Before Calibration (0 iteration)



After Calibration (3rd iteration)



Calibration between modules

Uncertainity calculation:

Maximum calculated from the liear fit: $y = A \cdot x + B$

So $x_0 = -B/A$

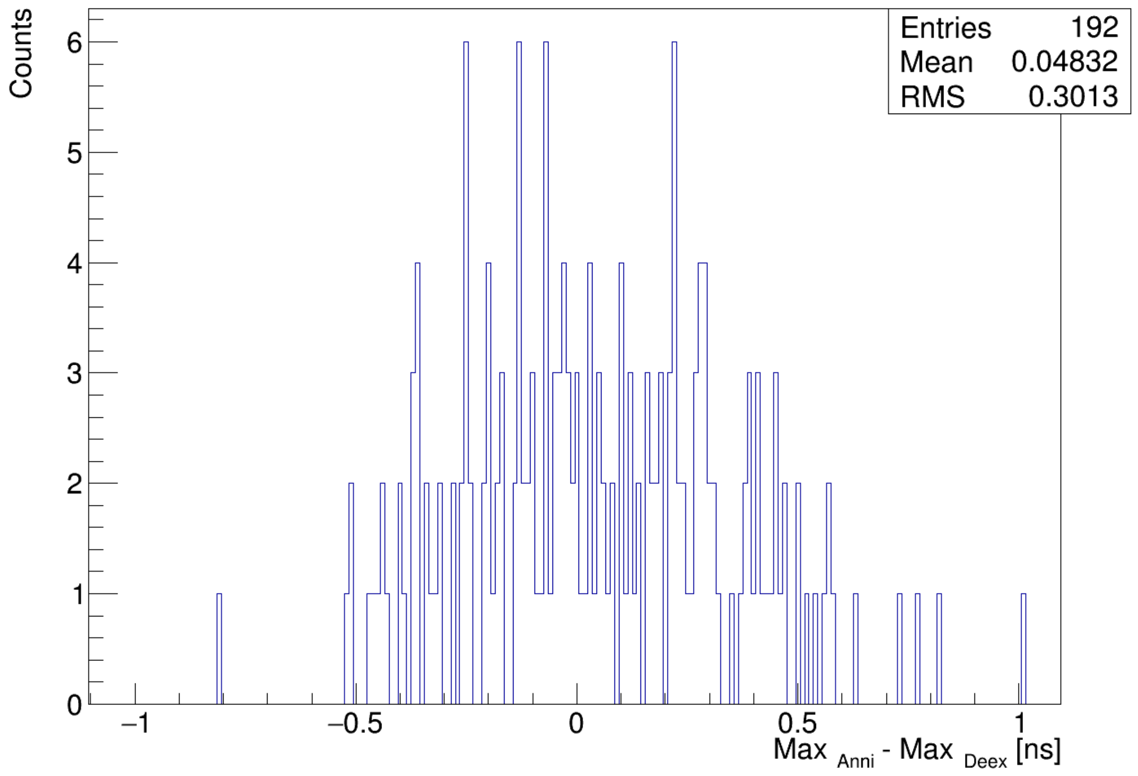
x_0 Error: $$dx_0 = \sqrt{\left(\frac{dB}{A}\right)^2 + \left(\frac{B \cdot dA}{A^2}\right)^2}$$

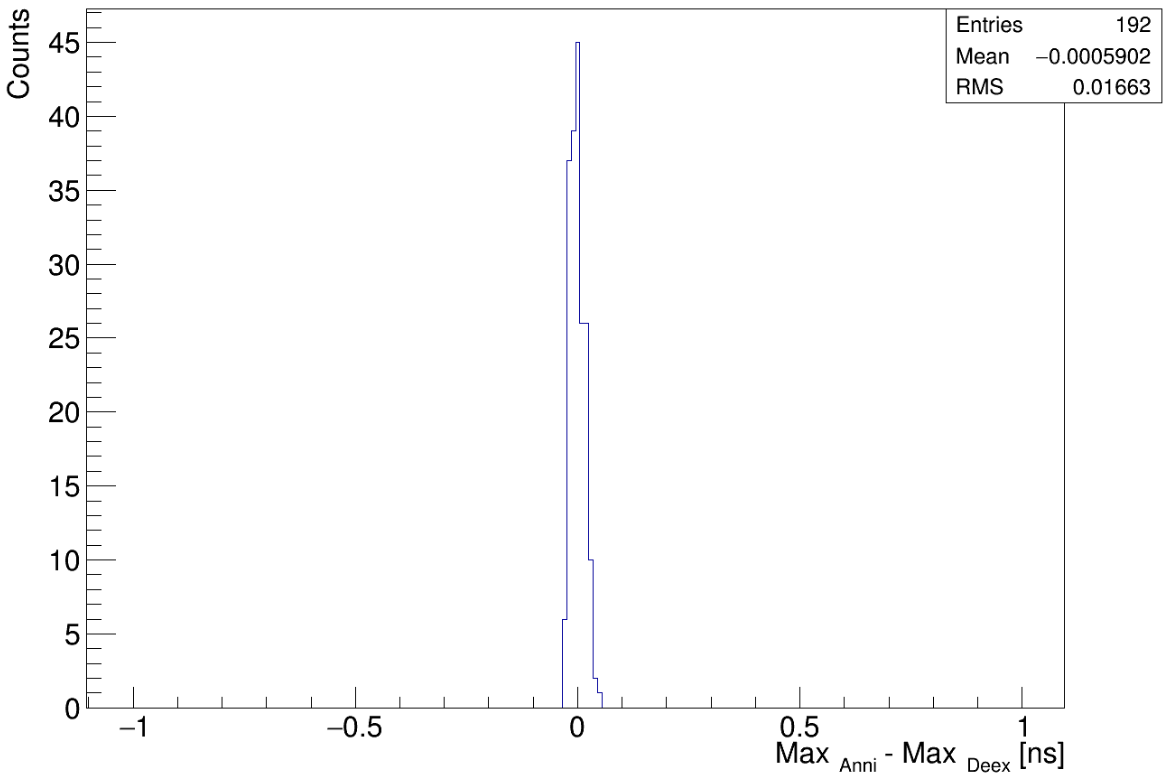
dA, dB from the formulas of uncertainity of linear fit

$$\hat{\varepsilon}_i = y_i - B - A\,x_i\,.$$

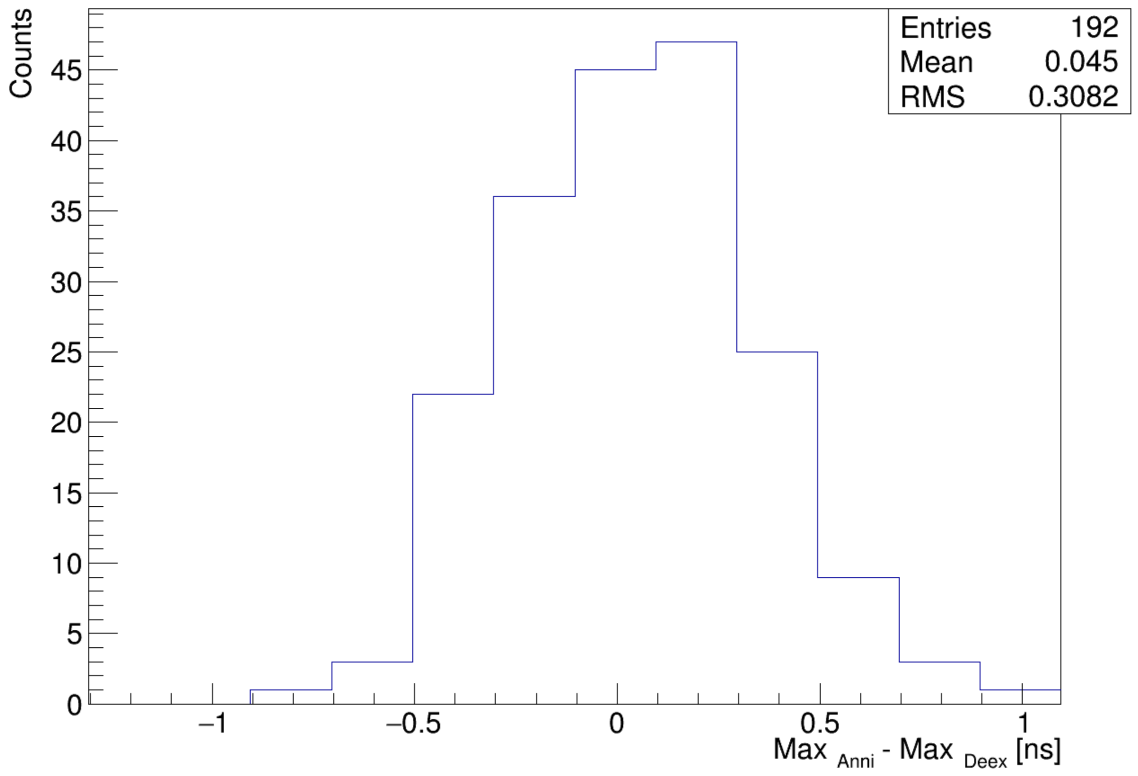
$$s_A = \sqrt{\frac{\frac{1}{n-2}\sum_{i=1}^n \hat{\varepsilon}_i^{\,2}}{\sum_{i=1}^n (x_i - \bar{x})^2}} \qquad s_B = s_A\sqrt{\frac{1}{n}\sum_{i=1}^n x_i^2} = \sqrt{\frac{1}{n(n-2)}\left(\sum_{i=1}^n \hat{\varepsilon}_j^{\,2}\right)\frac{\sum_{i=1}^n x_i^2}{\sum_{i=1}^n (x_i - \bar{x})^2}}$$

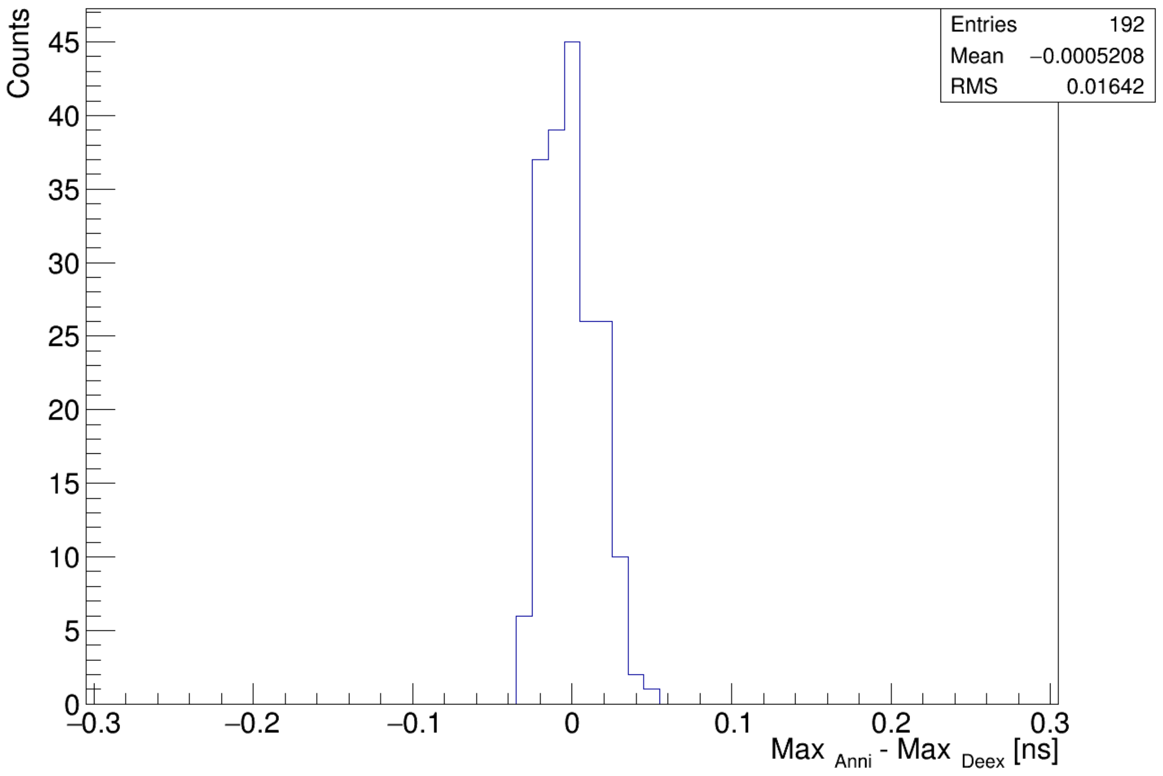
Calibration between modules



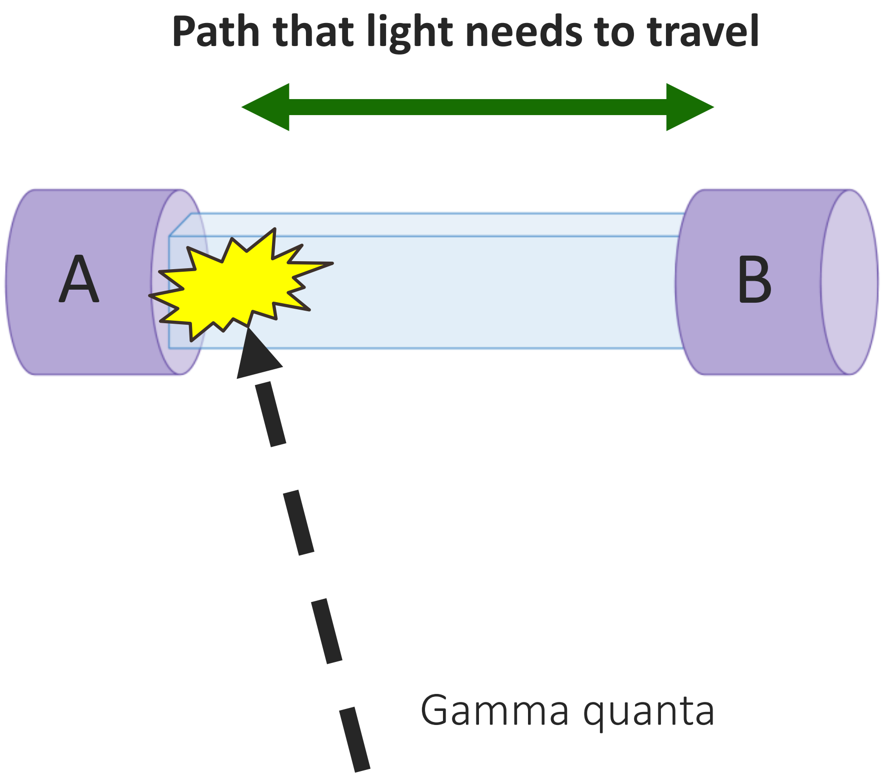


Calibration between modules

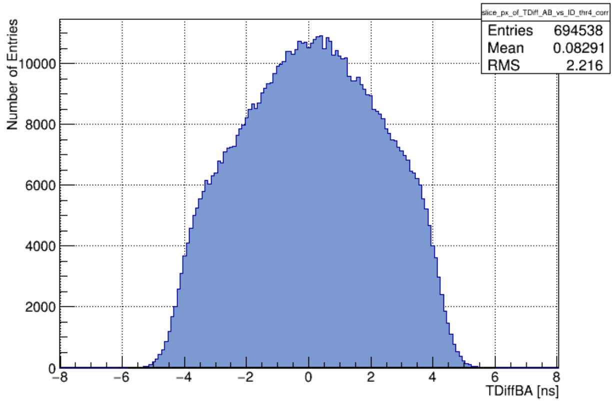




Velocity calibration

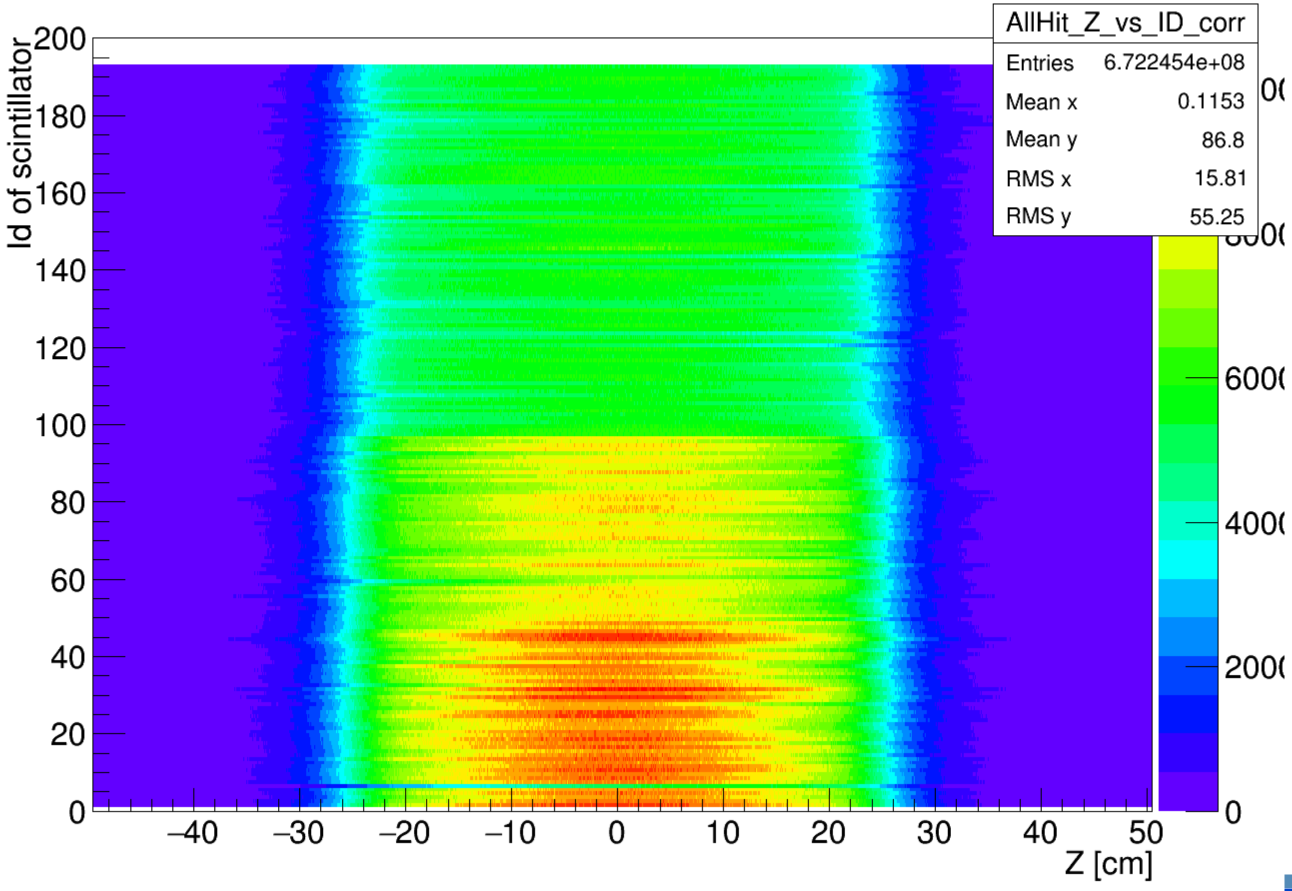


$$\text{Time difference BA} = \frac{\text{Path that light needs to travel}}{\text{Velocity of light in scintillator}}$$

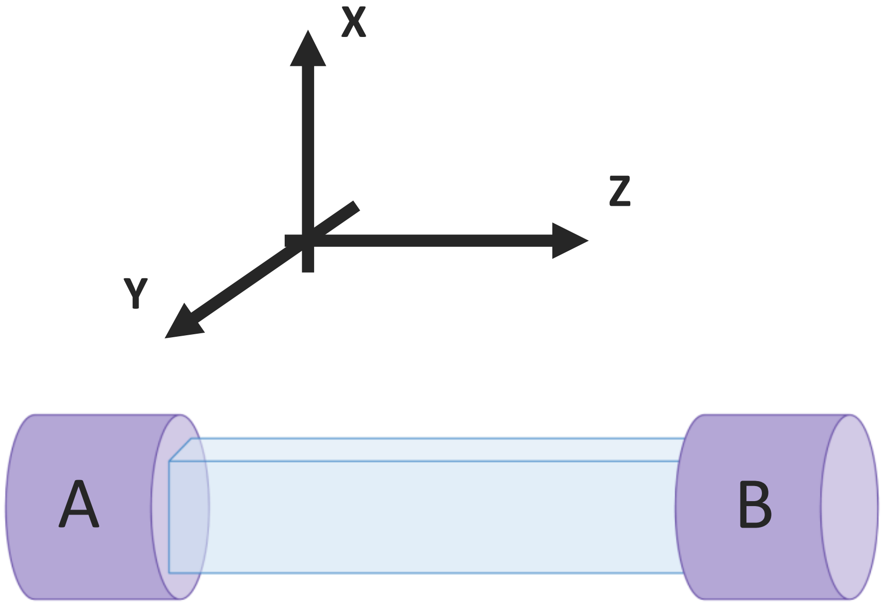


$$\text{Right Edge} - \text{Left Edge} = \frac{\text{Effective Length}}{\text{Velocity of light in scintillator}}$$

Velocity calibration

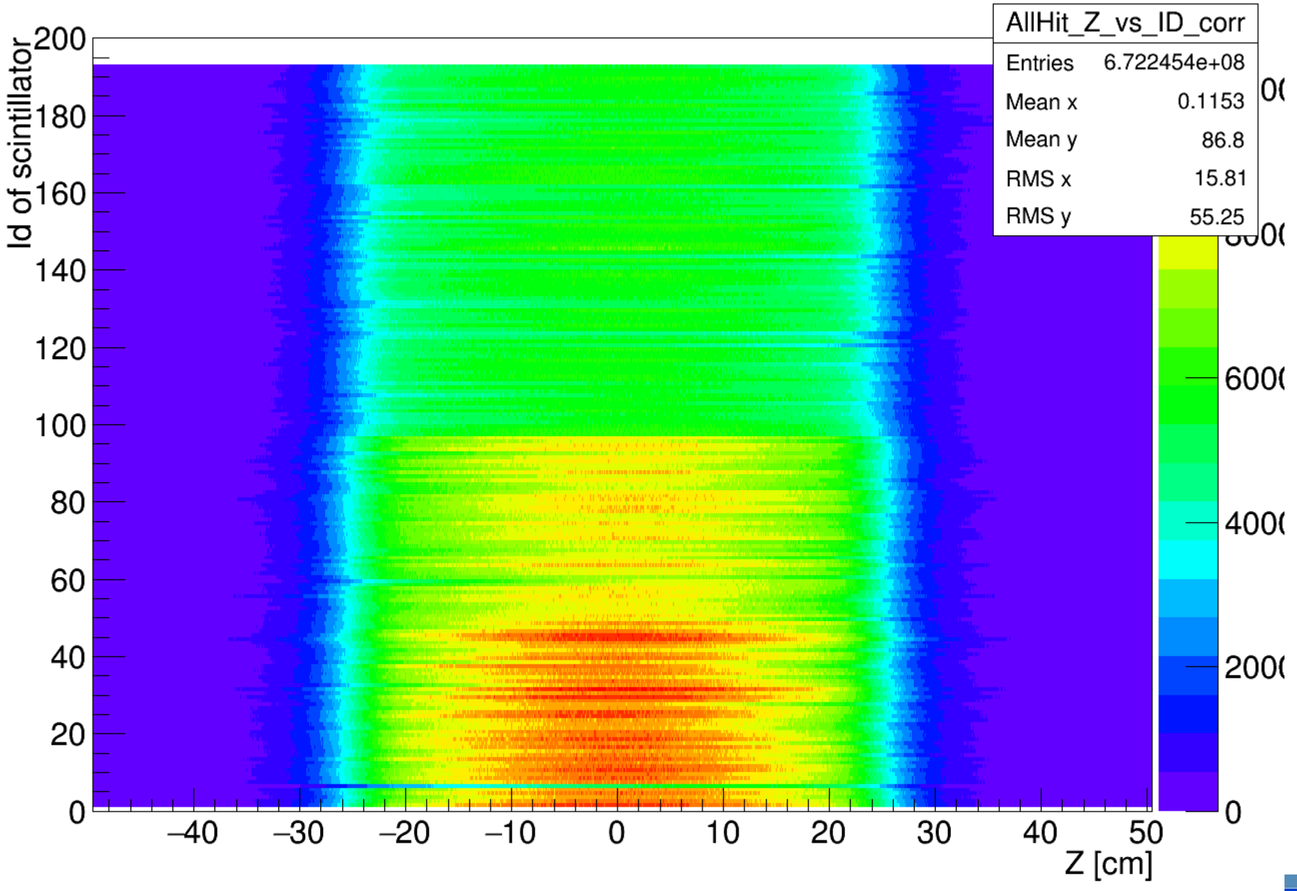


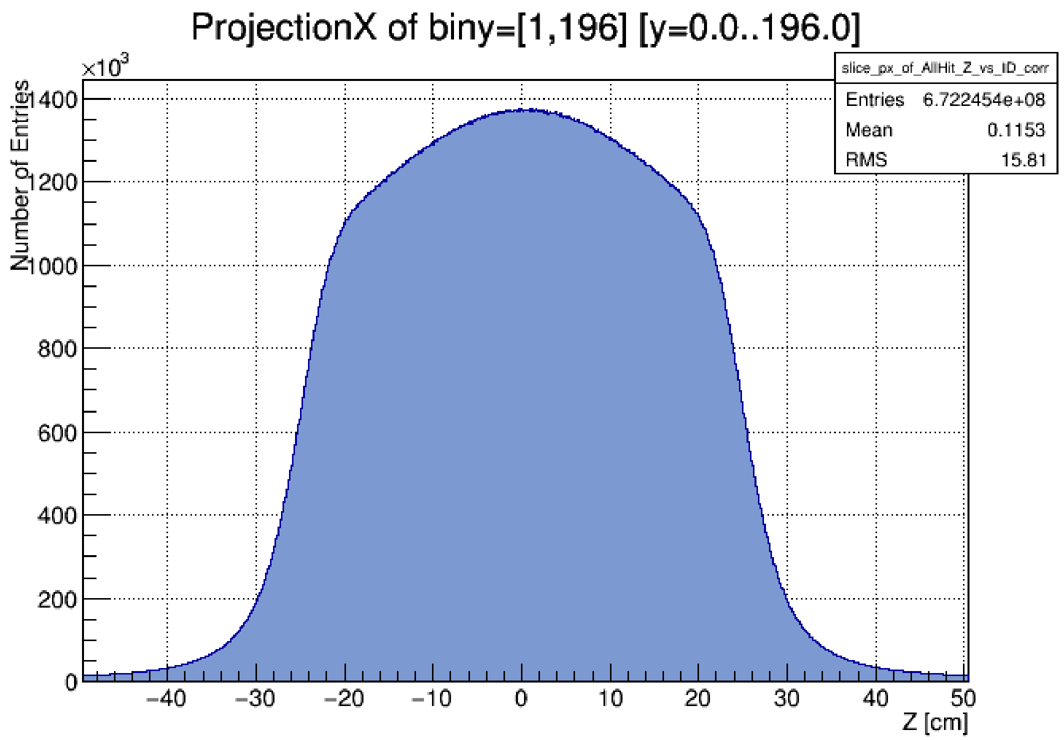
Assuming that Effective Length (later explanation) = 50 cm
Velocity = 50 / (MiddleEdgeRight – MiddleEdgeLeft)
Z position = Velocity * (TimeB – TimeA)/2



Velocity calibration

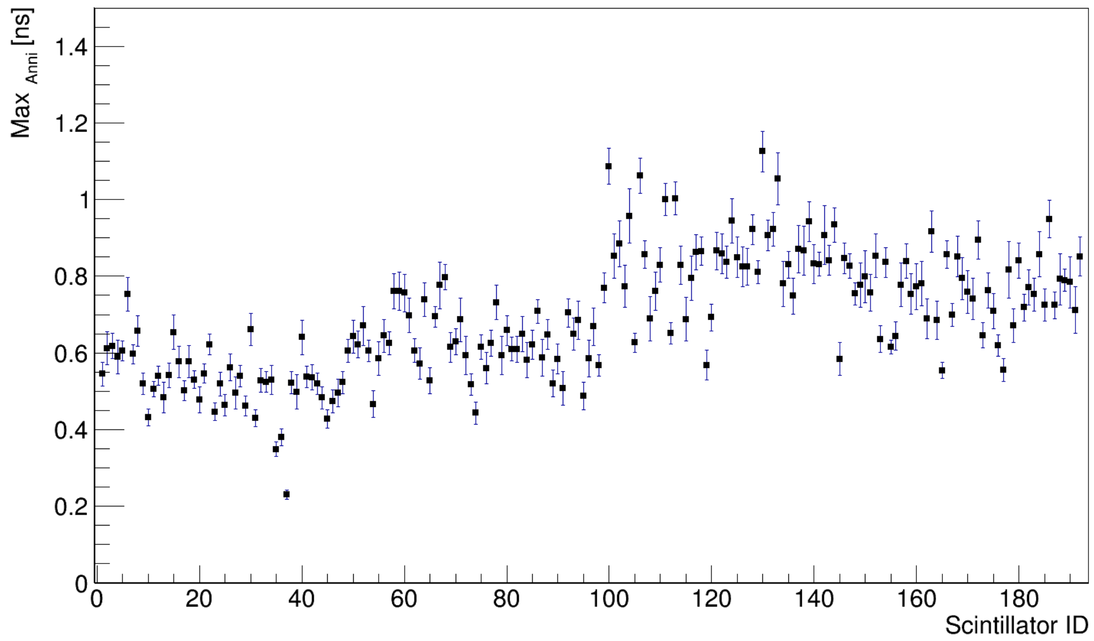
Assuming that Effective Length (later explanation) = 50 cm
Velocity = 50 / (MiddleEdgeRight – MiddleEdgeLeft)
Z position = Velocity * (TimeB – TimeA)/2



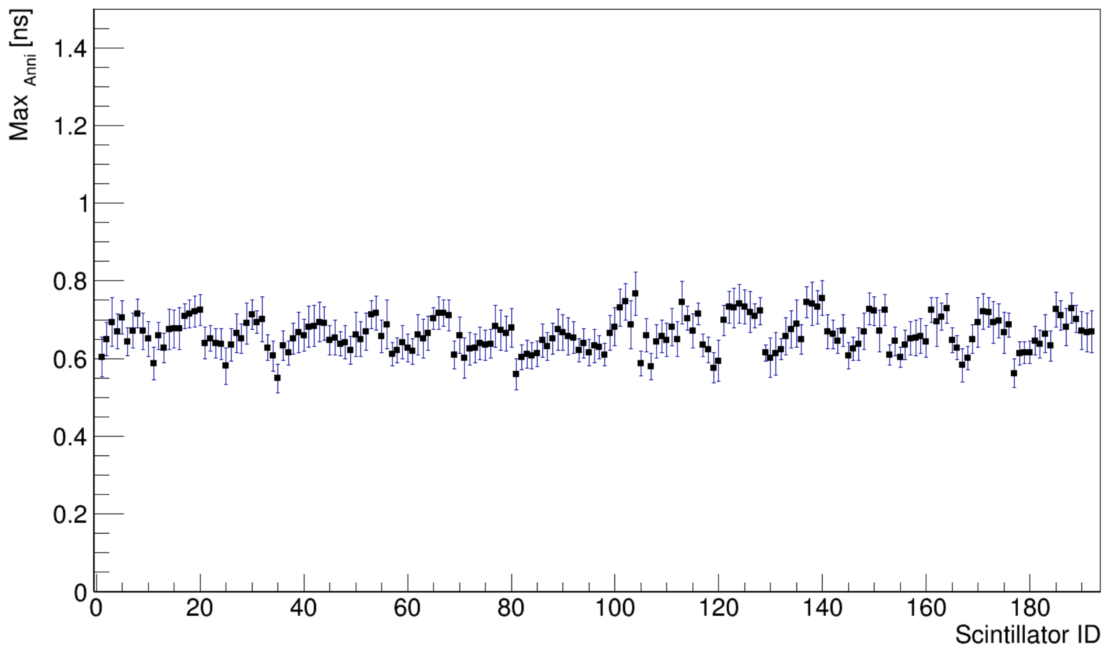


Calibration between modules

Before Calibration (0 iteration)

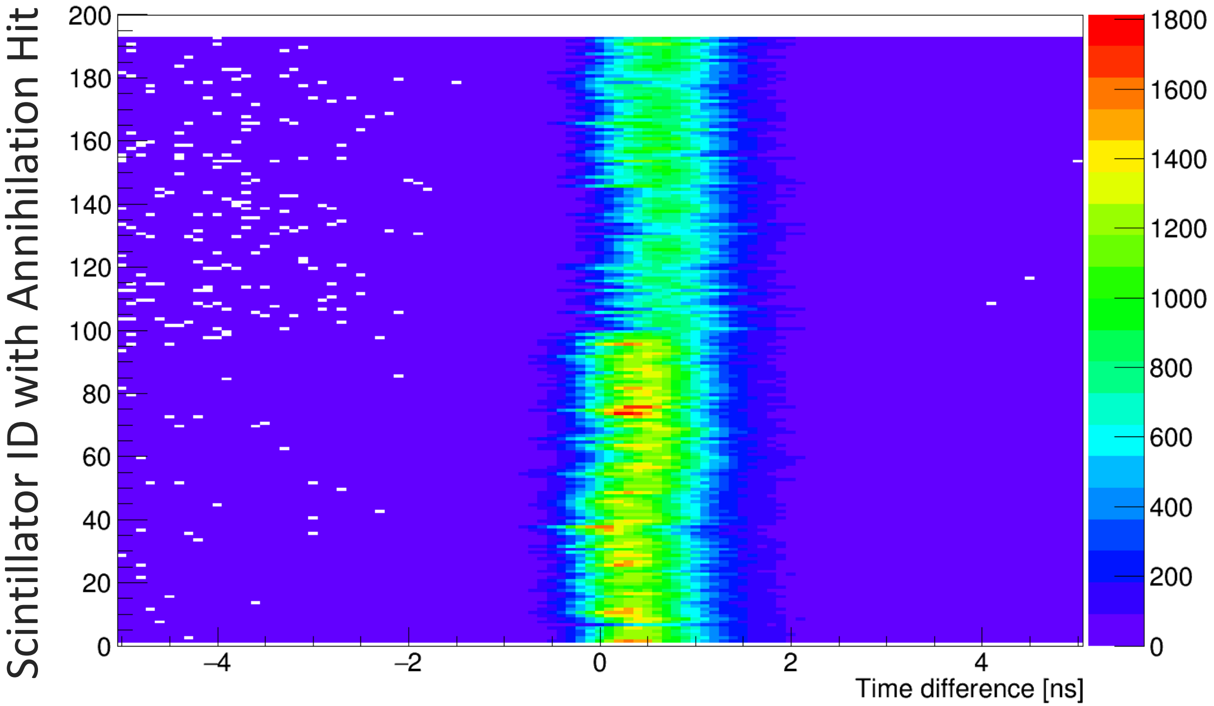


After Calibration (3rd iteration)

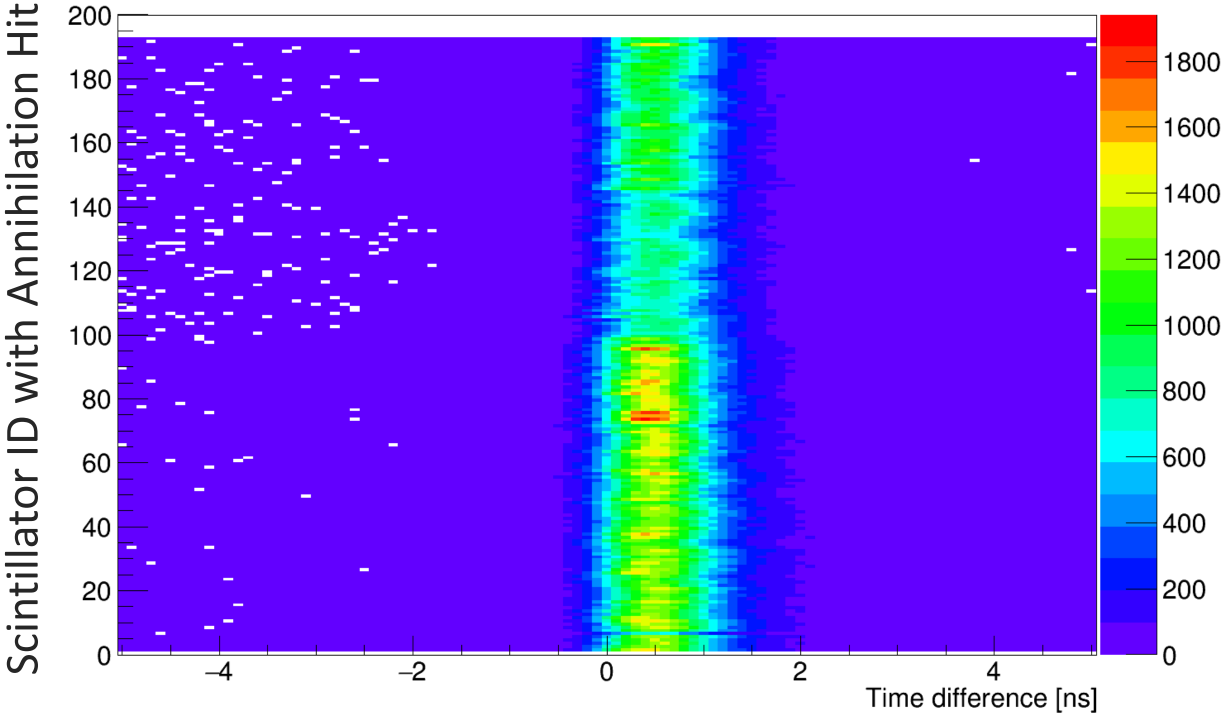


Calibration between modules

Before Calibration (0 iteration)

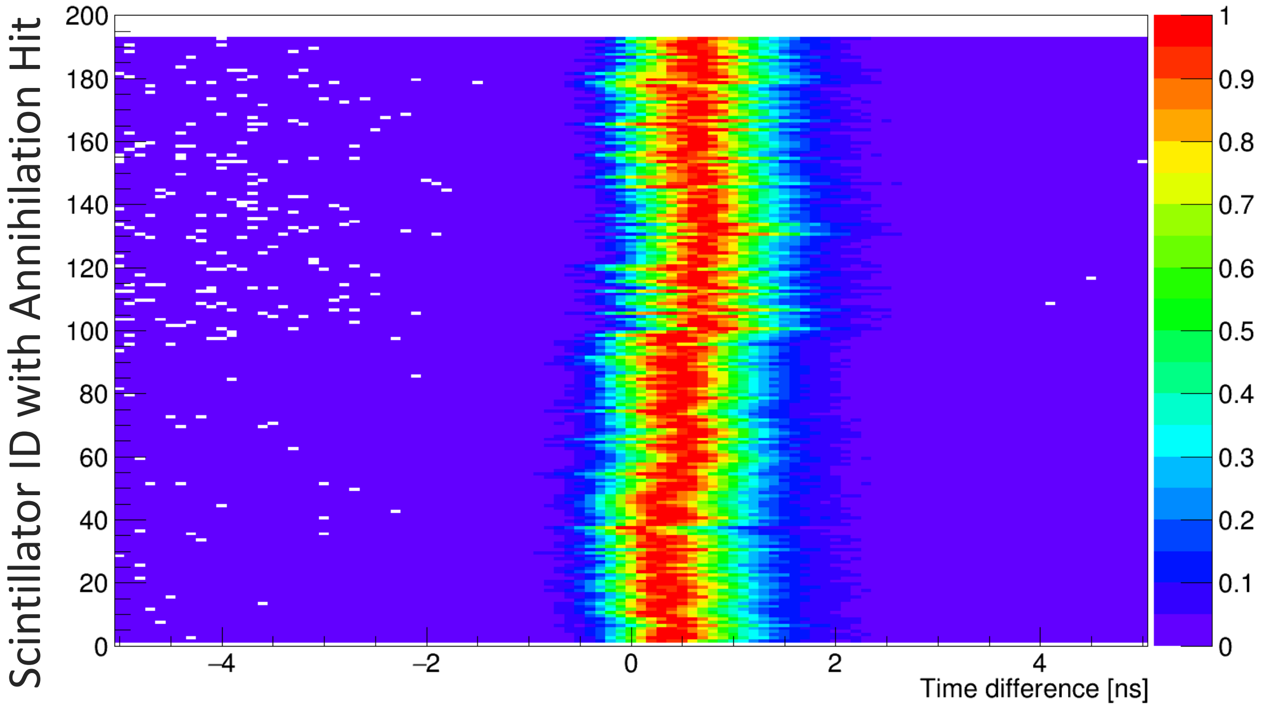


After Calibration (3rd iteration)

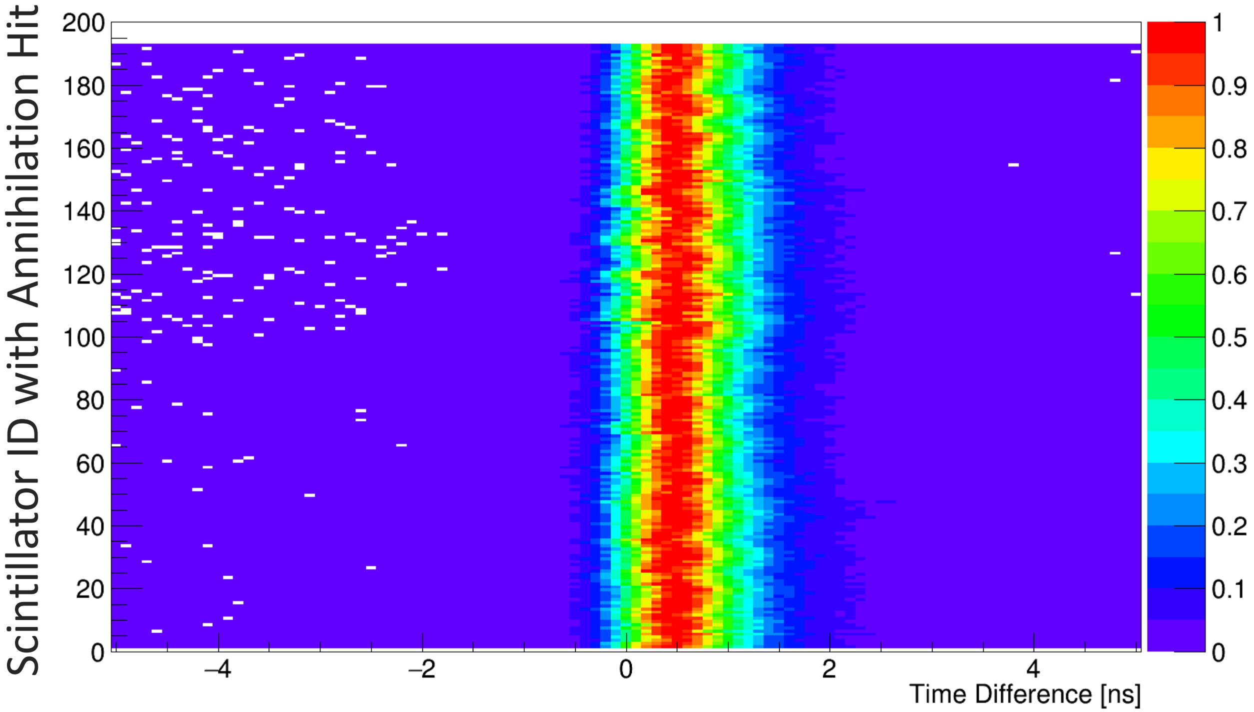


Calibration between modules

Before Calibration (0 iteration)

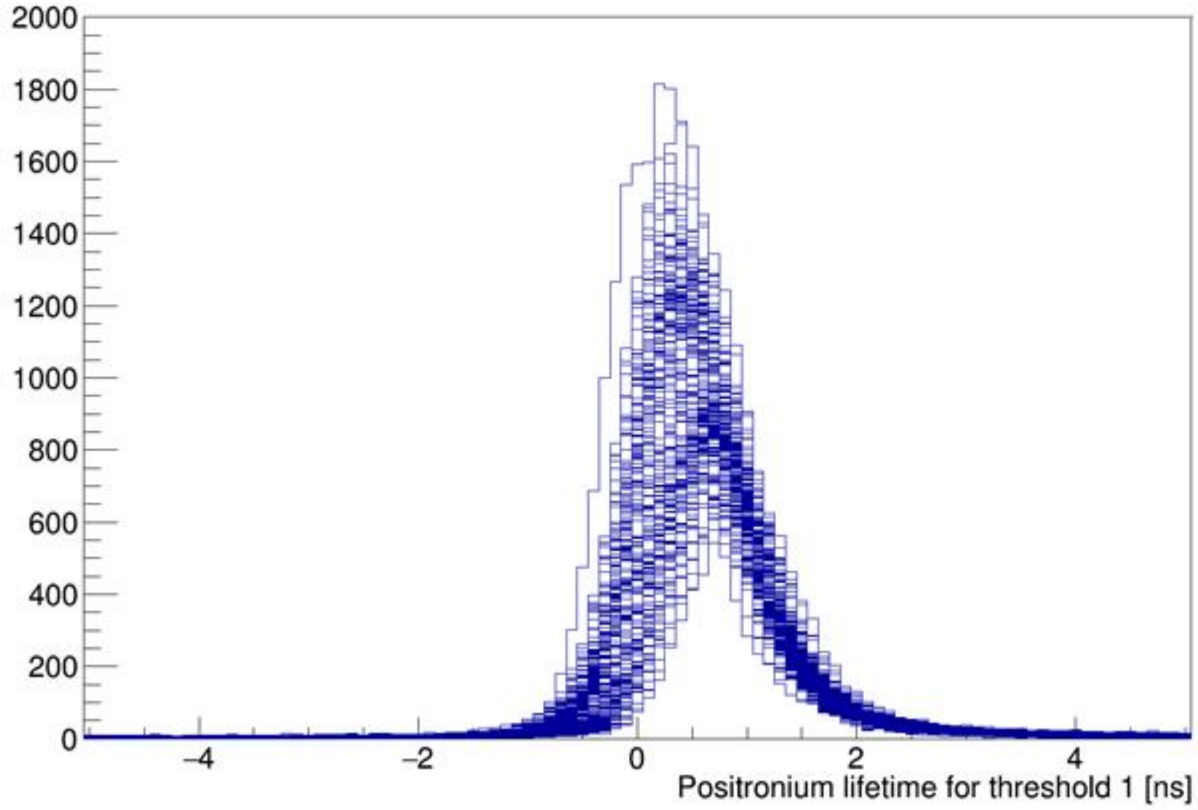


After Calibration (3rd iteration)

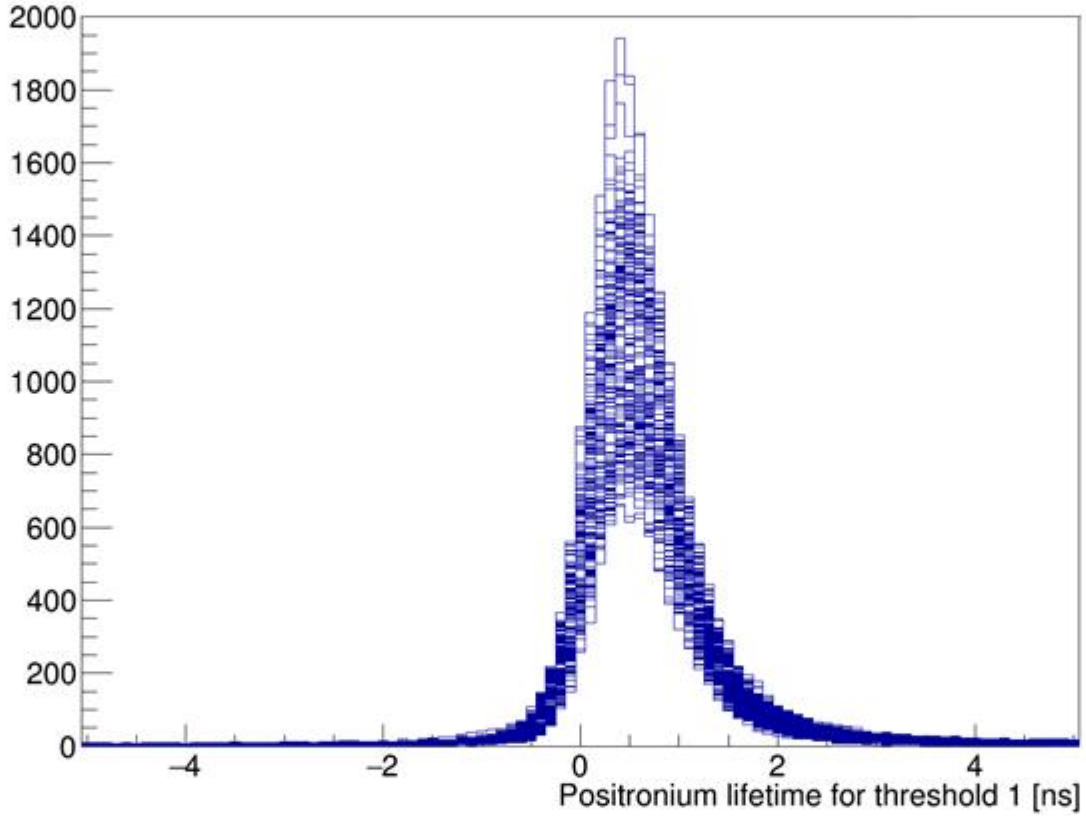


Calibration between modules

Before Calibration (0 iteration)



After Calibration (3rd iteration)



Effective Length studies

Calibration constant depends on chosen Effective Length, because:

- Effective Length used for calculation of the Z position of registered gamma quantum
- Time of the Hits used for Calibration, are corrected on TOF -> substracting the path before deposition of Energy (path depends on the Z)

For different assumed Effective Length the same calibration procedure was applied, to check how calibration constants changes with the change of Effective Length.

Calibration constants for Effective Length = 50 cm chosen as reference

Velocity of light in scintillator = Effective Length * (Right Edge – Left Edge)

Z position of Hit = Velocity of light in scintillator * (TimeB – TimeA)/2

Effective Length studies

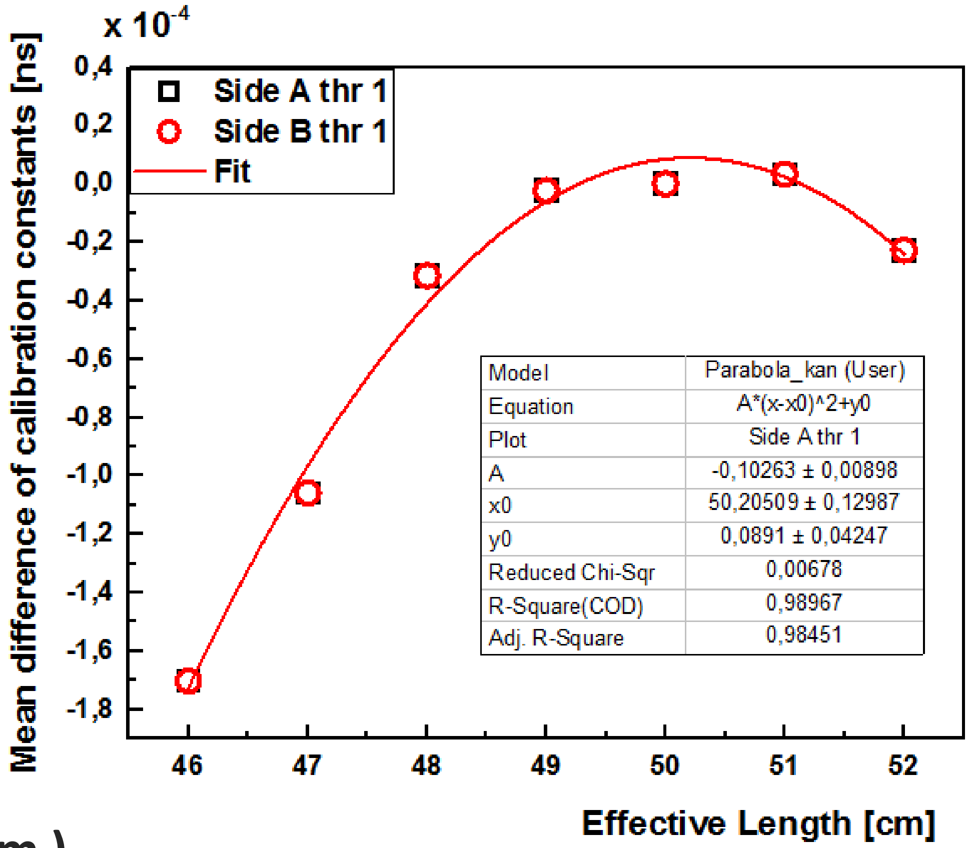
For different assumed Effective Length the same calibration procedure was applied, to check how calibration constants changes with the change of Effective Length.

Calibration constants for Effective Length = 50 cm chosen as reference.

Mean difference of calibration constant:

Mean over all IDs of:

(Correction for 50 cm)$_{ID}$ - (Correction for [Effective Length] cm)$_{ID}$



Effective Length studies

Calibration constant for 50 cm

y_1
y_2
y_3

...

Calibration constant for x cm

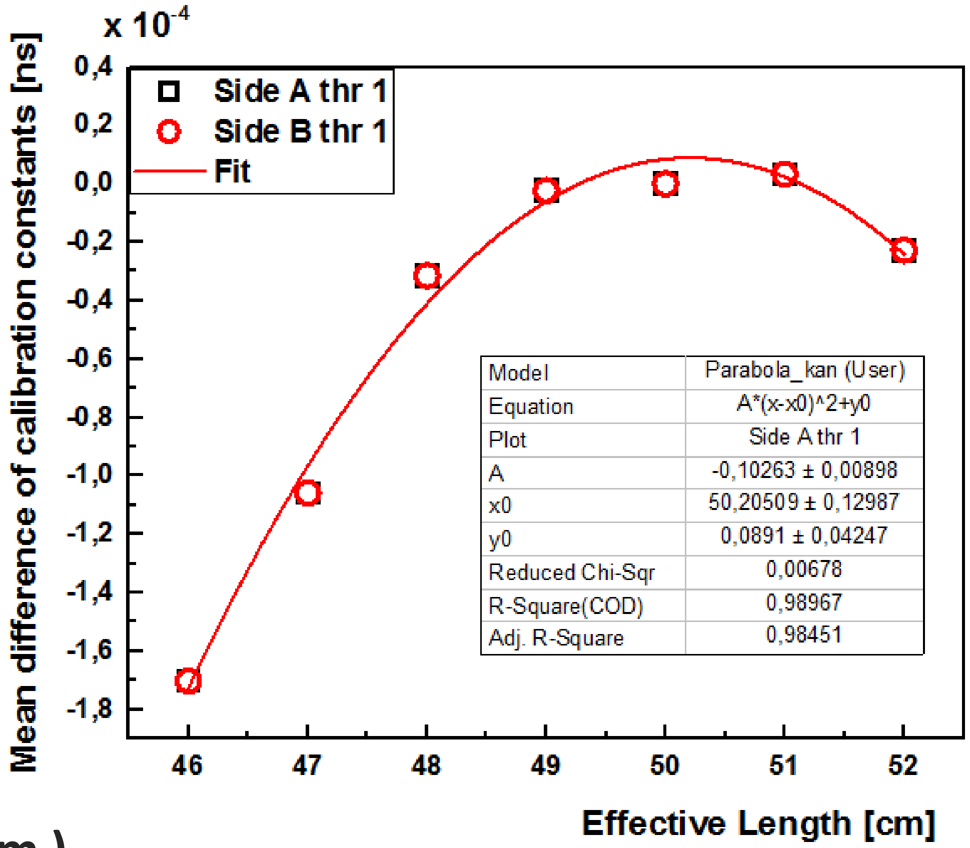
y_1'
y_2'
y_3'

Mean of set of $(y_i - y_i')$ for i=1 to i=192

↑

Mean over all IDs of:

(Correction for 50 cm)$_{ID}$ - (Correction for [Effective Length] cm)$_{ID}$



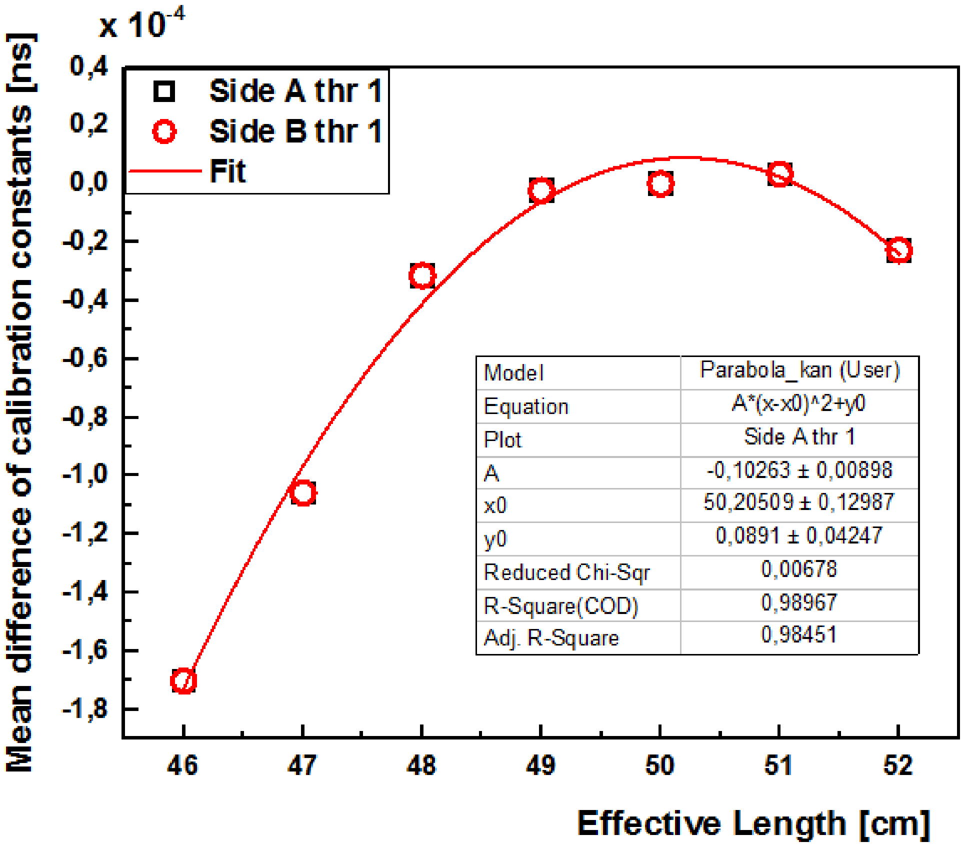
Effective Length studies

Nevertheless, the choice of Effective Length does not depend much on the Calibration Constant:

Effective length change by 1 cm causes the mean change of Calibration constant in the order of 0.1 ps (*Maximal change in the order of 1 ps*)

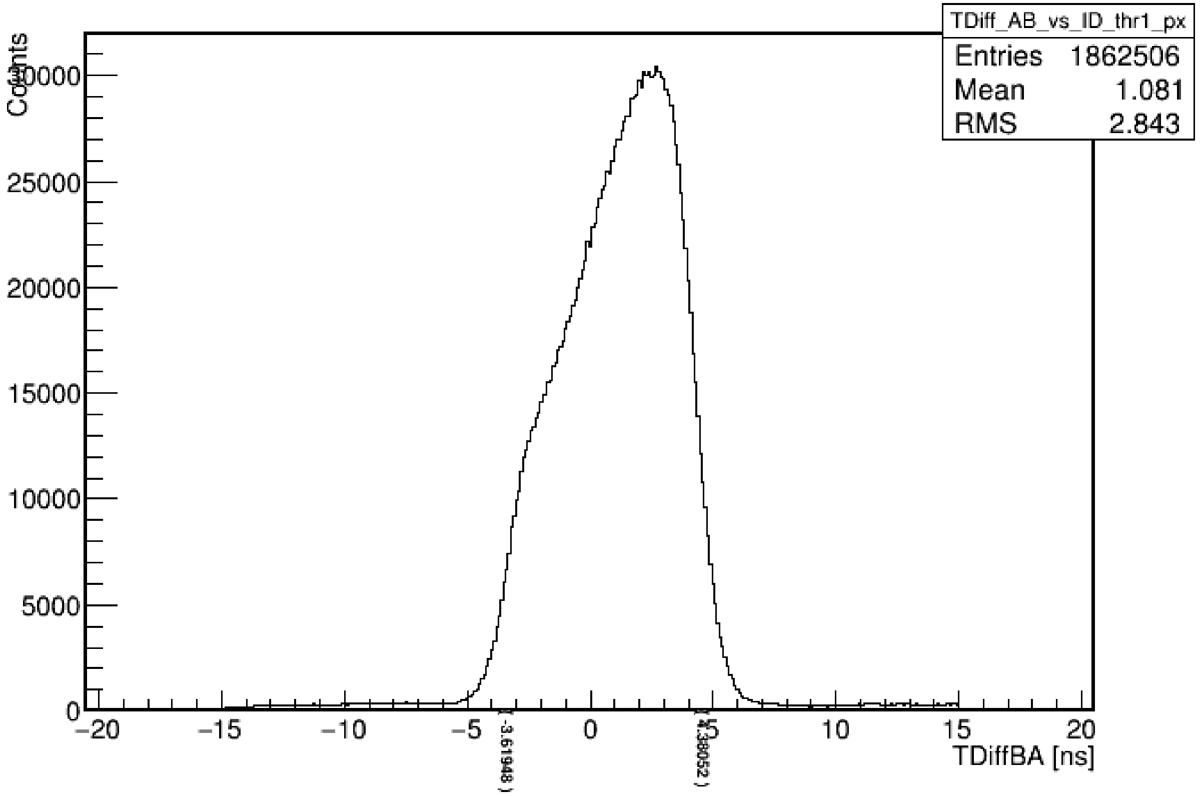
Z position of Hit = Velocity * (TimeB – TimeA)/2

Velocity = Effective Length * (Right Edge – Left Edge)

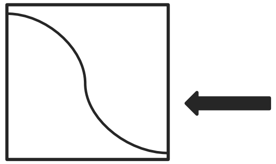


Supplementary slides

Example for problematic scintillator



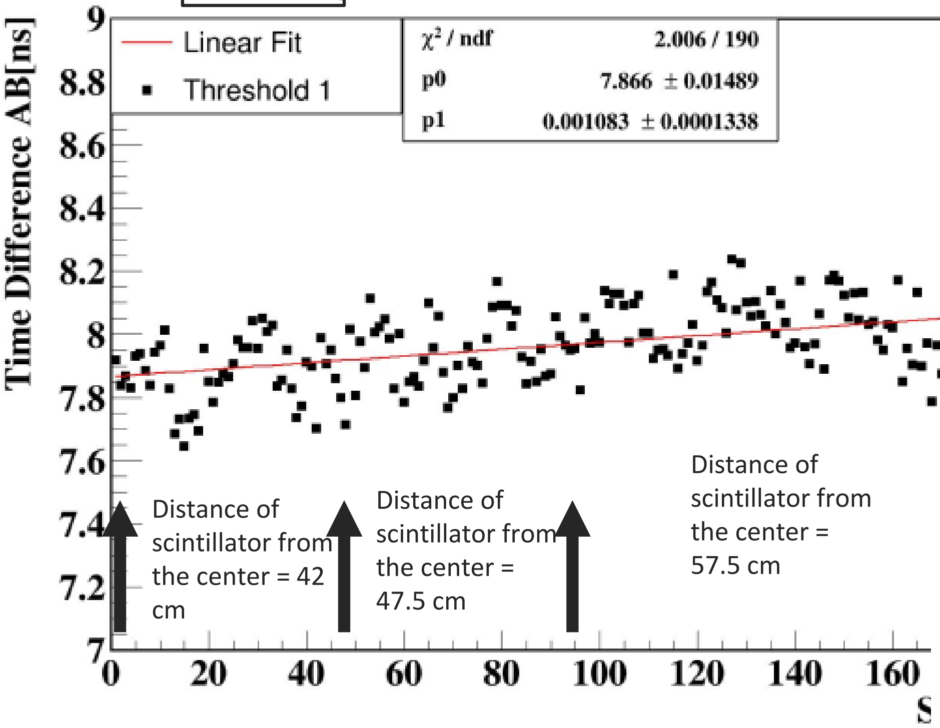
Different methods of determinig middle of the edge



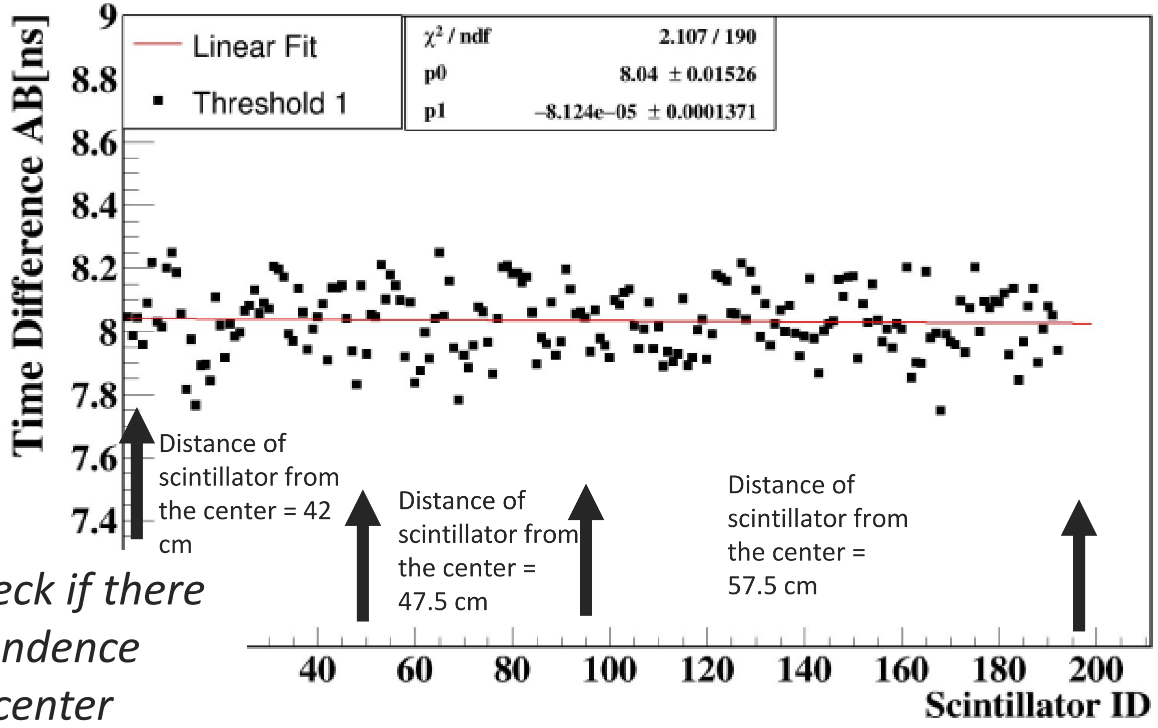
Fermi Fit

Method should not depend on the layer of scintillators

Zero of the second derivative

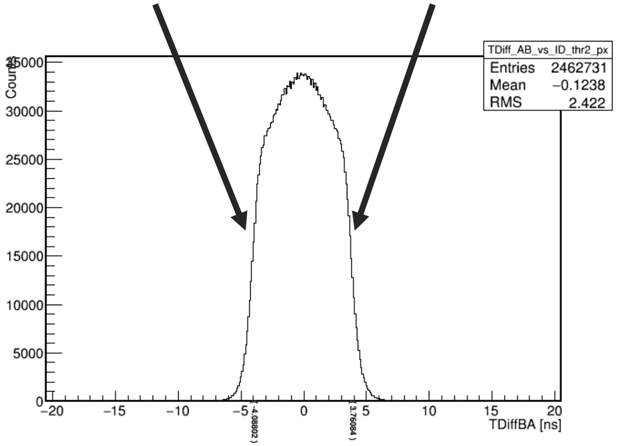


Linear fit only to check if there is a significant dependence over distance from center

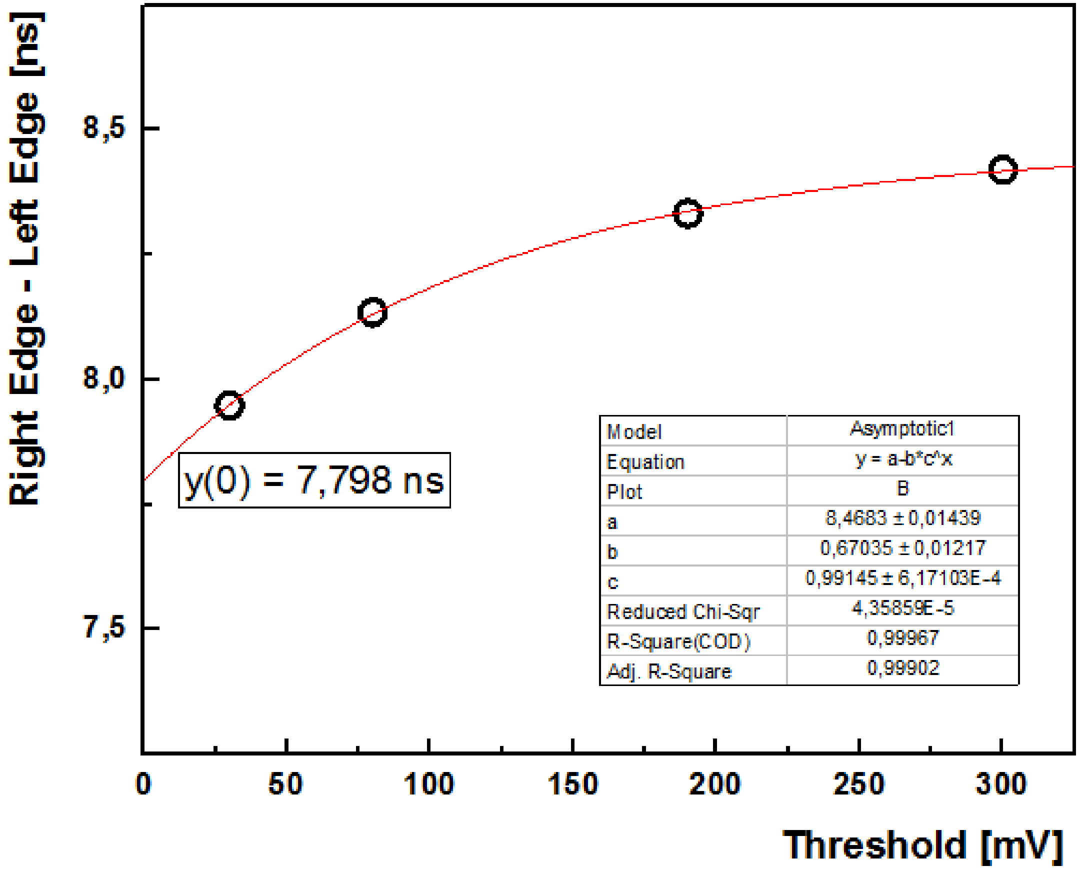


Comparison of mean width of TDiffAB distribution

Left Edge Right Edge

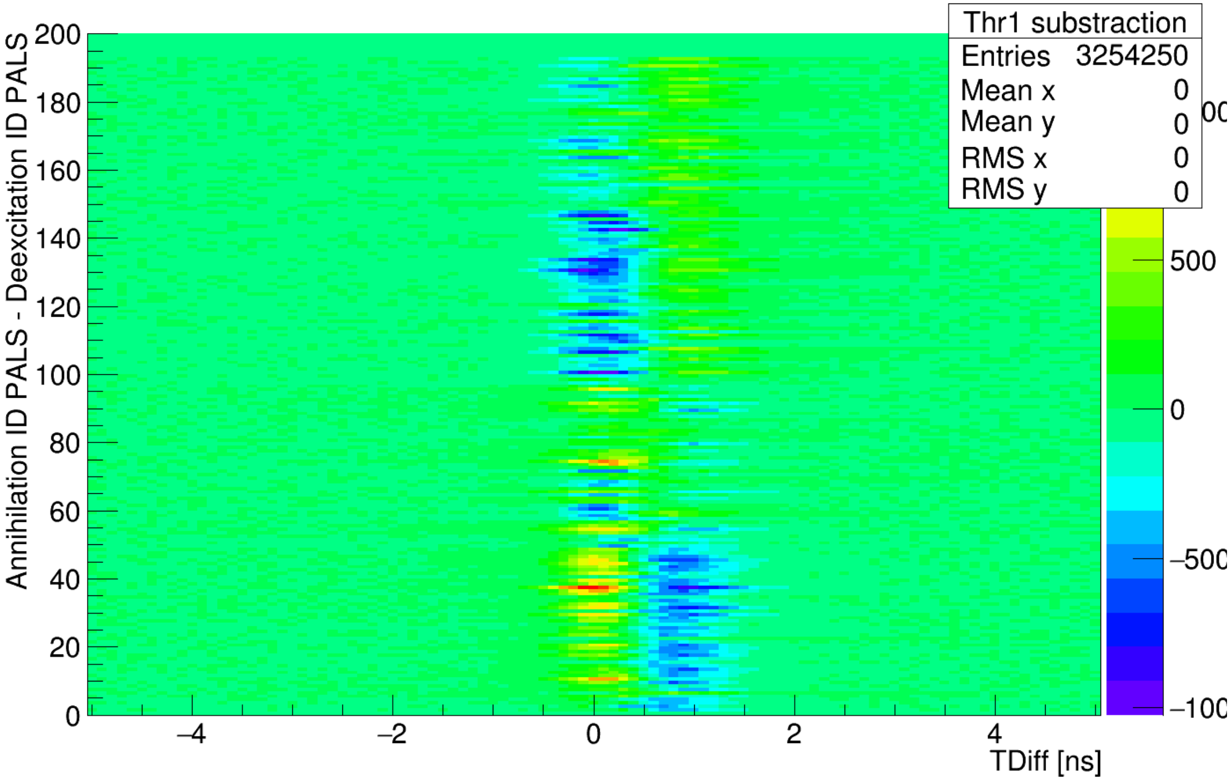


Higher Threshold – Greater WALK effect influence

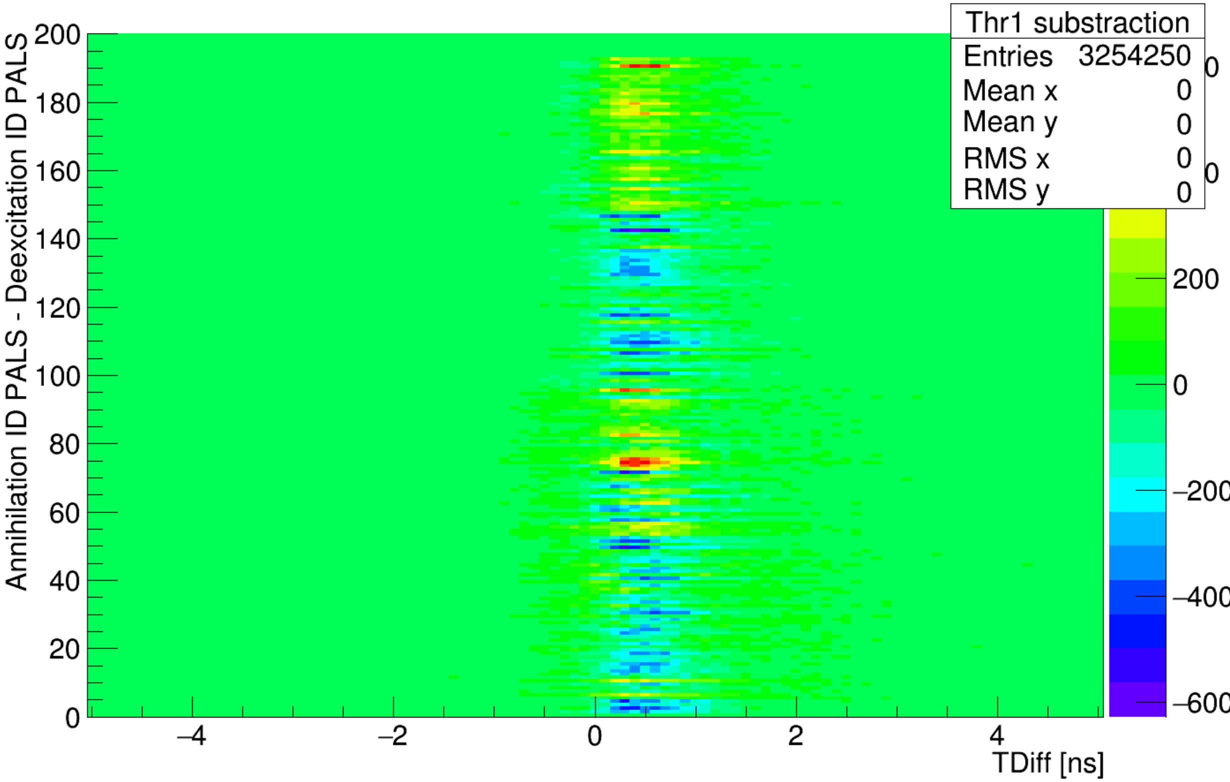


Calibration between modules

Before Calibration (0 iteration)

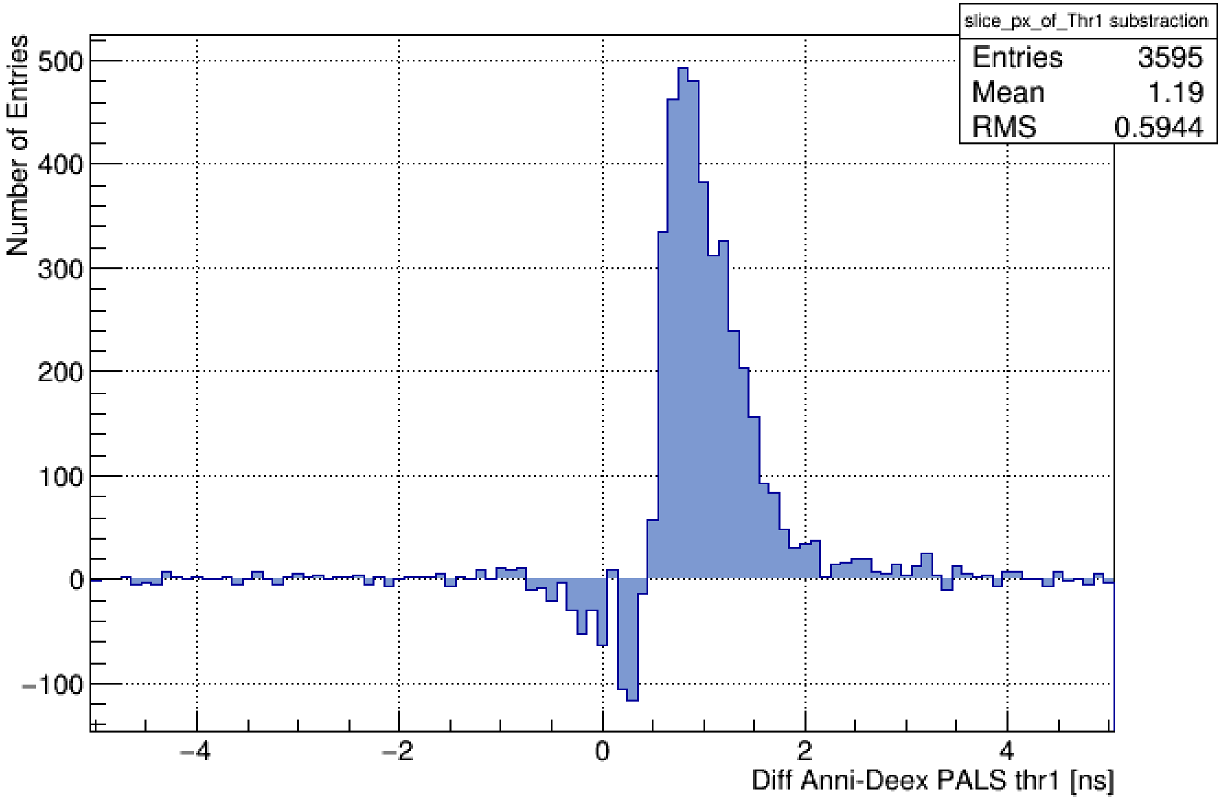


After Calibration (3rd iteration)



Calibration between modules

Before Calibration (0 iteration)



After Calibration (3rd iteration)