Studies of the positronium lifetime with the J-PET tomograph

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September 13th 2017

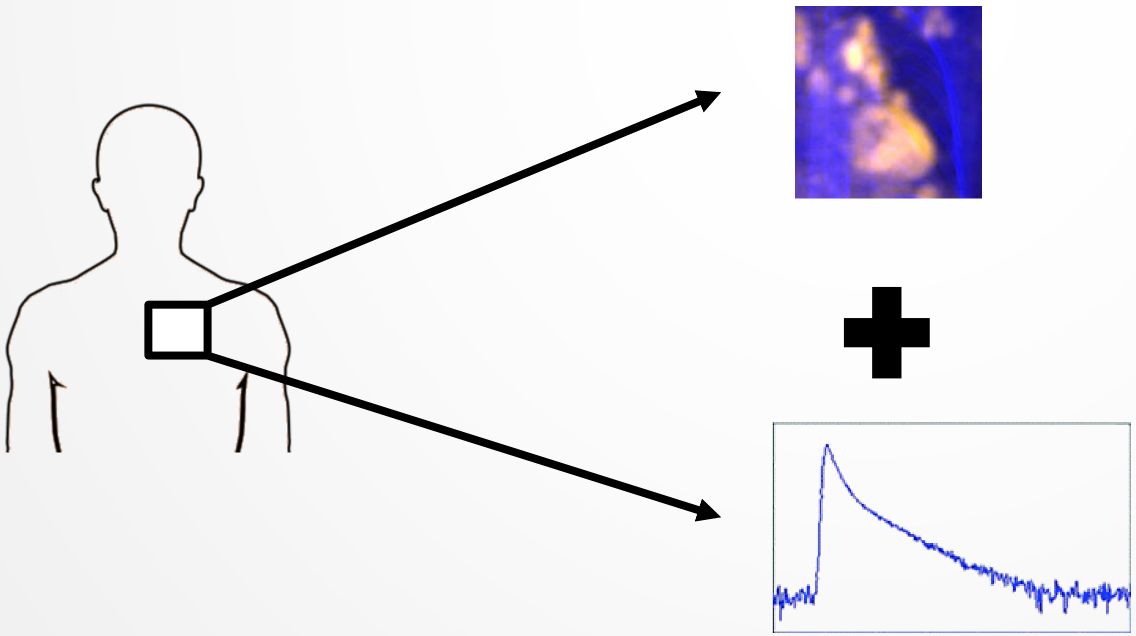
3rd Symposium on Positron Emission Tomography

Outline

- Motivation
- Measurement details
- Selection criteria
- Positonium lifetime spectra
- Calibration using lifetime spectra

Motivation

- Combining metabolic (from PET) and structural (from PALS) information
  -> ***Morphometric image*** *P. Moskal Patent: P405185, PCT/EP2014/068374*
- Possible by J-PET detector, which have access to both information about gamma quanta coming from annihilation of positronium and also from deexcitation of the source of positrons (Lifetime of positronium + position of annihilation)



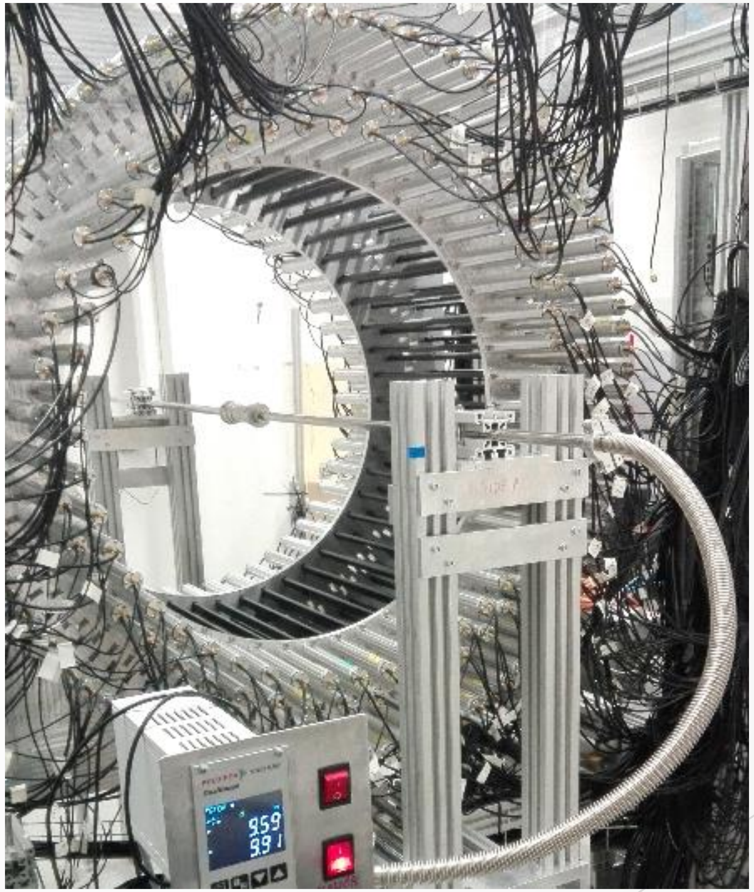
Measurement details

- Measurement with small chamber during the Run-2 (October 14th – November 8th)
- Positron source ^{22}Na (~1 MBq) in the center position (0,0,0), surrounded by XAD4 material (~25% $\frac{3\gamma}{2\gamma}$ [1])
- Pressure sustained in the setup: ~10 Pa

$$^{22}Na \rightarrow {}^{22}Ne^{*} + e^{+} + \nu_{e}$$

$$^{22}Ne^{*} \rightarrow {}^{22}Ne + \gamma_{1274\ keV} \quad \textit{(deexcitation)}$$

$$e^{+}e^{-} \rightarrow n \cdot \gamma_{annihilation} \quad \textit{(annihilation, } n = 2, 3, \ldots\textit{)}$$



[1] *B. Jasińska Acta Phys. Polon. B47, 453 (2016)*

Data analysis

- Early analysis is focused on creating Events -
described in more detail on Monday presentation of K. Kacprzak

Channels — *1 threshold*

↓

Signals — *Set of threshold from one photomultiplier*

↓

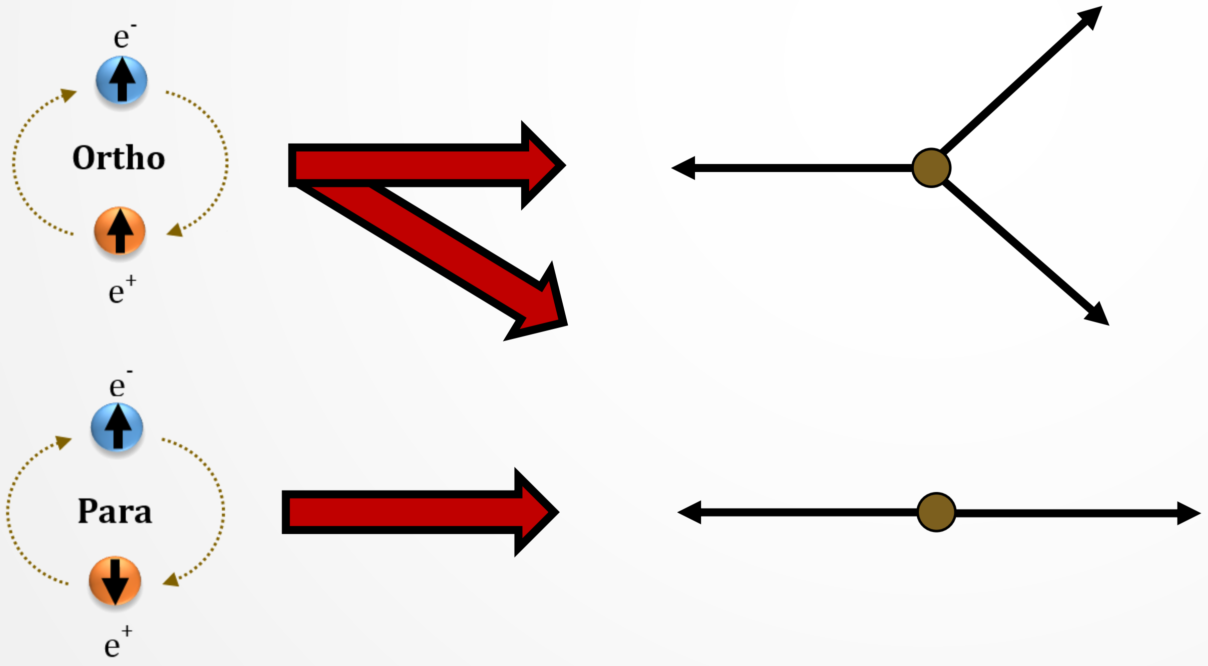
Hits — *Pair of Signals from one scintillator*

↓

Events — *Set of Hits in some Time Window*

Selection criteria

- In order to find events that can origin from true positronium annihilation, set of selection criteria are introduced.
- In general, the only types of annihilation that are taken under consideration are:



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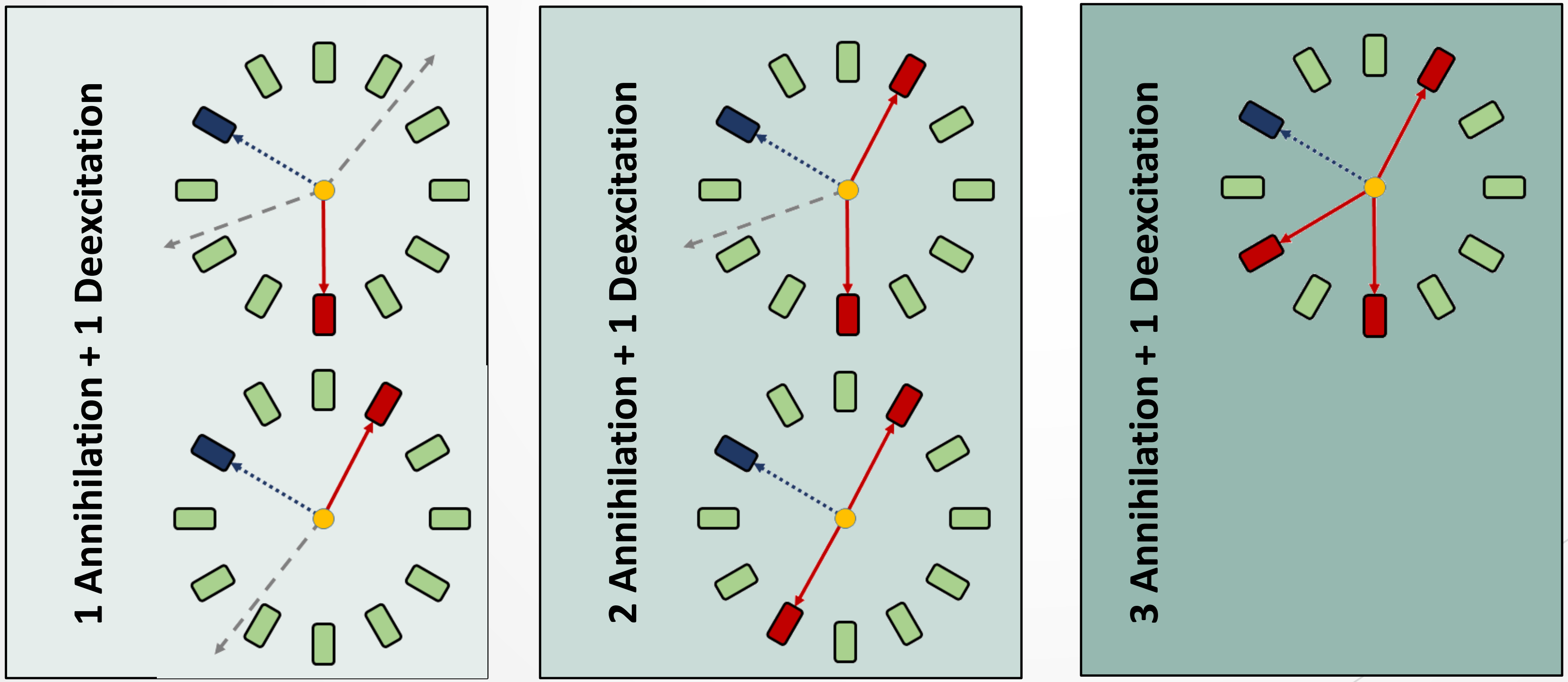
- Considered decays can be mostly detected by J-PET in three configurations



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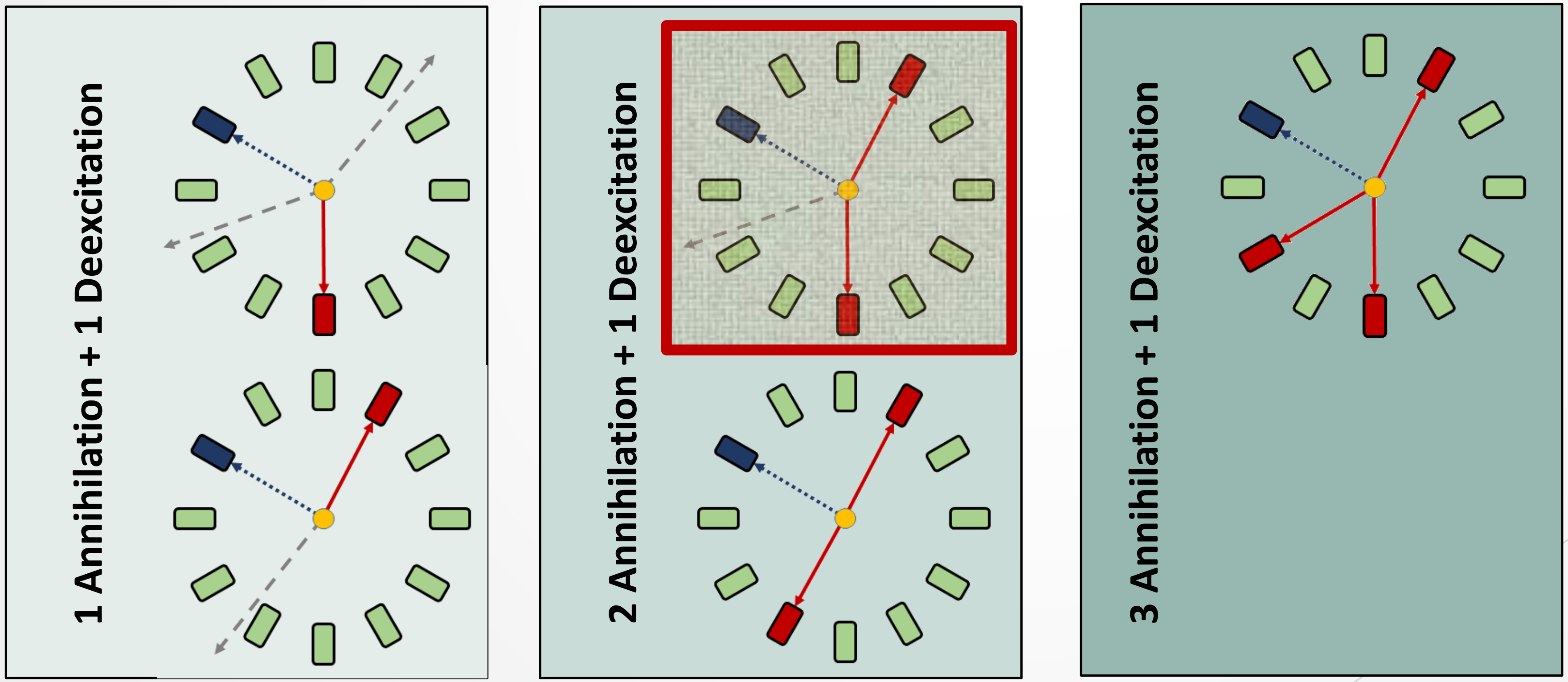


Selection criteria - TOT

- Based on Energy-dependent Time-Over-Threshold (TOT) value each hit is assigned to one of the three Hit-categories:

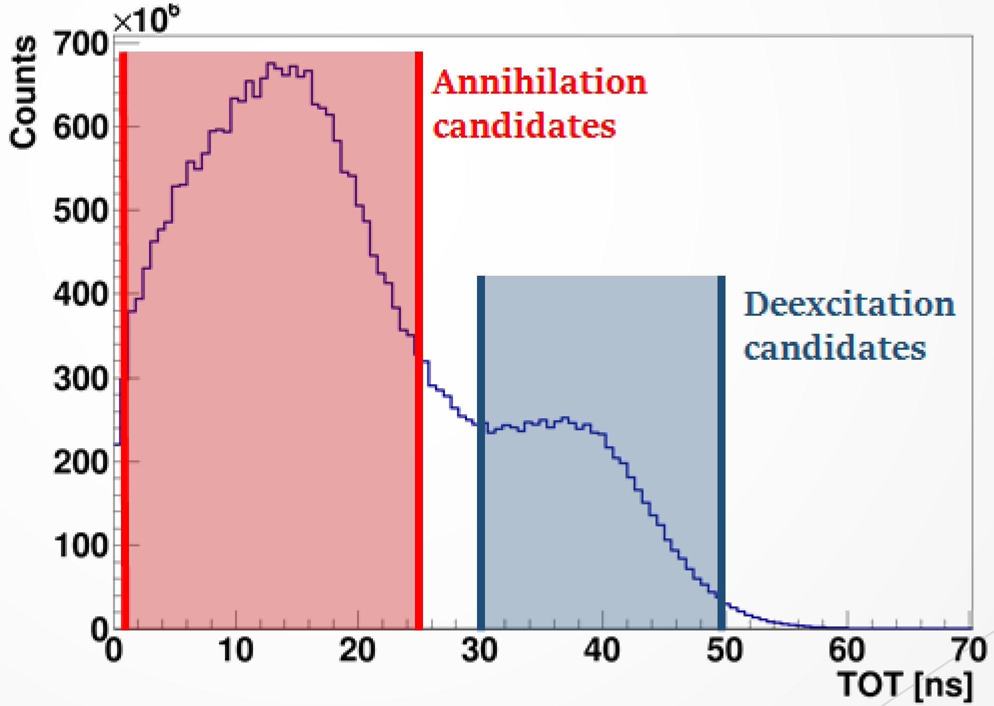
  - **Annihilation candidates**:

    with TOT between 1 and 25 ns

  - **Deexcitation candidates:**

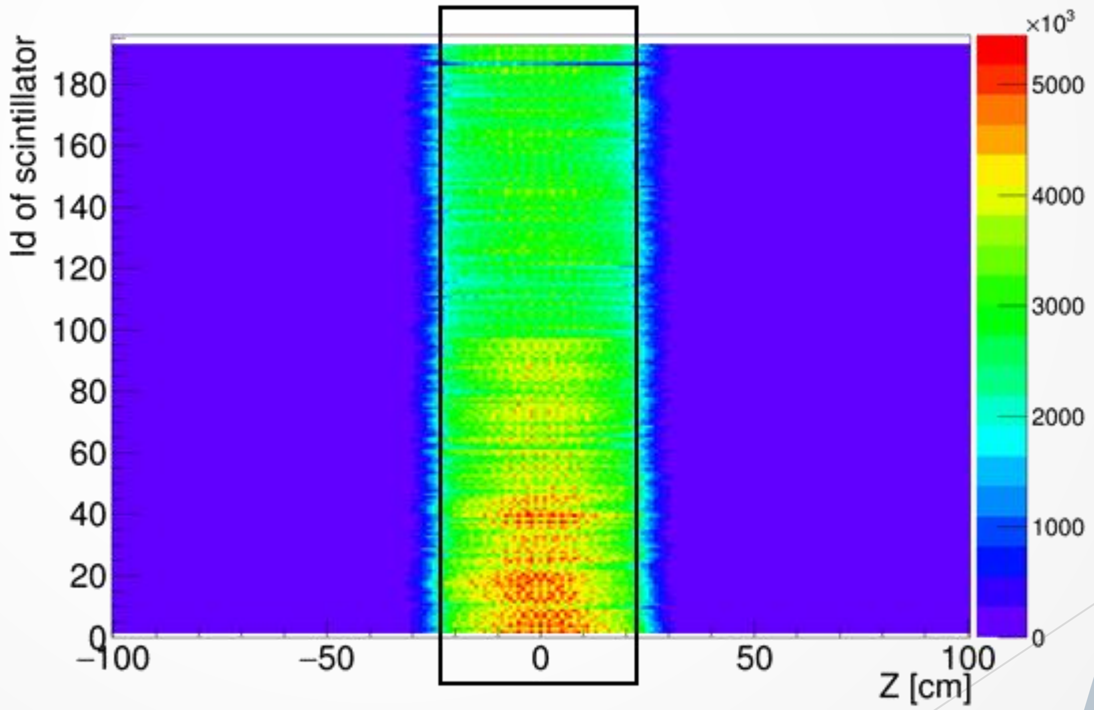
    with TOT between 30 and 50 ns

  - **Other**



Selection criteria – Z position

- Hits should be properly registered and come from real gamma quanta. That is why the reconstructed position of the Hit should be in the boundaries of the active part of detector – scintillators.
  - Scintillator length – 50 cm
  - 1 cm from each side of the scintillator is in the holder
  - 1 cm additionally cut to avoid taking Hit from the boundary of the scintillator
  - Acceptable part of the scintillator - 46 cm
  - Hit is accepted for next steps of analysis if:



$-23\ \text{cm} < Z_{hit} < 23\ \text{cm}$

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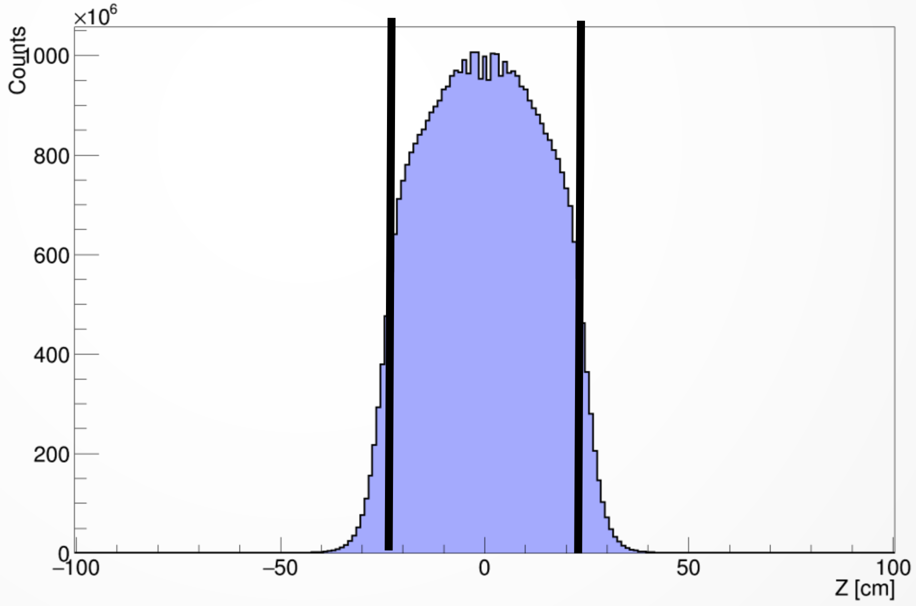
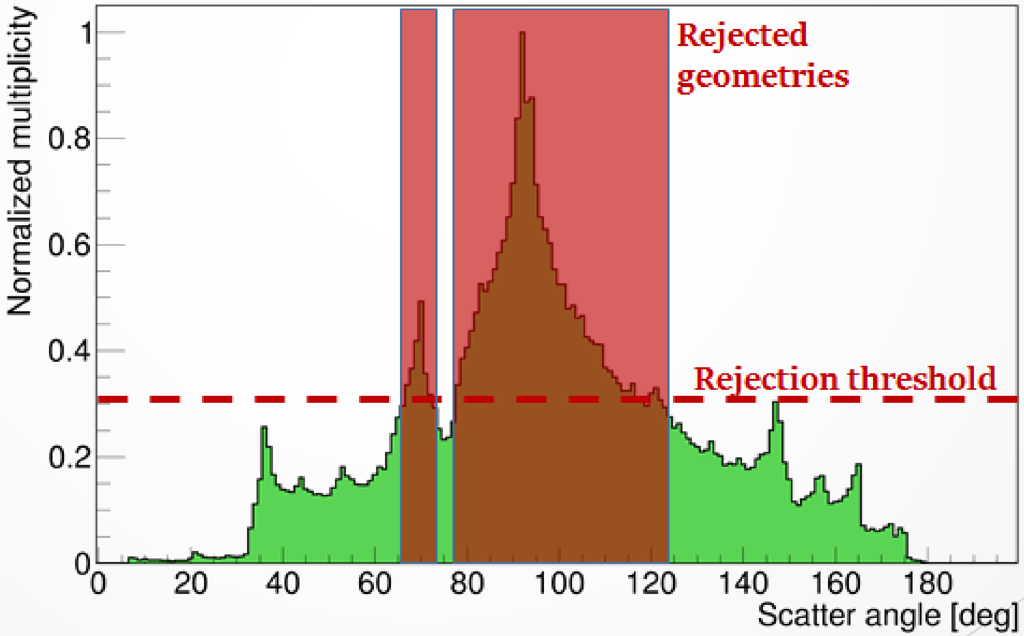


- 23 cm < Z_{hit} < 23 cm

Selection criteria – Scatter extenuation

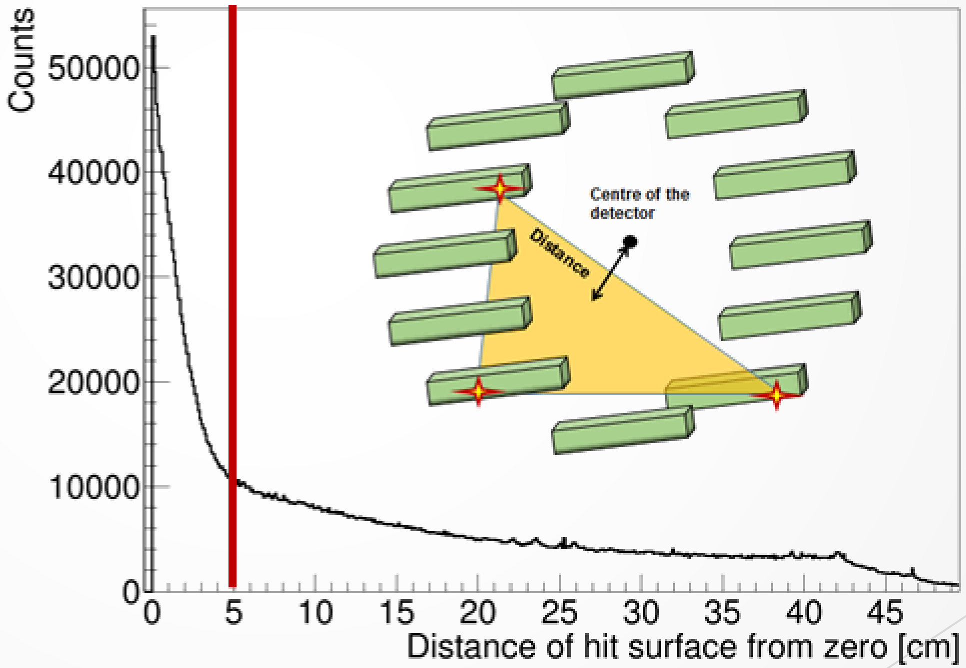
- In order to reject scatterings from the 1 Annihilation + 1 Deexcitation configuration (for other categories there is more information and scatterings can be rejected by other criteria) geometries that are most probably coming form scatterings are rejected.

Pair of Hits
Annihilation-Deexcitation
is rejected from the analysis
if the Scatter Angle calculated
from their position is in the
Rejected geomteries area



Selection criteria – Distance

- Source and material is in the center of the detector (0,0,0) – Position of the Annihilation of the Positronium and the Deexcitation of the source should take place near the center.
  - Distance of Hit surface constructed from the positions of the Hits should also be close to zero
    - Annihilation into 2 gamma quanta: Hit surface is constructed from 2 Annihilation Hits and 1 Deexcitation
    - Annihilation into 3 gamma quanta: Hit surface is constructed from 3 Annihilation Hits

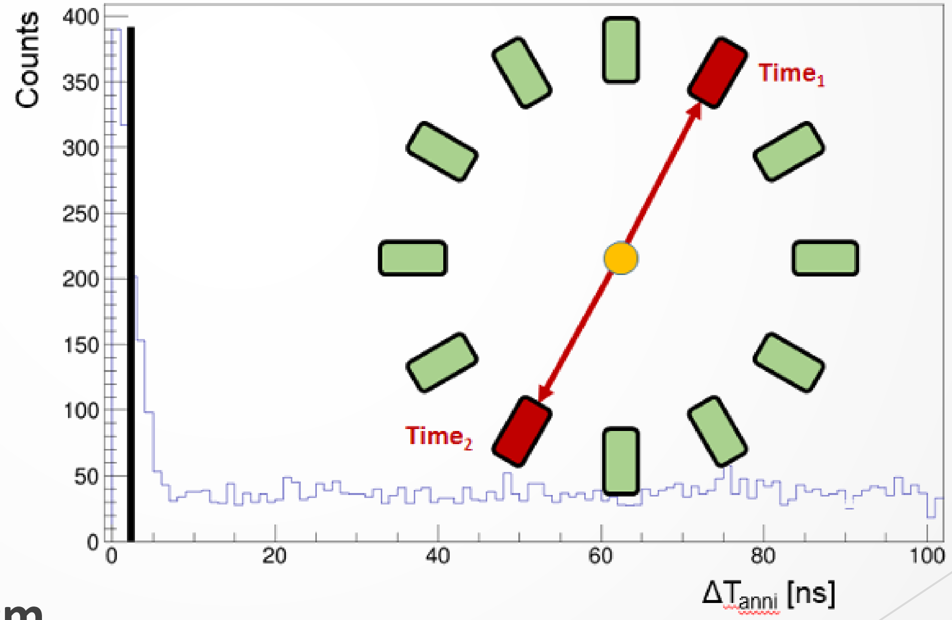


  - Event is assigned to Candidate for Annihilation into 2/3 if

Distance of Hit surface < 5 cm

Selection criteria – Time difference

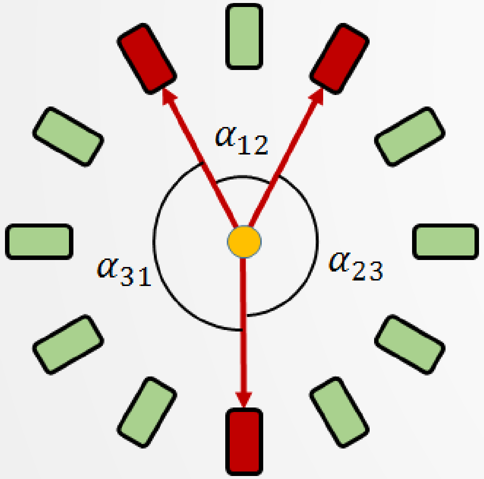
- Source and material is in the center of the detector (0,0,0) – Position of the Annihilation of the Positronium should take place near the center.
  - Annihilation Time difference (ΔT_{anni}) should be also close to zero
    - Annihilation into 2 gamma quanta: $\Delta T_{anni} = t_{Hit2} - t_{Hit1}$
    - Annihilation into 3 gamma quanta: $\Delta T_{anni} = t_{Hit3} - t_{Hit1}$
  - Event is assigned to Candidate for Annihilation into 2/3 if



Annihilation Time Difference < 1.5 cm

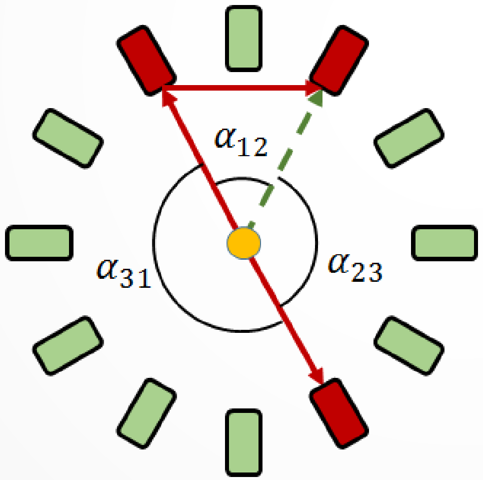
Selection criteria – Angles

- In order to distinguish Annihilation into 2 and Annihilation into 3 candidates, angle criterion is introduced
using the approach from D. Kisielewska Eur. Phys. J. C 76, 445 (2016)



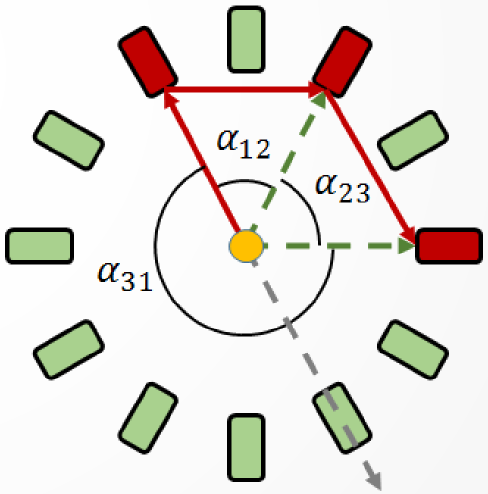
o-Ps into 3γ

$\alpha_{12} + \alpha_{23} > 180^o$



p-Ps + single scattering

$\alpha_{12} + \alpha_{23} = 180^o$

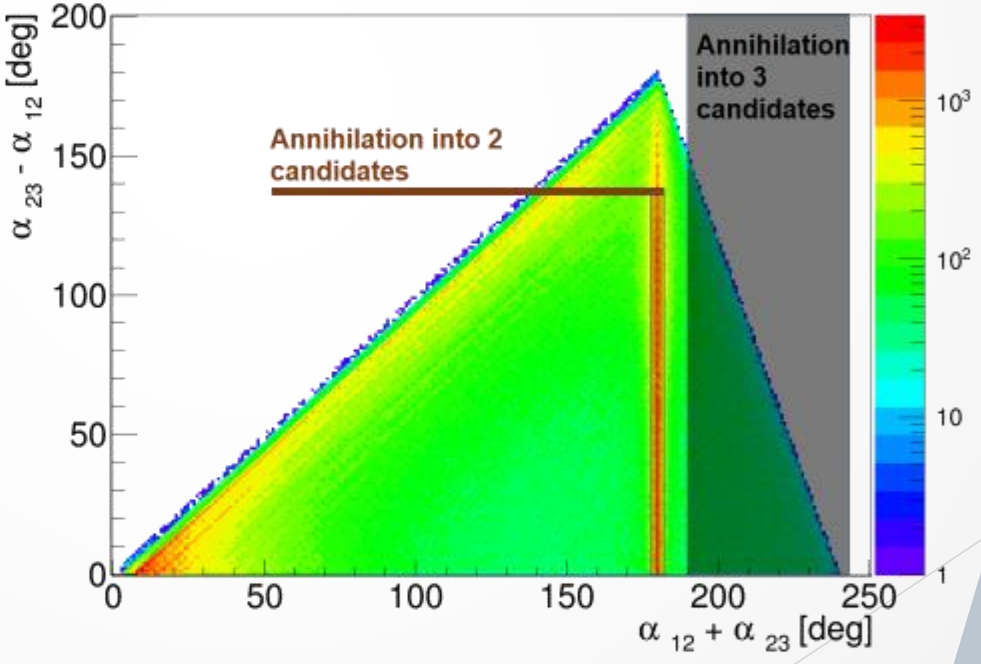


p-Ps + double scattering

$\alpha_{12} + \alpha_{23} < 180^o$

Selection criteria – Angles

- In order to distinguish Annihilation into 2 and Annihilation into 3 candidates, angle criterion is introduced
  using the approach from D. Kisielewska Eur. Phys. J. C 76, 445 (2016)
  - Sum of the two smalles angles ($\alpha_{12} + \alpha_{23}$) should be different for the different ways of annihilation



  - Annihilation into 2 gamma quanta:

177° < $\alpha_{12} + \alpha_{23}$ < 183°

Additionally to reduce impact of scatterings
$\alpha_{12} - \alpha_{23}$ < *130⁰*

  - Annihilation into 3 gamma quanta:
    190° < $\alpha_{12} + \alpha_{23}$

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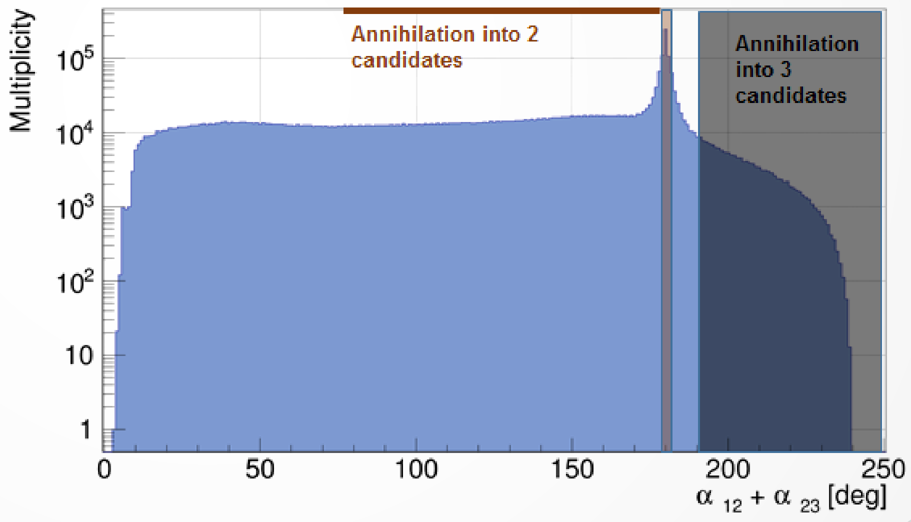


  - Annihilation into 2 gamma quanta:

$177^o < \alpha_{12} + \alpha_{23} < 183^o$

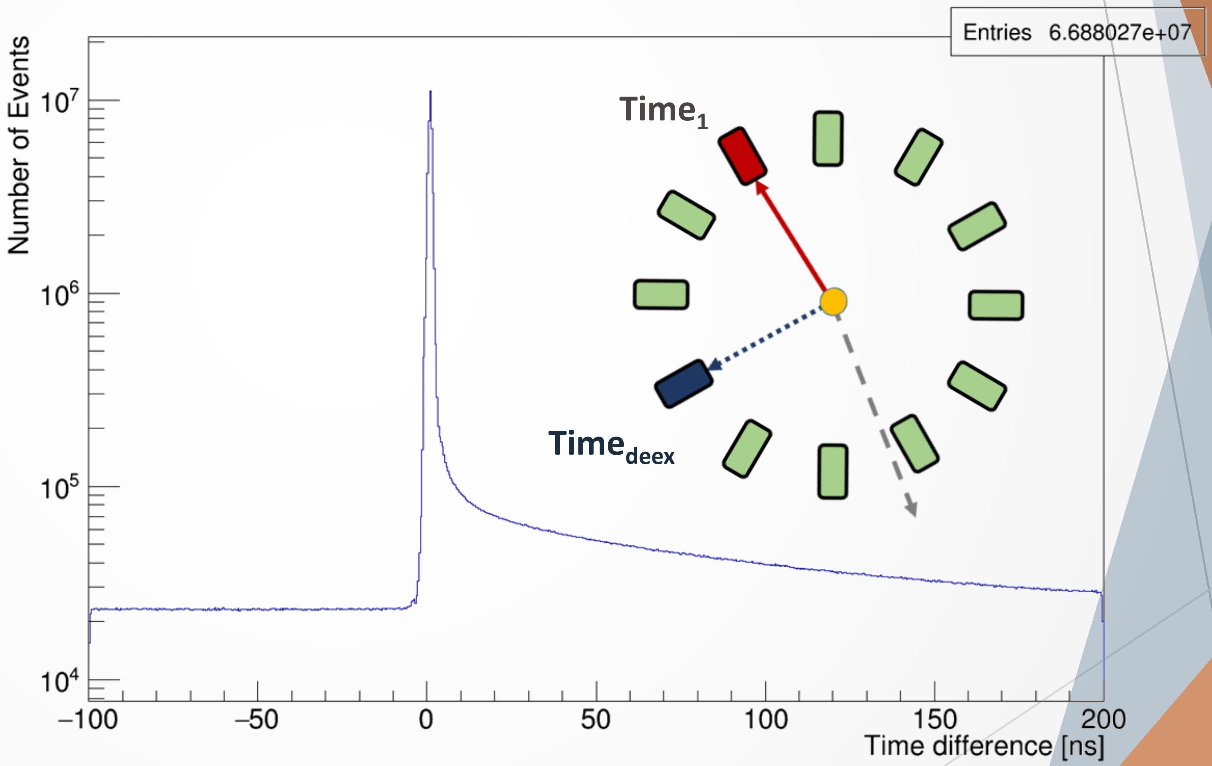
Additionally to reduce impact of scatterings $\alpha_{12} - \alpha_{23} < 130^0$

  - Annihilation into 3 gamma quanta:
    $190^o < \alpha_{12} + \alpha_{23}$

Positronium lifetime spectra – 1 Annihilation + 1 Deexcitation

Applied criteria:

- Only one Annihilation Hit and only one Deexcitation Hit in Event
- $- 23\text{ cm} < Z_{hit} < 23\text{ cm}$
- Pair Annihilation-Deexcitation pass Scatter extenuation
- Pair Annihilation-Deexcitation does not come from the same scintillator
- Times corrected on TOF to the center of the detector

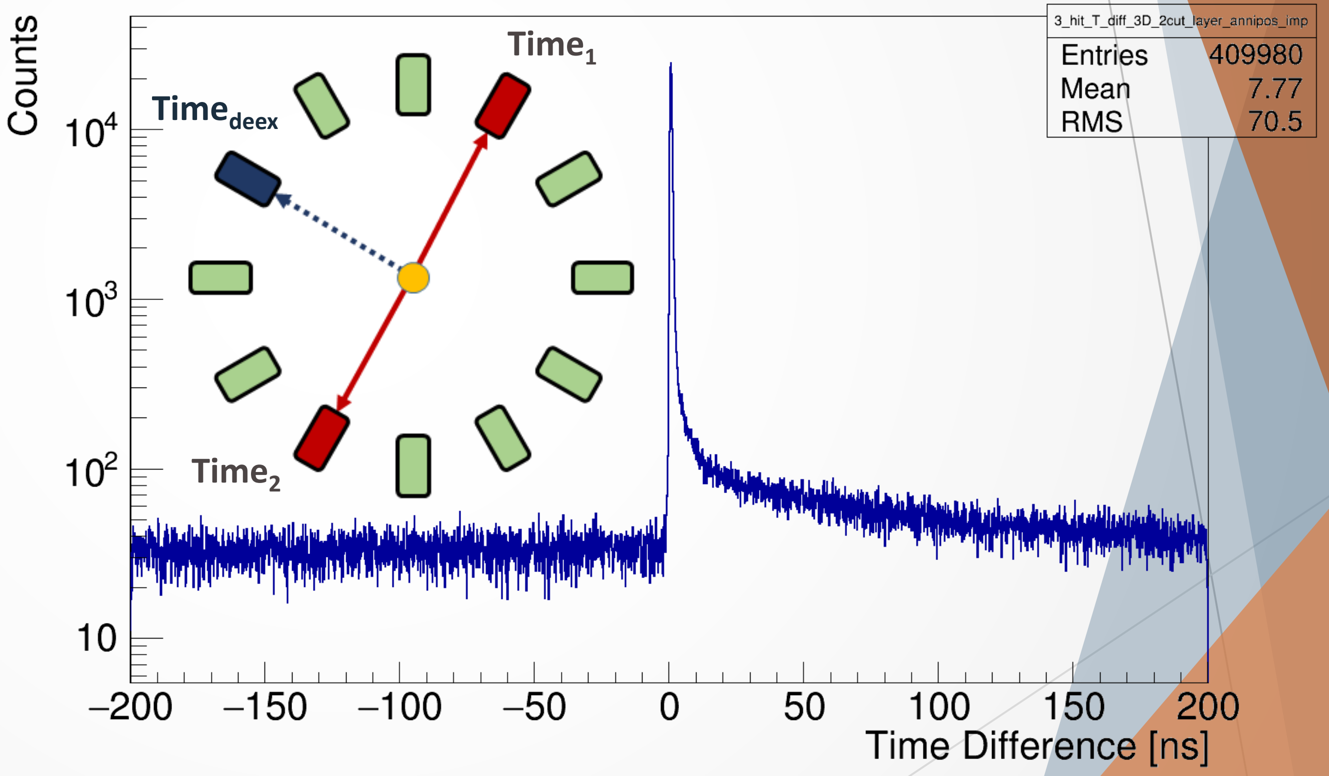


Time difference = $Time_1$ - $Time_{deex}$

Positronium lifetime spectra – 2 Annihilation + 1 Deexcitation

Applied criteria:

- Only two Annihilation Hits and only one Deexcitation Hit in Event
- -23 cm $< Z_{hit} <$ 23 cm
- Distance of Hit surface < 5 cm
- $\Delta t_{anni} < 1.5$ ns
- $177^o < \alpha_{12} + \alpha_{23} < 183^o$
  $\alpha_{12} - \alpha_{23} < 130^0$
- None of the possible Pair of Hits in Event come from the same scintillator
- Times corrected on TOF (Center for the Deexcitation, Position for Annihilation for the rest)

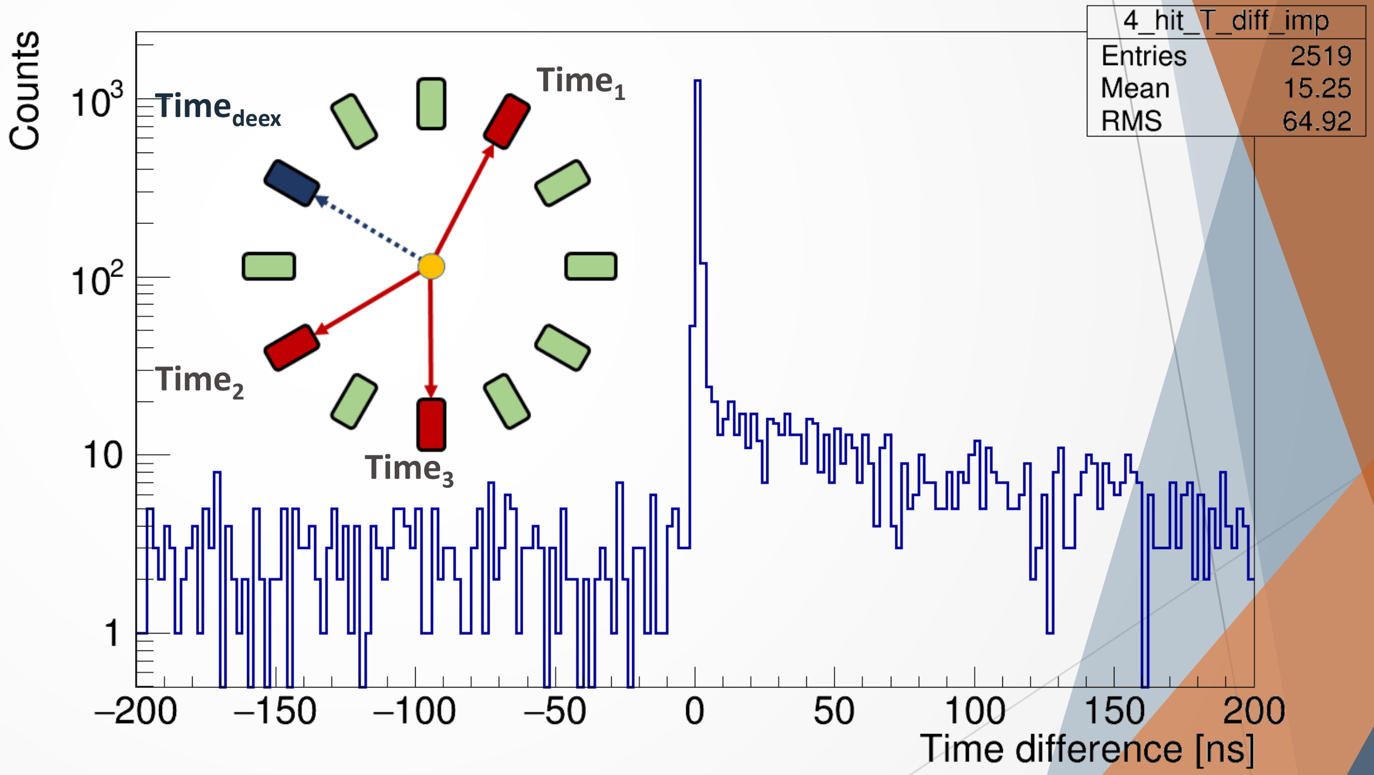


Time difference = $(\text{Time}_1 + \text{Time}_2)/2 - \text{Time}_{deex}$

Positronium lifetime spectra – 3 Annihilation + 1 Deexcitation

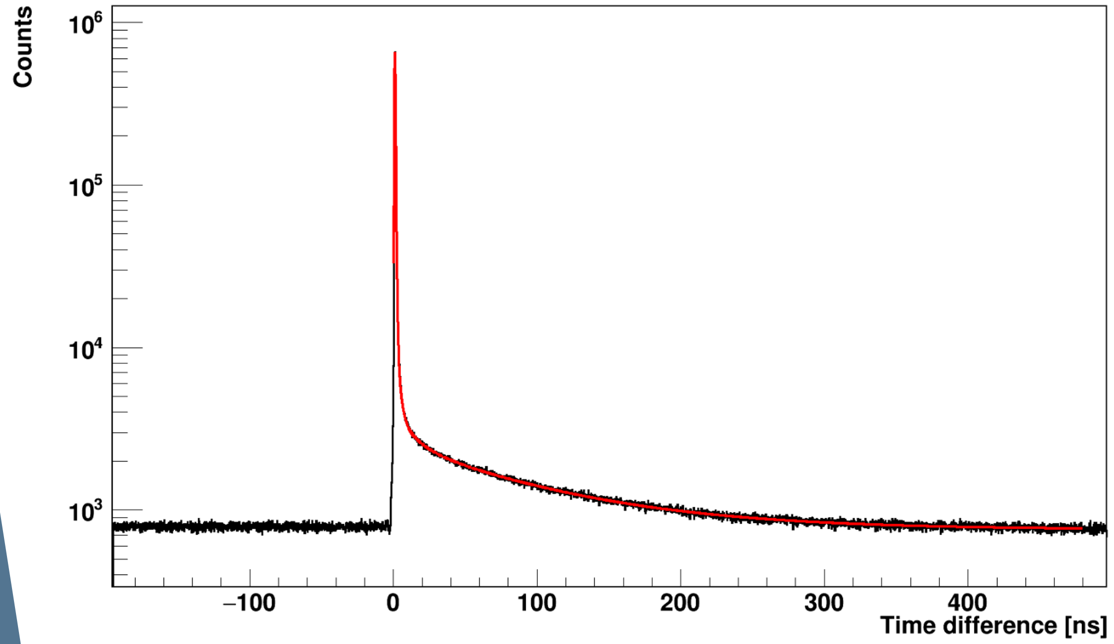
Applied criteria:

- Only three Annihilation Hits and only one Deexcitation Hit in Event
- - 23 cm < Z_{hit} < 23 cm
- Distance of Hit surface < 5 cm
- Δt_{anni} < 1.5 ns
- $\alpha_{12} + \alpha_{23}$ < 190°
- None of the possible Pair of Hits in Event come from the same scintillator
- Times corrected on TOF (Center for the Deexcitation, Position for Annihilation for the rest)



Time difference = ($Time_1$ + $Time_2$ + $Time_3$)/3 - $Time_{deex}$

Positronium lifetime spectra –
1 Annihilation + 1 Deexcitation – with fit

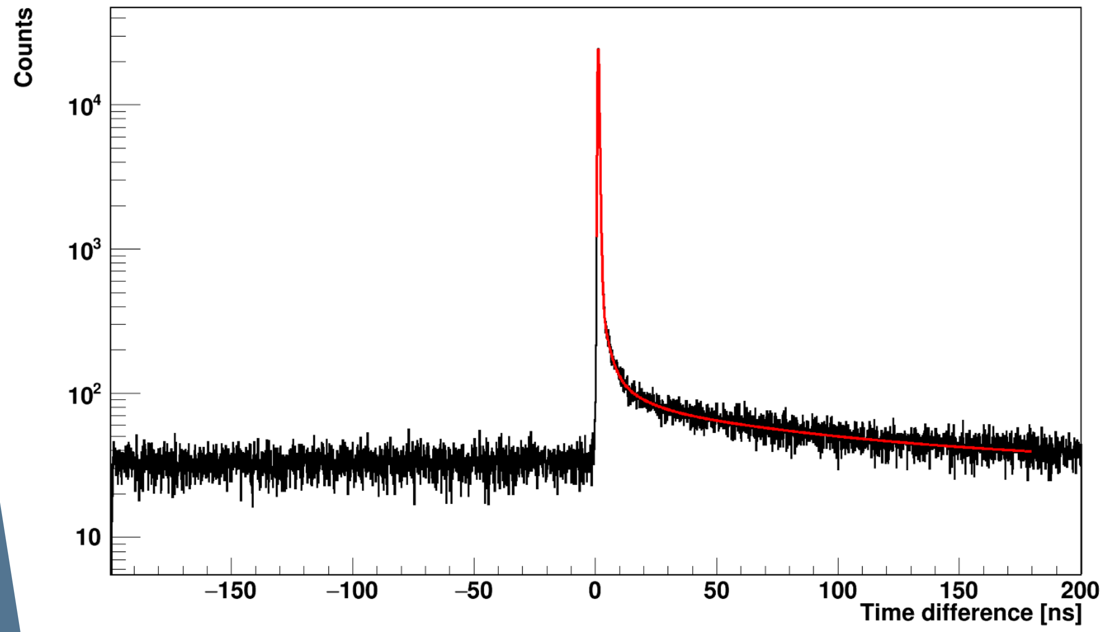


	PAv	[1]
Lifetime for 1 Component [ns] - fixed	*0.22*	-
Intensity for 1 Component in percent	19.9 (1.8)	-
Lifetime for 2 Component [ns] - source	*0.374*	*0.374*
Intensity for 2 Component in percent - source	*10*	*10*
Lifetime for 3 Component [ns]	0.487 (16)	
Intensity for 3 Component in percent	30.2 (4.2)	
Lifetime for 4 Component [ns]	2.174 (97)	2.45 (25)
Intensity for 4 Component in percent	3.54 (45)	3.3 (0.6)
Lifetime for 5 Component [ns]	12.10 (65)	10.2 (0.6)
Intensity for 5 Component in percent	2.17 (19)	2.8 (0.5)
Lifetime for 6 Component [ns]	94.1 (1.8)	90.8 (1.2)
Intensity for 6 Component in percent	21.9 (1.3)	40.4 (0.4)
Lifetime for p-PS Component - fixed	*0.125*	*0.125*
Intensity for p-PS Component in percent	20.1 (2.1)	
Rsquared	0.994	
ChiSquared/DegreesOfFreedom	1.0979	

Sigma for 1 Gauss [ns]	0.149 (16)
FWHM for 1 Gauss [ns]	0.352 (38)
Fraction for 1 Gauss	0.06 (01)
Sigma for 2 Gauss [ns]	0.267 (02)
FWHM for 2 Gauss [ns]	0.628 (04)
Fraction for 2 Gauss	0.94 (05)

[1] B. Jasińska Acta Phys. Polon. B47, 453 (2016)

Positronium lifetime spectra – 2 Annihilation + 1 Deexcitation – with fit



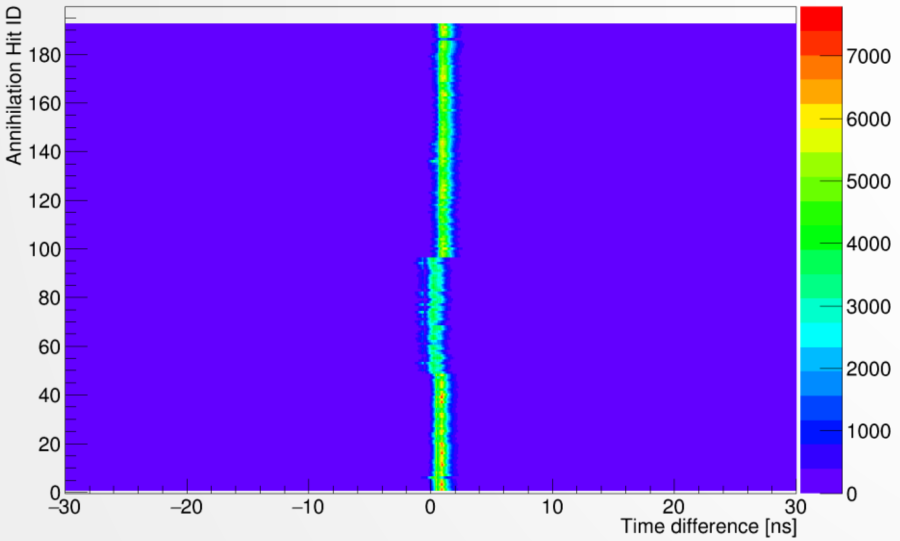
Sigma for 1 Gauss [ns]	0.275 (19)
FWHM for 1 Gauss [ns]	0.647 (45)
Fraction for 1 Gauss	0.23 (02)
Sigma for 2 Gauss [ns]	0.242 (04)
FWHM for 2 Gauss [ns]	0.571 (10)
Fraction for 2 Gauss	0.77 (03)

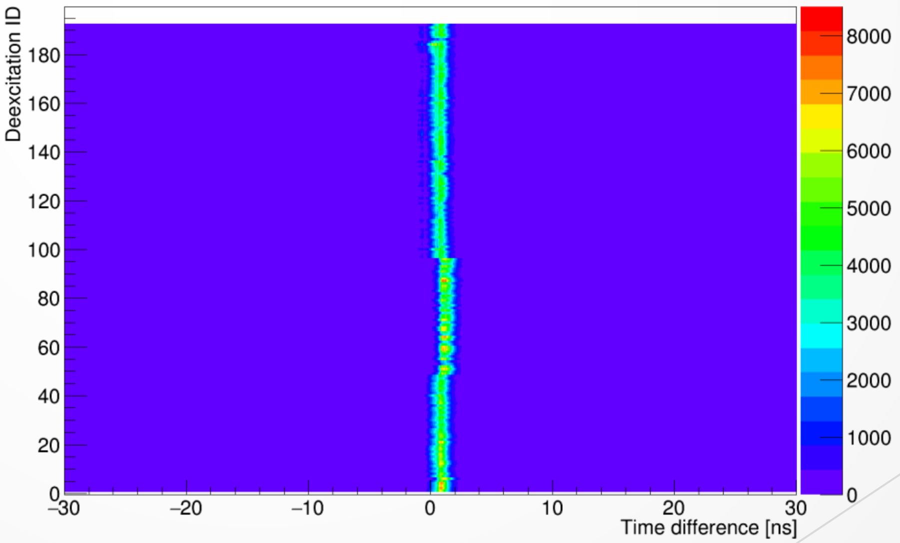
	PAv	[1]
Lifetime for 1 Component [ns] - fixed	*0.22*	-
Intensity for 1 Component in percent	13.6 (1.0)	-
Lifetime for 2 Component [ns] - source	*0.374*	*0.374*
Intensity for 2 Component in percent - source	*10*	*10*
Lifetime for 3 Component [ns]	0.397 (07)	
Intensity for 3 Component in percent	44.2 (1.9)	
Lifetime for 4 Component [ns]	2.88 (25)	2.45 (25)
Intensity for 4 Component in percent	4.52 (31)	3.3 (0.6)
Lifetime for 5 Component [ns]	10.90 (93)	10.2 (0.6)
Intensity for 5 Component in percent	2.53 (36)	2.8 (0.5)
Lifetime for 6 Component [ns]	90.9 (2.4)	90.8 (1.2)
Intensity for 6 Component in percent	18.29 (56)	40.4 (0.4)
Lifetime for p-PS Component - fixed	*0.125*	*0.125*
Intensity for p-PS Component in percent	16.87 (1.2)	
Rsquared	0.9964	
ChiSquared/DegreesOfFreedom	1.0244	

[1] B. Jasińska Acta Phys. Polon. B47, 453 (2016)

Calibration using lifetime spectra

- Positronium Lifetime Distribution can be also used as the calibration tool between scintillators, because lifetime distribution does not depend on the scintillators where gamma quanta coming from Deexcitation/Annihilation is detected.





Calibration using lifetime spectra

- Positronium Lifetime Distribution can be also used as the calibration tool between scintillators, because lifetime distribution does not depend on the scintillators where gamma quanta coming from Deexcitation/Annihilation is detected.

Proposition of iterative algorithm:

- Finding maximum of lifetime distribution for each Annihilation ID (Max^{Anni}_{ID})
- Finding maximum of lifetime distribution for each Deexcitation ID (Max^{Deex}_{ID})
- Correction for scintillator: = (Max^{Anni}_{ID} – Max^{Deex}_{ID})/2

Calibration using lifetime spectra

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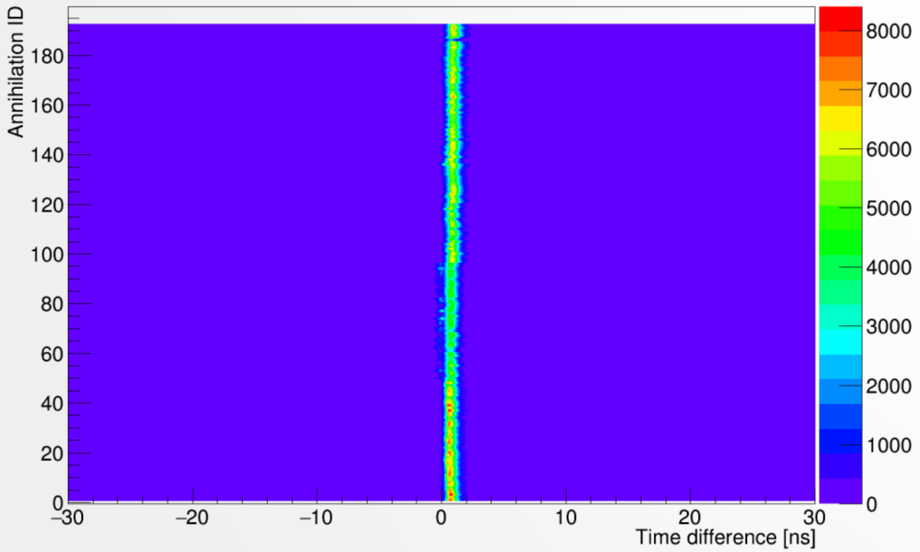
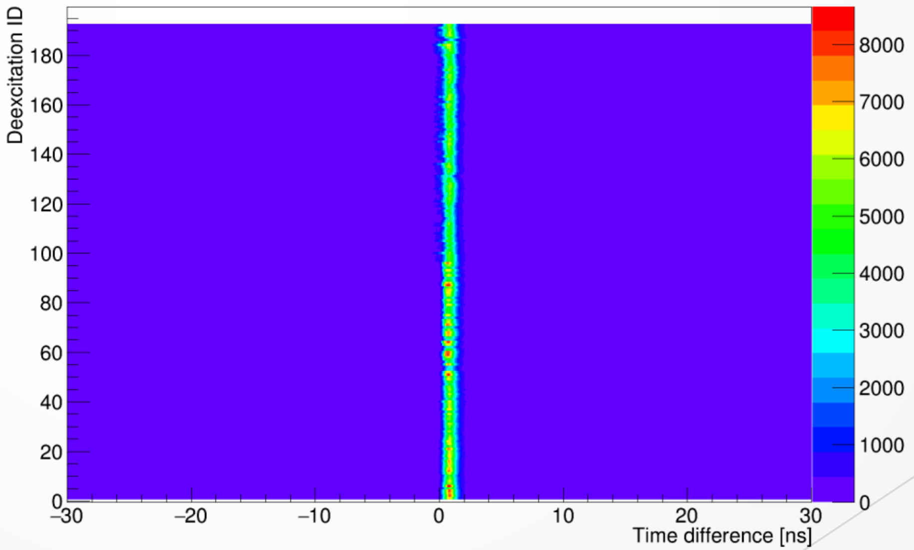




Summary

- Set of criteria were introduced to choose candidates for three configurations of positronium annihilation detected by J-PET detector
- Positronium Lifetime spectra were collected and analyzed
- Fit results were comparable with results from publication from standard PALS setup
- New idea for calibration was proposed

Next step:

- Measurement with different samples in the same time -> Morphometric imaging

Thank You For Your Attention

PALS Avalanche comparison with LT 9.2

PALS Avalanche – fitting procedure dedicated for J-PET detector for fitting positron lifetime spectra using ROOT software

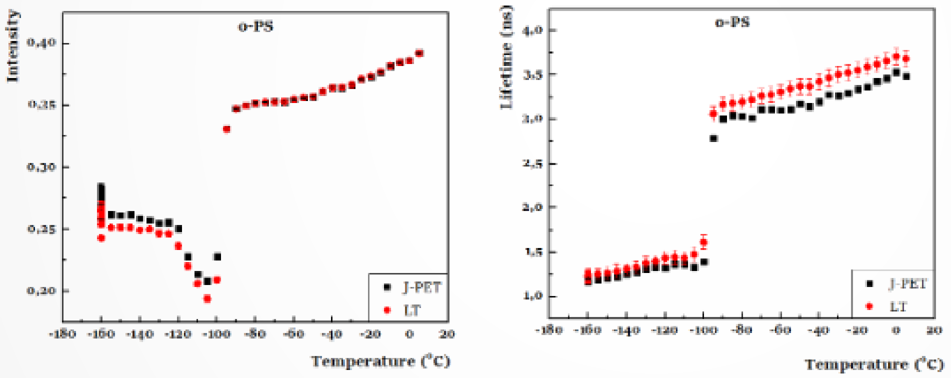


Fig. 3.3. Results of the hexane scan shown as dependence of ortho-Positroinum lifetime and intensity over temperature. In the left panel, data from LT and J-PET software above -100 °C are superimposed.

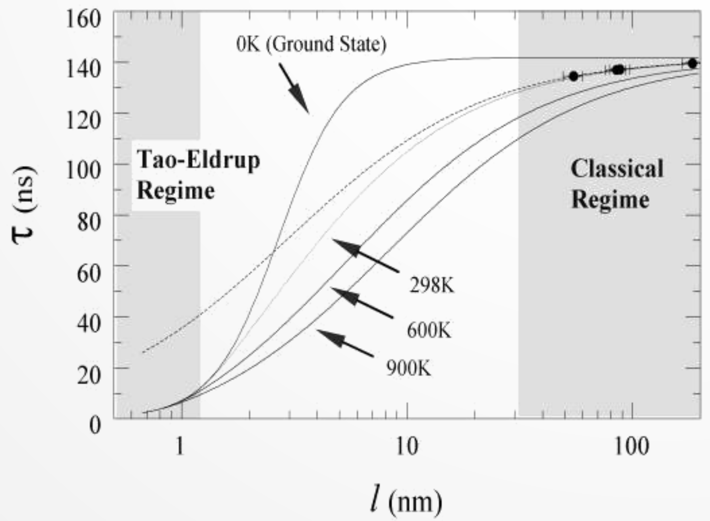
Analysis procedure of the positronium lifetime spectra for the J-PET detector

K. Dulski et al., Acta Phys. Polon. A 132, no. 5, 1637 (2017)

Structural information and Lifetime of Positronium

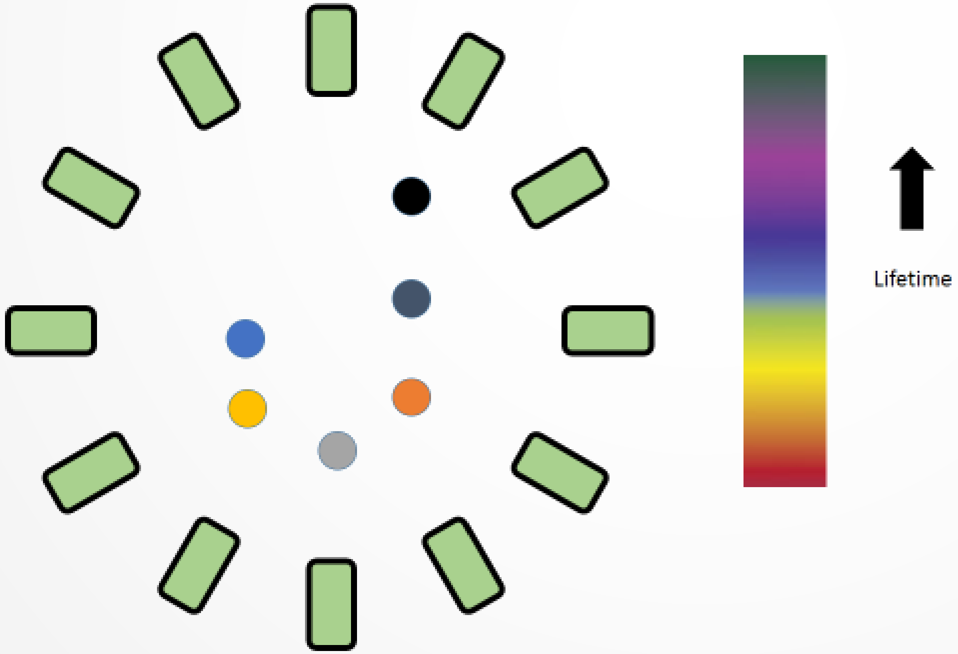
Positronium lifetime can be translated into radius of free volumes in material by Tao-Eldrup model and its modification

$$\tau_{o\text{-Ps}}^{-1}[\mathrm{ns}] = 2(\mathrm{ns})^{-1}\left[1 - \frac{R}{R_0} + \frac{1}{2\pi}\sin\left(\frac{2\pi R}{R_0}\right)\right]$$

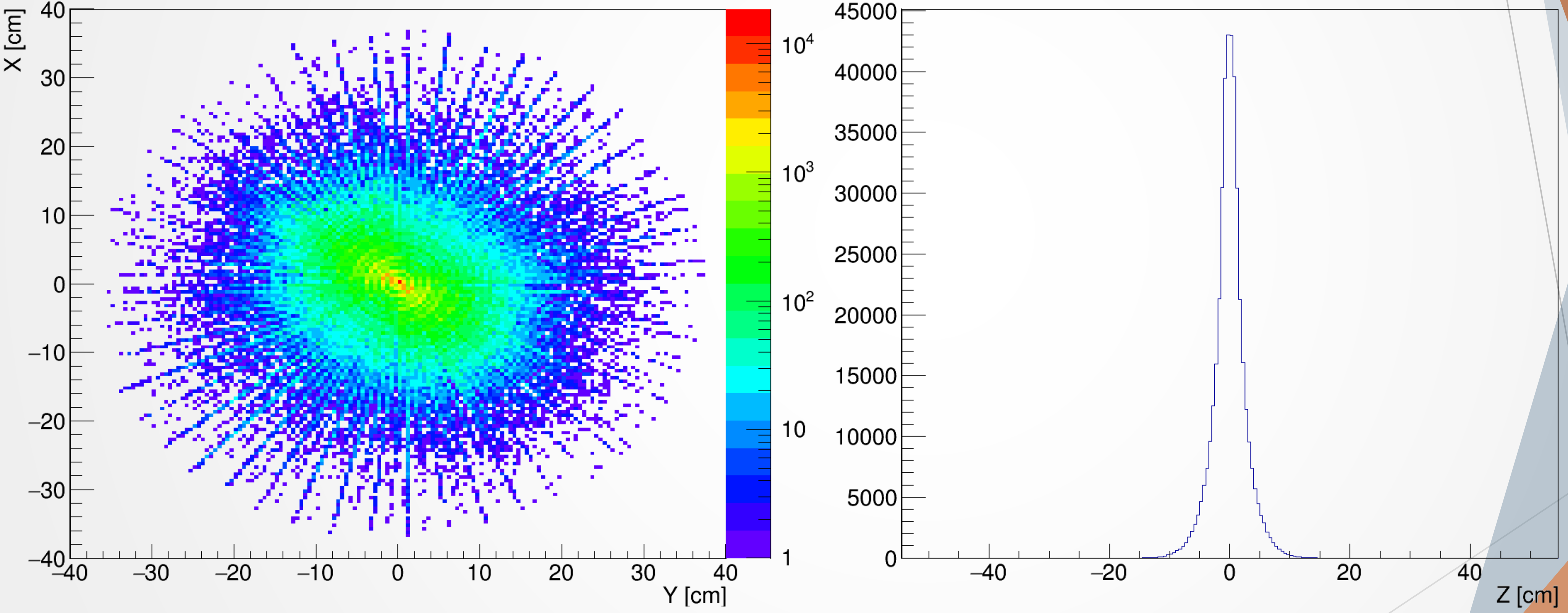


Idea of experiment for morphometric imaging

- Placing 6-8 source with different materials around them in the J-PET

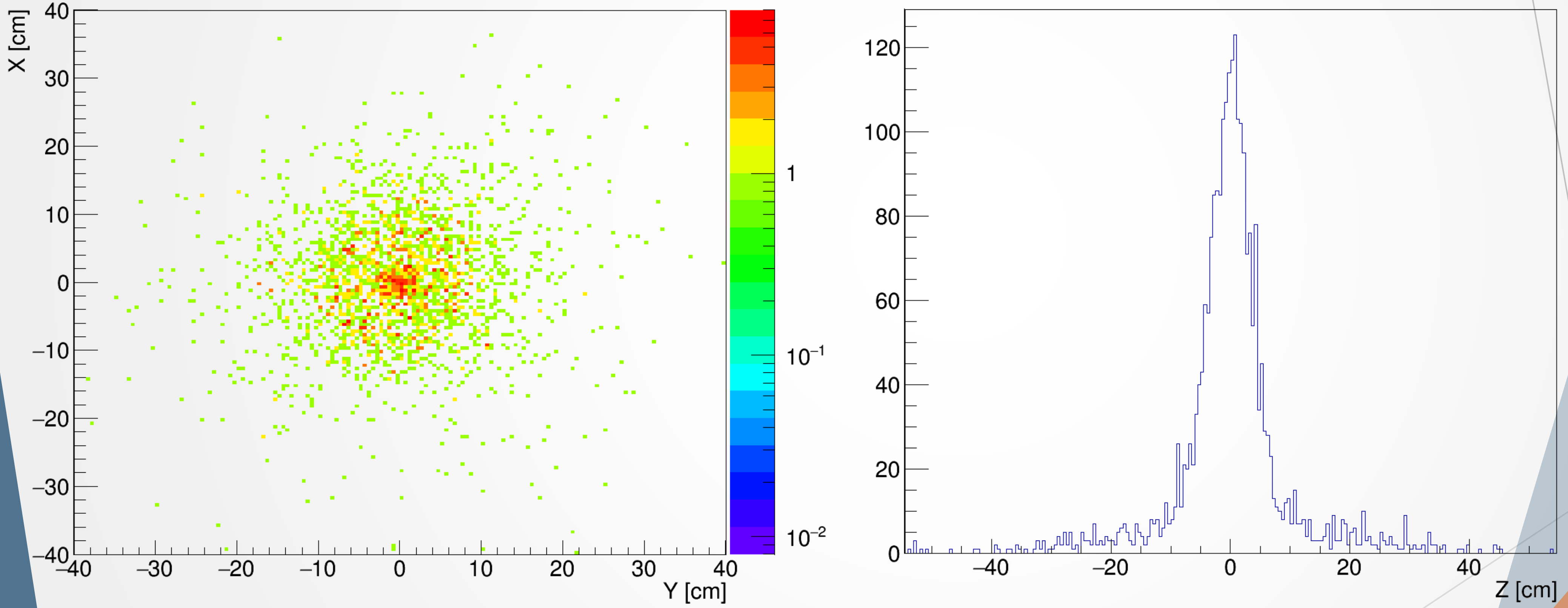


Reconstructed positions of Annihilation into 2 candidates



Naive reconstruction

Reconstructed positions of Annihilation into 3 candidates



GPS variational-like method