Identification and reocnstruction of ortho-positronium decays in J-PET

3rd Symposium on Positron Emission Tomography
September 11th 2018

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on behalf of the J-PET Collaboration
Jagiellonian University

European Funds Smart Growth
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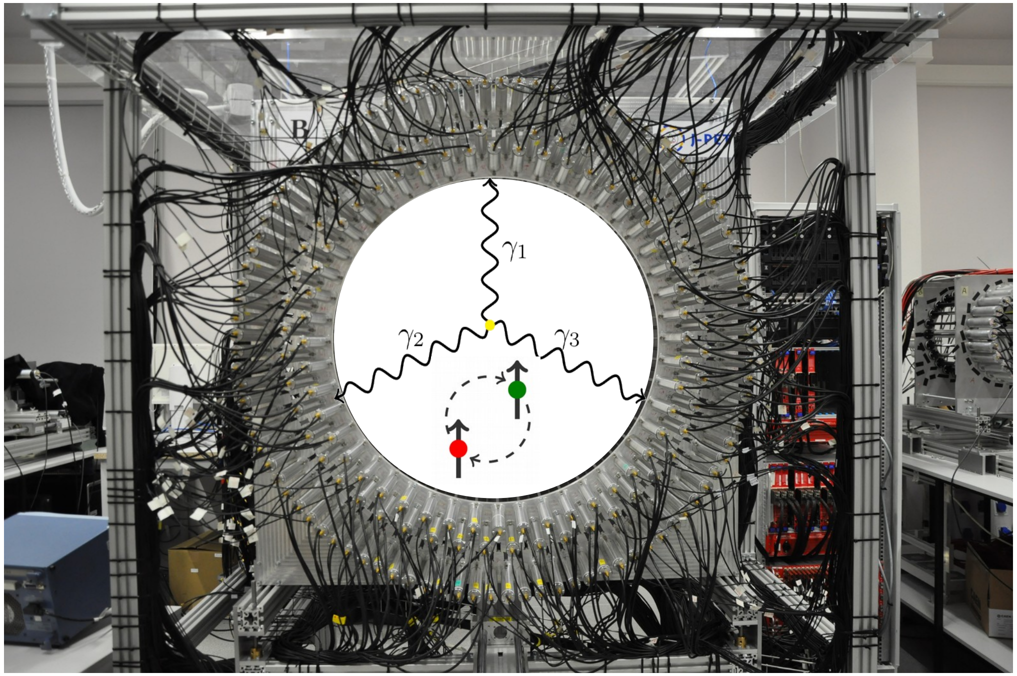
European Union European Regional Development Fund

Why do we need o-Ps → 3γ decays in J-PET?



Medical imaging with spatially-resolved Positron Annihilation Lifetime Spectroscopy

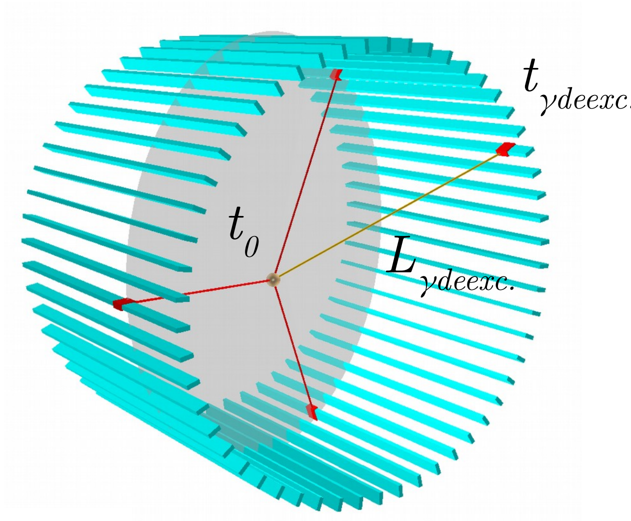
Tests of fundamental discrete symmetries with angular correlation operators in the o-Ps→3γ decays

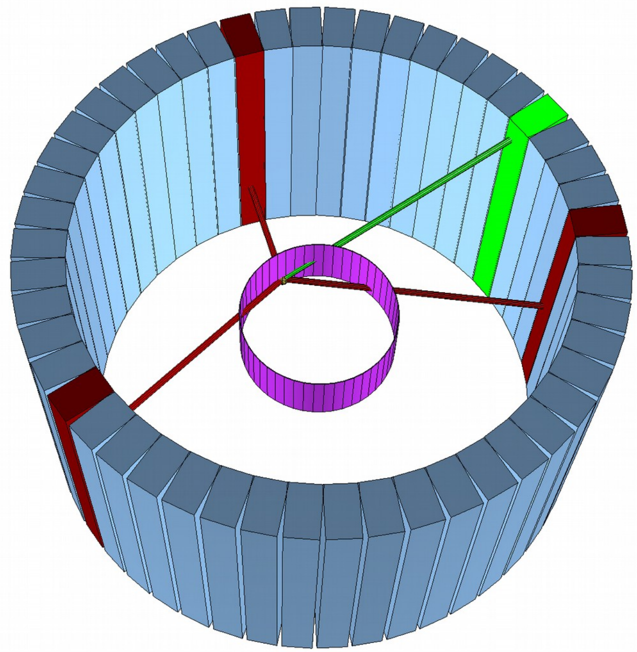
Motivation I: Medical imaging

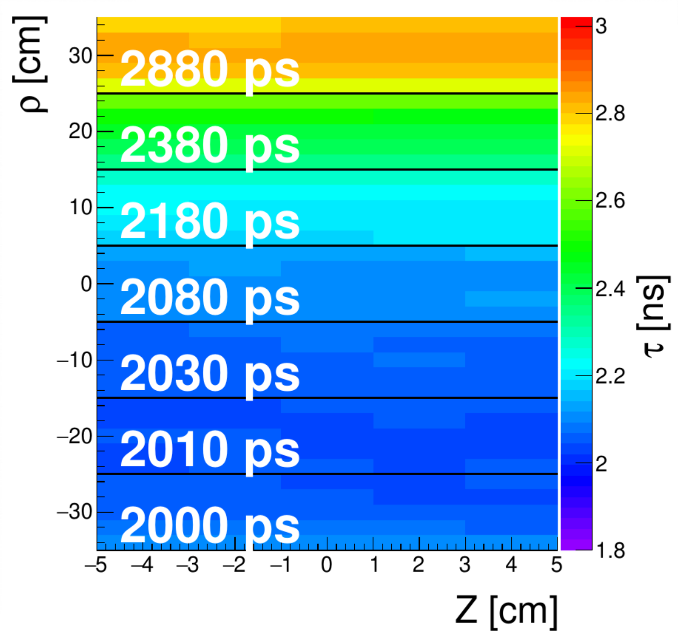
Spatially-resolved Positron Annihilation Lifetime Spectroscopy

- Determination of:
  - mean o-Ps lifetime
  - o-Ps / p-Ps production ratio

  separately in each voxel of the examined object
- Principle well validated with J-PET MC simulations







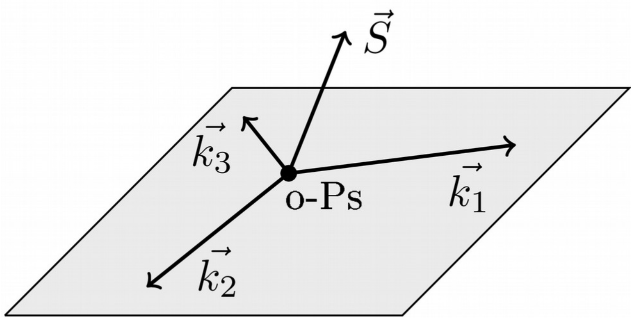
(Patent no. PCT/PL2015/050038)

(P. Moskal, D. Kisielewska *et al.*, arXiv:1805.11696)

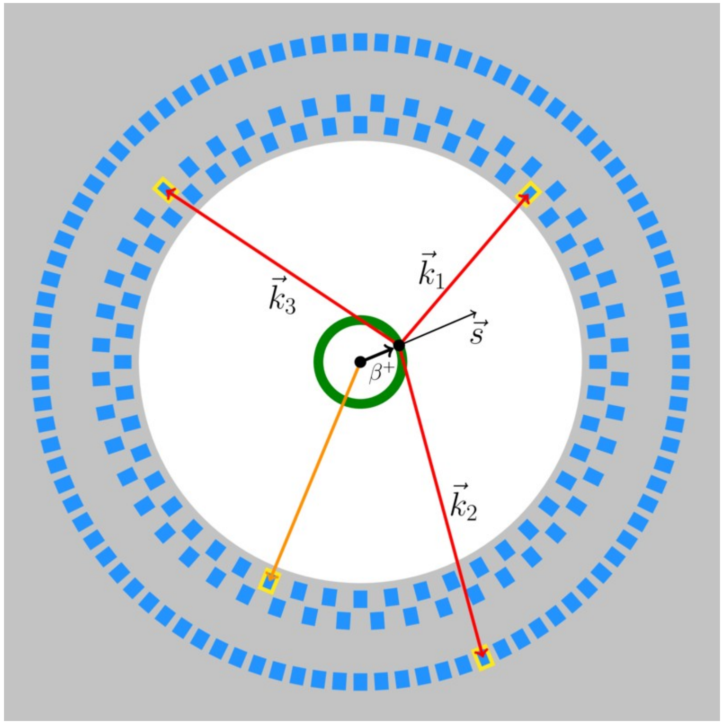
Motivation II: Discrete symmetry tests

- Measurement of expectation values of angular corelation operators odd under a given discrete symmetry transformation

See the talk by M. Silarski
Session 7, Wednesday 12:30

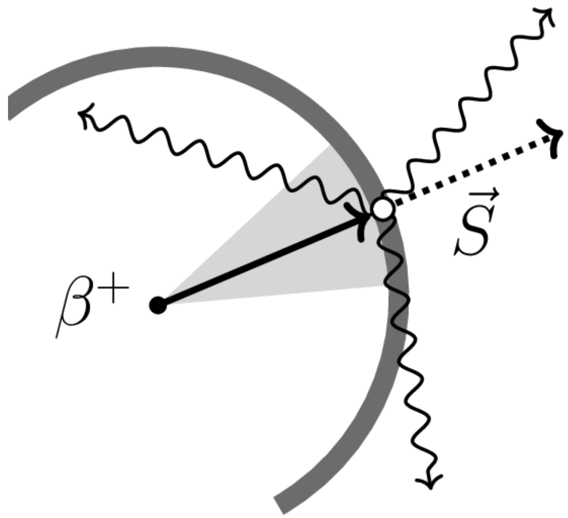


operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	−	+	−	−
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	−	+	−
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))$	+	−	−	−	+



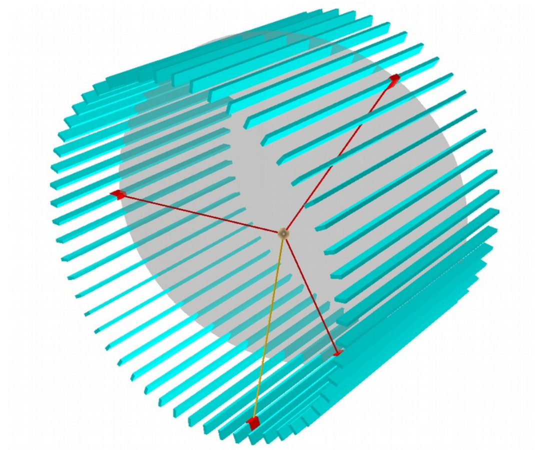
- Knowledge of the spin of ortho-positronium is required
- An alternative to using external magnetic field:

  Estimating the original positron spin event-by-event

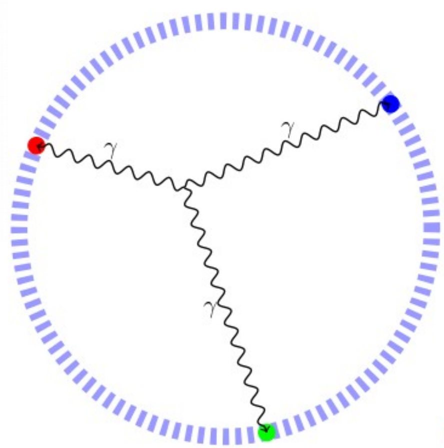


(A. Gajos et al., NIM A 819 (2016), 54-59)

Reconstruction of o-Ps→3γ decays in J-PET



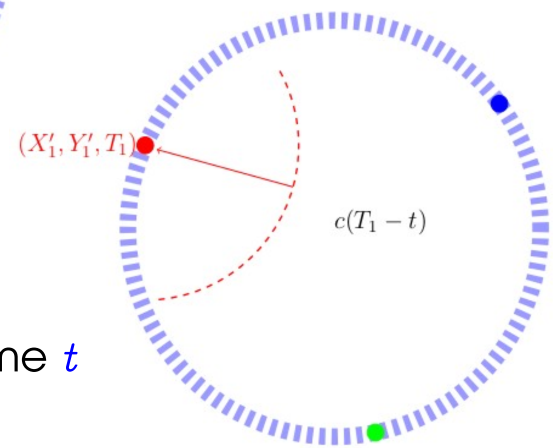
1. Find the decay plane containing the 3 hits in the J-PET barrel



2. Transform the hit coordinates to a 2D coordinate system in the decay plane

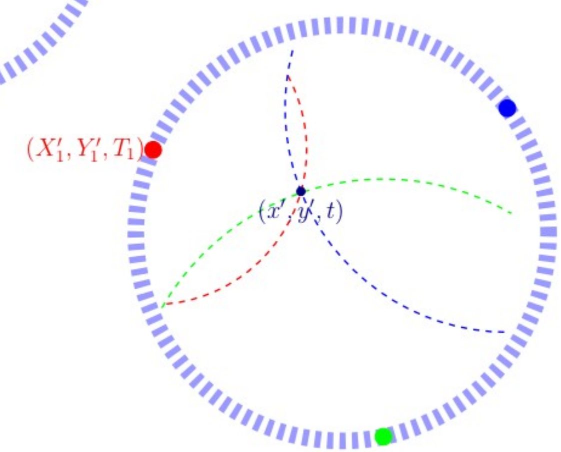
$$(X_i, Y_i, Z_i, T_i) \rightarrow (X_i', Y_i', 0, T_i)$$

3. For each of the recorded γ hits, define a circle of possible origin points of the incident γ assuming o-Ps decay at time t



4. The decay point (x', y') in the decay plane and time t is an intersection of 3 such circles:

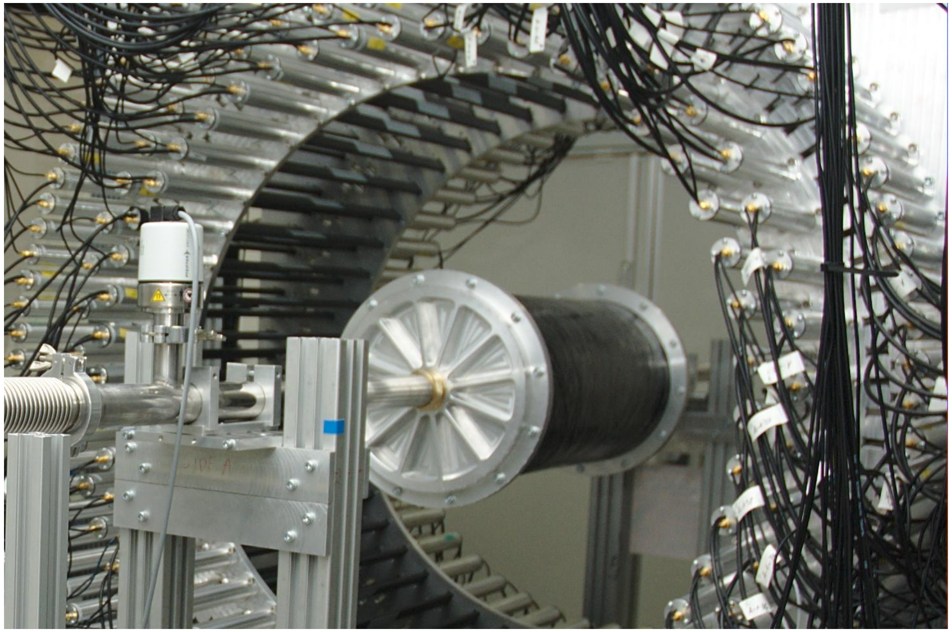
$$(T_i - t)^2 c^2 = (X_i' - x')^2 + (Y_i' - y')^2, \quad i = 1, 2, 3$$



Reconstructing o-Ps→3γ in the J-PET data

- For studies of o-Ps decays without reconstruction of the decay position, see the talk by K. Dulski, Session 10, Thursday at 12:25
- Two measurements were done with extensive-size annihilation chambers inside J-PET (details presented by Marek Gorgol on Monday)

Run 3 chamber, R ≈ 7 cm
No o-Ps production medium
2 days of measurement



Run 6 chamber, R ≈ 12 cm
Walls coated with a porous polymer
180 days of measurement

Data analysis flow for o-Ps→3γ identification

- Assembling of PMT signals and photon hits in the scintillator strips using the standard J-PET procedures
  - Details presented by K. Kacprzak in the same session

↓

- Identification of candidates for:
  - annihilation photons
  - prompt photons

  based on the Time-Over-Threshold (TOT) values

↓

- Requirement of 3 annihilation photon candidates in a 2.5 ns event

↓

- Rejection of multiple subsequent γ scatterings in the detector

↓

- Study of the angular topology of the events

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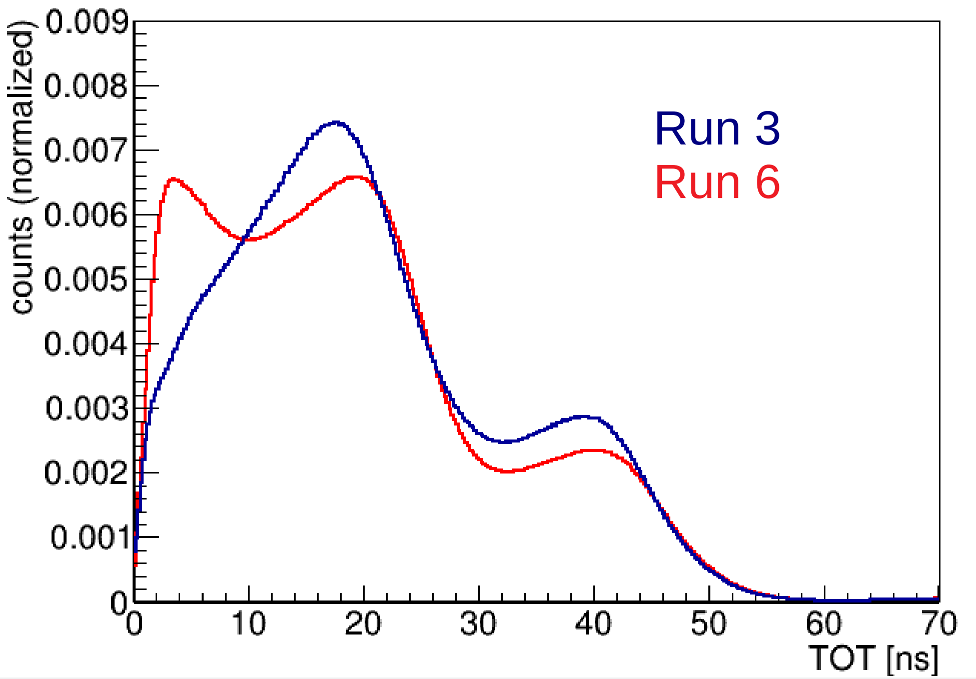
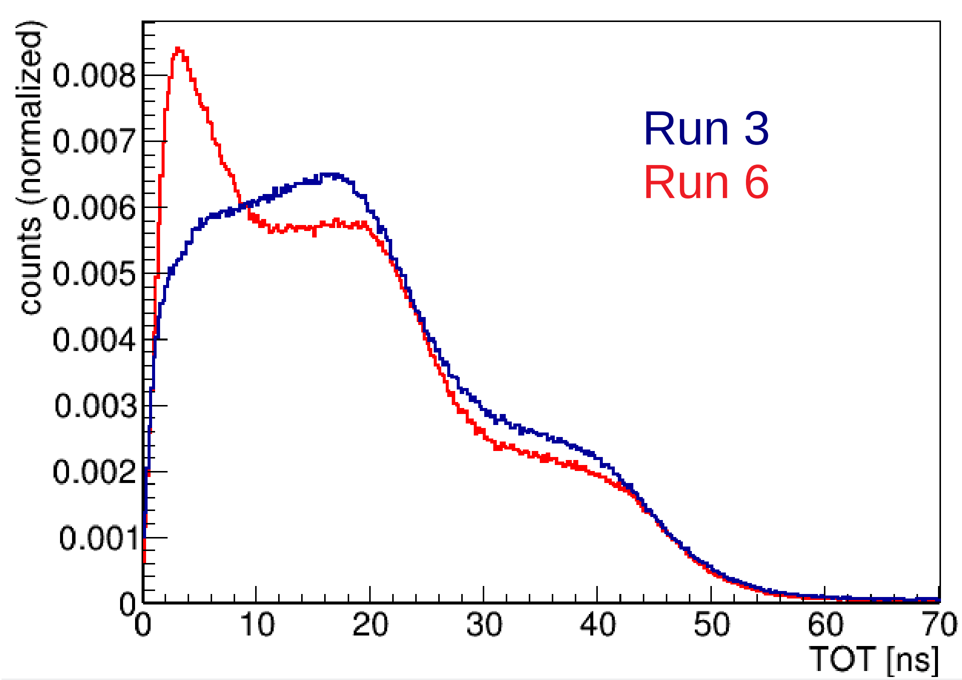
- Trilateration-based reconstruction of o-Ps → 3γ decay point and time

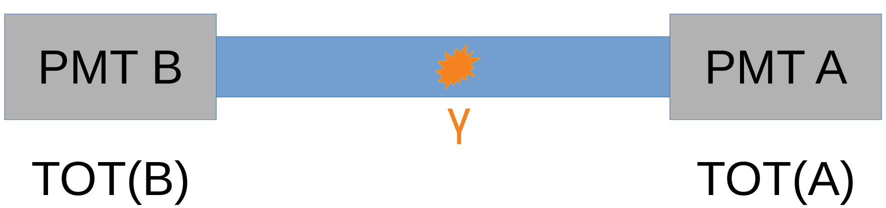
Time Over Threshold (TOT) distributions

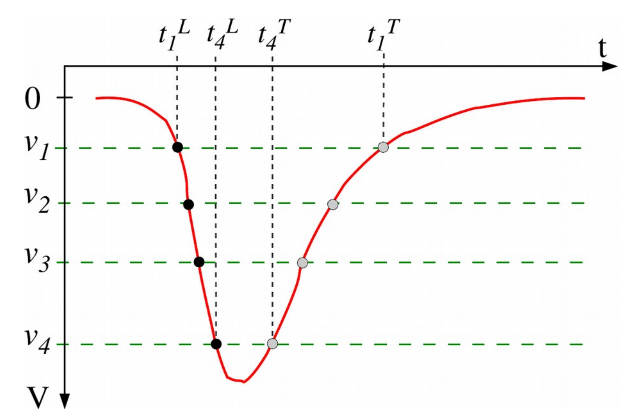
TOT for all recorded γ hits



TOT for γ hits recorded in events with at least 3 hits within 20 ns





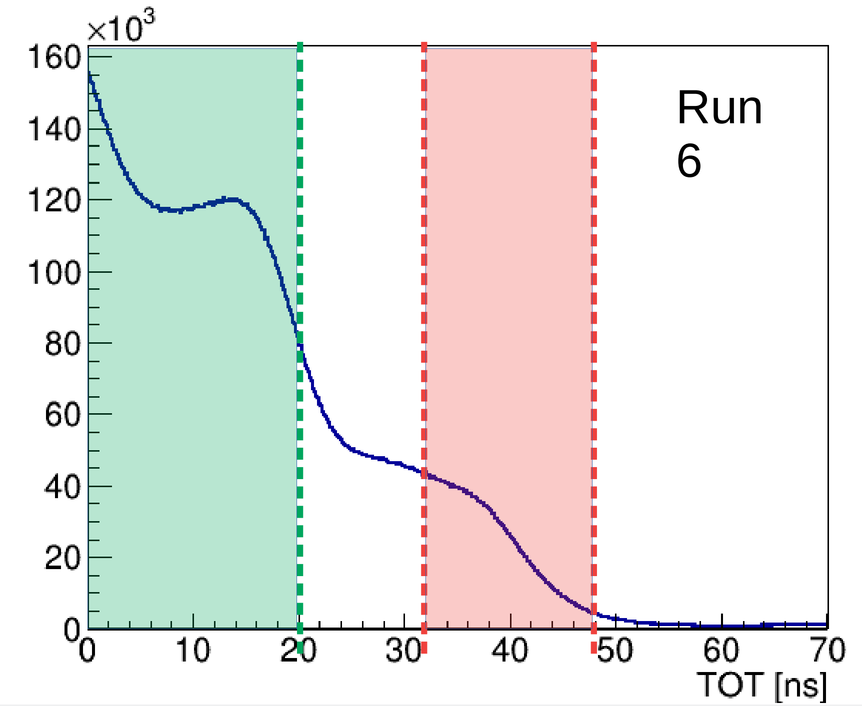


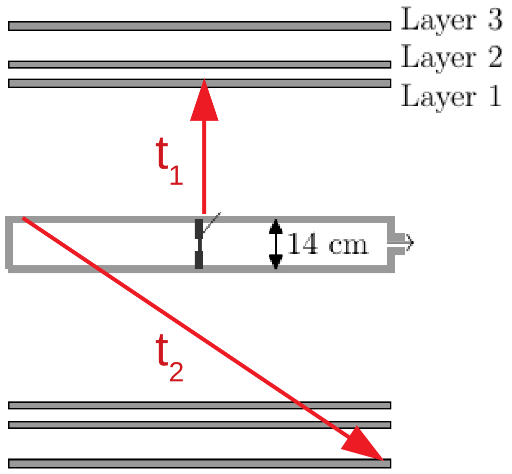
Using TOT to identify prompt and annihilation γ

- Normalized TOT spectrum including a simple correction for uneven charge response of particluar detection modules

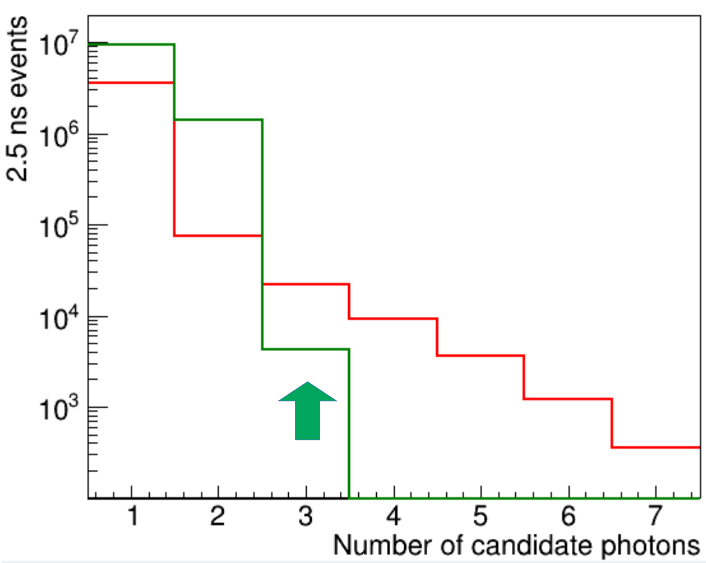
o-Ps → 3γ annihilation (E<511 keV)
^{22}Ne* de-excitation (E=1274 keV)

- Counting candidates in a 2.5 ns time window





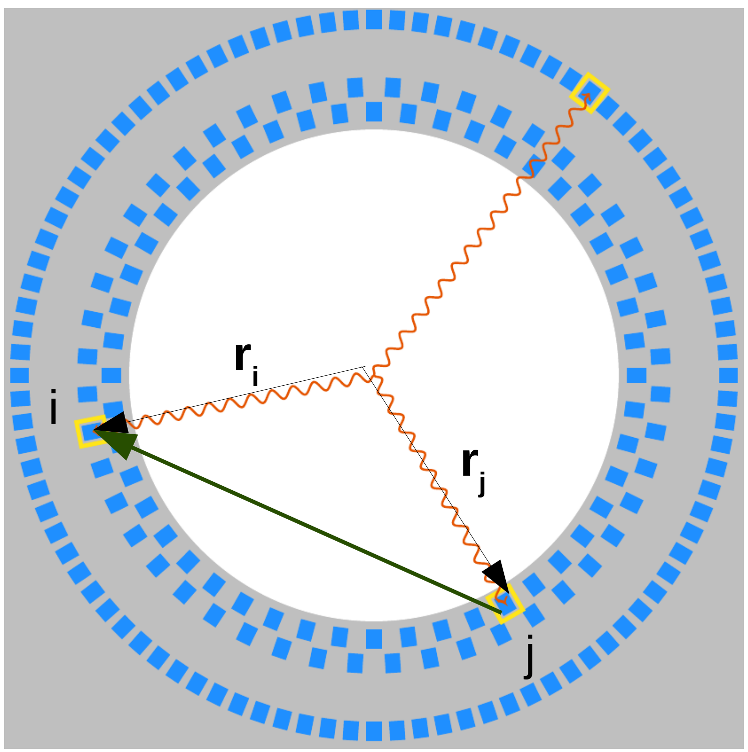
$t_2 - t_1 \approx 1.7$ ns



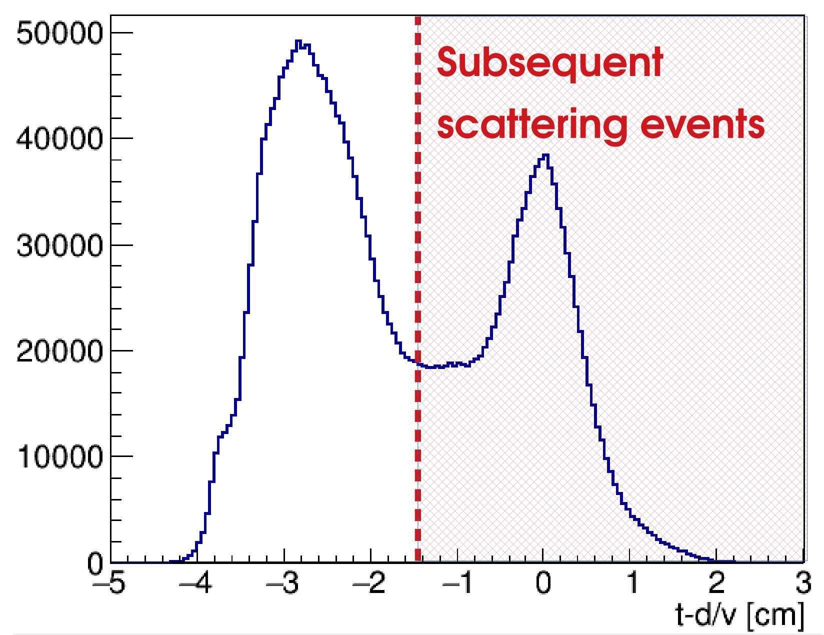
Rejection of subsequent scatterings in the detector

- See talks by J. Raj and N. Krawczyk in Session 6 for the cases when we **do not** want to reject these scatterings
- For each pair of annihilation photon candidates *i* and *j* (*i*,*j*=1,2,3) the following figure is computed:

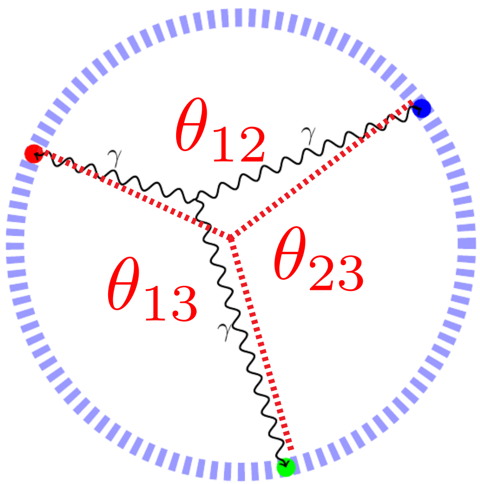
$$\delta t_{ij} = |t_i - t_j| - \frac{1}{c}|\vec{r}_i - \vec{r}_j|$$



Distribution of the minimum δt_{ij} over all photon pair choices in an events:

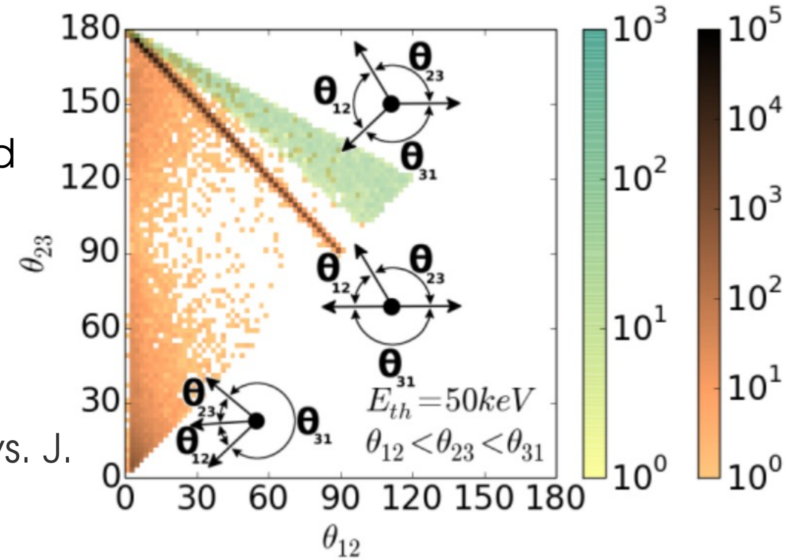


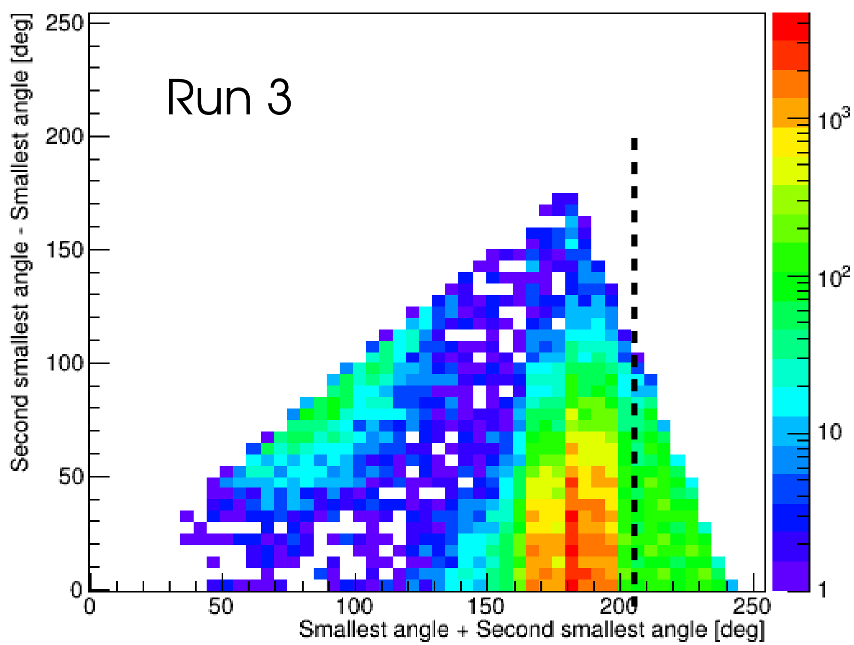
Angular topology of three-photon events

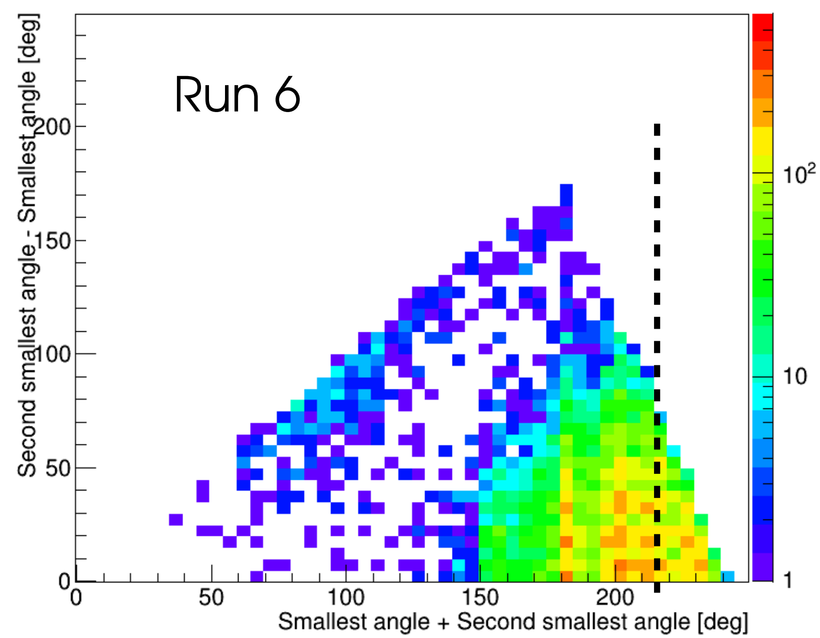


Reference:
Angles between three photons' momenta expected for different types of events (MC simulation results)

(D. Kamińska et al., Eur. Phys. J. C76 (2016) no.8, 445)





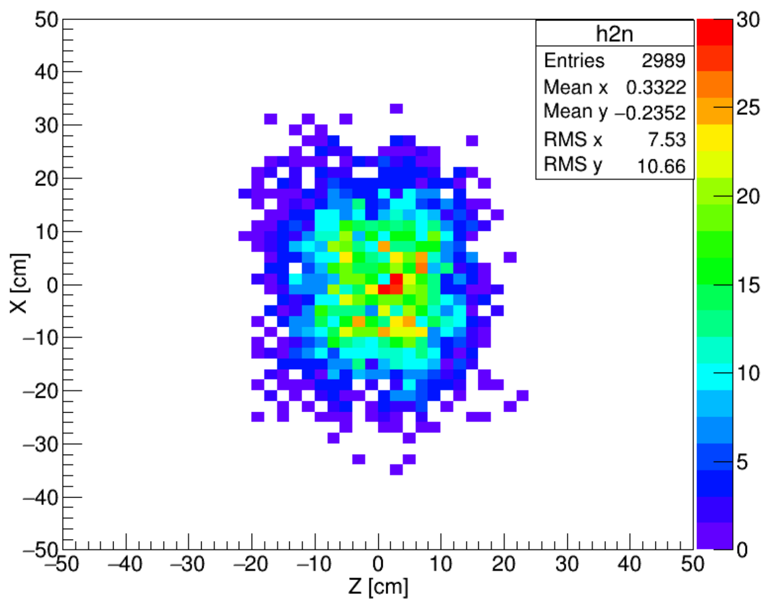


For details on the 2γ event properties, see the talk by M. Mohammed, Session 8, Wed 15:50

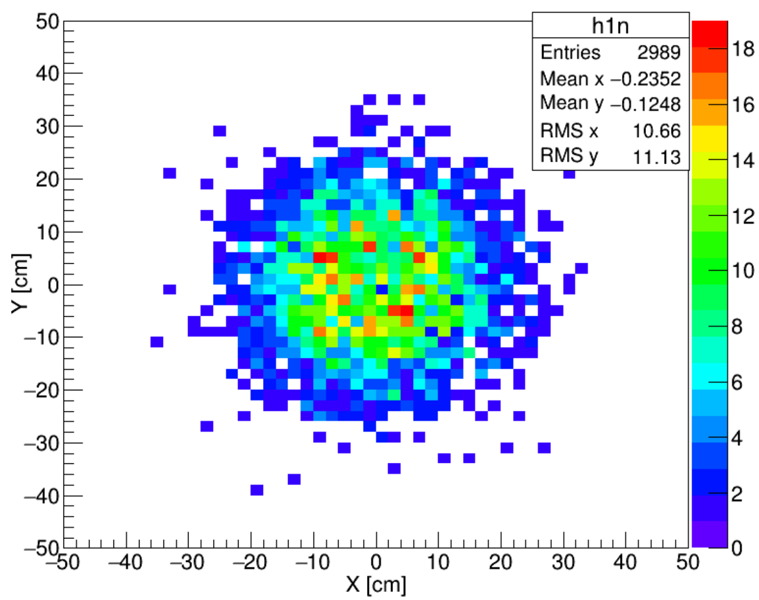
Reconstructed o-Ps → 3γ decay points

Results obtained with the trilaterative decay point reconstruction

Using about 3 % of the collected Run 6 data



Longitudinal view



Transverse view

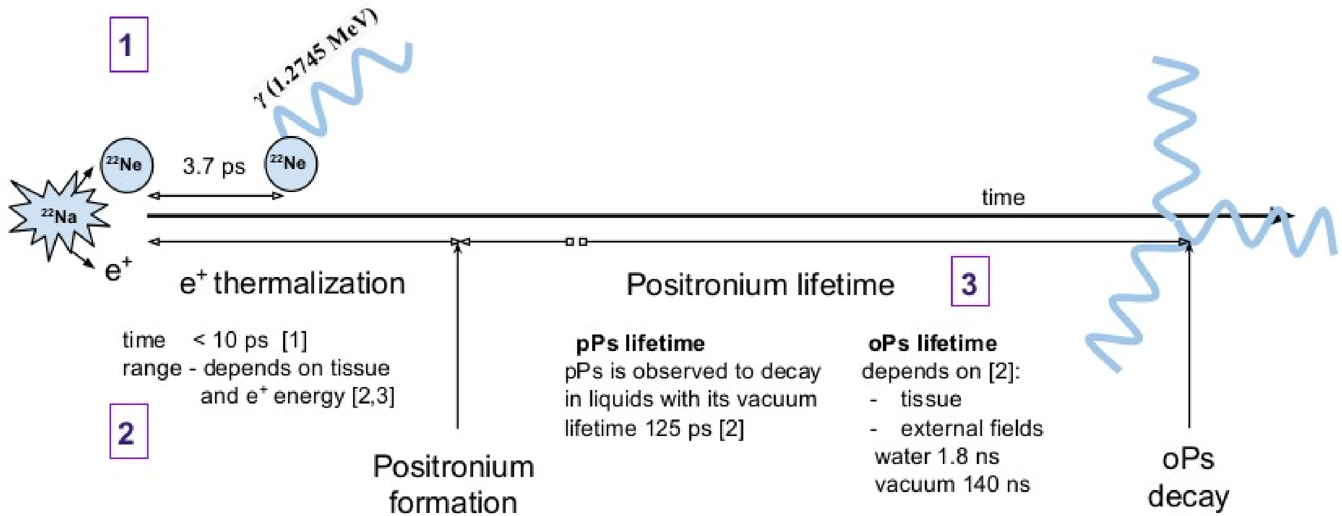
Summary

- Identification and reconstruction of o-Ps → 3γ decays in J-PET allow for
  - Medical imaging with positronium lifetime and o-Ps / p-Ps ratio
  - Polarization control in studies of discrete symmetries
- Two measurements were conducted with extensive-size annihilation chambers
- A preliminary set of o-Ps decay event selection criteria has been devised, based on time over threshold of the recorded photon ineractions as well as angular event topology
- A method for reconstruction of 3γ decays based on trilateration has been devised for J-PET, allowing to reconstruct the point and time of the ortho-positronium annihilations

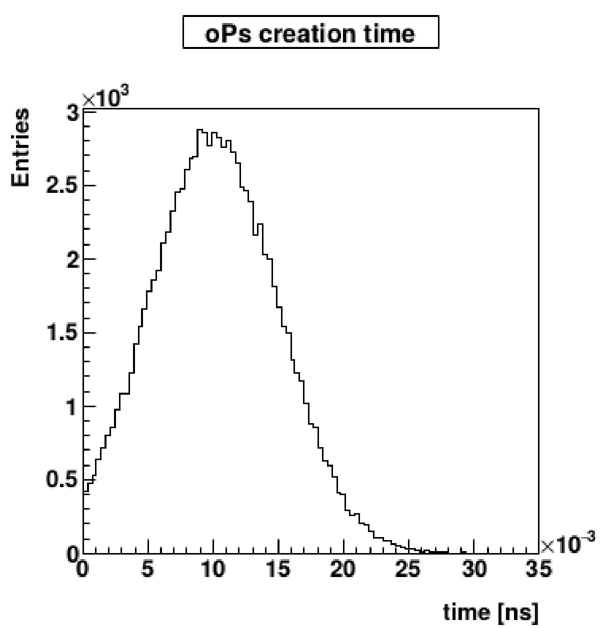
Thank you for your attention!

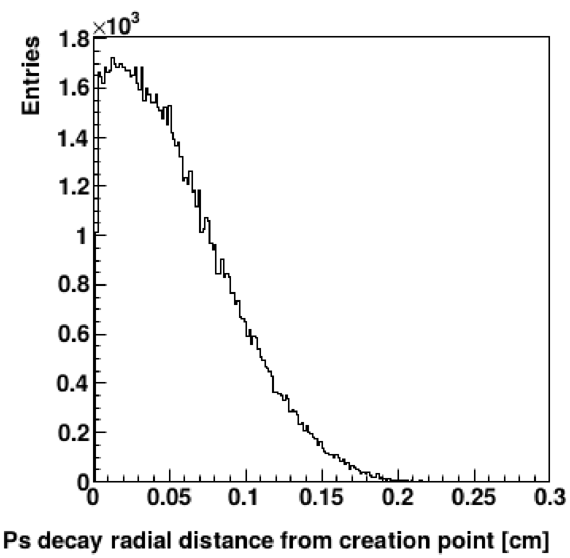
Backup Slides

O-Ps creation and decay

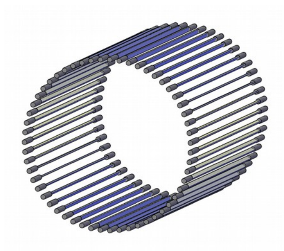


[1] P. Kubica and A. T. Stewart, Phys. Rev. Lett. 34 (1975) 852
[2] M. Harpen Med.Phys. 31 (2004) 57-61
[3] J Cal-Gonzalez et al, Phys. Med. Biol. 58 (2013) 5127–5152





Distinguishing o-Ps→3γ and e⁺e⁻→2γ



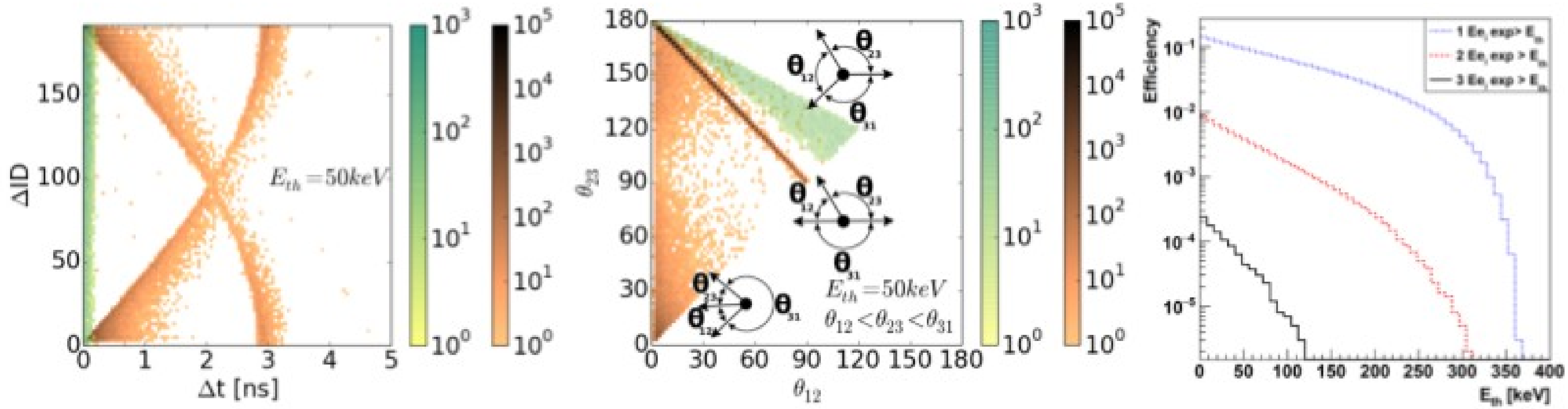


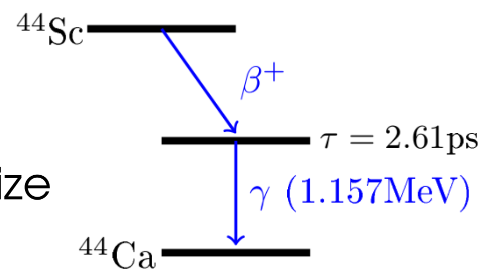
Figure 9. (Left) Simulated distributions of differences between detectors ID (ΔID) and differences of hit-times (Δt) for events with three hits registered from the annihilation e+e- → 2γ (gold colours) and o-Ps → 3γ (green colours). **(Middle)** Disribution of relative angles between reconstructed directions of gamma quanta. The numbering of quanta was assinged such that $\theta_{12} < \theta_{23} < \theta_{31}$. Shown distributions were obtained requiring three hits each with energy deposition larger than Eth = 50 keV. Gold colour scale shows results for simulations of e+e- → 2γ and green scale corresponds to o-Ps → 3γ. Typical topology of o-Ps → 3γ and two kinds of background events is indicated. **(Right)** Detection efficiency of the J-PET detector for registration of one, two and three gamma quanta from o-Ps → 3γ decay. The efficiency is shown as a function of threshold energy applied in the analysis to each gamma quantum.

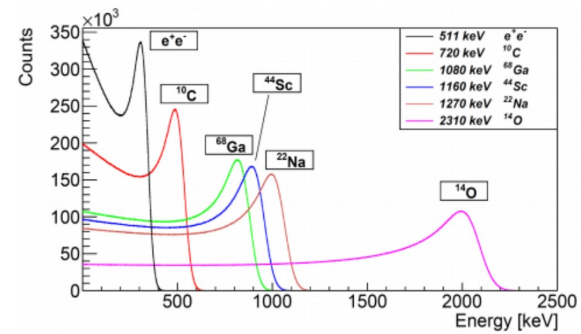
(J-PET: P.Kowalski, P.Moskal, in preparation)

Ortho-positronium decay tomography

Motivation:

- Ortho-positronium (o-Ps) lifetime in tissue strongly depends on inter-cellular spaces' size
- Morphological imaging possible through determination of o-Ps lifetime
- 4-th photon coming from β^+ emitter deexcitation is used to estimate o-Ps creation time
- o-Ps→3γ decay location and time must be reconstructed using 3 recorded photons

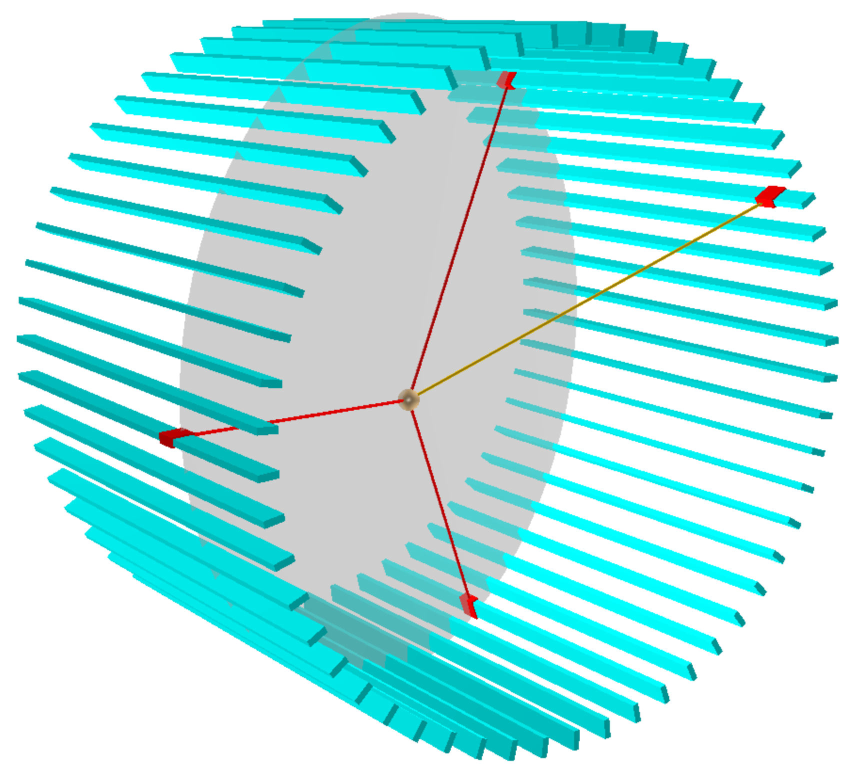




(P.M. et al., Patent Application: PCT/EP2014/068374; WO2015028604)

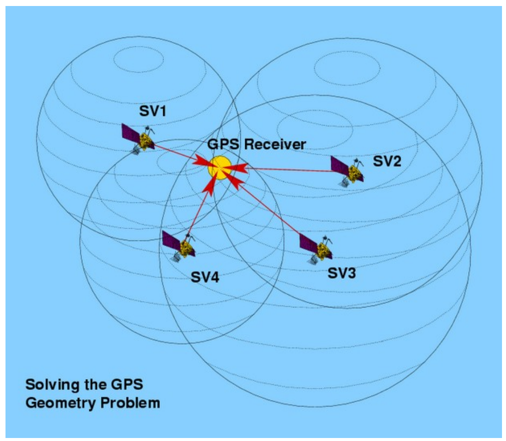
Properties of the process:

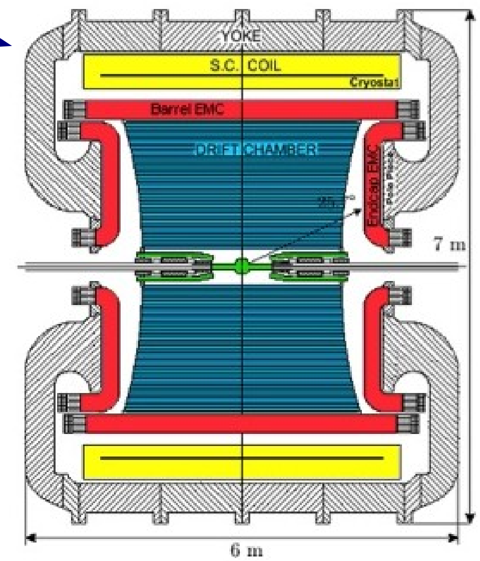
- Momenta of the 3 photons from o-Ps decay lie in one plane (in the o-Ps ref. frame)
- 4-th (deexcitaion) photon momentum is not correlated with the other three
- o-Ps→3γ decay and deexcitation photon emission differ by distance and time related to free e^+ path and positronium life



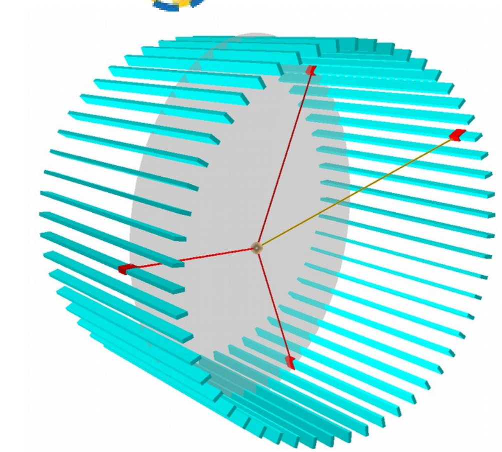
Origin of the reconstruction method

- The reconstruction method applied to o-Ps decays in J-PET was originally created for kaon decays at the KLOE detector (A. Gajos Dipl.Thesis (2013) Jagiellonian University) (Acta Phys. Pol. B 46 (2015) 13)
- Mathematical principle of the reconstruction is similar to GPS positioning





J-PET

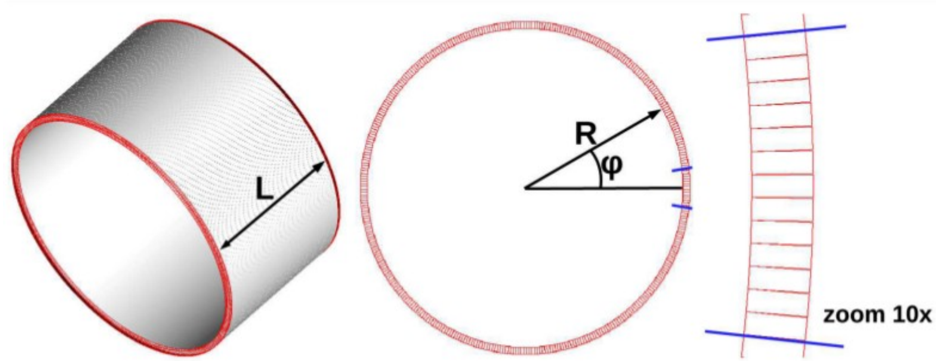


	GPS	$K_L \to 3\pi^0 \to 6\gamma$ at KLOE	o-Ps$\to 3\gamma$ at J-PET
Shere centers	Satellite locations	γ hits in KLOE calorimeter	γ hits in J-PET barrel
Whose travel time is measured?	Radio signals from satellites	Photons from π^0 decays	Photons from o-Ps decay
Reconstructing position of	GPS receiver	$K_L \to 3\pi^0 \to 6\gamma$ decay	o-Ps$\to 3\gamma$ decay
Reconstructed time	Current GPS time	Time of K_L decay	Time of positronium decay
Using information on	At least 4 satellites	4-6 recorded photons	3 recorded photons and coplanarity

MC simulation of o-Ps decays in J-PET

- Monte Carlo simulations of o-Ps decays recorded by the J-PET detector were prepared
- J-PET detector with 384 scintillator strips was assumed in simulations
  - Single strip size: $7 \times 19 \times 500 mm^3$
  - Barrel dimensions:

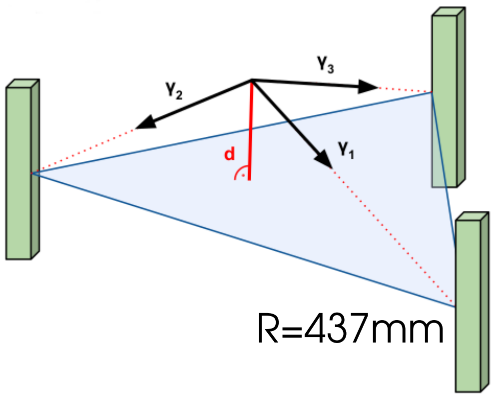
    R = 43cm, L = 50cm
  - Resolution in XY plane: $\Delta\varphi \approx 0.5$deg

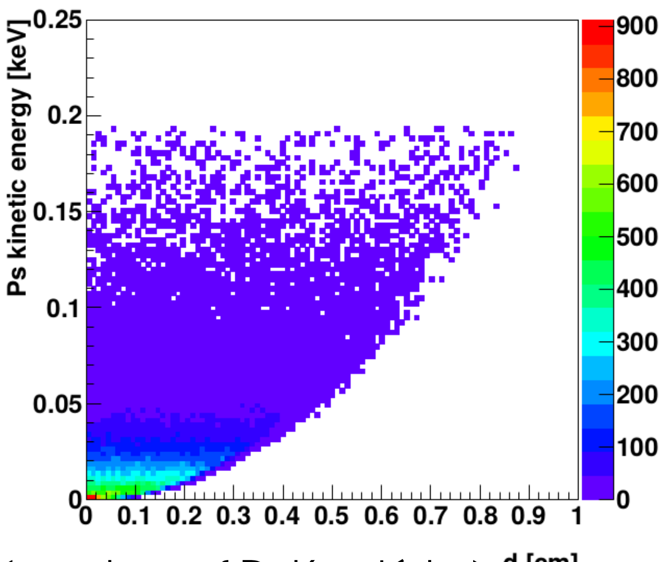


- Simulation includes:
  - β^+ emitter deexcitation and prompt gamma emission
  - Positron thermalization before positronium creation (in water)
  - Ortho-positronium lifetime (for water)
  - Momentum of the decaying positronium – deviation from 3 photons' coplanarity in LAB frame

Effects included in the simulation

Non-coplanarity of photons' momenta

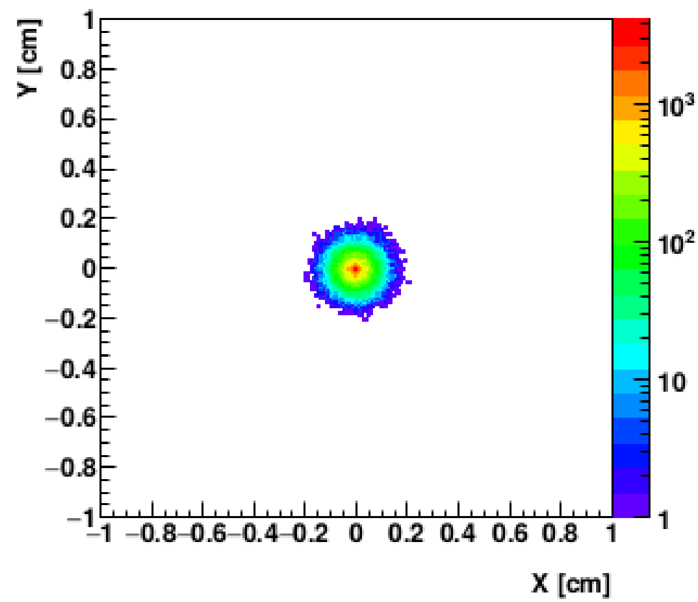




(courtesy of D. Kamińska)

Positron thermalization and oPs flight before decay

result in a difference between the o-Ps decay point and the deexcitation photon emission point



o-Ps decay point distribution for a point β^+ source placed at (0,0)
(courtesy of D. Kamińska)

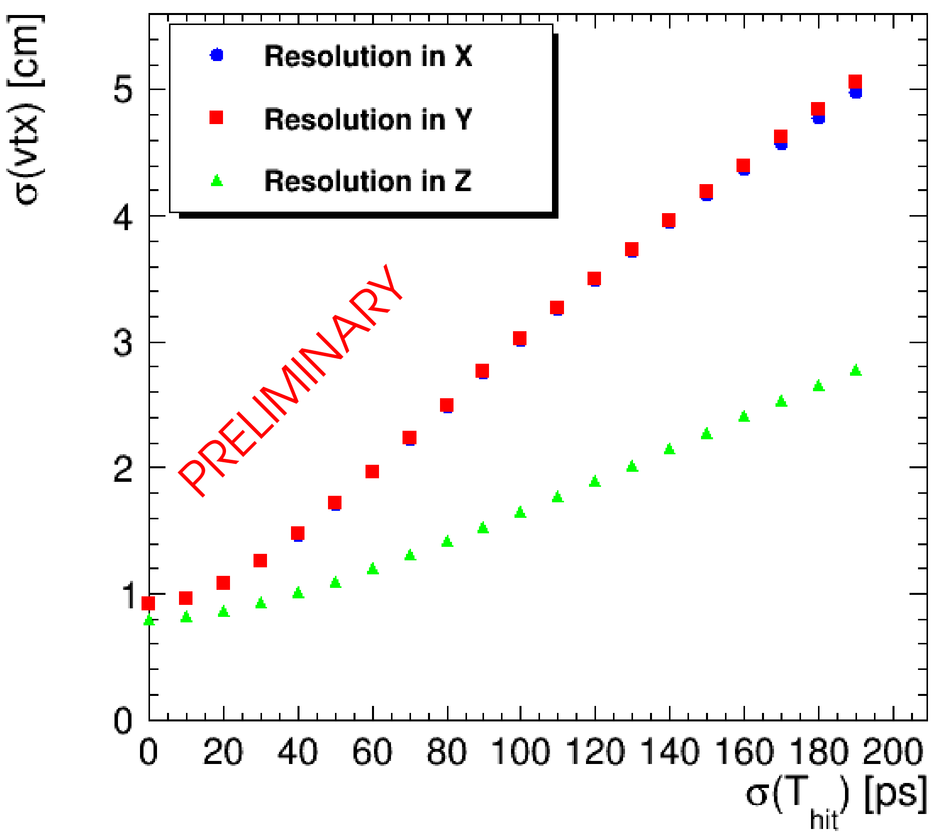
Both effects are negligible within reconstruction resolution (presented on next slides).

Resolution dependence on γ hit time resolution

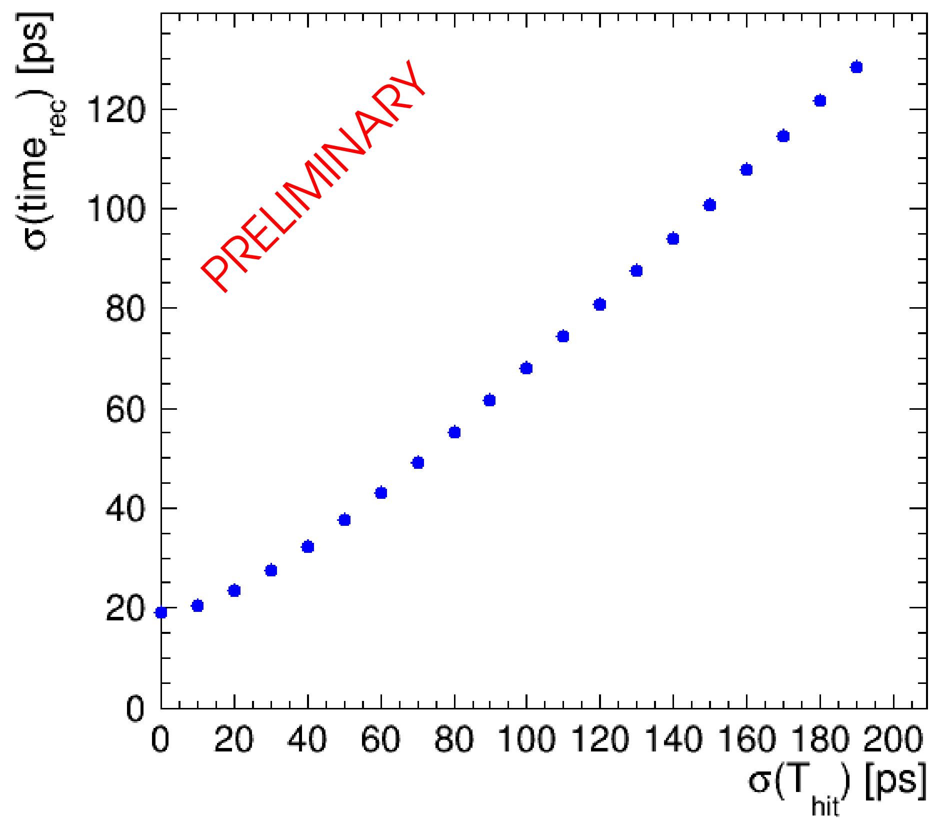
The resolution of o-Ps decay obtained with the presented reconstruction method depends predominantly on the timing resolution of γ hits in scintillator strips.

O-Ps decay resolution

spatial



time



Ortho-positronium life time resolution

For each event of o-Ps decay, the positronium decay time can be estimated as:

$$\tau^{rec}_{o-Ps} = t_0 - \left(t_{\gamma deexc.} - \frac{L_{\gamma deexc.}}{c} \right)$$

where t_0 is the o-Ps decay time reconstucted with the presented method and $L_{\gamma deexc.}$ is calculated using reconstructed o-Ps decay point.