Reconstruction of three-photon events for positronium tomography and 3γ-PET technique with the J-PET scanner

Jagiellonian Symposium
on Fundamental and Applied Subatomic Physics

June 9 2015

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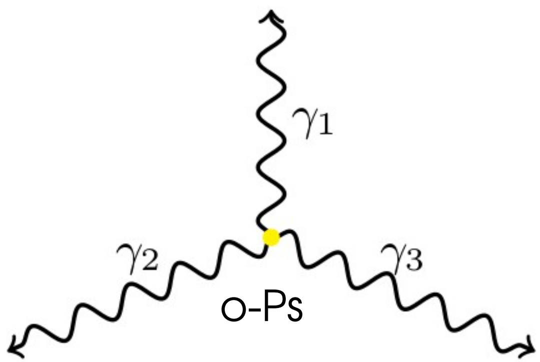
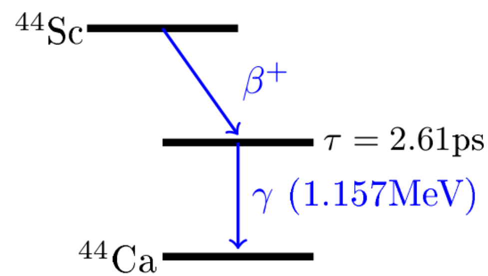
Jagiellonian University

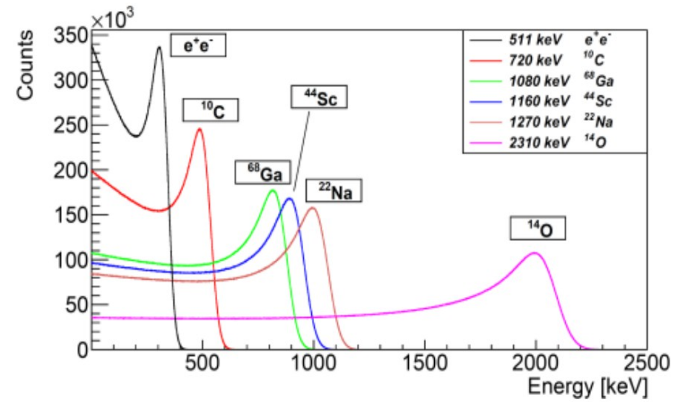
J-PET

PET tomography with 3 photons

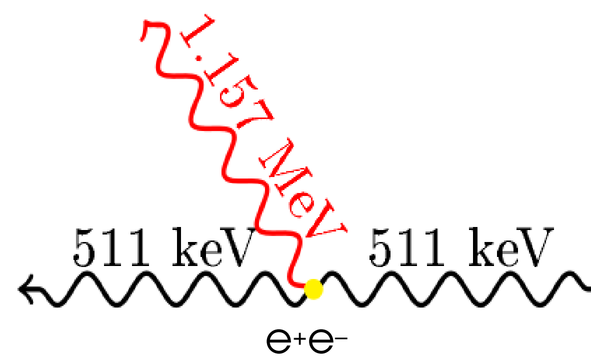
Ortho-positronium tomography with o-Ps→3γ decays







e+e- annihilation with additional photon from β+ emitter deexcitation



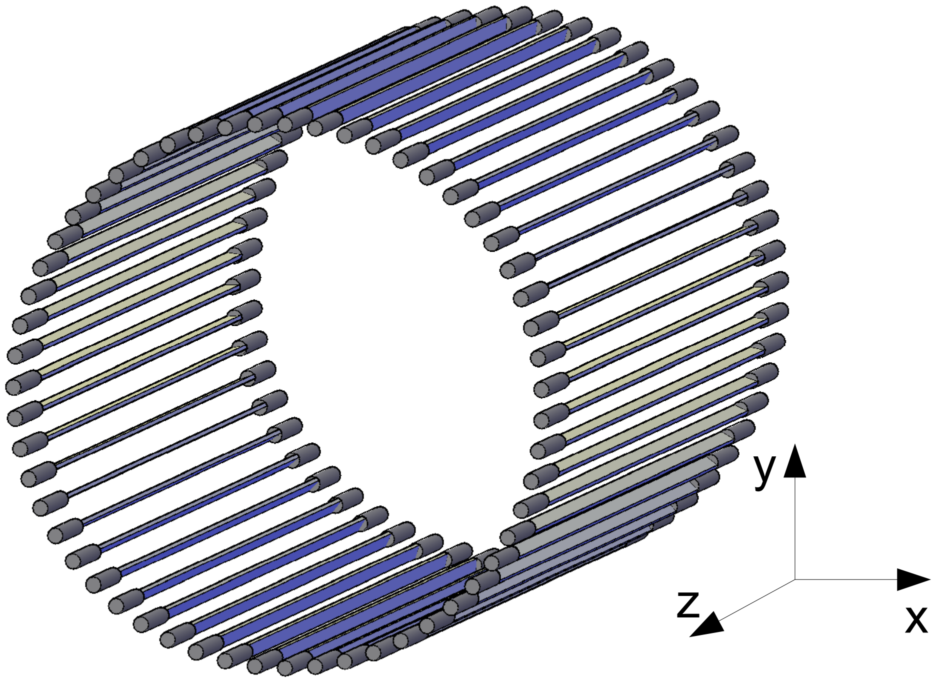
- Positronium lifetime tomography with J-PET requires reconstruction of o-Ps decays into three photons with good resolution of decay point and time
- Momenta of three photons created in o-Ps decay are co-planar

- Original idea by K. Parodi *et al.* (JINST **9** (2014) 01008)
- The additional photon is used to increase imaging resolution
- Presence of the deexcitation photon can also be exploited by the J-PET detector
- 2 annihilation photons are created back-to-back
- deexcitation photon momentum is independent

The J-PET detector

J-PET (Jagiellonian PET)

A novel concept of a PET detector developed at the Jagiellonian University

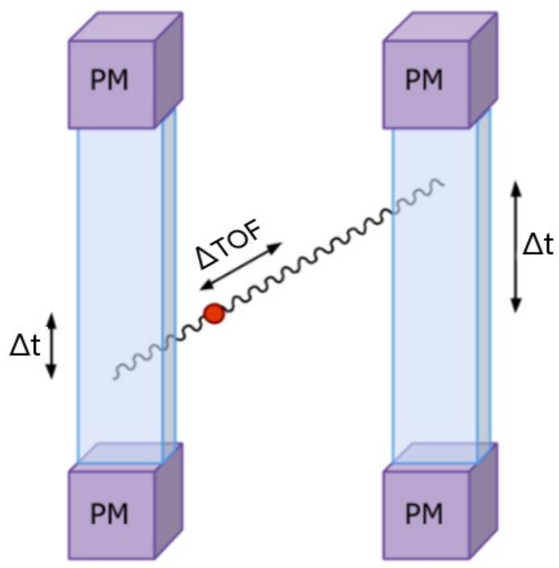


Using plastic scintillator strips read out by photomultipliers at both ends

- large acceptance easily achievable
- excellent timing resolution

Resolution results obtained with prototypes:

- $\sigma(t)$ = 80ps (J-PET: NIM A 764 (2014) 317-321) (J-PET: NIM A 764 (2014) 186-192)
- $\sigma(z)$ = 0.93cm (J-PET: NIM A 786 (2015) 105-112)
- $\sigma(TOF)$ = 125ps (J-PET: NIM A 775 (2015) 54-62)



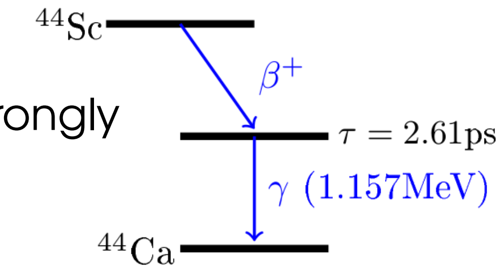
Ortho-positronium decay tomography

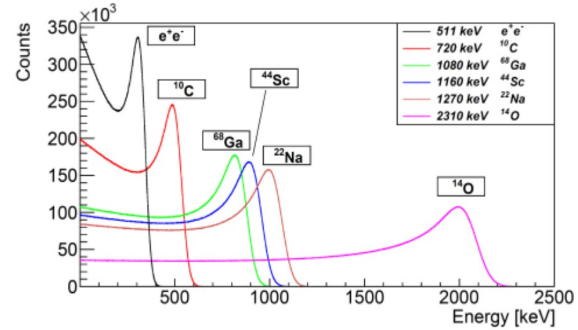
Motivation:

- 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

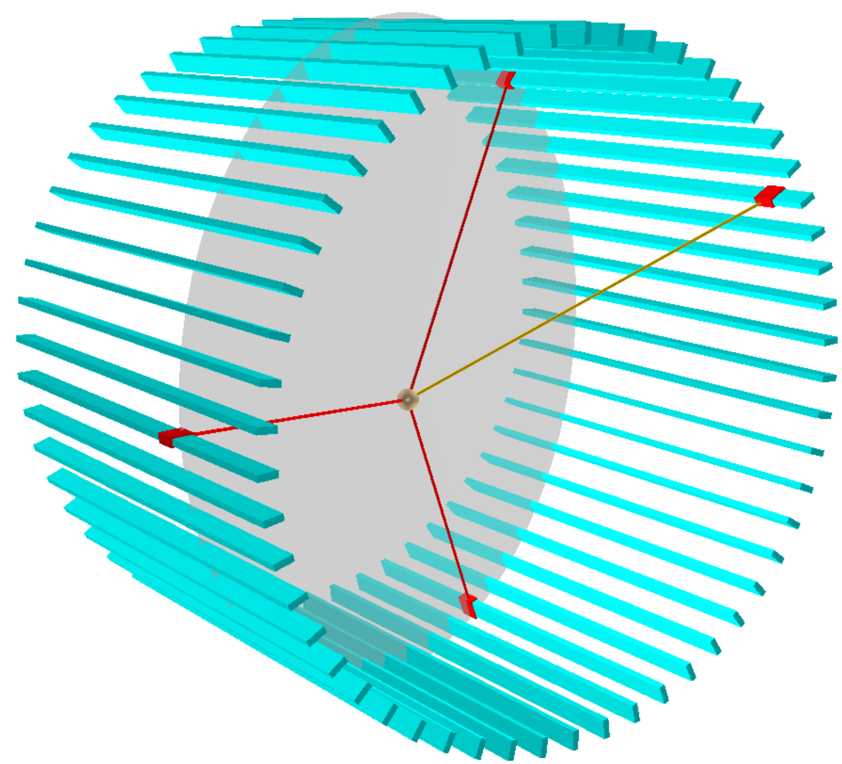
Properties of the process:

- 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



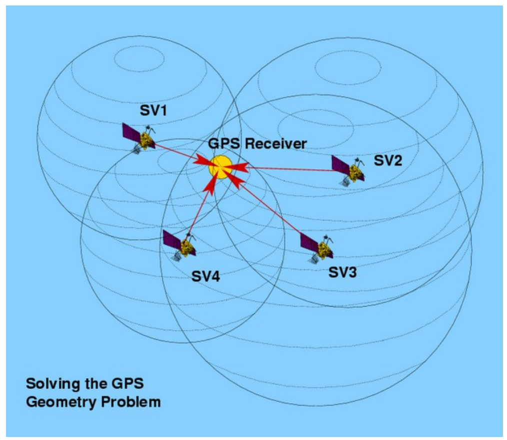


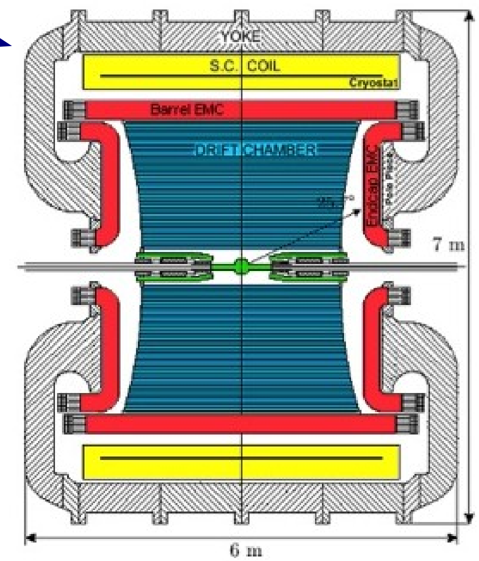
(P.M. et al., Patent Application: PCT/EP2014/068374; WO2015028604)



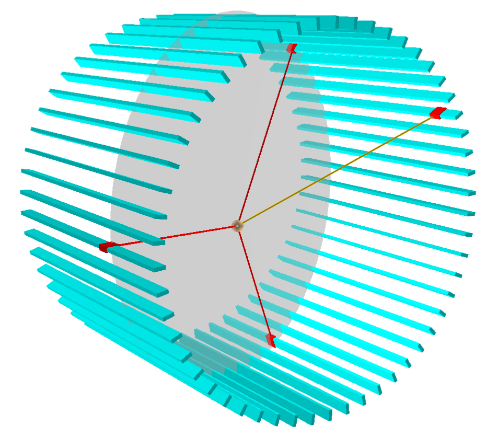
Origin of the reconstruction method

- 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



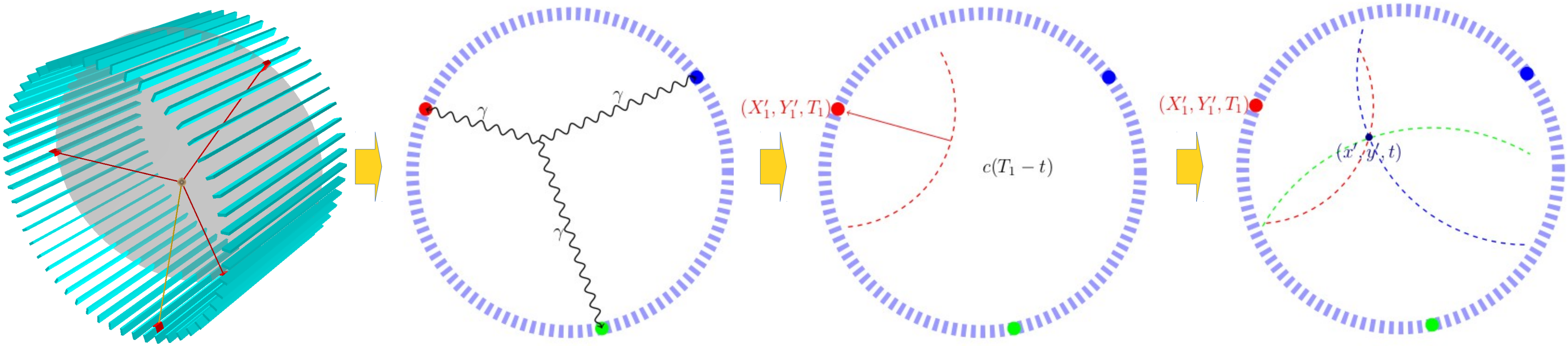


J-PET



	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

Principle of o-Ps decay reconstruction



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 photon assuming o-Ps decay at time t
4. Find the decay point (x', y') in the decay plane and time t as an intersection of 3 circles by solving the following equation system:

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

Where: x, y, z, t – unknowns, T_i – time of the i-th hit

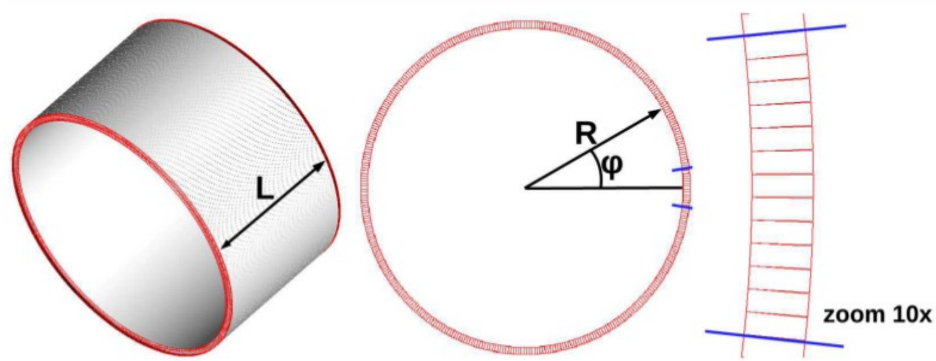
X'_i, Y'_i – coordinates of the i-th hit in the barrel expressed in the decay plane

5. Transform (x', y', t) of the decay point back to the detector 3D coordinate system

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: 7x19x500mm^3
  - Barrel dimensions:

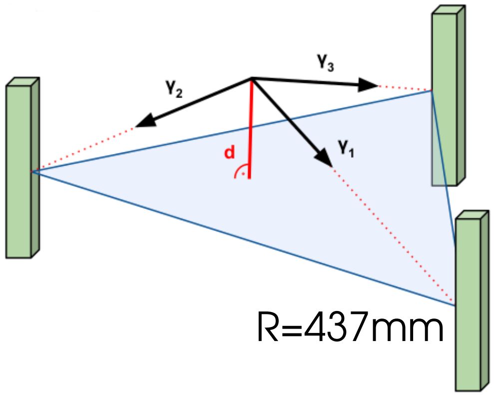
    R = 43cm, L = 50cm
  - Resolution in XY plane: $\Delta\varphi \approx 0.5$deg

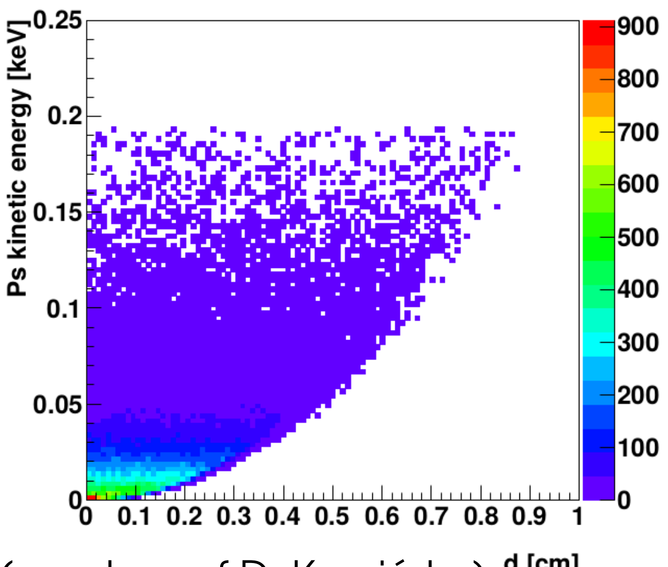


- Simulation includes:
  - β^+ emitter deexcitation and prompt gamma emission
  - Positron thermalization before positronium creation (in water)
  - Ortho-positronium lifetime (for water)
  - Momentum of the decaying positronium – deviation from 3 photons' coplanarity in LAB frame

Effects included in the simulation

Non-coplanarity of photons' momenta

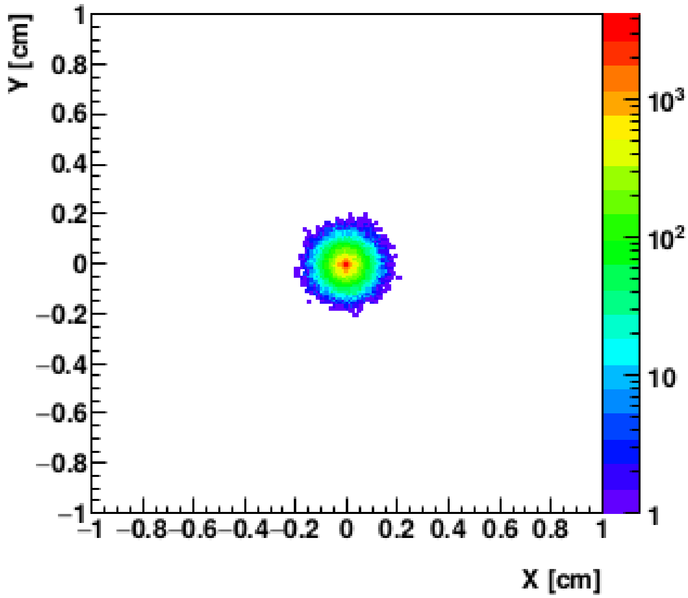




(courtesy of D. Kamińska)

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)

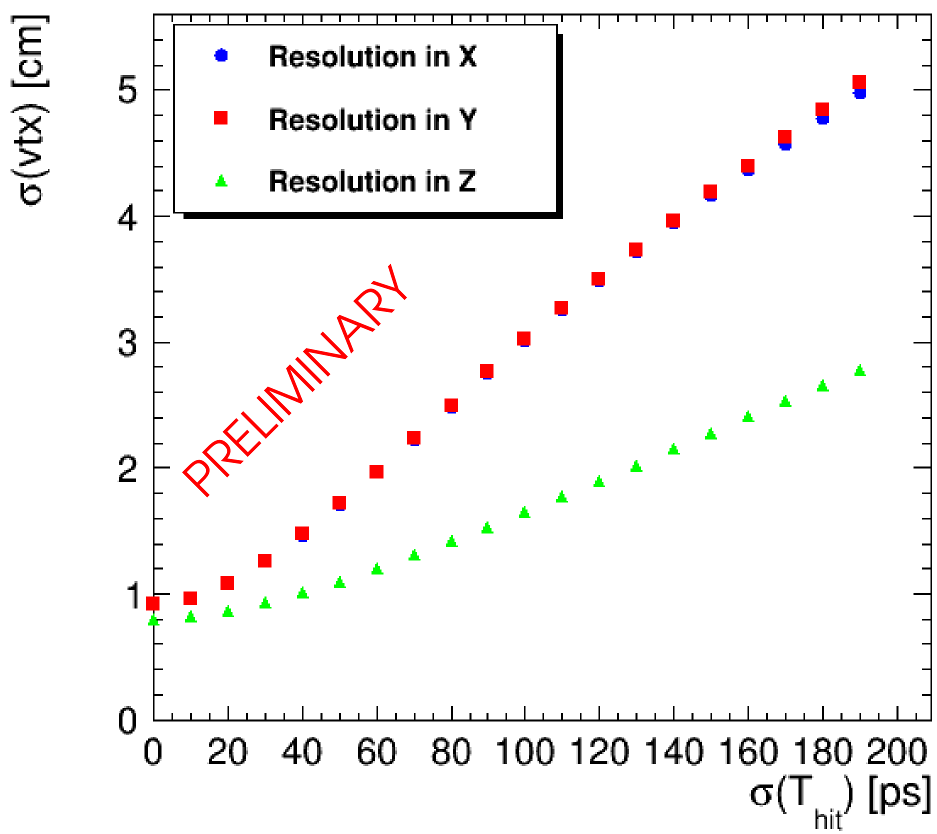
Both effects are negligible within reconstruction resolution (presented on next slides).

Resolution dependence on γ hit time resolution

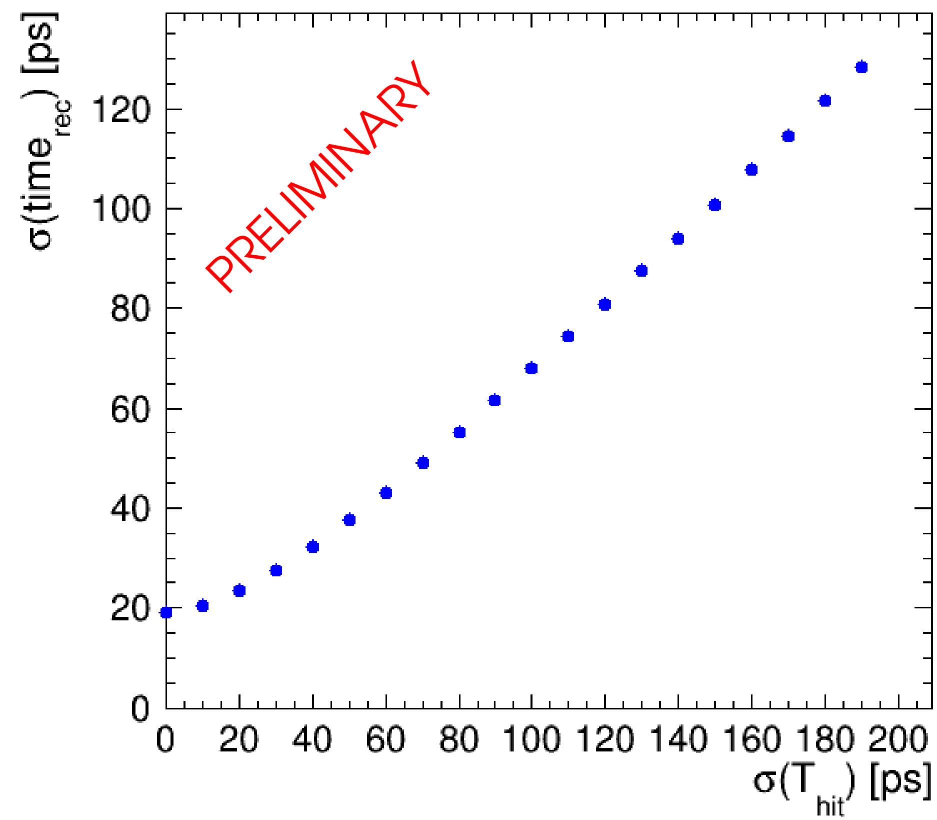
The resolution of o-Ps decay obtained with the presented reconstruction method depends predominantly on the timing resolution of γ hits in scintillator strips.

O-Ps decay resolution

spatial



time

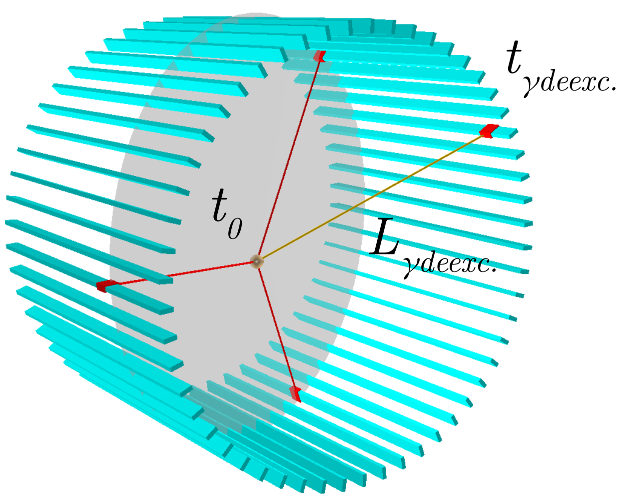


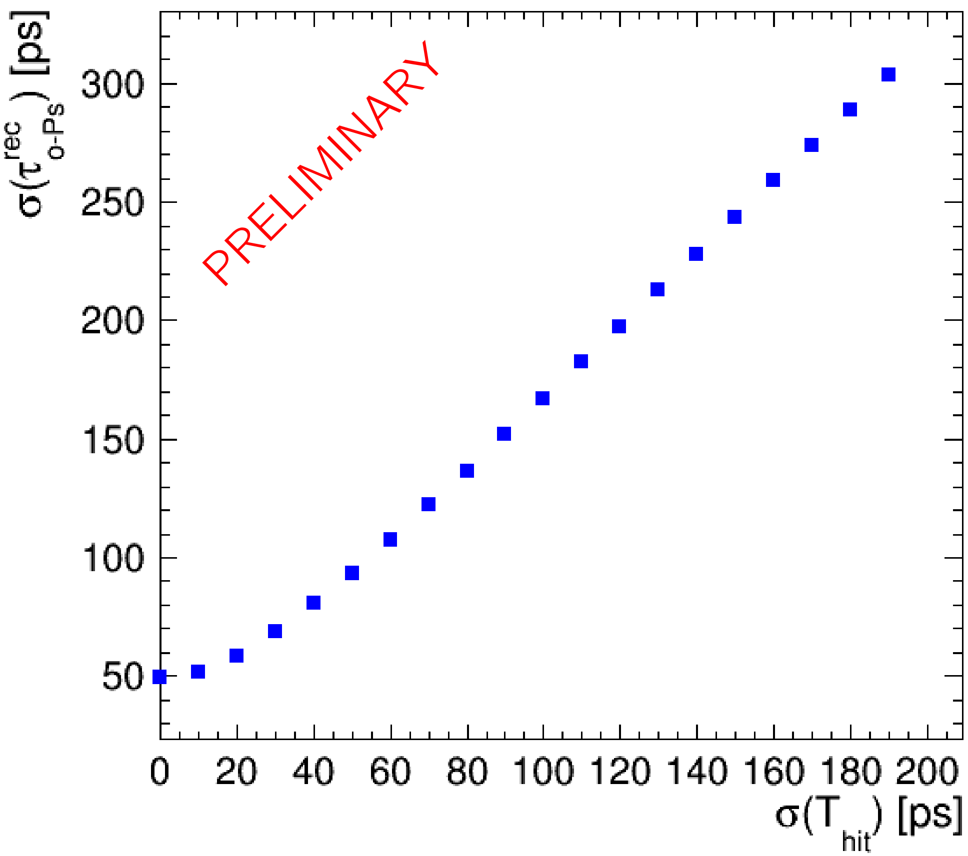
Ortho-positronium life time resolution

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

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

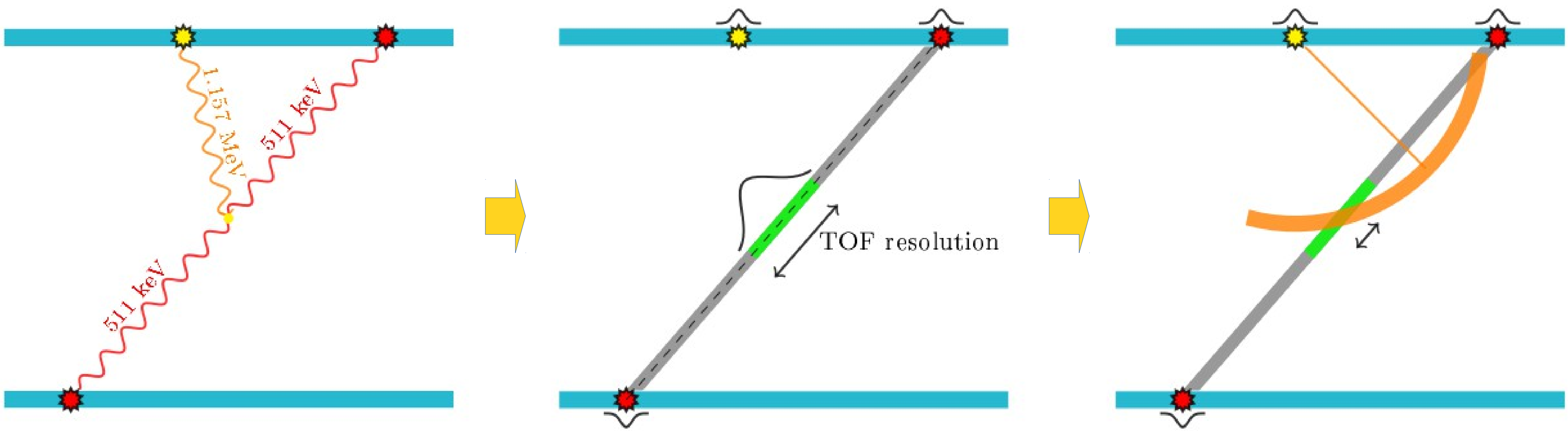
where t_0 is the o-Ps decay time reconstucted with the presented method and $L_{\gamma deexc.}$ is calculated using reconstructed o-Ps decay point.





3γ-PET technique with the J-PET detector

- Large acceptance offered by the J-PET apparatus allows for simultaneous recording of both annihilation photons as well as the deexcitation photon
- PET imaging resolution strongly depends on TOF resolution along the line of response (LOR)
- Information on the deexcitation photon can be used to improve resolution along LOR



e^+e^- annihilation and a prompt γ from deexcitation of β^+ emitter

TOF resolution along line of response obtained using classical TOF-PET methods

Addition of information on the prompt γ time of flight allows to improve the annihilation point resolution along LOR

Performance of this 3γ-PET technique with J-PET is presently studied with MC simulations.

Summary

- The J-PET detector is capable of performing measurements beyond the classical PET technique, with processes involving three and four photons
- Ortho-positronium decays can be recorded and reconstructed in J-PET for morphological imaging by means of positronium lifetime spectroscopy
- Simulations show that o-Ps decay can be reconstructed in the J-PET device with spatial resolution of the order of 1cm and time resolution of tens of picoseconds with presently achieved timing resolution of the detector
- Perspectives exist for applying the 3γ-PET technique at J-PET in order to improve resolution of e^+e^- annihilation point along the line of response by using information on third photon coming from β^+ emitter de-excitation

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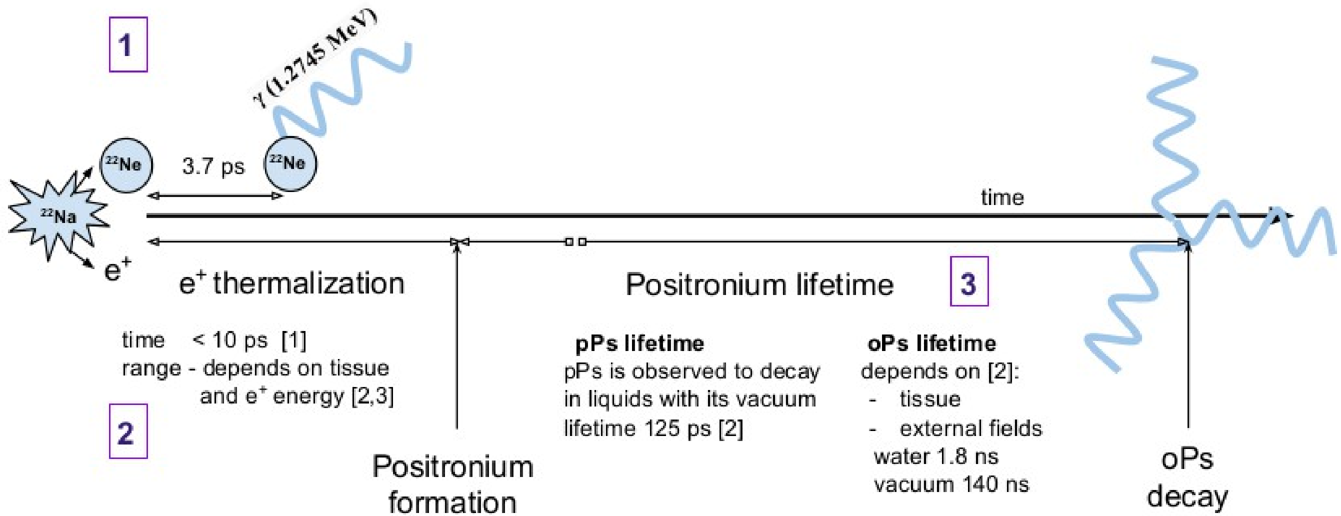
Thank you for your attention!

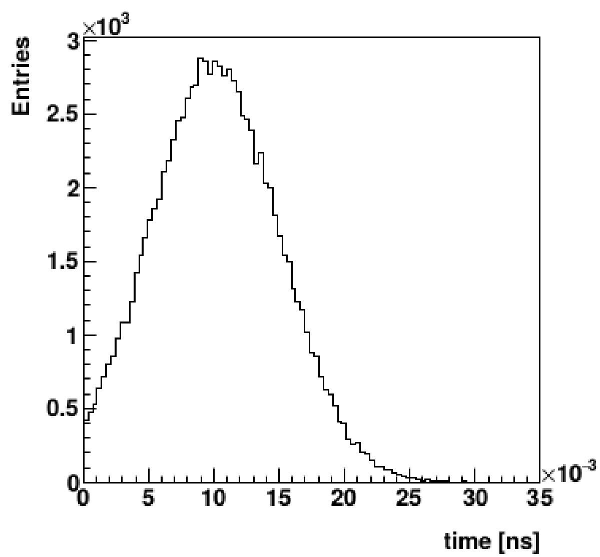
Backup Slides

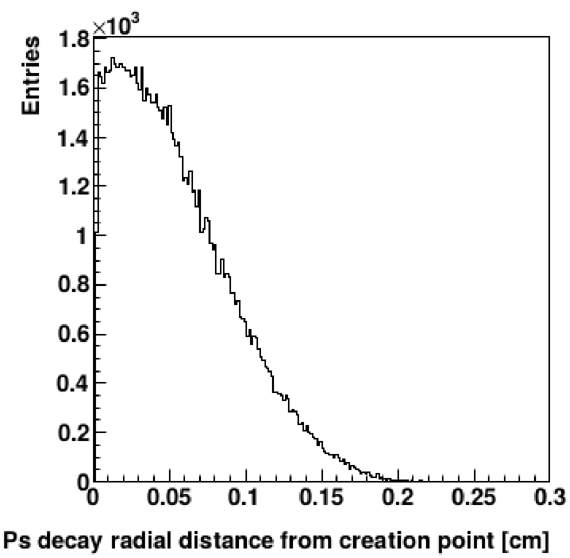
O-Ps creation and decay



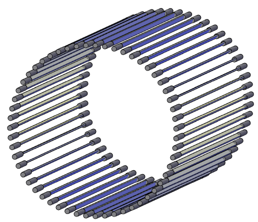
[1] P. Kubica and A. T. Stewart, Phys. Rev. Lett. 34 (1975) 852
[2] M. Harpen Med.Phys. 31 (2004) 57-61
[3] J Cal-Gonzalez et al, Phys. Med. Biol. 58 (2013) 5127–5152

oPs creation time





Distinguishing o-Ps→3γ and e⁺e⁻→2γ



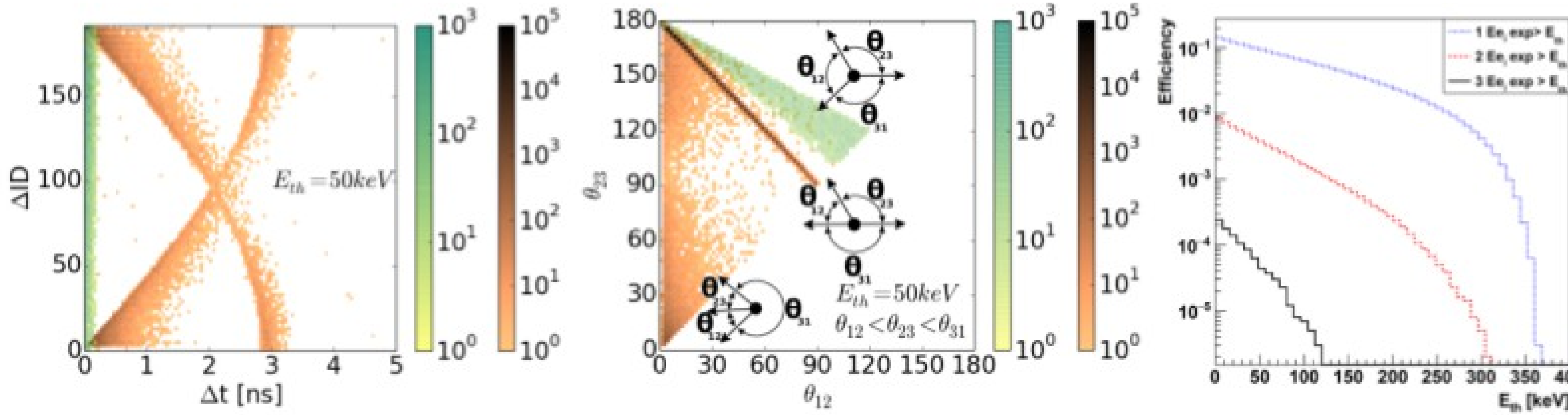


Figure 9. (Left) Simulated distributions of differences between detectors ID (ΔID) and differences of hit-times (Δt) for events with three hits registered from the annihilation e+e- → 2γ (gold colours) and o-Ps → 3γ (green colours). **(Middle)** Disribution of relative angles between reconstructed directions 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)