Searches for discrete symmetry violation signals in decays of positronium atoms at J-PET

3rd Jagiellonian Symposium
on Fundamental and Applied Subatomic Physics

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on behalf of the J-PET Collaboration
Jagiellonian University

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Testing discrete symmetries with ortho-positronium: motivation

- Discrete symmetries are scarcely tested in the leptonic sector

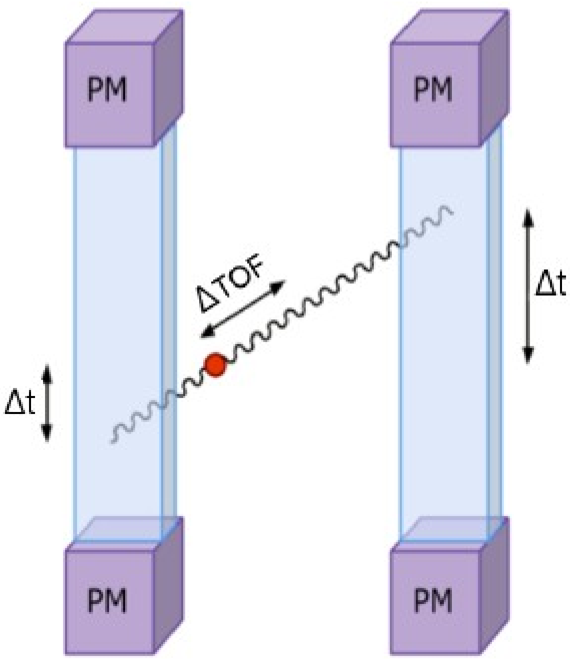
- To date, positronium is the only system consisting of charged leptons used for tests of CP and CPT
  - Current results saw no violation effects at the precision level of 10^{-3}
  - Experimental sensitivity limit:
    - false asymmetries from $\gamma\gamma$ interactions in the final state
    - only expected at the 10^{-9} level

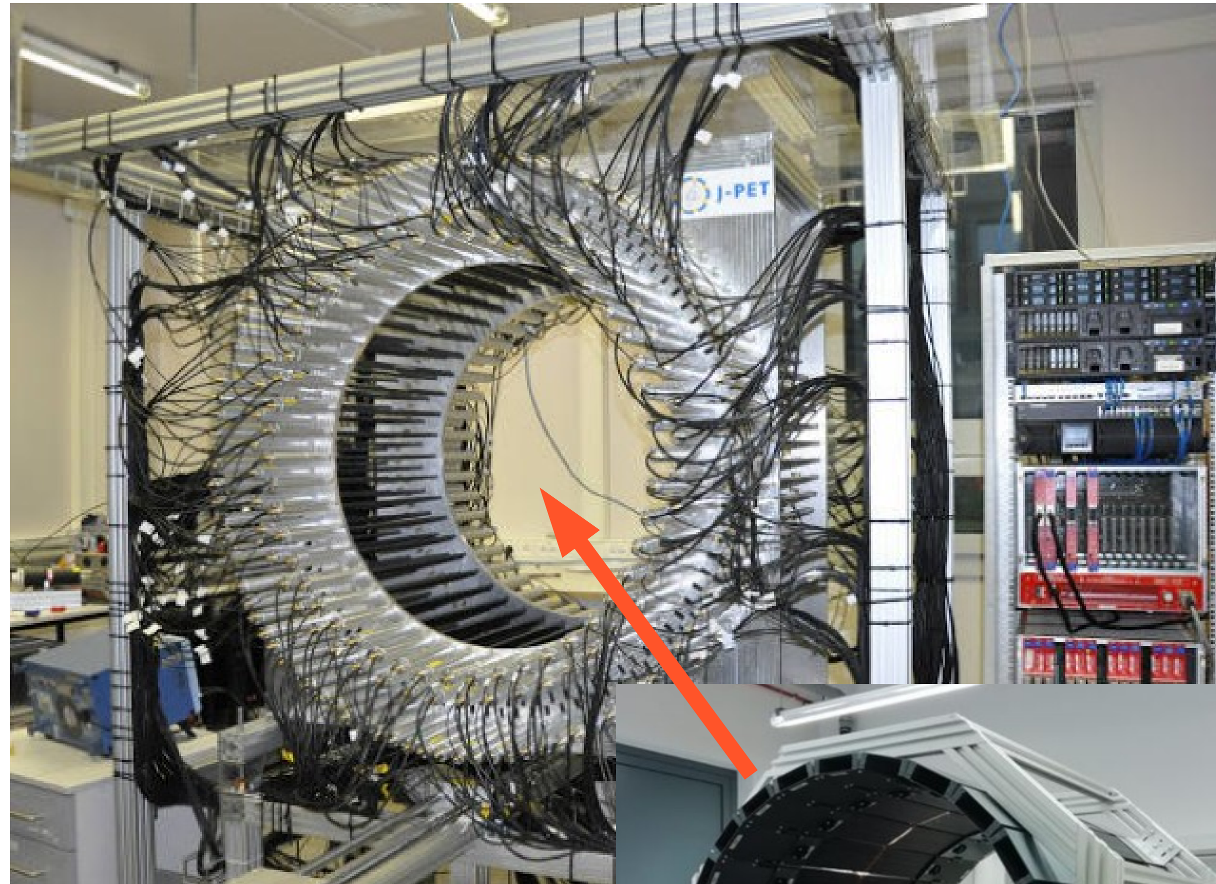
  => several orders of magnitude of tests' precision yet to explore

- To date, Ps is the only alternative to neutrinos in the leptonic sector
  - Can be used in smaller-scale experiments like J-PET constructed and operating at the Jagiellonian University

The Jagiellonian PET (J-PET) Detector

- Constructed at the Jagiellonian University
- Fist PET device using strips of plastic scintillators
  - Photons recorded through Compton scattering
- At the same time: a robust photon detector for fundamental research!

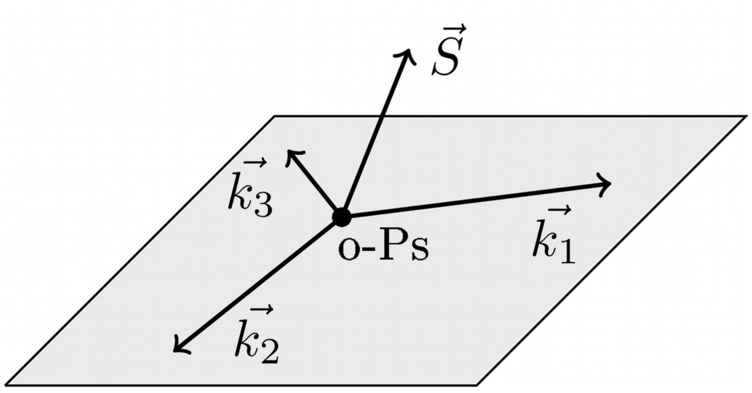




A new inner layer
with digital readout
→ 3x higher sensitivity
for single γ
→ See talks by:
G. Korcyl & Sz. Niedźwiecki
On Thursday

Testing discrete symmetries with ortho-positronium

$$e^+e^- \to \text{o-Ps} \to 3\gamma$$



$$|\vec{k}_1| > |\vec{k}_2| > |\vec{k}_3|$$

$$\left\langle \hat{O} \right\rangle \stackrel{?}{=} 0 \quad \text{for an odd operator}$$

$$\Leftrightarrow \mathcal{CPT}(\hat{O}) = -1$$

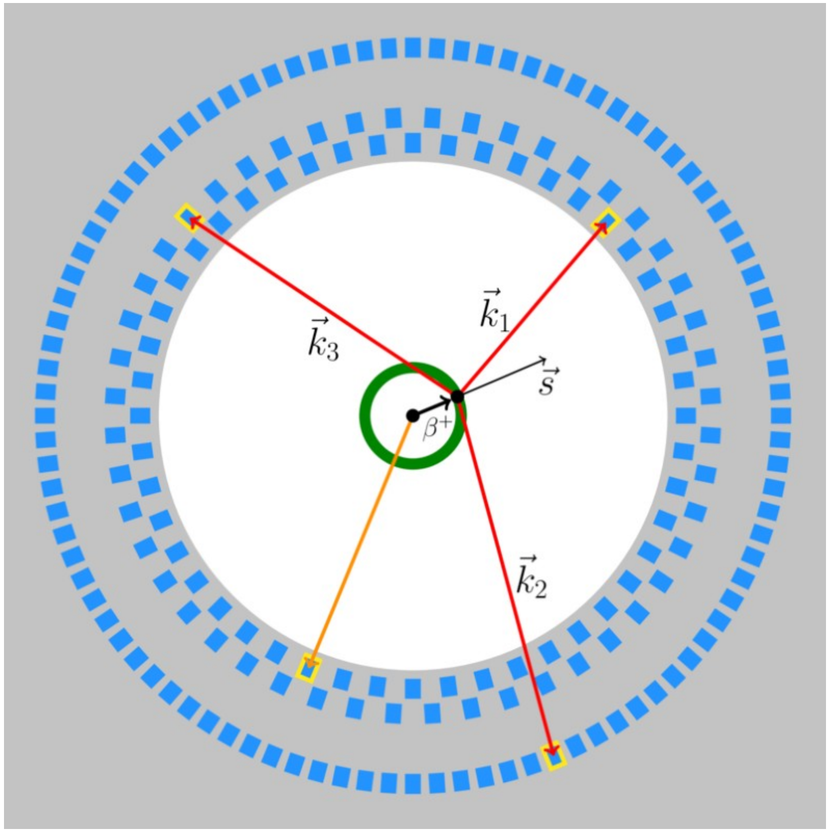
$$\Leftrightarrow \mathcal{T}(\hat{O}) = -1$$

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

This talk presents the study of the following T and CPT-odd operator:

$$\hat{S} \cdot (\vec{k}_1 \times \vec{k}_2)/|\vec{k}_1 \times \vec{k}_2| = cos(\theta)$$

θ – angle between o-Ps spin and decay plane normal



Front view of the J-PET detector

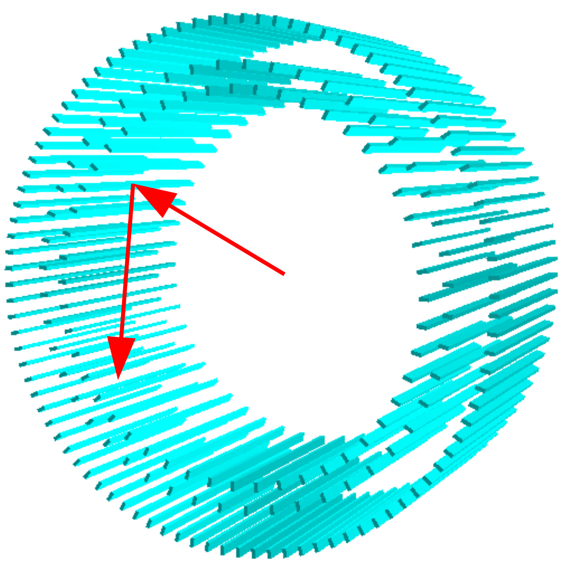
Testing discrete symmetries with ortho-positronium

If polarization direction of the photons (ϵ) can be estimated, a new class of operators becomes available for measurement!

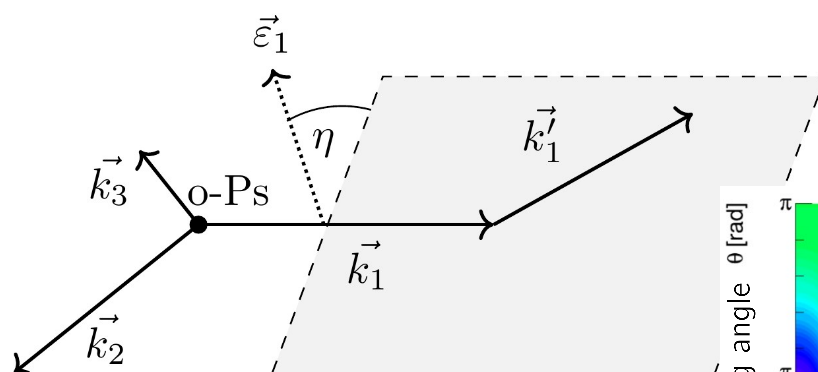
For details of the study of this operator at J-PET see the talk of J. Raj in the same session

operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k_1}$	+	−	+	−	−
$\vec{S} \cdot (\vec{k_1} \times \vec{k_2})$	+	+	−	+	−
$(\vec{S} \cdot \vec{k_1})(\vec{S} \cdot (\vec{k_1} \times \vec{k_2}))$	+	−	−	−	+
$\vec{k}_2 \cdot \vec{\epsilon}_1$	+	−	−	−	+
$\vec{S} \cdot \vec{\epsilon}_1$	+	+	−	+	−
$\vec{S} \cdot (\vec{k}_2 \times \vec{\epsilon}_1)$	+	−	+	−	−

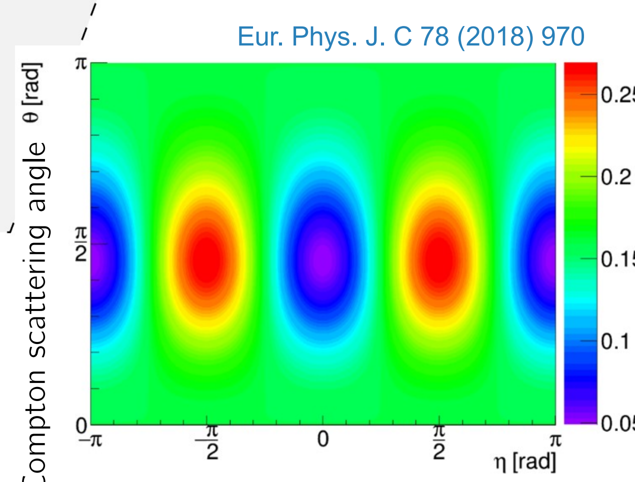
[P. Moskal *et al., Acta Phys. Polon. B47 (2016) 509*]



J-PET can determine the scattering plane in events with secondary Compton scatterings!



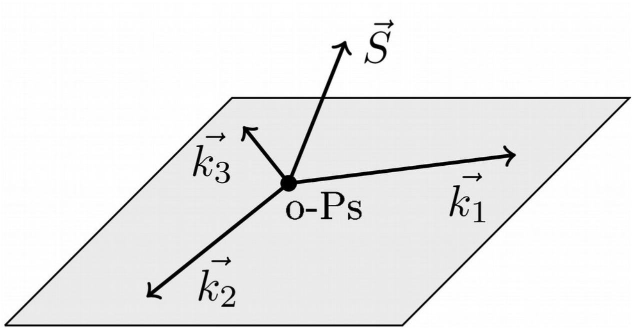
$$|\vec{k}_1| > |\vec{k}_2| > |\vec{k}_3|$$



Angle between ϵ and the scattering plane

Symmetry-sensitive operators involving o-Ps spin

Goal: measurement of expectation values of angular corelation operators odd under a given discrete symmetry transformation



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

Using external magnetic field to polarize the o-Ps along a pre-defined axis
→ The only case when $(\vec{S}\cdot\vec{k}_1)(\vec{S}\cdot(\vec{k}_1\times\vec{k}_2))$ can be studied

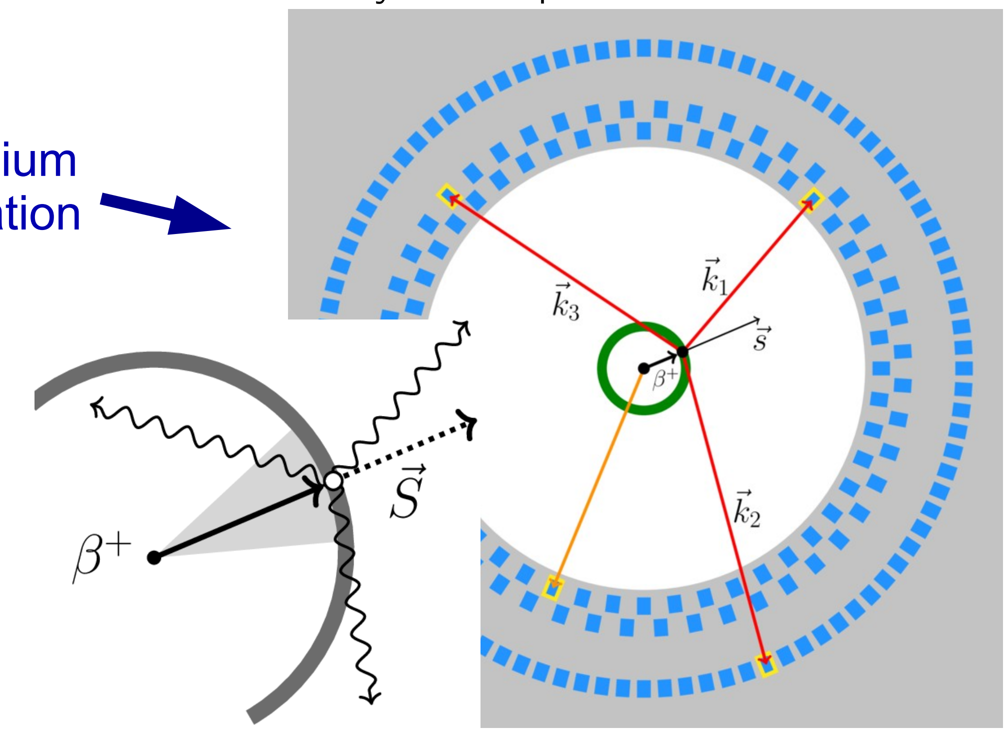
Ortho-positronium spin determination is required

Limiting the momentum direction of positrons forming o-Ps to some solid angle

$$P = \frac{v}{c}(1+\cos\alpha)/2$$

For a cone of opening angle α

Event-by-event spin estimation at J-PET

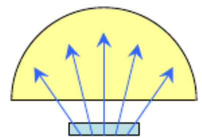


[A. Gajos et al., NIM A 819 (2016), 54-59]

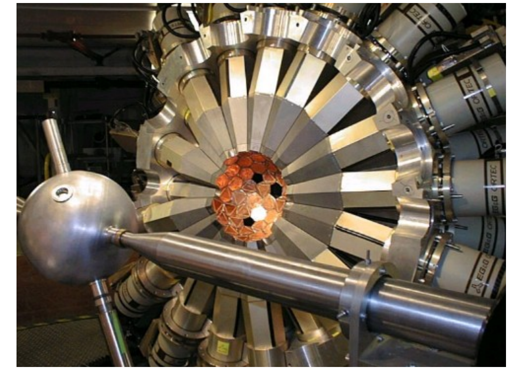
J-PET vs previous experiments

CPT test @ Gammasphere

$$\vec{S} \cdot (\vec{k_1} \times \vec{k_2})$$



$$P_{e+} = \frac{v}{c} \cdot 0.5$$



C_{CPT}= 0.0026±0.0031

β^+ emitter activity 1 MBq

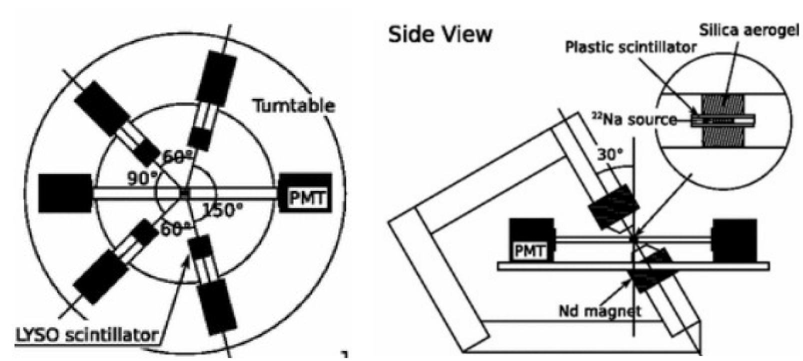
[P.A. Vetter et al., Phys. Rev. Lett. 91 (2003) 263401]

CP test using $(\vec{S} \cdot \vec{k_1})(\vec{S} \cdot (\vec{k_1} \times \vec{k_2}))$

- Polarizing o-Ps using magnetic field
- Inclusive measurement

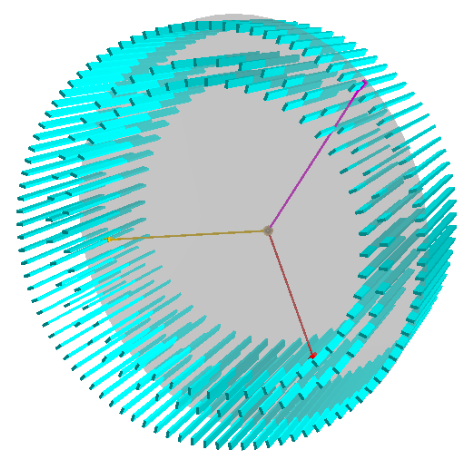
$-0.0023 < C_{CP} < 0.0049$.

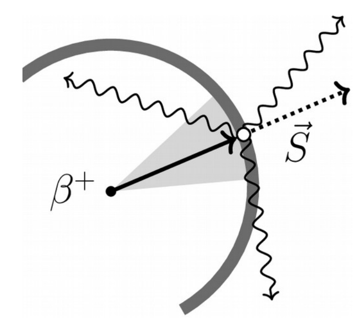
[T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401]



CPT and CP tests at J-PET

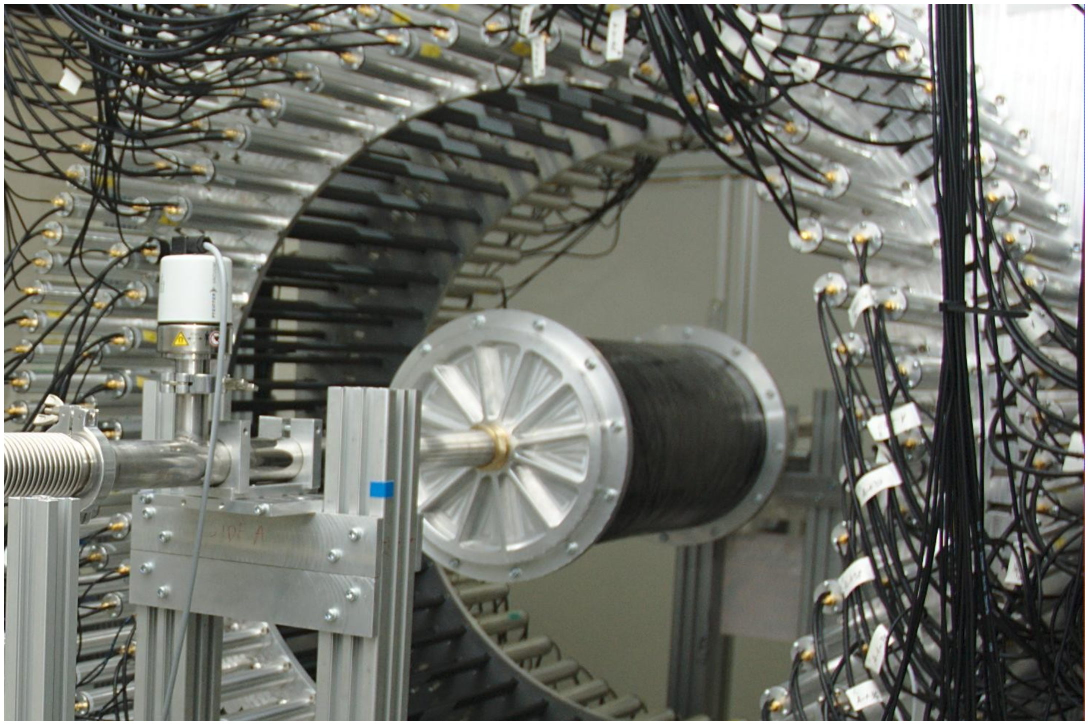
- Estimating e+ spin event-by-event
- Recording multiple geometrical configurations at the same time
- Fast timing = high β^+ emitter activities (tested <= 10 MBq)

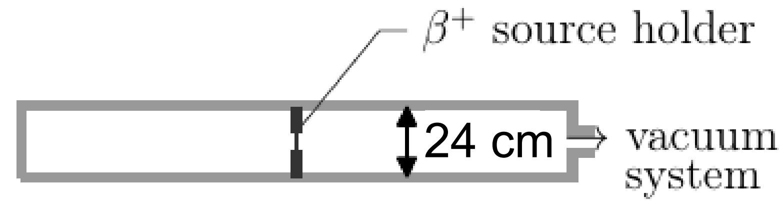




$$P_{e+} = \frac{v}{c} \cdot 0.98$$

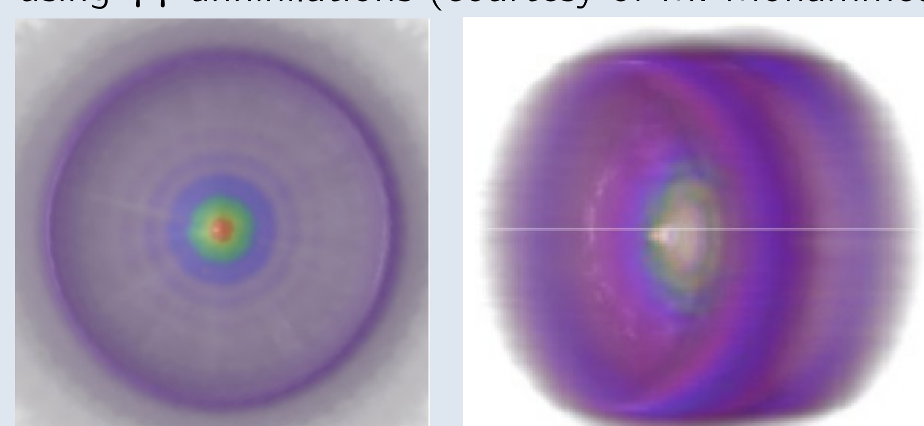
Producing and recording o-Ps→3γ in J-PET with extensive-size vacuum chamber





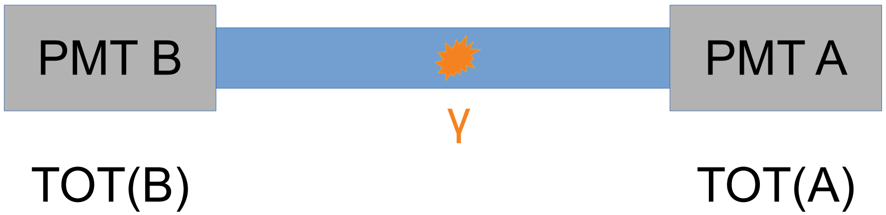
- Extensive-size vacuum chamber, R ≈ 12 cm
- Walls coated with XAD-4 porous material enhancing o-Ps formation
- β^+ emitter placed in the centre of the chamber
- 2 different ^{22}Na source activities used
  - **10 Mbq - 180 days of measurement**
  - **0.8 Mbq - 14 days of measurement**

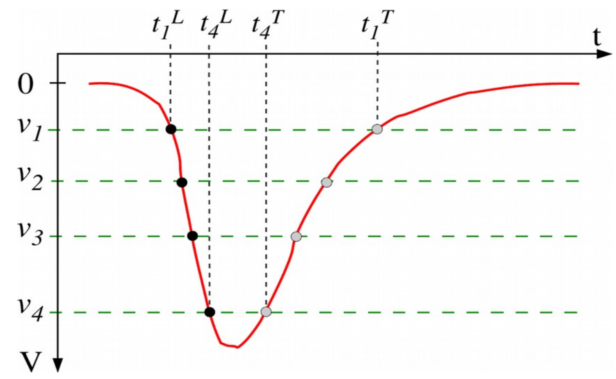
Tomographic images of the chamber obtained using γγ annihilations (courtesy of M. Mohammed)



Using Time Over Threshold to identify prompt and annihilation photons

TOT provides a measure of energy deposited in Compton scattering

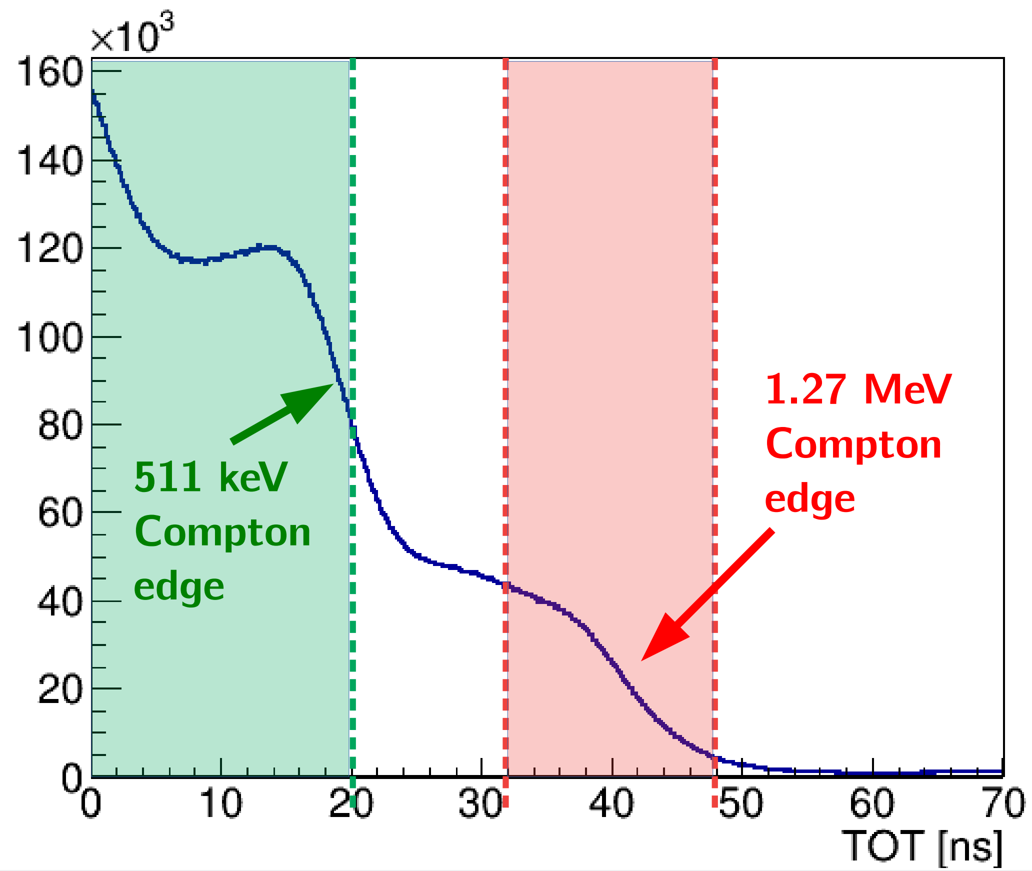




Photon identification:

o-Ps →3γ annihilation (E<511 keV) photon candidates

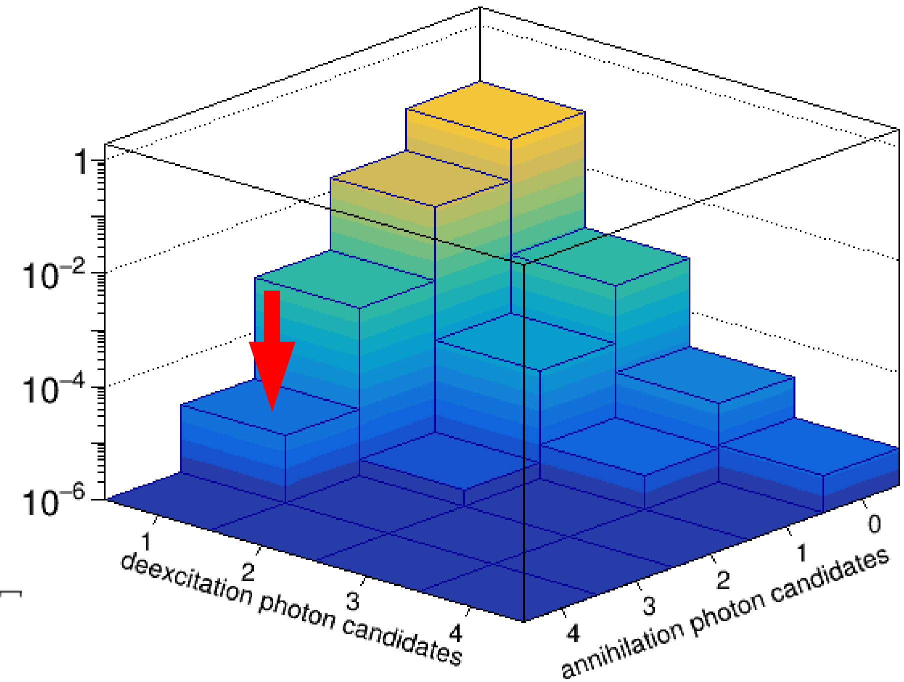
^{22}Ne* de-excitation (E=1.27 MeV) photon candidates



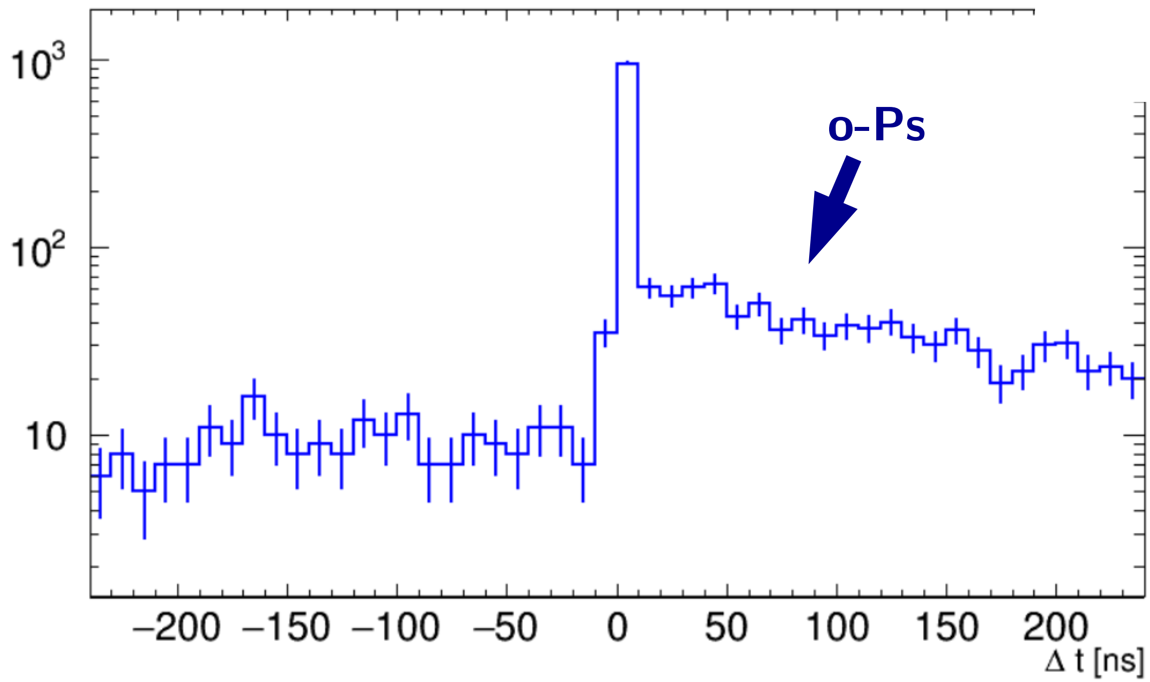
o-Ps → 3γ in J-PET

Considering events where:

- 3 annihilation photon candidates were identified within 2.5 ns
- in coincidence with a single deexcitation candidate in a 250 ns time window



Time between 3γ annihilation and deexcitation of β+ emitter

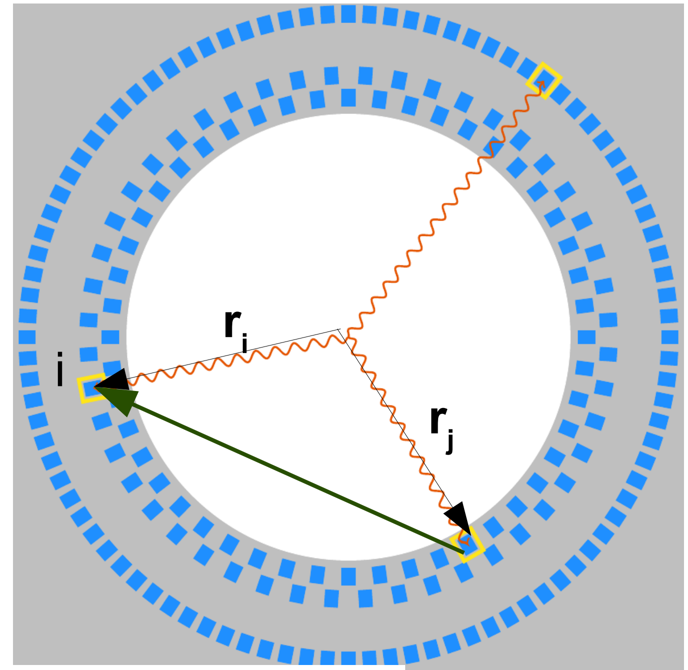


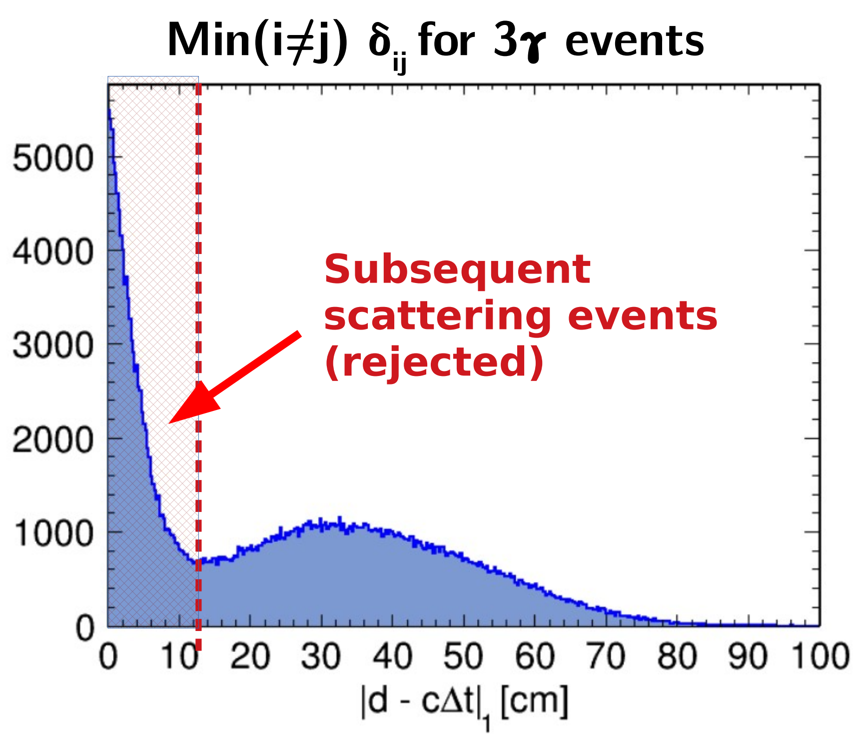
Rejection of subsequent scatterings in the detector

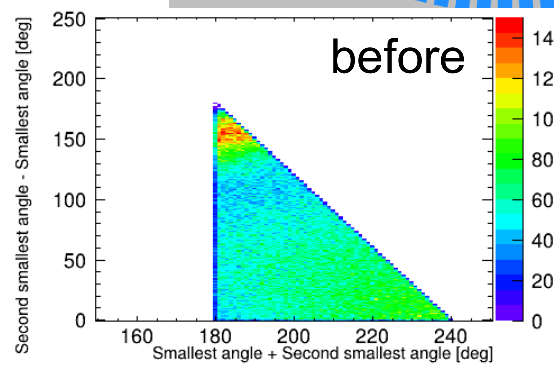
- See the talk by J. Raj for the case when we **do not** want to reject such scatterings
- For each pair of annihilation photon candidates *i* and *j* (*i*,*j*=1,2,3) the following figure is computed:

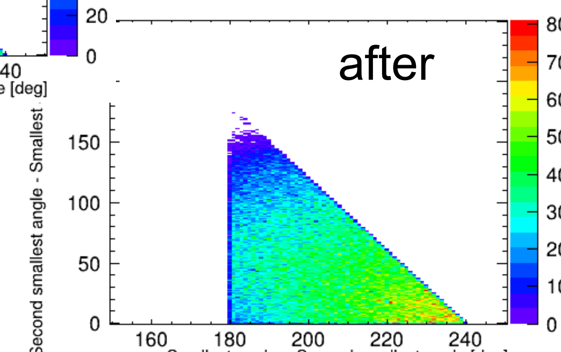
$$\delta t_{ij} = |d_{ij} - c\Delta t_{ij}|$$

where $d_{ij} = |\vec{r}_i - \vec{r}_j|$



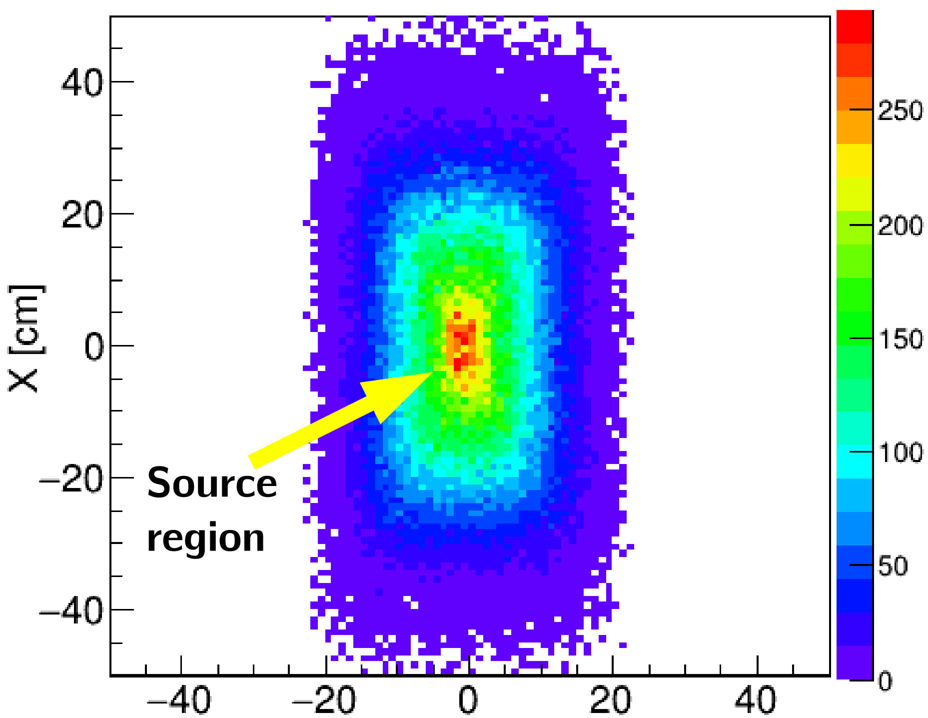


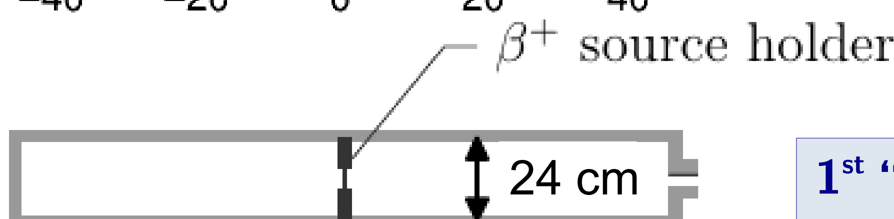




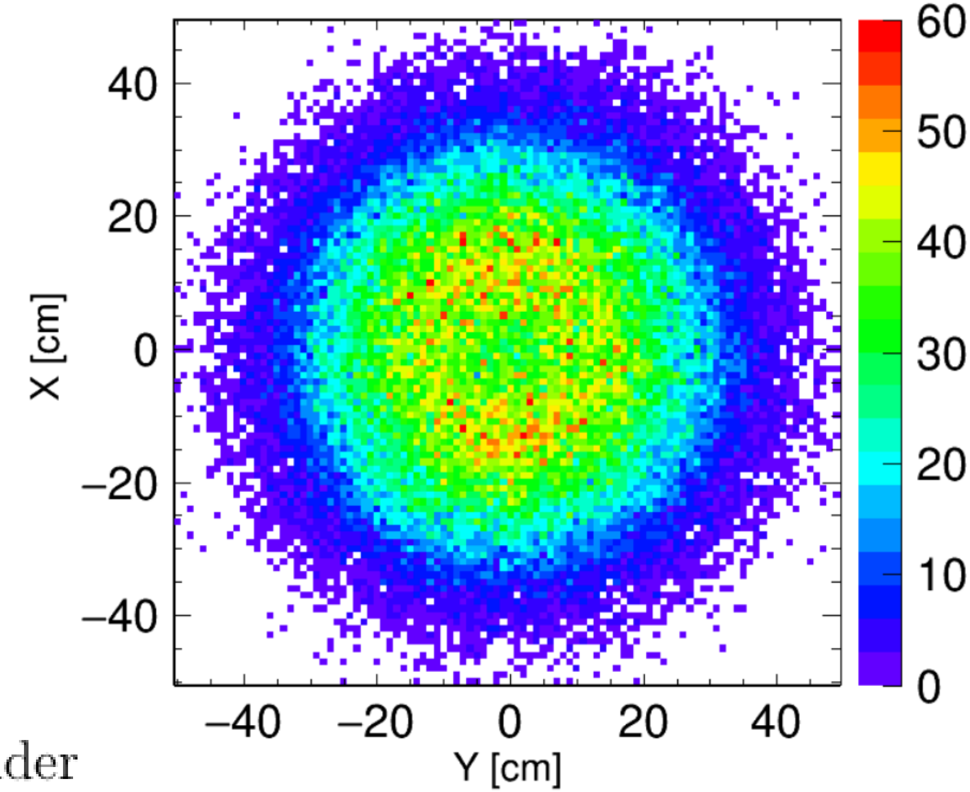
3γ image of the o-Ps production chamber

Side view of the detector



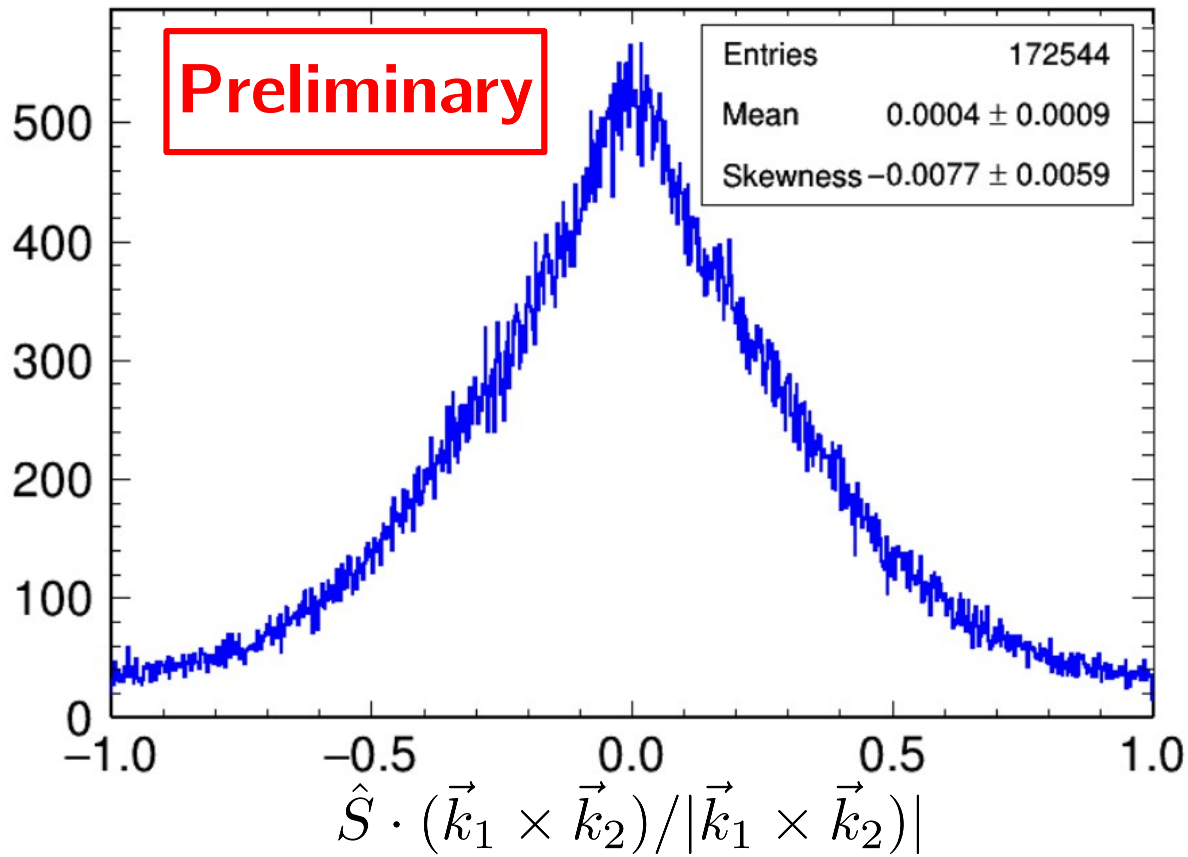


Transverse view of the detector
excluding the source region (|Z| > 2 cm)



1st "image" of an extensive-size object obtained using annihilations into three photons

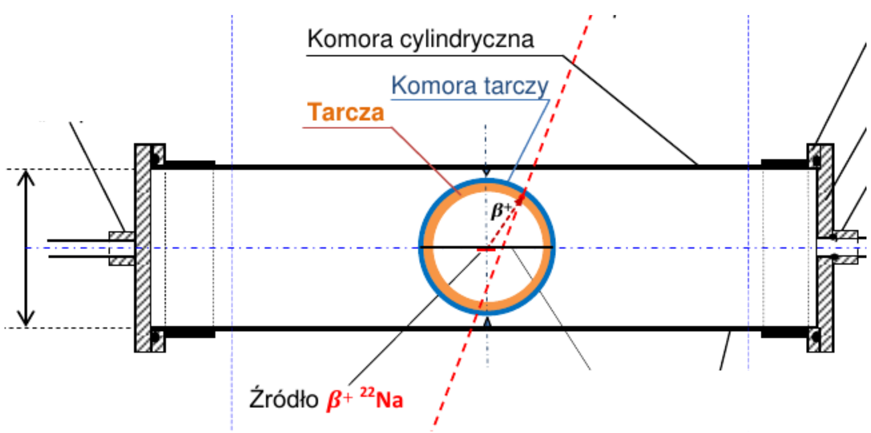
CPT-violation sensitive operator

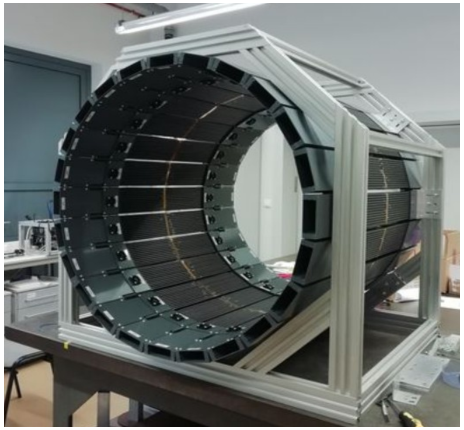


- Uncertainty: 9×10^{-4} (statistical only)
- Using 9% of the already available dataset (~300 TB total)
- Not yet corrected for detector acceptance

Summary and perspectives

- Positronium is the only system composed of charged leptons used to test discrete symmetries to date
- Available results indicate no CP nor CPT violation at the sensitivity level of 10^{-3}
- The J-PET detector is capable of an exclusive registration of o-Ps $\rightarrow 3\gamma$ annihilations
  - Including determination of spatial location of the annihilation point
  - Thus allowing for e+ and o-Ps spin estimation on an event-by-event basis
- J-PET aims at improving the sensitivity limits to in tests of discrete symmetries by at least an order of magnitude
  - With prospects for further improvement





Thank you for your attention!

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European Funds Smart Growth
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FNP Foundation for Polish Science
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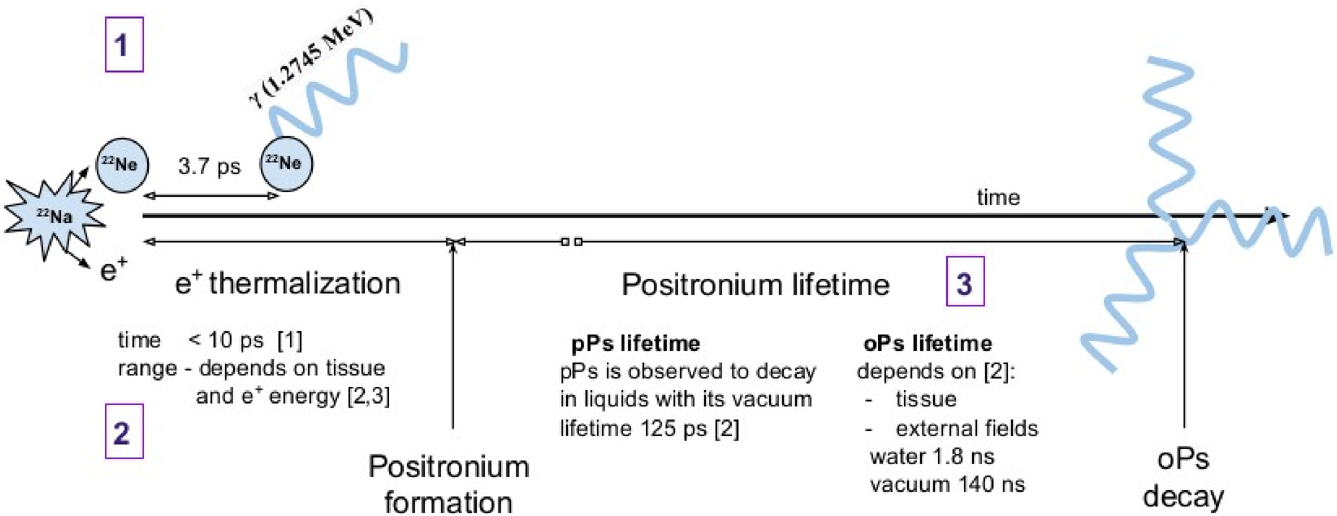
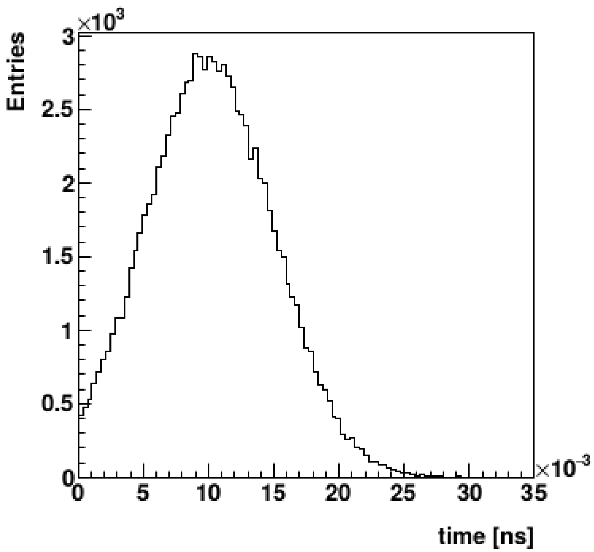
Backup Slides

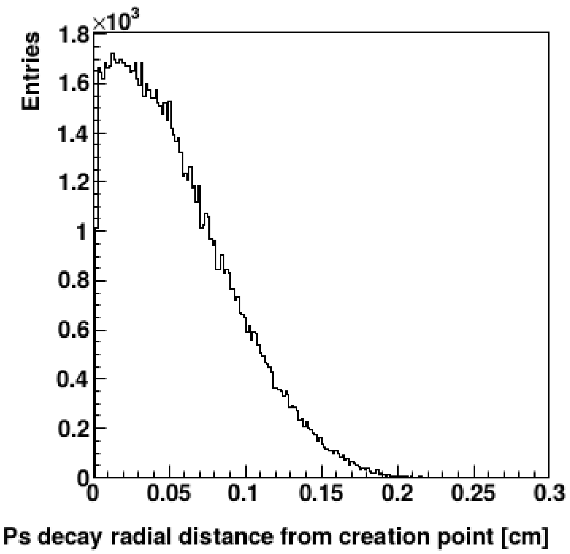
O-Ps creation and decay



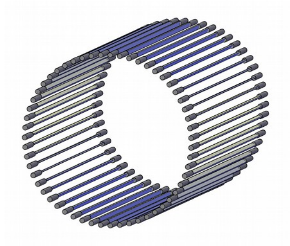
[1] P. Kubica and A. T. Stewart, Phys. Rev. Lett. 34 (1975) 852
[2] M. Harpen Med.Phys. 31 (2004) 57-61
[3] J Cal-Gonzalez et al, Phys. Med. Biol. 58 (2013) 5127–5152

oPs creation time





Distinguishing o-Ps→3γ and e^+e^- →2γ



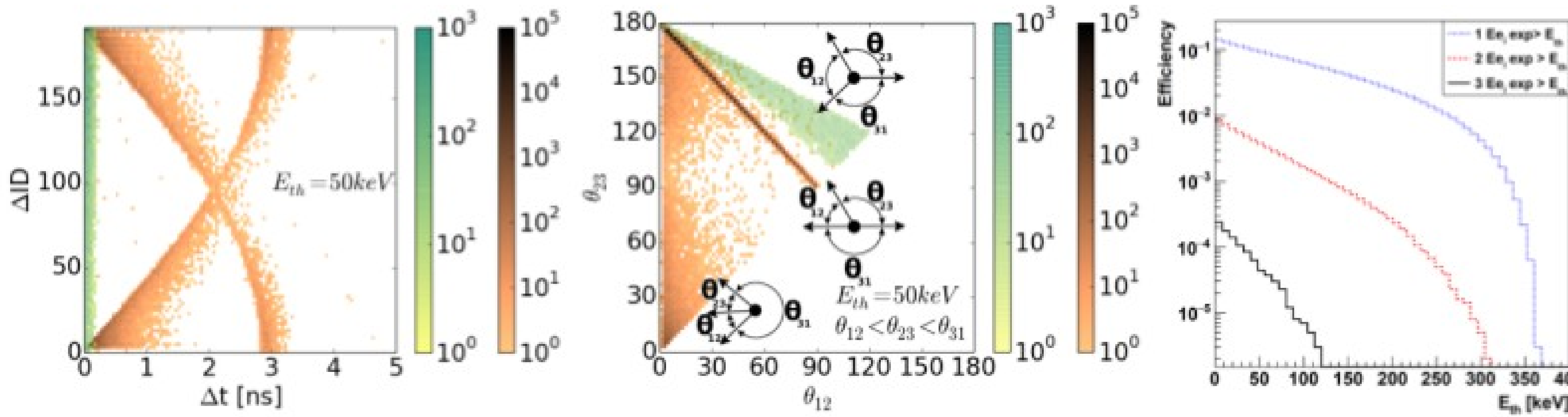


Figure 9. (Left) Simulated distributions of differences between detectors ID (ΔID) and differences of hit-times (Δt) for events with three hits registered from the annihilation e+e- → 2γ (gold colours) and o-Ps → 3γ (green colours). **(Middle)** Disribution of relative angles between reconstructed directions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

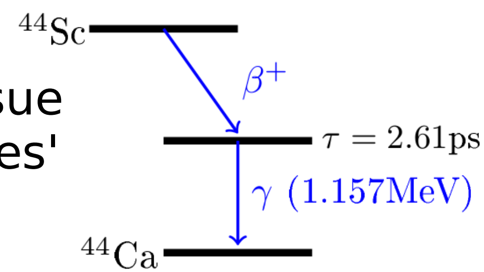
Ortho-positronium decay tomography

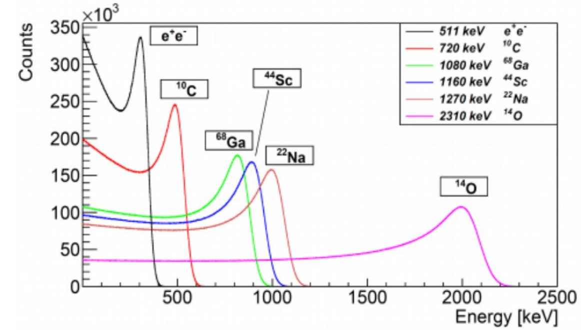
Motivation:

- 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

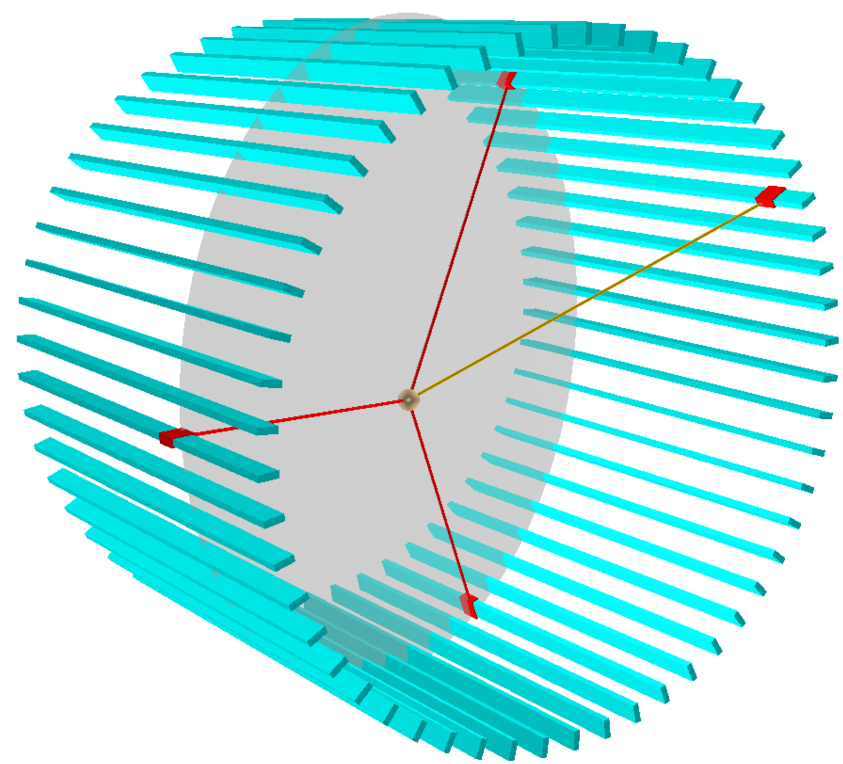
Properties of the process:

- 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

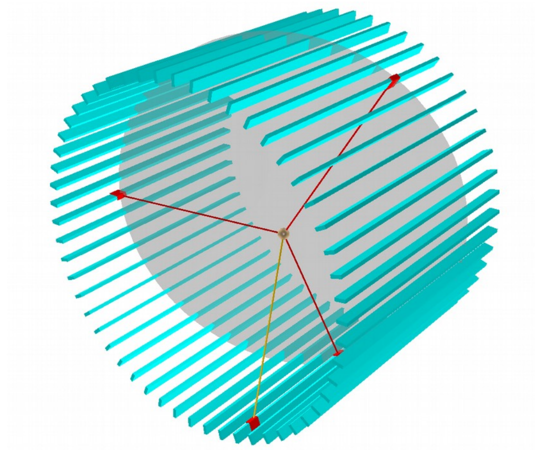




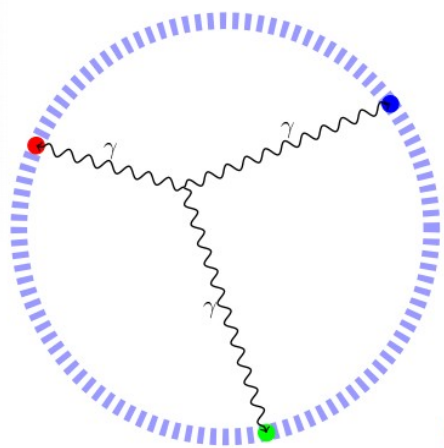
[P.M. et al., Patent Application: PCT/EP2014/068374; WO2015028604]



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



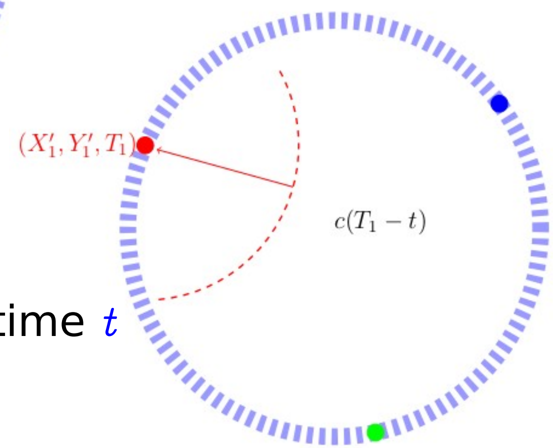
1. Find the decay plane containing the 3 hits in the J-PET barrel



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

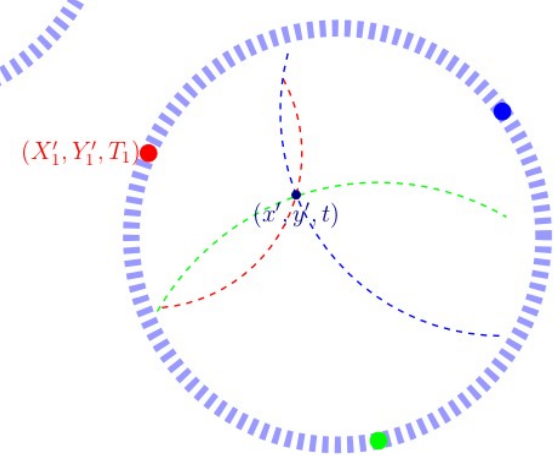
$$(X_i, Y_i, Z_i, T_i) \rightarrow (X_i', Y_i', 0, T_i)$$

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



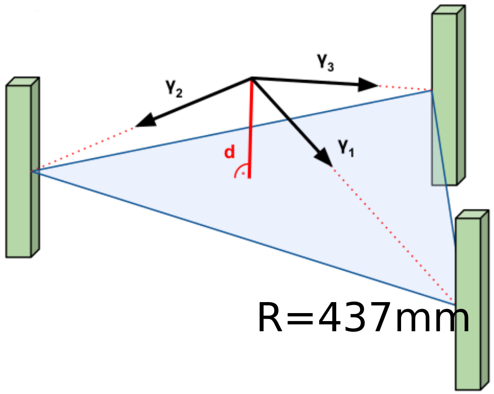
4. The decay point (x', y') in the decay plane and time t is an intersection of 3 such circles:

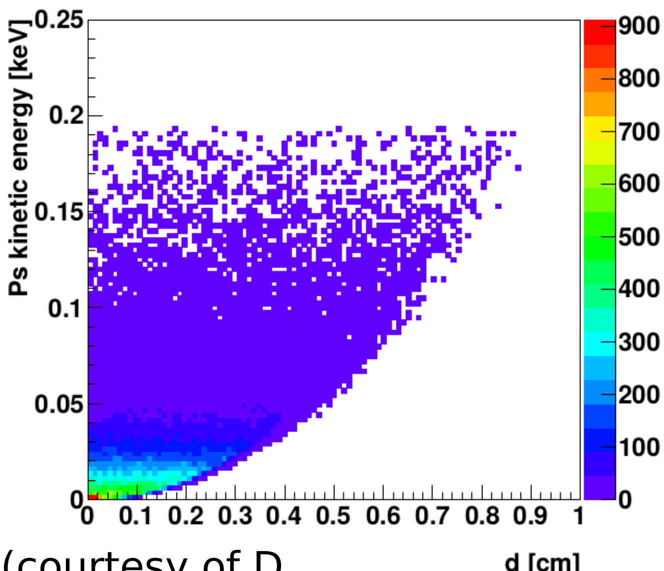
$$(T_i - t)^2 c^2 = (X_i' - x')^2 + (Y_i' - y')^2, \quad i = 1, 2, 3$$



Effects included in the simulation

Non-coplanarity of photons' momenta

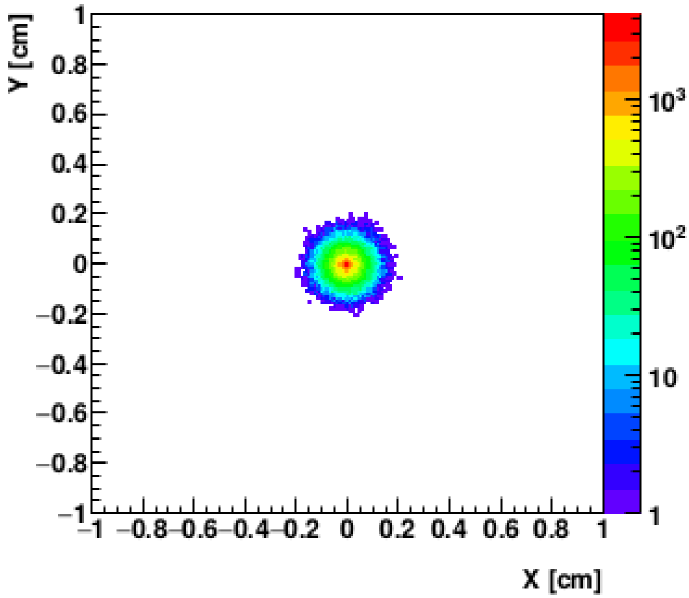




(courtesy of D. Kamińska)

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)

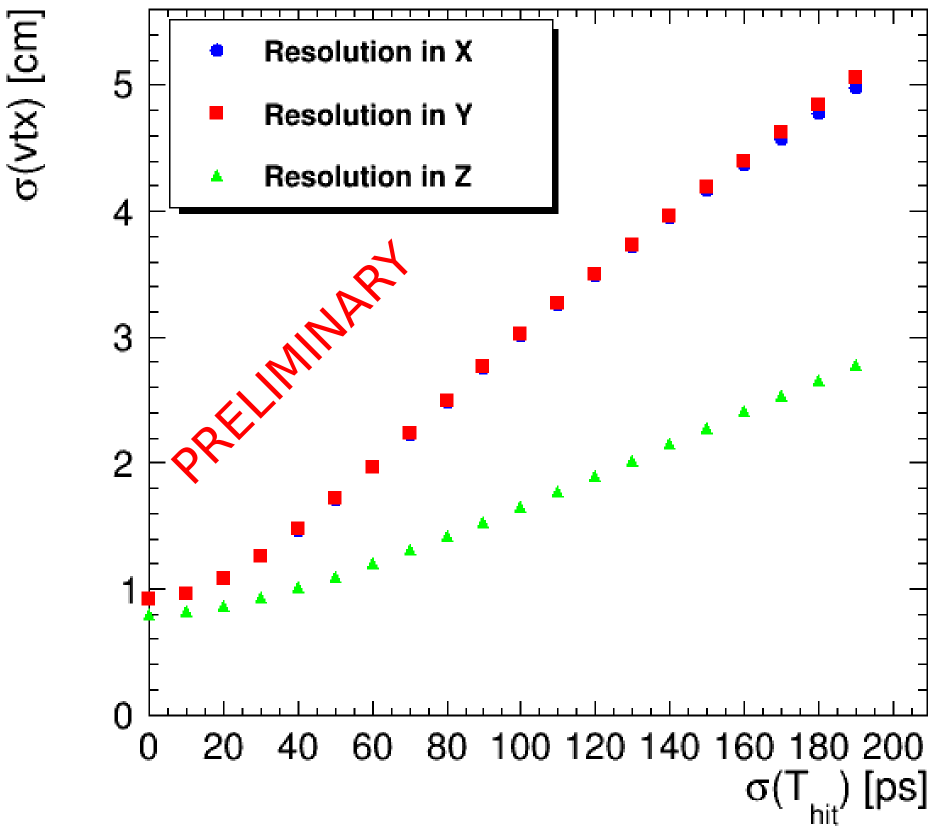
Both effects are negligible within reconstruction resolution (presented on next slides).

Resolution dependence on γ hit time resolution

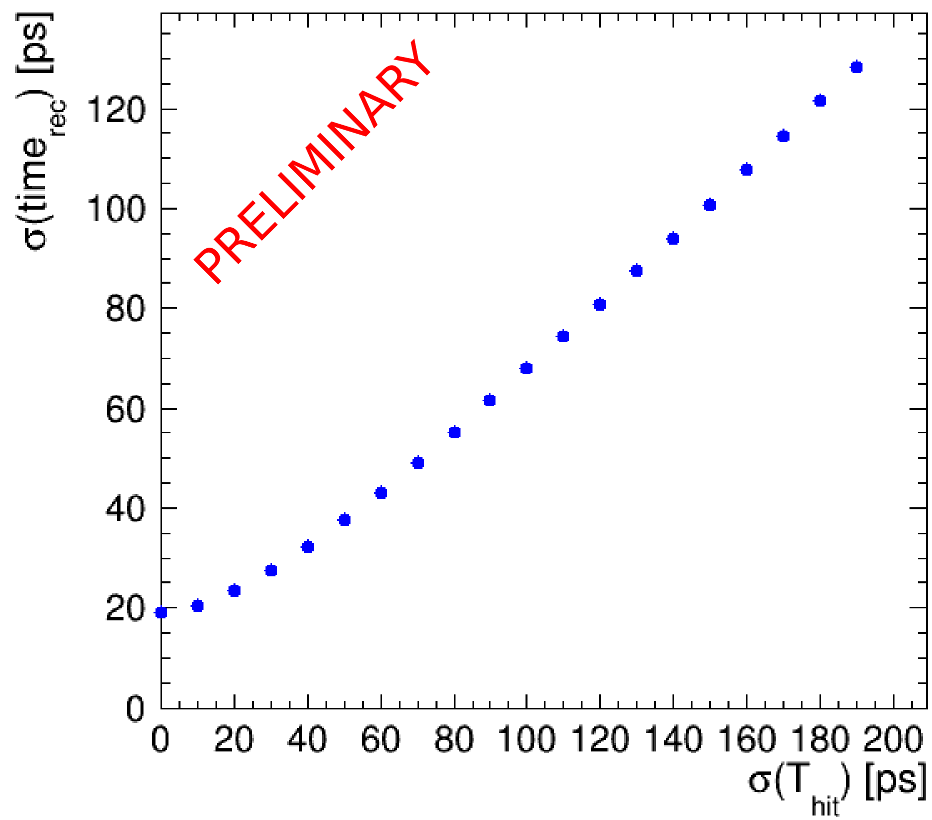
The resolution of o-Ps decay obtained with the presented reconstruction method depends predominantly on the timing resolution of γ hits in scintillator strips.

O-Ps decay resolution

spatial



time

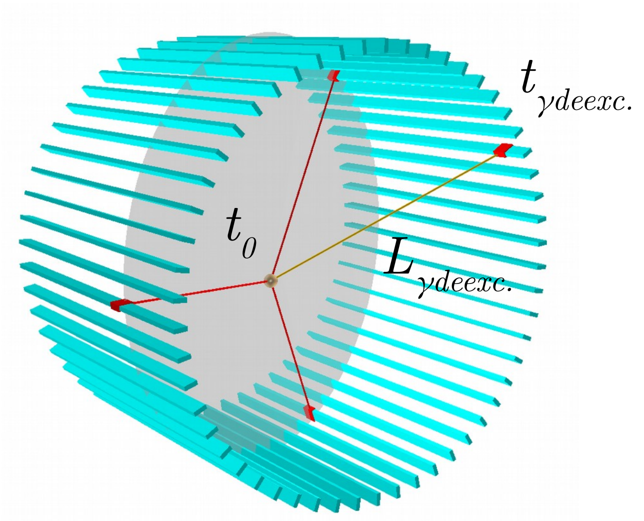


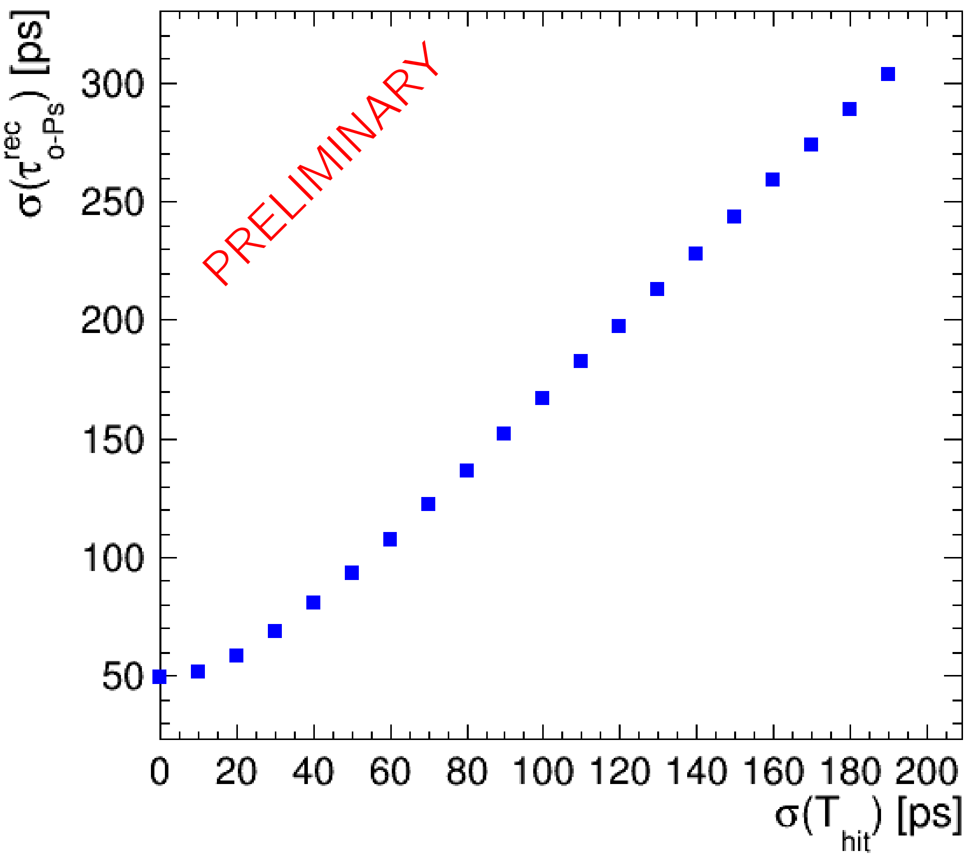
Ortho-positronium life time resolution

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.





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

- 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

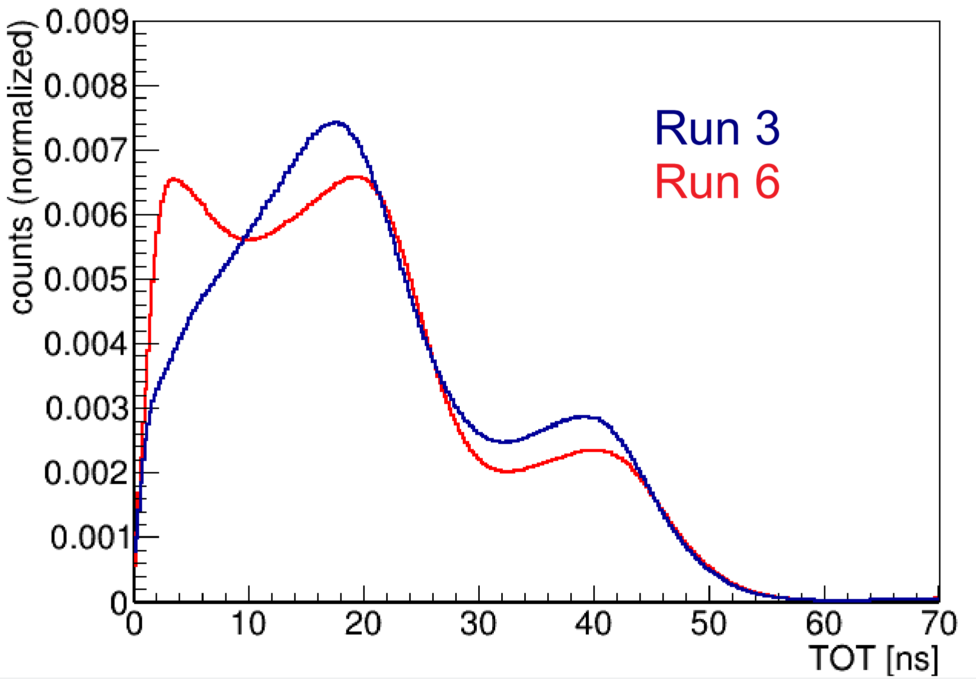
- Rejection of multiple subsequent γ scatterings in the detector

- Study of the angular topology of the events

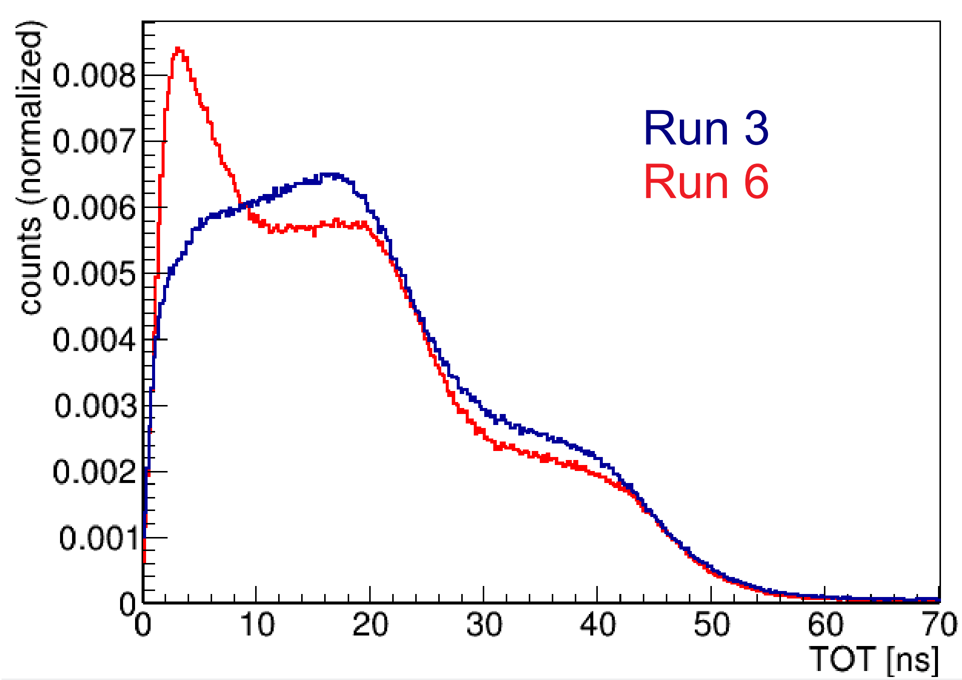
- Trilateration-based reconstruction of o-Ps → 3γ decay point and time

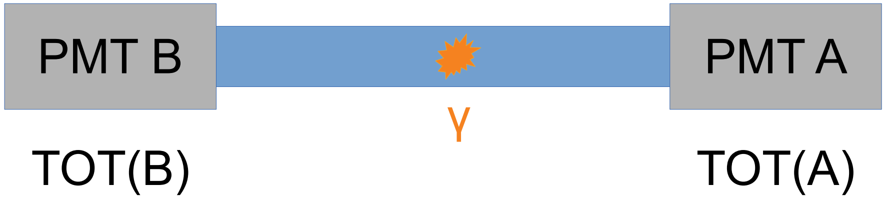
Time Over Threshold (TOT) distributions

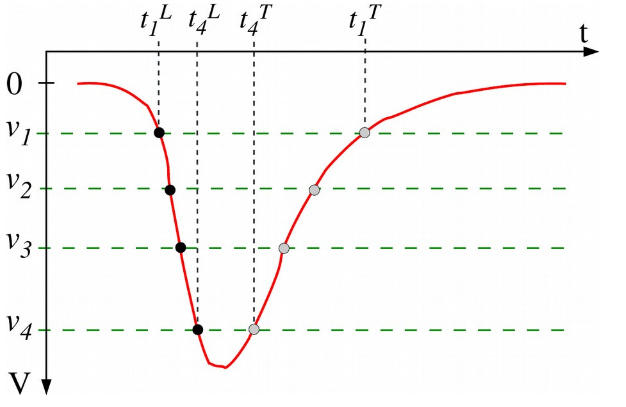
TOT for all recorded γ hits



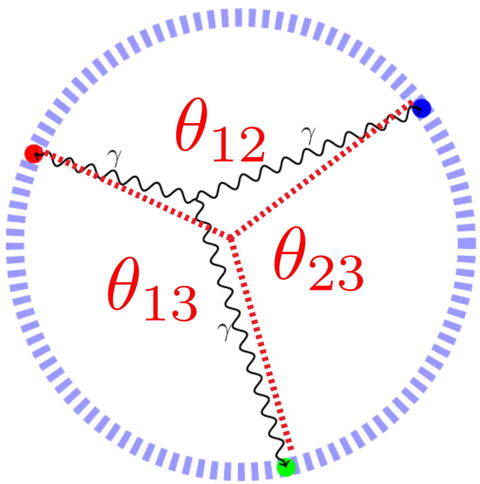
TOT for γ hits recorded in events with at least 3 hits within 20 ns





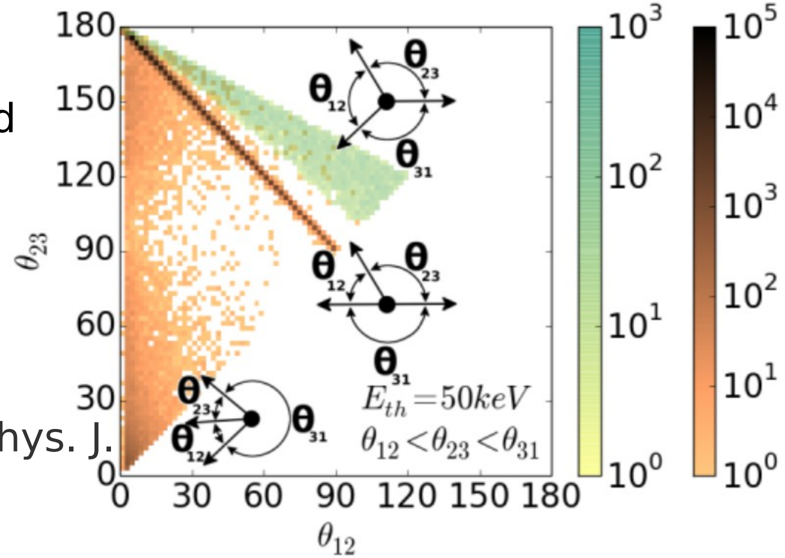


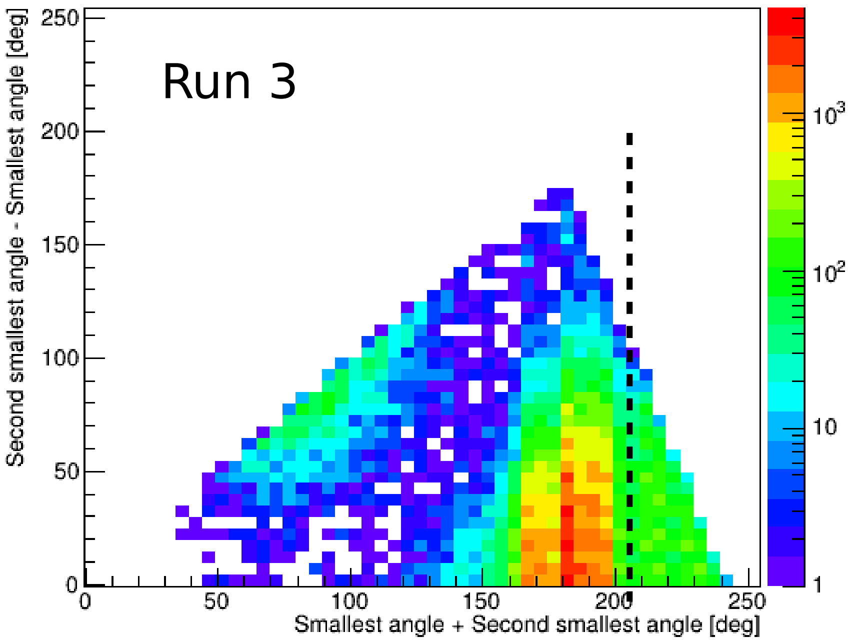
Angular topology of three-photon events

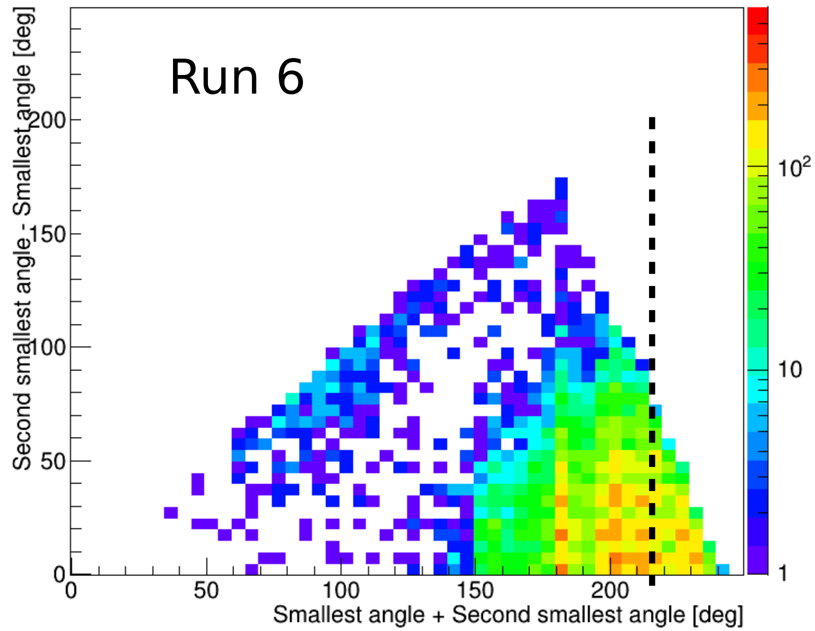


Reference:
Angles between three photons' momenta expected for different types of events (MC simulation results)

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



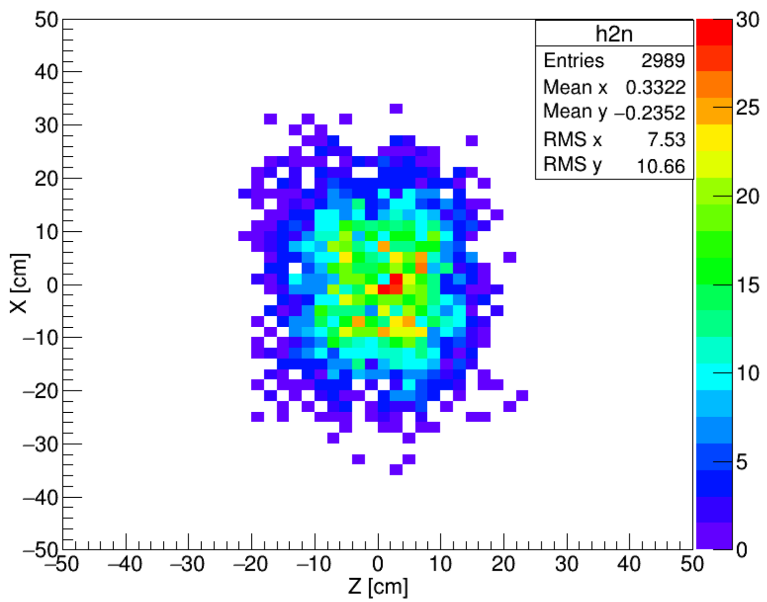




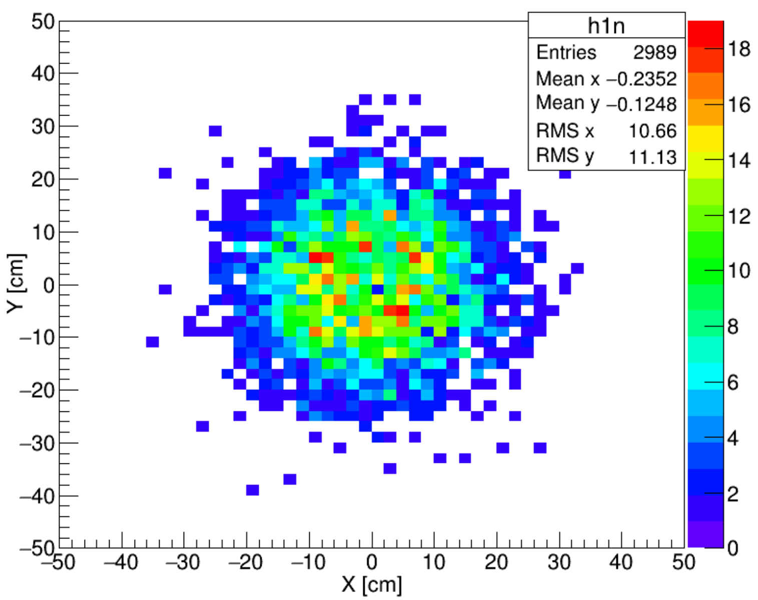
For details on the 2γ event properties, see the talk by M. Mohammed, Session 8, Wed 15:50

Reconstructed o-Ps → 3γ decay points

Results obtained with the trilaterative decay point reconstruction
Using about 3 % of the collected Run 6 data



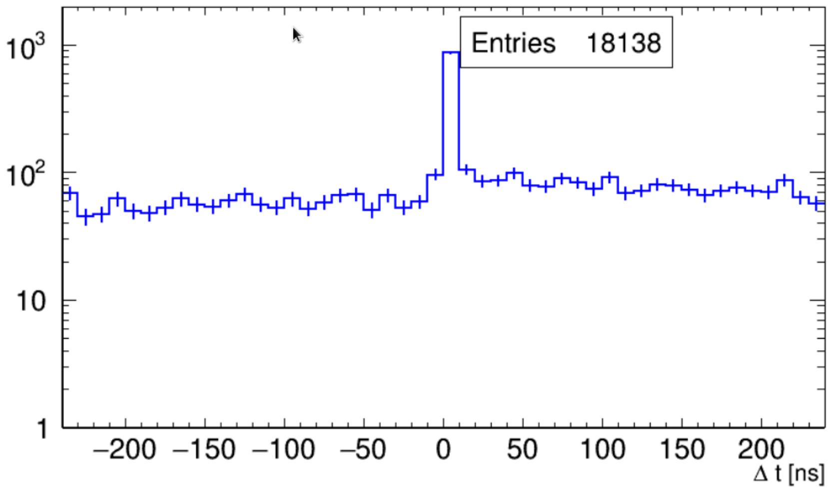
Longitudinal view



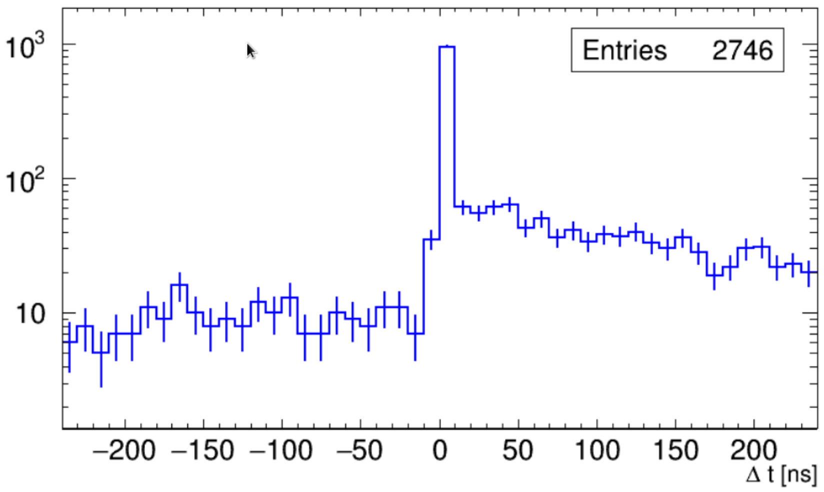
Transverse view

O-Ps lifetime spectra and accidental conicidences

Scheme with a propmt photon followed by an o-Ps → 3g annihilations



Soure activity 10 MBq



Soure activity 0.8 MBq