Test of the CPT symmetry in positronium annihilations at sub-permil precision using the J-PET tomography device

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Aleksander Gajos
on behalf of the J-PET Collaboration
Jagiellonian University

J-PET

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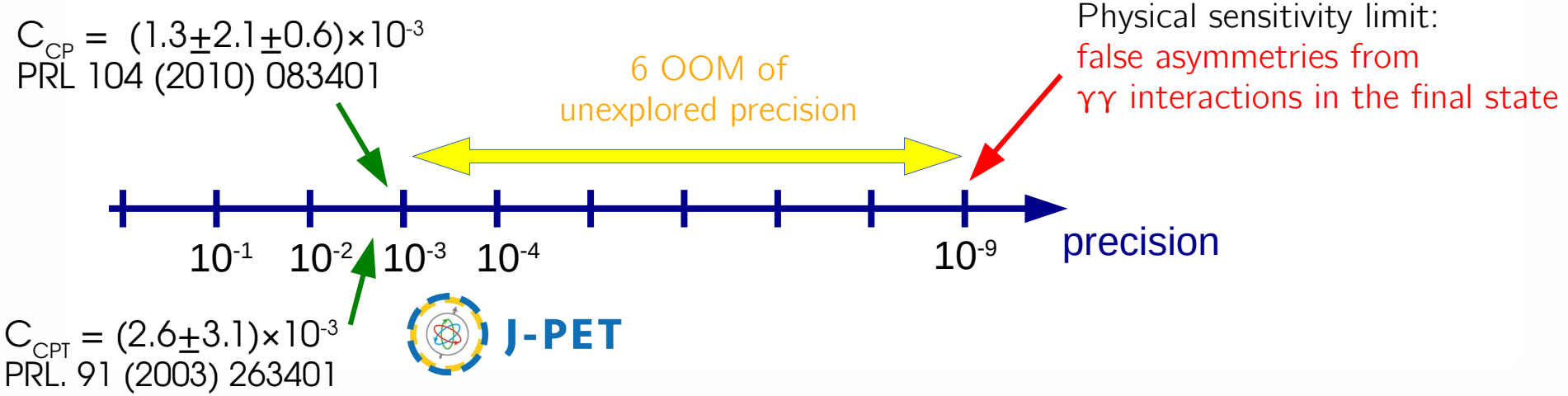
Motivation: discrete symetry tests with o-Ps → 3γ decays

- Discrete symmetries are scarcely tested with leptonic systems
- Prominent results from neutrinos oscillation experiments
  - Dirac phase, δ_{CP} ~3σ level [T2K, *Nature* 580 (2020) 339]
- Electron EDM < 1.1×10^{-29} [ACME, Nature 562 (2018) 355]
- Positronium – the lightest purely leptonic bound state,
  the only system consisting of charged leptons used for tests of CP and CPT to date

How can we test discrete symmetries in the positronium system?

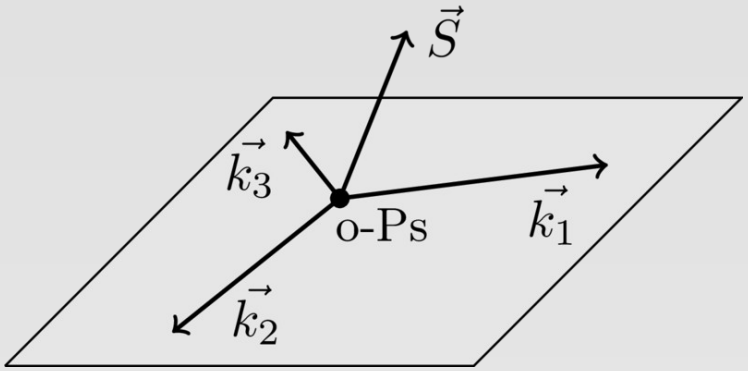
- Searches for **prohibited positronium annihilations**
  (see the talks by Sz. Niedźwiecki, Session A2 and P. Moskal, today's Plenary Session)
- Certain SME-based searches for CPT violation were proposed with **positronium spectroscopy** [Phys. Rev. D92 (2015) 056002]

- **Searches for non-vanishing symmetry-odd correlations**



Testing discrete symmetries with angular correlations in o-Ps $\to 3\gamma$ decays

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



$$\left\langle \hat{O} \right\rangle \stackrel{?}{=} 0 \quad \text{for an odd operator}$$
$$\Leftrightarrow \mathcal{CPT}(\hat{O}) = -1$$
$$\Leftrightarrow \mathcal{T}(\hat{O}) = -1$$

$$|\vec{k_1}| > |\vec{k_2}| > |\vec{k_3}|$$

Using ortho-positronium spin
Requires either:
- polarization
- spin control
- spin estimation

Using photon polarization

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

[W. Bernreuther *et al., Z. Phys. C41 (1988) 143*]

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

o-Ps $\longrightarrow$ 3γ operators involving spin

Presently studied with J-PET:

$\vec{S} \cdot (\vec{k_1} \times \vec{k_2})$ T & CPT-violation sensitive

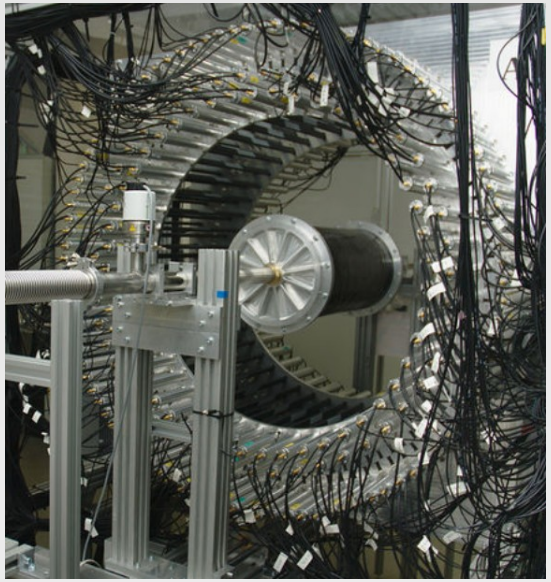
$\vec{S} \cdot \vec{k_1}$ CP-violation sensitive

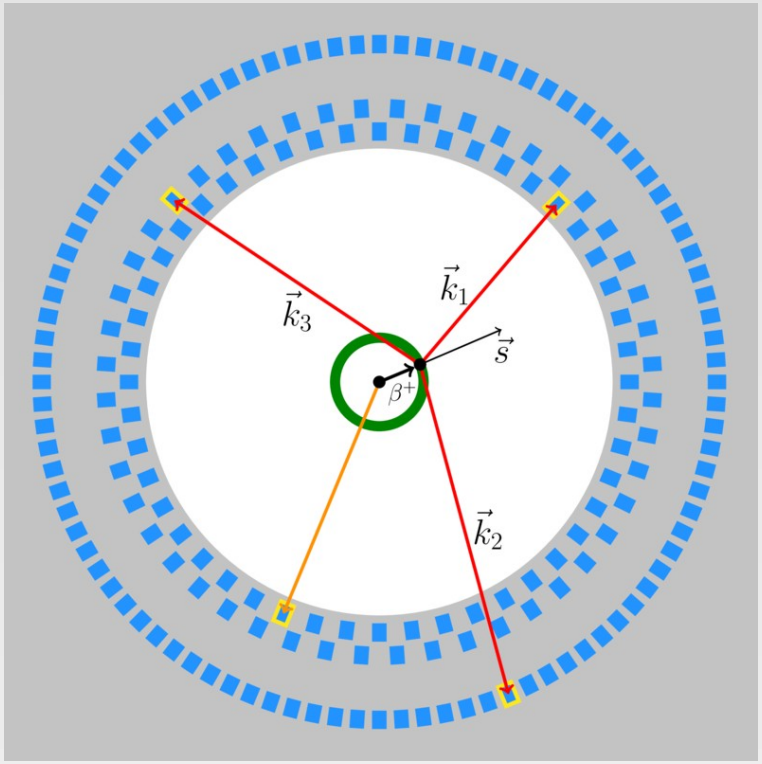
$(\vec{S} \cdot \vec{k_1})(\vec{S} \cdot (\vec{k_1} \times \vec{k_2}))$

T & CP-violation sensitive but requires o-Ps tensor polarization $\rightarrow$ not available with the current J-PET approach

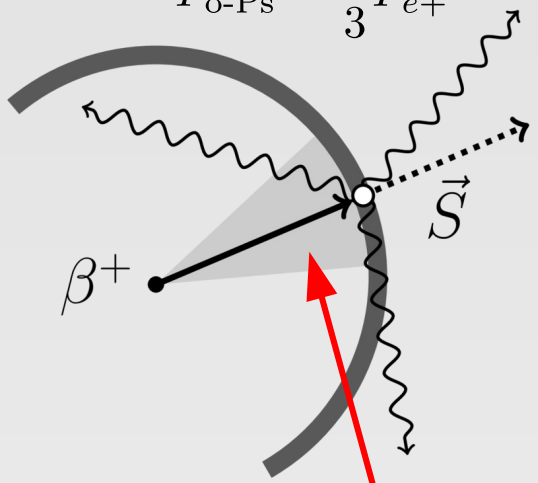
Event-by-event spin estimation

Using an extensive-size o-Ps production and annihilation medium





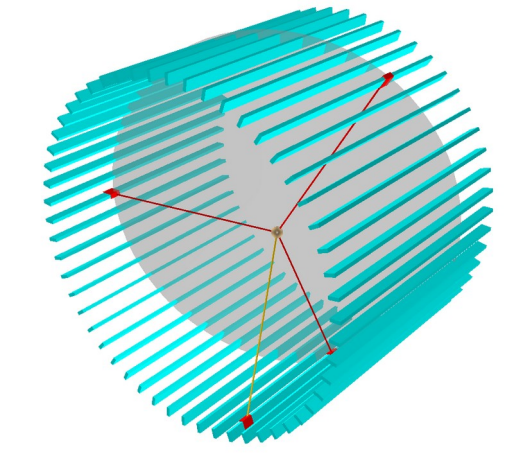
$$P_{\text{o-Ps}} = \frac{2}{3} P_{e+}$$



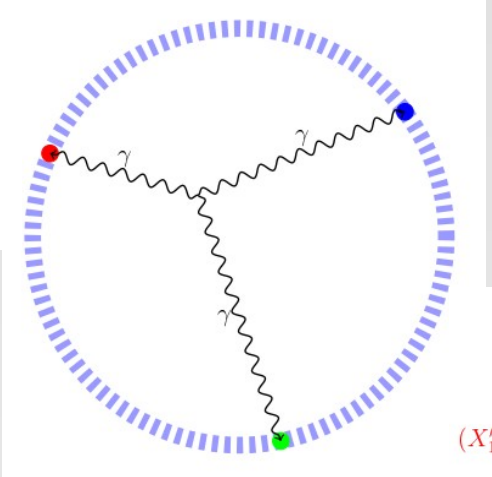
$$P_{e+} \approx \frac{v}{c} \cdot \frac{1}{2}(\cos\alpha + 1)$$

Effective polarization depends on o-Ps$\rightarrow$3γ vertex resolution

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

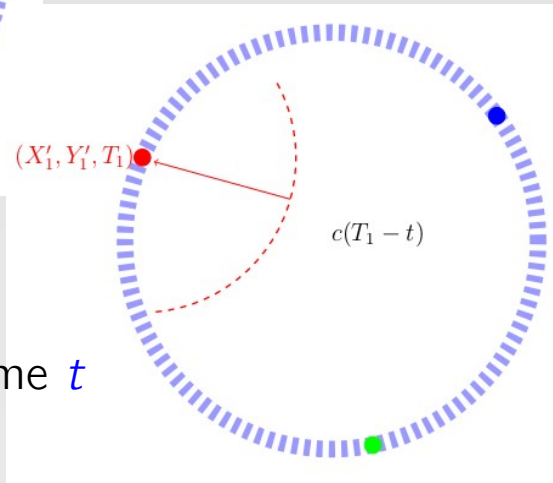


1. Find the decay plane containing the 3 hits in the J-PET barrel

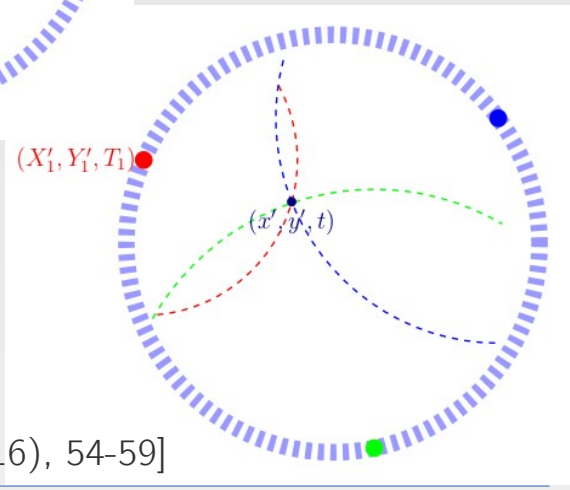


2. Transform the hit coordinates to a 2D coordinate system in the decay plane

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



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:

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

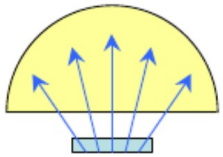
[A. Gajos et al., NIM A 819 (2016), 54-59]

J-PET vs previous measurements

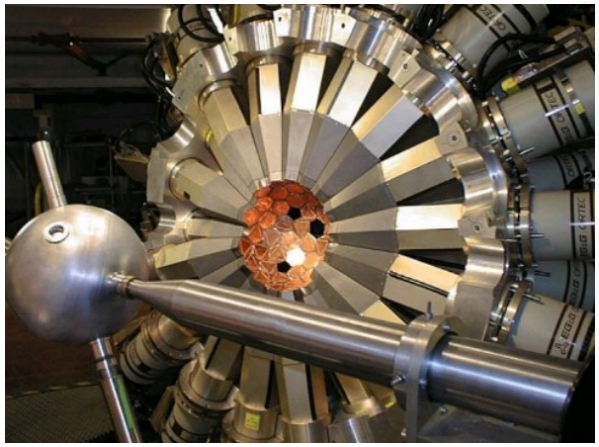
Gammasphere
PRL. 91 (2003) 263401

$C_{CPT} = (2.6 \pm 3.1) \times 10^{-3}$

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



$$P_{e+} = \frac{v}{c} \cdot 0.686$$

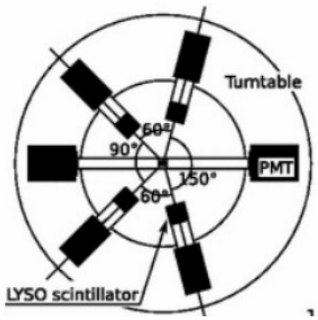


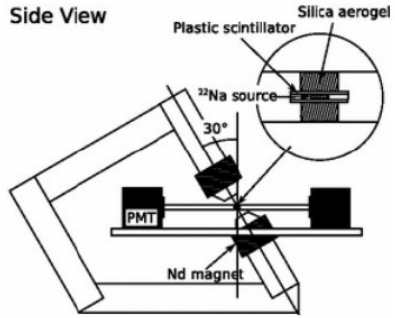
Limiting positron emission direction
1 Mbq β^+ emitter activity
4π detector but low angular resolution

Yamazaki et al.
PRL 104 (2010) 083401

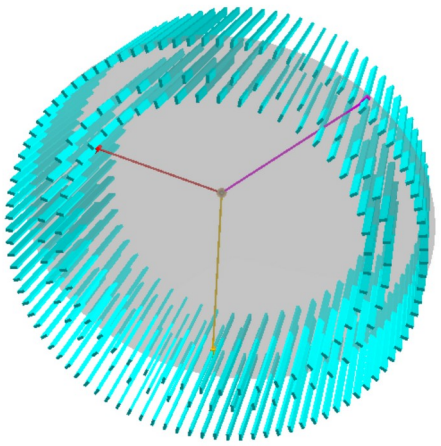
$$(\vec{S} \cdot \vec{k_1})(\vec{S} \cdot (\vec{k_1} \times \vec{k_2}))$$

$C_{CP} = (1.3 \pm 2.1 \pm 0.6) \times 10^{-3}$





Polarized o-Ps using external B field
Inclusive measurement
Only certain angular configurations



J-PET

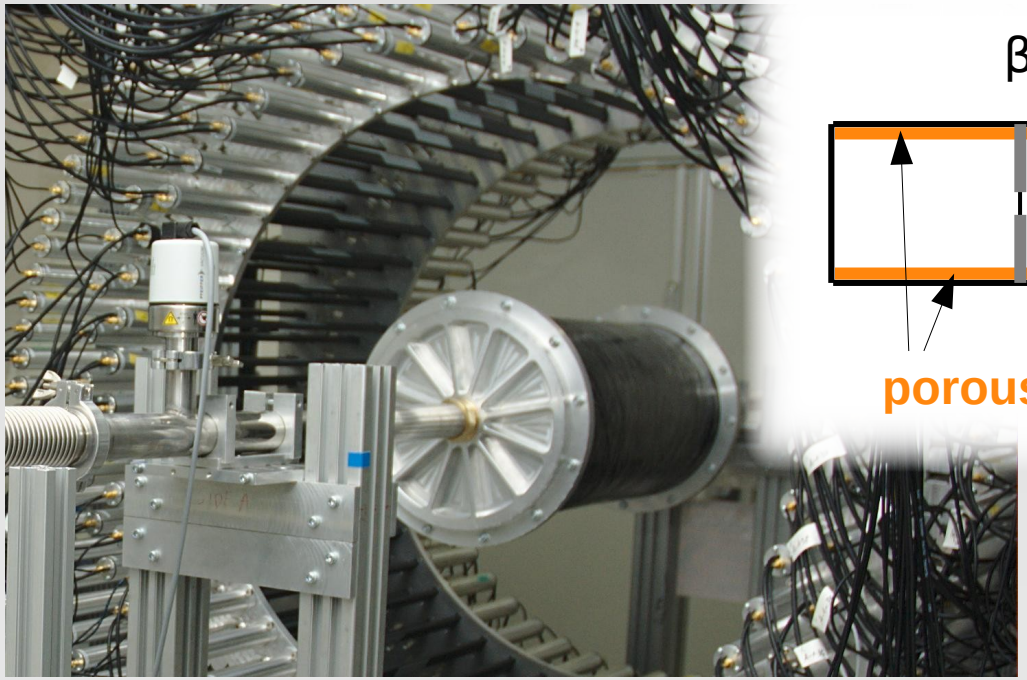
Recording multiple geometrical configurations

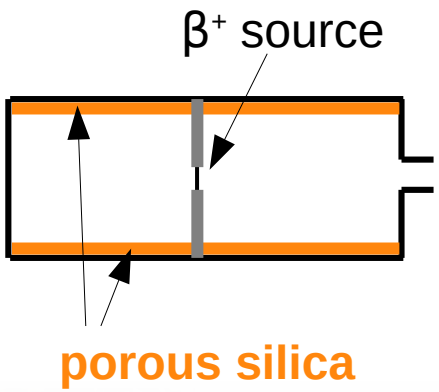
e+ spin estimated event-by-event

$$P_{e+} \approx \frac{v}{c} \cdot 0.91$$

- Plastic scintillators = fast timing
  → using high β^+ emitter activity (tested up to 10 Mbq)
- Recording all 3 annihilation photons
- Angular resolution at 1° level

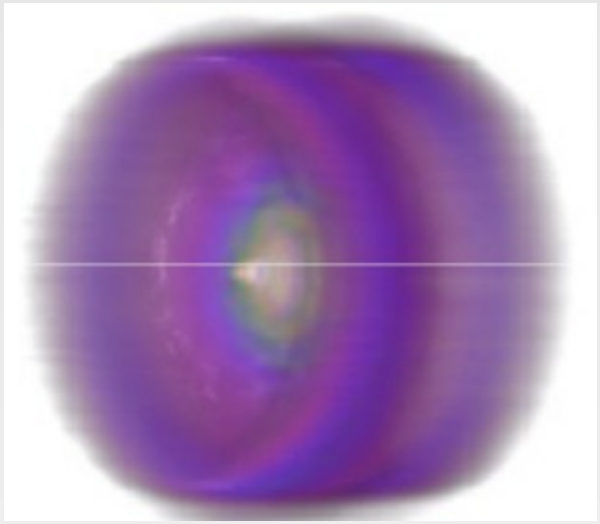
o-Ps production in J-PET with an extensive size annihilation chamber

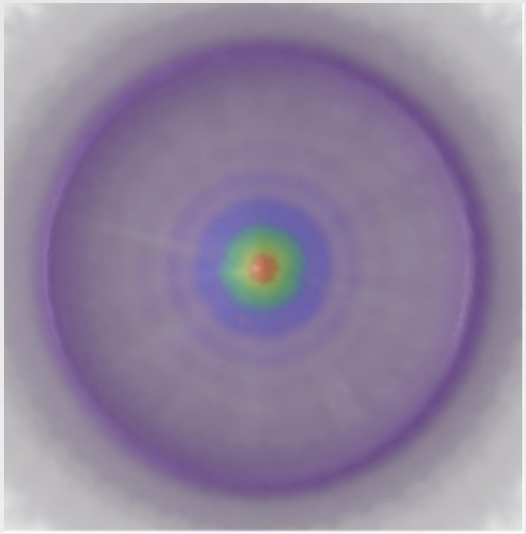




Tomographic images of the chamber obtained using γγ annihilations:

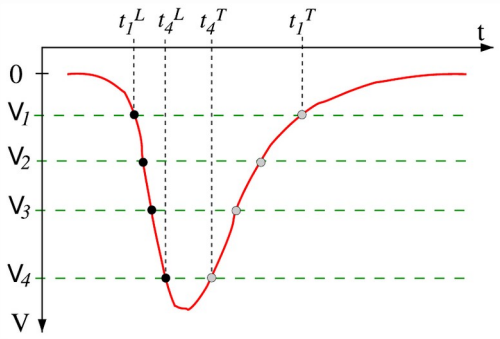
- Extensive-size chamber, R=12 cm
- Walls coated with porous silica material enhancing o-Ps formation
- 10 MBq β^+ emitter (^{22}Na) placed in the center of the chamber

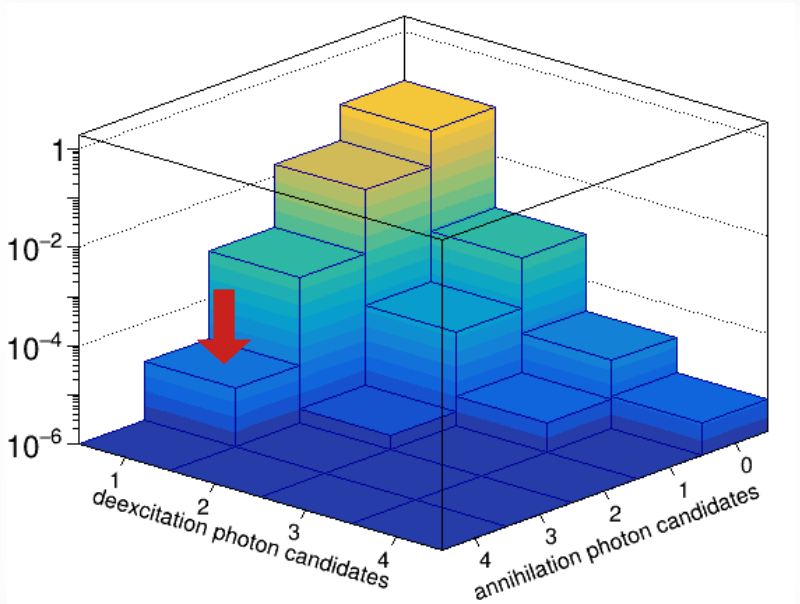


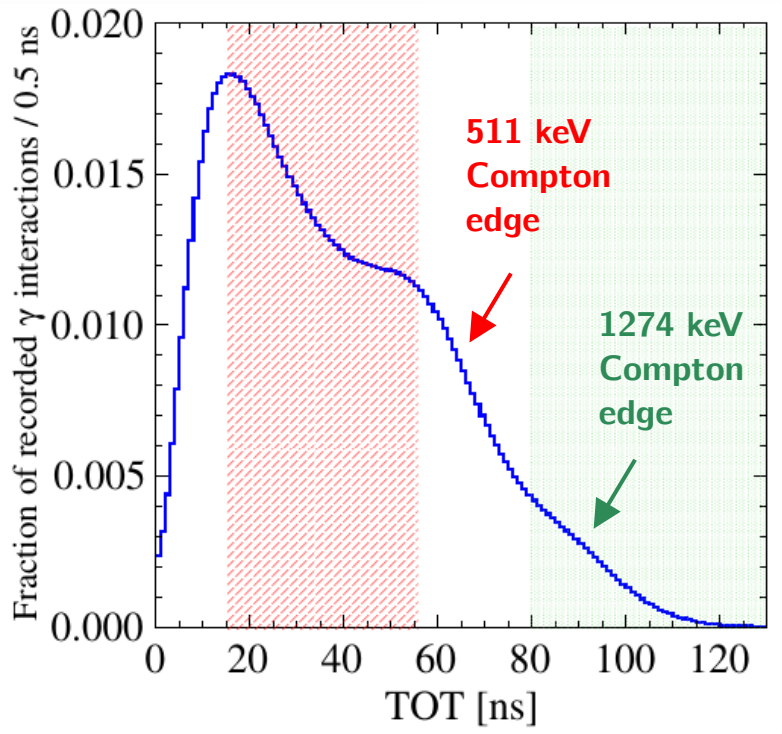


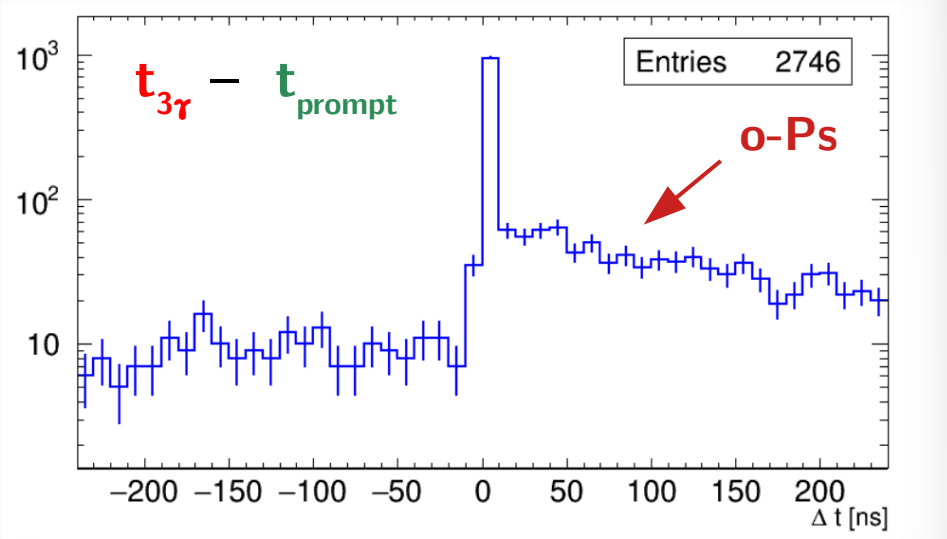
Identification of o-Ps → 3γ events in J-PET

Using total Time Over Threshold (TOT) of PMT signals from a scintillator strip









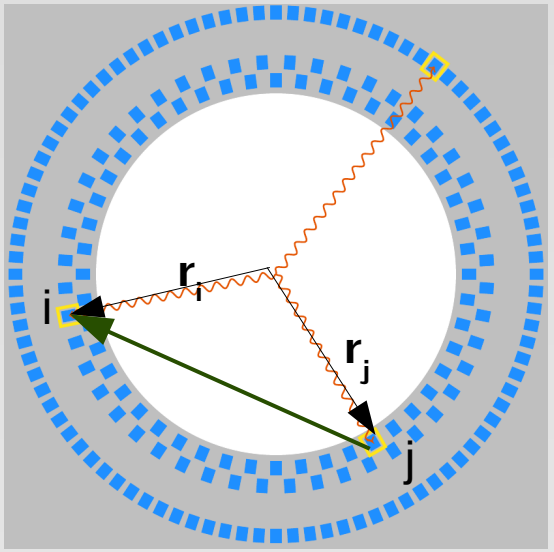
o-Ps →3γ annihilation (E<511 keV)

^{22}Ne* de-excitation (E=1274 keV)

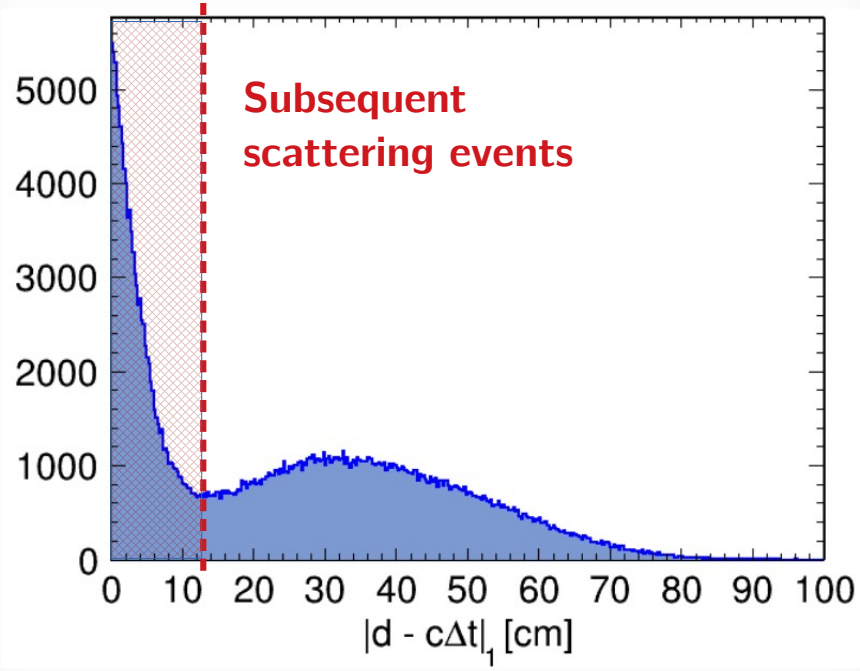
Rejection of subsequent scatterings in the detector

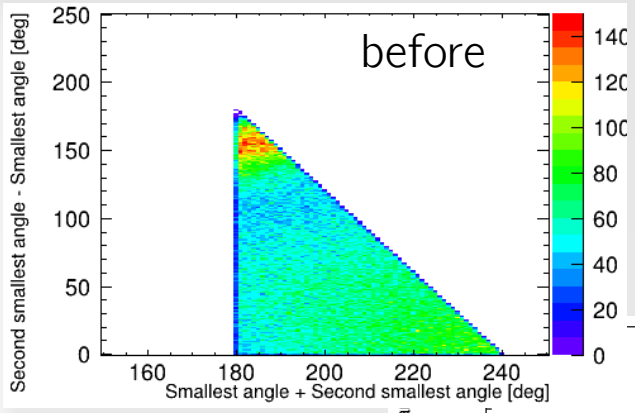
- Secondary Compton-scattered photons may be recorded by J-PET again
- For each pair of annihilation photon candidates *i* and *j* (*i*,*j*=1,2,3) the following figure is computed:

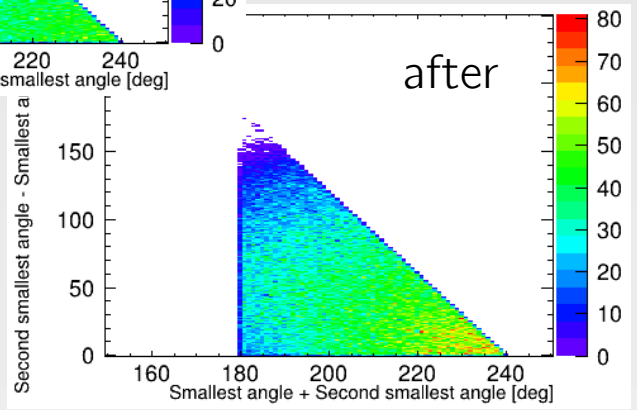
$$\delta t_{ij} = |d_{ij} - c\Delta t_{ij}| = ||\vec{r}_i - \vec{r}_j| - c(t_i - t_j)|$$



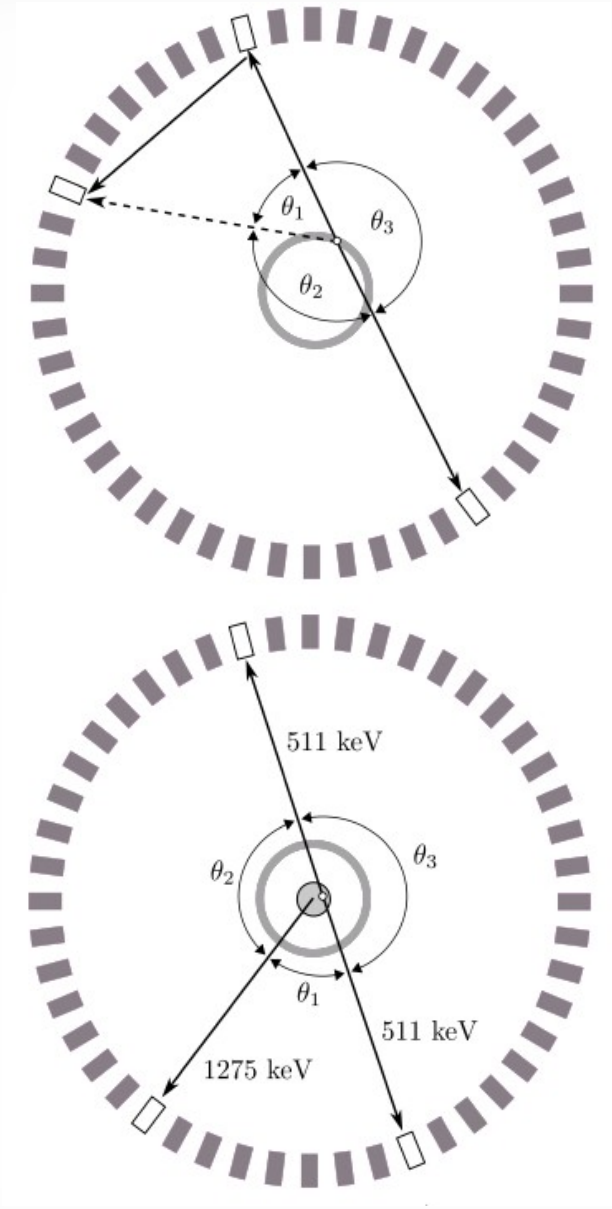
Distribution of the minimum δt_{ij} over all photon pair choices in a events:



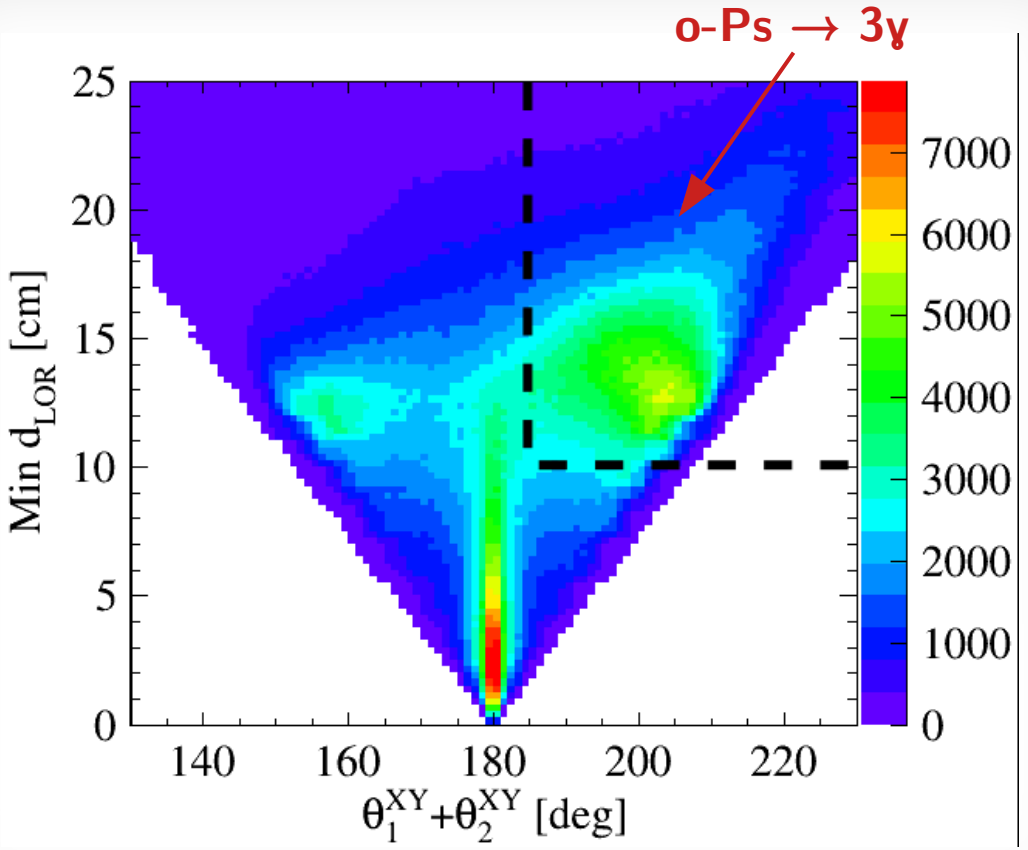




Rejection of direct 2γ annihilations

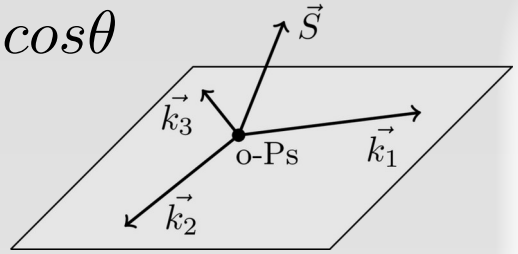


- Using angular topology of the event in XY detector plane
- Considering all hypothetical back-to-back 2γ pairs (tomographic "Lines Of Response")



Evaluation of the CPT-asymmetric observable

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



Standard asymmetry:

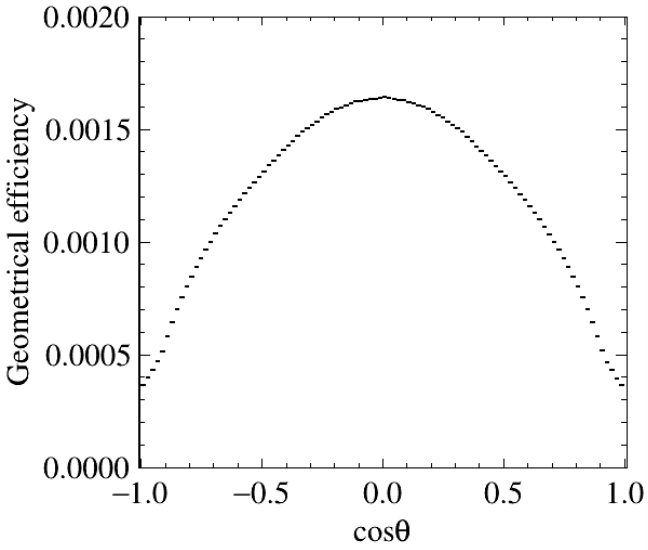
$$A = \frac{N_+ - N_-}{N_+ + N_-} \qquad N_+ \Leftrightarrow cos\theta > 0$$

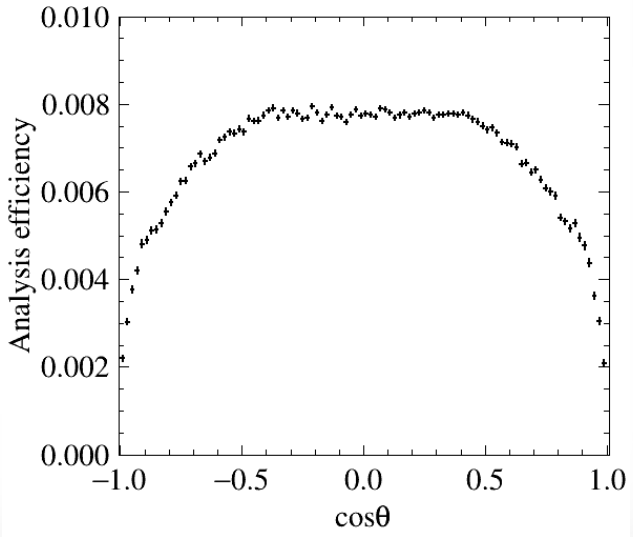
is generalized by the **mean value of cosθ**:

$$\frac{\int N(\cos\theta)\cos\theta}{\int N(\cos\theta)}$$

J-PET is sensitive to the full range of this operator

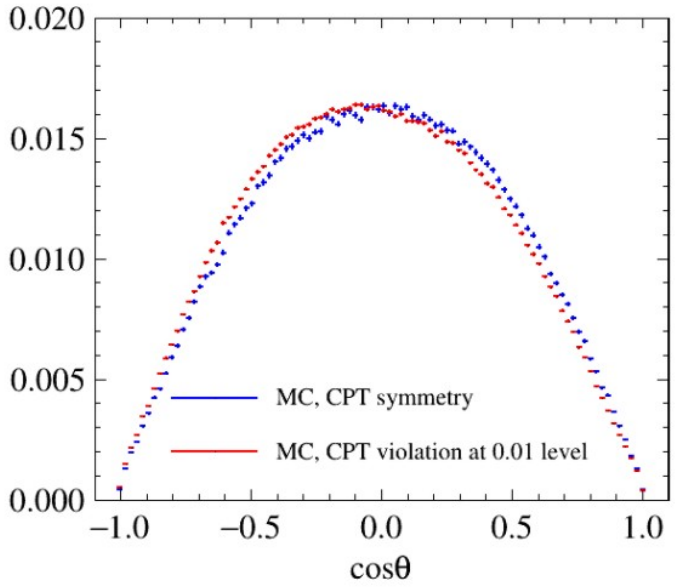
Efficiencies evaluated with MC are **symmetric in cosθ**





Expected effect with CPT-asymmetric Simulations (exaggerated violation)

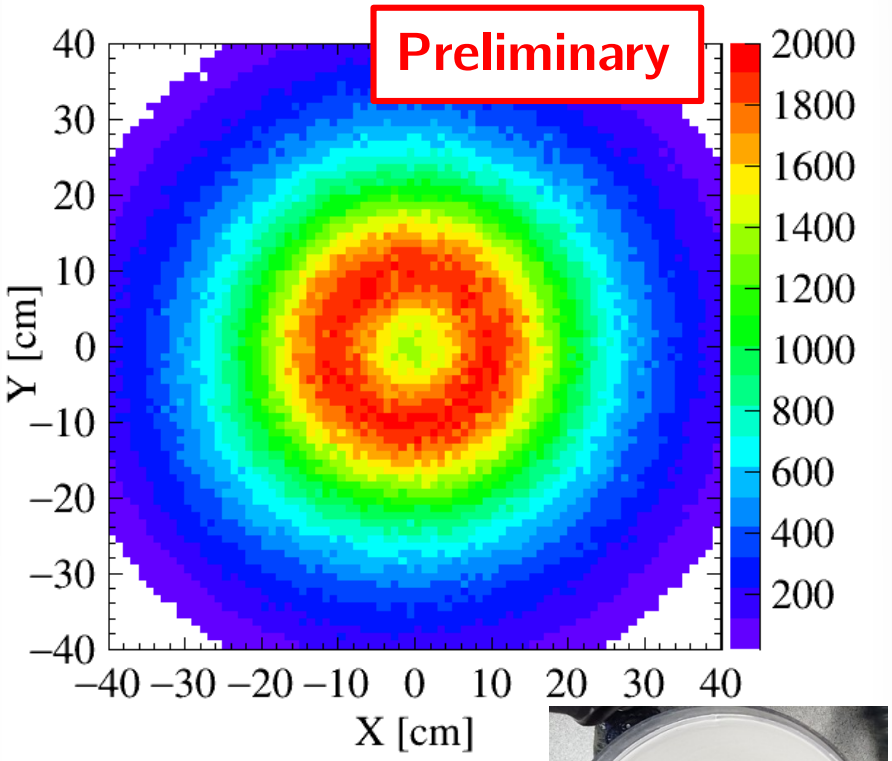
[see also *Symmetry* 12 (2020) 8, 1268]



Results of the CPT test

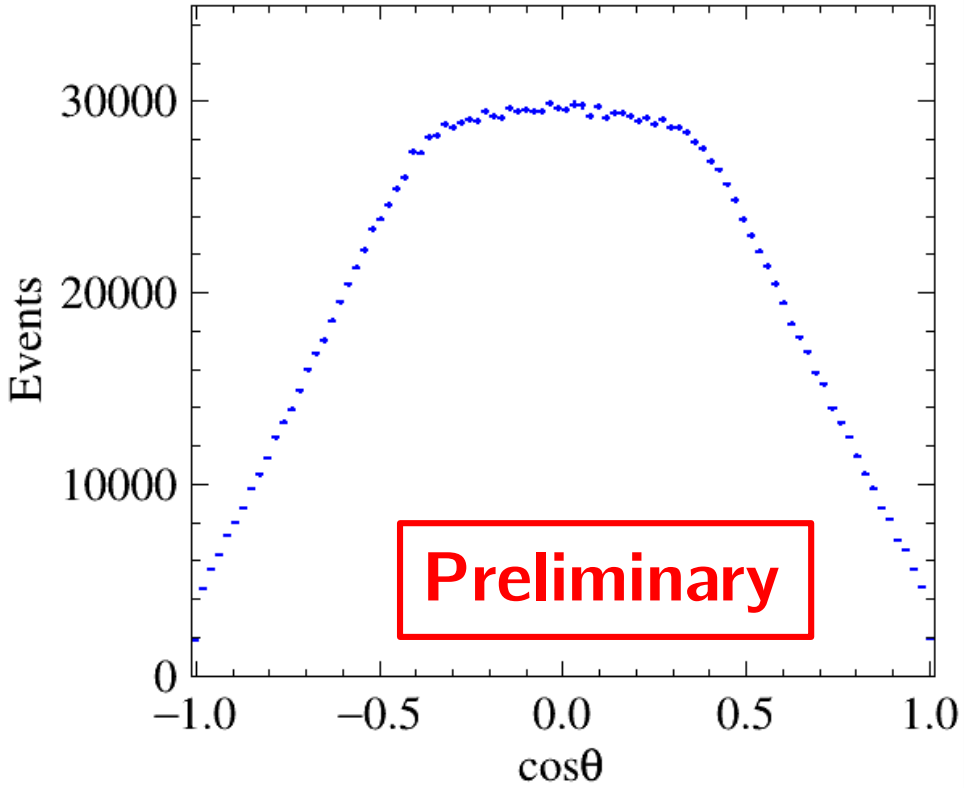
Using 2 x 10^6 of identified
o-Ps → 3γ annihilations

3γ image of the o-Ps production chamber in the tranverse view of the detector



The first image of an extensive-size object obtained with o-Ps→3γ annihilations

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

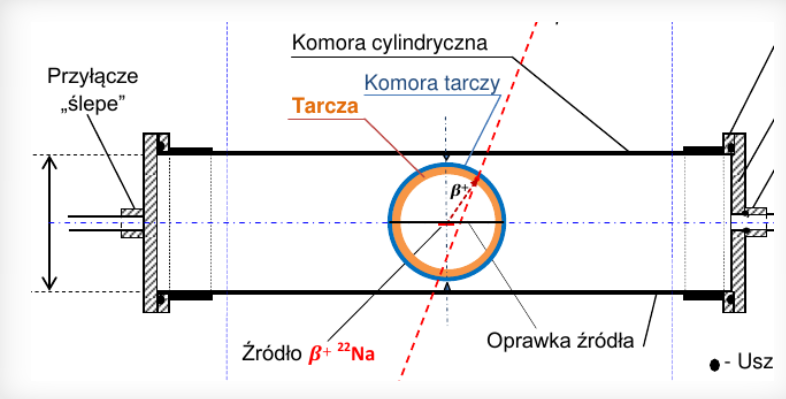


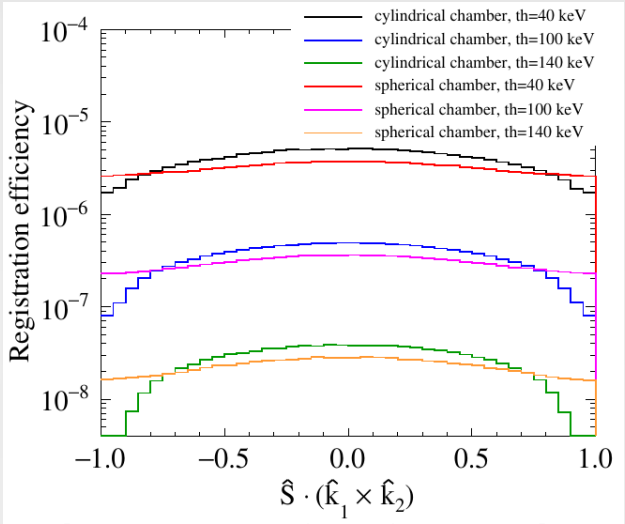
<cosθ> statistical uncertainty: **3.3 x 10^{-4}**
systematic uncertainty **1.4 x 10^{-4}**

Analyzing power S = 37.4 %
(polarization-dominated)

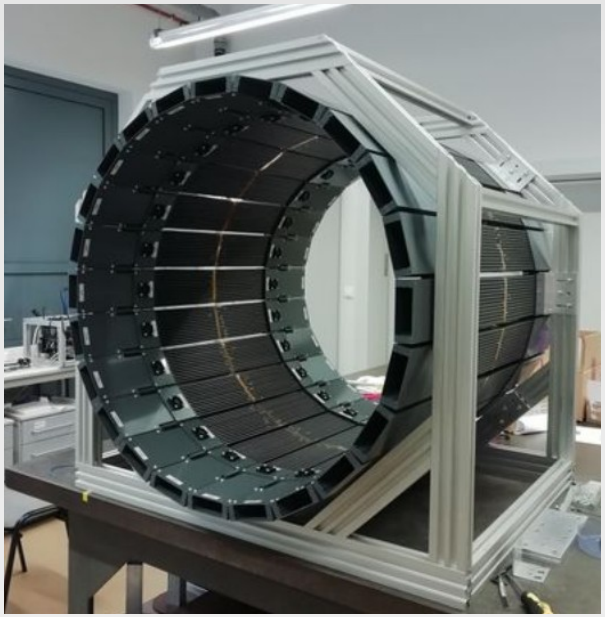
Summary and further perspectives

- The J-PET detector is capable of exclusive registration of o-Ps→3γ annihilations
  - Full event recontruction including determination of the annihilaiton point in an extensive-size medium
  - Estimation of o-Ps spin on an event-by-event basis
  - The first image of an extensive-size object otained solely with o-Ps annihilations
- **Sub-permil precision of the CPT test reached with the first J-PET measurement**
- **J-PET aims at the sensitivity of the CP and CPT symmetry tests at the level of 10^{-5} with the pending improvements to the setup:**





[*Symmetry* 12 (2020) 8, 1268]



Thank you for your attention!

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