Testing CP and CPT symmetries in ortho-positronium decays with J-PET detector

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on Symmetries in Subatomic Physics

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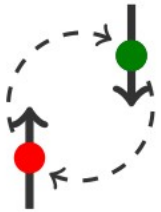
Aleksander Gajos
on behalf of the J-PET Collaboration
Jagiellonian University

NATIONAL SCIENCE CENTRE
POLAND

Motivation: discrete symetry tests with o-Ps $\rightarrow 3\gamma$ decays

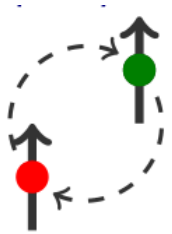
- Positronium – lightest purely leptonic bound state
- Eigenstate of C and P

Para-positronium
singlet state
τ = 125 ps



p-Ps $\rightarrow 2\gamma,\ 4\gamma, \ldots$

Ortho-positronium
triplet state
τ = 142 ns

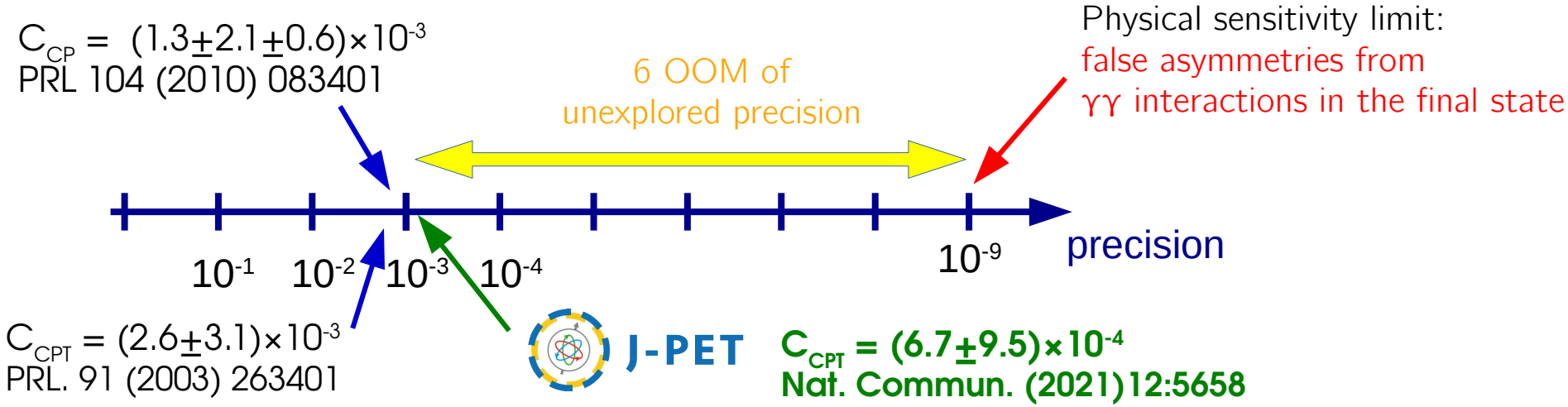


o-Ps $\rightarrow 3\gamma,\ 5\gamma, \ldots$

How can we test discrete symmetries in the positronium system?

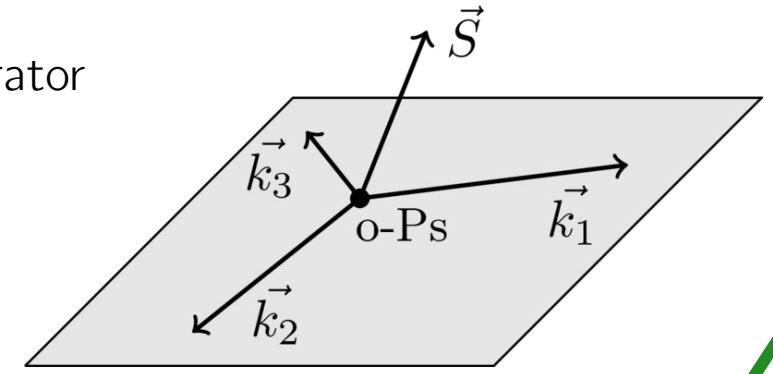
- Searches for **prohibited positronium annihilations**
- SME-based searches for CPT violation proposed with **positronium spectroscopy** [Phys. Rev. D92 (2015) **056002]**

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



Testing discrete symmetries in ortho-positronium annihilations

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

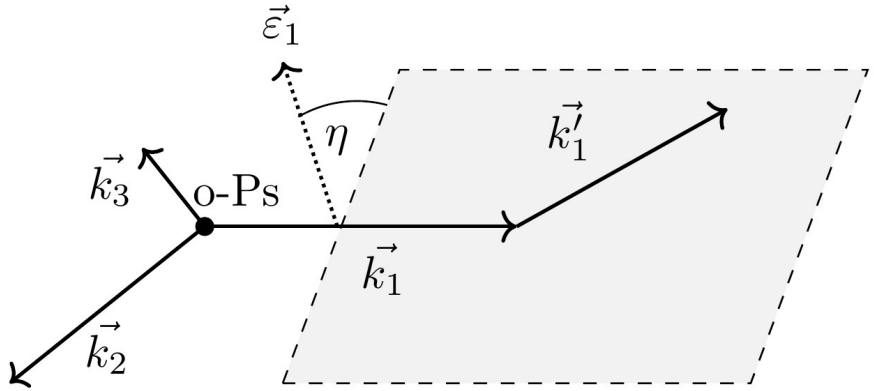


$$|\vec{k_1}| > |\vec{k_2}| > |\vec{k_3}|$$

Using ortho-positronium spin requires either:
- polarization
- spin estimation

operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k_1}$	+	−	+	−	−
$\vec{S} \cdot (\vec{k_1} \times \vec{k_2})$	+	+	−	+	−
$(\vec{S} \cdot \vec{k_1})(\vec{S} \cdot (\vec{k_1} \times \vec{k_2}))$	+	−	−	−	+
$\vec{k_2} \times \vec{\epsilon_1}$	+	−	−	−	+
$\vec{S} \cdot \vec{\epsilon_1}$	+	+	−	+	−
$\vec{S} \cdot (\vec{k_2} \times \vec{\epsilon_1})$	+	−	+	−	−

If polarization direction of the photons (ϵ) can be estimated, a new class of operators becomes available for measurement!
- Never measured before J-PET

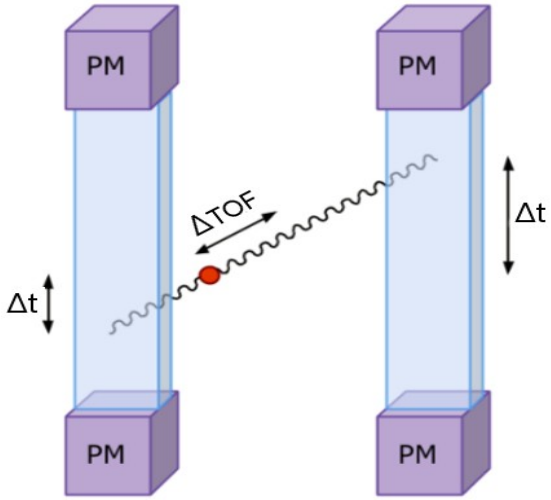


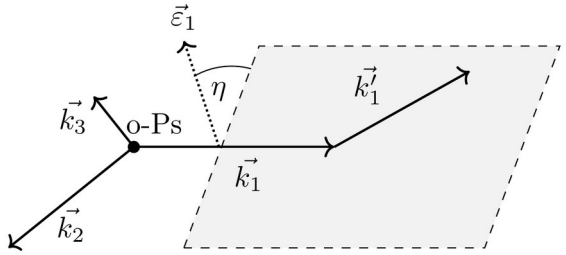
[W. Bernreuther *et al., Z. Phys. C41 (1988) 143*]

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

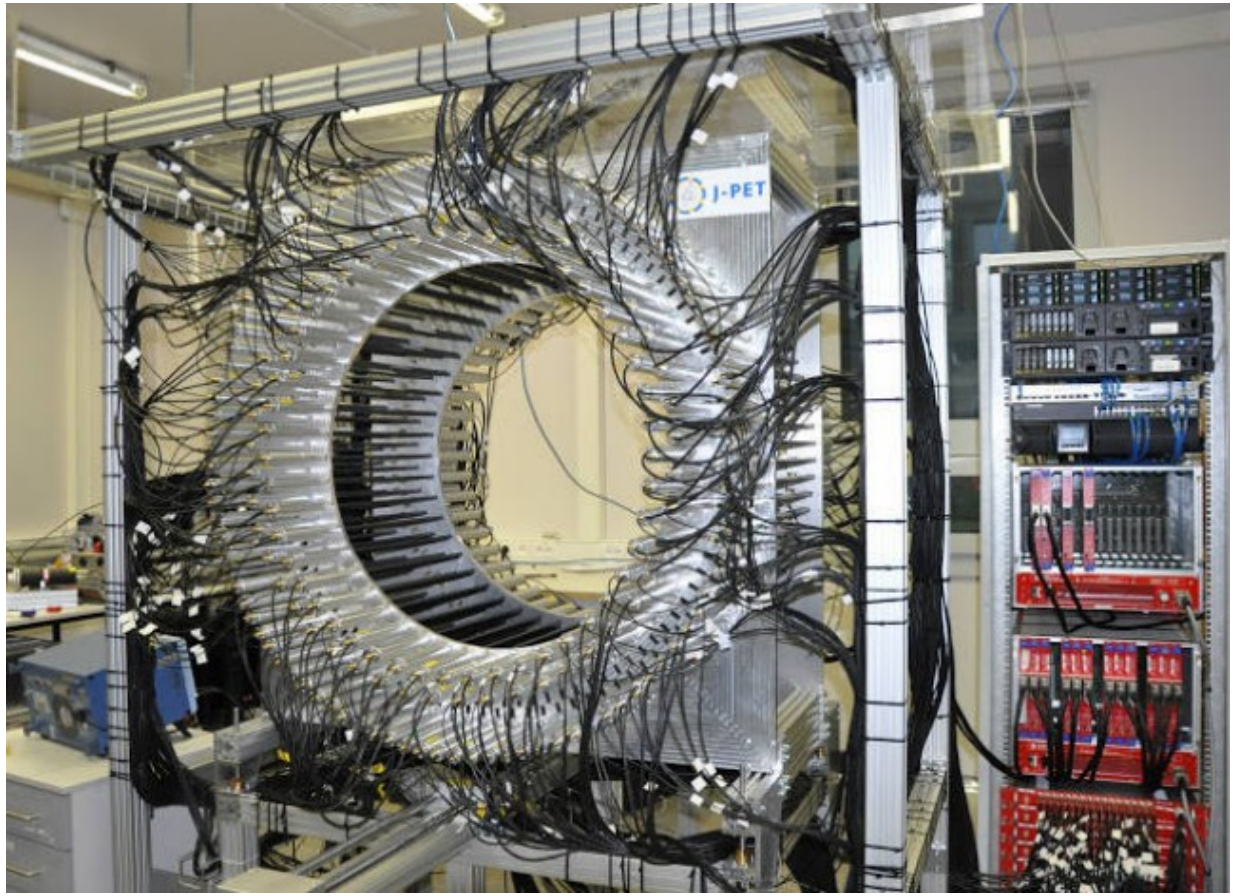
The Jagiellonian PET (J-PET) tomographic detector

- Conceived at the Jagiellonian University as the 1st Positron Emission Tomograph based on plastic scintillators
- At the same time a robust photon detector for fundamental research!
- 192 scintillator strips (50 cm long) arranged in 3 concentric layers
- Photons interact via Compton scattering
  - Cascades of subsequent scatterings can be recorded
    → **estimation of γ polarization**





[J-PET: NIM A 764 (2014) 317-321]
[J-PET: NIM A 764 (2014) 186-192]
[J-PET: NIM A 786 (2015) 105-112]
[J-PET: NIM A 775 (2015) 54-62]

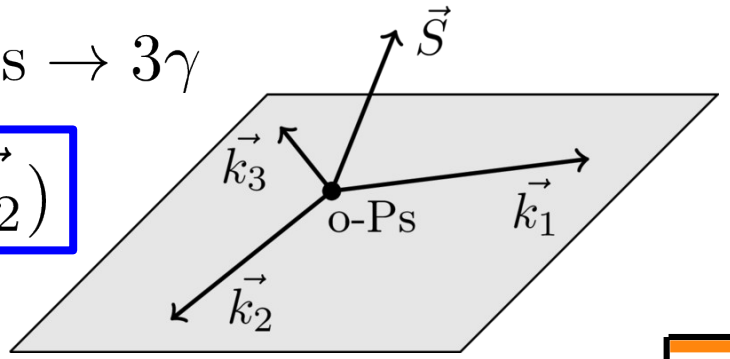


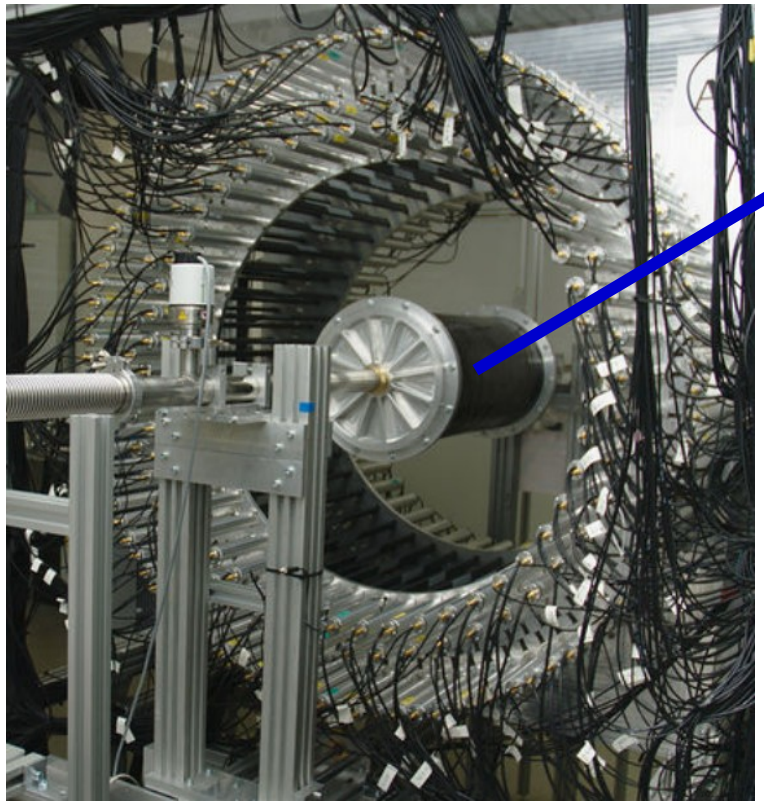
Ortho-positronium spin estimation for the $S(k_1 x k_2)$ measurement

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

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

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

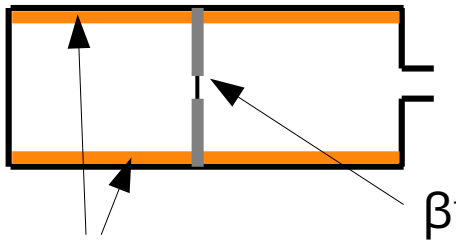




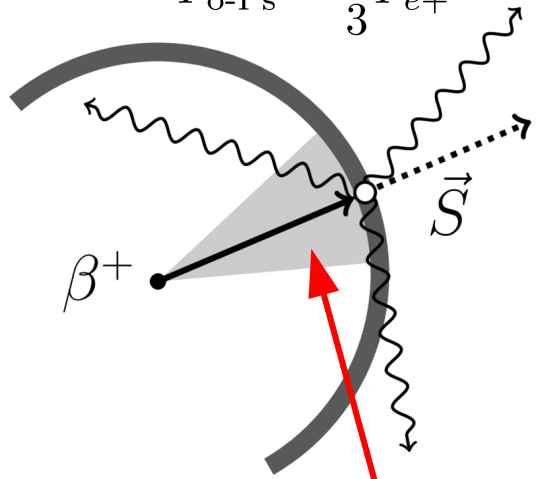
Event-by-event spin estimation

- Extensive-size chamber, R=12 cm
- Walls coated with porous silica enhancing o-Ps formation
- 10 MBq β^+ emitter (^{22}Na) placed in the chamber center
- o-Ps $\rightarrow 3\gamma$ annihilation point reconstructed using trilateration

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



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



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

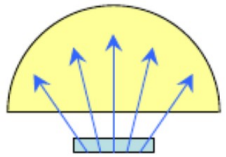
J-PET vs previous measurements

Gammasphere
PRL. 91 (2003) 263401

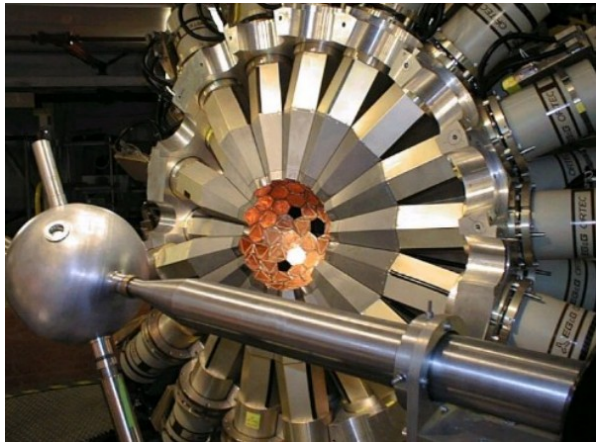
$C_{CPT} = (2.6 \pm 3.1) \times 10^{-3}$

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

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



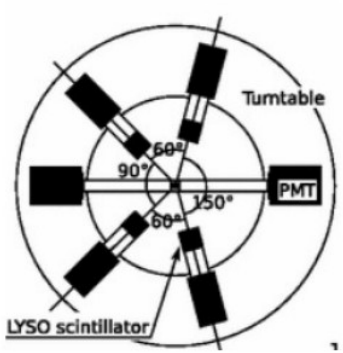
- Limiting e+ emission direction
- 1 Mbq β^+ emitter activity
- 4π detector but low angular resolution

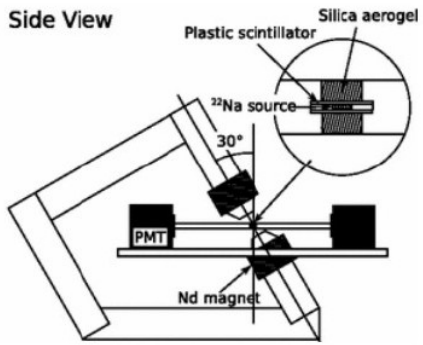


Yamazaki et al.
PRL 104 (2010) 083401

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

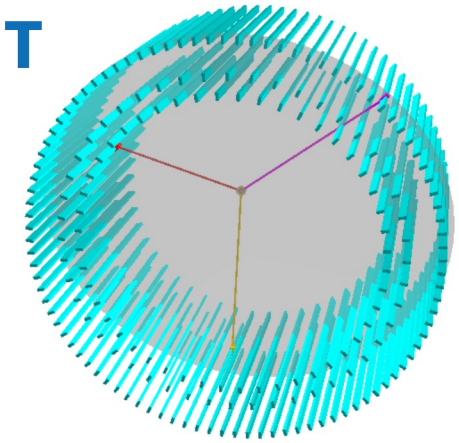
$$(\vec{S} \cdot \vec{k_1})(\vec{S} \cdot (\vec{k_1} \times \vec{k_2}))$$





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

J-PET



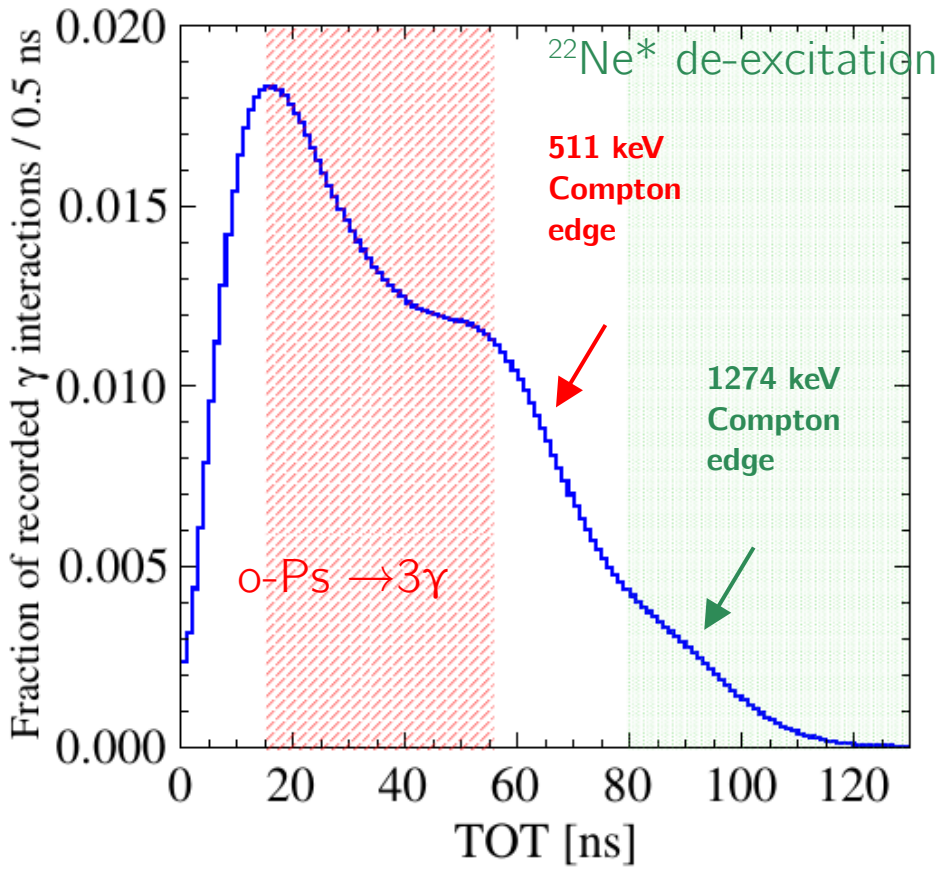
- Recording multiple geometrical configurations
- e+ spin estimated event-by-event

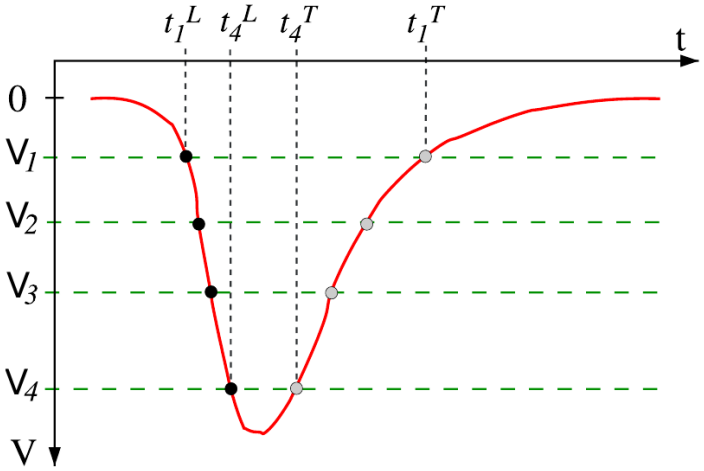
$$P_{e+} \approx \frac{v}{c} \cdot 0.91$$

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

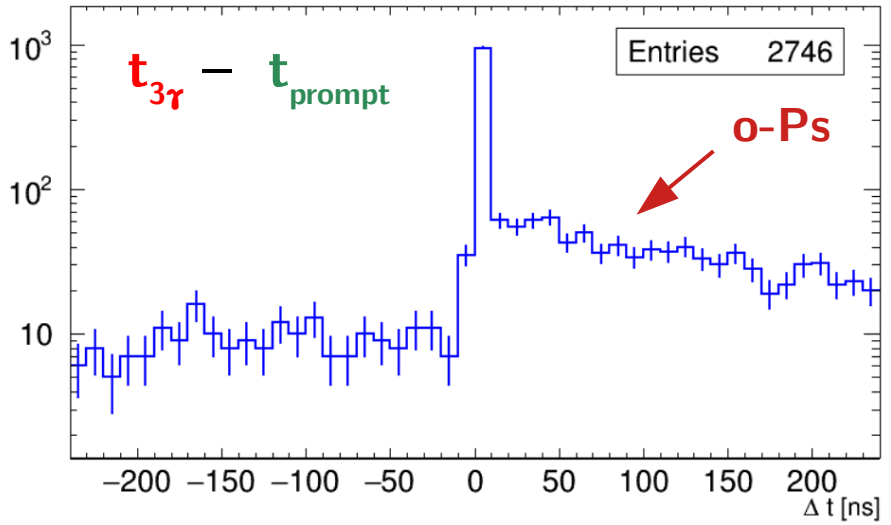
Identification of o-Ps → 3γ events in J-PET

Using total Time Over Threshold (TOT) of PMT signals from a scintillator strip
→ a measure of γ deposited energy





Confirming o-Ps presence with positron lifetime distribution

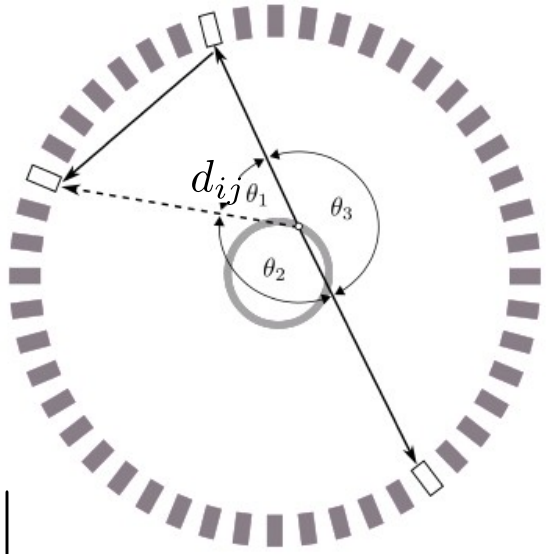


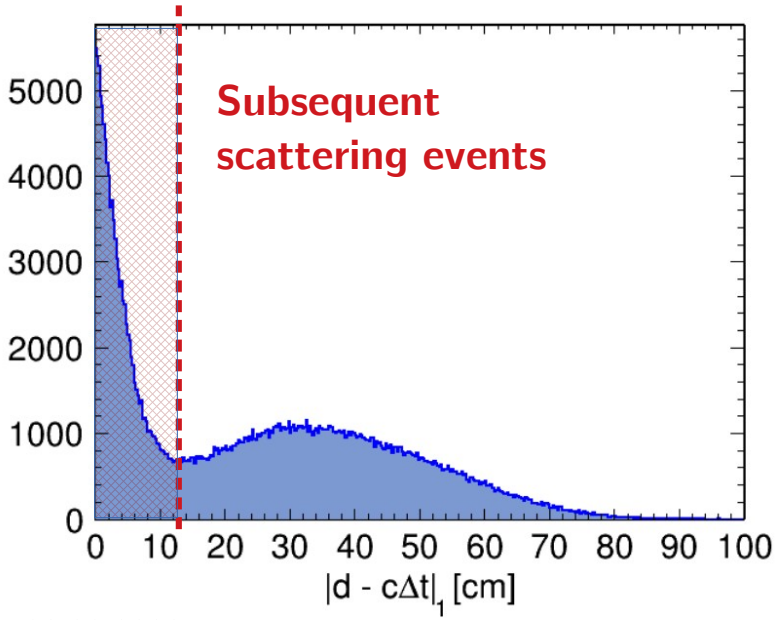
CPT test with $S(k_1 x k_2)$: Main background sources

Secondary Compton scatterings

- 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) we compute:

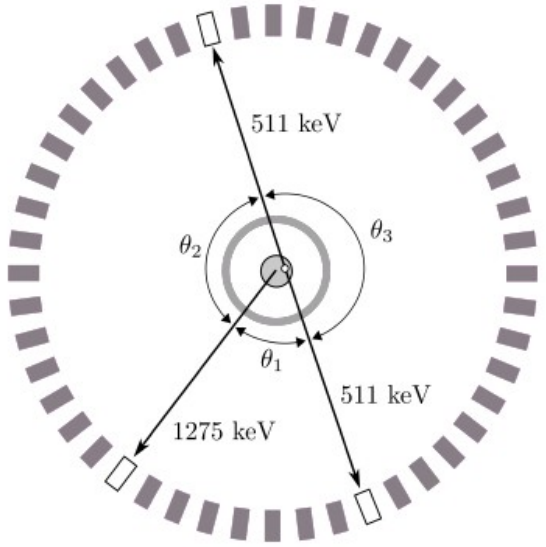
$$\delta t_{ij} = |d_{ij} - c\Delta t_{ij}|$$



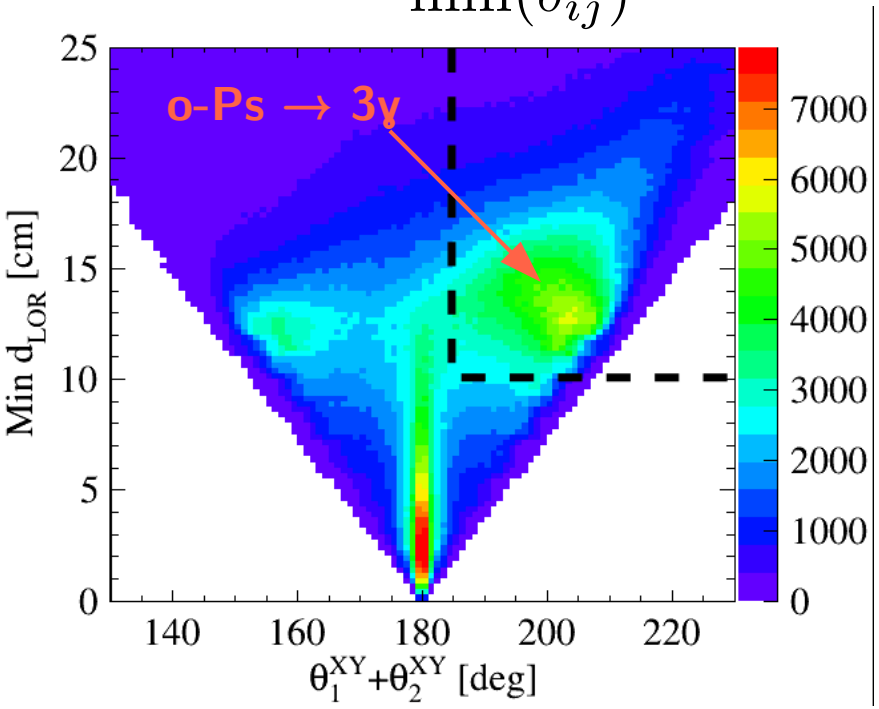


2γ from the β+ source setup

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

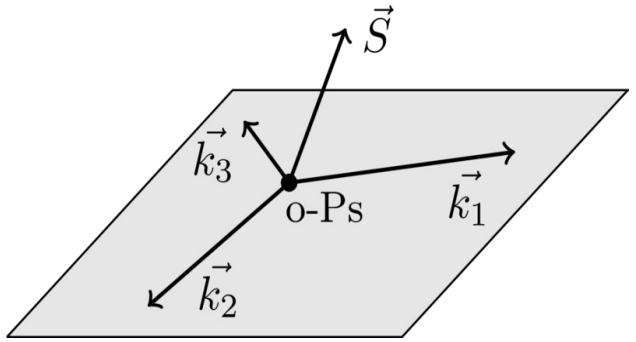


$\min(\delta_{ij})$



Evaluation of the CPT-asymmetric observable

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



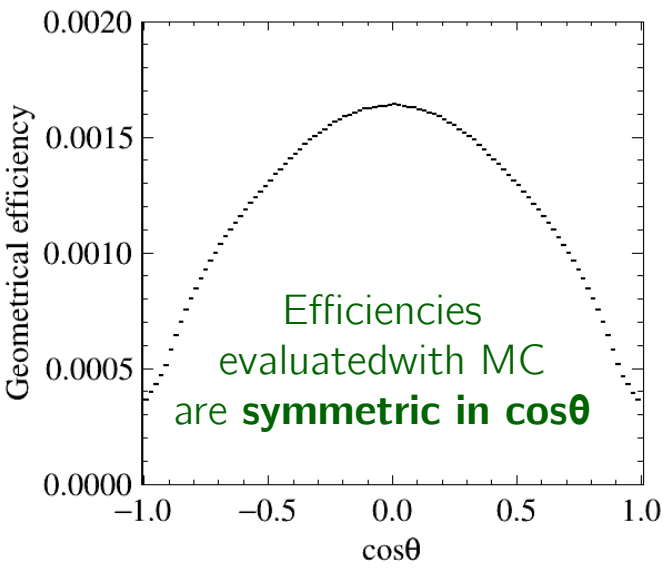
Standard asymmetry:

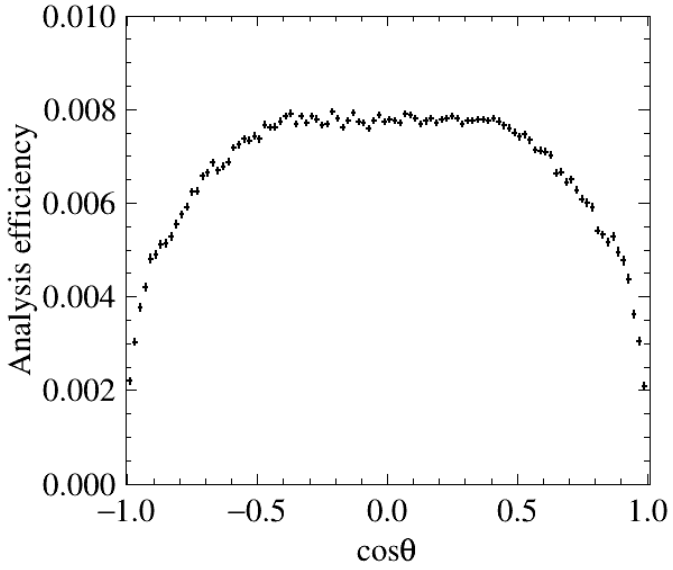
$$A = \frac{N_+ - N_-}{N_+ + N_-} \qquad N_+ \Leftrightarrow cos\theta > 0$$

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

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

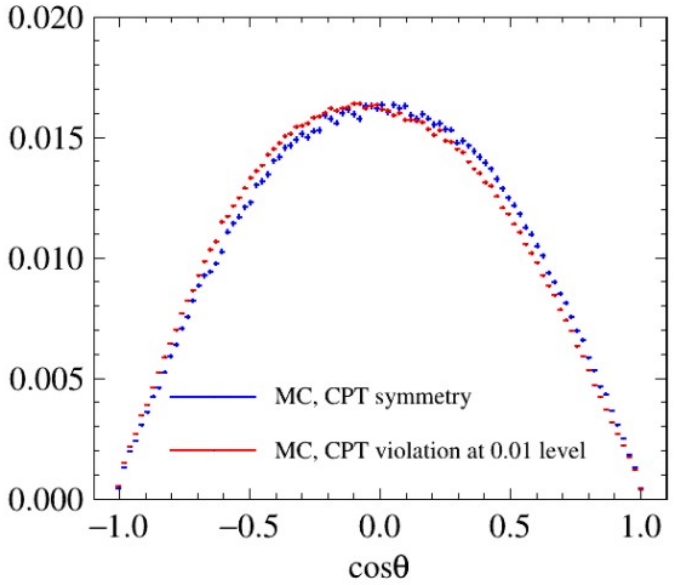
J-PET is sensitive to the full range of the operator





Expected effect with CPT-asymmetric simulations (exaggerated violation)

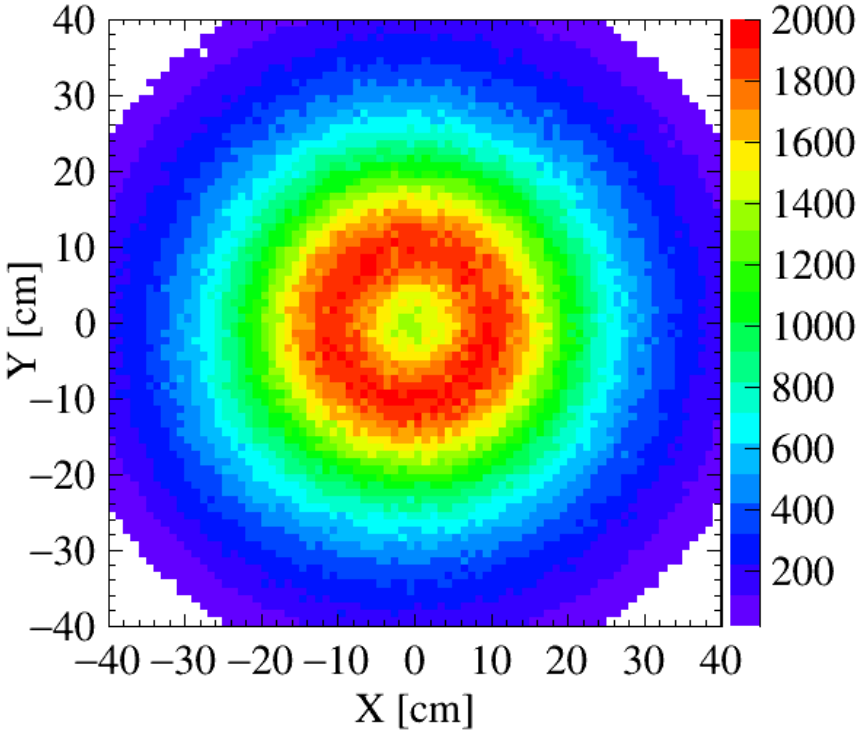
[*Symmetry* 12 (2020) 8, 1268]



Results of the 1st CPT test with J-PET

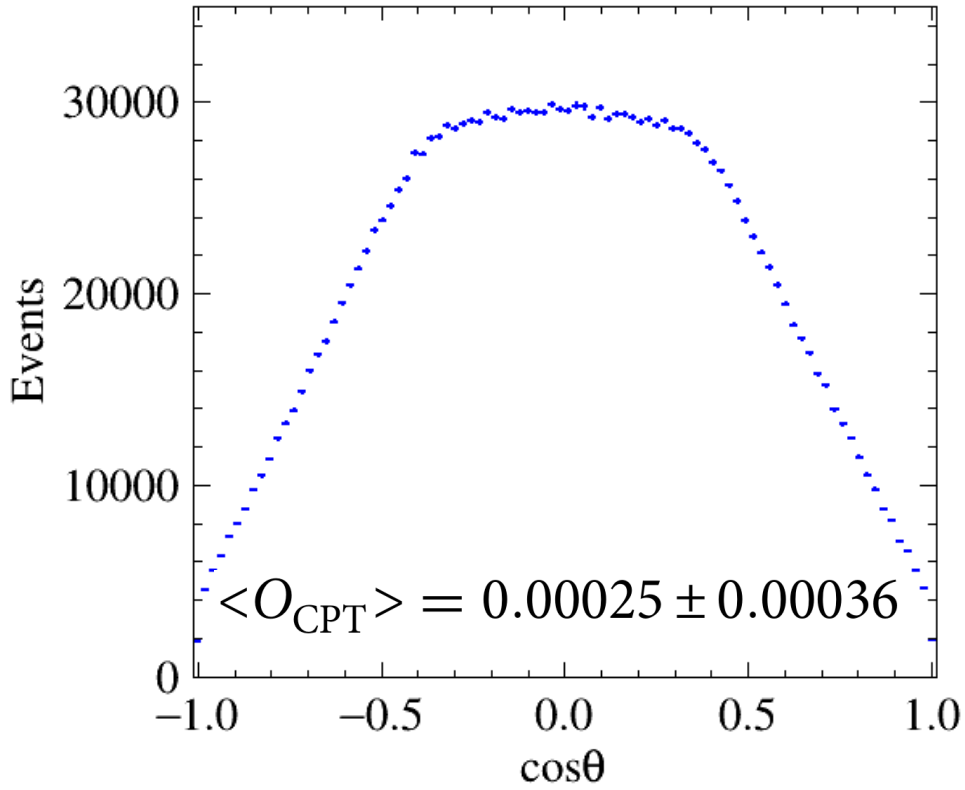
Using 2 x 10^6 of identified o-Ps → 3γ annihilations

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

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

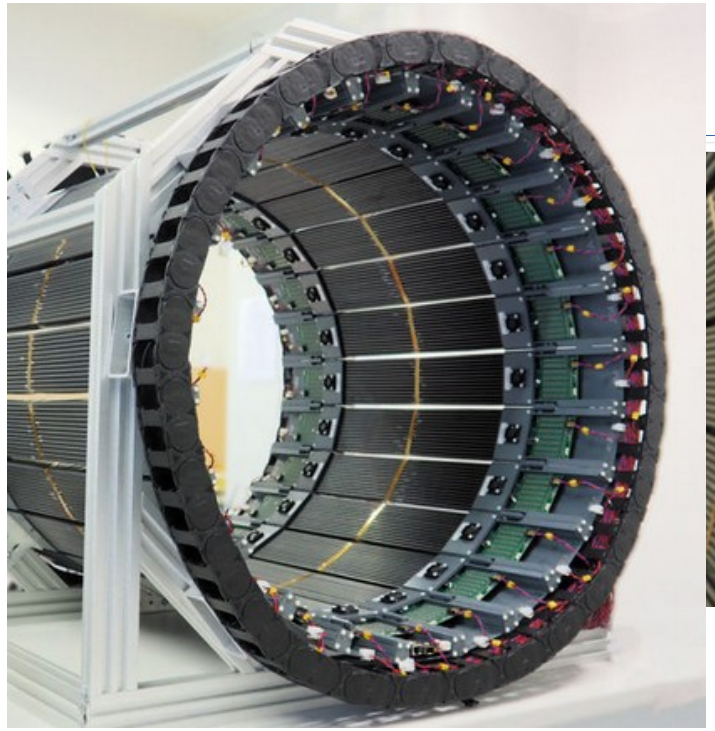


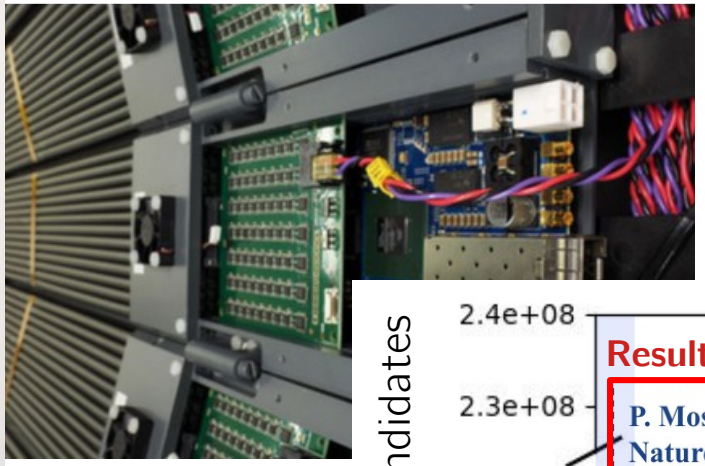
$$C_{CPT} = <O_{CPT}>/P = 0.00067 \pm 0.00095$$

37.4% (polarization-dominated)

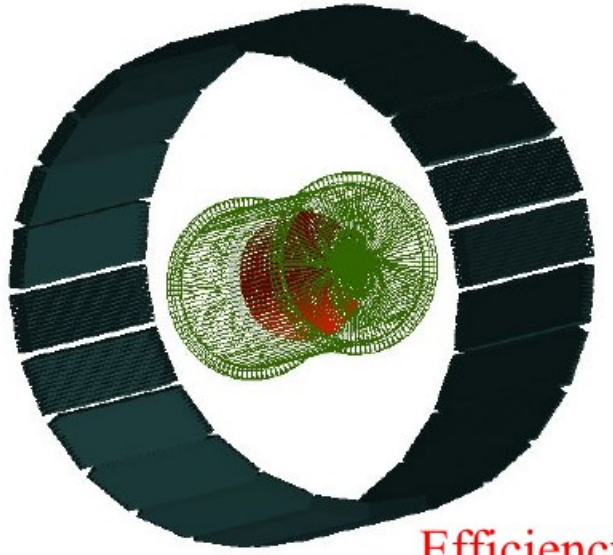
Nature Commun. 12, 5658 (2021)

Towards the sensitivity of 10^{-5}

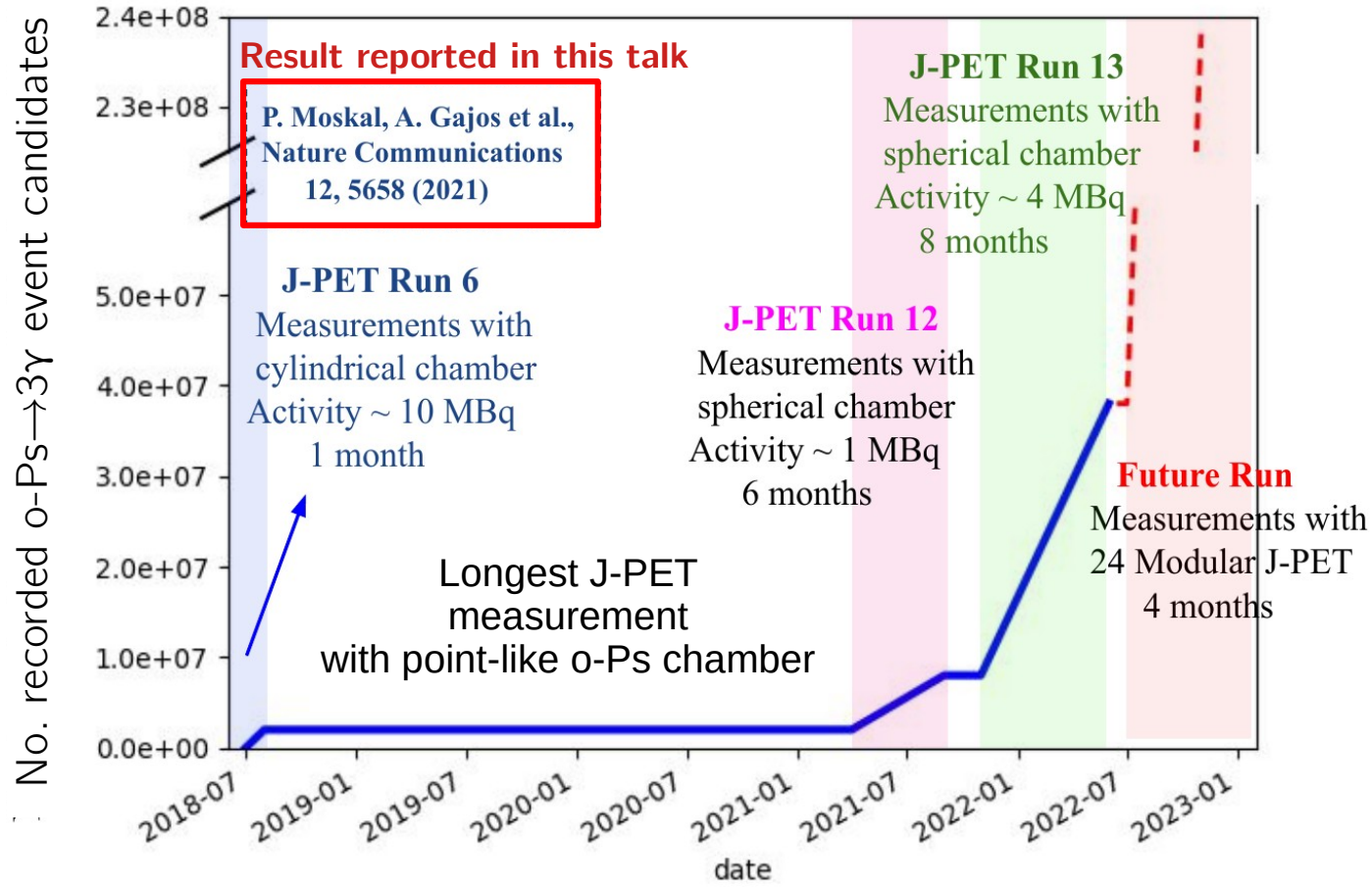




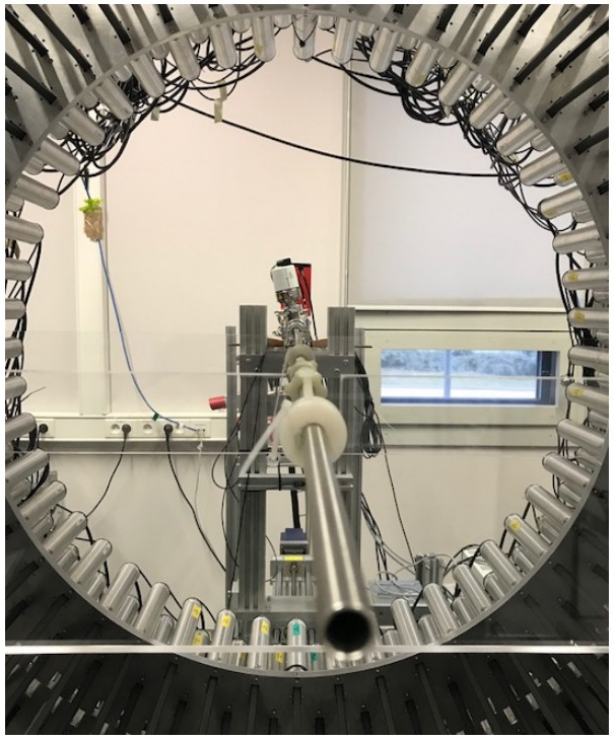
- New J-PET with dense geometry & digital SiPM readout
- Spherical annihilation chamber to enhance e+ utilization



Efficiency ~ 11
w.r.t present J-PET

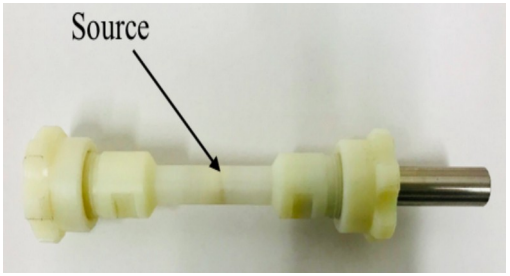


Test of the CP symmetry using γ polarization



Experiment:

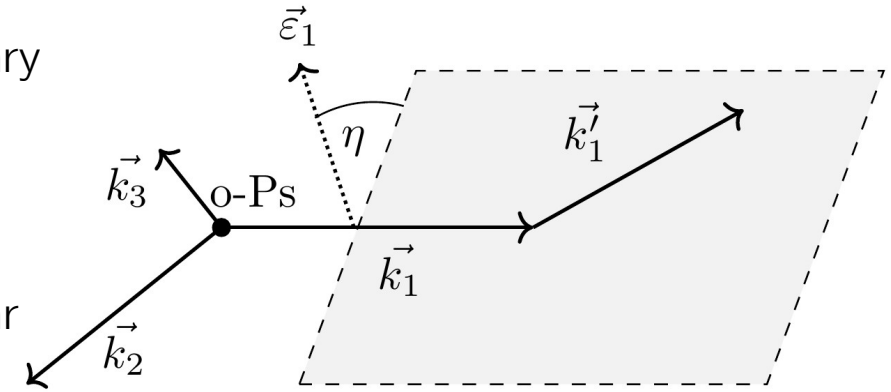
- Using a small positronium production chamber in the center of J-PET
- ^{22}Na positron source and XAD-4 porous material

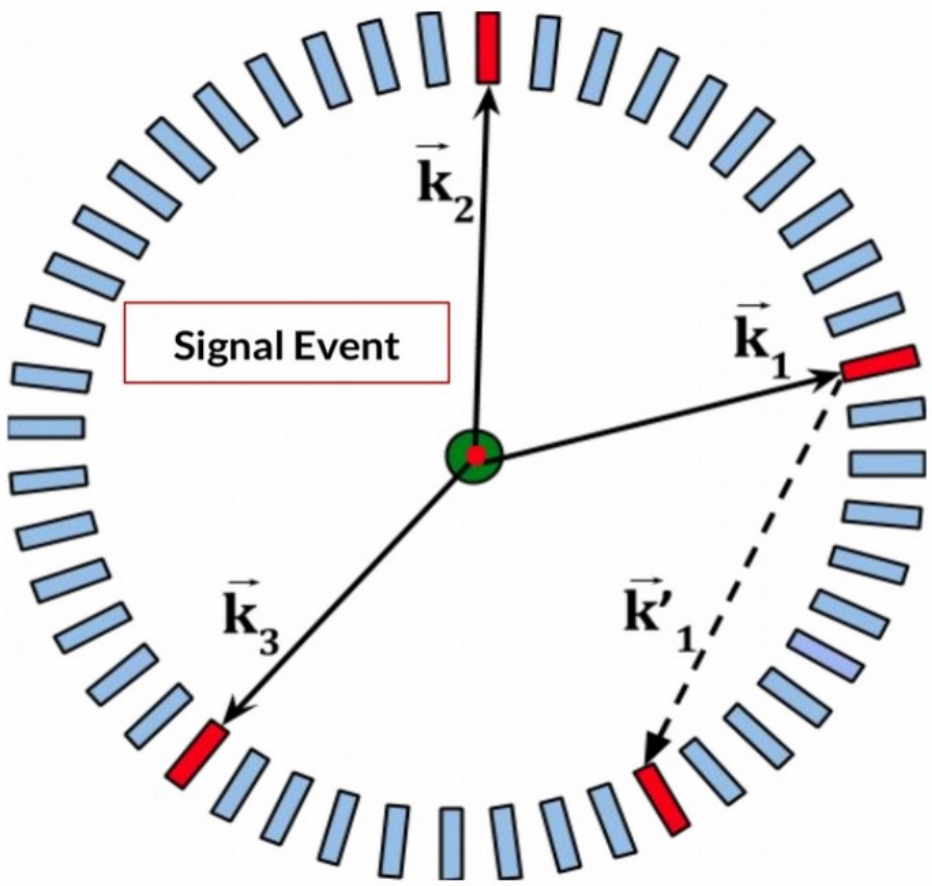


- Three primary photon interactions from o-Ps→3γ
- **Observable of the test:**

$$\langle \varepsilon_i \cdot k_j \rangle$$

- Using events where an additional secondary Compton scattering was recorded
- Polarization most probable perpendicular to scattering plane

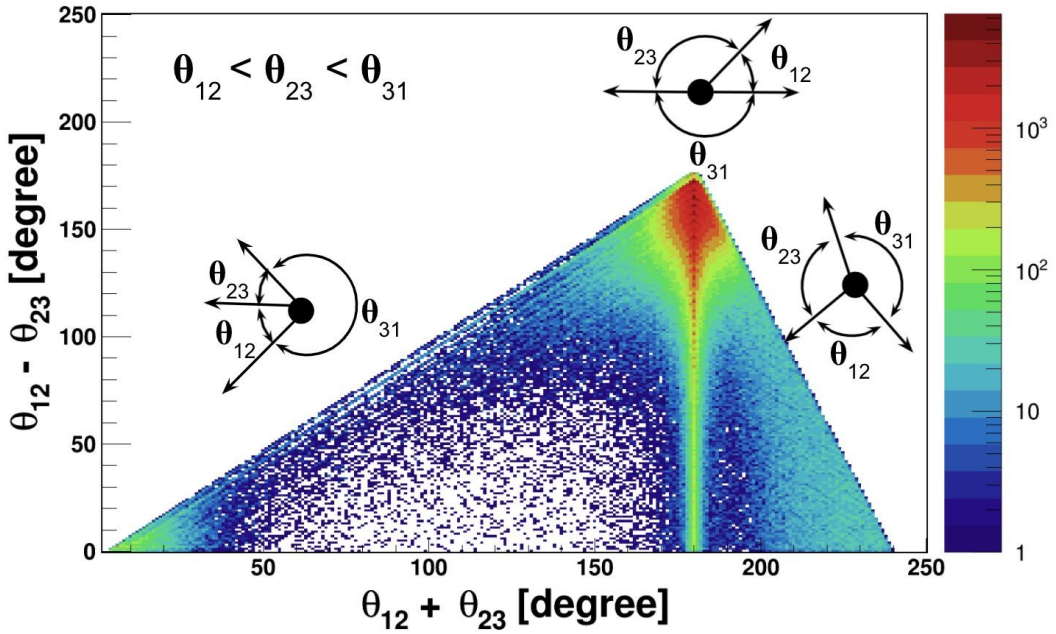


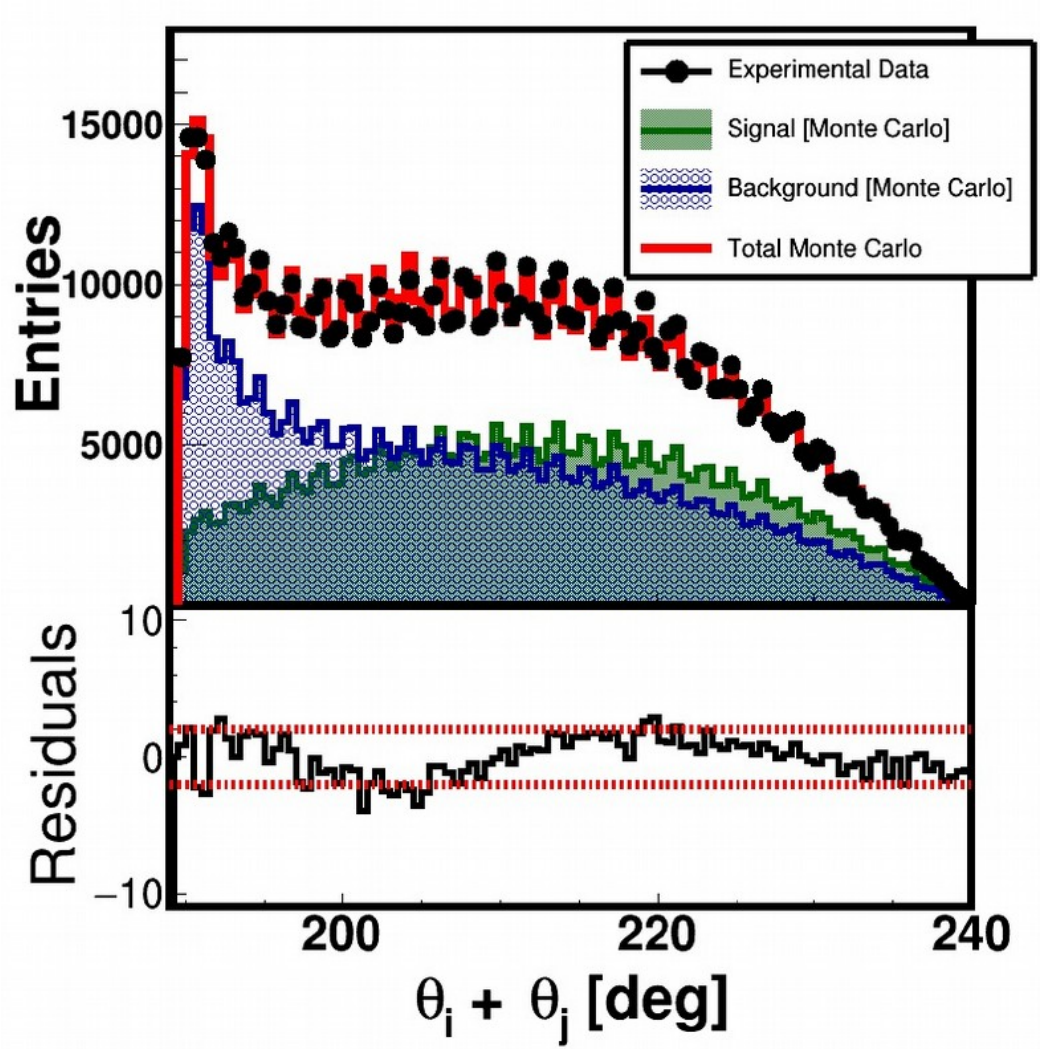


CP test with γ polarization – data analysis

Selection of o-Ps → 3γ + γ' events:

- Time-Over-Threshold (TOT) of photon interactions
- Angular event topology
- Common emission time of 3 photons
- Distance of the annihilation plane from the o-Ps source





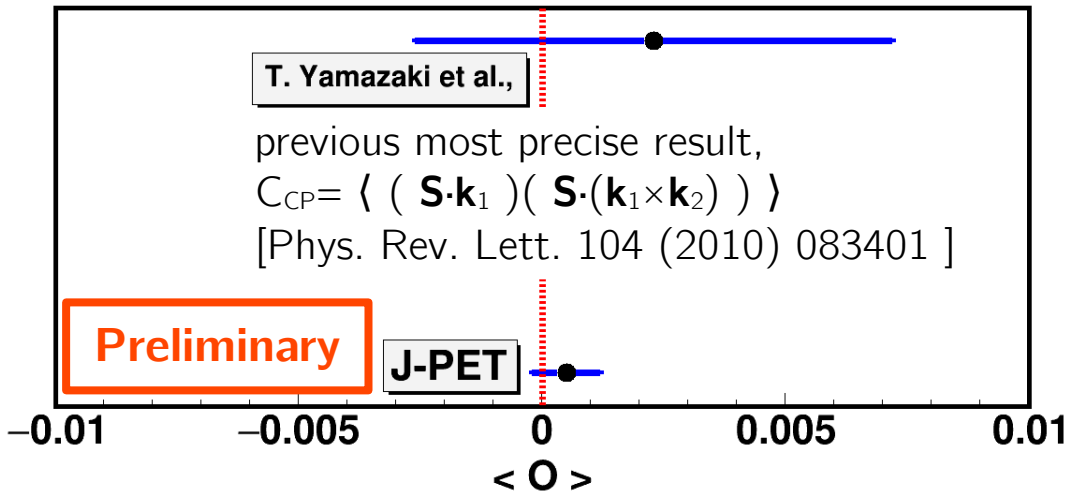
CP test with γ polarization – preliminary result

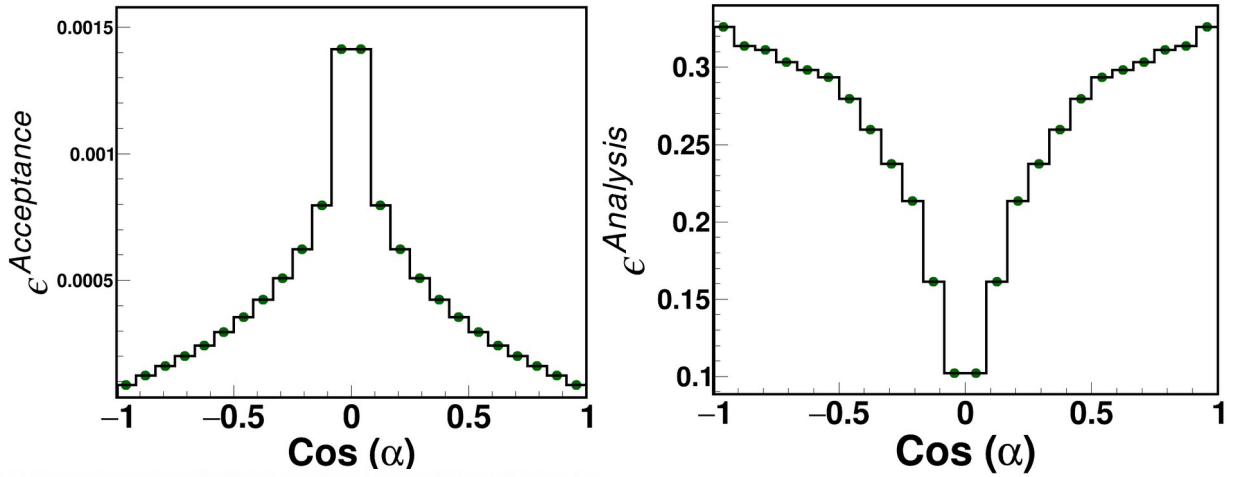
J-PET result:

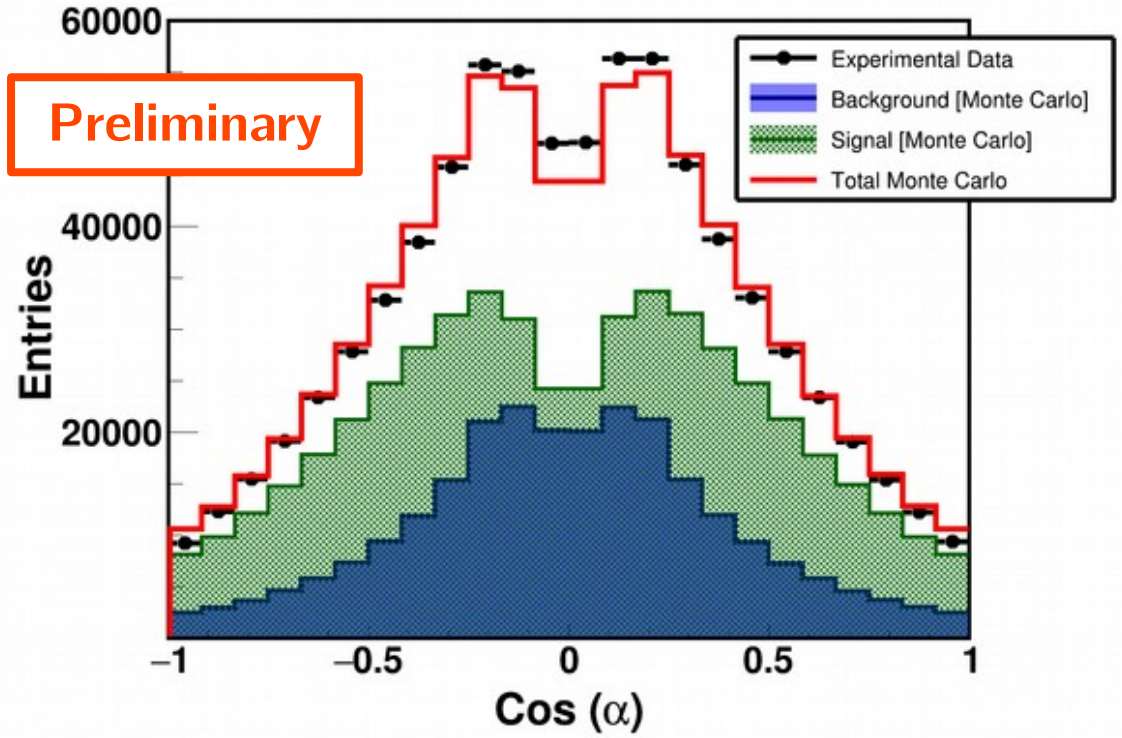
$C_{CP} = \langle \varepsilon_i \cdot k_j \rangle = 0.00052 \pm 0.00067_{stat}$

1st measurement of an angular correlation operator involving photon polarization in o-Ps annihilations!

- Using MC simulations of the entire experiment
- Probing the full spectrum of the operator values
- Result uncertainty dominated by statistical error
- Publication in preparation
- **Future: more statistics already available!**







Summary

- The J-PET detector, originally conceived as a tomographic scanner, has demonstrated its capability as a photon detector for studies of ortho-positronium annihilations with a high acceptance and angular resolution
- **J-PET measured the $S(k_1 x k_2)$ angular correlation o-Ps $\rightarrow 3\gamma$ annihilations sensitive to CPT-violating effects reaching sub-permil precision**
  - 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
- **Recently, J-PET performed the 1st measurement of a CP-violation-sensitive angular correlation involving photon polarization in o-Ps $\rightarrow 3\gamma$ annihilations**

Thank you for your attention!

This work is supported in the framework of the Opus grant no. 2019/35/B/ST2/03562 of the National Science Centre of Poland.

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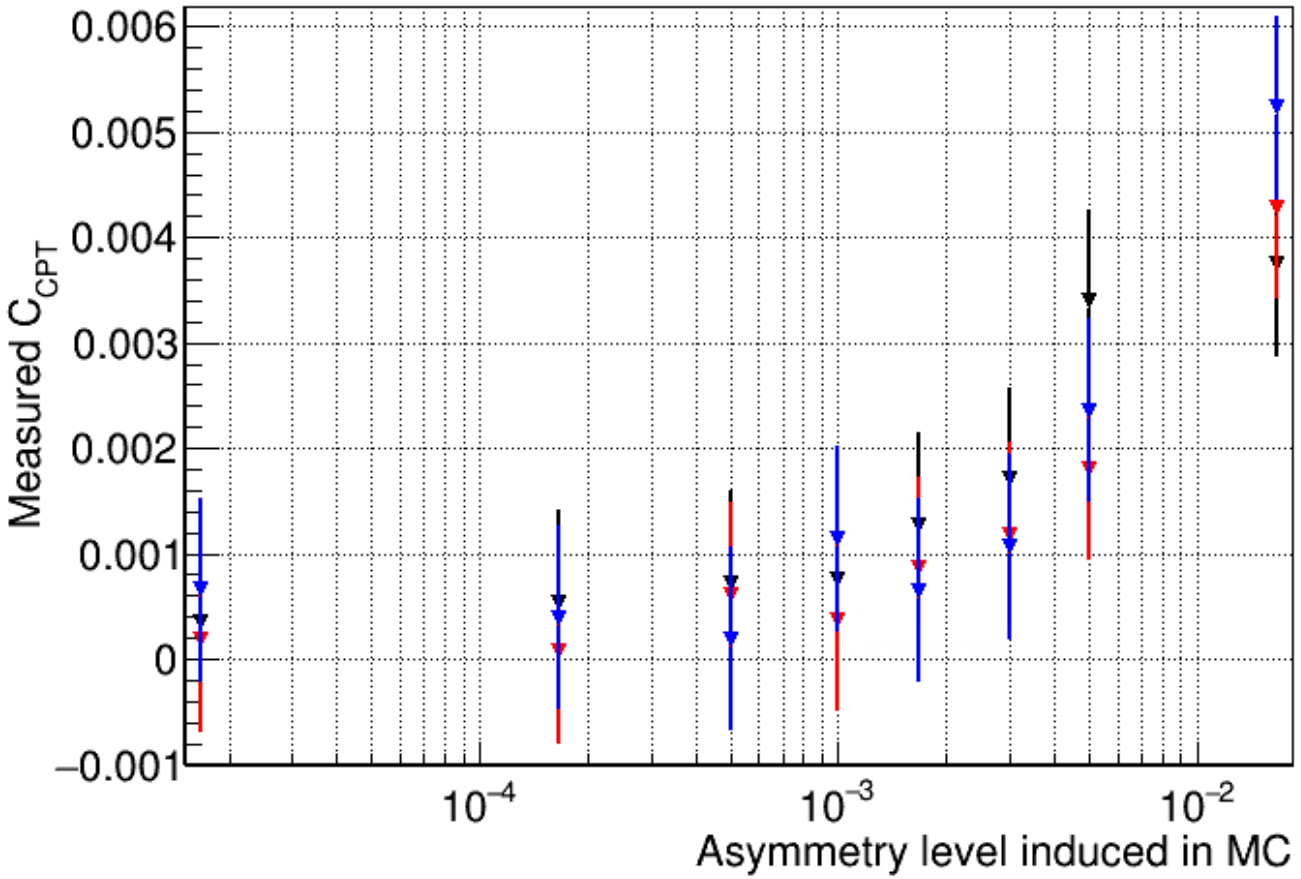
Backup Slides

Evaluation of the experiment's sensitivity

- MC-simulating same statistics as experimental data
  - Artificially inducing different levels of CPT violation
- Applying identical analysis as used on data
- Testing observed level of violation (C_{CPT})



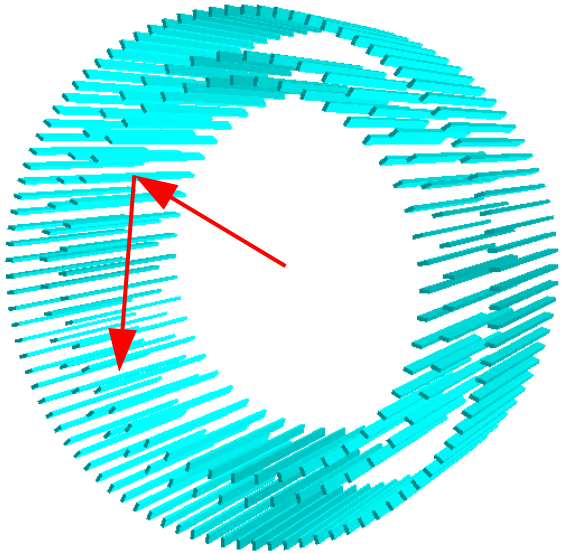
Different colors denote independent simulations

Testing discrete symmetries with ortho-positronium

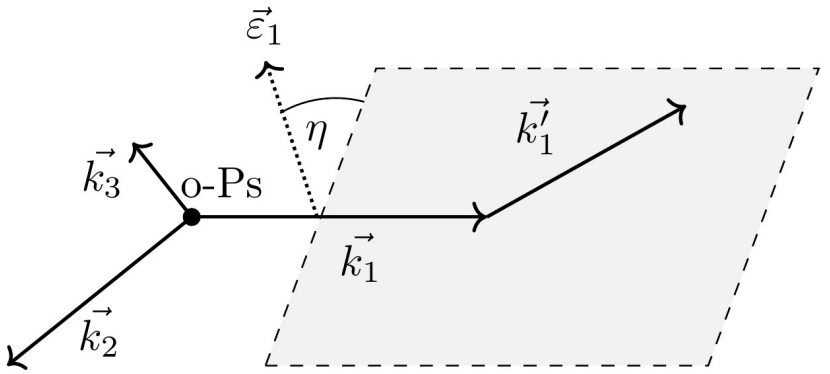
If polarization direction of the photons (ϵ) can be estimated, a new class of operators becomes available for measurement!

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*]

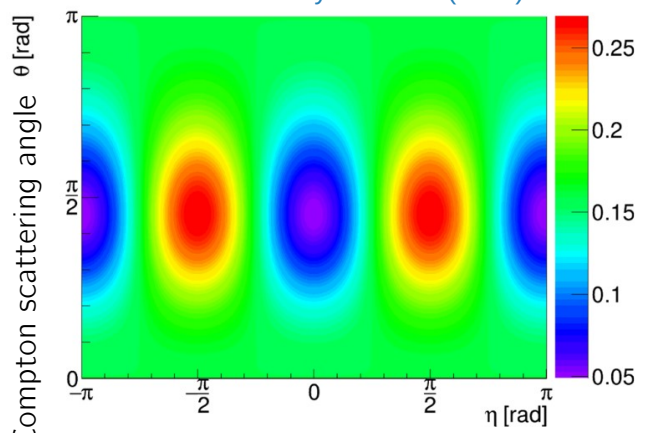


J-PET can determine the scattering plane in events with secondary Compton scatterings!



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

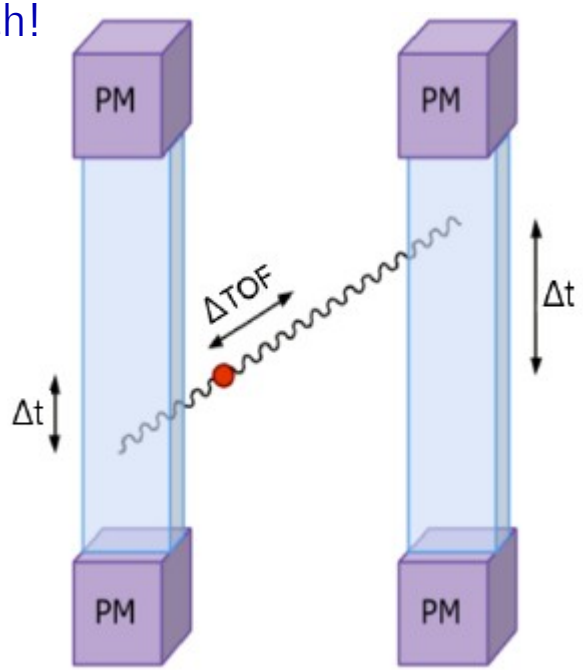
Eur. Phys. J. C 78 (2018) 970

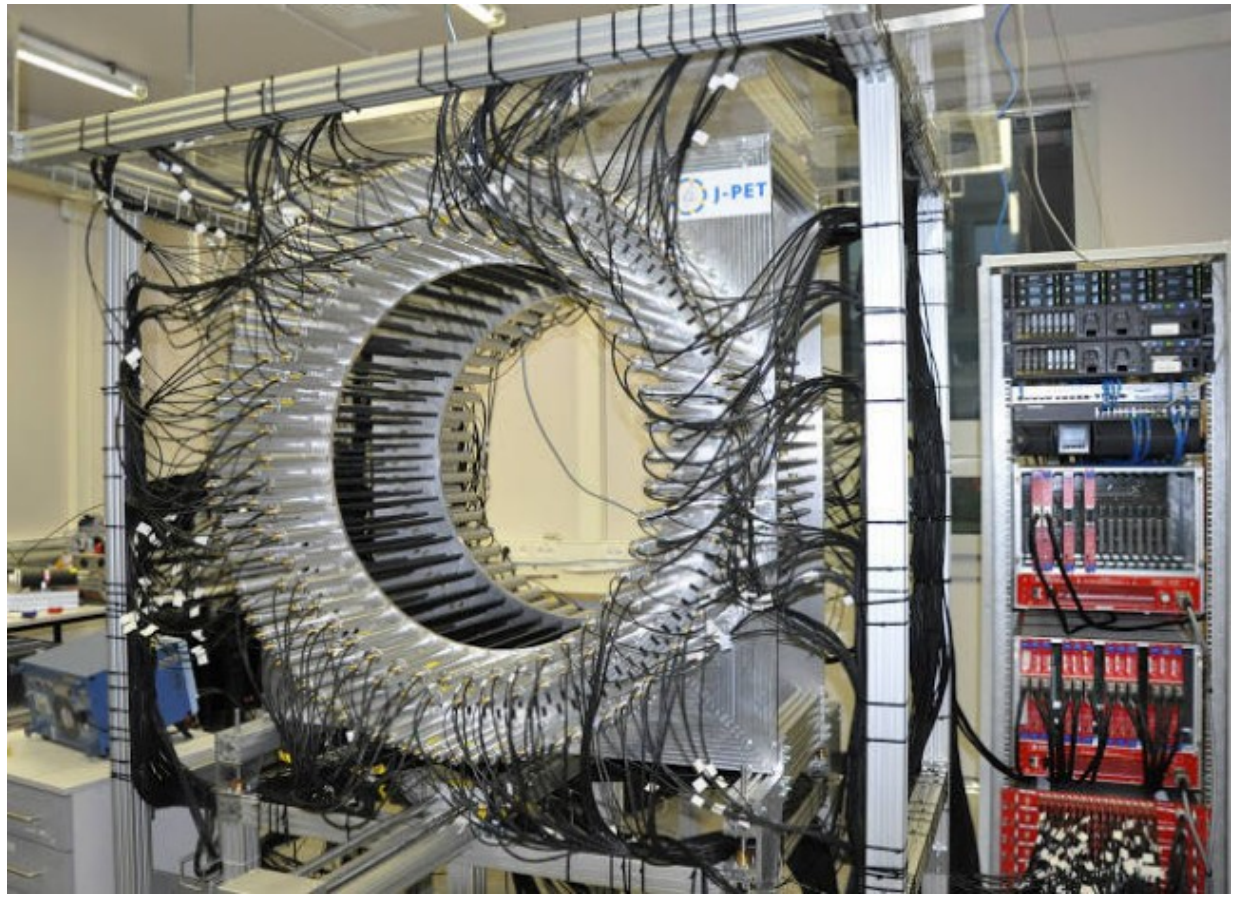


Angle between ϵ and the scattering plane

The J-PET Detector

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





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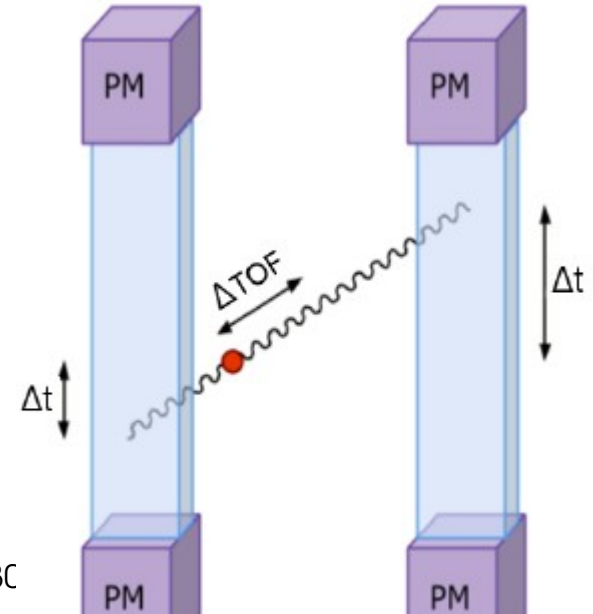
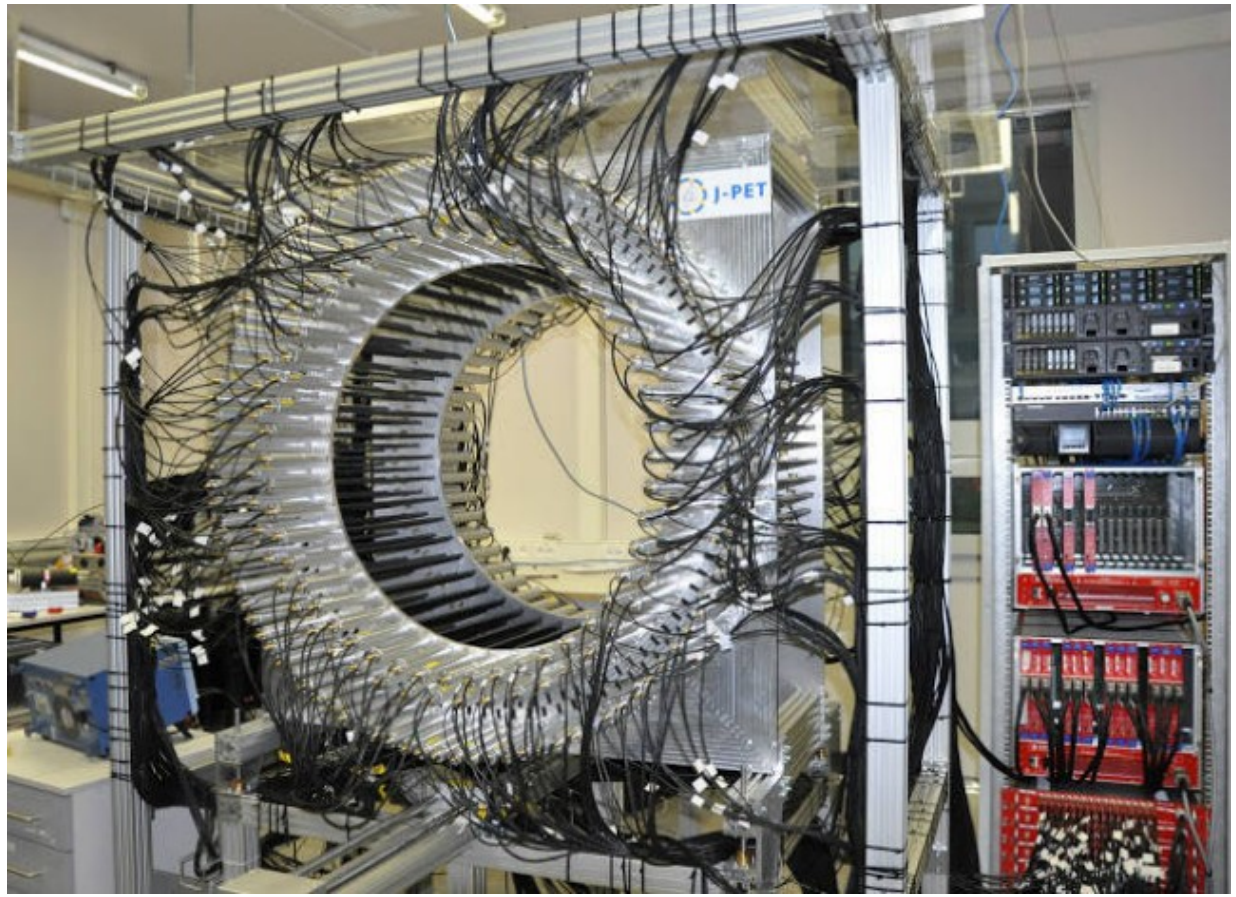
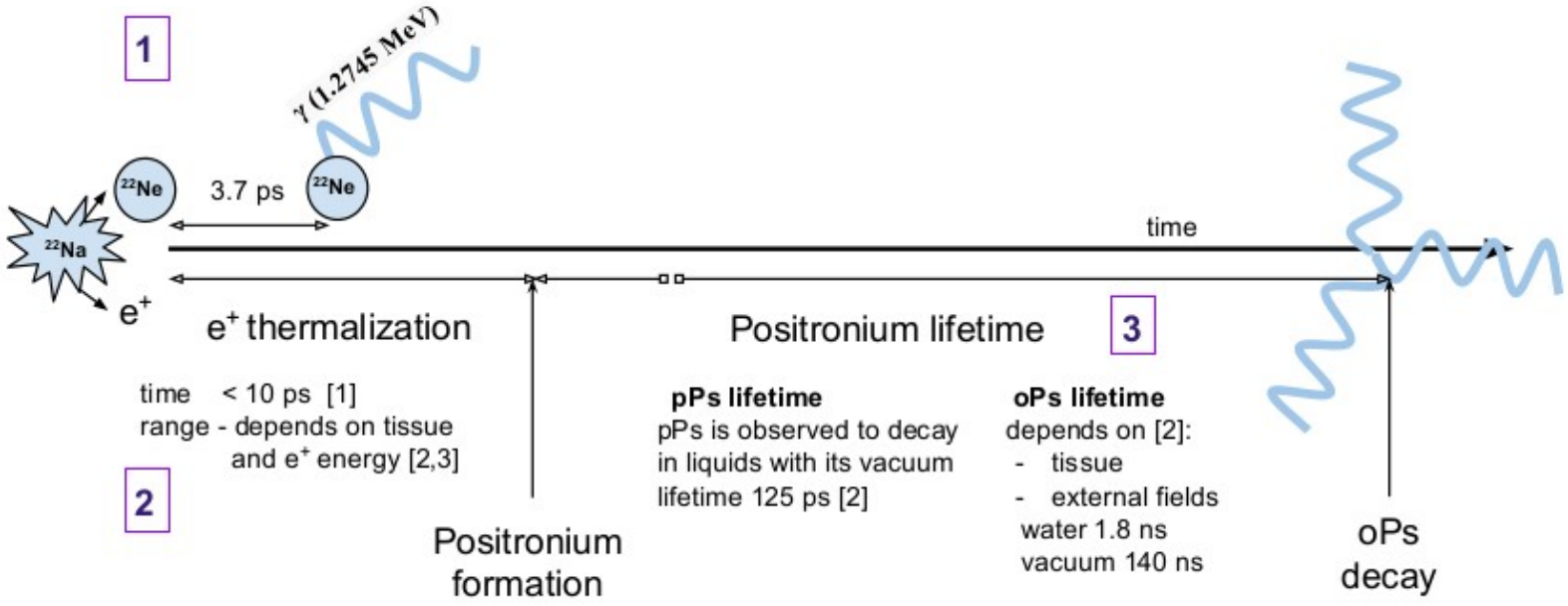




O-Ps creation and decay



[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

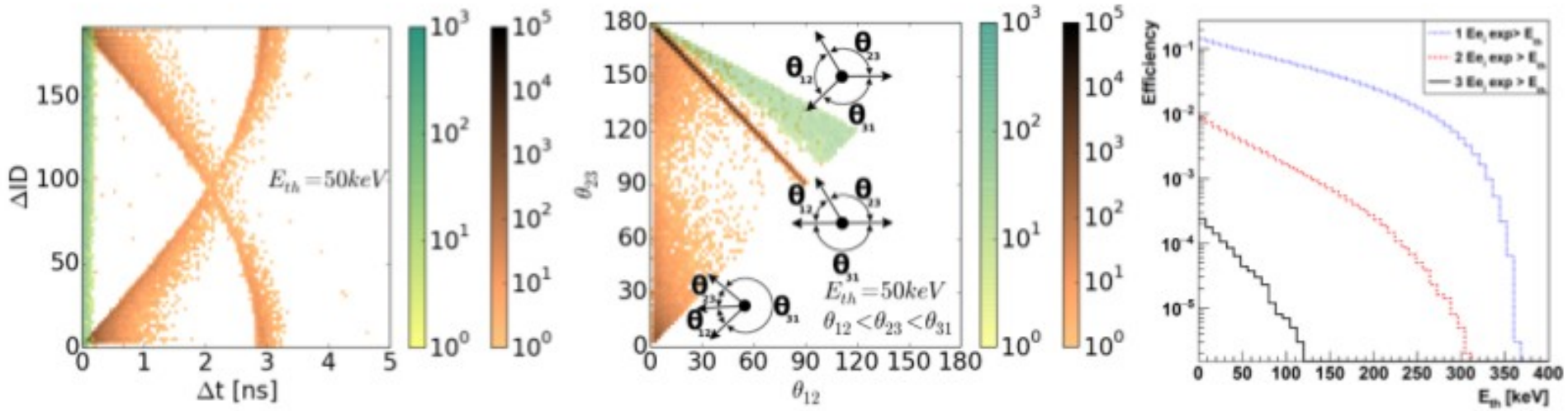
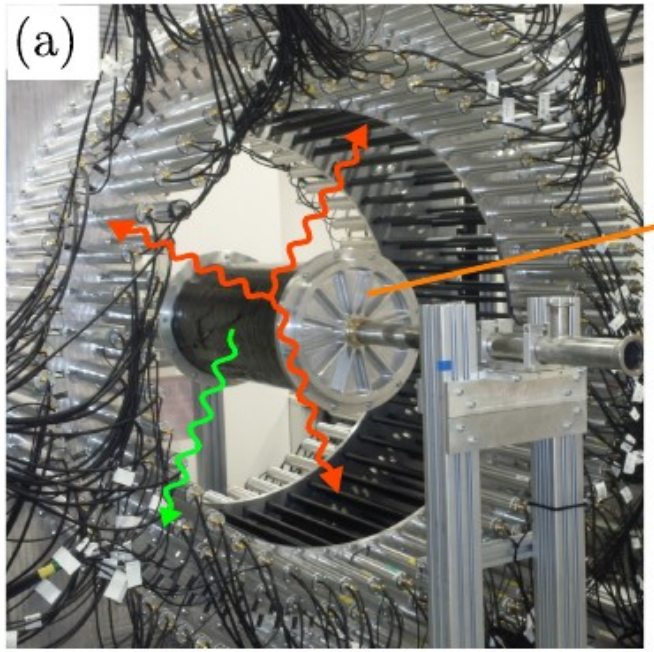
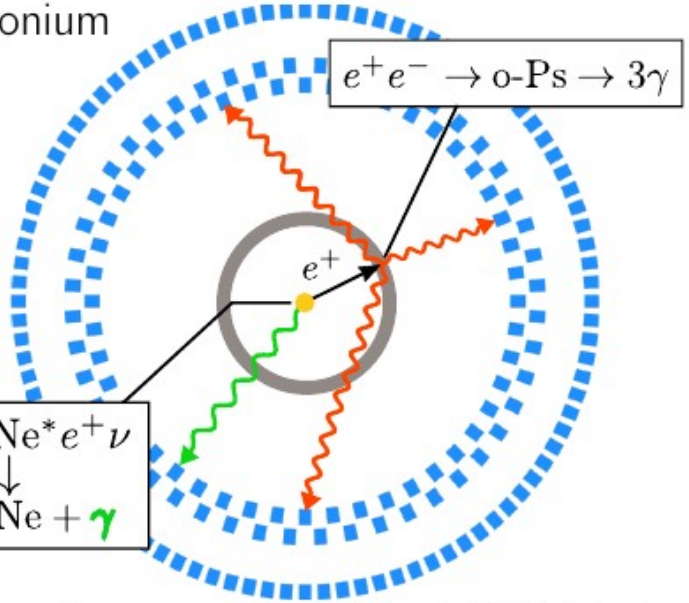


Figure 9. (Left) Simulated distributions of differences between detectors ID (ΔID) and differences of hit-times (Δt) for events with three hits registered from the annihilation e+e- → 2γ (gold colours) and o-Ps → 3γ (green colours). **(Middle)** Disribution of relative angles between reconstructed directions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

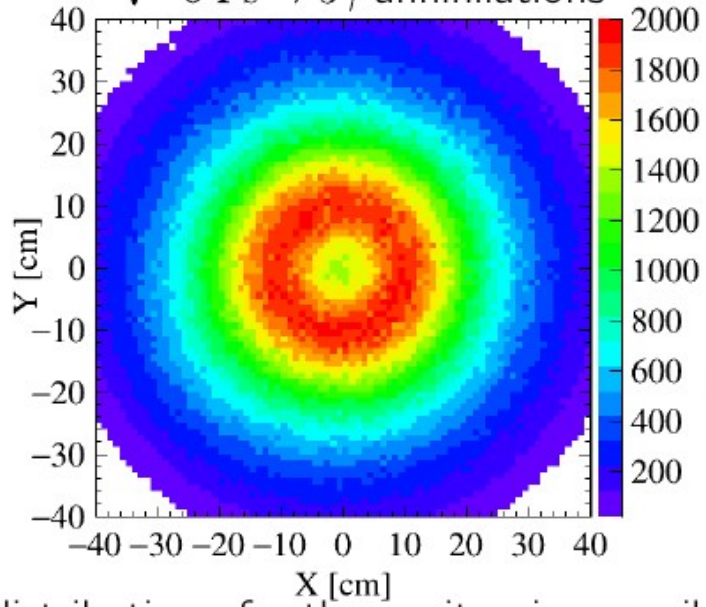


(b) ortho-positronium production



Schematic cross section of the J-PET detector

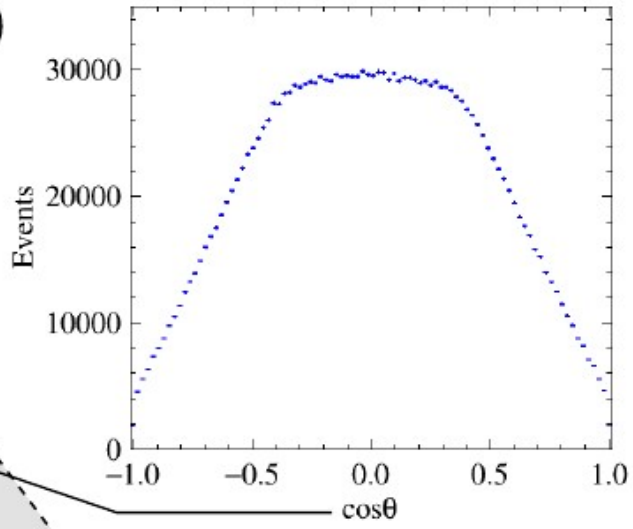
(c) identification of o-Ps $\rightarrow 3\gamma$ annihilations

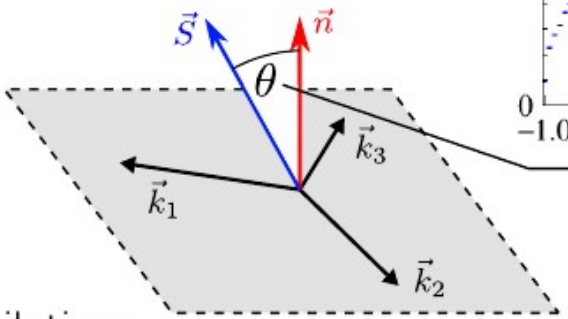


distribution of ortho-positronium annihilations

extraction of CPT-asymmetric angular correlation

(d)

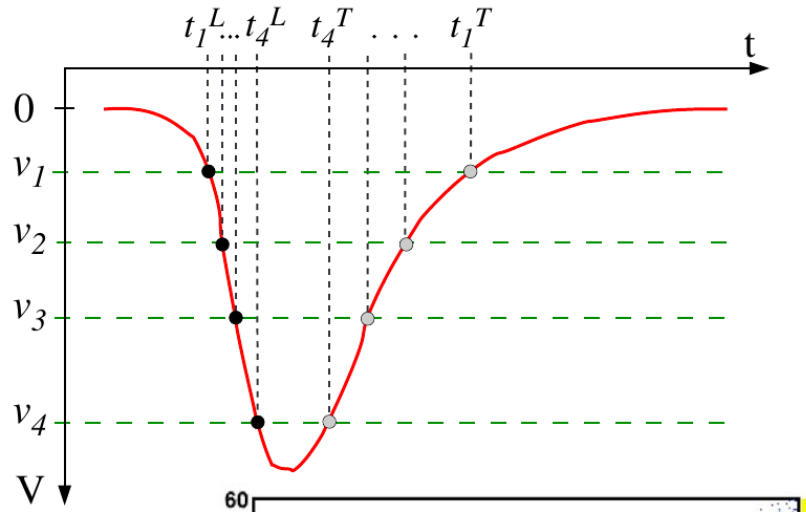


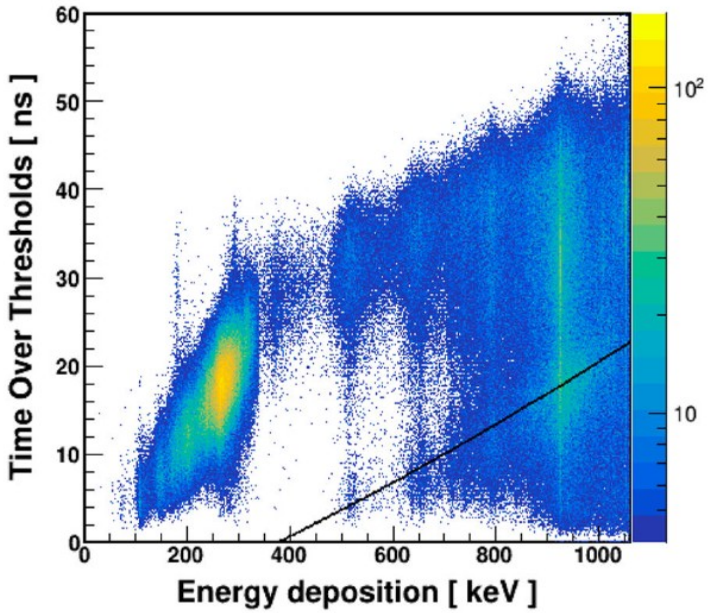


o-Ps spin - decay plane correlation

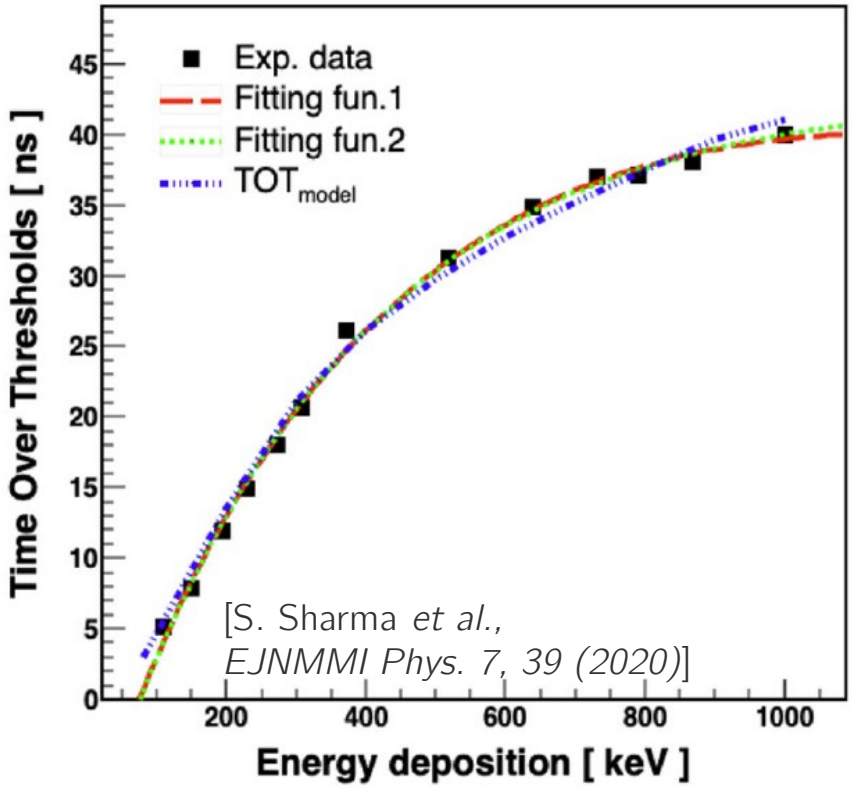
Time-Over-Threshold as a measure of deposited γ energy

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



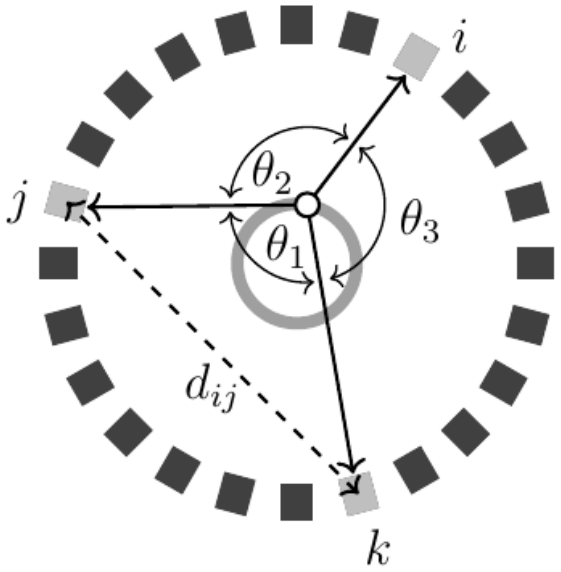


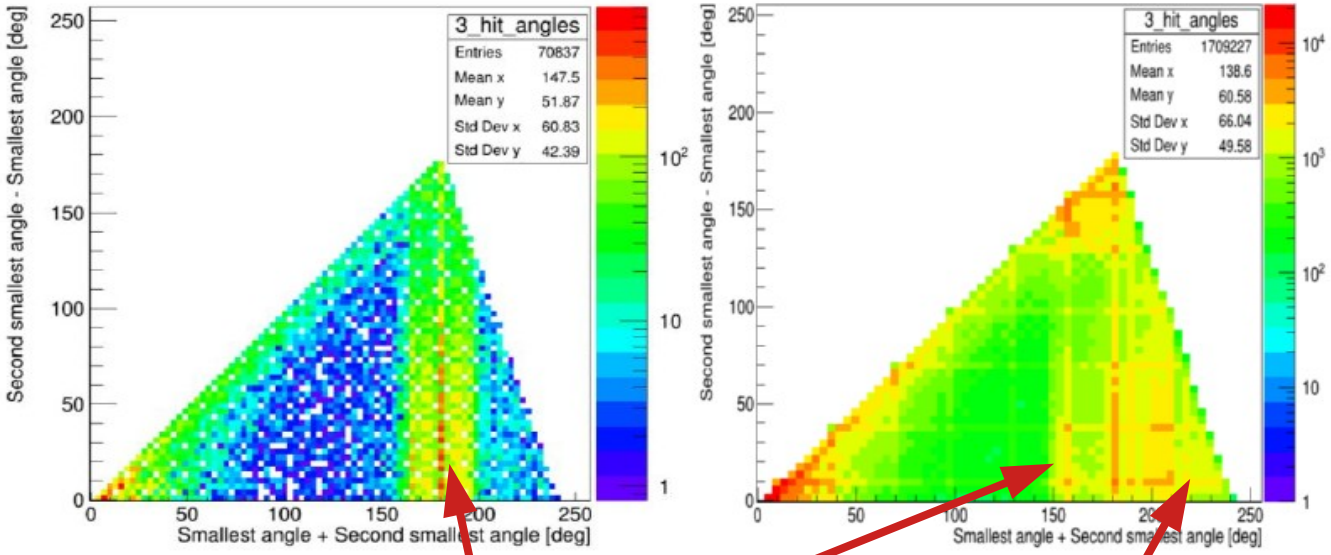
The relation between TOT and energy deposited by a photon in Comton scattering is under an extensive study right now.



Angular topology of the 3γ events

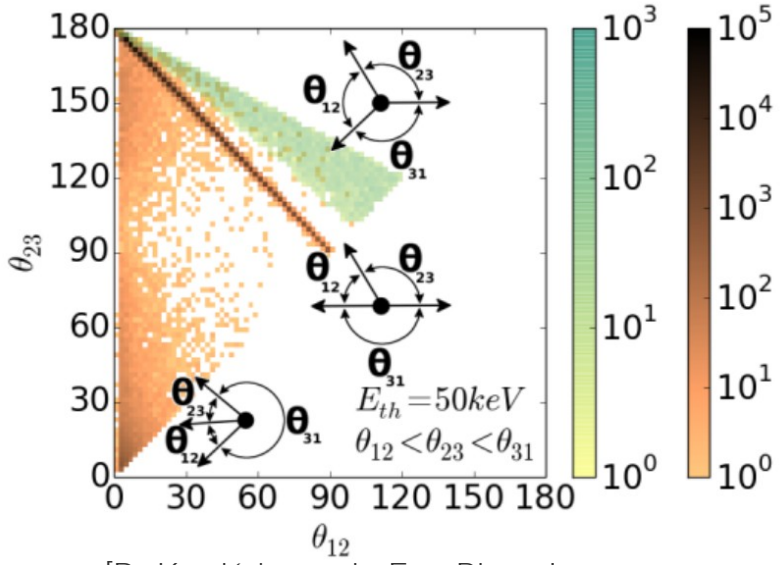
Angles defined in the transverse plane only



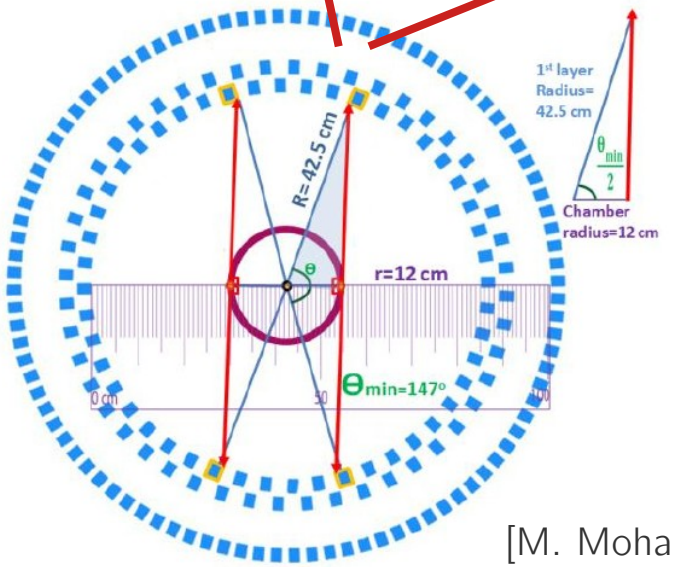


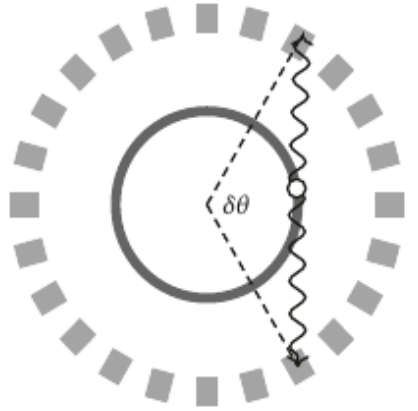
2-photon

o-Ps



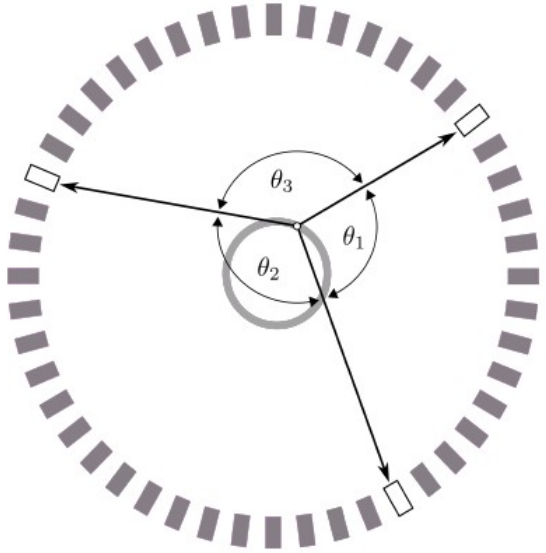
[D. Kamińska et al., Eur. Phys. J. C76 (2016) no.8, 445]



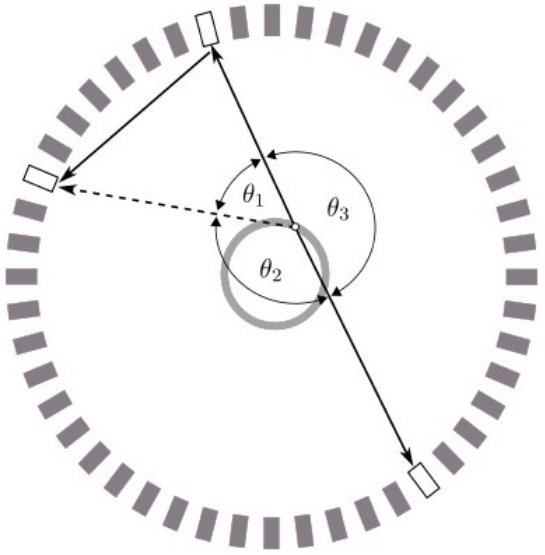


[M. Mohammed, PhD thesis, 2020]

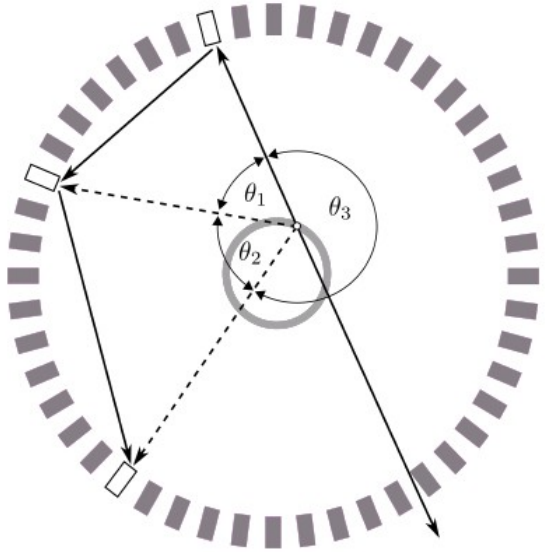
Signal & background events

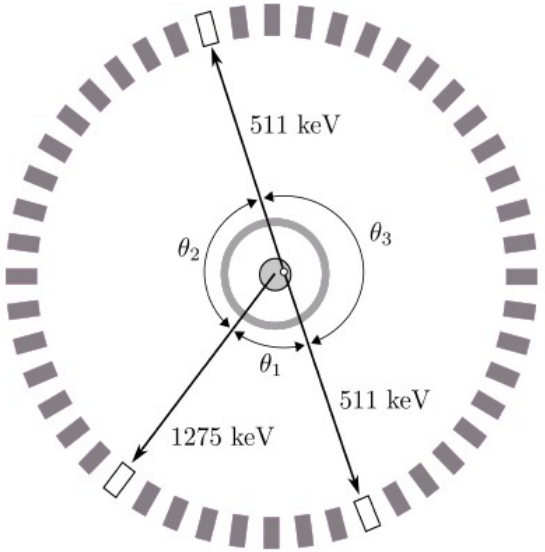


(a) Signal (o-Ps→3γ) event.

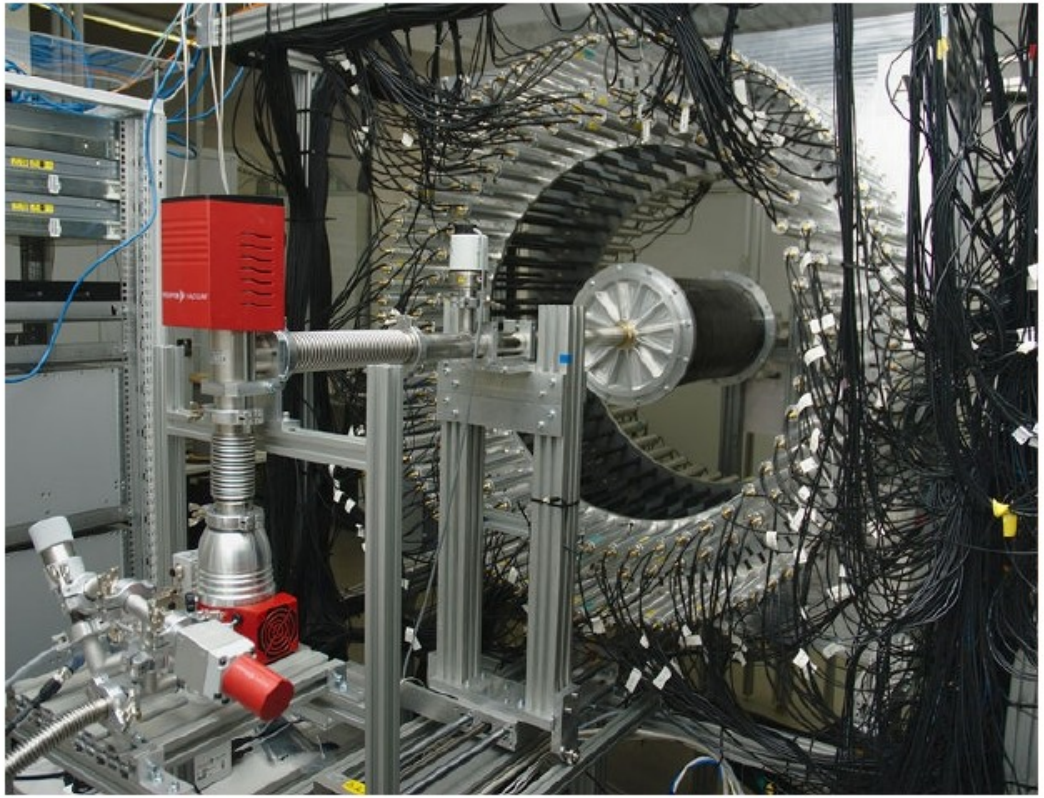


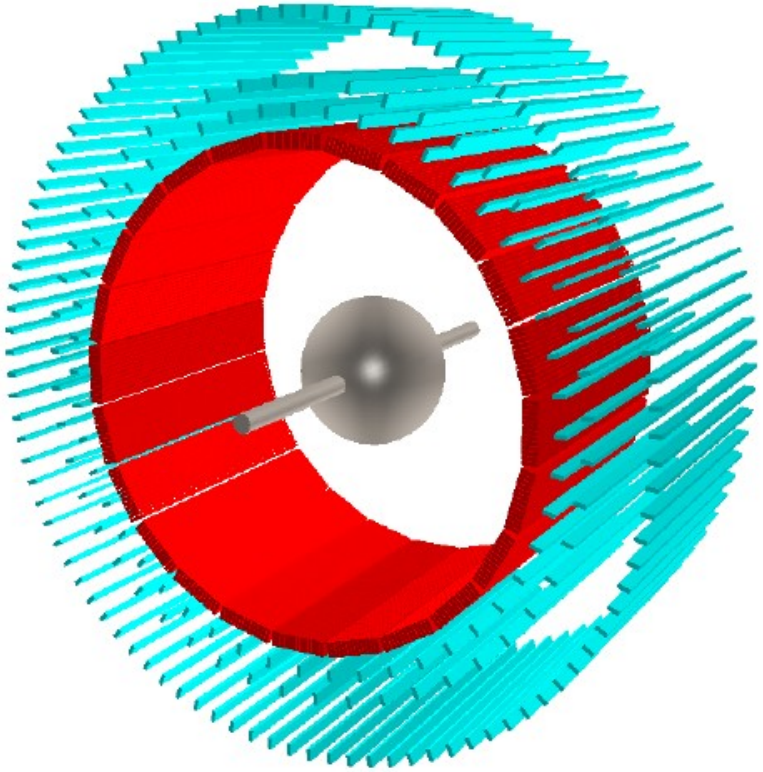
(b) 2γ annihilation with secondary Compton scattering.



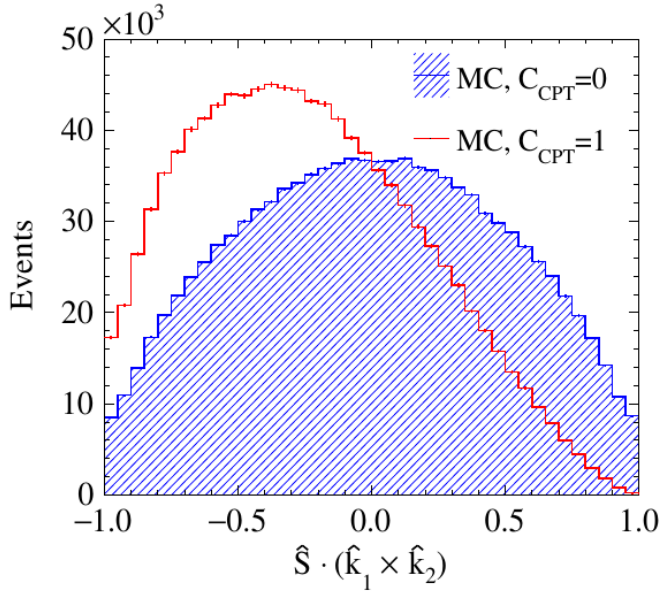


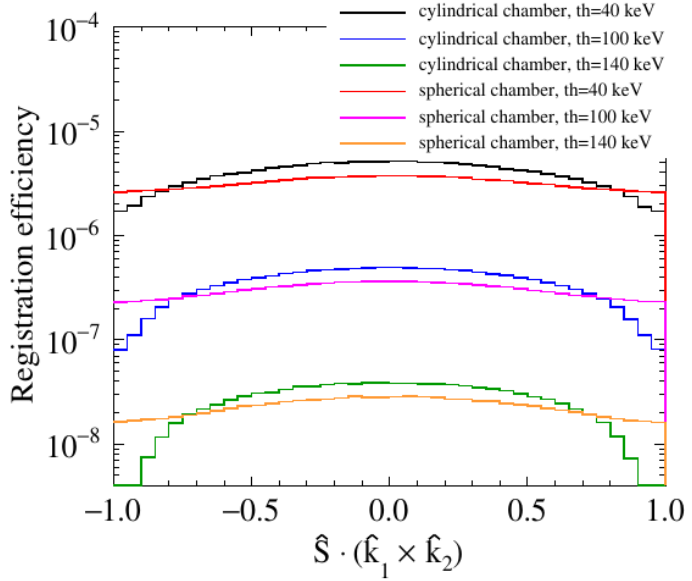
Detector improvements

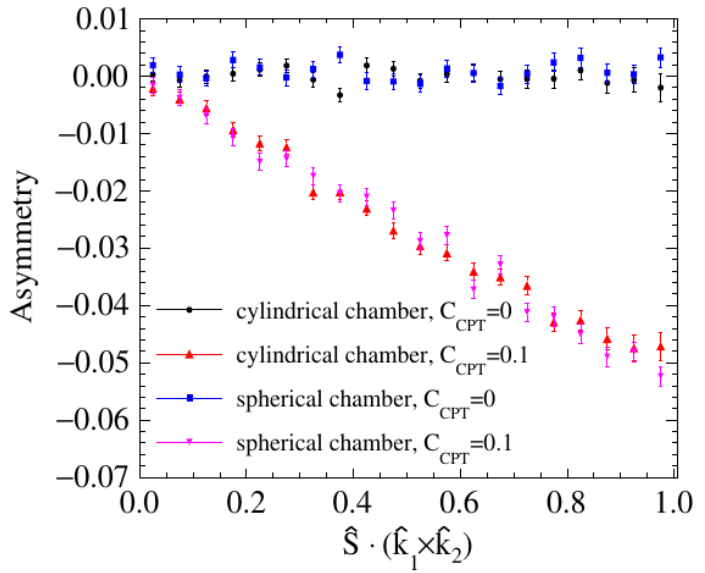




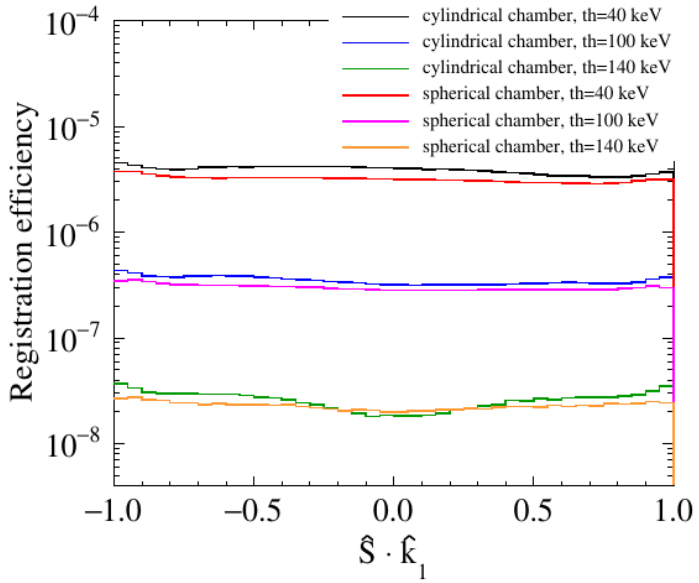
Expected sensitivity

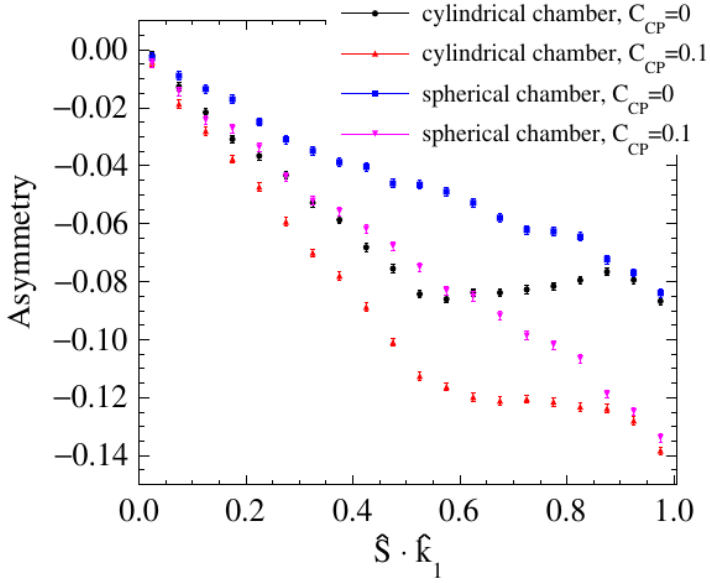






No.	Operator	C	P	T	CP	CPT
1	$\vec{S}\cdot\vec{k_1}$	+	−	+	−	−
2	$\vec{S}\cdot(\vec{k_1}\times\vec{k_2})$	+	+	−	+	−
3	$(\vec{S}\cdot\vec{k_1})(\vec{S}\cdot(\vec{k_1}\times\vec{k_2}))$	+	−	−	−	+





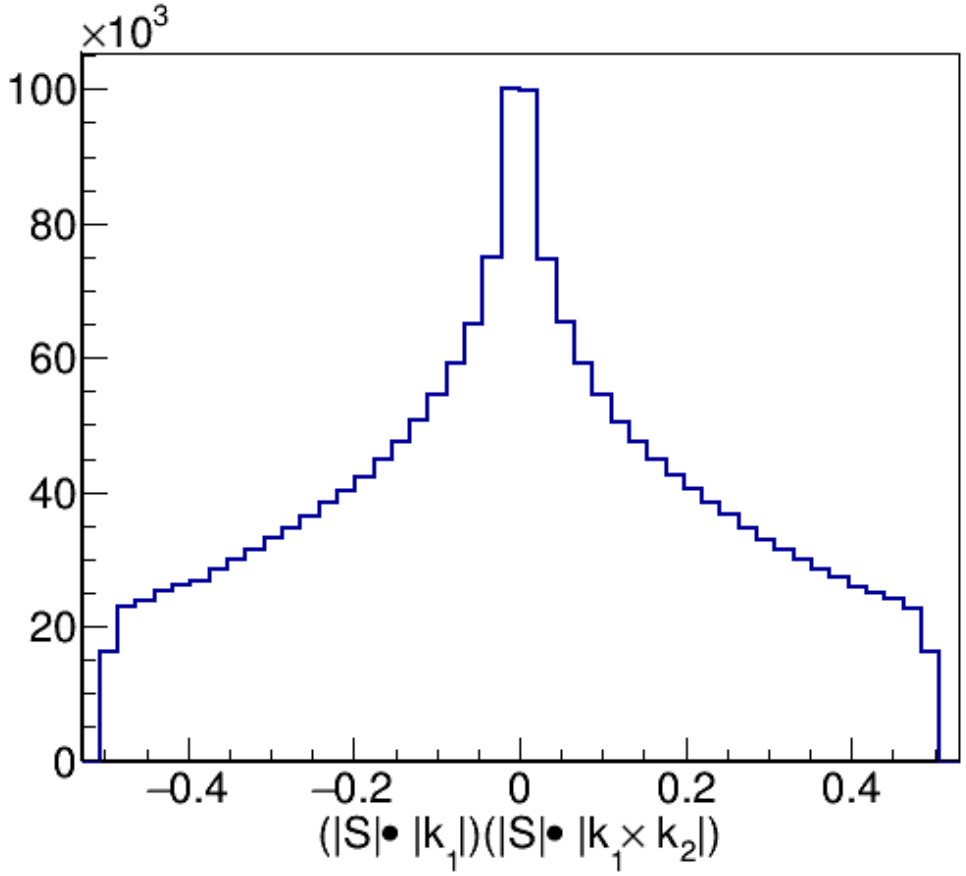
[*Symmetry* 12 (2020) 8, 1268]

Control of detector asymmetries

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

- Insensitive to CPT violation in absence of o-Ps tensor polarization
- No B field used in the current experiment

  => we expect <0> unless spurious asymmetries originate from detector/chamber geometry



<0> = (0.99 +/- 1.7) x 10^{-4}

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

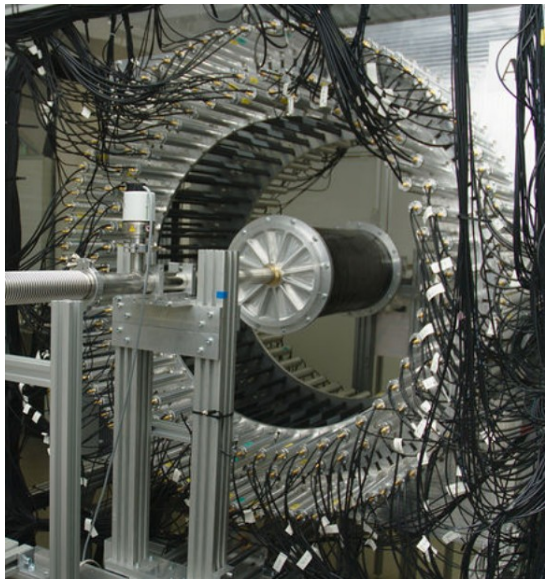
$\vec{S} \cdot \vec{k_1}$ CP-violation sensitive

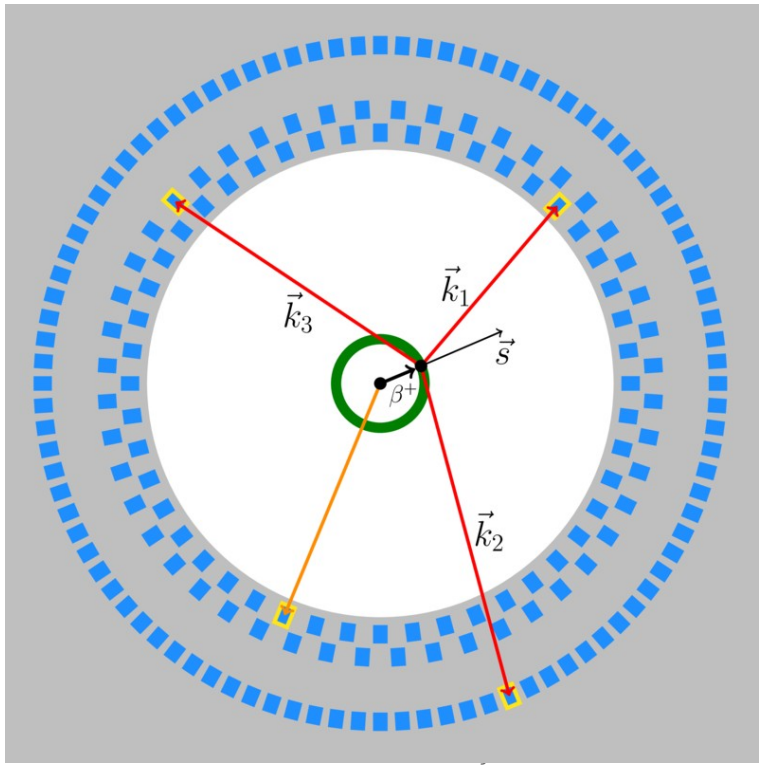
$(\vec{S} \cdot \vec{k_1})(\vec{S} \cdot (\vec{k_1} \times \vec{k_2}))$

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

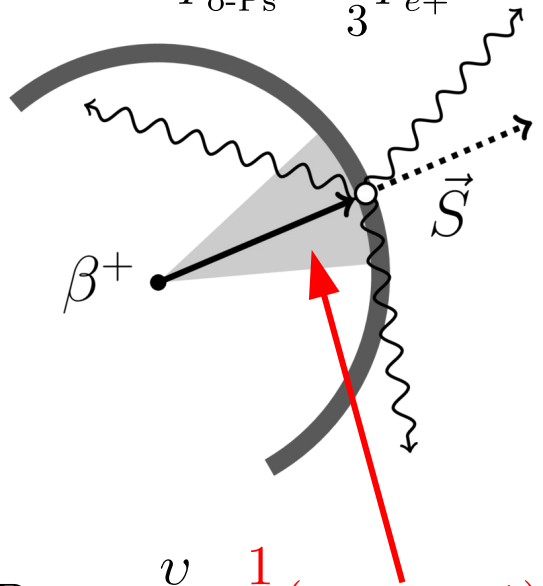
Event-by-event spin estimation

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





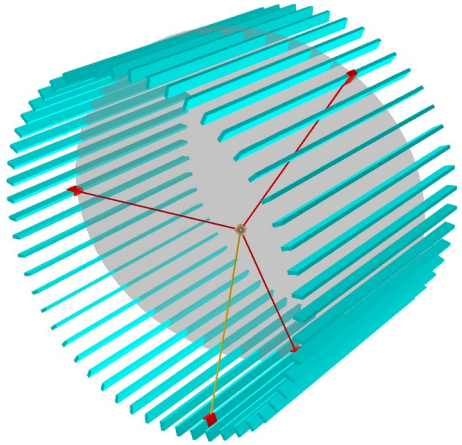
$P_{\text{o-Ps}} = \frac{2}{3} P_{e+}$



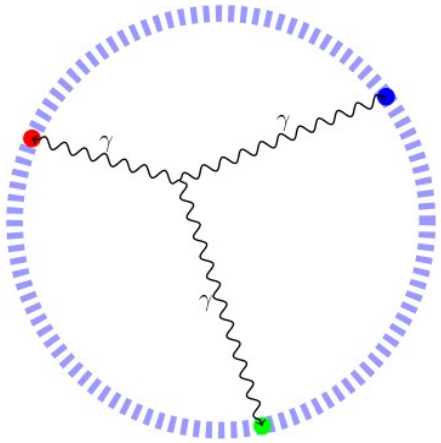
$P_{e+} \approx \frac{v}{c} \cdot \frac{1}{2}(\cos\alpha + 1)$

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

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

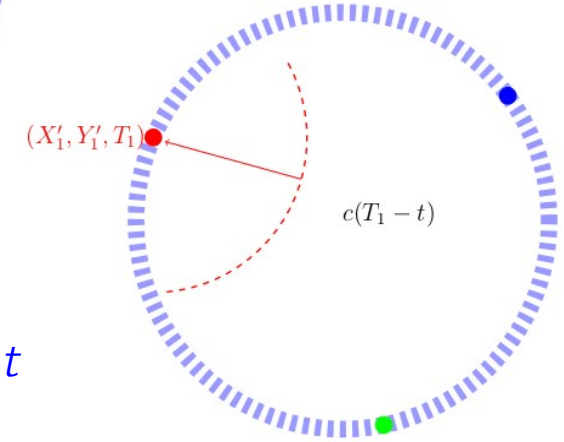


1. Find the decay plane containing the 3 hits in the J-PET barrel

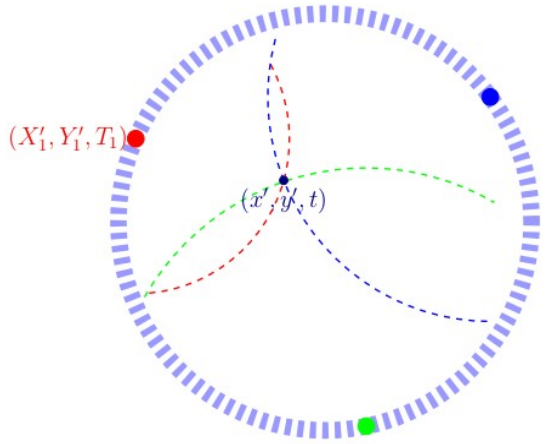


2. Transform the hit coordinates to a 2D coordinate system in the decay plane

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



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:

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