ICHEP 2022 BOLOGNA
ICHEP 2022
XLI
International Conference
on High Energy Physics
Bologna (Italy)
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Testing CPT symmetry in ortho-positronium decays with the J-PET detector

July 8th 2022

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on behalf of the J-PET Collaboration
Jagiellonian University

J-PET

European Funds Smart Growth
Republic of Poland
FNP Foundation for Polish Science
European Union
European Regional Development Fund

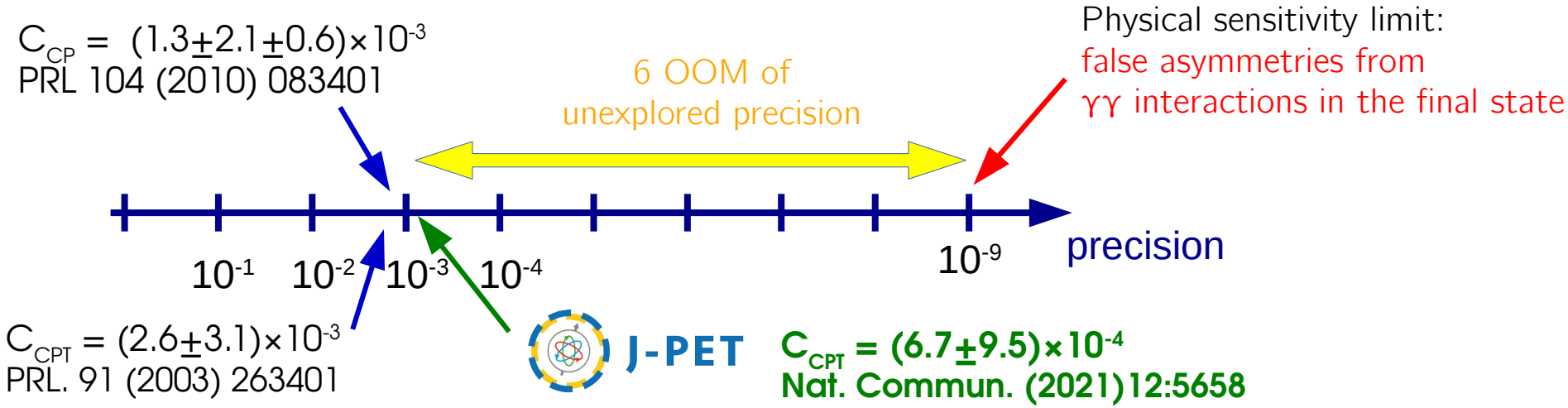
Motivation: discrete symetry tests with o-Ps → 3γ decays

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

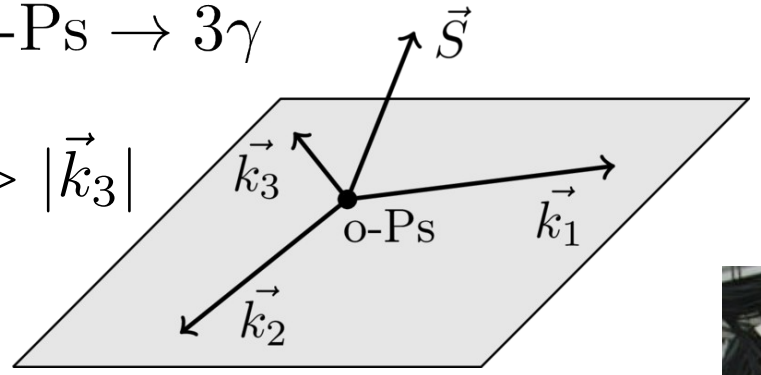
- **Searches for non-vanishing symmetry-odd correlations**



Testing discrete symmetries with angular correlations in o-Ps → 3γ decays

$e^+e^- \rightarrow$ o-Ps $\rightarrow 3\gamma$

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



$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$ T & CPT-violation sensitive

$\vec{S} \cdot \vec{k}_1$ CP-violation sensitive

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

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

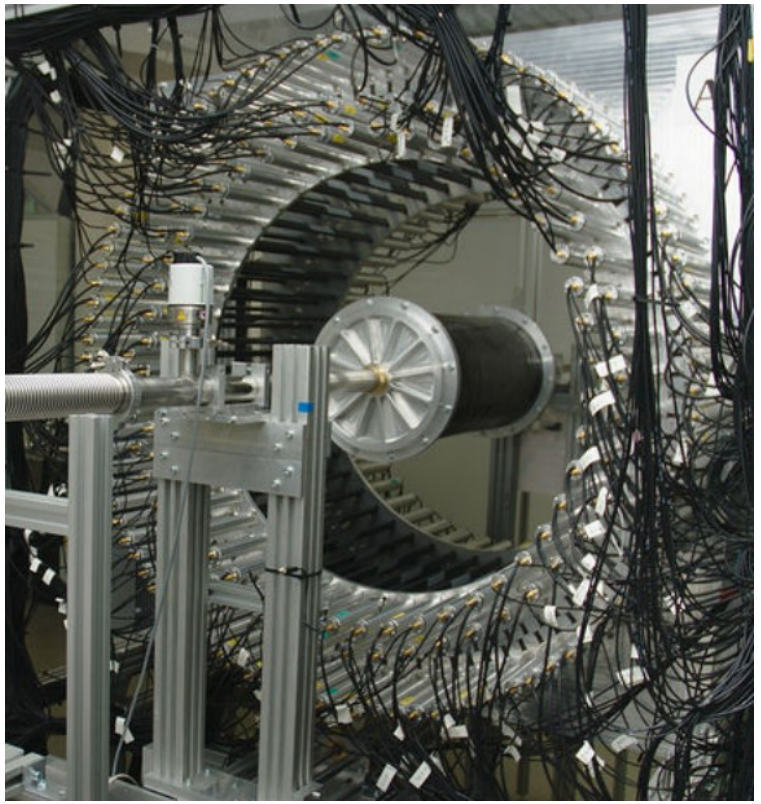
$\Leftrightarrow \mathcal{T}(\hat{O}) = -1$

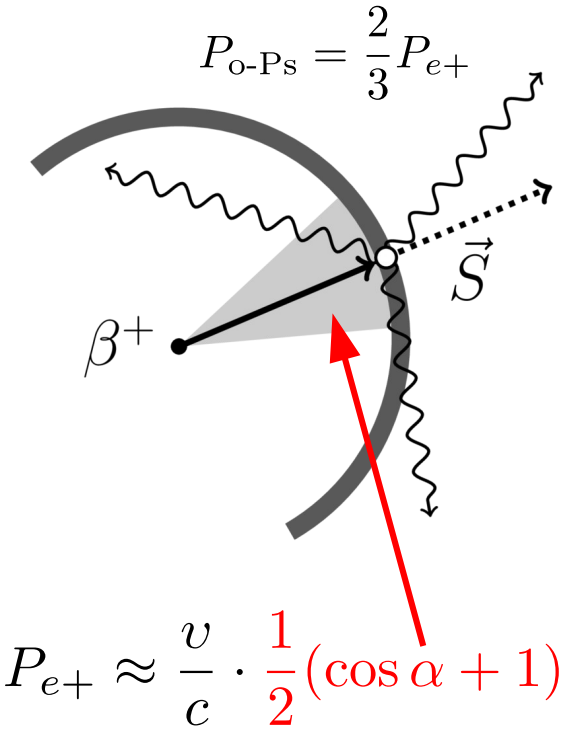
[W. Bernreuther *et al., Z. Phys. C41 (1988) 143*]

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

Event-by-event spin estimation

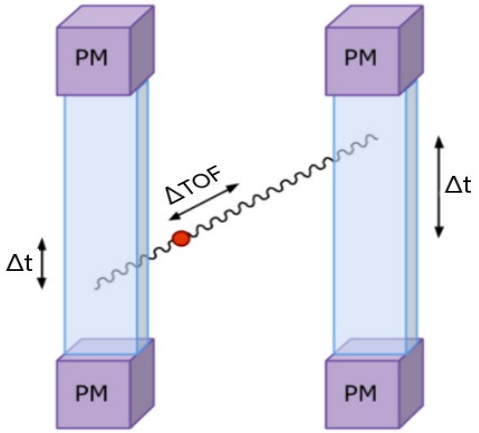
Using an extensive-size o-Ps production and annihilation medium



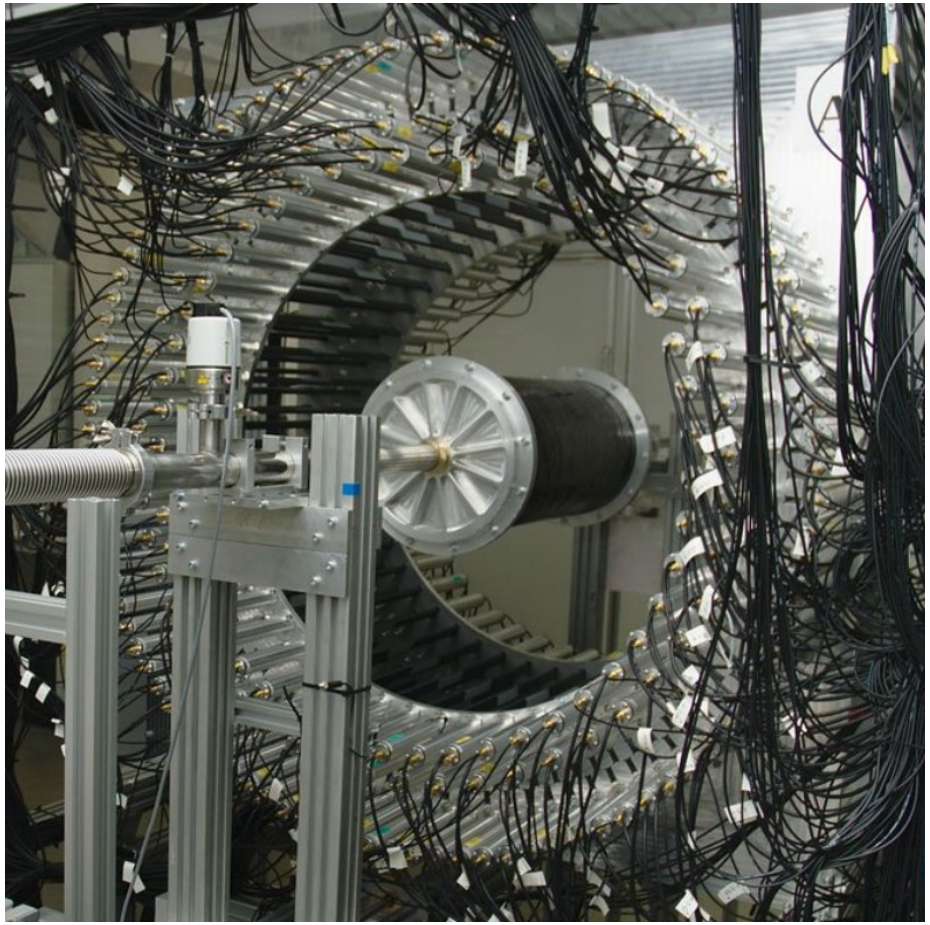


The J-PET detector and ortho-positronium production

- Conceived 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

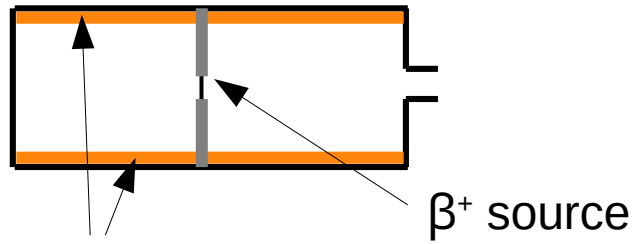


[J-PET: NIM A 764 (2014) 317-321]
[J-PET: NIM A 764 (2014) 186-192]
[J-PET: NIM A 786 (2015) 105-112]
[J-PET: NIM A 775 (2015) 54-62]



See yesterday's talk by Shivani in *Technology and Industrial Applications*

- 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



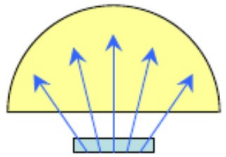
J-PET vs previous measurements

Gammasphere
PRL. 91 (2003) 263401

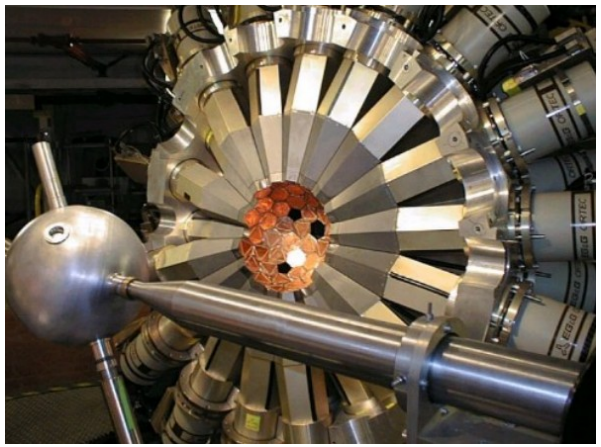
$C_{CPT} = (2.6 \pm 3.1) \times 10^{-3}$

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

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



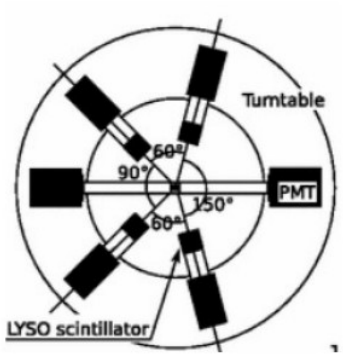
- Limiting e+ emission direction
- 1 Mbq β^+ emitter activity
- 4π detector but low angular resolution

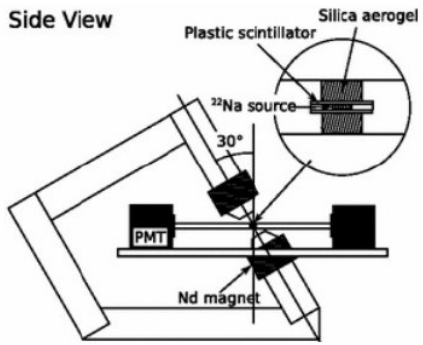


Yamazaki et al.
PRL 104 (2010) 083401

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

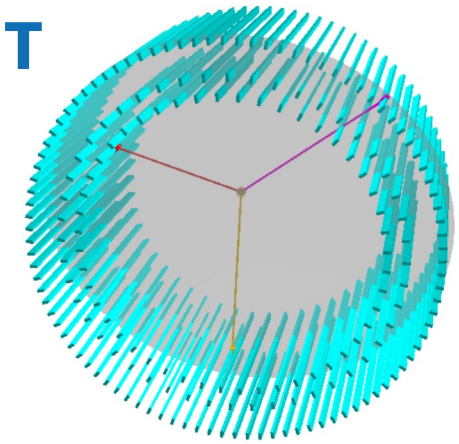
$(\vec{S} \cdot \vec{k_1})(\vec{S} \cdot (\vec{k_1} \times \vec{k_2}))$





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

J-PET

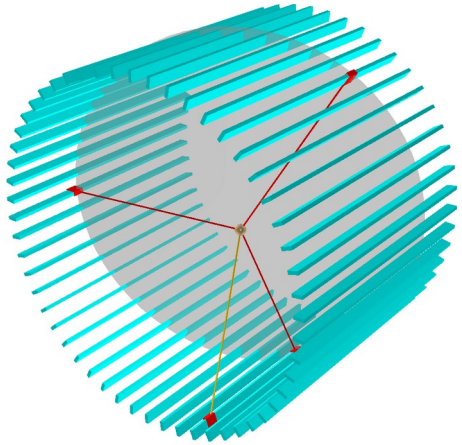


- Recording multiple geometrical configurations
- e+ spin estimated event-by-event

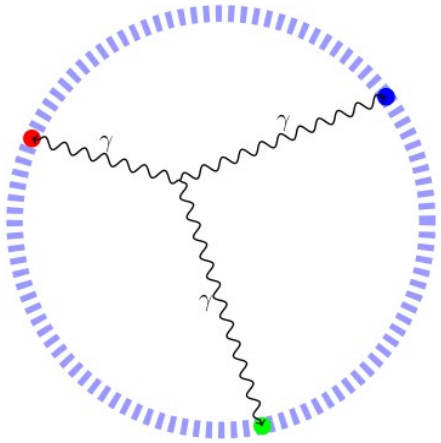
$$P_{e+} \approx \frac{v}{c} \cdot 0.91$$

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

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

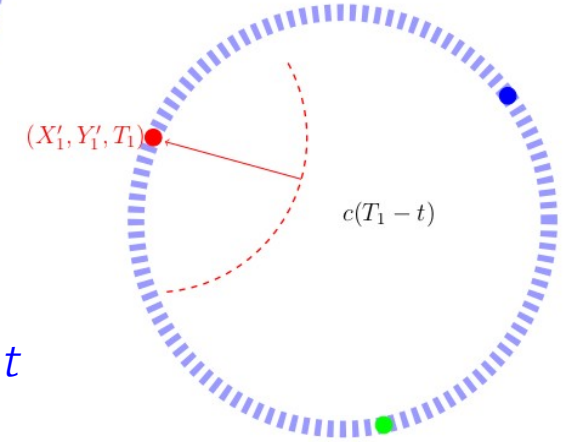


1. Find the decay plane containing the 3 hits in the J-PET barrel

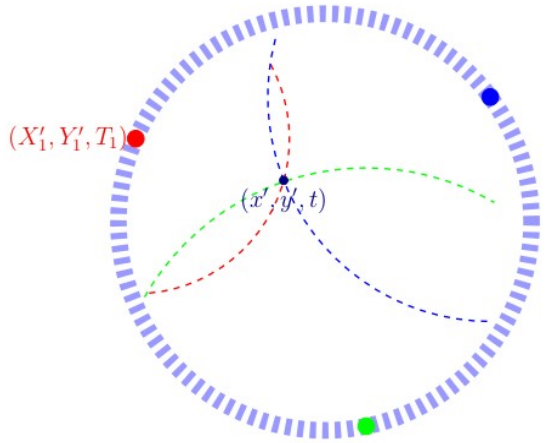


2. Transform the hit coordinates to a 2D coordinate system in the decay plane

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



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



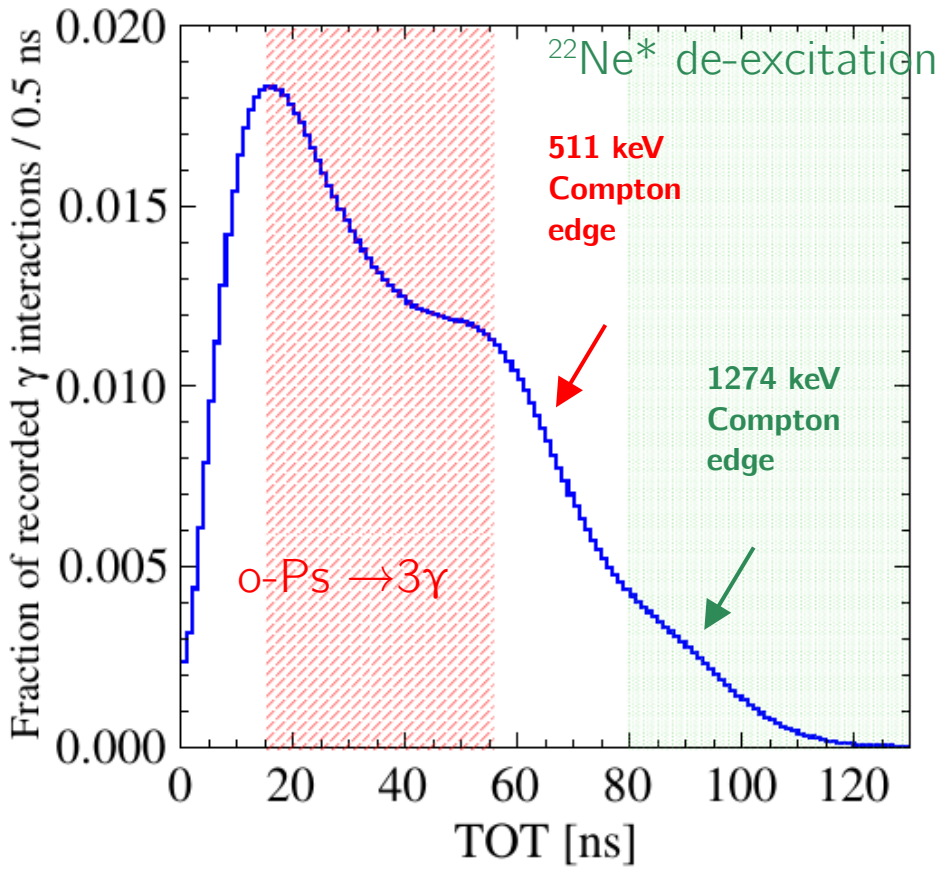
4. The decay point (x',y') in the decay plane and time t is an intersection of 3 such circles:

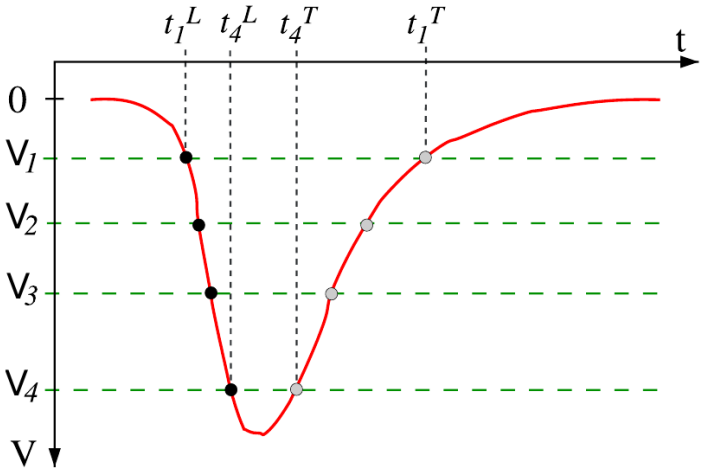
$$(T_i - t)^2 c^2 = (X'_i - x')^2 + (Y'_i - y')^2, \quad i = 1, 2, 3$$

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

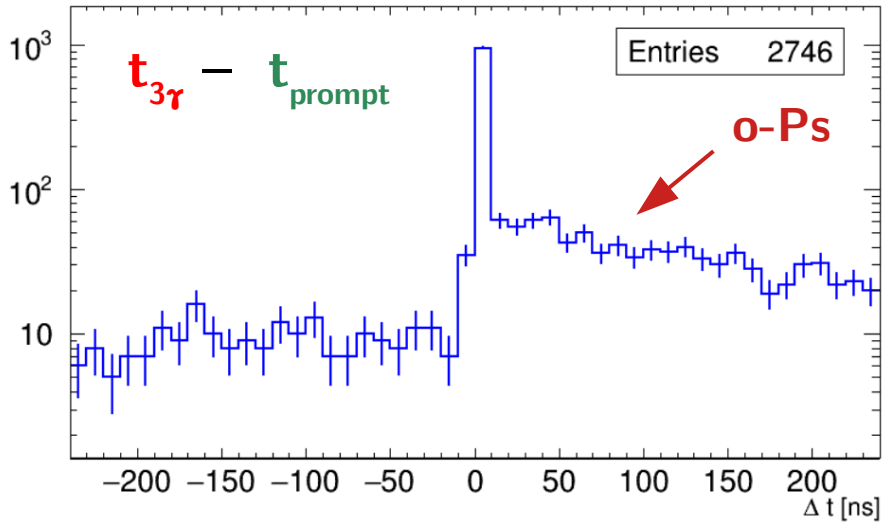
Identification of o-Ps → 3γ events in J-PET

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

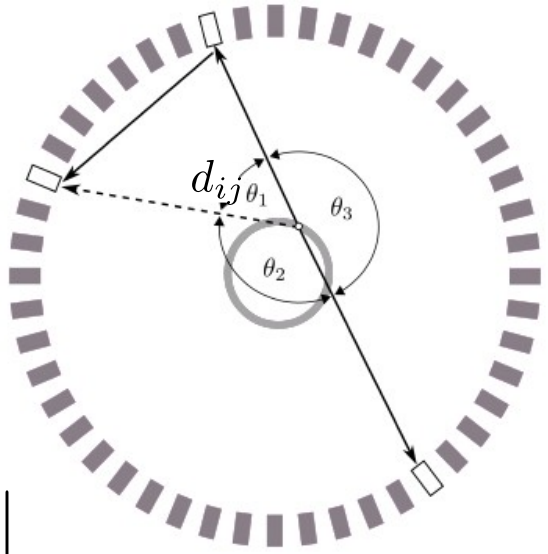


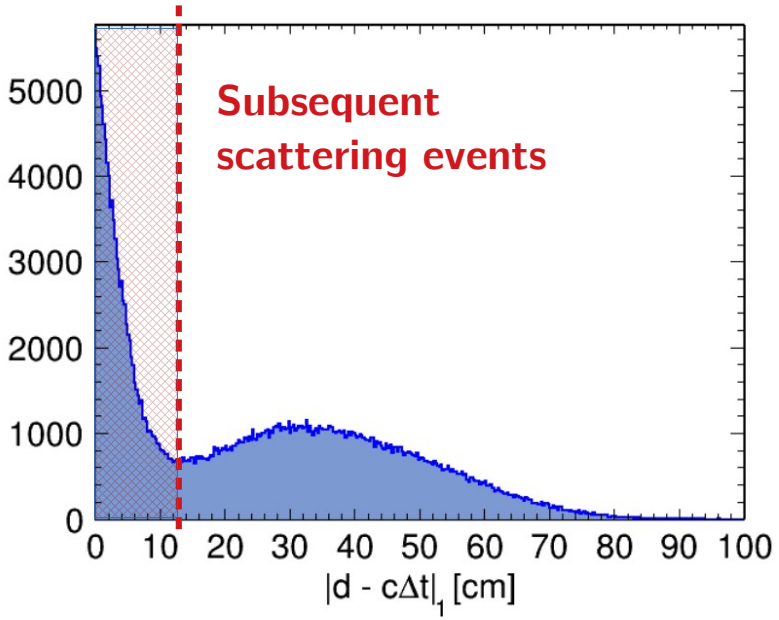
Treatment of main background sources

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:

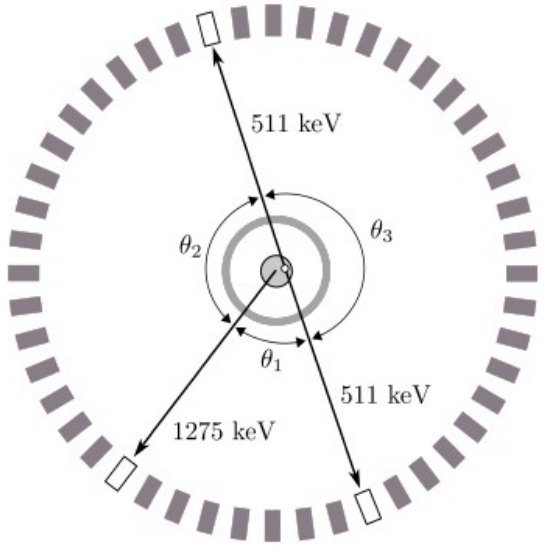
$$\delta t_{ij} = |d_{ij} - c\Delta t_{ij}|$$



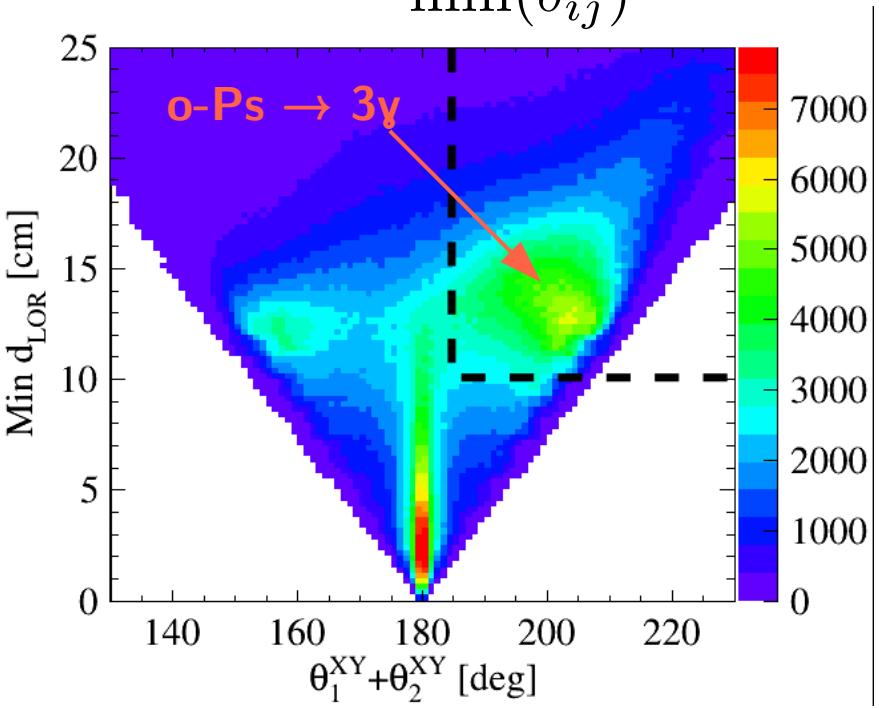


2γ from the β+ source setup

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

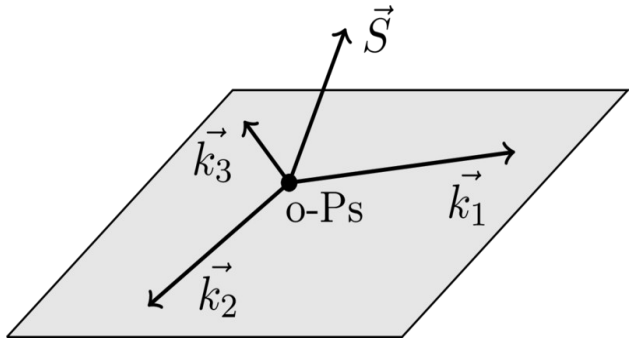


$\min(\delta_{ij})$



Evaluation of the CPT-asymmetric observable

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



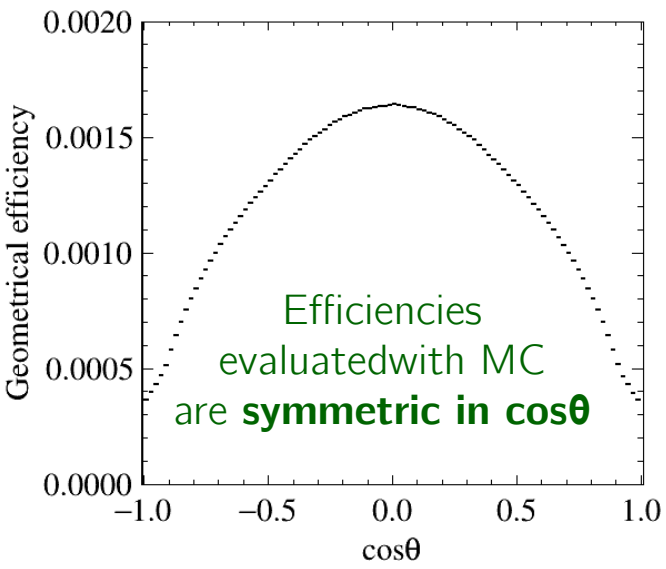
Standard asymmetry:

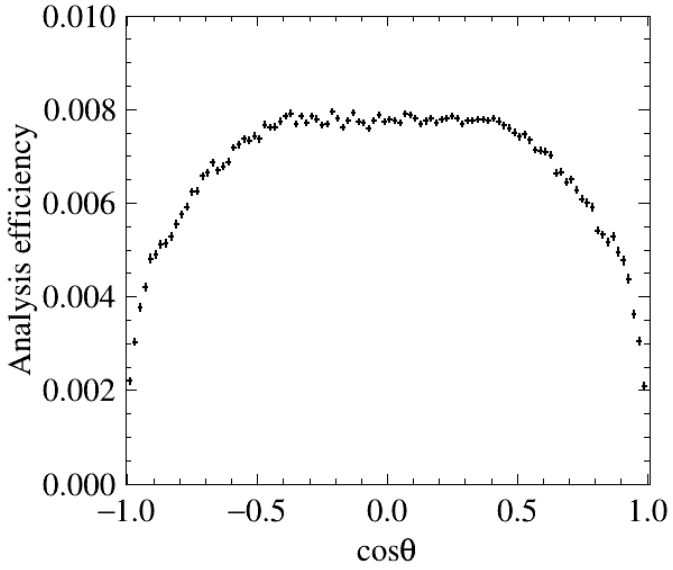
$$A = \frac{N_+ - N_-}{N_+ + N_-} \qquad N_+ \Leftrightarrow cos\theta > 0$$

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

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

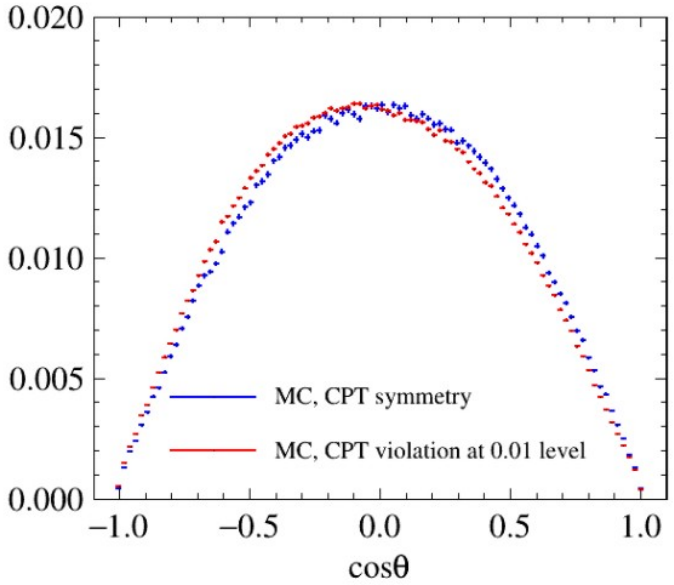
J-PET is sensitive to the full range of the operator





Expected effect with CPT-asymmetric simulations (exaggerated violation)

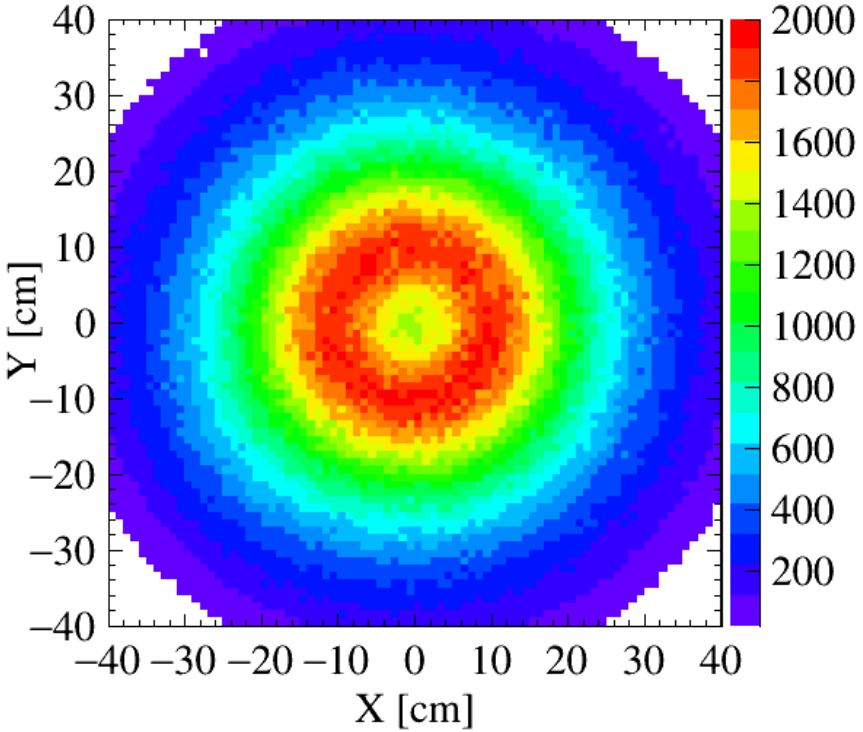
[*Symmetry* 12 (2020) 8, 1268]



Results of the 1st CPT test with J-PET

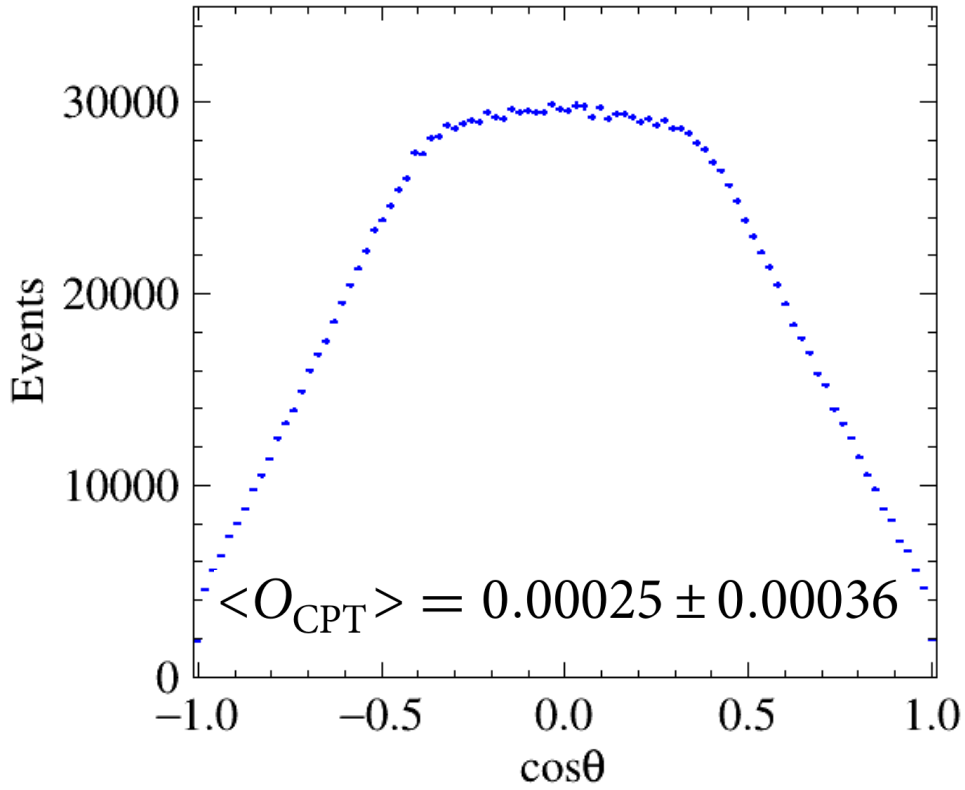
Using 2 x 10^6 of identified o-Ps → 3γ annihilations

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

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

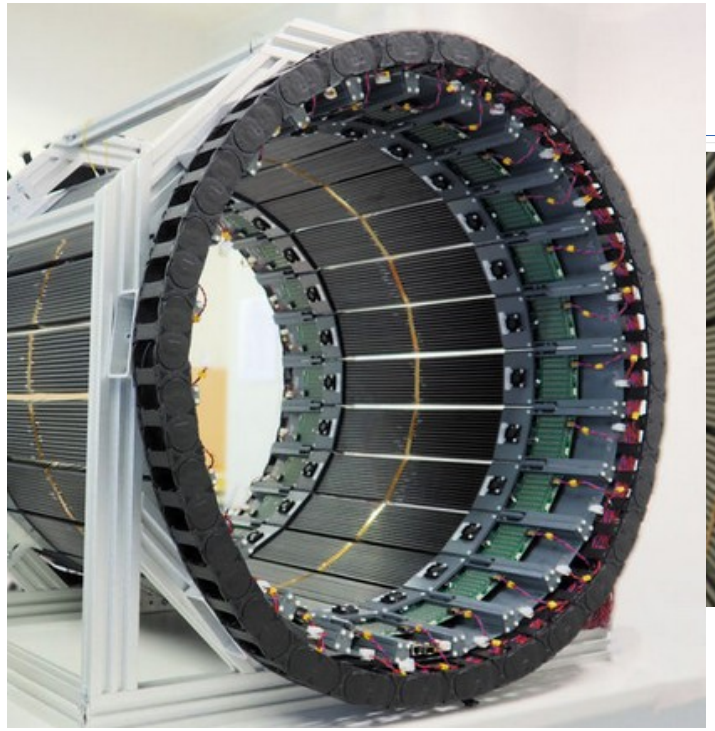


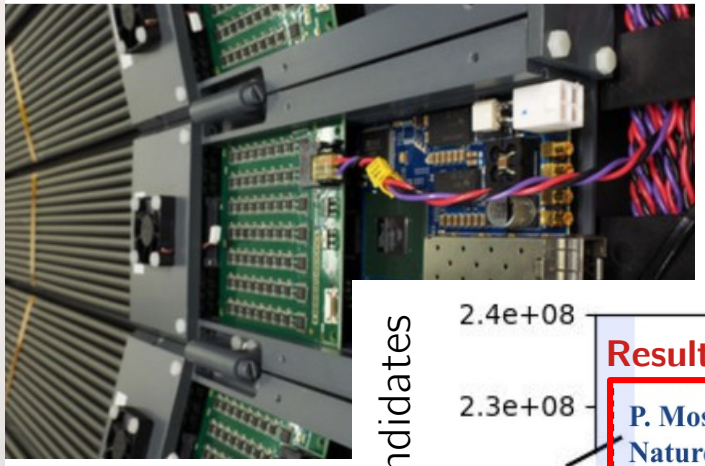
$$C_{CPT} = <O_{CPT}>/P = 0.00067 \pm 0.00095$$

37.4% (polarization-dominated)

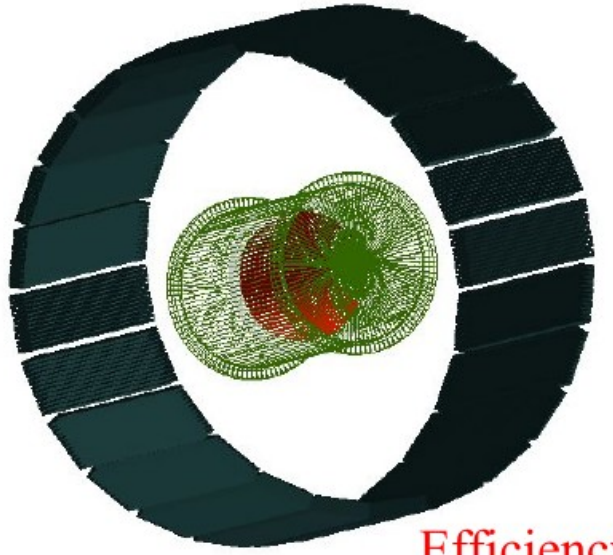
Nature Commun. 12, 5658 (2021)

Towards the sensitivity of 10^{-5}

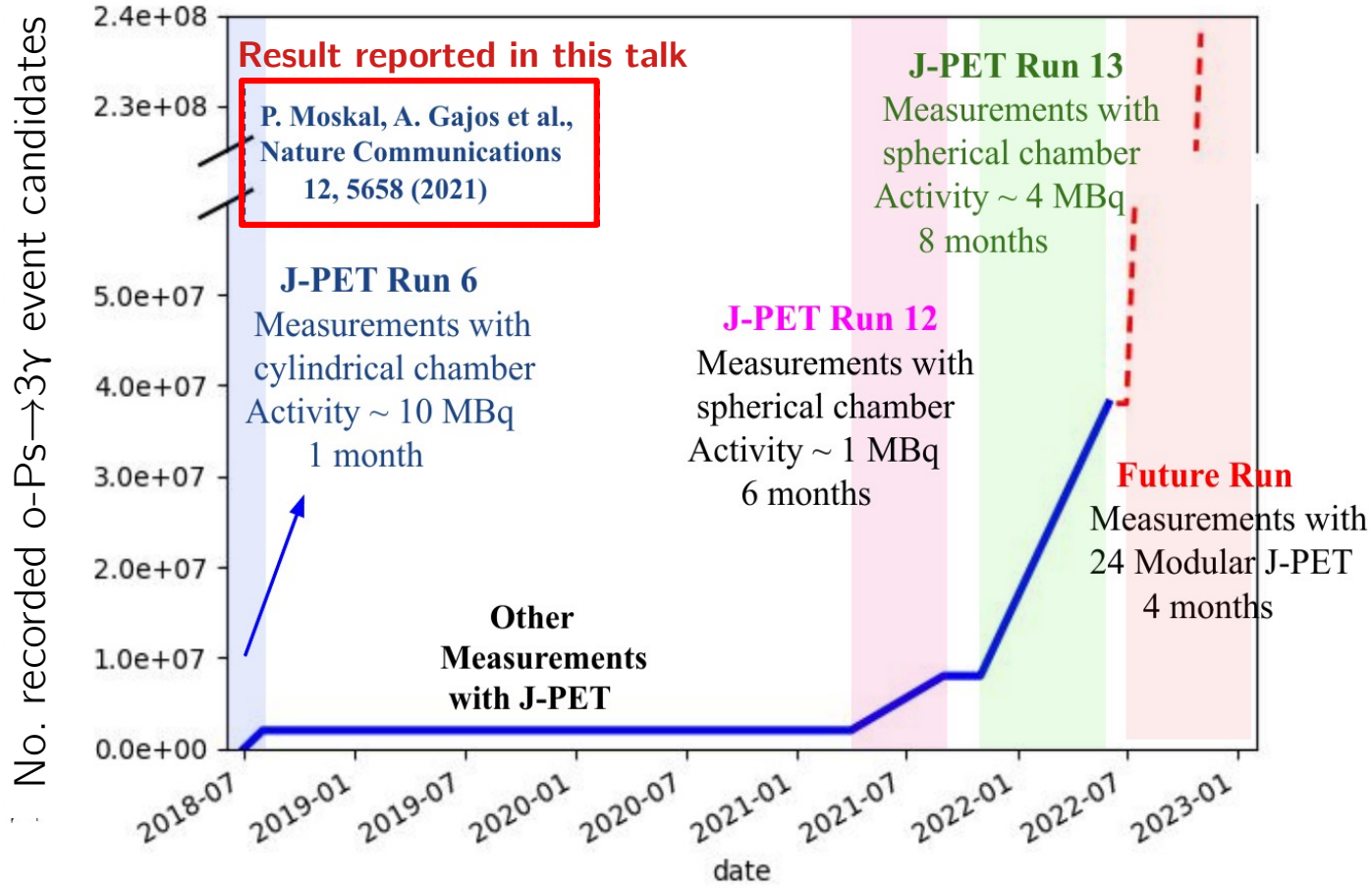




- New J-PET with dense geometry & digital SiPM readout
- Spherical annihilation chamber to enhance e+ utilization



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



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 an improved positronium production and photon detection setup**

Thank you for your attention!

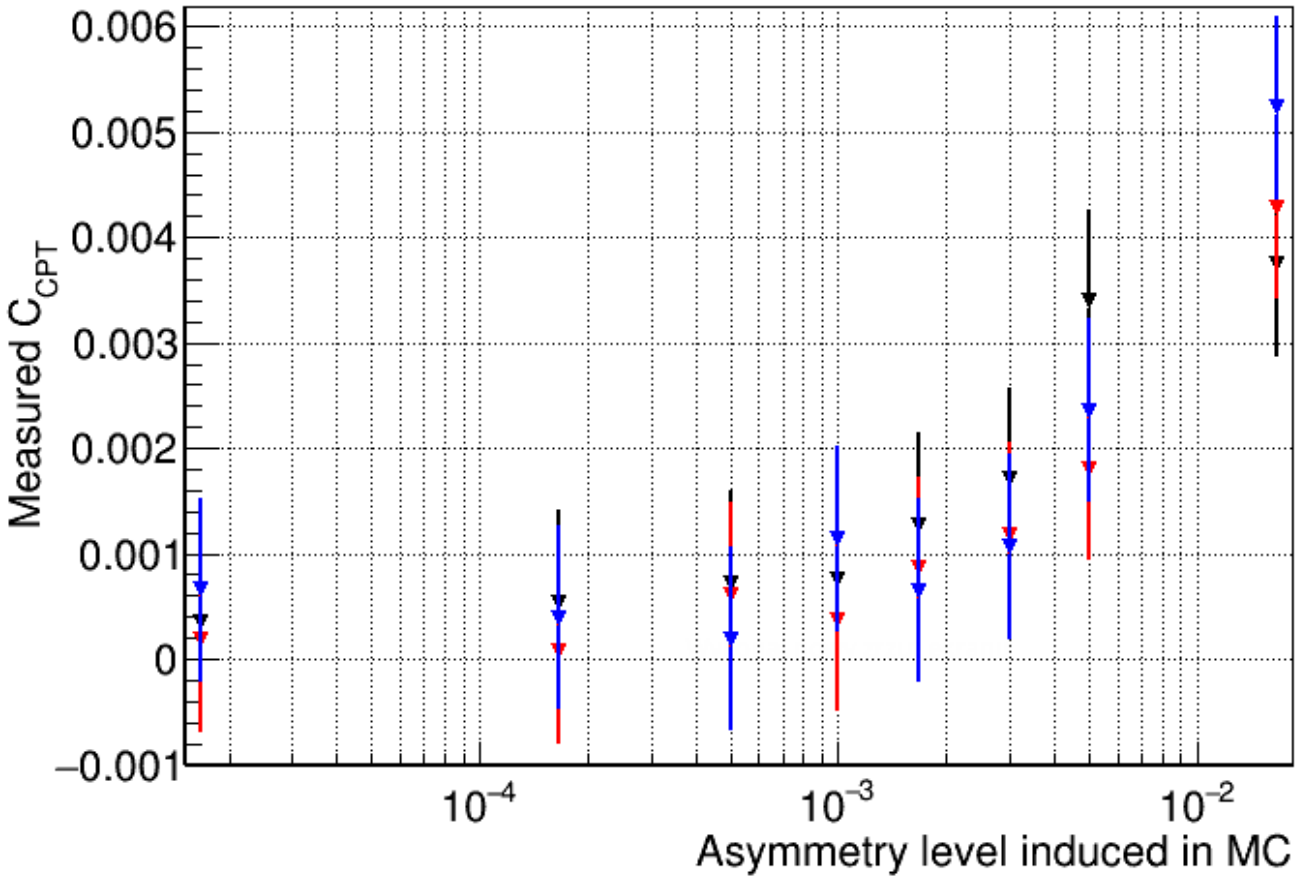
This work is supported in the framework of the TEAM POIR.04.04.00-00-4204/17 Programme of the Foundation for Polish Science

European Funds Smart Growth
Republic of Poland
FNP Foundation for Polish Science
European Union European Regional Development Fund

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})



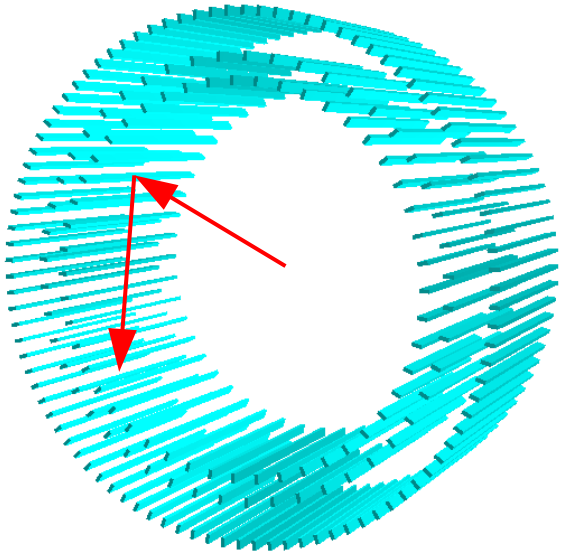
Different colors denote independent simulations

Testing discrete symmetries with ortho-positronium

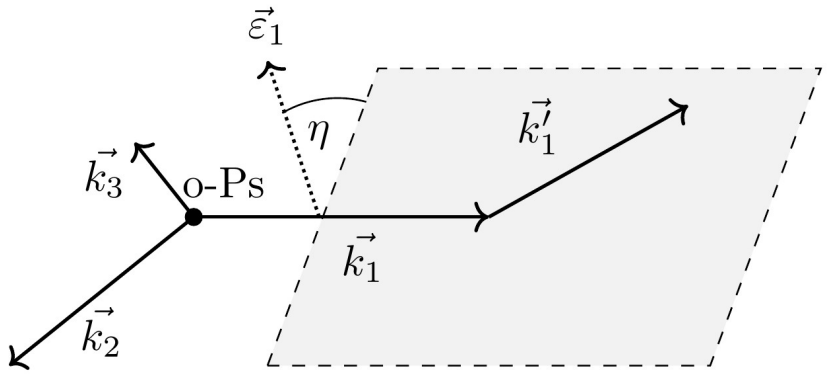
If polarization direction of the photons (ϵ) can be estimated, a new class of operators becomes available for measurement!

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

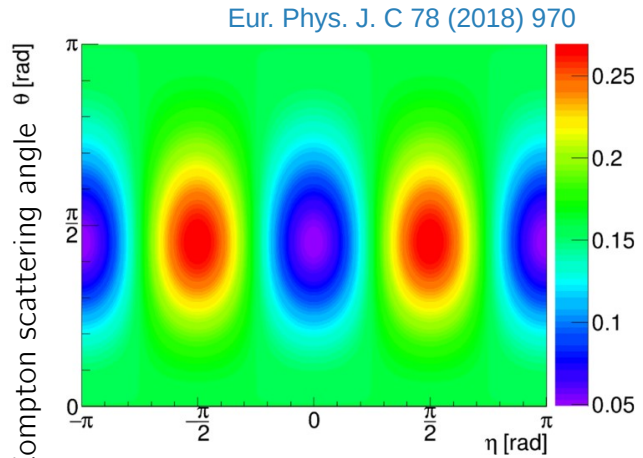
[W. Bernreuther *et al.*, *Z. Phys. C41 (1988) 143*]
[P. Moskal *et al.*, *Acta Phys. Polon. B47 (2016) 509*]



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



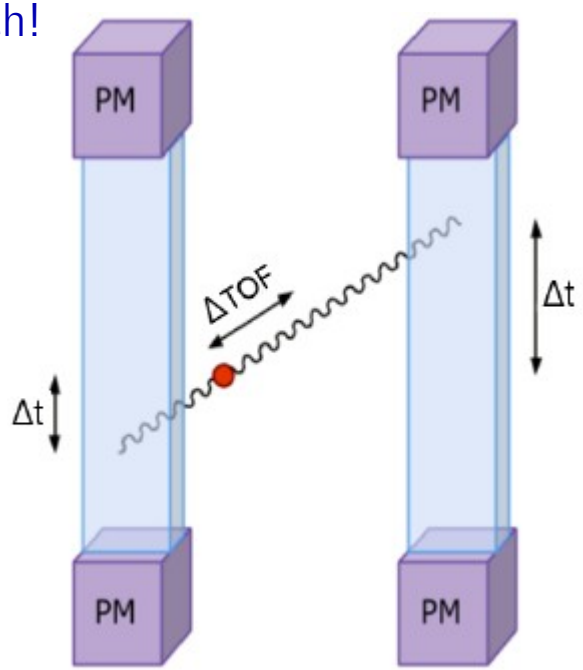
$$|\vec{k}_1| > |\vec{k}_2| > |\vec{k}_3|$$

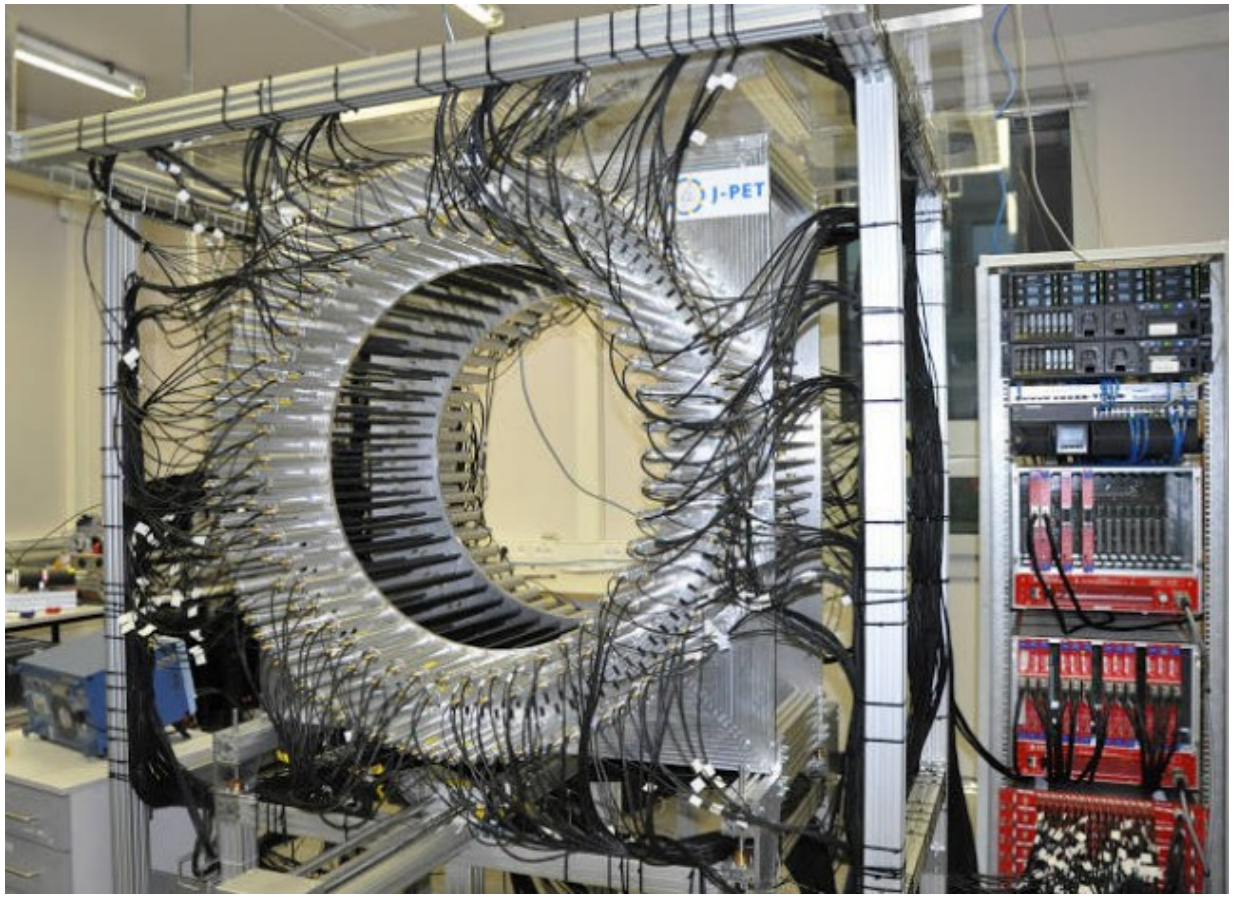


Angle between ϵ and the scattering plane

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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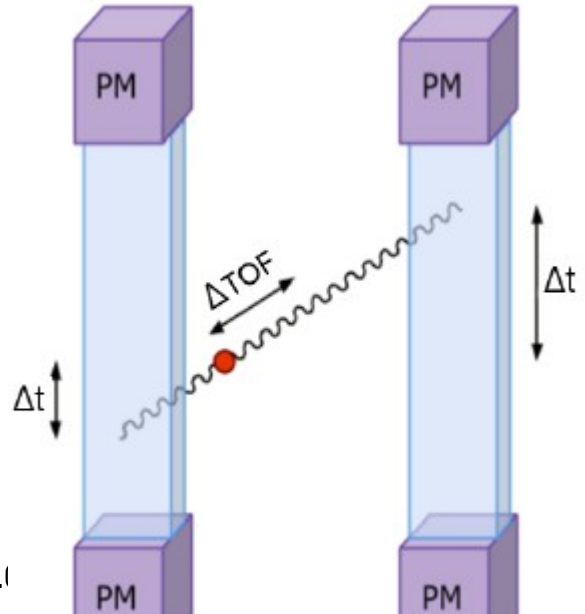
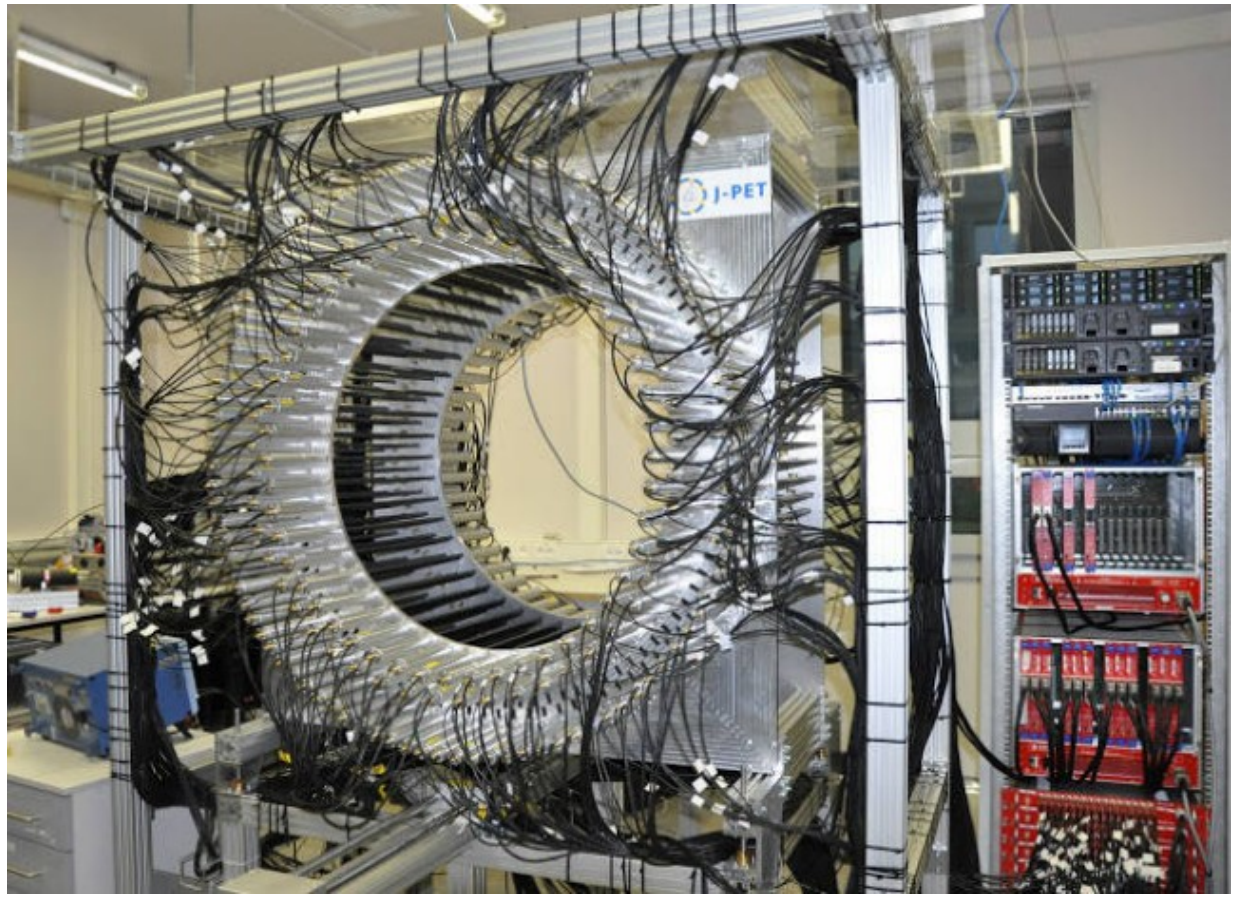
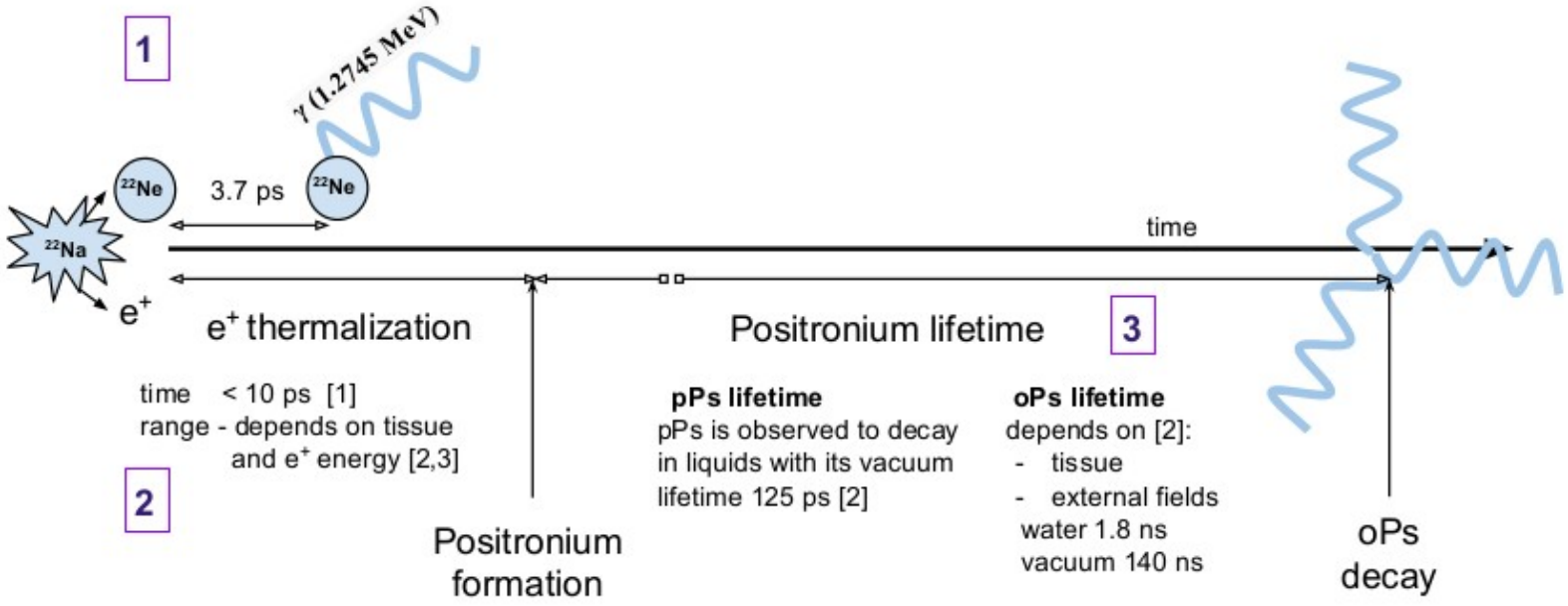




O-Ps creation and decay



[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

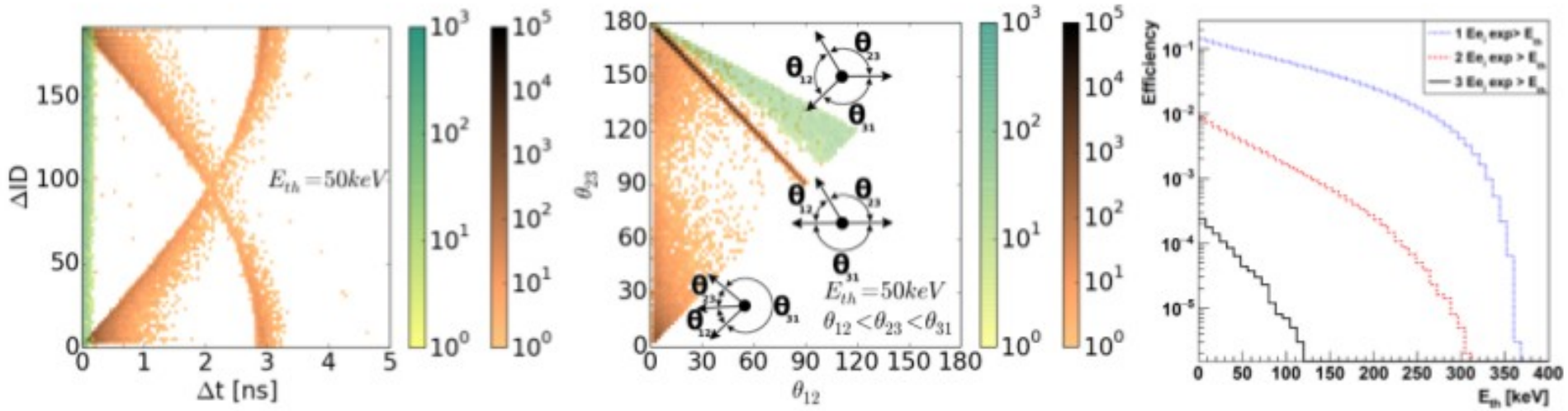
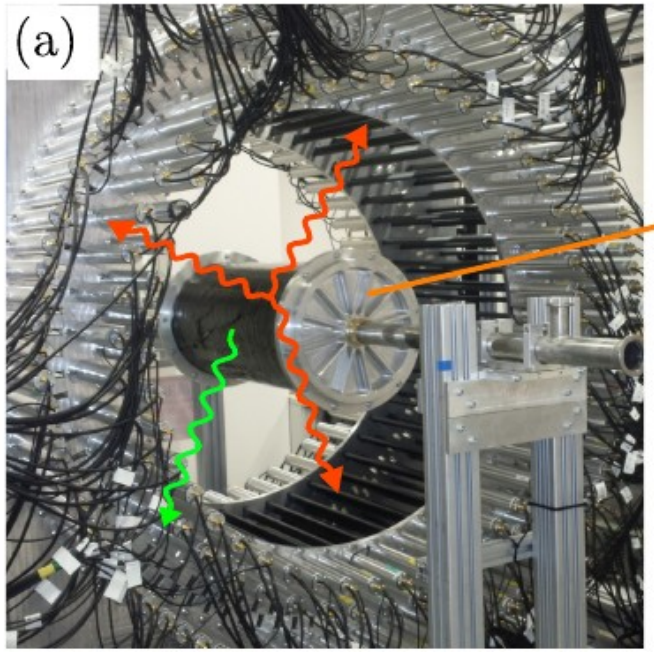


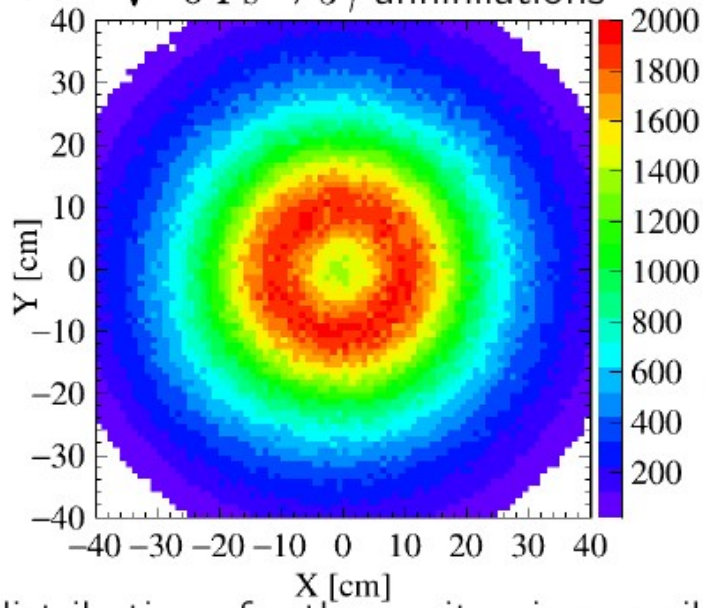
Figure 9. (Left) Simulated distributions of differences between detectors ID (ΔID) and differences of hit-times (Δt) for events with three hits registered from the annihilation e+e- → 2γ (gold colours) and o-Ps → 3γ (green colours). **(Middle)** Disribution of relative angles between reconstructed directions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

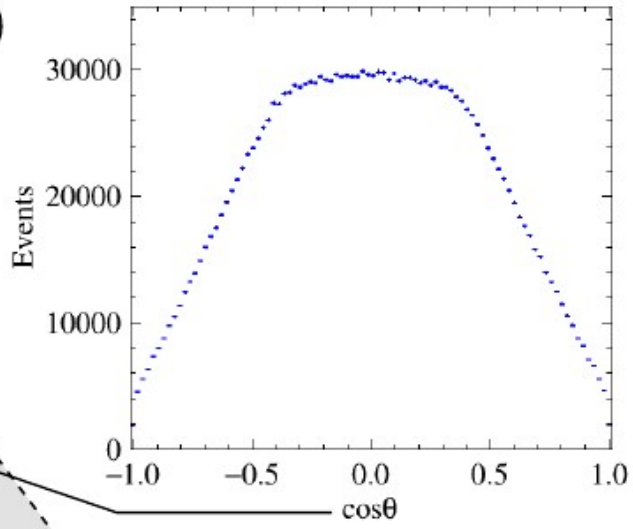
(c) identification of o-Ps $\rightarrow 3\gamma$ annihilations

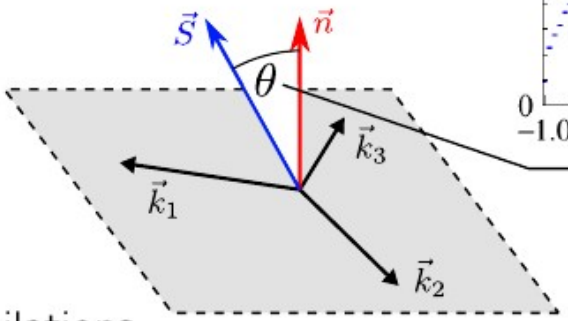


distribution of ortho-positronium annihilations

extraction of CPT-asymmetric angular correlation

(d)

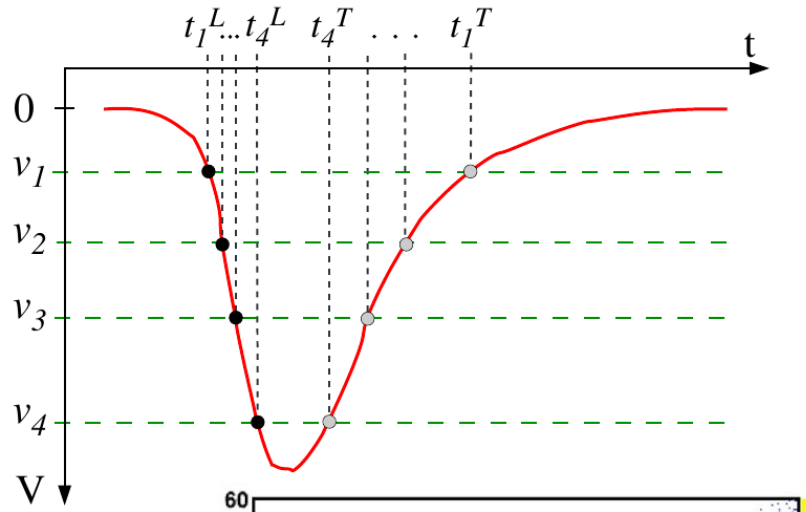


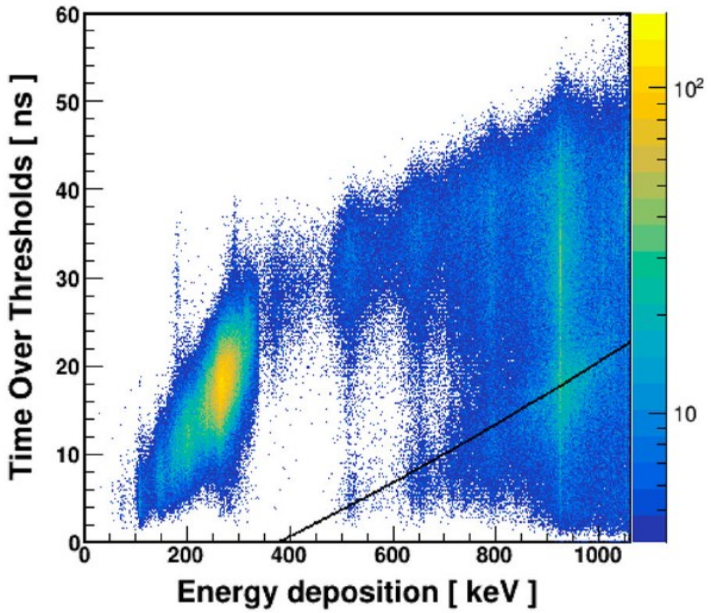


o-Ps spin - decay plane correlation

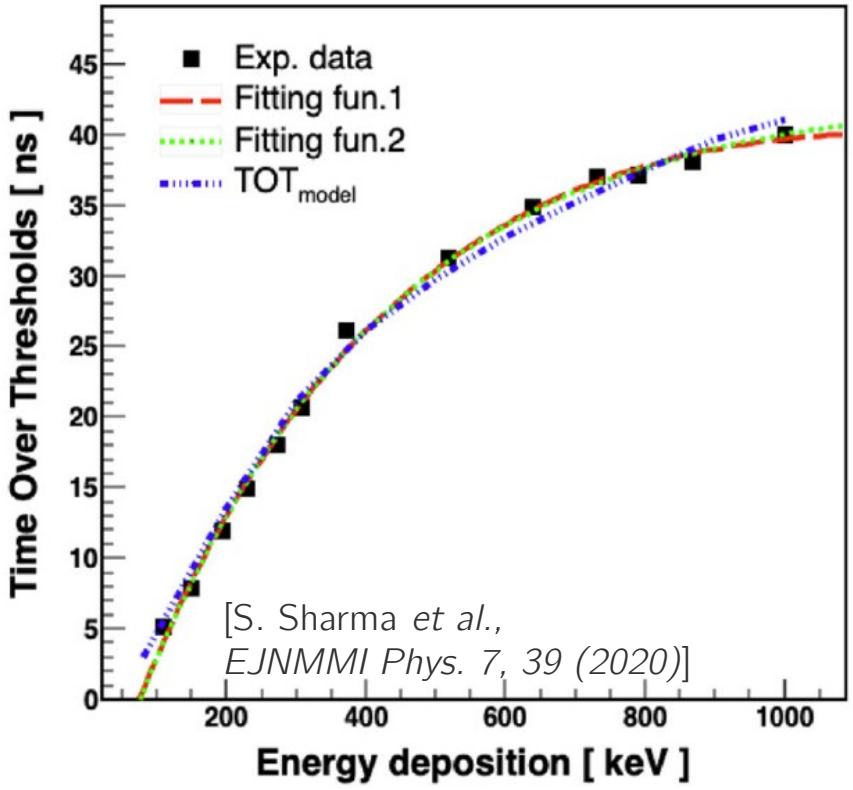
Time-Over-Threshold as a measure of deposited γ energy

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



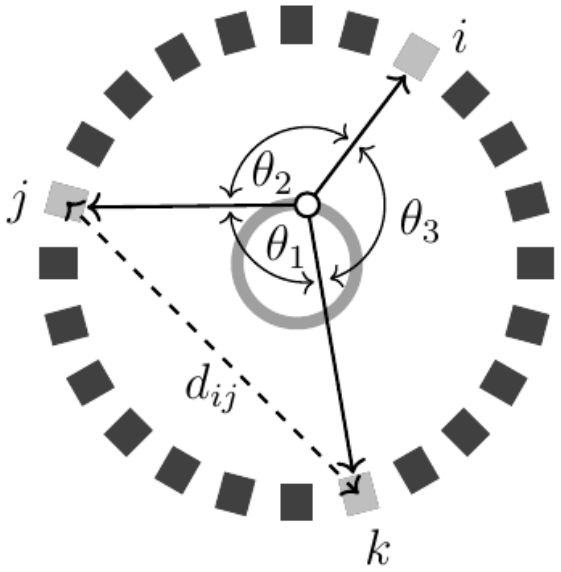


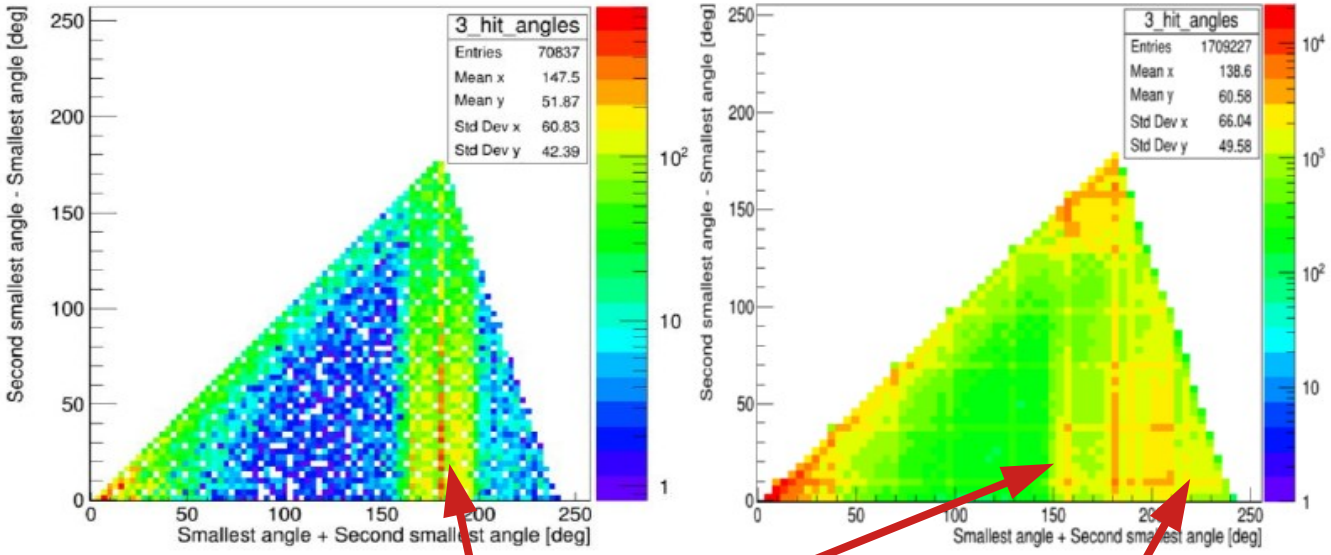
The relation between TOT and energy deposited by a photon in Comton scattering is under an extensive study right now.



Angular topology of the 3γ events

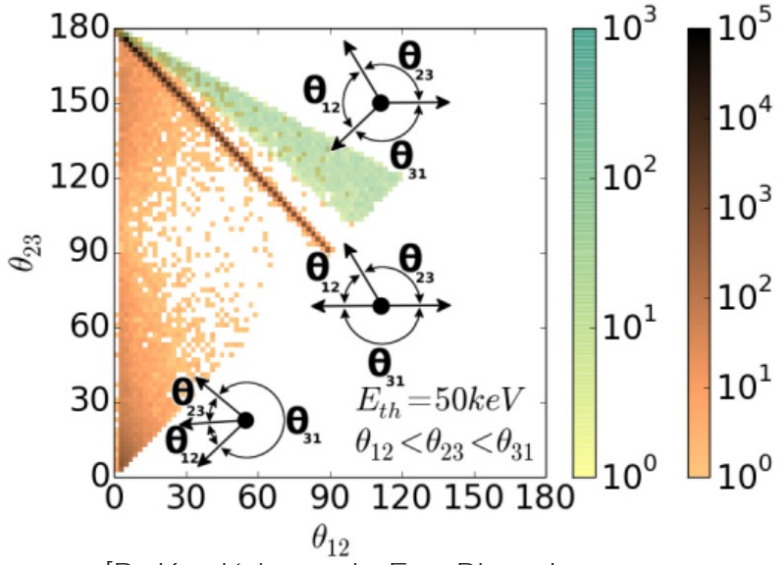
Angles defined in the transverse plane only



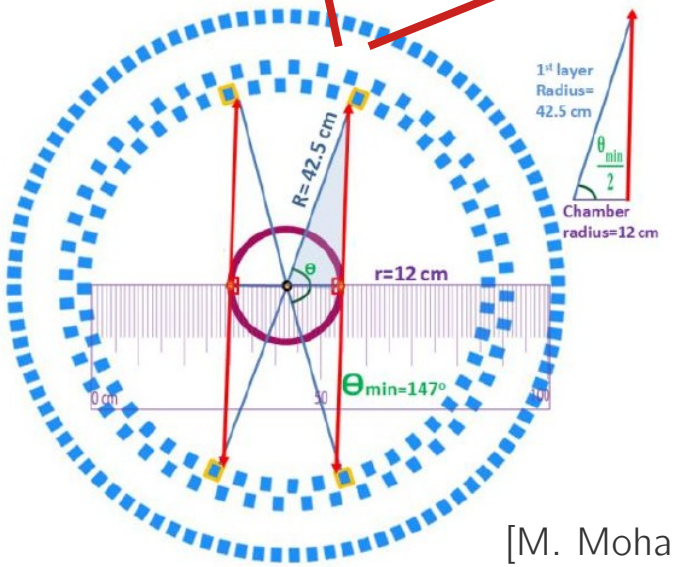


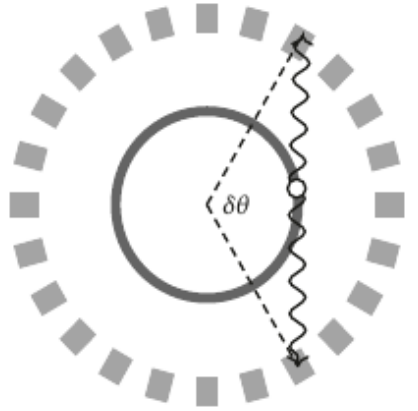
2-photon

o-Ps



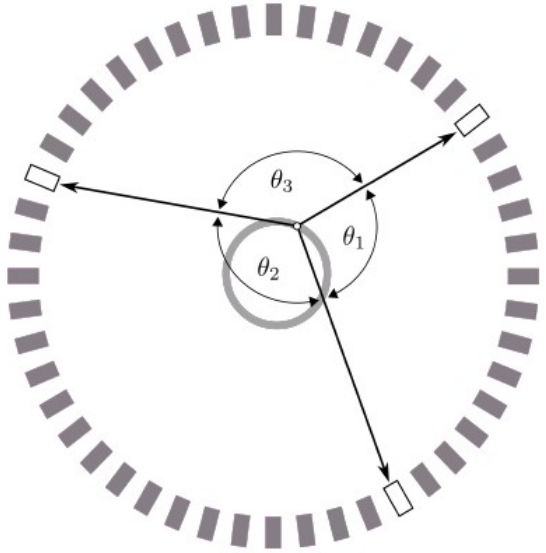
[D. Kamińska et al., Eur. Phys. J. C76 (2016) no.8, 445]



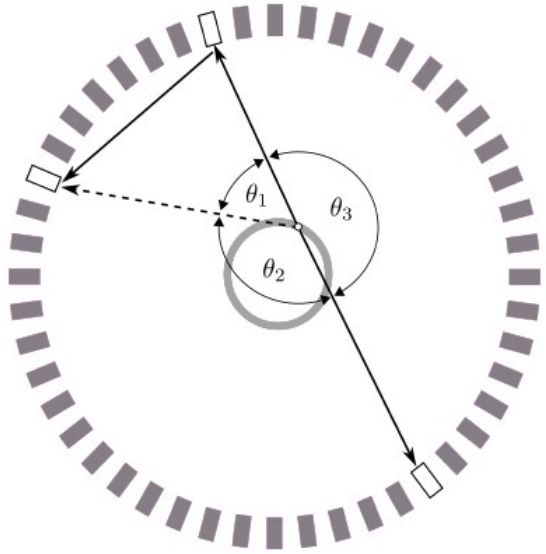


[M. Mohammed, PhD thesis, 2020]

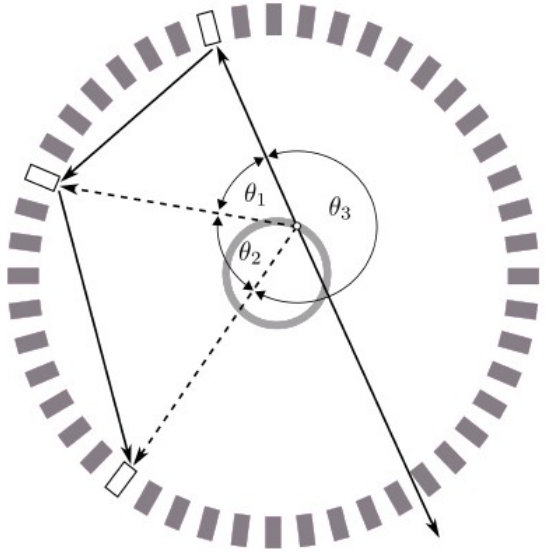
Signal & background events

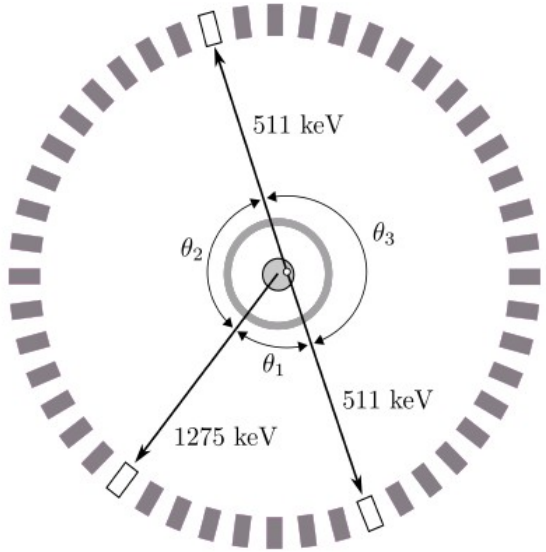


(a) Signal (o-Ps→3γ) event.

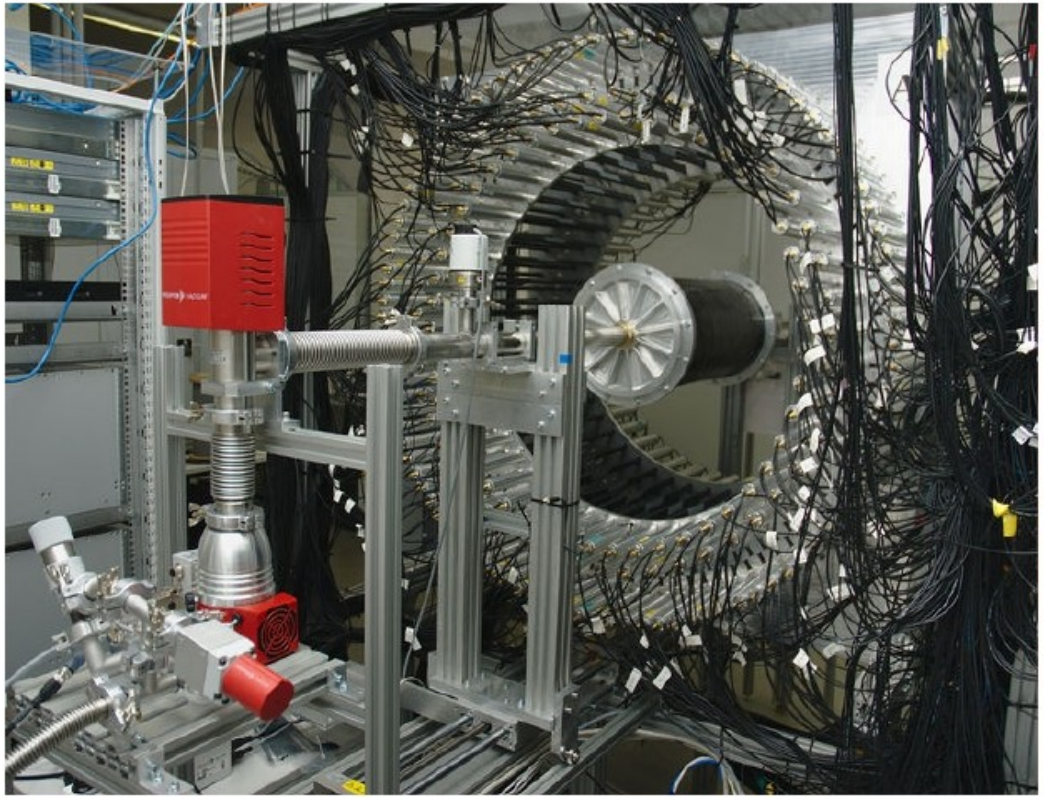


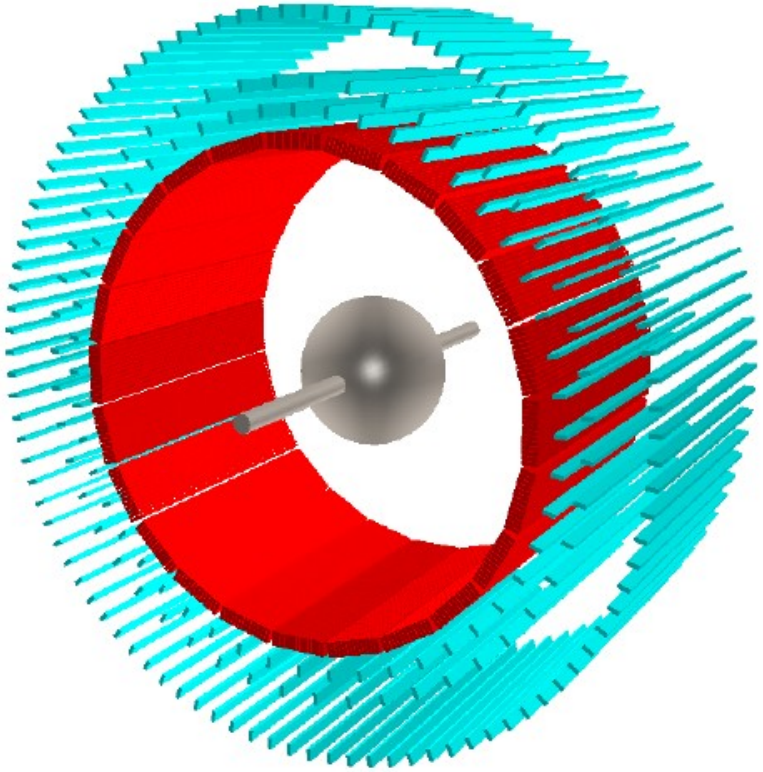
(b) 2γ annihilation with secondary Compton scattering.



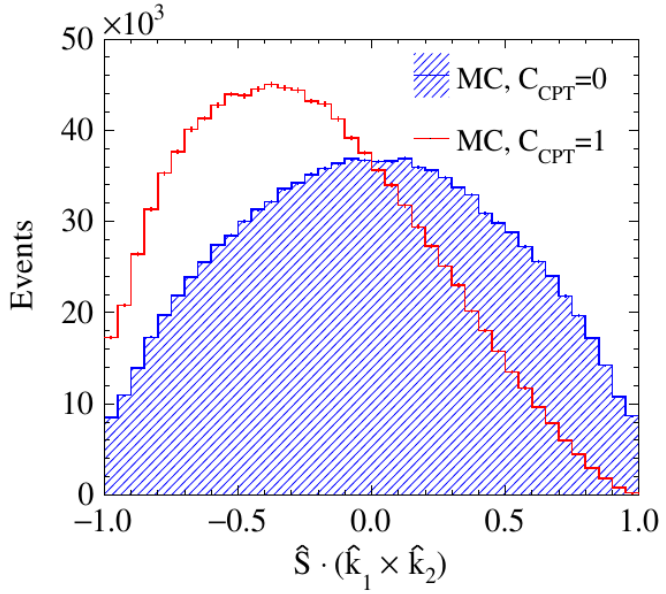


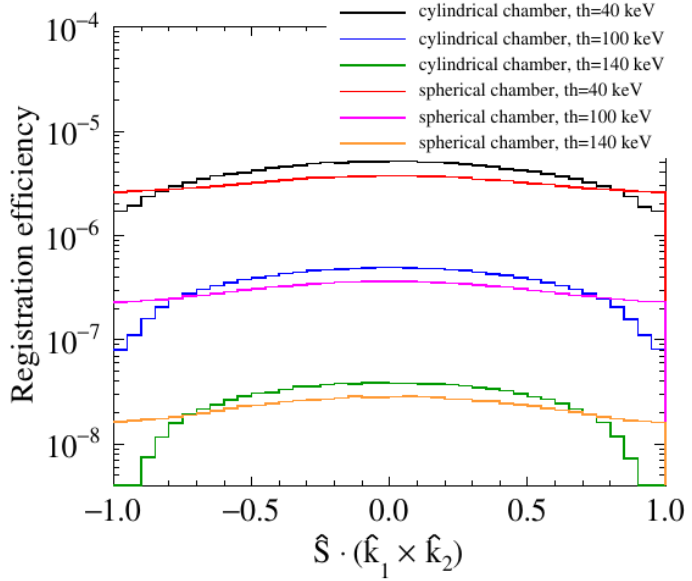
Detector improvements

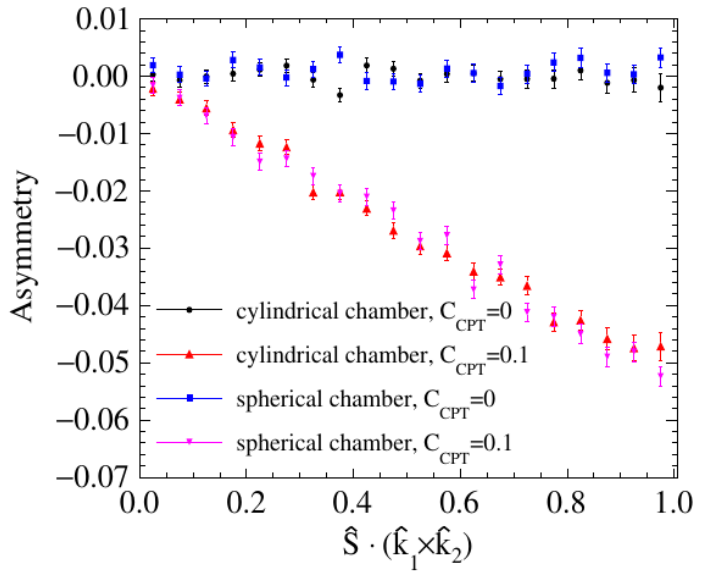




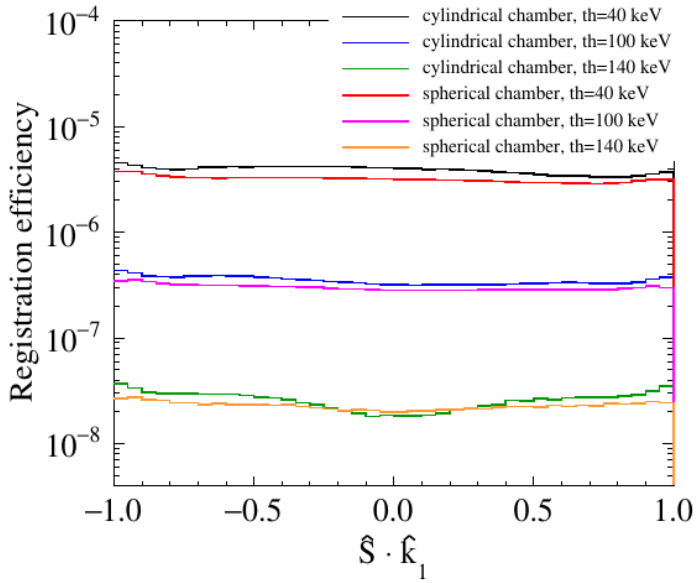
Expected sensitivity

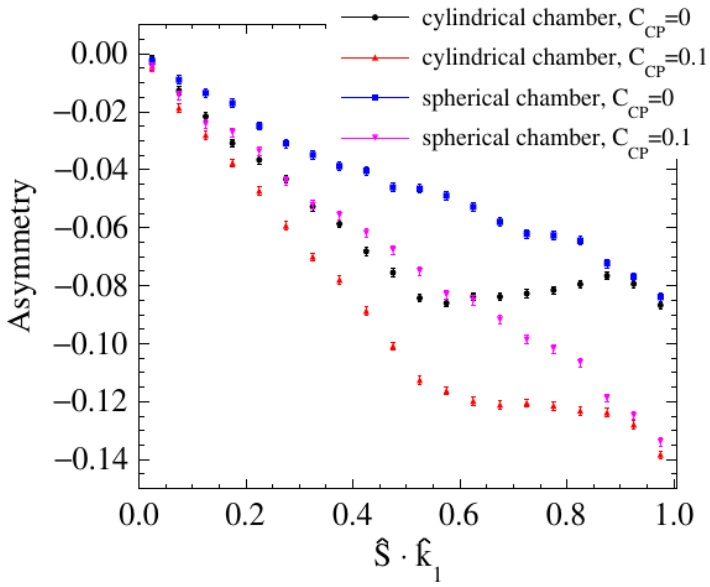






No.	Operator	C	P	T	CP	CPT
1	$\vec{S}\cdot\vec{k_1}$	+	−	+	−	−
2	$\vec{S}\cdot(\vec{k_1}\times\vec{k_2})$	+	+	−	+	−
3	$(\vec{S}\cdot\vec{k_1})(\vec{S}\cdot(\vec{k_1}\times\vec{k_2}))$	+	−	−	−	+





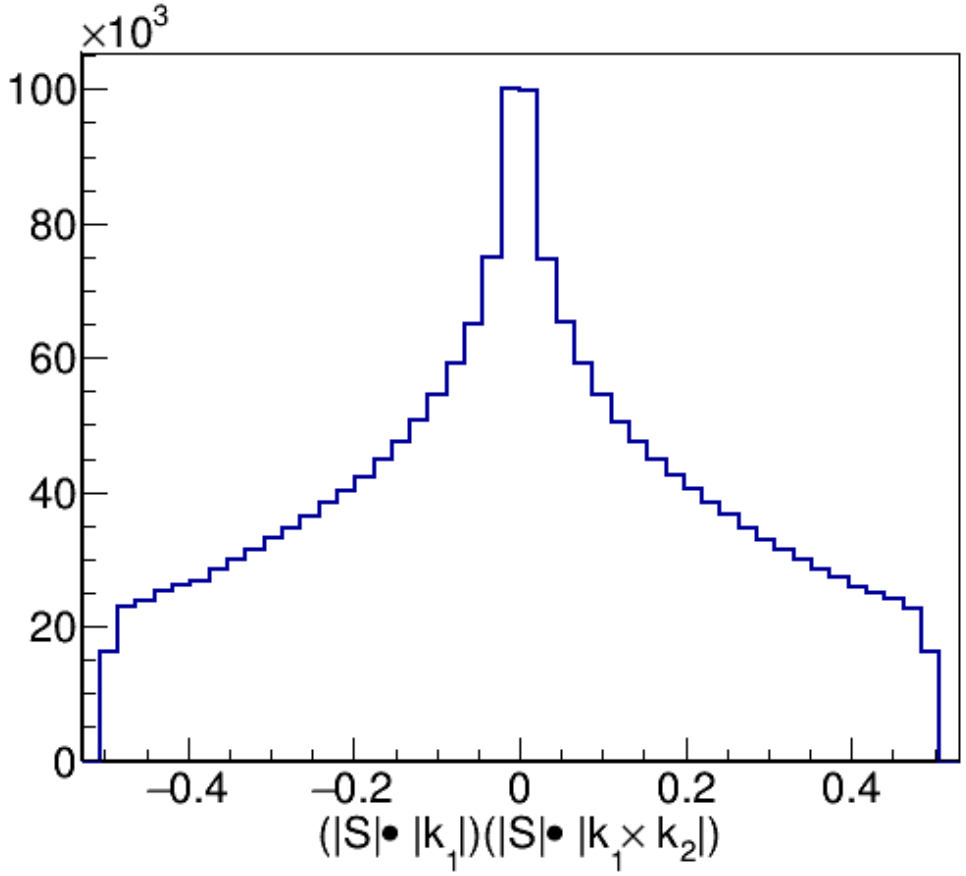
[*Symmetry* 12 (2020) 8, 1268]

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

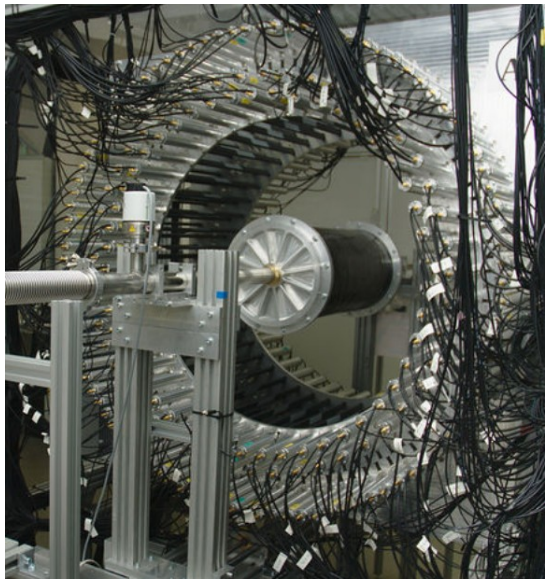
$\vec{S} \cdot \vec{k_1}$ CP-violation sensitive

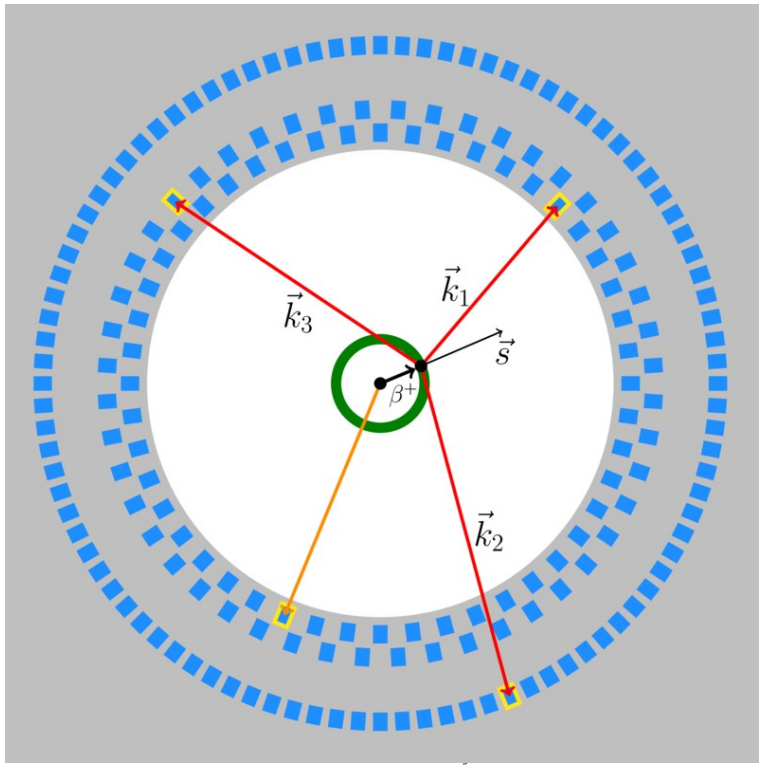
$(\vec{S} \cdot \vec{k_1})(\vec{S} \cdot (\vec{k_1} \times \vec{k_2}))$

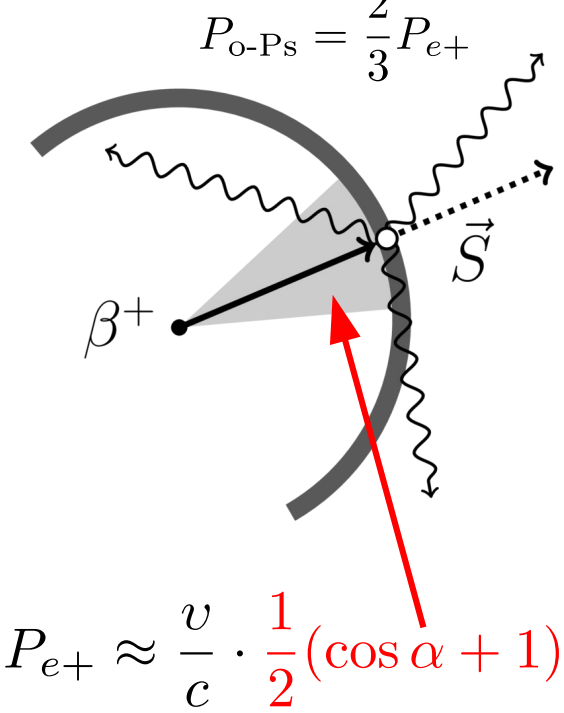
T & CP-violation sensitive but requires o-Ps tensor polarization $\rightarrow$ not available with the current J-PET approach

Event-by-event spin estimation

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







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

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