TWENTIETH LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS

August, 19-25, 2021

MOSCOW STATE UNIVERSITY

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

August 22nd 2021

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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 $\rightarrow 3\gamma$ 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?

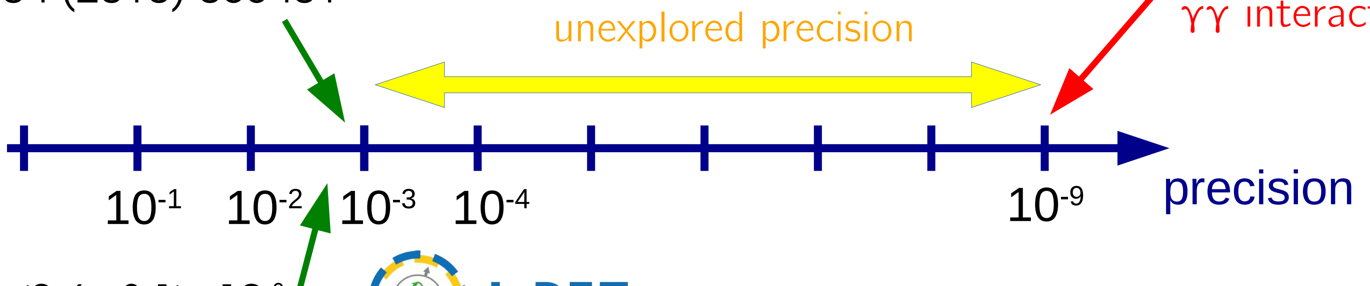
- Searches for **prohibited positronium annihilations**
- Certain SME-based searches for CPT violation were proposed with **positronium spectroscopy** [Phys. Rev. D92 (2015) 056002]

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

$C_{CP} = (1.3 \pm 2.1 \pm 0.6)\times10^{-3}$
PRL 104 (2010) 083401

6 OOM of
unexplored precision

Physical sensitivity limit:
false asymmetries from
$\gamma\gamma$ interactions in the final state

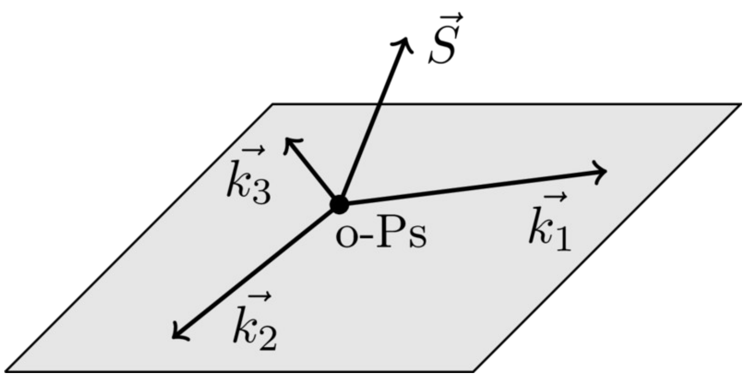


$C_{CPT} = (2.6 \pm 3.1)\times10^{-3}$
PRL. 91 (2003) 263401

J-PET

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

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

Using photon polarization

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

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

o-Ps → 3γ operators involving spin

Presently studied with J-PET:

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

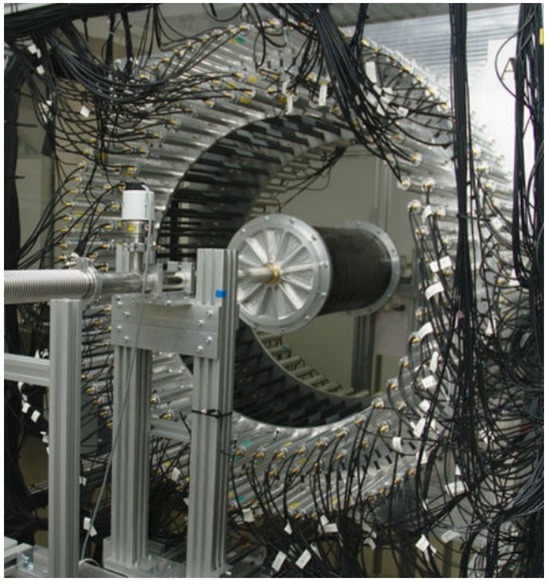
$\vec{S} \cdot \vec{k_1}$ CP-violation sensitive

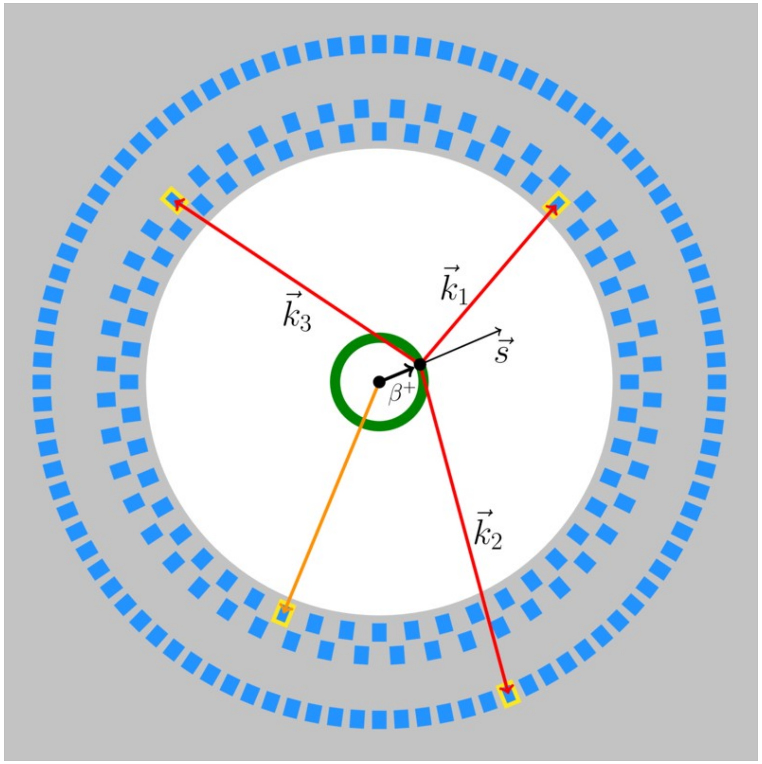
$(\vec{S} \cdot \vec{k_1})(\vec{S} \cdot (\vec{k_1} \times \vec{k_2}))$

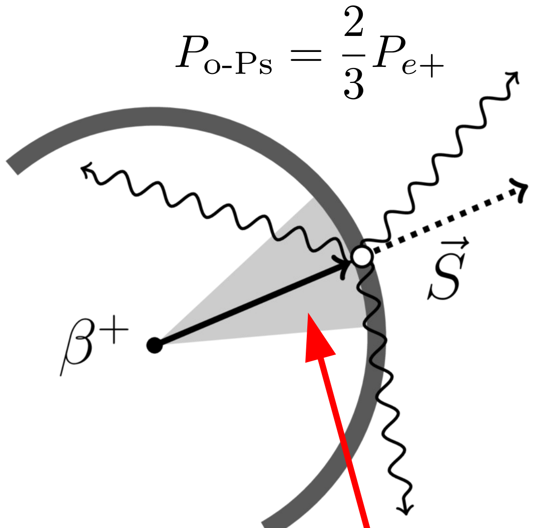
T & CP-violation sensitive but requires o-Ps tensor polarization → not available with the current J-PET approach

Event-by-event spin estimation

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



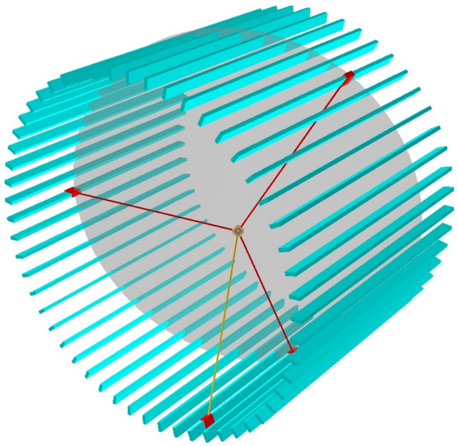




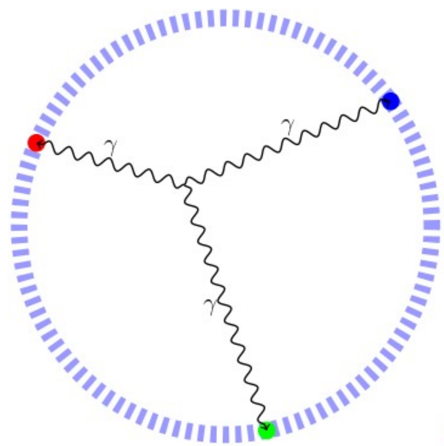
$$P_{e+} \approx \frac{v}{c} \cdot \frac{1}{2}(\cos\alpha + 1)$$

Effective polarization depends on o-Ps→3γ vertex resolution

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

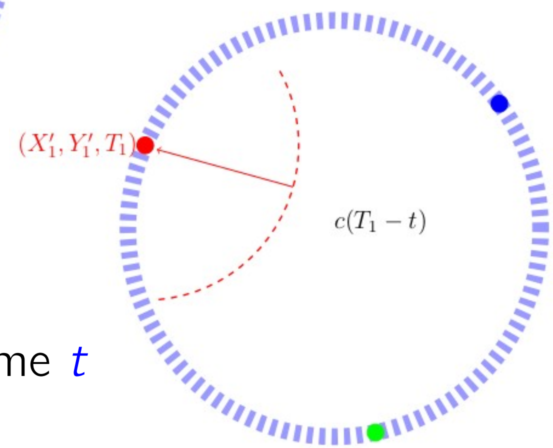


1. Find the decay plane containing the 3 hits in the J-PET barrel

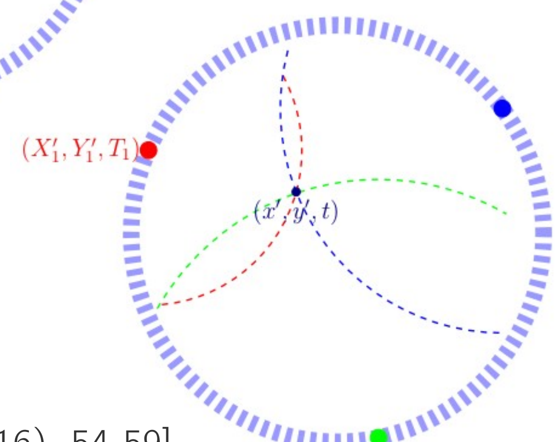


2. Transform the hit coordinates to a 2D coordinate system in the decay plane

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



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:

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

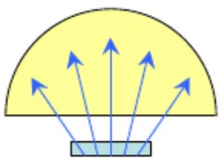
[A. Gajos et al., NIM A 819 (2016), 54-59]

J-PET vs previous measurements

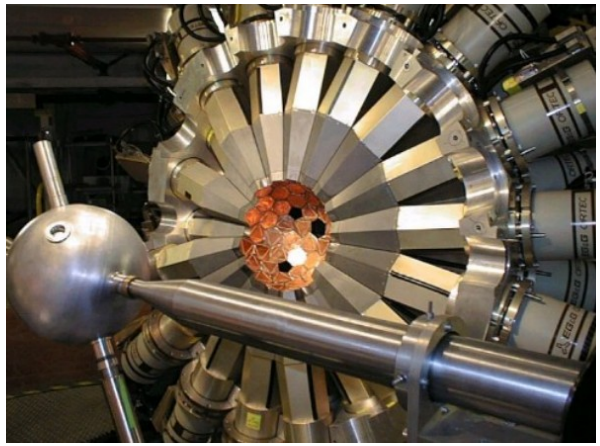
Gammasphere
PRL. 91 (2003) 263401

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

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



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

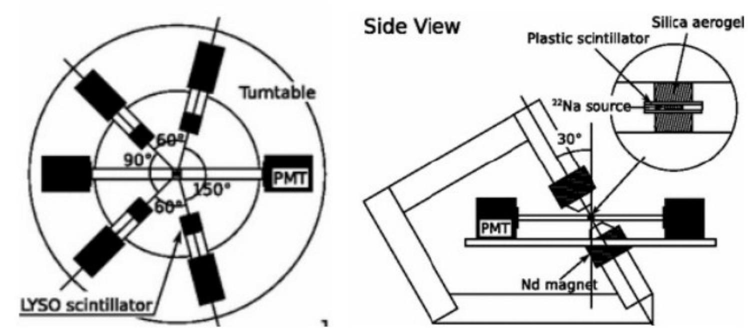


Limiting positron emission direction
1 Mbq β^{+} emitter activity
4π detector but low angular resolution

Yamazaki et al.
PRL 104 (2010) 083401

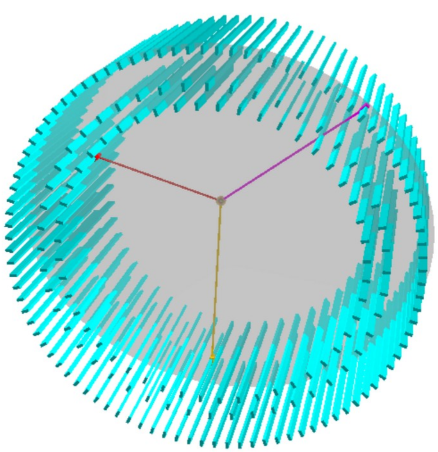
$$(\vec{S} \cdot \vec{k_1})(\vec{S} \cdot (\vec{k_1} \times \vec{k_2}))$$

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



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

J-PET



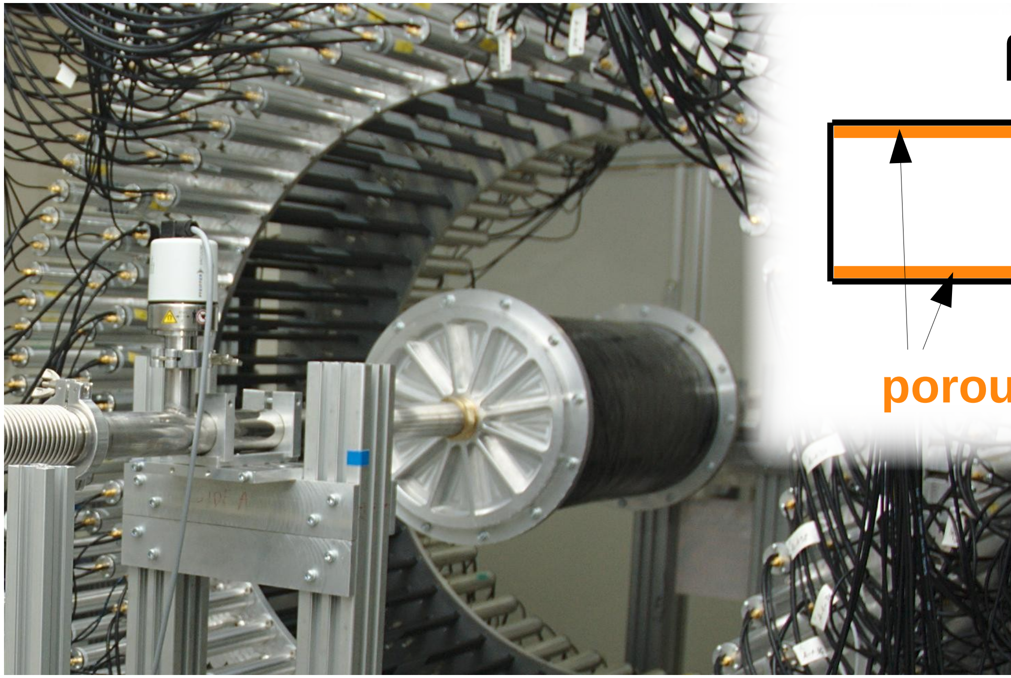
Recording multiple geometrical configurations

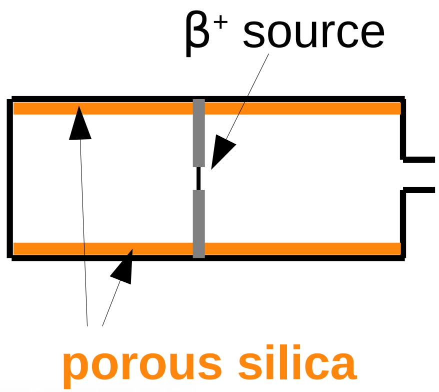
e+ spin estimated event-by-event

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

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

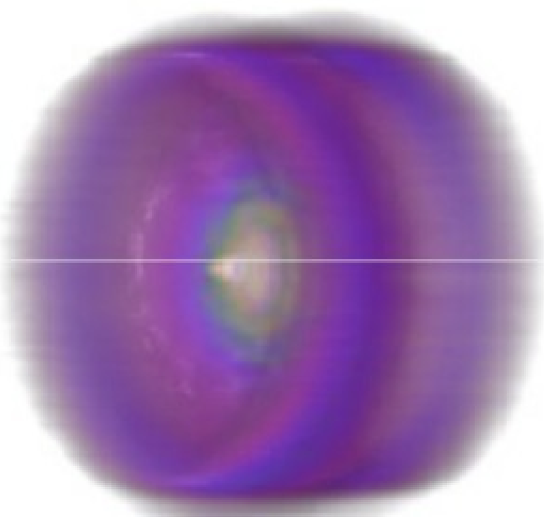
o-Ps production in J-PET with an extensive size annihilation chamber

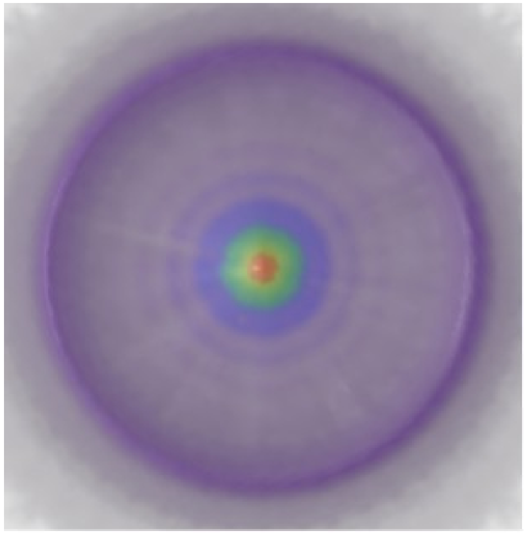




Tomographic images of the chamber obtained using $\gamma\gamma$ annihilations:

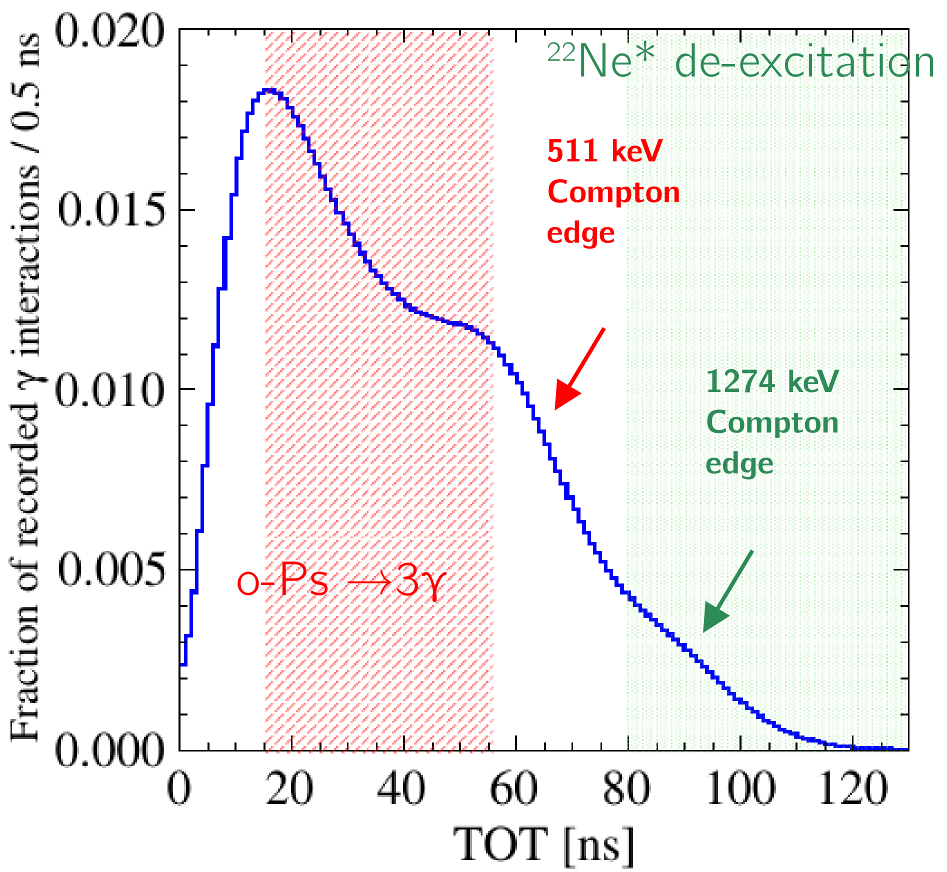
- Extensive-size chamber, R=12 cm
- Walls coated with porous silica material enhancing o-Ps formation
- 10 MBq β^{+} emitter (^{22}Na) placed in the center of the chamber

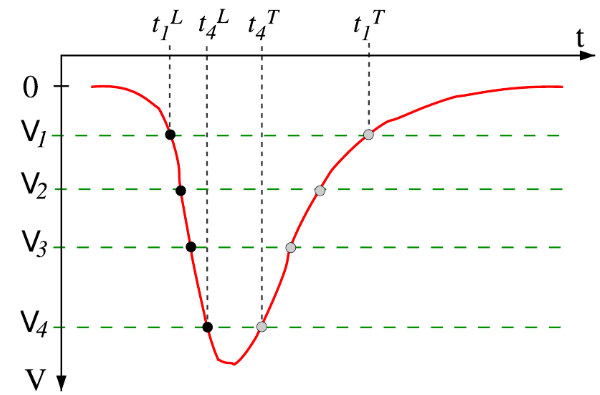




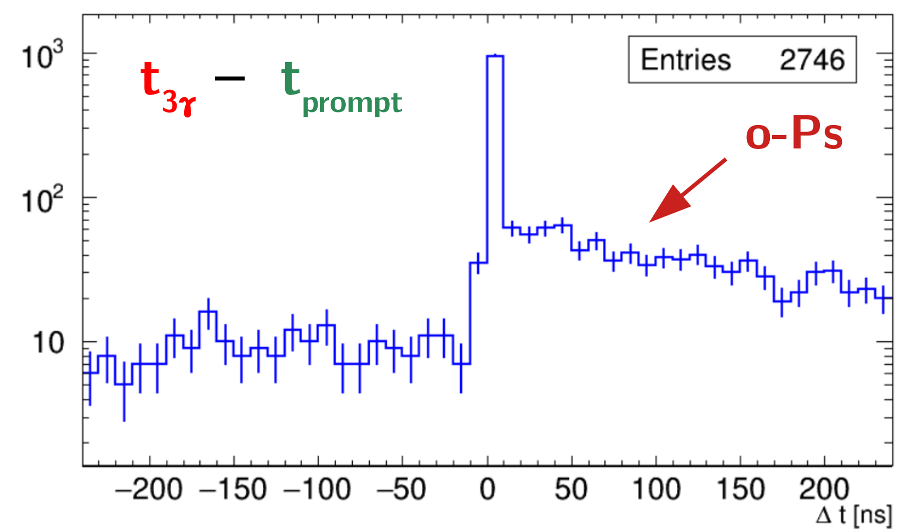
Identification of o-Ps → 3γ events in J-PET

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





Confirming o-Ps presence with positron lifetime distribution

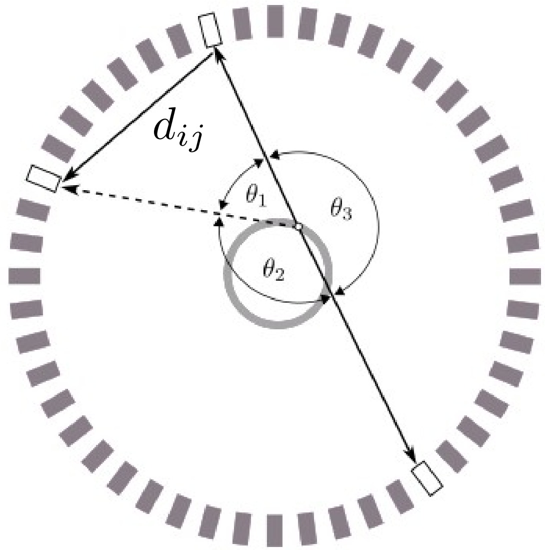


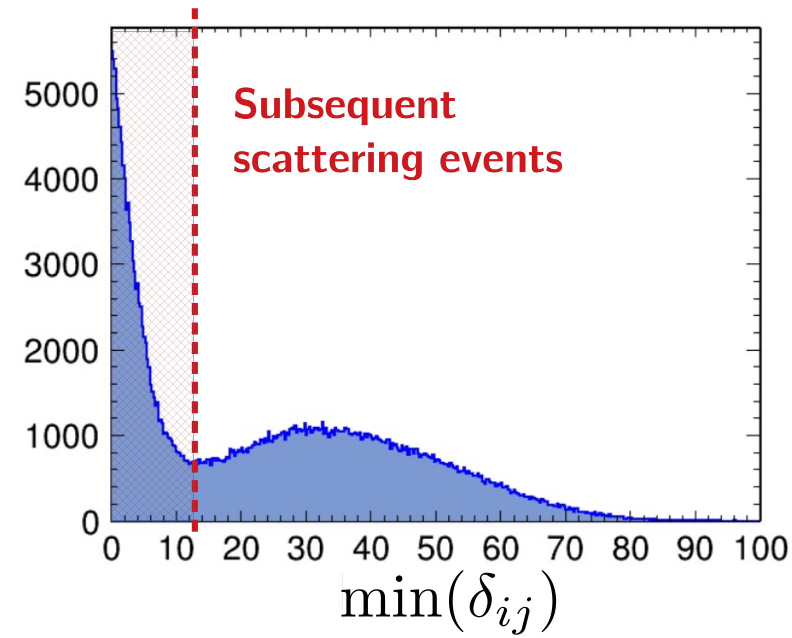
Treatment of main background sources

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:

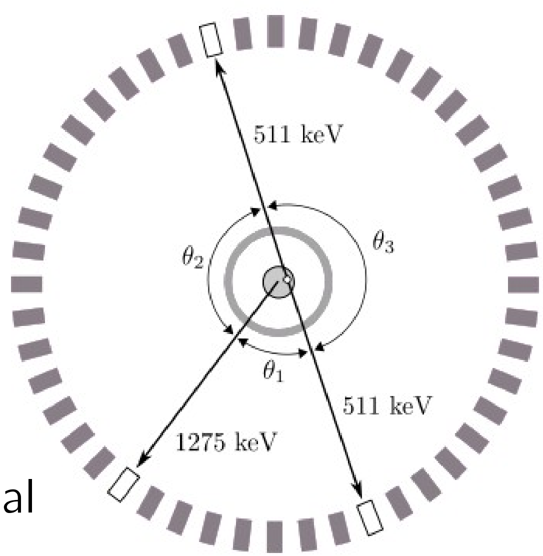
$$\delta t_{ij} = |d_{ij} - c\Delta t_{ij}|$$

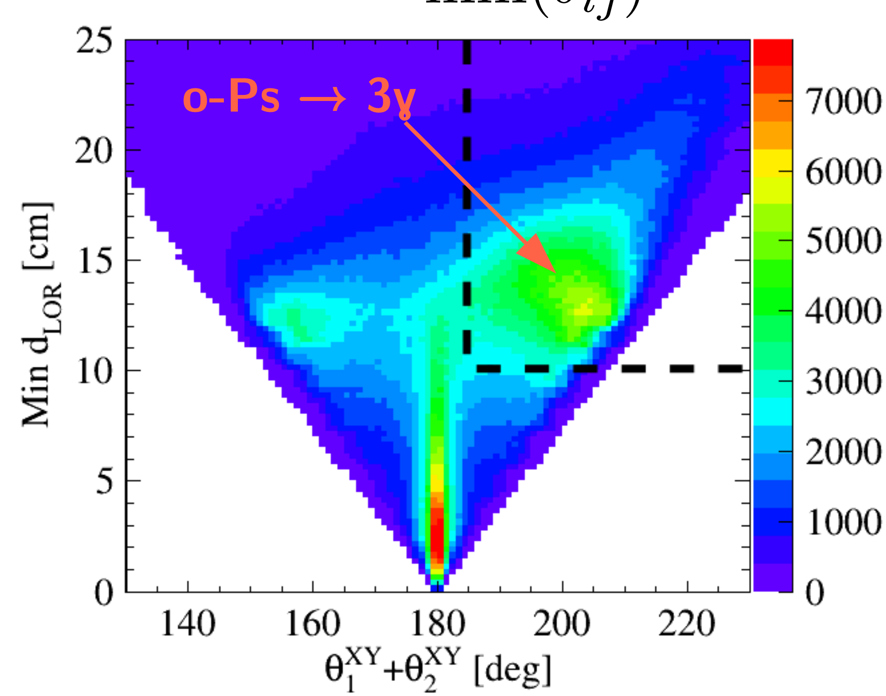




2γ from the β+ source setup

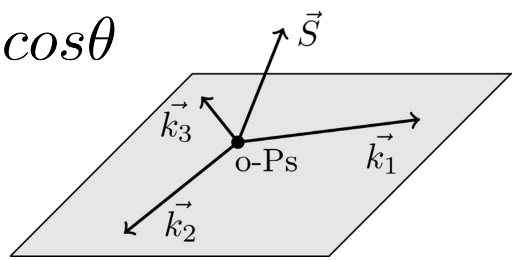
- Using angular topology of the event in XY detector plane
- Considering all hypothetical back-to-back 2γ pairs (tomographic "Lines Of Response")





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:

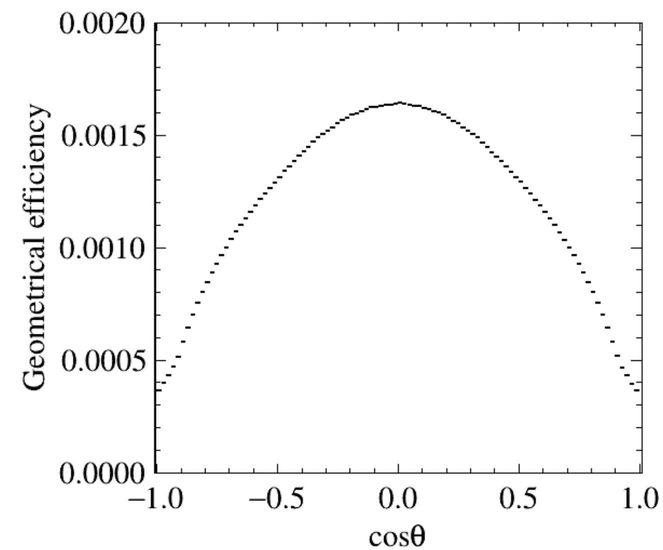
$$A = \frac{N_+ - N_-}{N_+ + N_-} \quad N_+ \Leftrightarrow cos\theta > 0$$

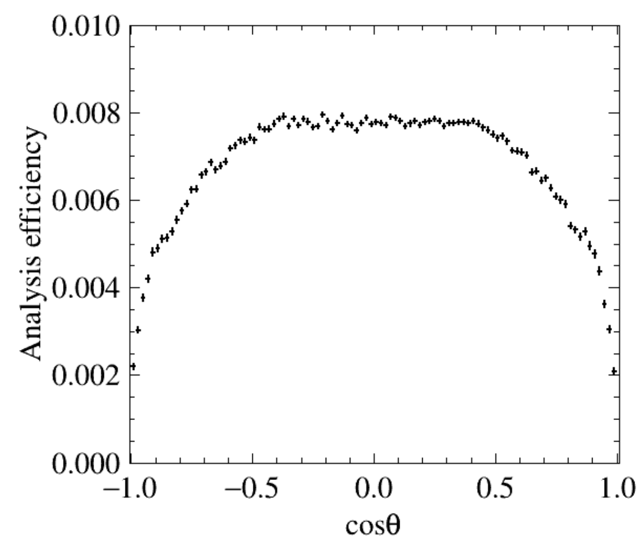
is generalized by the **mean value of cosθ**:

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

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

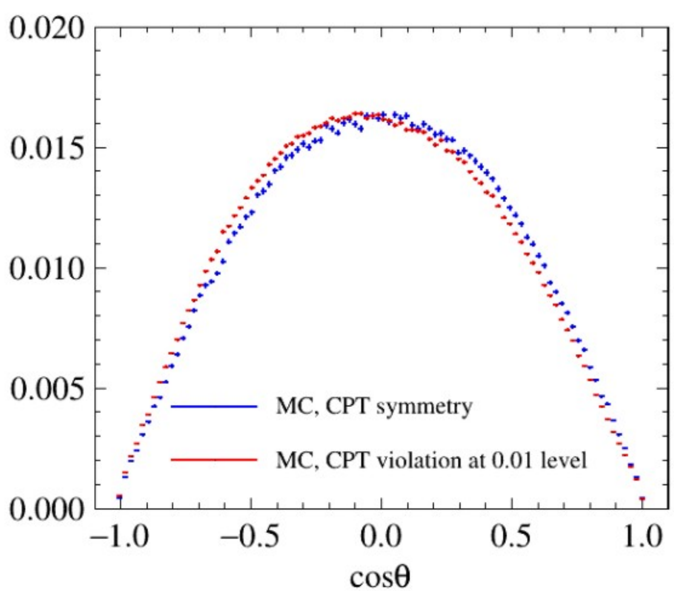
Efficiencies evaluated with MC are **symmetric in cosθ**





Expected effect with CPT-asymmetric Simulations (exaggerated violation)

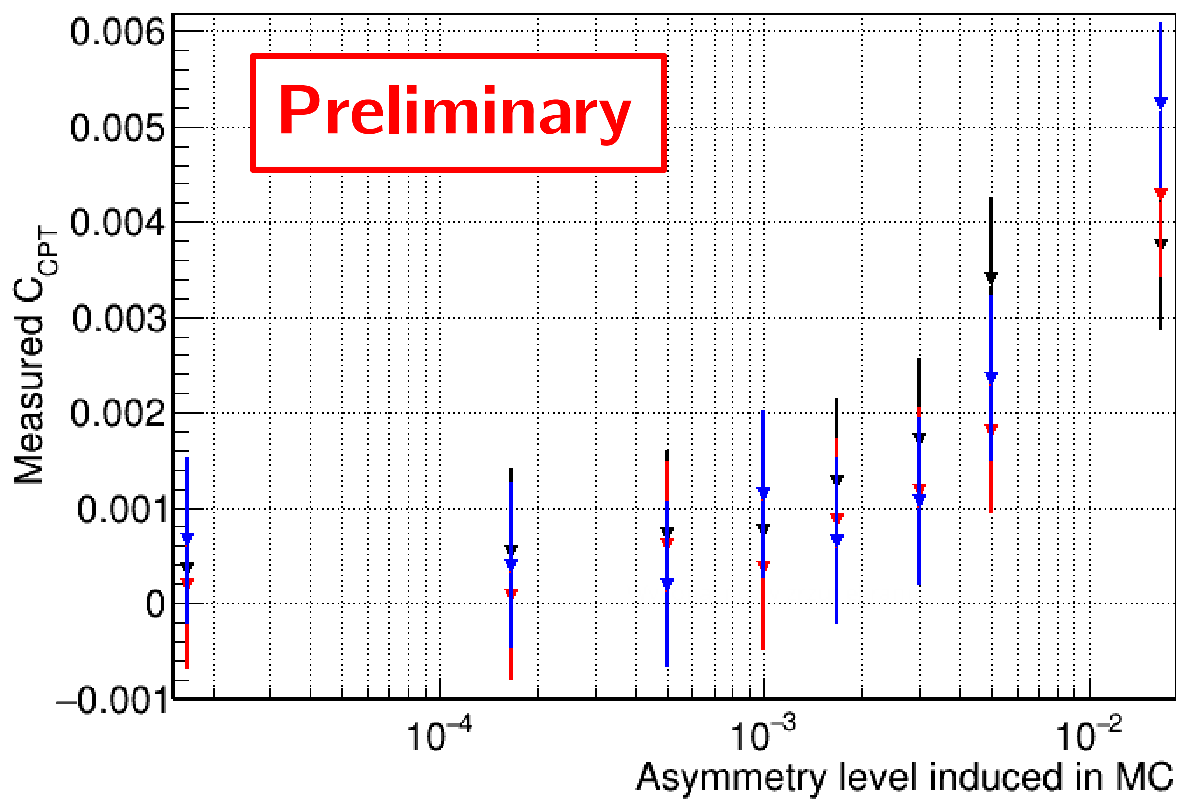
[see also *Symmetry* 12 (2020) 8, 1268]



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})

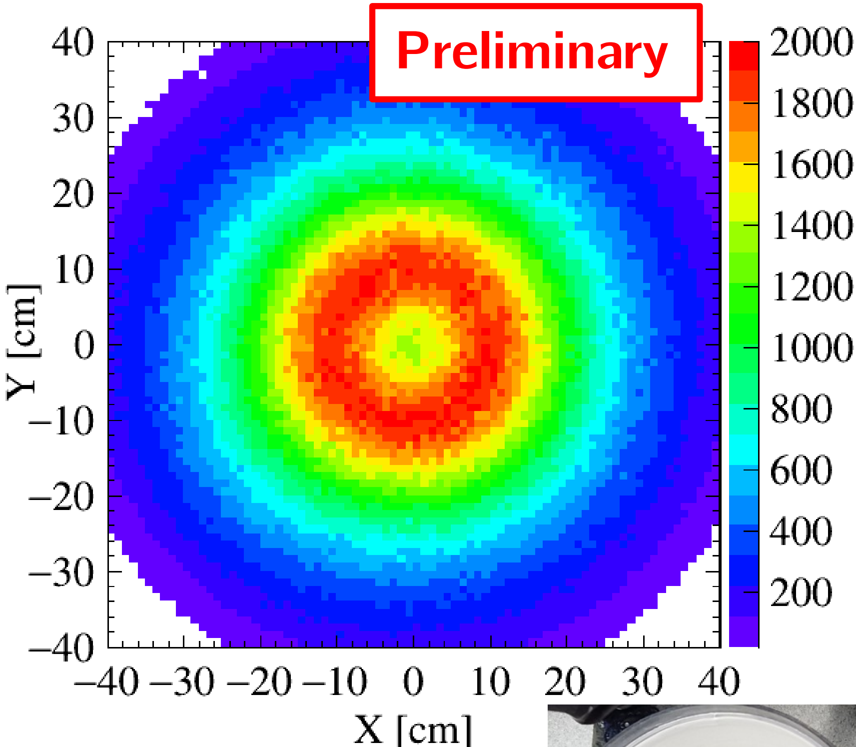
Different colors denote independent simulations



Results of the CPT test

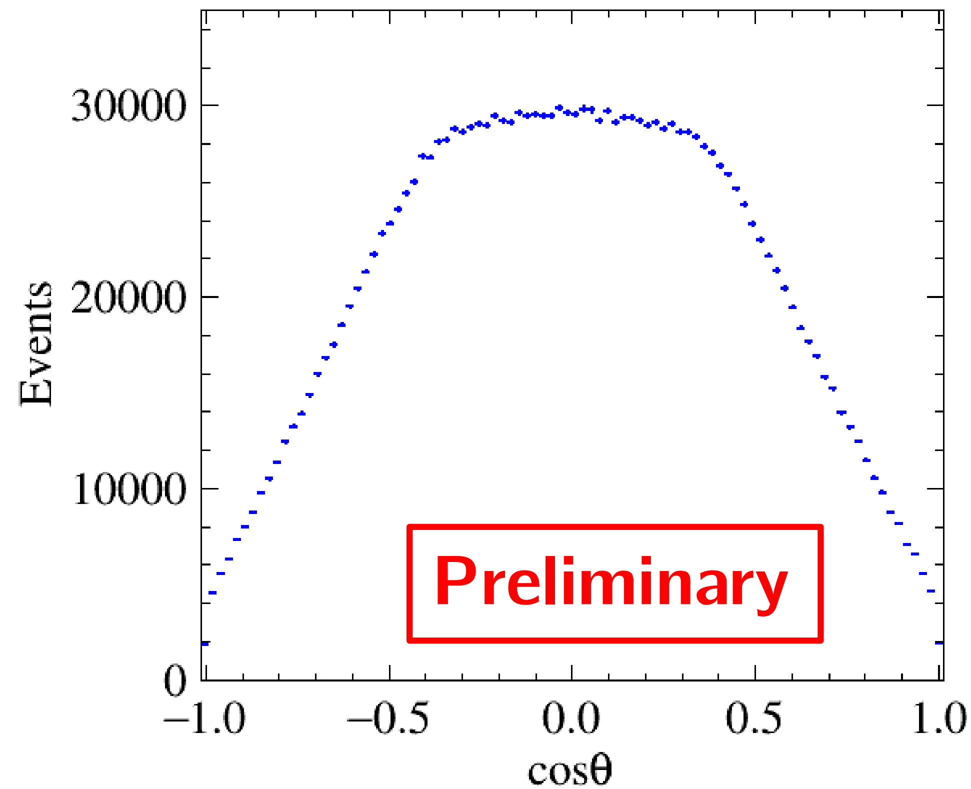
Using 2 x 10^6 of identified
o-Ps $\rightarrow$ 3ɣ annihilations

3ɣ 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→3ɣ annihilations

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

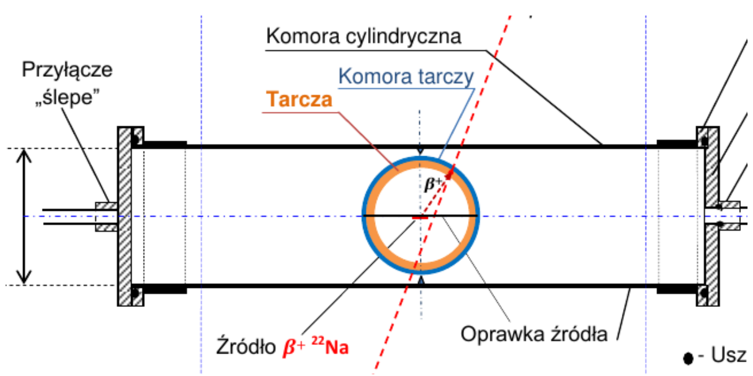


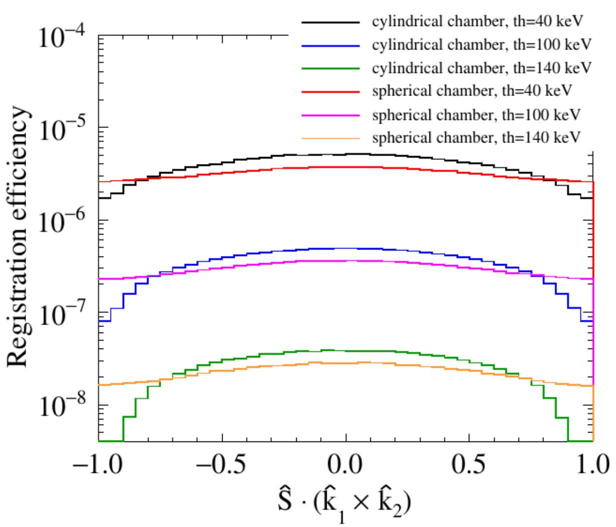
<cosθ> statistical uncertainty: **3.3×10^{-4}**
systematic uncertainty **1.4×10^{-4}**

Analyzing power S = 37.4 %
(polarization-dominated)

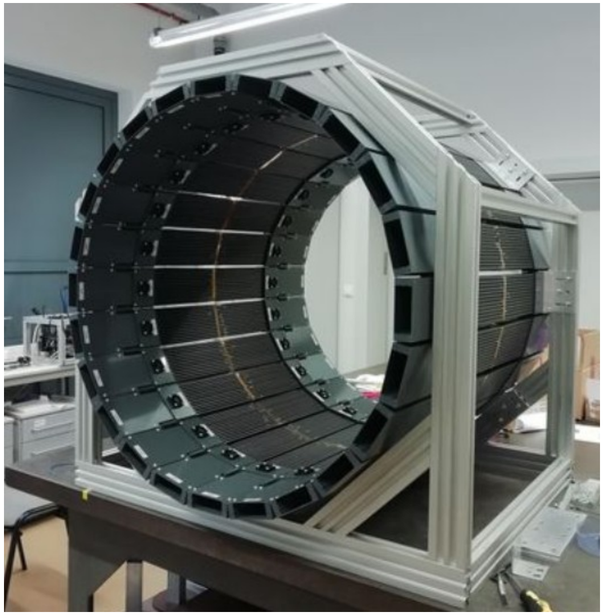
Summary and further perspectives

- 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!

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

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European Union European Regional Development Fund

Backup Slides

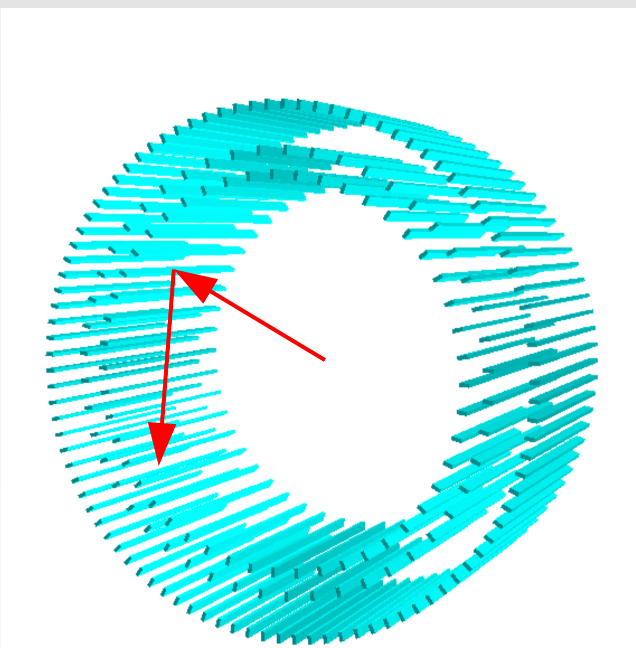
Testing discrete symmetries with ortho-positronium

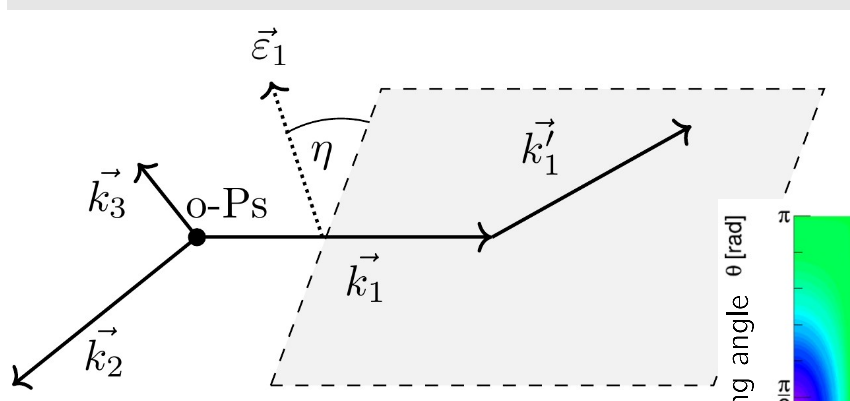
operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	−	+	−	−
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	−	+	−
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))$	+	−	−	−	+
$\vec{k}_2 \cdot \vec{\epsilon}_1$	+	−	−	−	+
$\vec{S} \cdot \vec{\epsilon}_1$	+	+	−	+	−
$\vec{S} \cdot (\vec{k}_2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

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

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

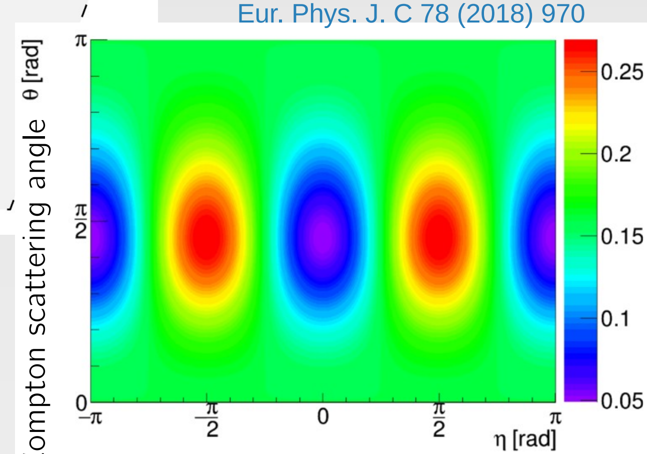
[P. Moskal *et al., Acta Phys. Polon. B47 (2016) 509*]





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

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

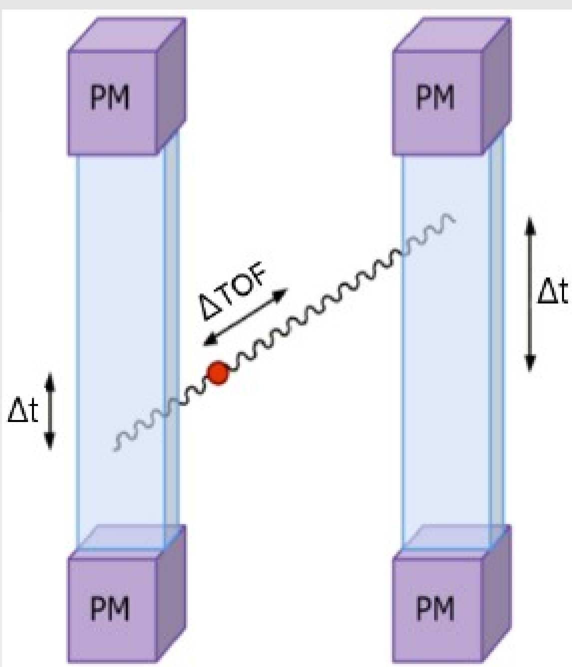


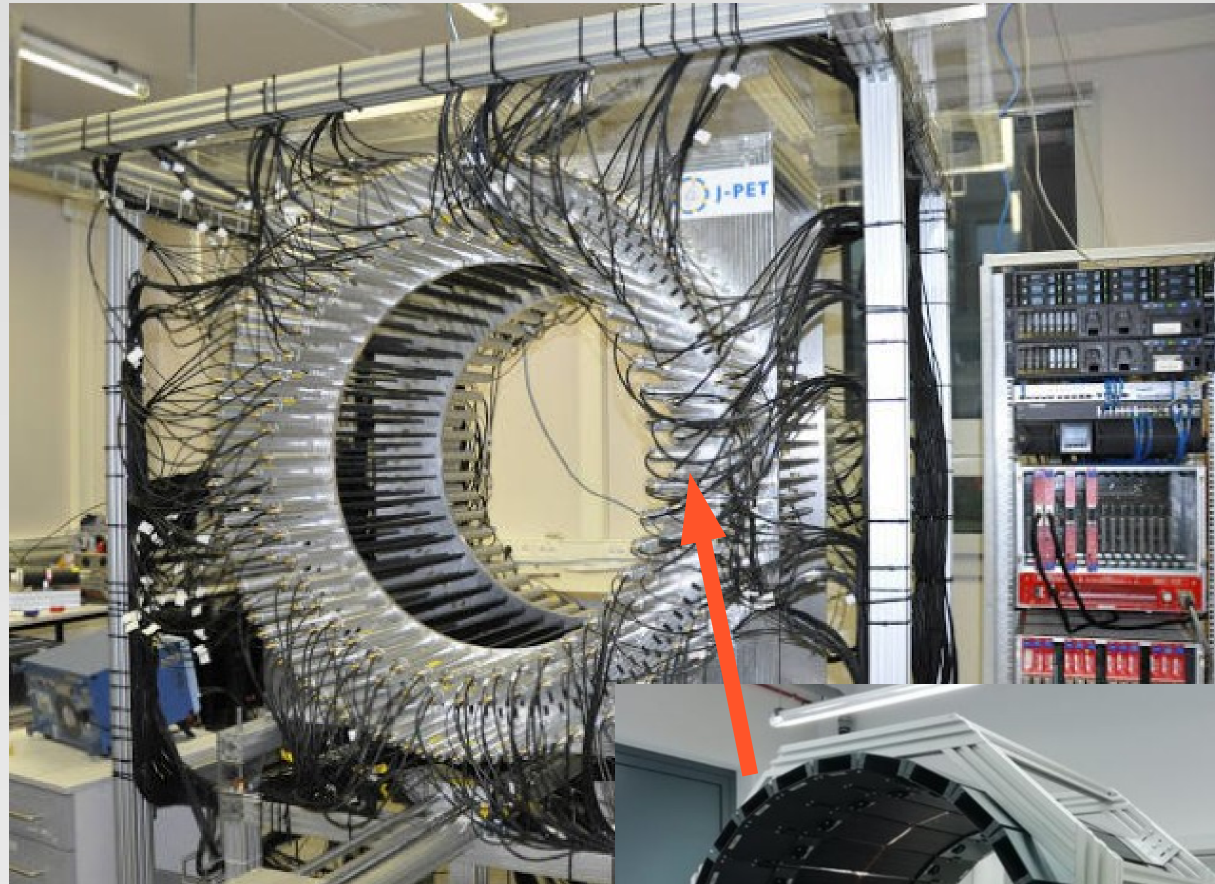
Angle between ϵ and the scattering plane

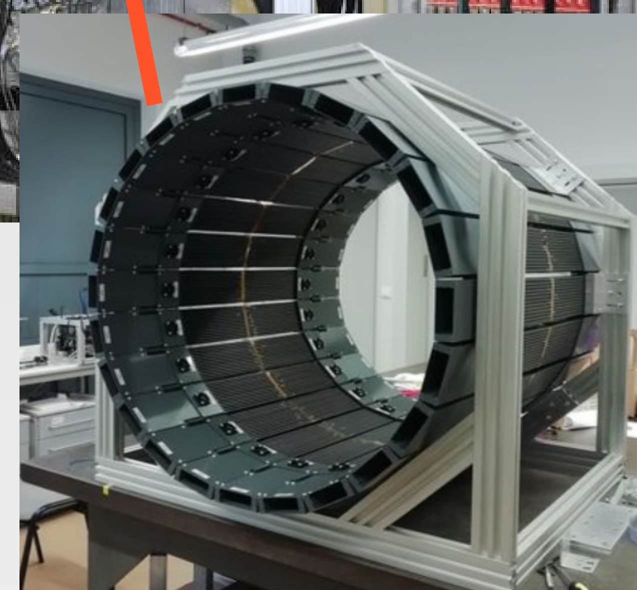
J-PET can determine the scattering plane in events with secondary Compton scatterings!

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!

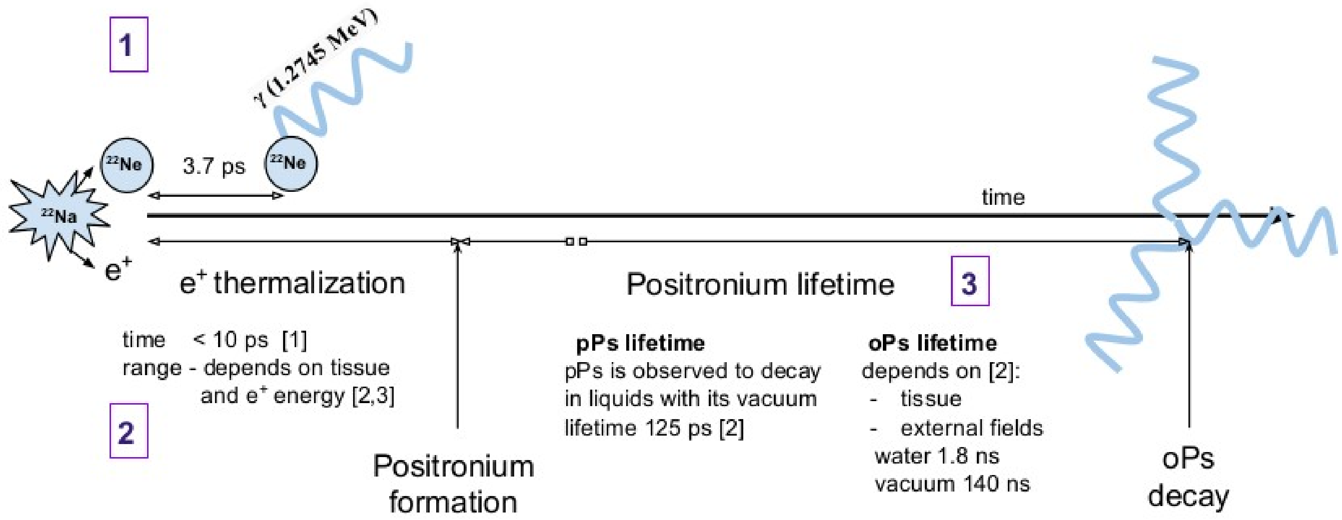




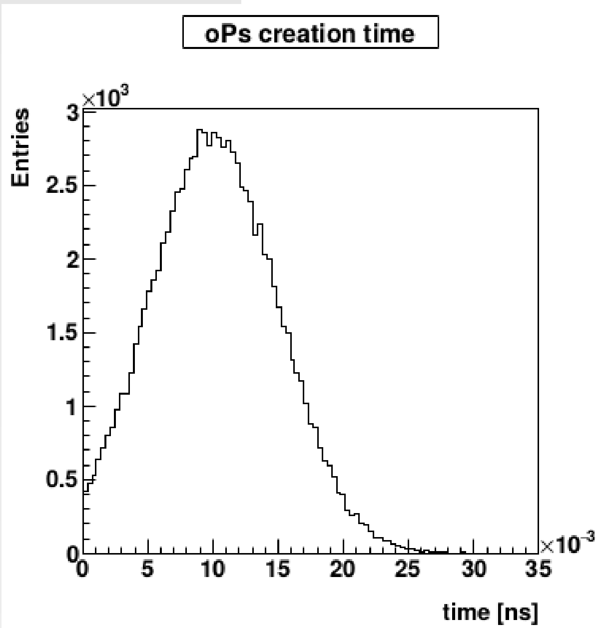


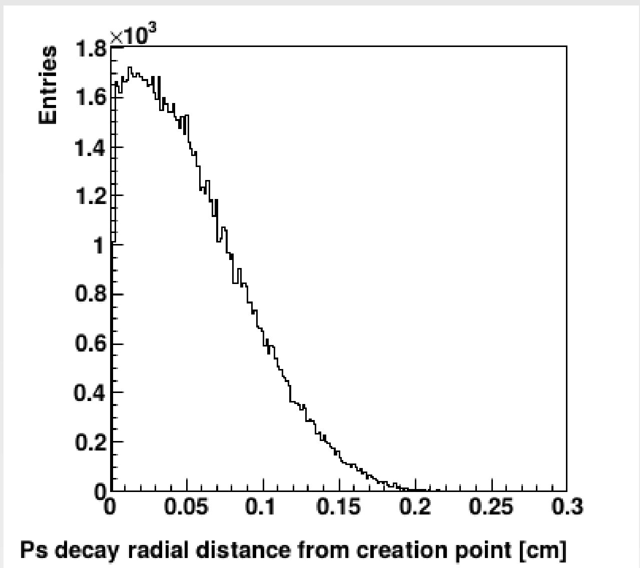
A new inner layer
with digital readout
→ See talks by:
G. Korcyl
Sz. Niedźwiecki
On Thursday

O-Ps creation and decay

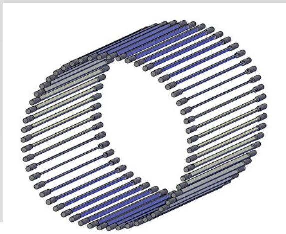


[1] P. Kubica and A. T. Stewart, Phys. Rev. Lett. 34 (1975) 852
[2] M. Harpen Med.Phys. 31 (2004) 57-61
[3] J Cal-Gonzalez et al, Phys. Med. Biol. 58 (2013) 5127–5152





Distinguishing o-Ps→3γ and e^+e^-→2γ



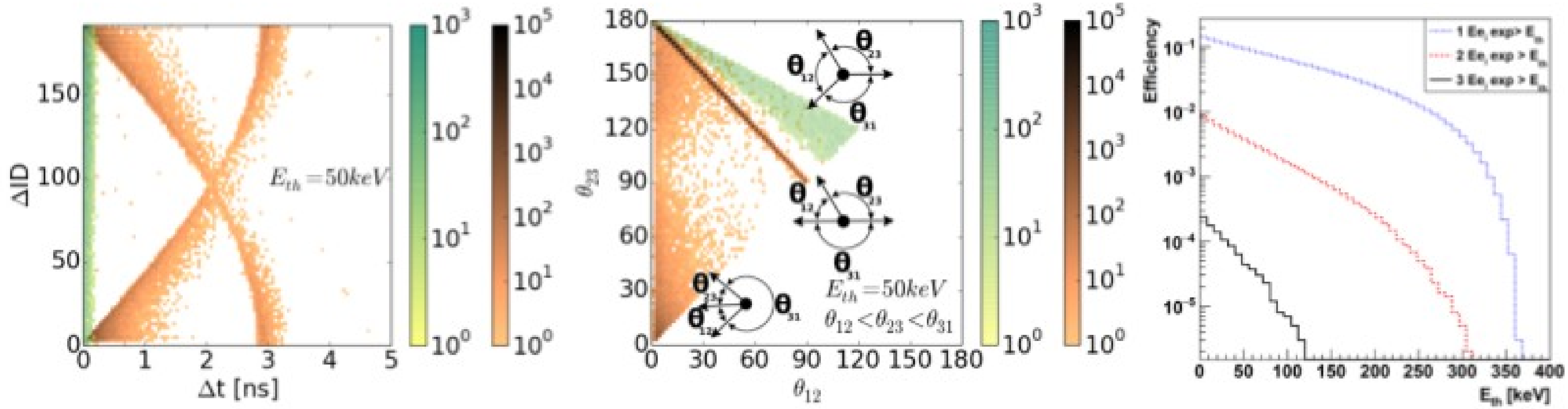


Figure 9. (Left) Simulated distributions of differences between detectors ID (ΔID) and differences of hit-times (Δt) for events with three hits registered from the annihilation e+e- → 2γ (gold colours) and o-Ps → 3γ (green colours). **(Middle)** Disribution of relative angles between reconstructed directions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

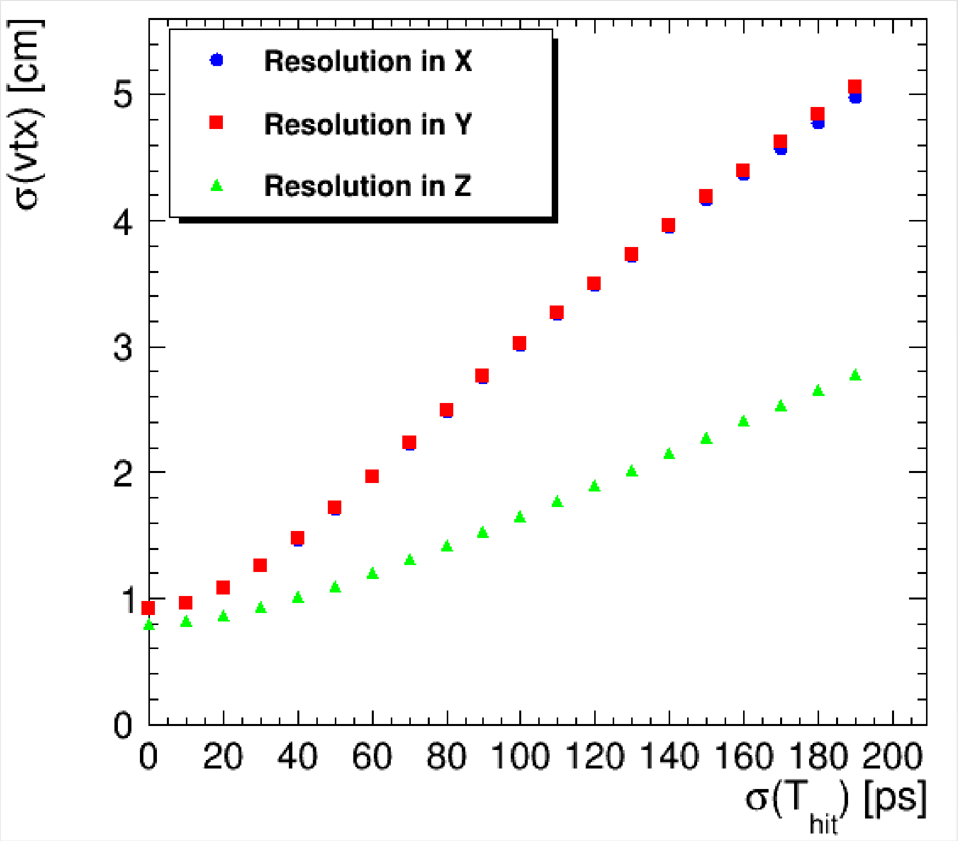
[J-PET: P.Kowalski, P.Moskal, in preparation]

Resolution dependence on γ hit time resolution

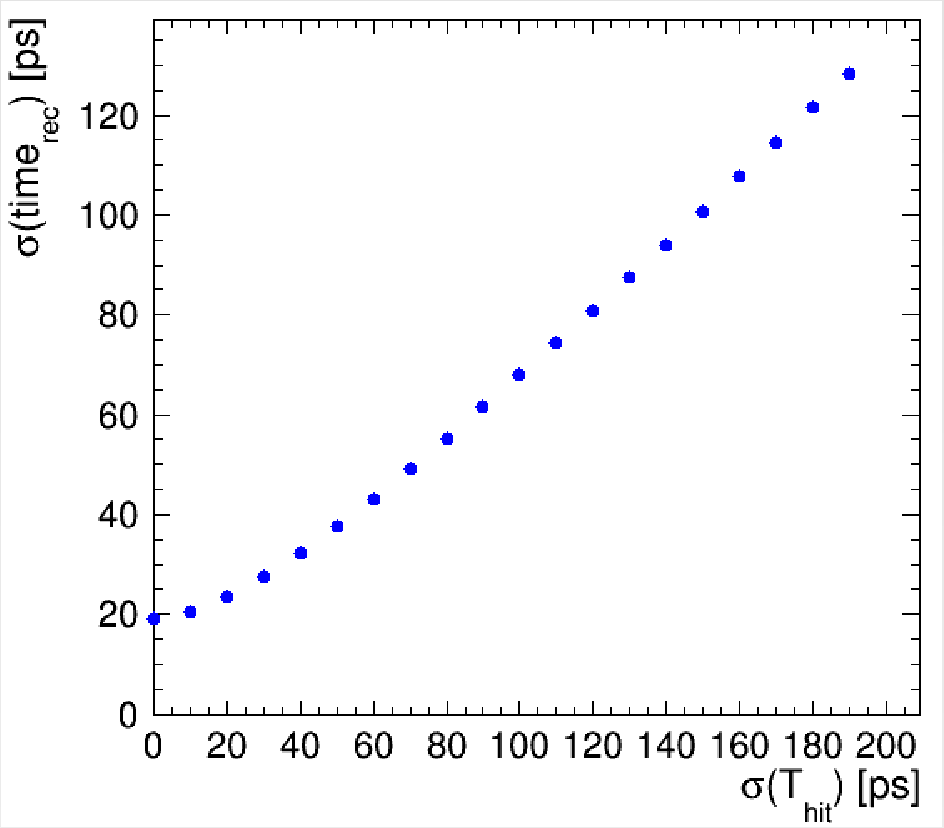
The resolution of o-Ps decay obtained with the presented reconstruction method depends predominantly on the timing resolution of γ hits in scintillator strips.

O-Ps decay resolution

spatial



time

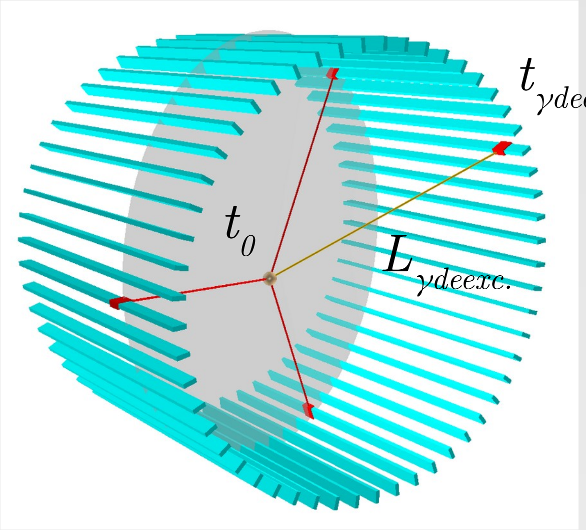


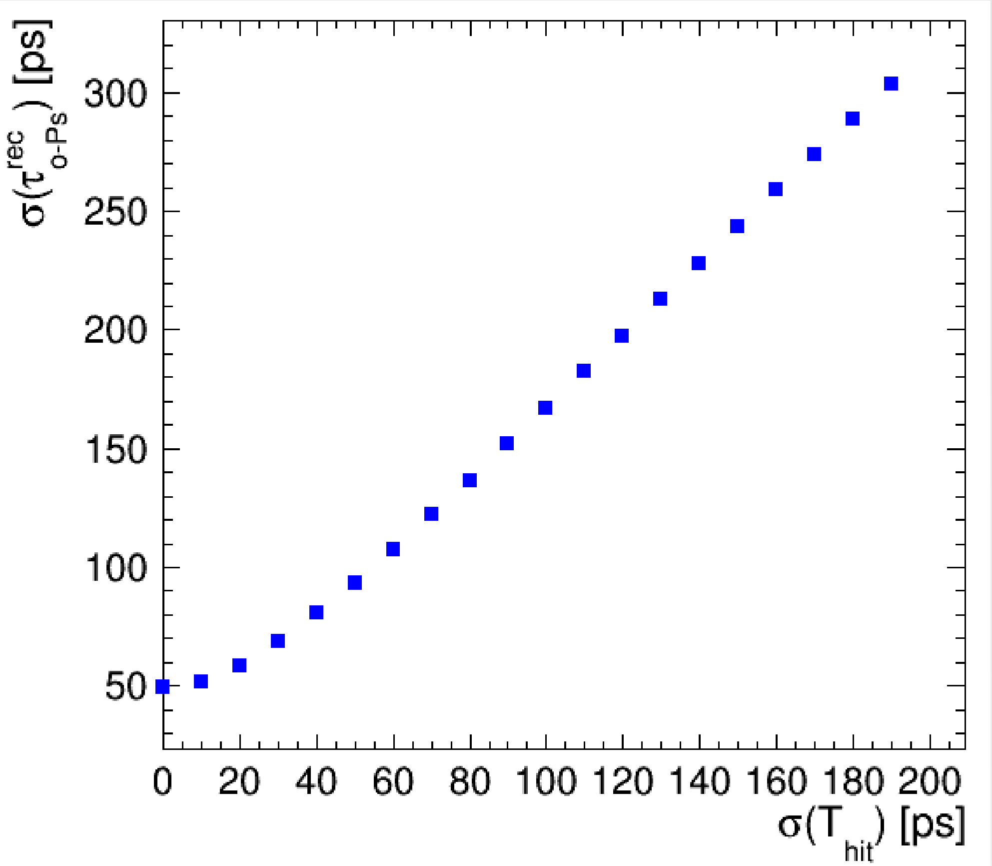
Ortho-positronium life time resolution

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

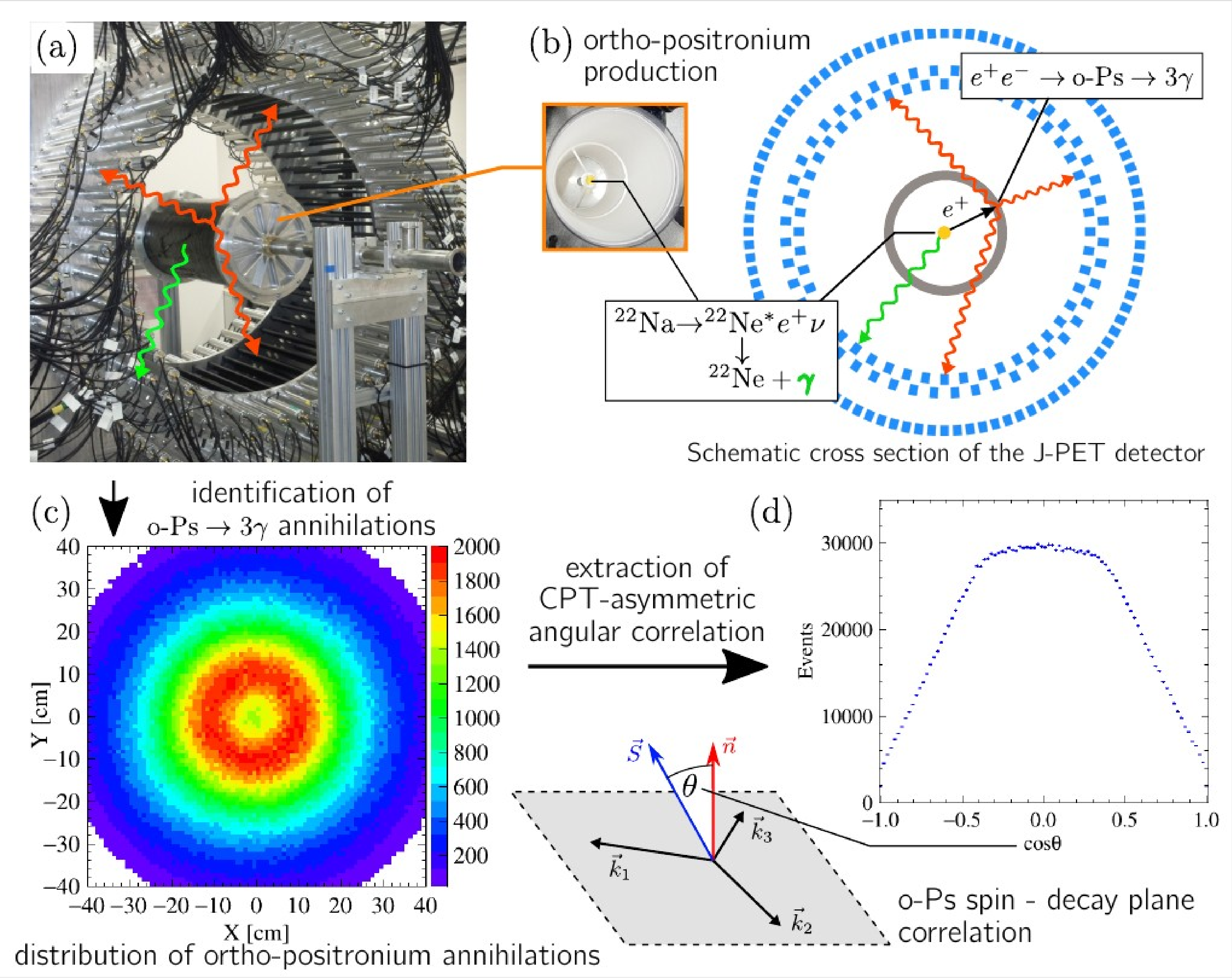
$$\tau^{rec}_{o-Ps} = t_0 - \left(t_{\gamma deexc.} - \frac{L_{\gamma deexc.}}{c} \right)$$

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.



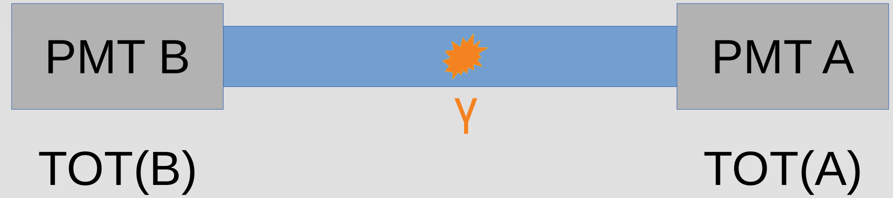


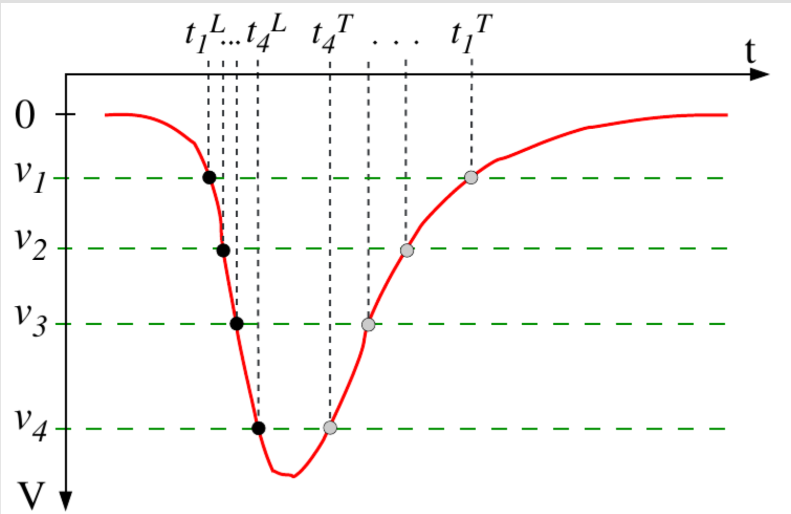
Scheme of the experiment



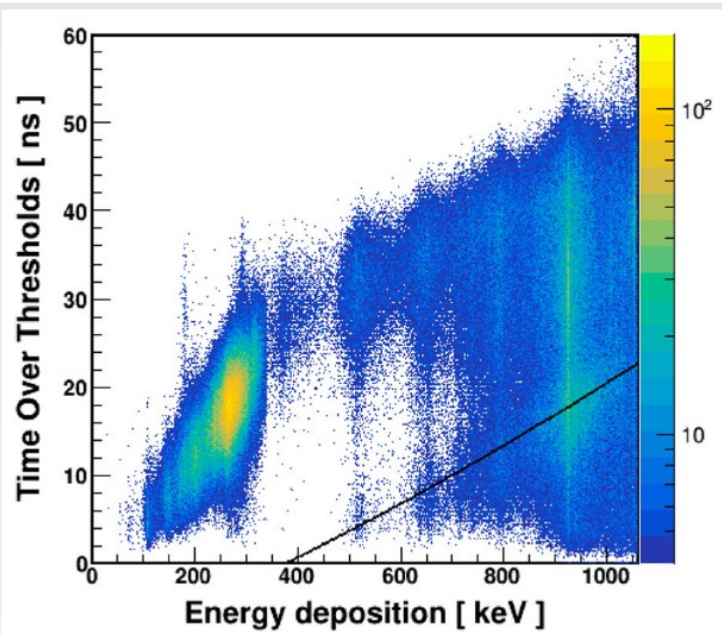
Time-Over-Threshold as a measure of deposited γ energy

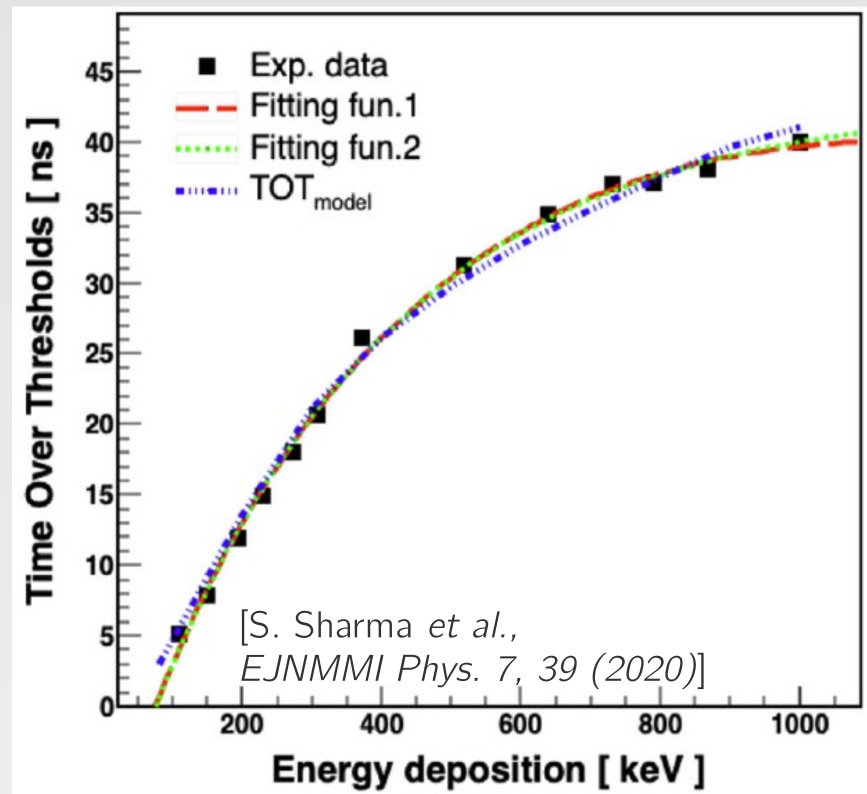
Using total Time Over Threshold (TOT) of PMT signals from a scintillator strip





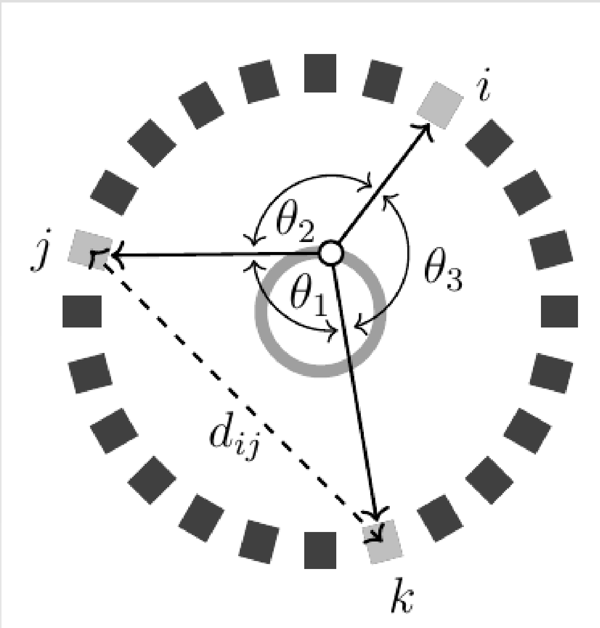
The relation between TOT and energy deposited by a photon in Comton scattering is under an extensive study right now.



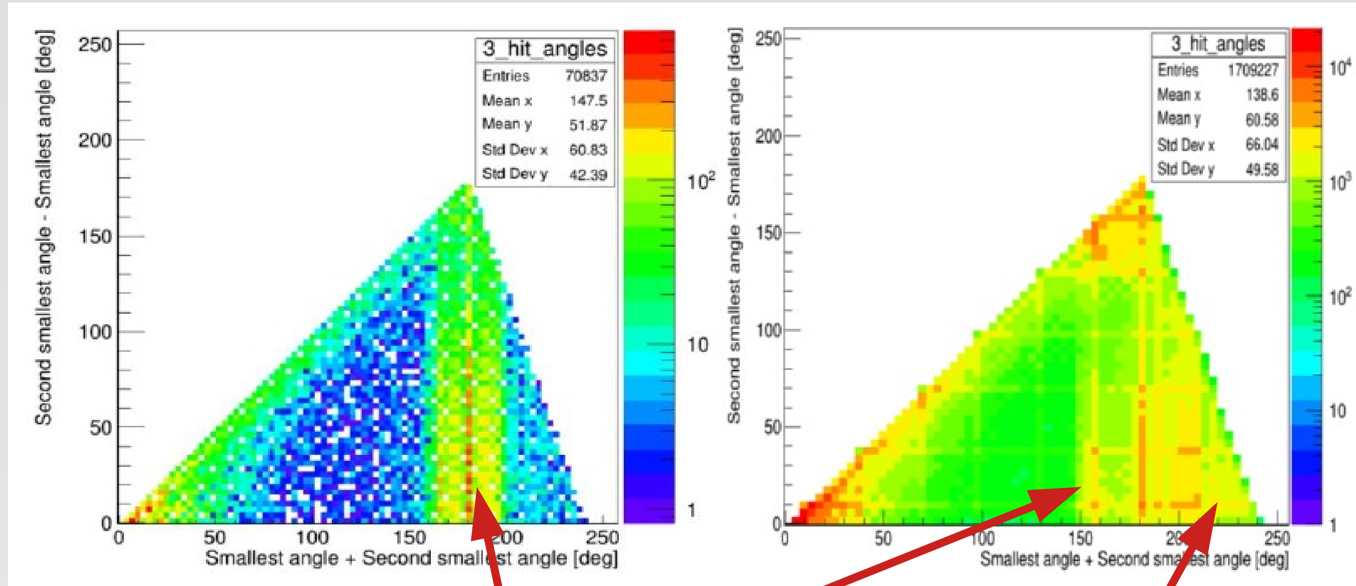


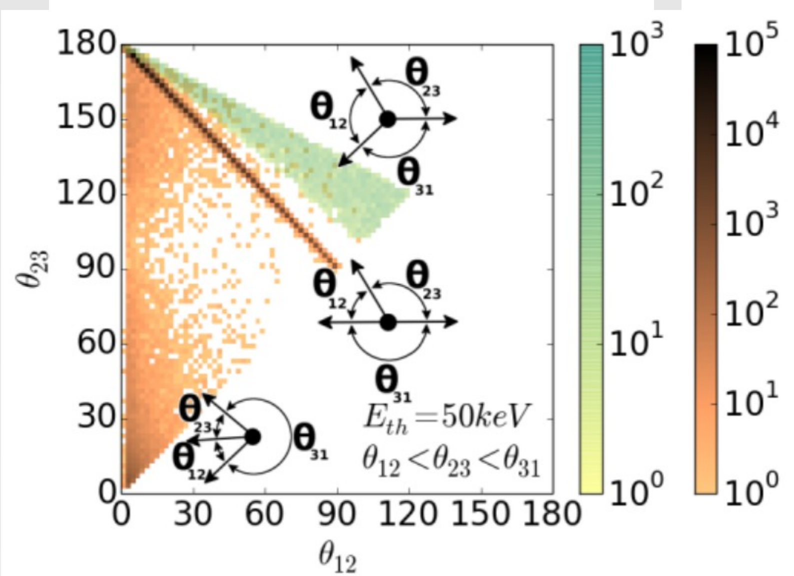
[S. Sharma *et al.*, *EJNMMI Phys. 7, 39 (2020)*]

Angular topology of the 3γ events

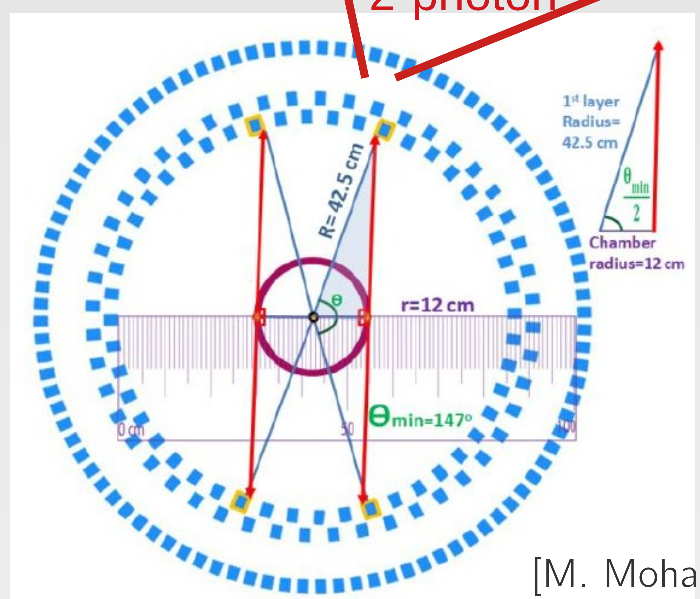


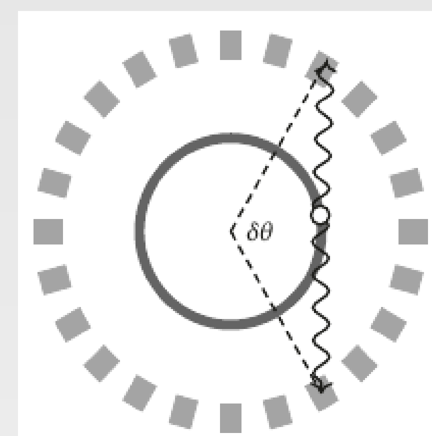
Angles defined in the transverse plane only





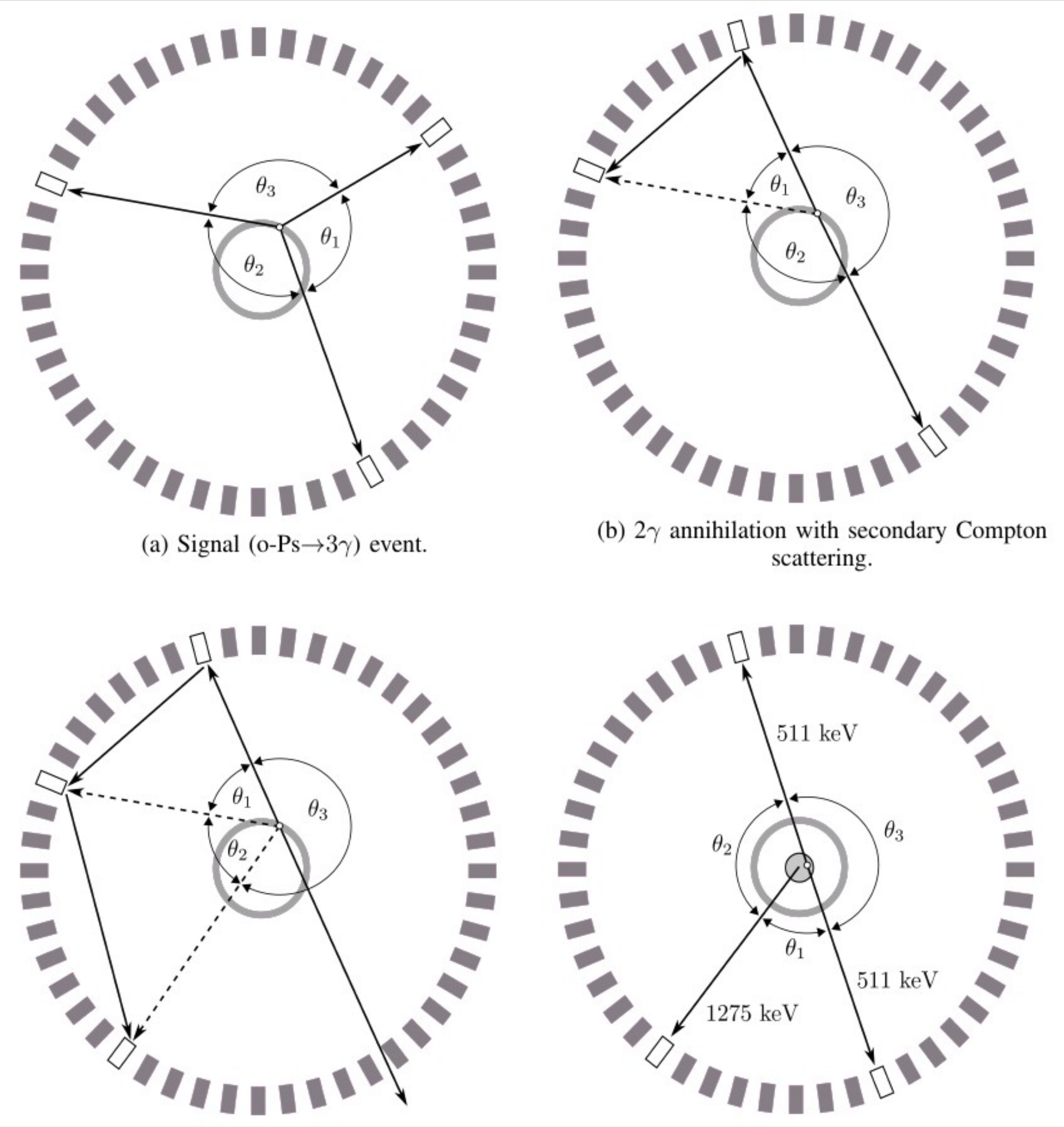
[D. Kamińska et al., Eur. Phys. J. C76 (2016) no.8, 445]



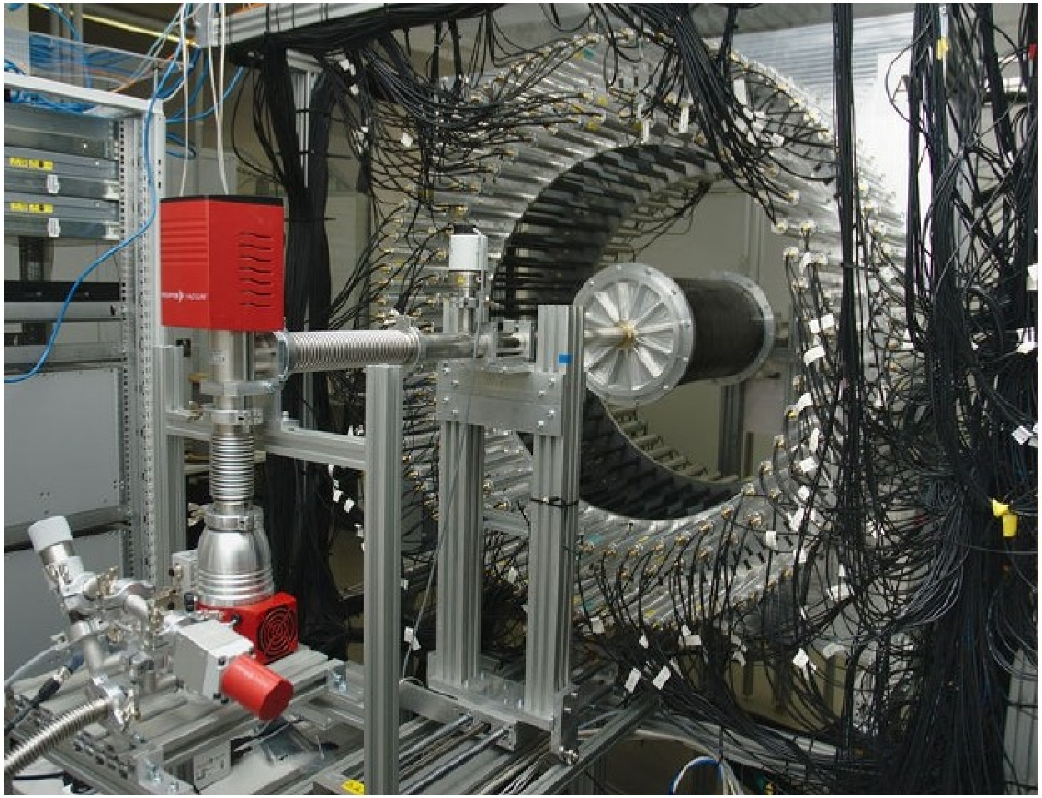


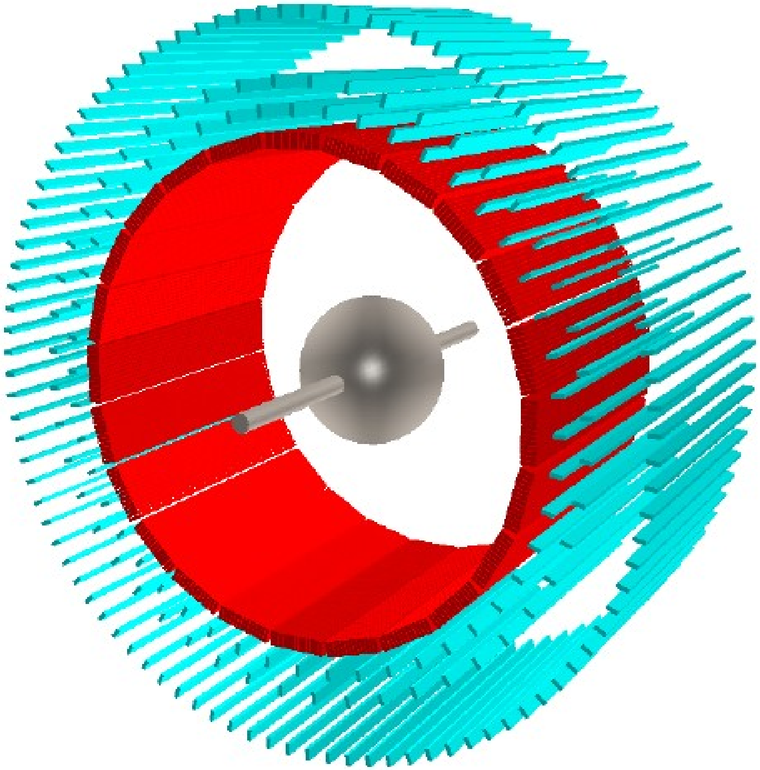
[M. Mohammed, PhD thesis, 2020]

Signal & background events

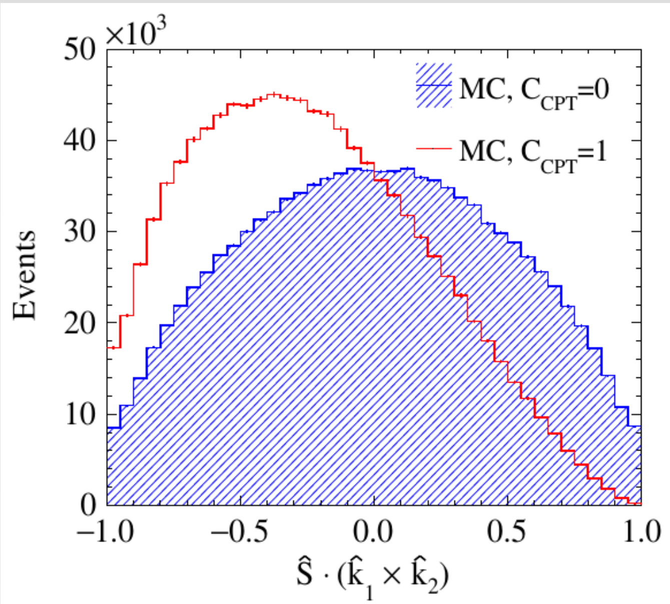


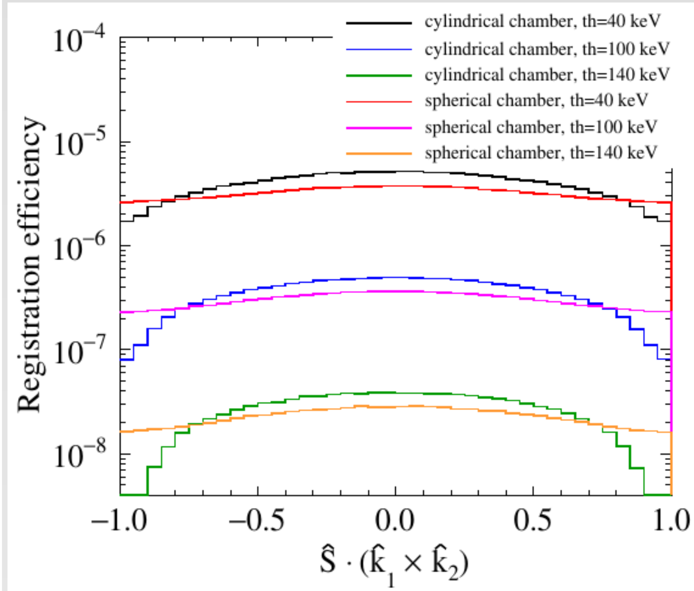
Detector improvements

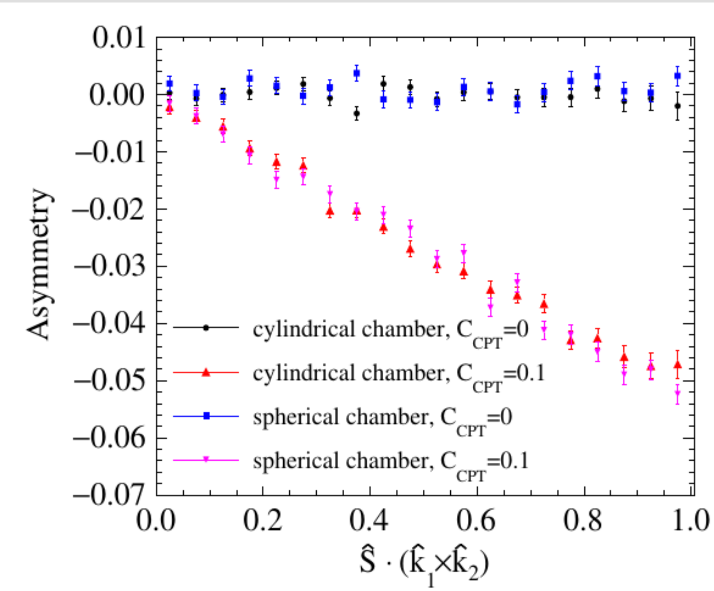




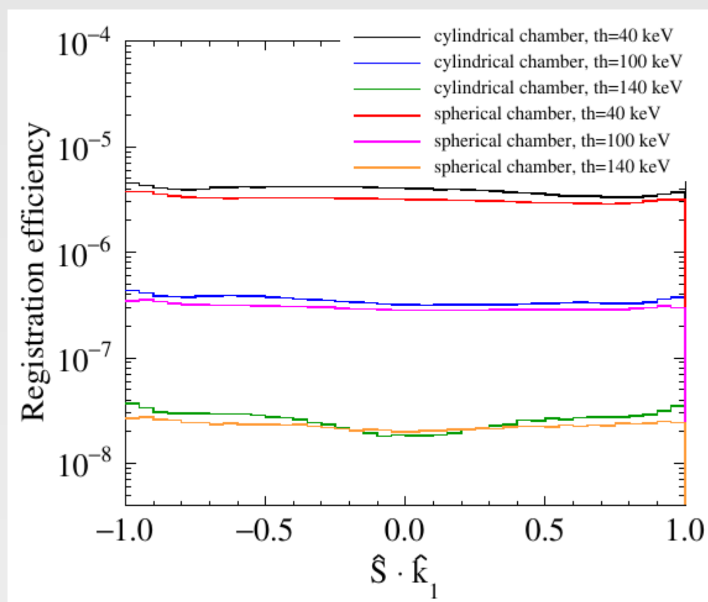
Expected sensitivity

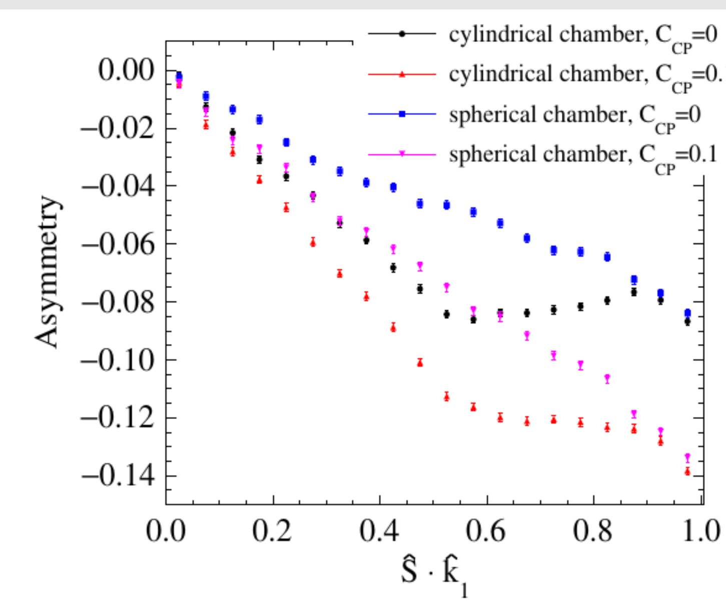






No.	Operator	C	P	T	CP	CPT
1	$\vec{S} \cdot \vec{k_1}$	+	−	+	−	−
2	$\vec{S} \cdot (\vec{k_1} \times \vec{k_2})$	+	+	−	+	−
3	$(\vec{S} \cdot \vec{k_1})(\vec{S} \cdot (\vec{k_1} \times \vec{k_2}))$	+	−	−	−	+





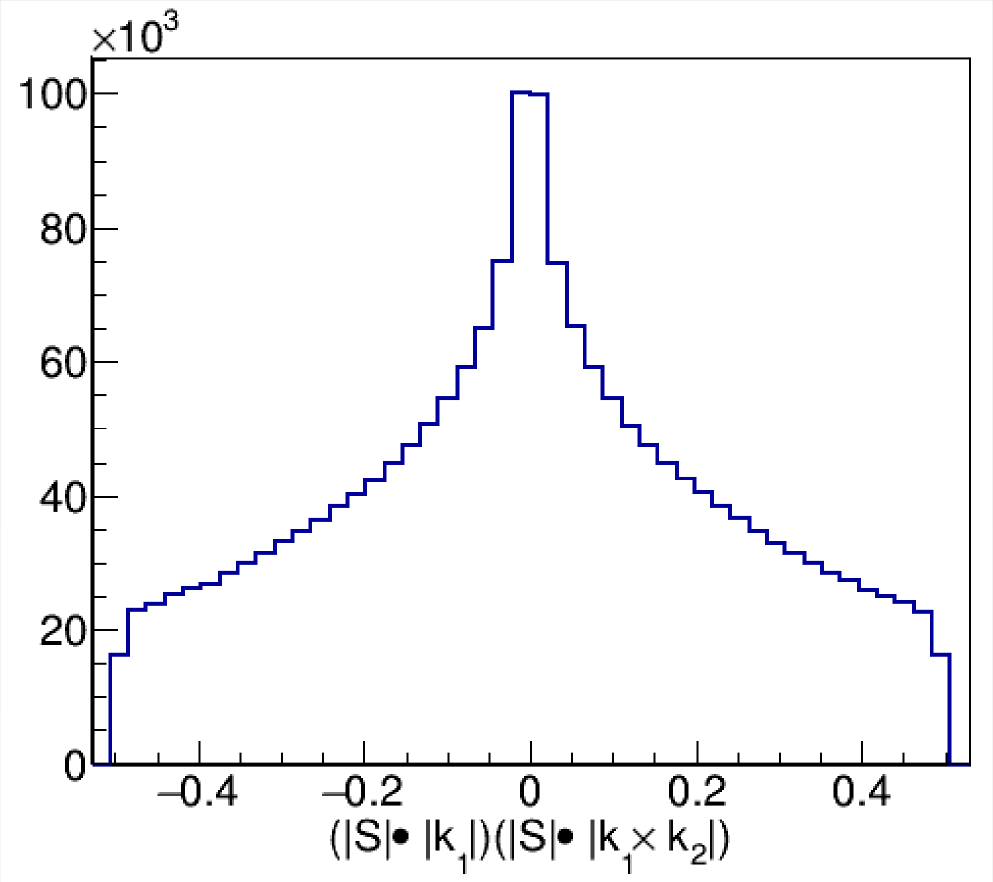
[Symmetry 12 (2020) 8, 1268]

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



$\langle O \rangle = (0.99 \pm 1.7) \times 10^{-4}$