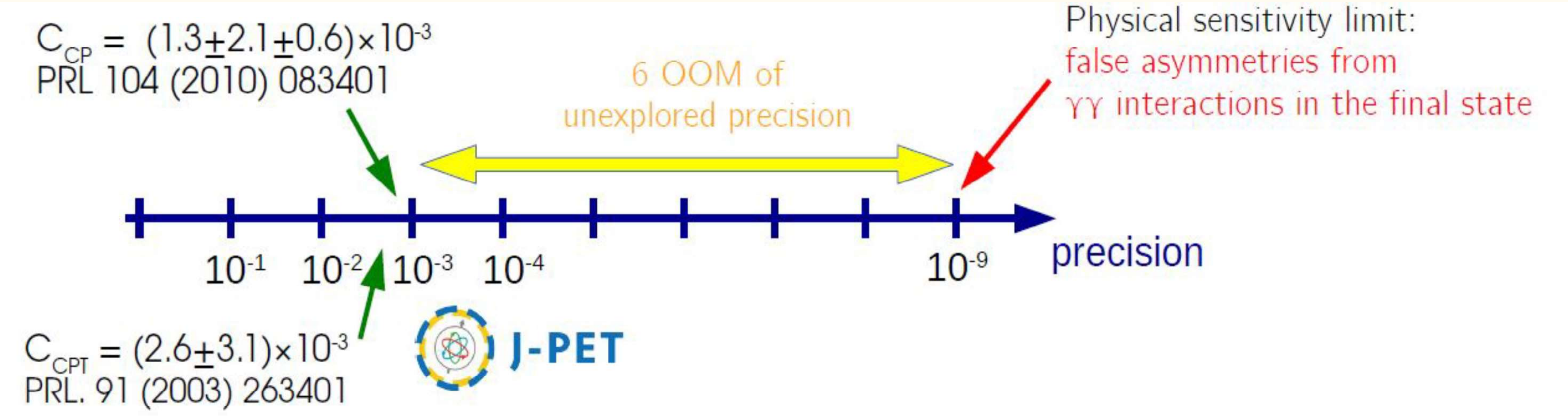
Discreet Symmetries Investigation in Positronium decays with J-PET facility

Magdalena Skurzok
on behalf of the **J-PET** Collaboration

KAMPAI workshop
Trento, 30.09-4.10.2024

Motivation: discrete symmetry tests with o-Ps decays

- Discrete symmetries are scarcely tested with leptonic systems
  - Neutrino oscillations: Dirac phase, δCP ~3σ level [T2K, *Nature 580 (2020) 339*]
  - Electron EDM < 4.1×10^{-30} [Science 381 *(2023)* adg4084]
- Violation of CP and T symmetries have been observed only for systems including quarks, never discovered in any processes involving purely leptonic matter
- So far performed experiments with Ps atoms excluded violation of discrete symmetries as CP, T or CPT only at the level of about 0.3% - many orders of magnitude less precise than the accuracies achieved in the quark sector
  Ps is the only system consisting of charged leptons used for tests of CP and CPT to date



- symmetries tests can be made with a very high precision limited, only by the effects due to the weak interaction: 10^{-14} and photon-photon interaction: 10^{-9}. (Standard Model Calculations)

[Phys. Rev. A 37, 3189 (1988), Z. Phys. C 41, 143 (1988), M. S Sozzi "Discreet Symmetries and CP violation"]

Motivation: discrete symmetry tests with o-Ps decays

➢ **POSITRONIUM - the lightest purely leptonic object**

bound by a central potential

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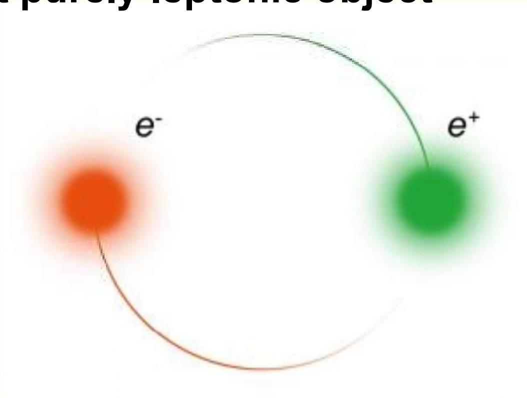
is eigenstate of the parity operator P

$$P|Ps>=(-1)^L|Ps>$$



symmetric under the exchange of particles - anti-particles

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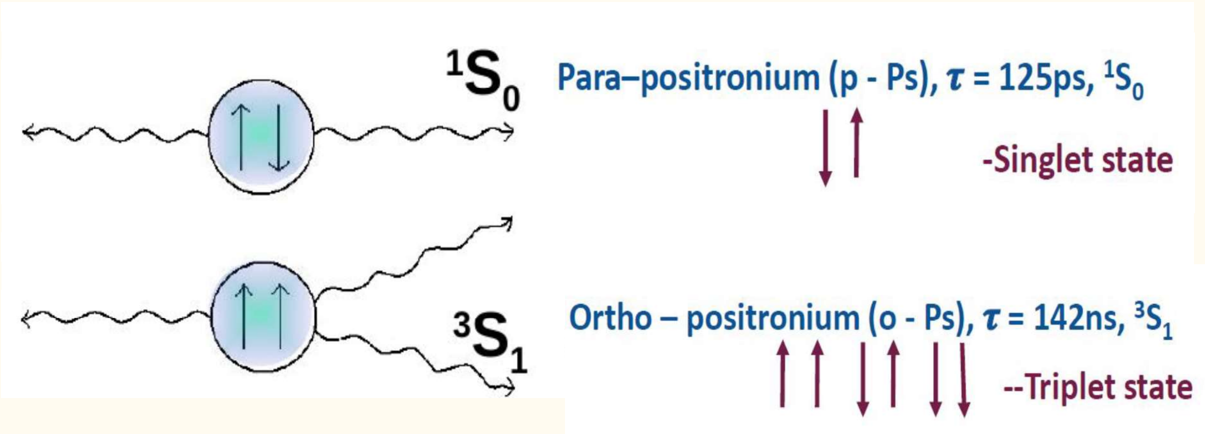
is eigenstate of the charge conjugation operator C

$$C|Ps>=(-1)^{L+S}|Ps>$$

eigenstate of the CP operator



even number of photons

symm. of charge conjugation C

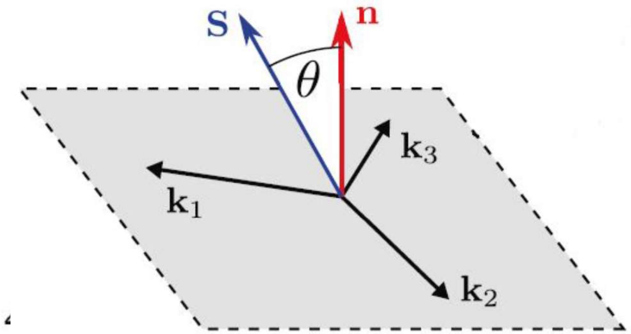
odd number of photons

Ps state	τ [ns]	L	S	J	J_z	P	C	CP
$^1S_0$ (para-Ps)	0.125	0	0	0	0	-	+	-
$^3S_1$(ortho-Ps)	142	0	1	1	-1,0,1	-	-	+

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

Measurement the expectation value of the symmetry odd-operators

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



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

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

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

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

Required:

- the o-Ps spin determination
- of o-Ps→3γ decays selection (determination of photons momenta)
- determination of annihilation γ polarization

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

$$O_{CP} = \vec{k}_1 \cdot \vec{\varepsilon}_2/|\vec{k}_1||\vec{\varepsilon}_2| = cos\theta$$

Operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	-	+	-	-
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	-	+	-
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))$	+	-	-	-	+
$\vec{k}_1 \cdot \vec{\varepsilon}_2$	+	-	-	-	+
$\vec{S} \cdot \vec{\varepsilon}_1$	+	+	-	+	-
$\vec{S} \cdot (\vec{k}_2 \times \vec{\varepsilon}_1)$	+	-	+	-	-

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

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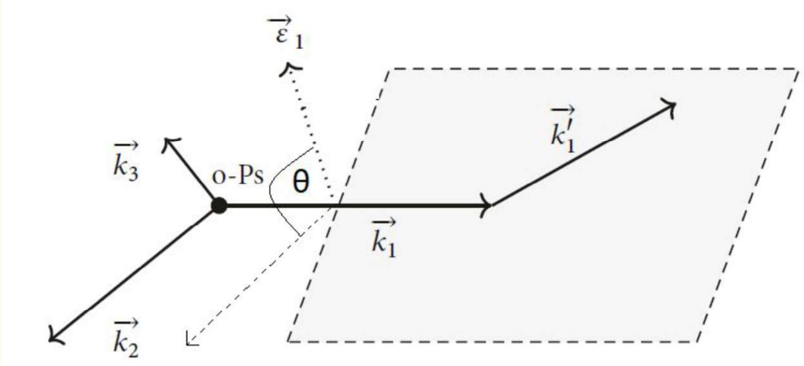

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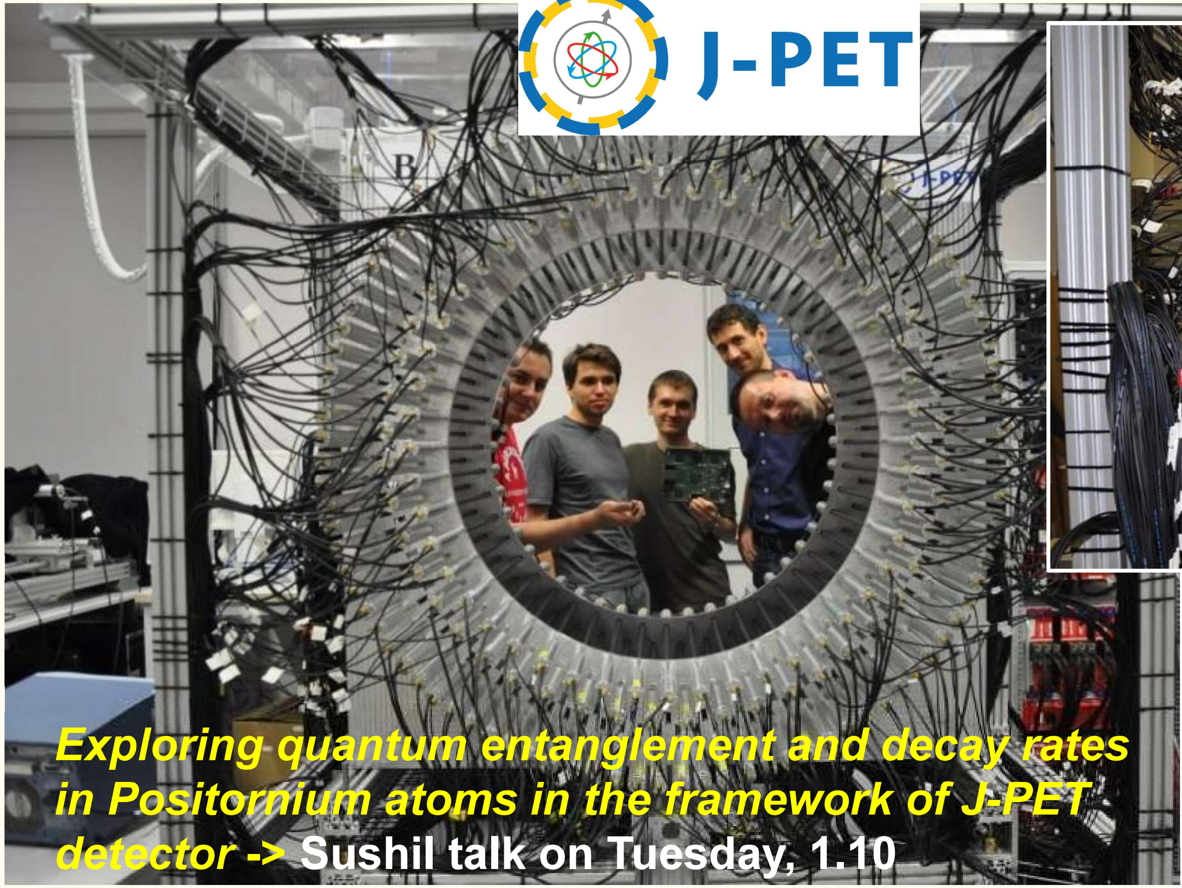
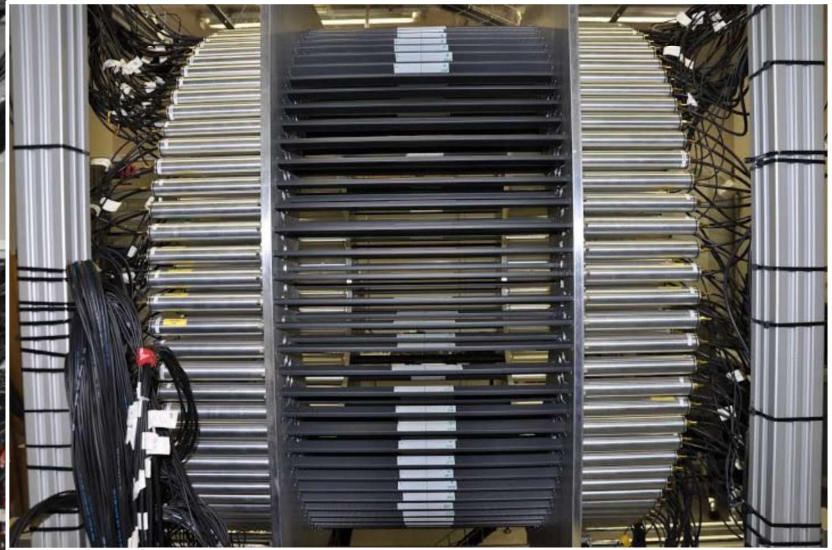
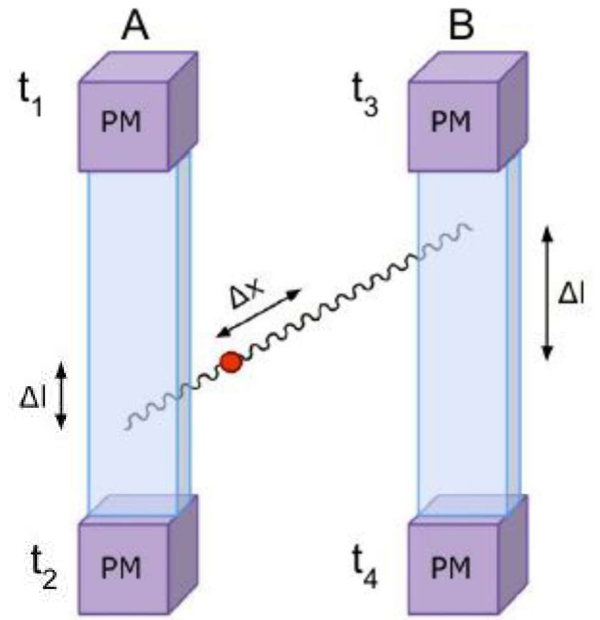
$\vec{k}_1 \cdot \vec{\varepsilon}_2$	+	-	-	-	+
$\vec{S} \cdot \vec{\varepsilon}_1$	+	+	-	+	-
$\vec{S} \cdot (\vec{k}_2 \times \vec{\varepsilon}_1)$	+	-	+	-	-

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

J-PET detector at Jagiellonian University in Kraków, Poland



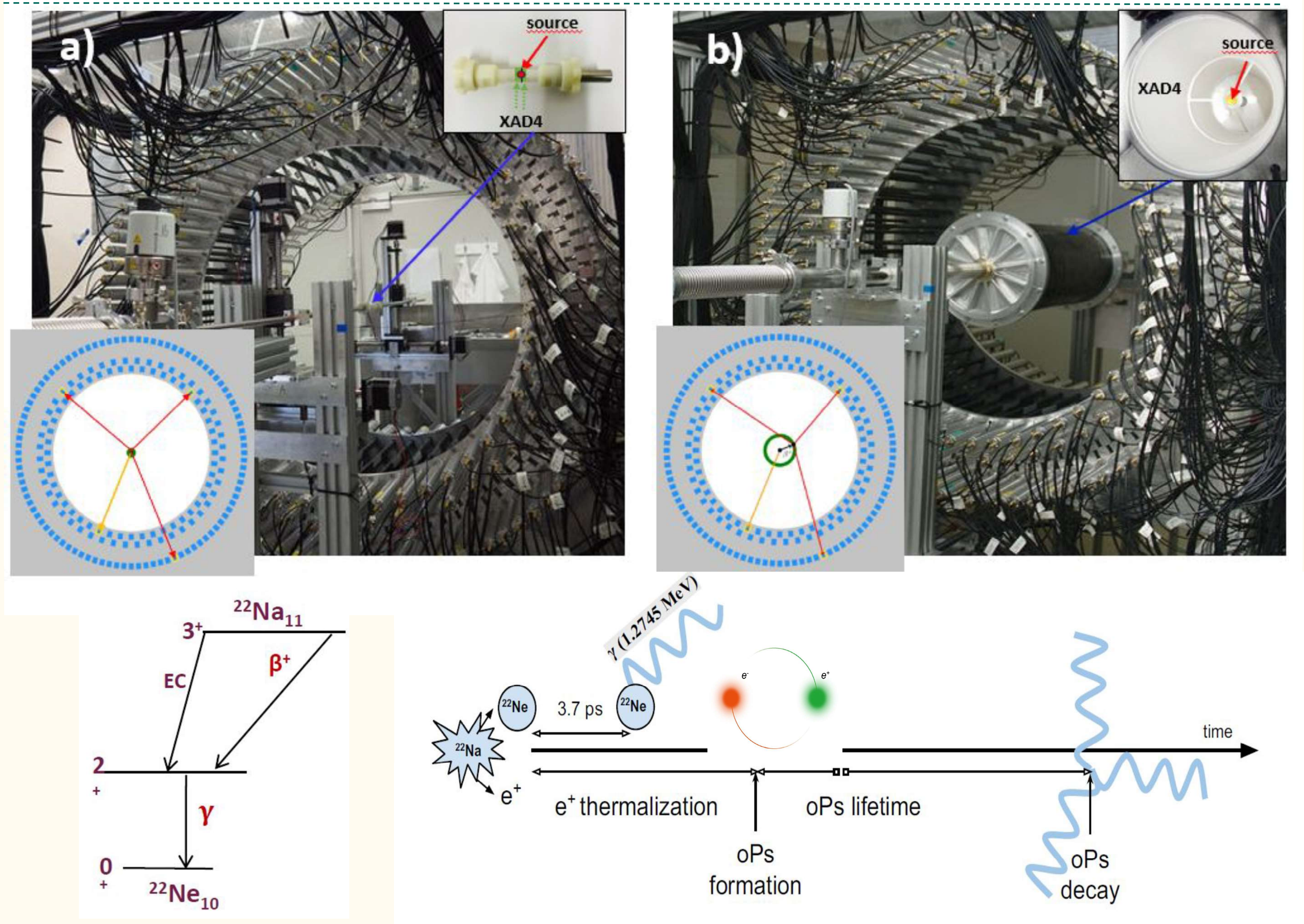


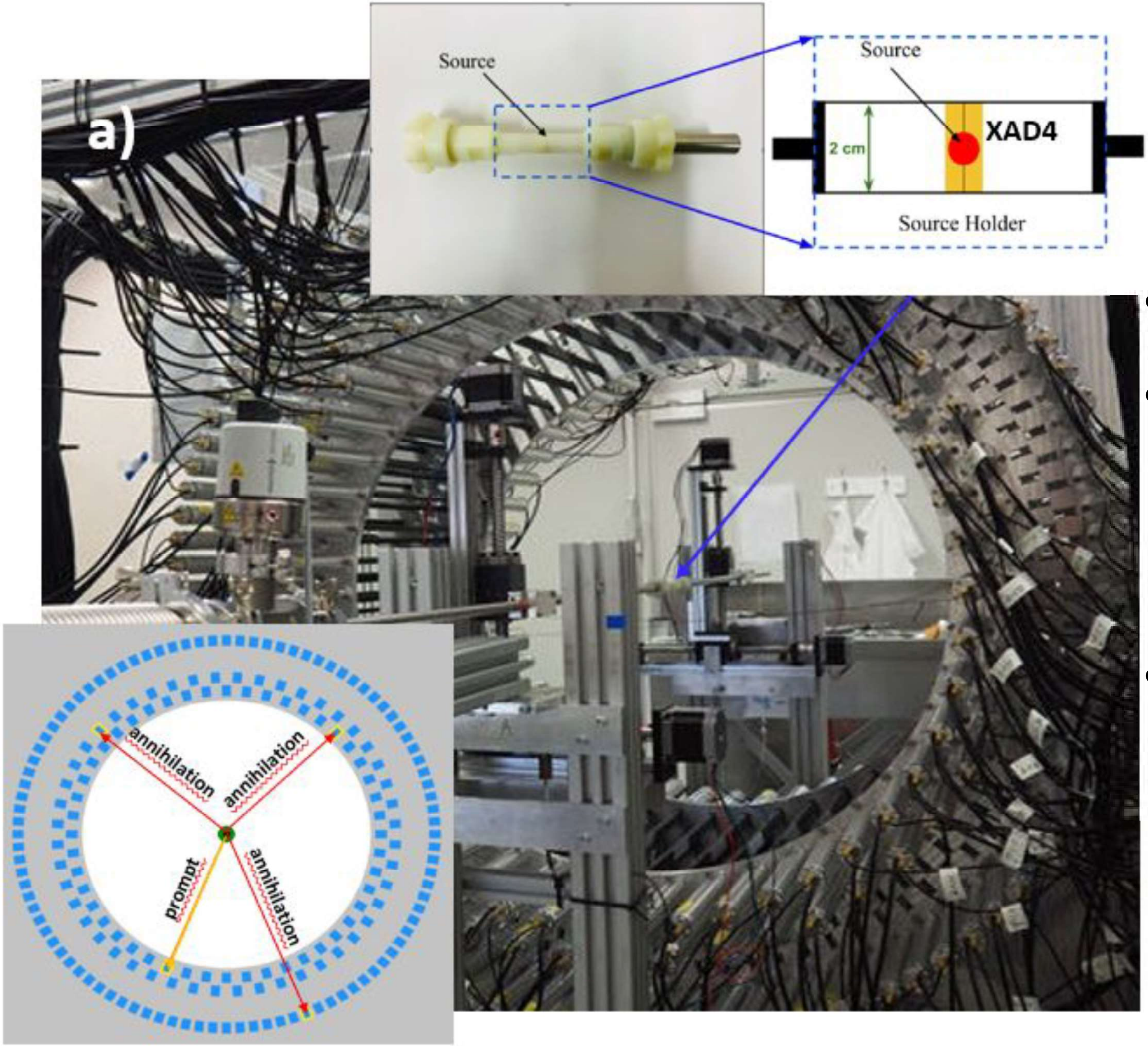


- 3 layers,192 EJ-230 scintillators: 7x19x500 mm^3
- 85 cm radius, 384 R9800 photomultipliers,1536 channels
- plastic scintillators - small light attenuation
- multithreshold digital electronics and and the novel trigger-less DAQ
- interaction time resolution ~250ps, angular resolution ~ 1deg

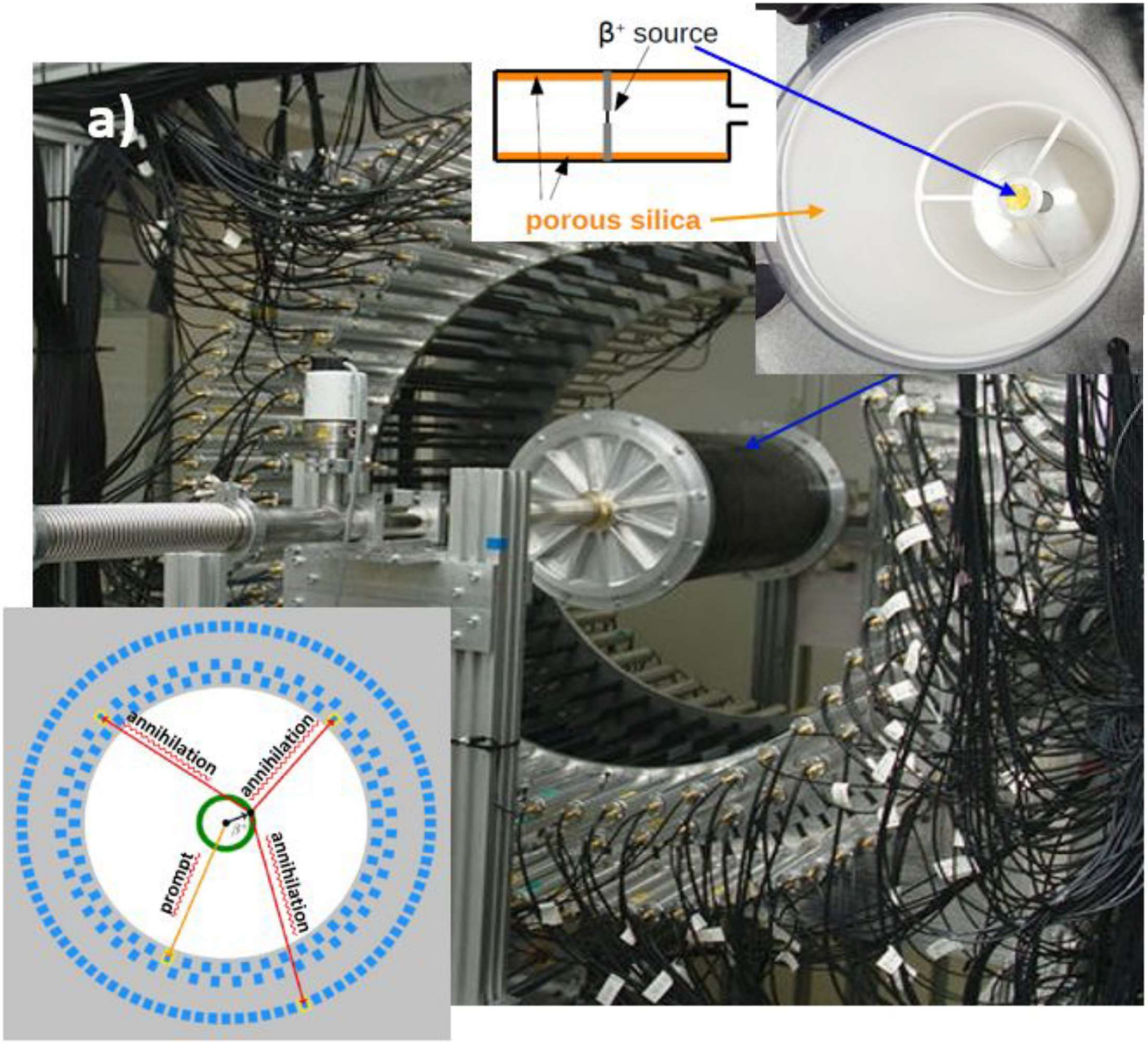
[P. Moskal et al., Acta Phys. Polon. B47 (2016) 509; G. Korcyl, et al., IEEE Trans. Med. Imag. 37, 2526 (2018)]

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



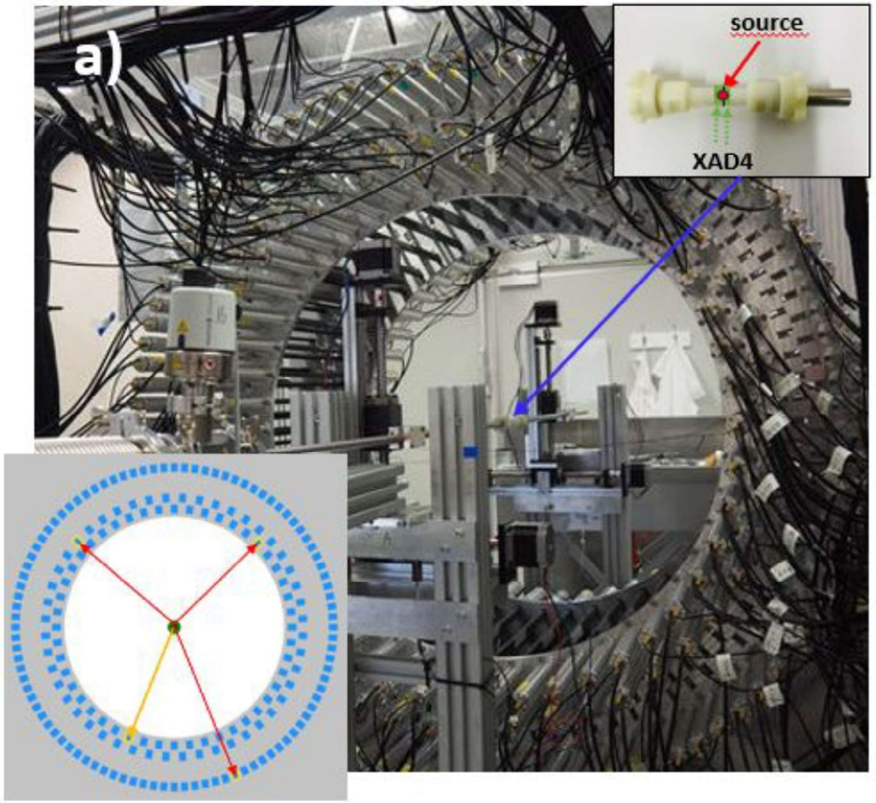


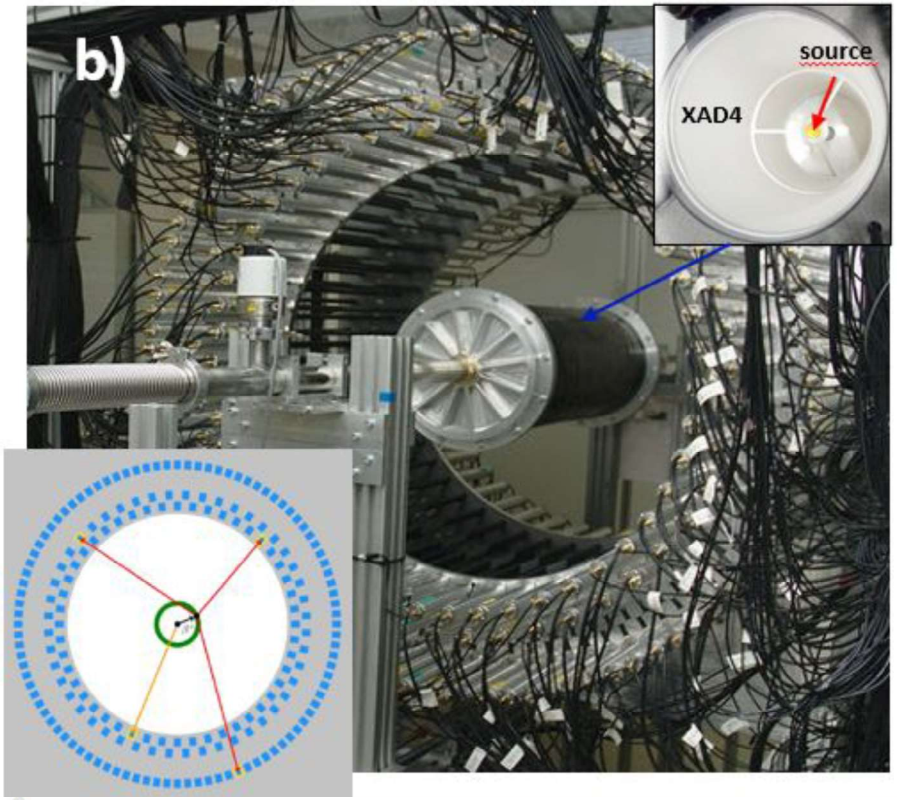
- Small annihilation chamber, R= 7cm
- with internal "bucket" including a positron source surrounded with a layer of porous material XAD4
- 1 or 5 MBq β+ ^{22}Na source placed in the center

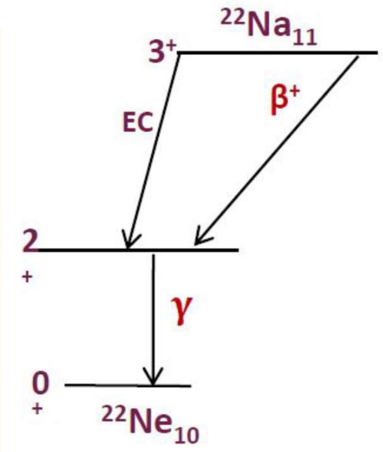


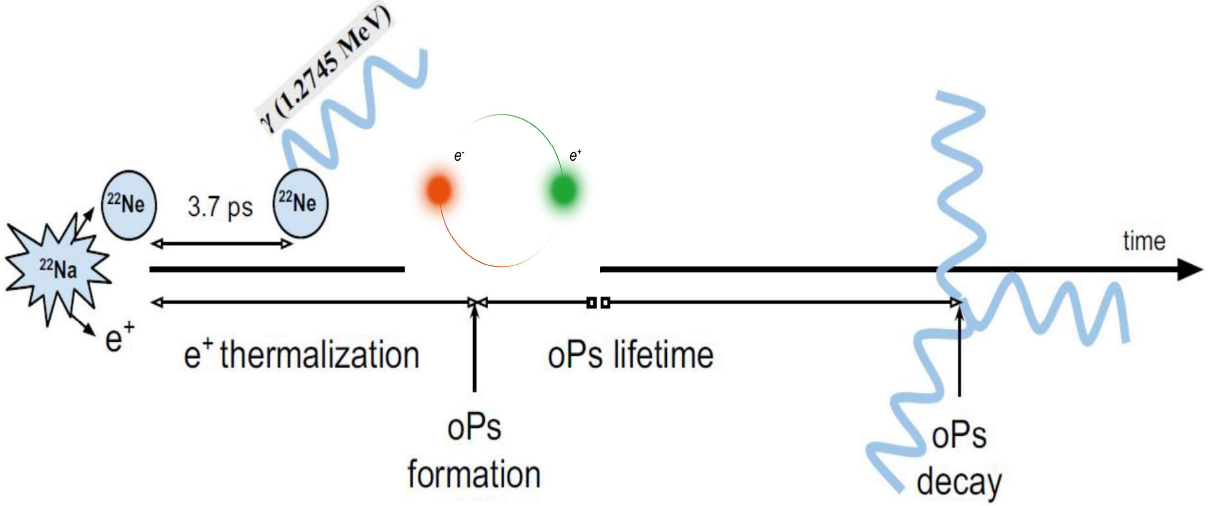
- Extensive-size chamber, R=12 cm
- Walls coated with porous silica material (o-Ps target)
- 10 MBq β+ ^{22}Na source placed in the center

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

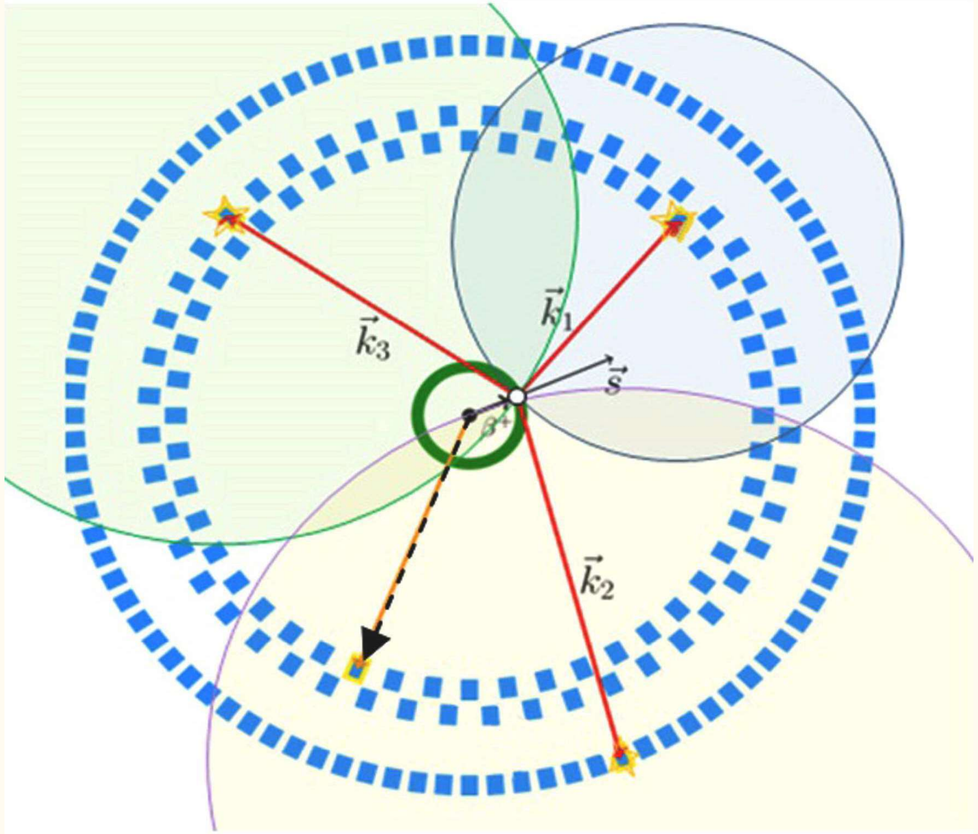




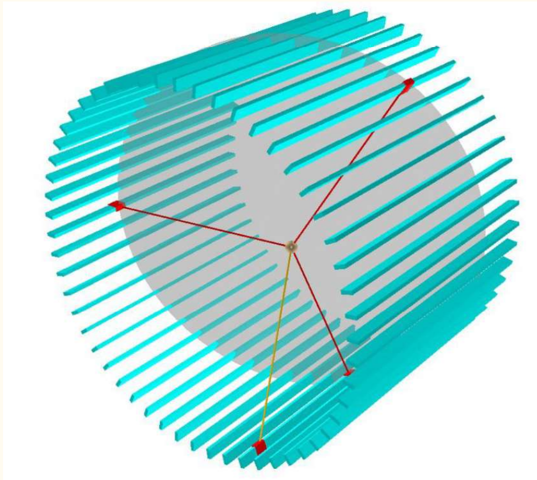




o-Ps→3γ decays reconstruction in J-PET



Trilateration-based reconstruction to determine the o-Ps annihilation point



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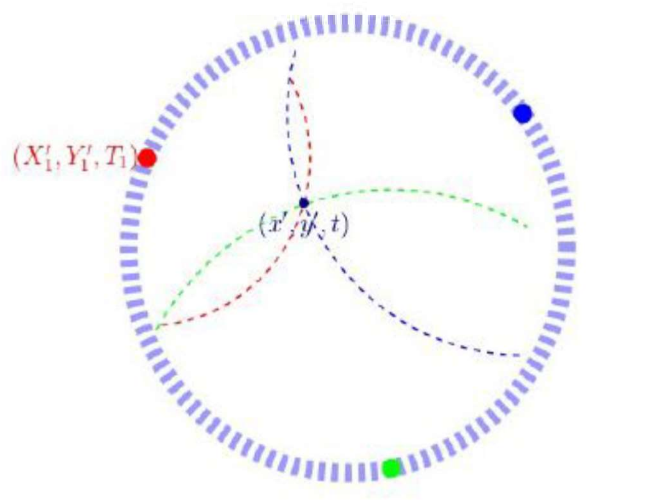


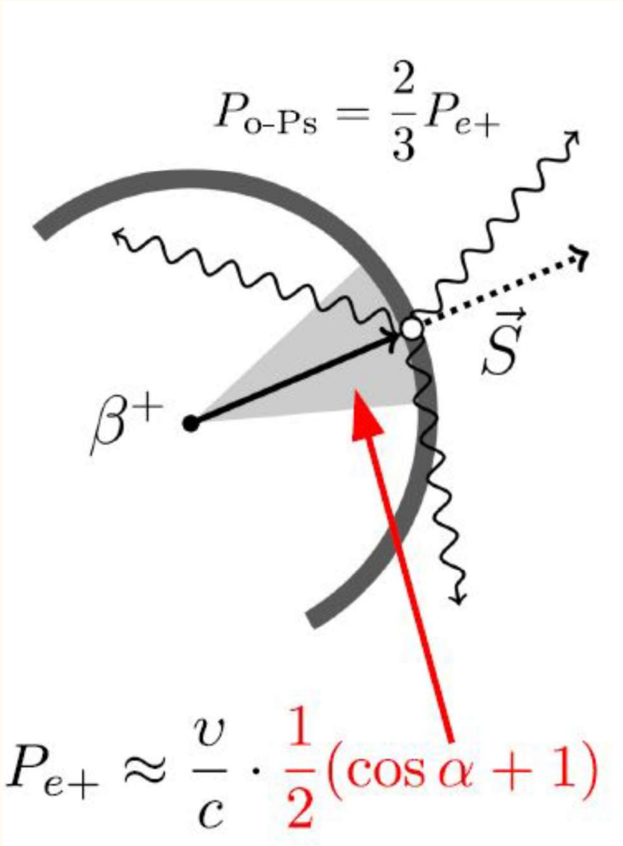
The decay point **(x',y')** in the decay plane and time **t** is an intersection of 3 circles, each corresponding to a possible origin points of the incident γ

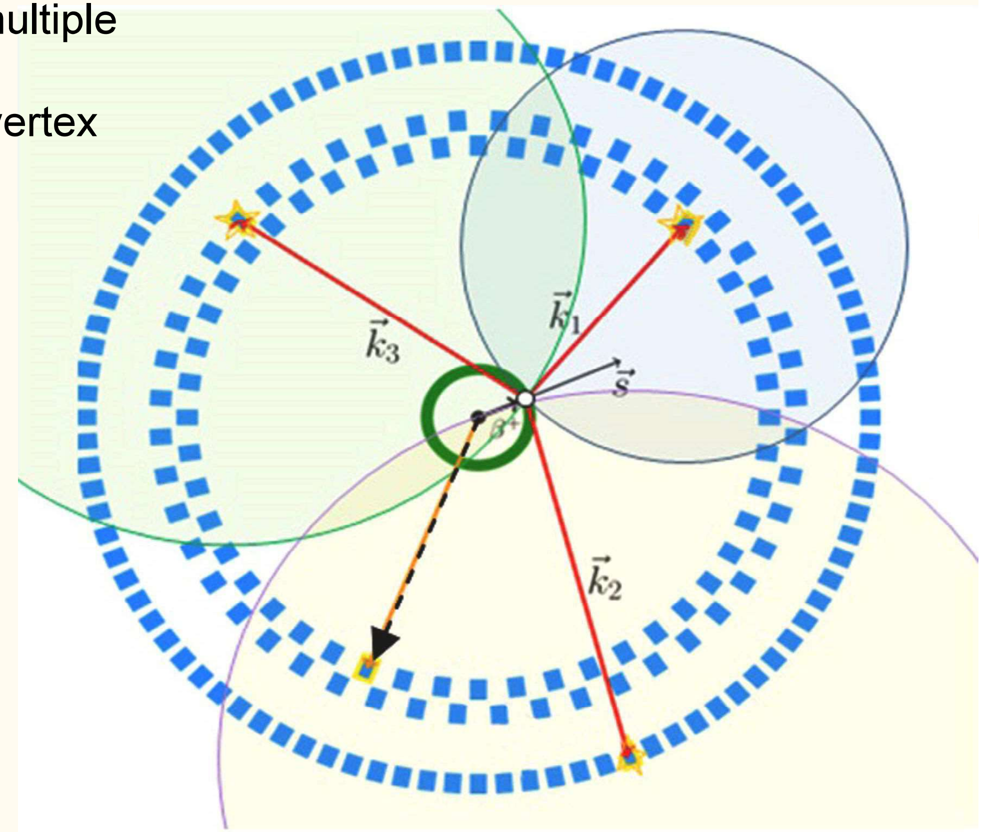
$$(T_i - t)^2 c^2 = (X'_i - x')^2 + (Y'_i - y')^2, \quad i = 1, 2, 3$$

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

o-Ps spin determination in J-PET

✶without magnetic field or polarised positronium source
✶e^+ spin estimated event-by-event recording multiple geometrical configurations
✶ effective polarization depends on o-Ps→3γ vertex resolution

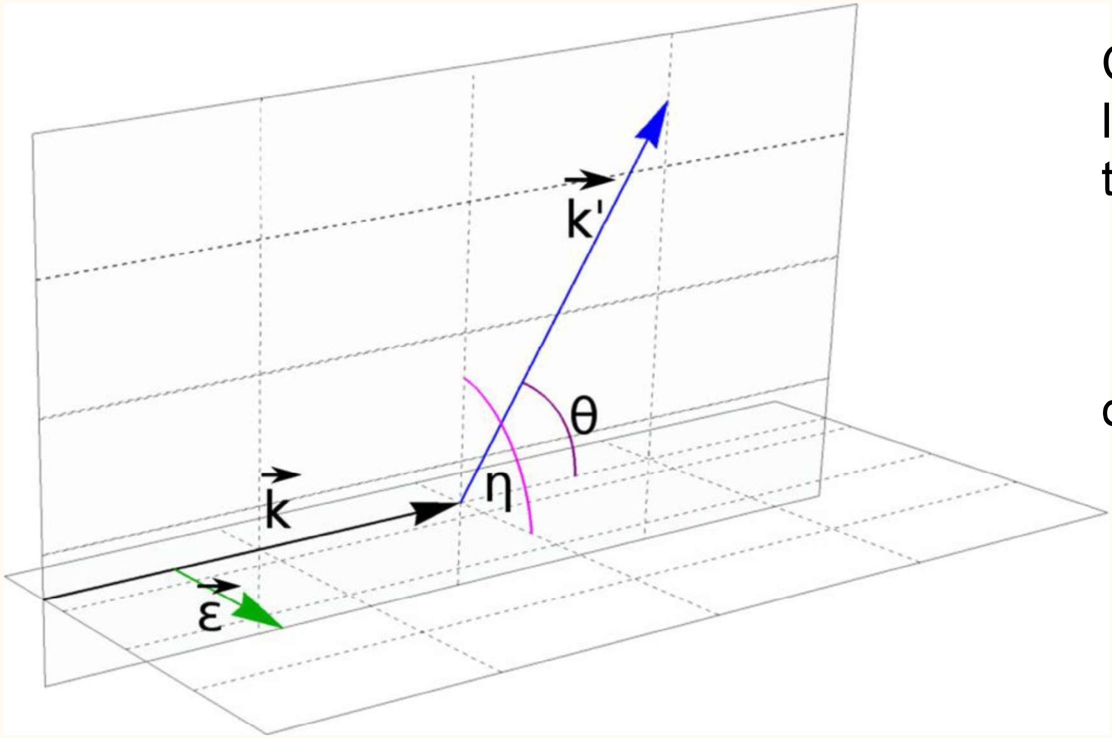




★ parity violation in the beta decay (weak interaction) => e^+ emitted from ^{22}Na source are **longitudinally spin-polarized**
★ o-Ps polarization is by a factor of 2/3 smaller with respect to the spin of the positron polarization since the spin of electrons in the target is not polarized

P. Moskal et al., Acta Phys. Polon. B 47 (2016) 509
M. Mohammed, et al., Acta Phys. Pol. A 132, 1486 (2017)]

determination of annihilation γ polarization in J-PET



Compton scattering is at most likely in the plane perpendicular to the electric vector of the photon

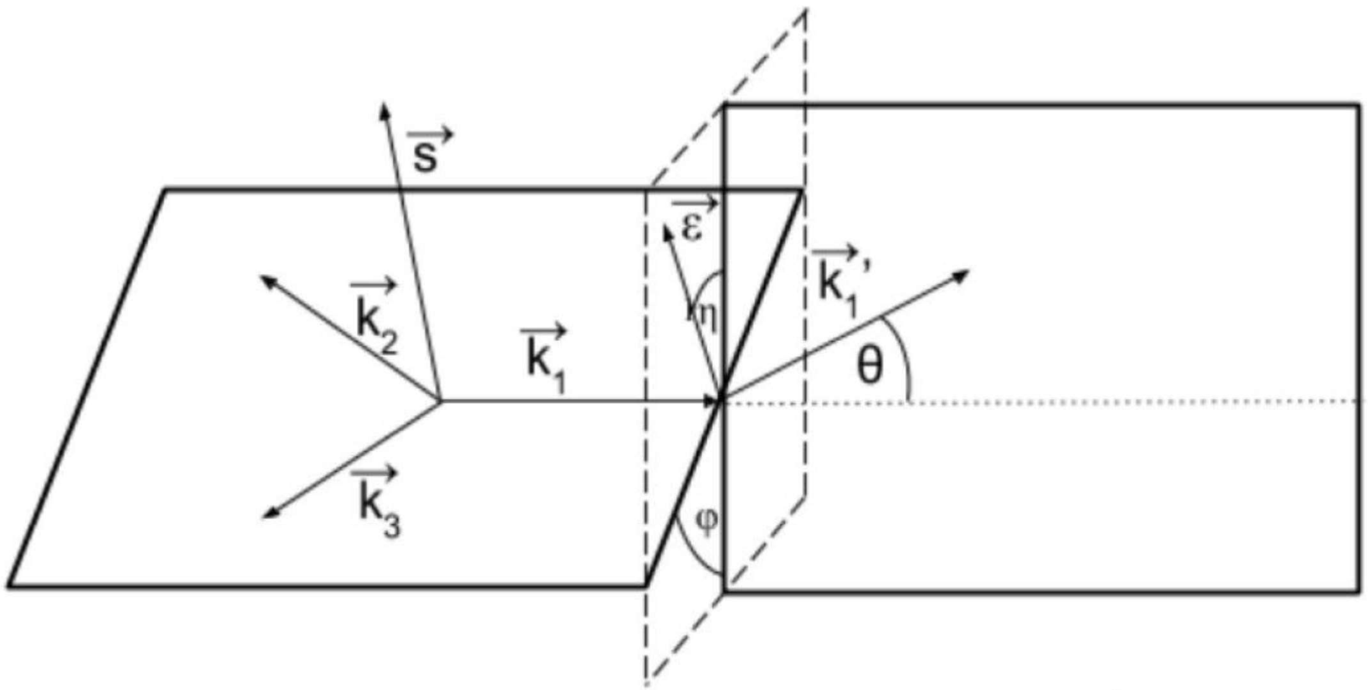
direction of its linear polarization

$$\vec{\varepsilon} = \vec{k} \times \vec{k}'$$

independently of the value of theta the **probability of the scattering has its maximum** value when the **scattering plane is perpendicular to the direction of the electric vector of the primary photon**

P. Moskal et al., Acta Phys. Polon. B 47 (2016) 509
P. Moskal et al., Eur. Phys. J. C78 (2018) 970

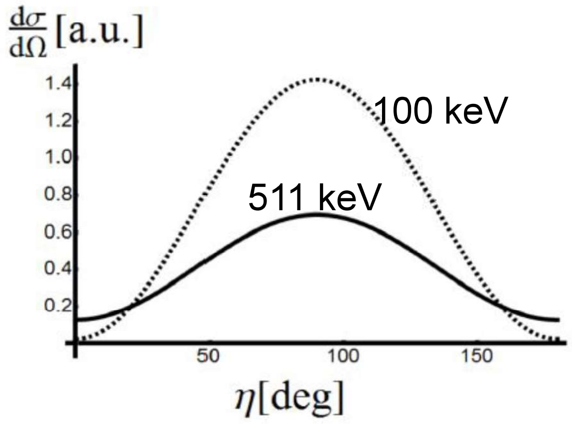
determination of annihilation γ polarization in J-PET



$$\vec{\varepsilon} = \vec{k} \times \vec{k}'$$

$$\frac{d\sigma(E,\theta,\eta)}{d\Omega} = \frac{r_0^2}{2}\left(\frac{E'}{E}\right)^2\left(\frac{E}{E'} + \frac{E'}{E} - 2\sin^2\theta\cos^2\eta\right)$$

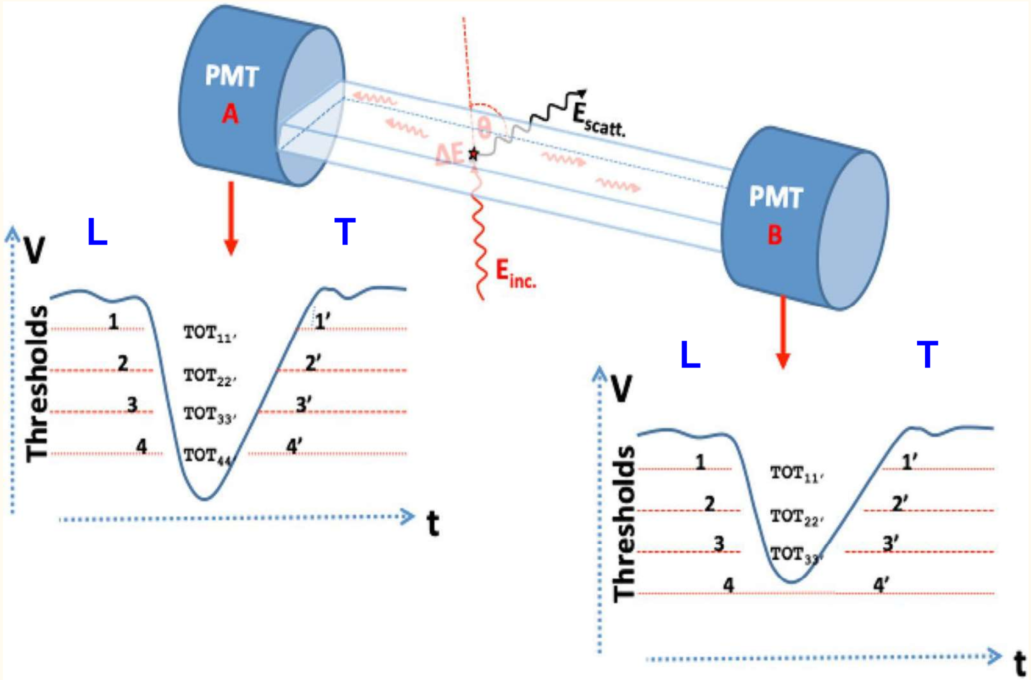
$$E'(E,\theta) = \frac{E}{1 + \frac{E}{m_e c^2}(1 - cos\theta)}$$

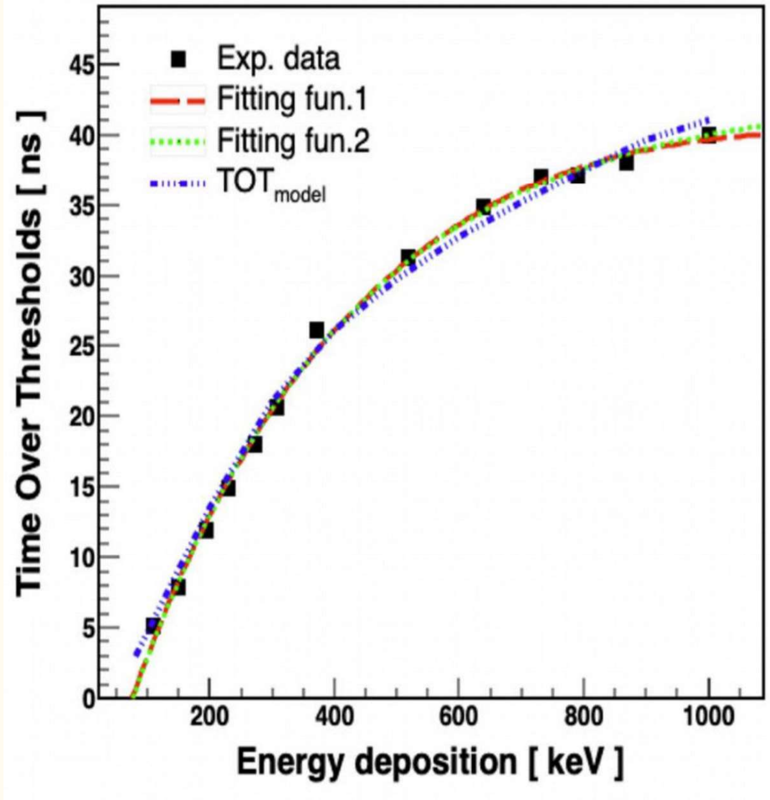


P. Moskal et al., Acta Phys. Polon. B 47 (2016) 509
P. Moskal et al., Eur. Phys. J. C78 (2018) 970

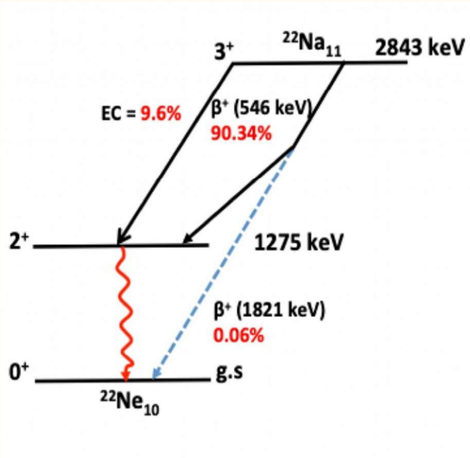
cross-section is maximum for η = 90deg

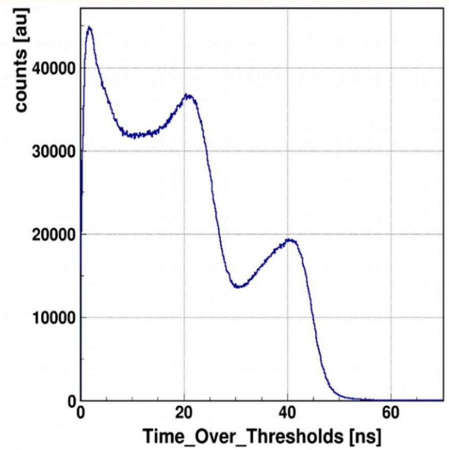
TOT as a measure of energy





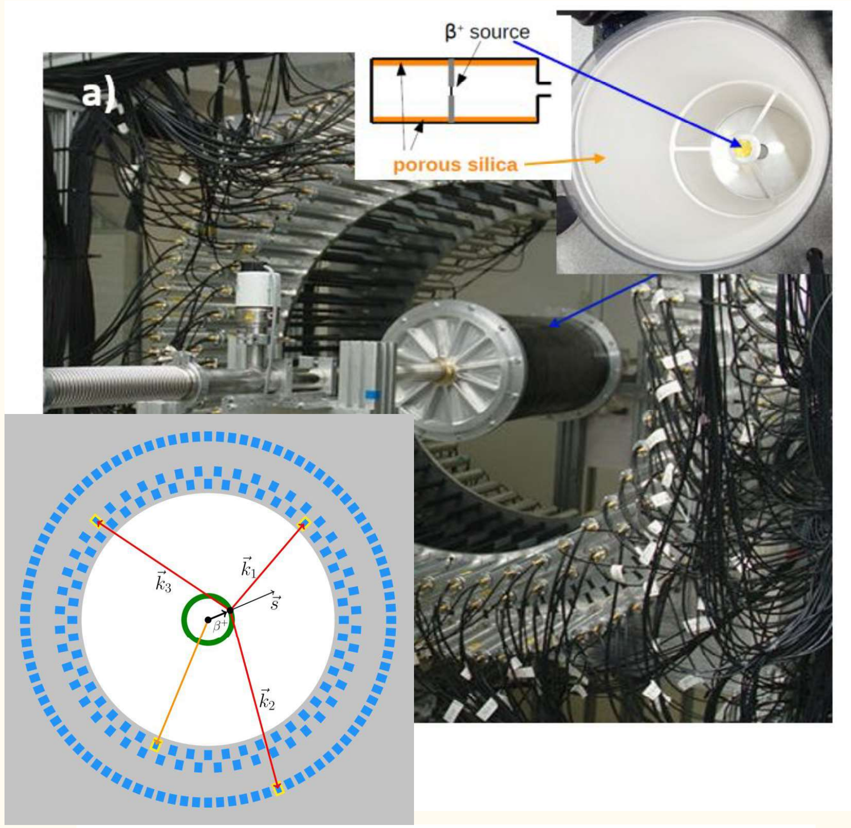
Time Over Threshold (TOT) of PMT signals from a scintillator strip corresponds to ɣ deposited energy

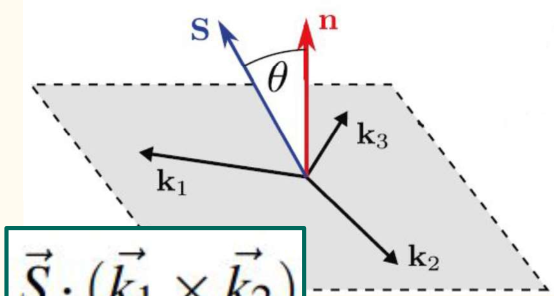




[S. Sharma, eta al., EJNMMI Phys. 7, 39 (2020)
S. Sharma, eta al., EJNMMI Phys. 10(28) (2023)]

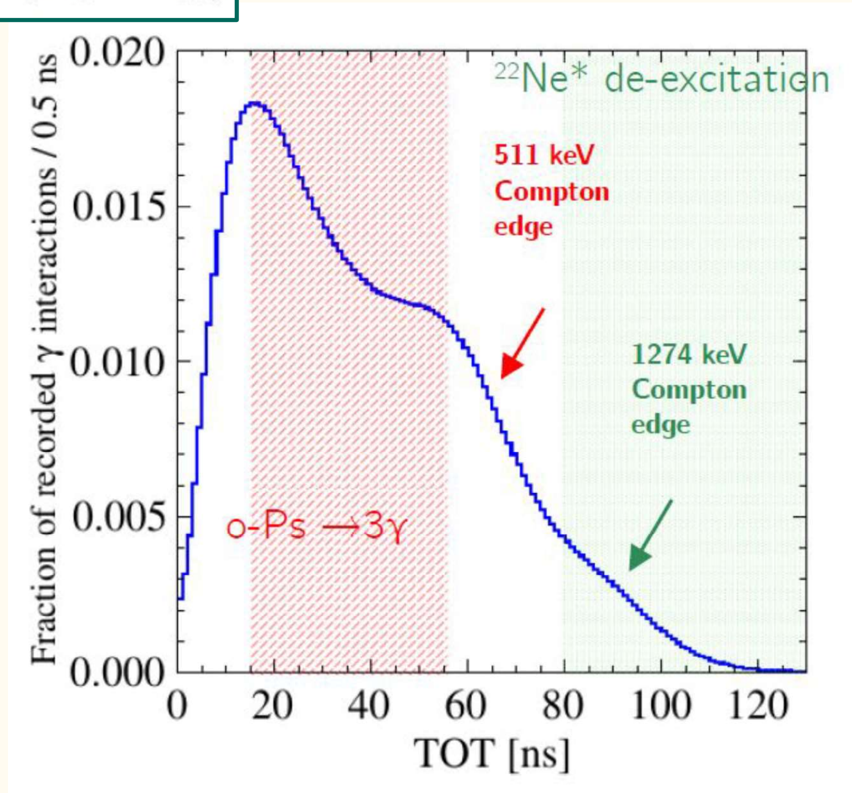
Towards <O$_{CPT}$> determination: Identification of o-Ps→3γ events

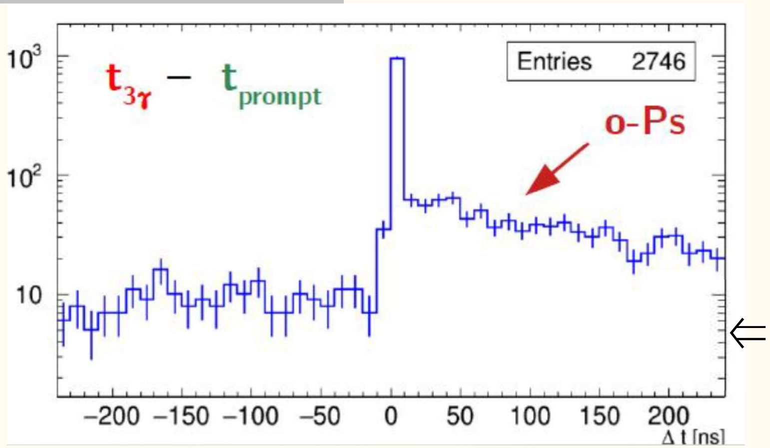




$$\vec{S}\cdot(\vec{k}_1 \times \vec{k}_2)$$

26 days measurement
10MBq Na source
7.3×10^6 event candidates





⇐ **o-Ps presence in positronium lifetime distribution**

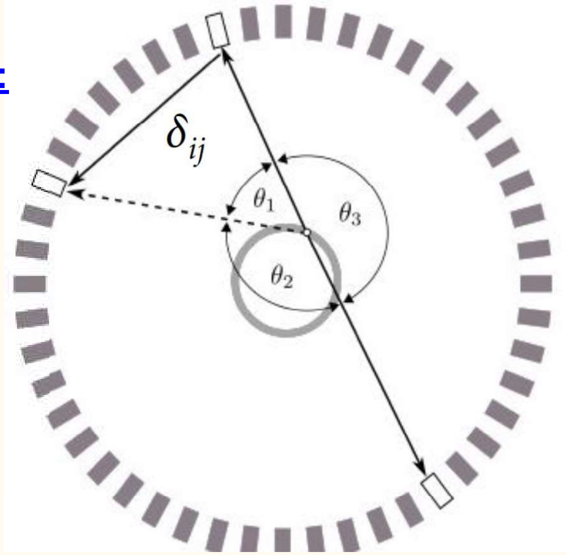
event time window: 2.5ns

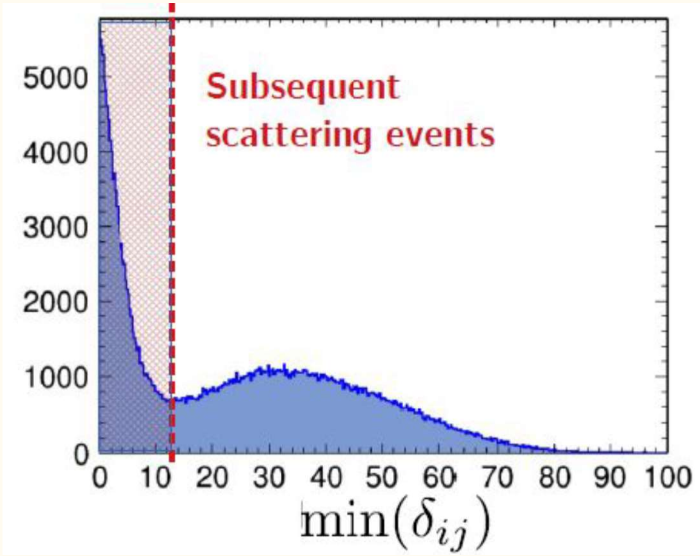
Towards <O$_{CPT}$> determination: Background subtraction

Secondary Compton scatterings:

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

computed for each pair of annihilation photon candidates i and j (i,j=1,2,3)

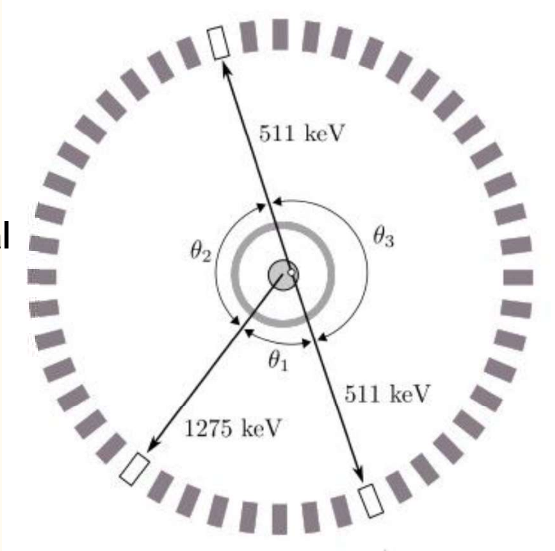


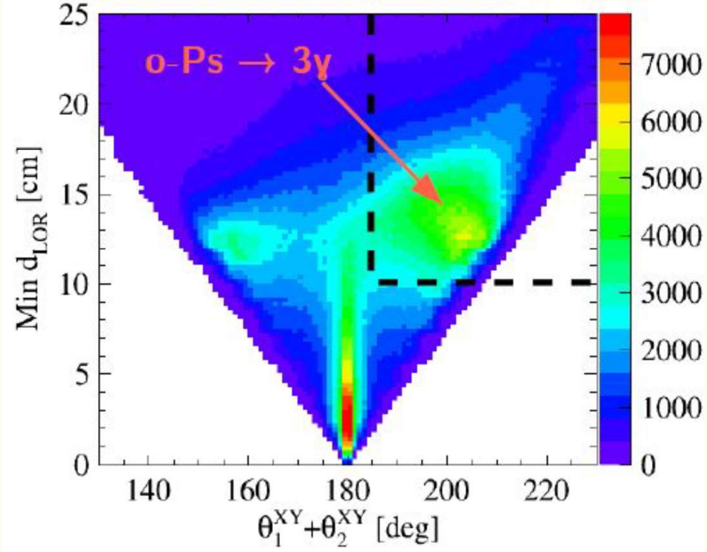


2γ from the β+ source setup coincident with de-excitation photon:

✶ distance between the β+ source location and the closest hypothetical 2γ annihilation point on a LOR between two recorded photon interactions

✶ the sum of the two smallest angles between azimuthal coordinates of the recorded γ interaction points



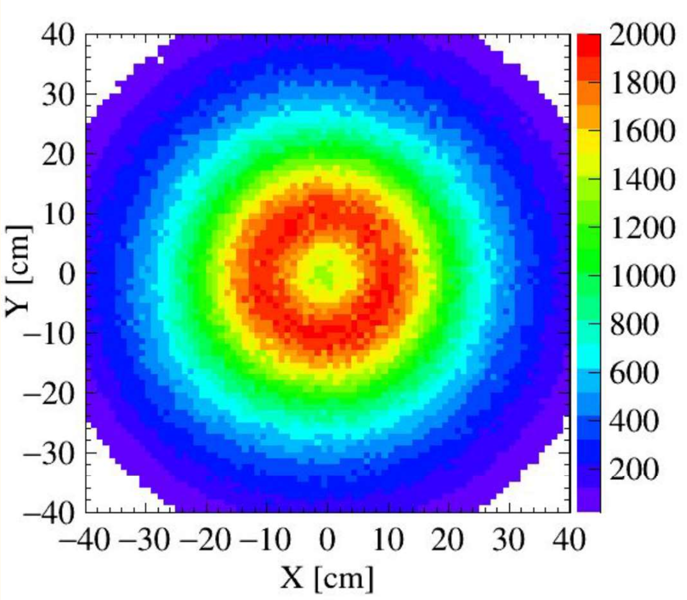


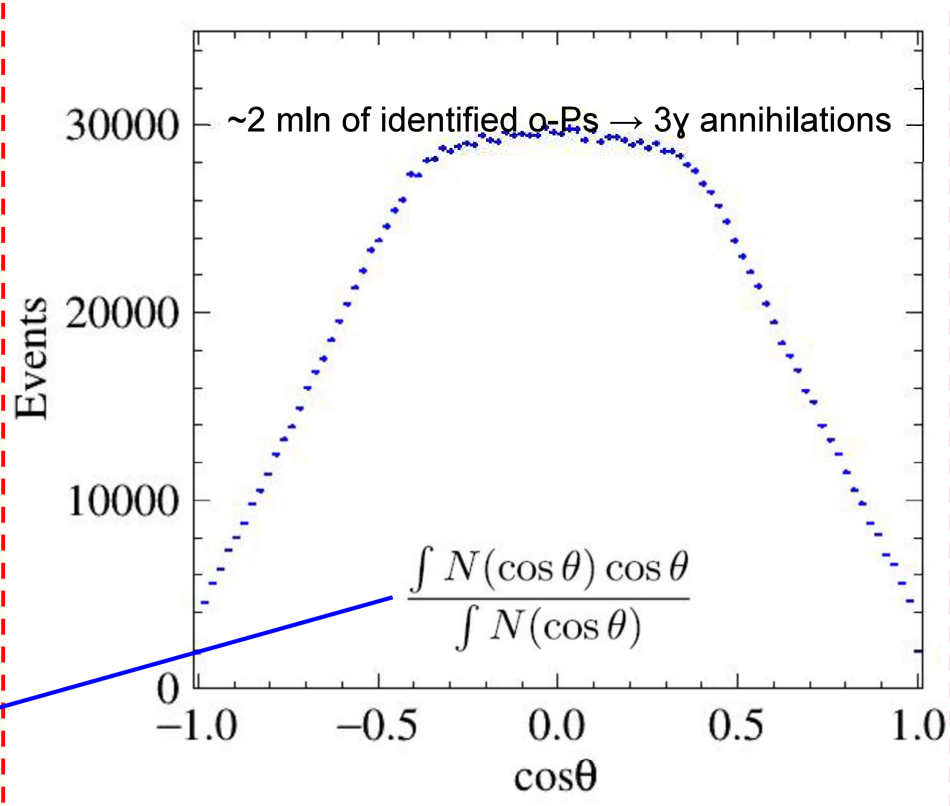
Towards <O_{CPT}>: determination of the CPT - asymmetric observable

$$O_{CPT} = \vec{S} \cdot (\vec{k_1} \times \vec{k_2}) / |\vec{k_1} \times \vec{k_2}| = cos\theta$$

the angle between the direction of initial spin of the o-Ps atom and the normal to the decay plane

3γ image of the o-Ps production chamber in the tranverse view of the detector (the first!)





$$<O_{CPT}> = 0.00025 \pm 0.00036$$

P. Moskal, et al., Nature Commun. 12, 5658 (2021)

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

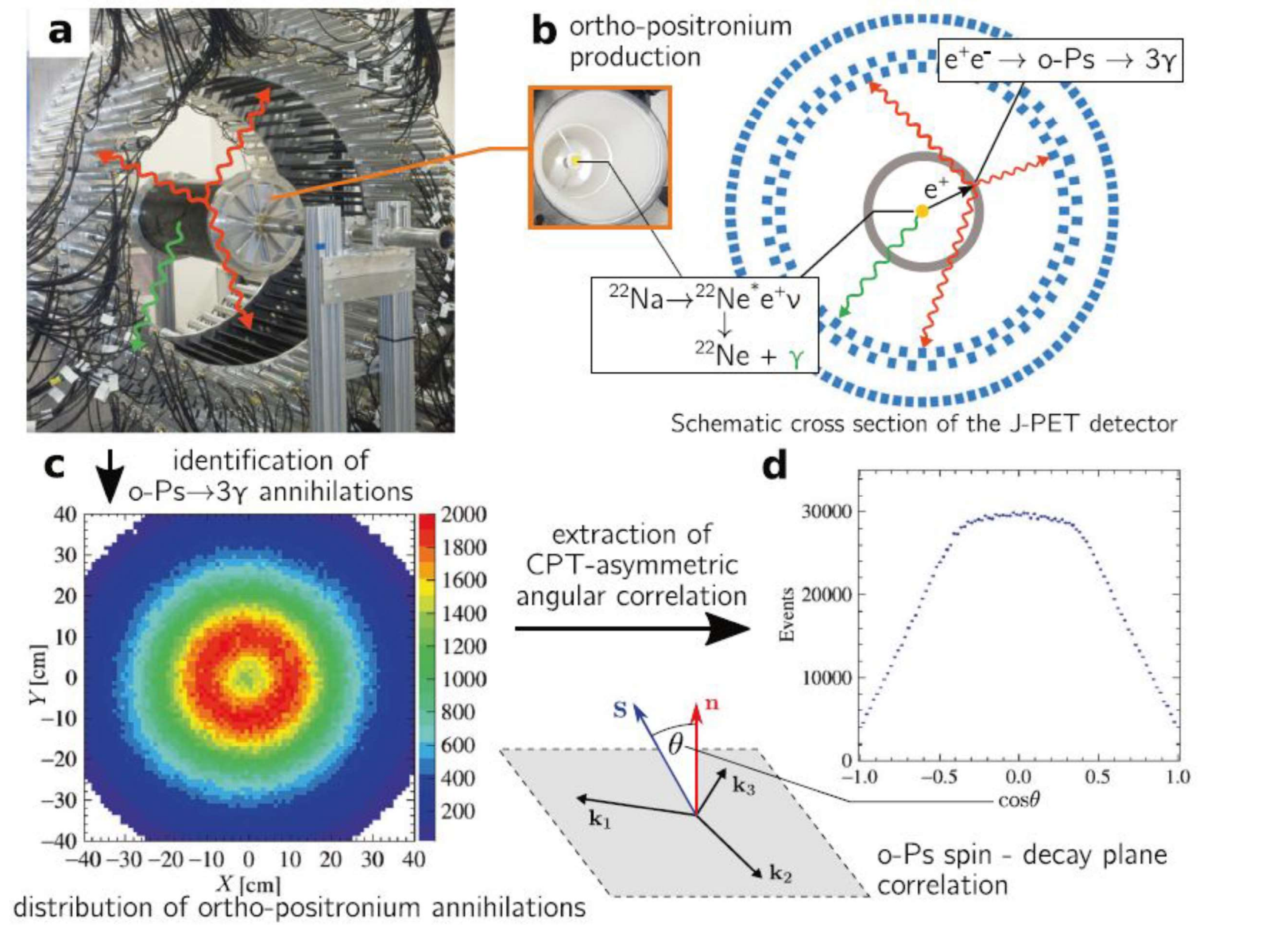
the level of observed CPT violation (after correction of analyzing power - 37.4%)

stat error : 3.3 x 10^{-4}
syst error: 1.4 x 10^{-4}

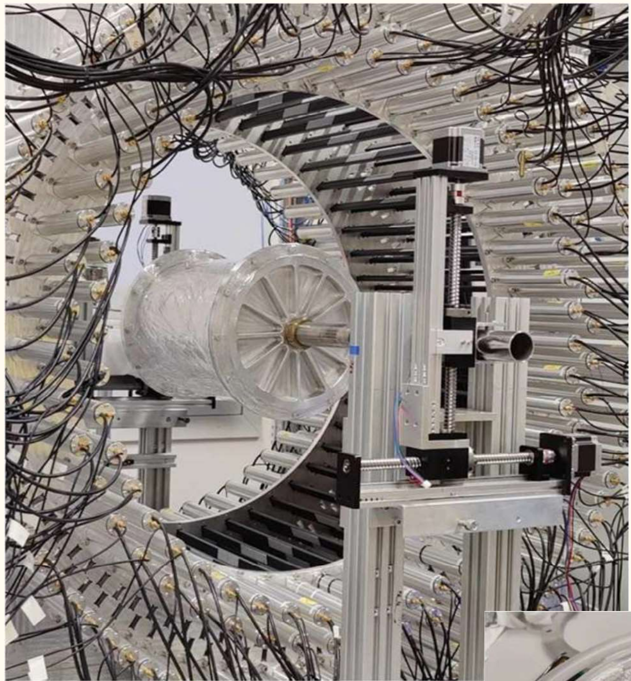
C_{CPT} = 0.0026 ± 0.0031 [Phys. Rev. Lett. 91 (2003) 263401]

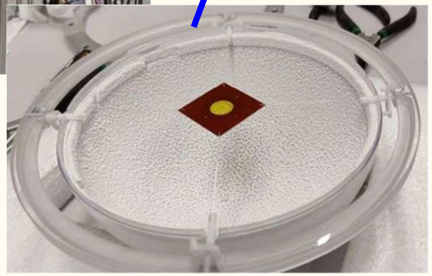
Towards <O_{CPT}>: summary

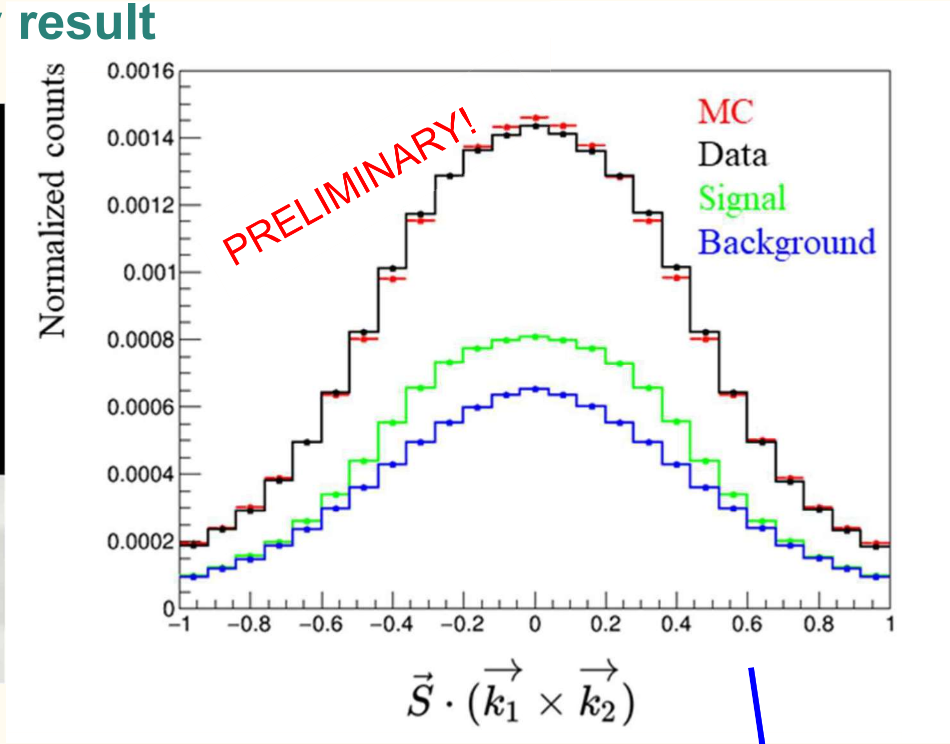
26 days of measurement, sodium source activity 10 MBq, 7.3×10^6 event candidates



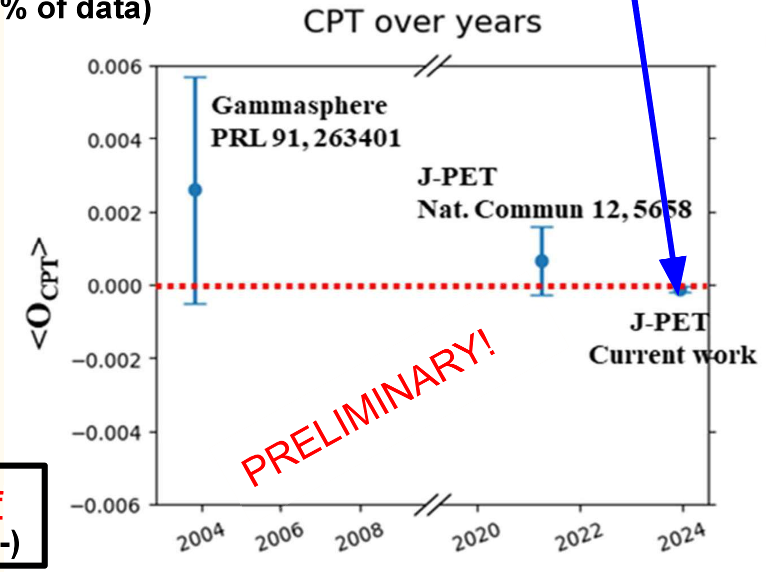
Towards <O_{CPT}>: new preliminary result







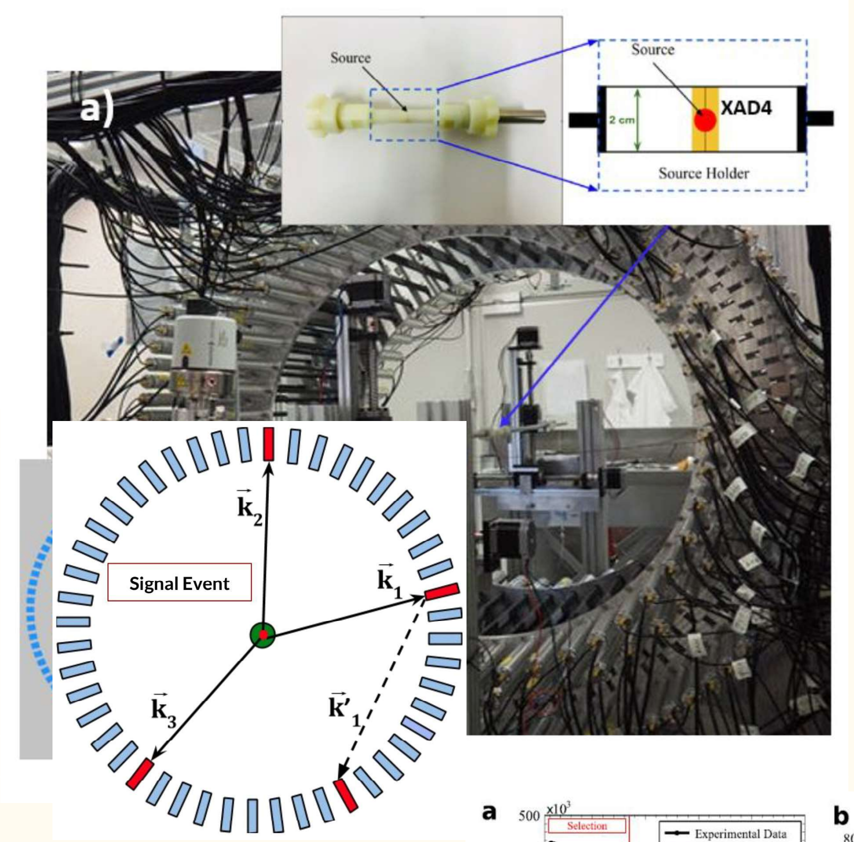
$2.8 * 10^6$ identified o-Ps events from data with 1 MBq source activity (22% of data)



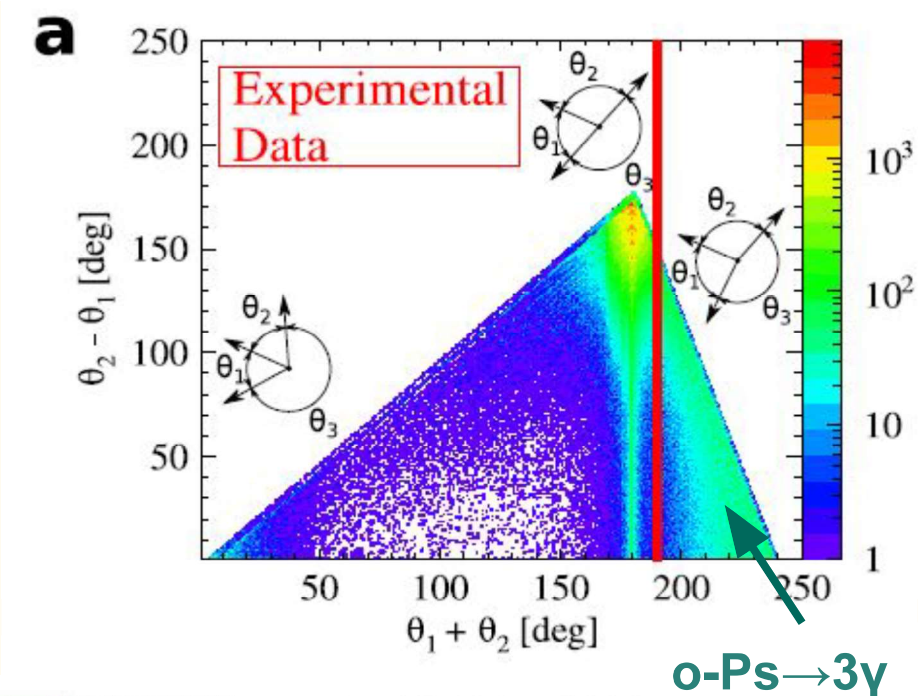
- ➔ **Spherical annihilation chamber** is used to increase positronium formation
- ➔ ^{22}Na source with activity of 1 MBq and 4 MBq
- ➔ 16 months of continuous data-taking (2021 - 2022)
- ➔ about 40mln of event candidates

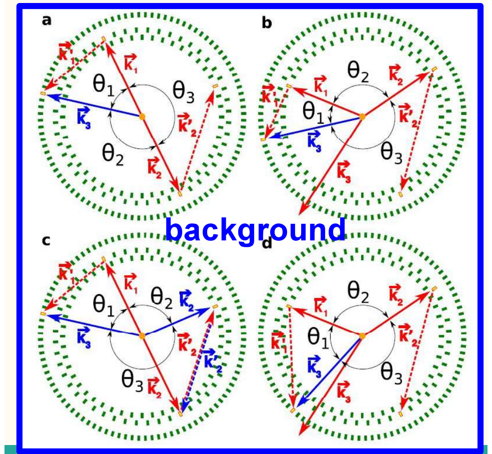
The achieved precision is a factor of four better than the previous results :-)

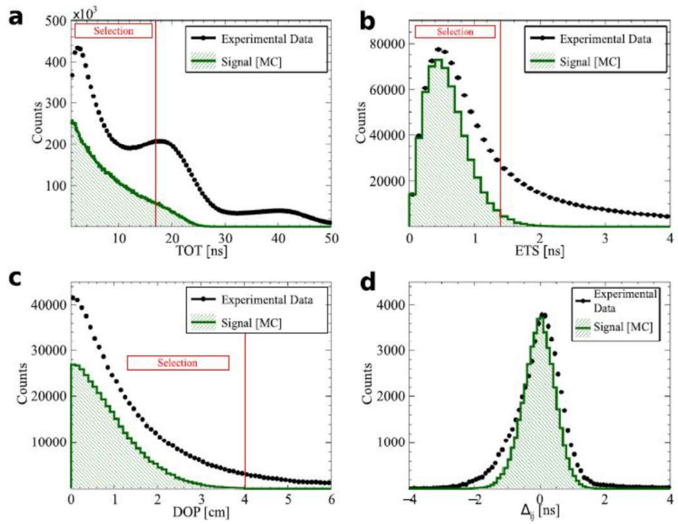
Towards $\langle O_{CP} \rangle$ determination: Identification of o-Ps→3γ events

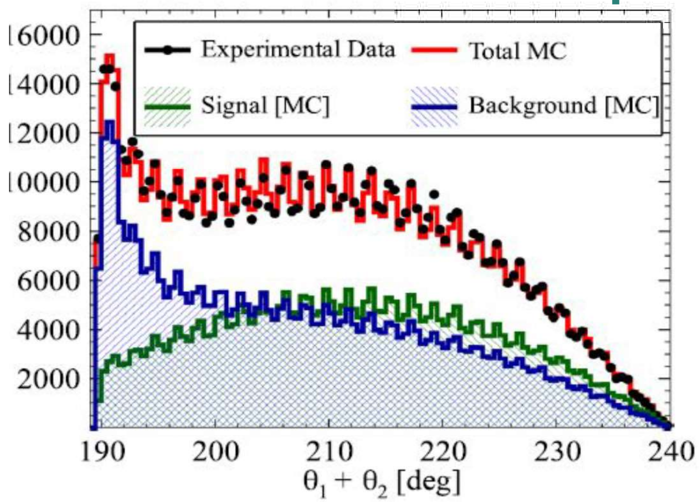


$$\vec{k}_1 > \vec{k}_2 > \vec{k}_3 \qquad \vec{\varepsilon}_i \bullet \vec{k}_j \qquad \vec{\varepsilon}_i = \vec{k}_i \times \vec{k}'_i$$

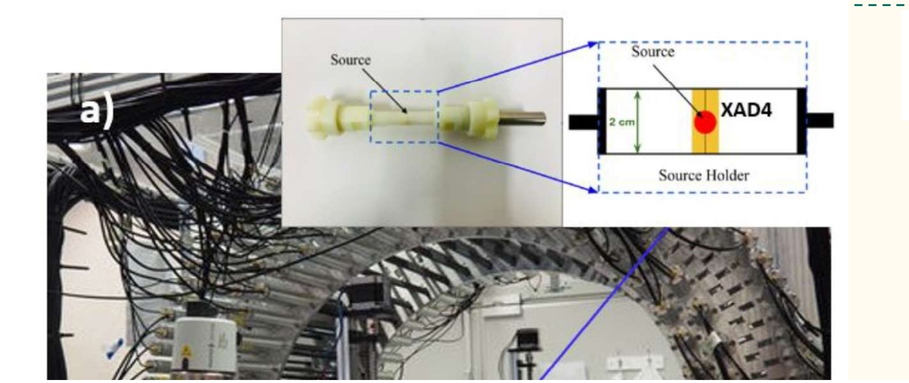




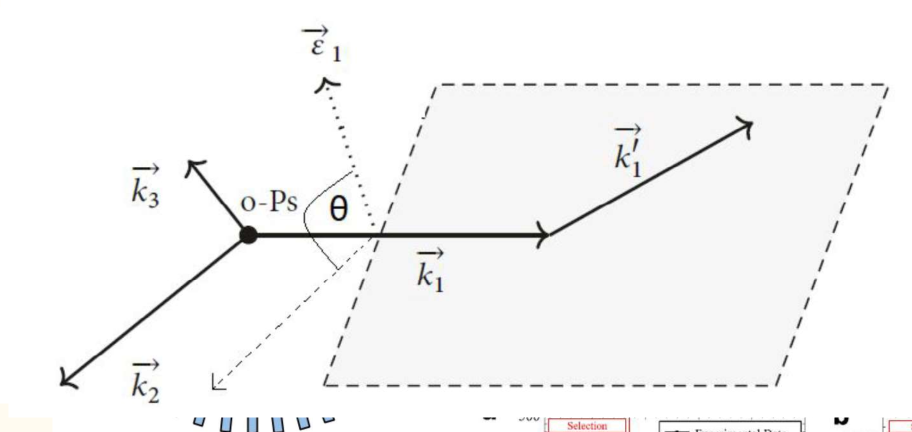


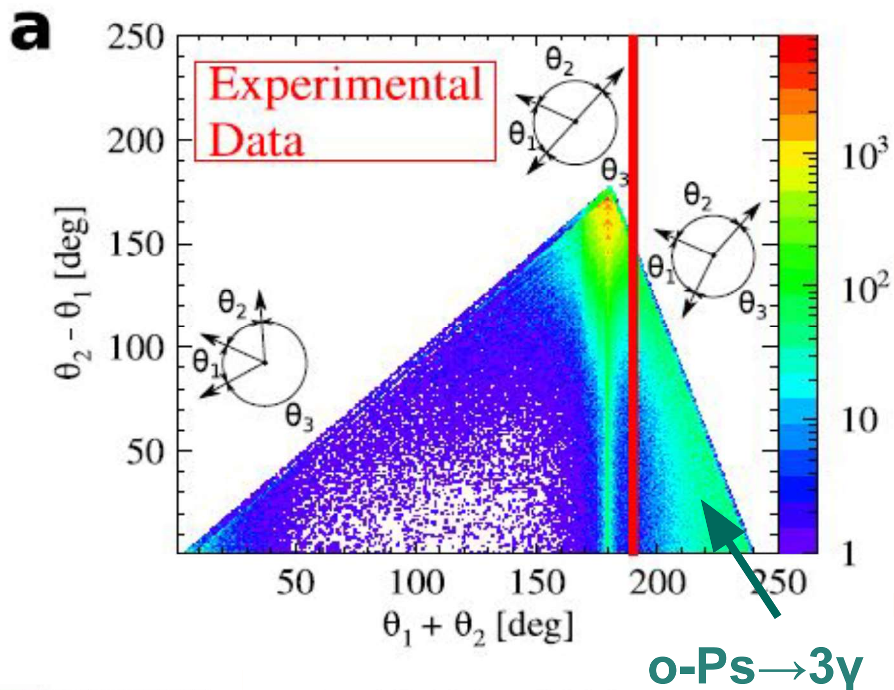


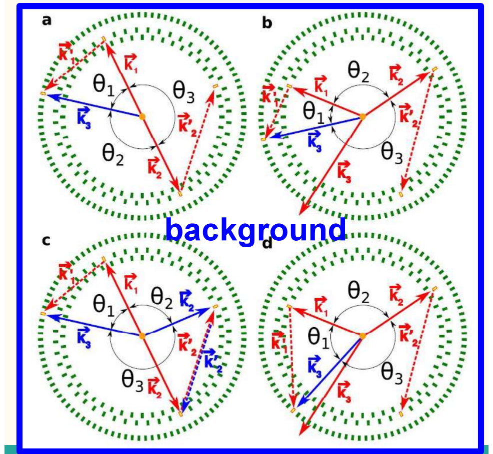
Towards <O_{CP}> determination: Identification of o-Ps→3γ events

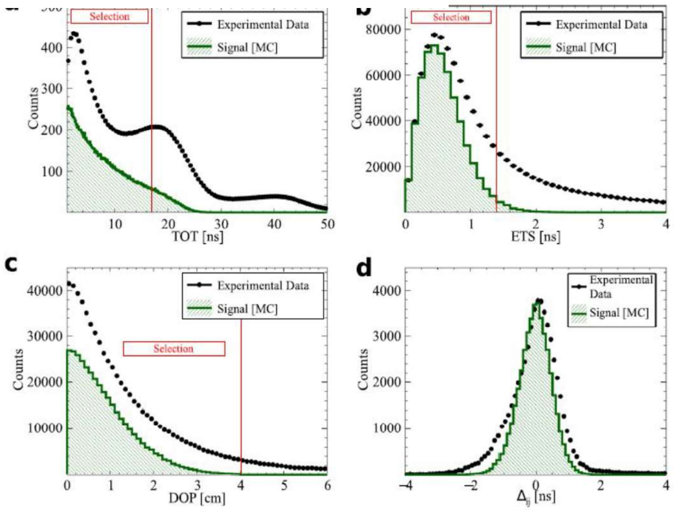


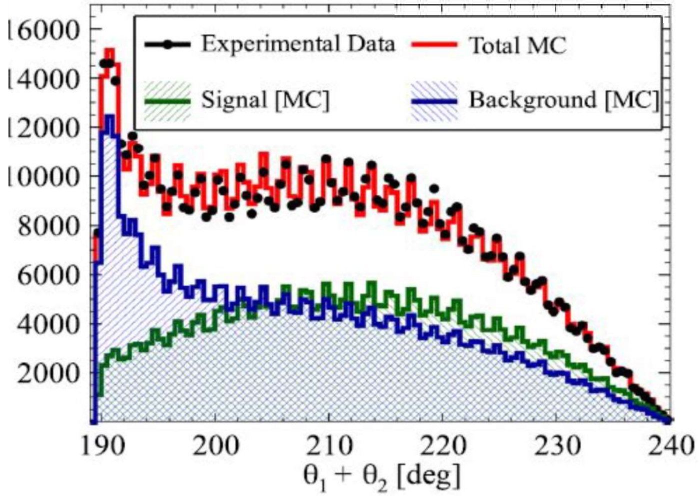
$\vec{k}_1 > \vec{k}_2 > \vec{k}_3$ $\quad \vec{\varepsilon}_i \cdot \vec{k}_j$ $\quad \vec{\varepsilon}_i = \vec{k}_i \times \vec{k}'_i$



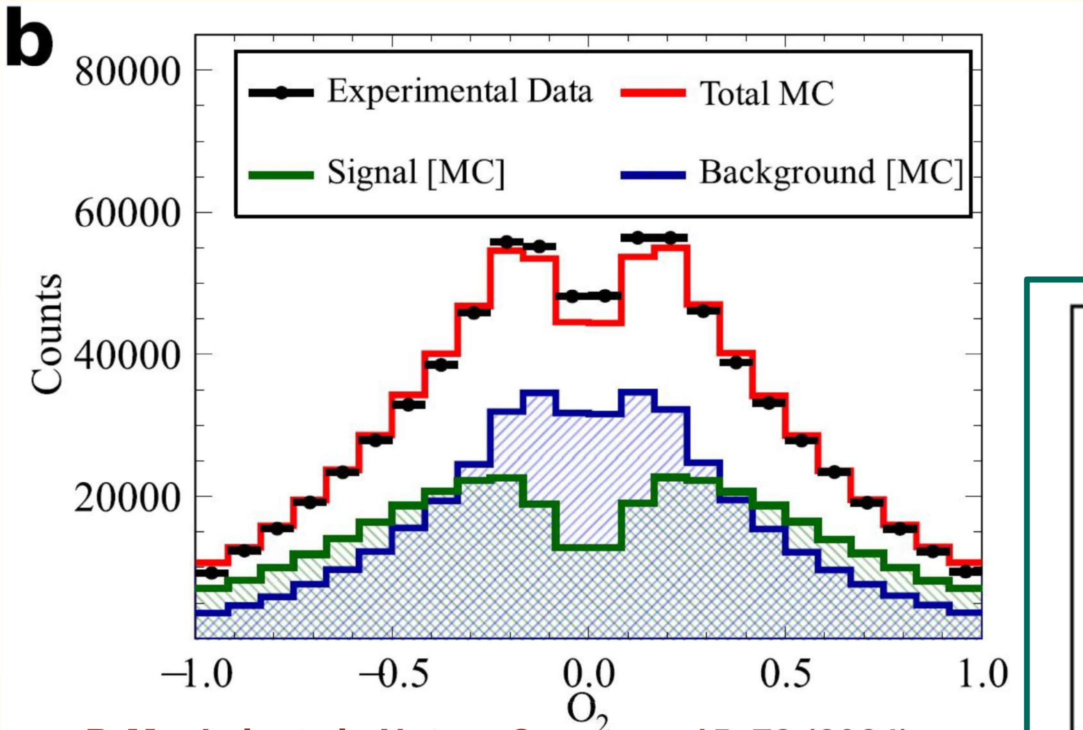








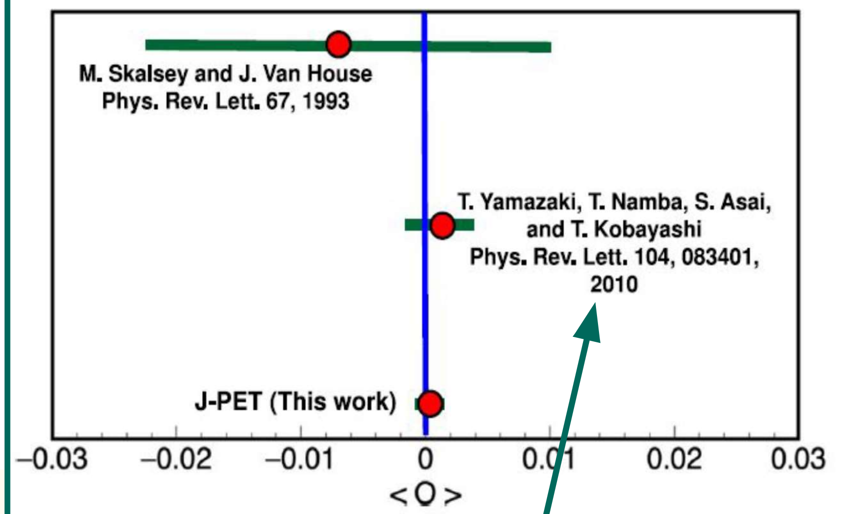
Towards $\langle O_{CP} \rangle$: determination of the CP observable $O_{CP} = \vec{k}_1 \cdot \vec{\varepsilon}_2 / |\vec{k}_1||\vec{\varepsilon}_2| = \cos\theta$



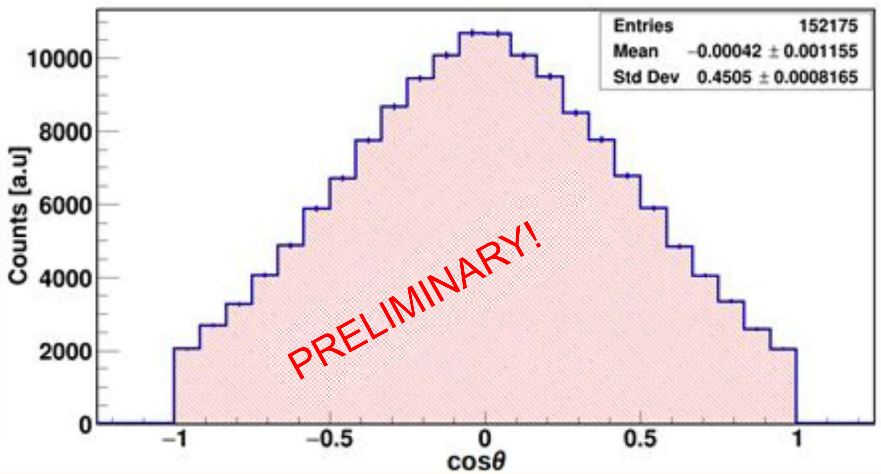
P. Moskal, et al., Nature Commun. 15, 78 (2024)

122 days of measurement, four data runs: 2 with ^{22}Na source of 5 MBq activity and 2 with activity of 1 MBq, 7.7 × 10^5 events

$$< O_{CP} >= 0.0005 \pm 0.0007_{stat.}$$



$$< C_{CP}[(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))] >= 0.0013 \pm 0.0022_{stat.}$$



NEW analysis ongoing for 250 days of measurement, ^{22}Na source of 0.702 MBq

13% of data sample

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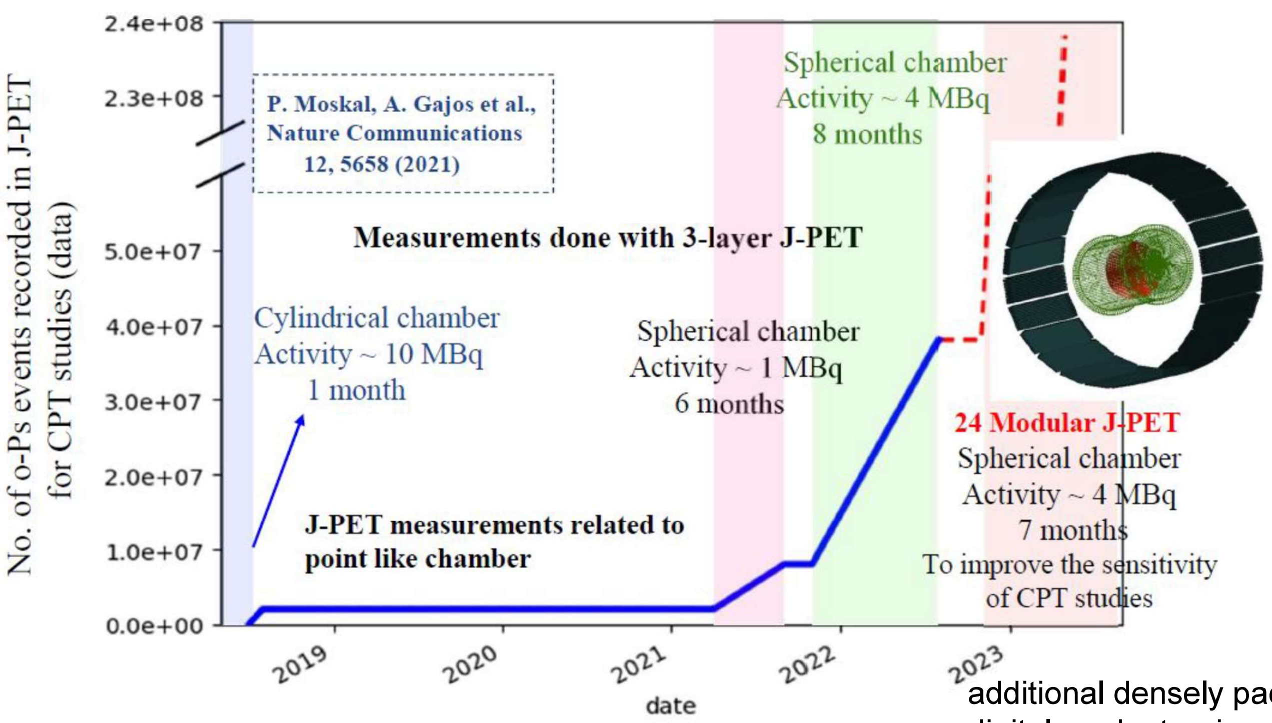
Summary and Perspectives

- With J-PET scanner, we are able to perform exclusive measurement of ortho-positronium (o-Ps) annihilation into 3 photons
  - o-Ps spin event-by-event estimation
  - o-Ps→3γ decays reconstruction including determination of the annihilation point in an extensive-size medium
  - determination of polarization of annihilation γ quanta

- **Sub-permil precision of the CPT and CP tests reached with the first J-PET measurements: over factor of 3 better** than the previous results

- 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



additional densely packed layer of plastic scintillators with a fully digital readout -> increase of detection efficiency by factor of 64

Thank you for your attention