Exploring the limits of CPT symmetry in ortho-positronium decays with J-PET

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Jagiellonian University, Poland

J-PET (Jagiellonian-PET Tomograph)

J-PET Collaboration headed by Prof. Paweł Moskal

P. Moskal, Acta Phys. Pol. B 47, 509 (2016)

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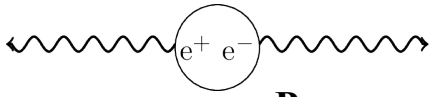
Motivation

- Testing discrete symmetry in the **charged leptonic** sector.
- Search for the CPT Symmetry violation in ***ortho-positronium decays.***
- Testing CPT symmetry using the **angular correlations** between spin and decay plane of oPs → 3ɣ.
- Searching for non-zero expectation value of **CPT odd** angular correlation operators.

Positronium - a bound state of **e^+ and e^-**

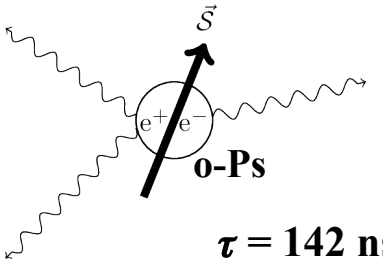
para-positronium $^1S_0$



p-Ps

τ = 125 ps

ortho-positronium $^3S_1$



o-Ps

τ = 142 ns

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

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

$$< O^{(-)}_{CPT} > \stackrel{?}{=} 0$$

W. Bernreuther, Z. Phy. C 41, 143 (1988)

P. Moskal, Acta Phys. Pol. B 47, 509 (2016)

CPT symmetry test in o-Ps→3γ decay

Experimental search for CPT violating decay processes in positronium using $\vec{S} \cdot (\vec{k_1} \times \vec{k_2})$

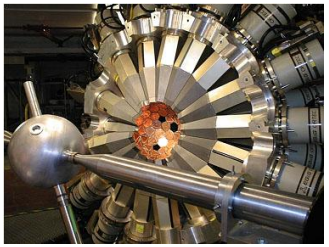
Main aim

Gammasphere detector

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

PRL 91, 263401

$\mathcal{O}(10^{-3})$

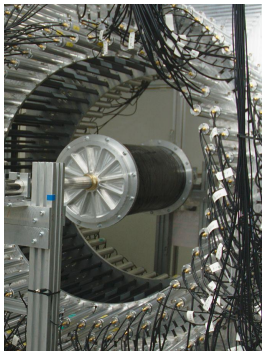


J-PET

$C_{CPT} = (6.7 \pm 9.5) \times 10^{-4}$

Nat. Commun 12, 5658

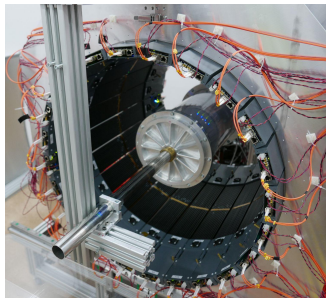
$\mathcal{O}(10^{-4})$



Modular J-PET

To extend the sensitivity

$\mathcal{O}(10^{-5})$



Physical sensitivity limit

False asymmetry from γγ interactions

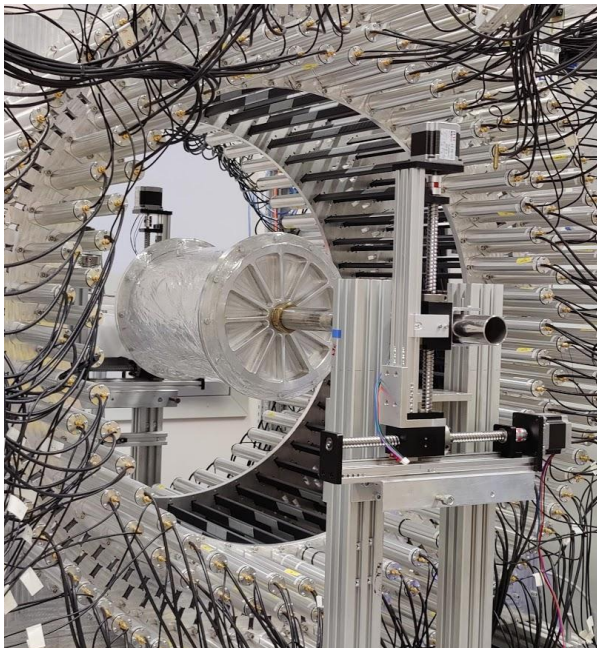
Z. Phy. C 41, 143 (1988)

$\mathcal{O}(10^{-9})$

Precision

W. Bernreuther, Z. Phy. C 41, 143 (1988)

The J-PET detector



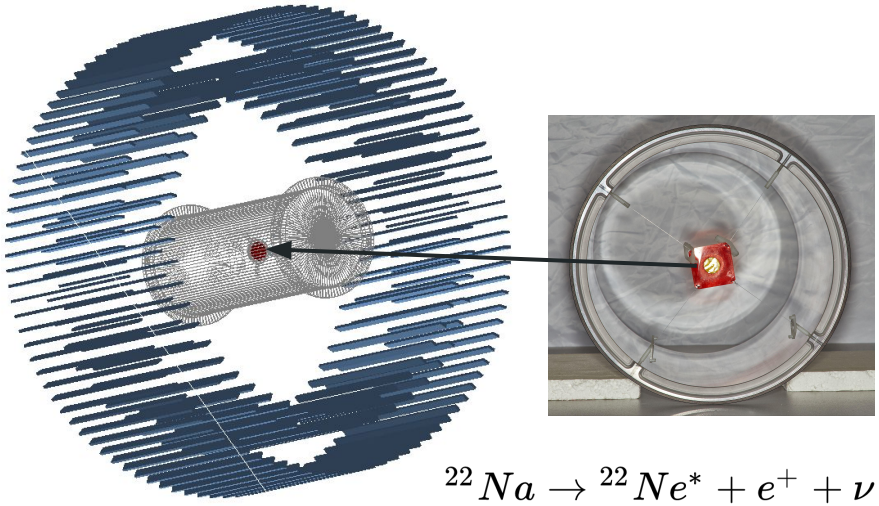
Jagiellonian Positron Emission Tomograph

- A cost-effective PET scanner build from **192 plastic scintillators.**
- Detects photons based on Compton scattering.
- Time resolution ~ 250 ps & Angular resolution ~ 1°
- Applications in fundamental and medical research.

Talk by D. Kumar* on 24 August in *Detector R&D and Data Handling section

Annihilation chamber

- ❑ **β^+ emitter** source placed at the center of chamber.
- ❑ Coating of **porous silica** on the inner walls of chamber to enhance positronium (Ps) formation.
- ❑ Annihilation chamber is **vacuum**

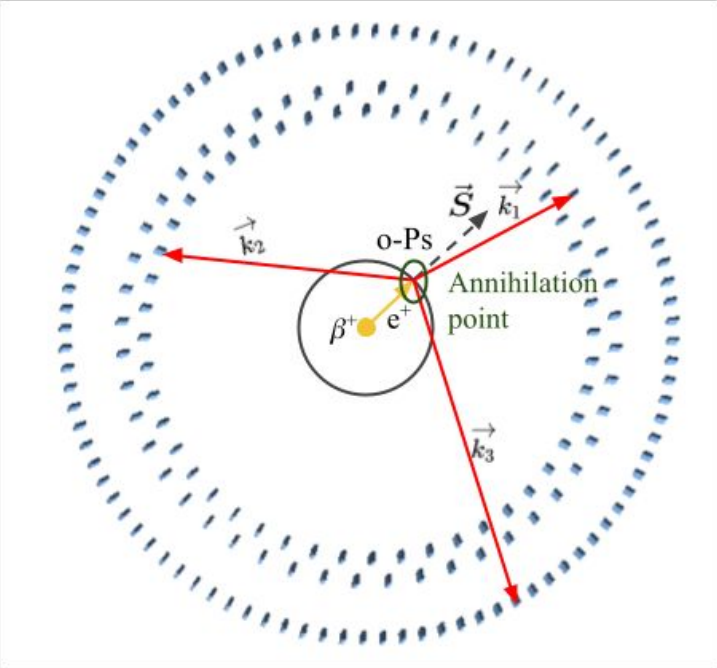


$$^{22}Na \rightarrow {}^{22}Ne^{*} + e^{+} + \nu$$

Geometrical representation of annihilation chamber inside the J-PET detector

S. Niedźwiecki, Acta Phys. Pol. B 48, 1567 (2017)

CPT odd operator study with J-PET

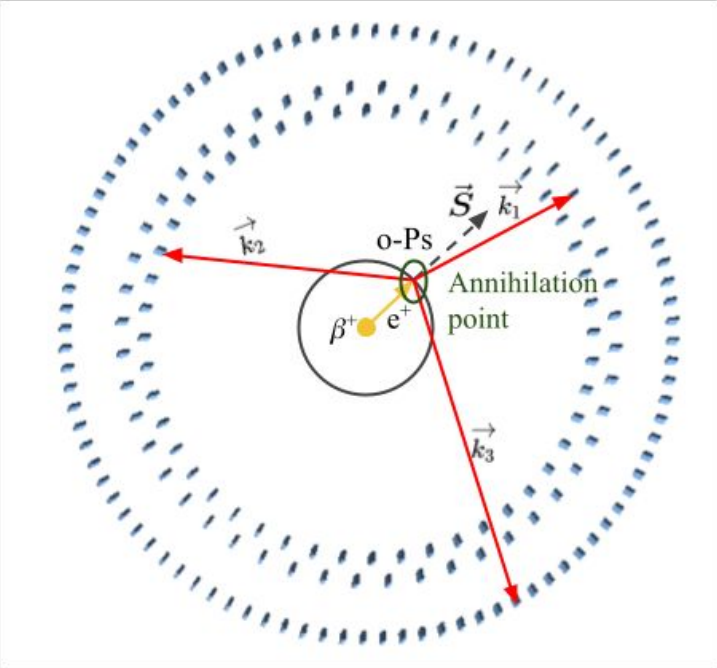


$$e^+e^- \rightarrow o\text{-}Ps \rightarrow 3\gamma$$

- Trilateration method: o-Ps annihilation point
- **Spin** of o-Ps is estimated event-by-event
- Direction of photons' momenta
- $\vec{S} \cdot (\vec{k_1} \times \vec{k_2})$: CPT - violation sensitive operator

A.Gajos, NIM A 819 (2016), 54

CPT odd operator study with J-PET



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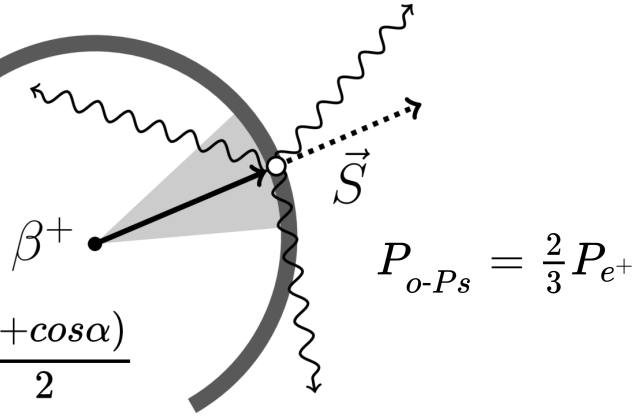
$$O_{CPT} = \hat{S}.\frac{(\vec{k_1}\times\vec{k_2})}{|\vec{k_1}\times\vec{k_2}|} = cos\theta$$

$$C_{CPT} = \frac{<O_{CPT}>}{P}$$



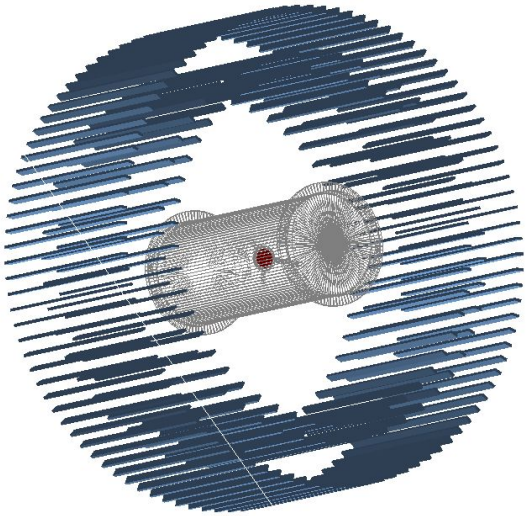
$$P_{e^+} = \frac{v}{c} \cdot \frac{1}{2}\frac{(1+cos\alpha)}{2}$$

C_{CPT} : amplitude of CPT violating effect

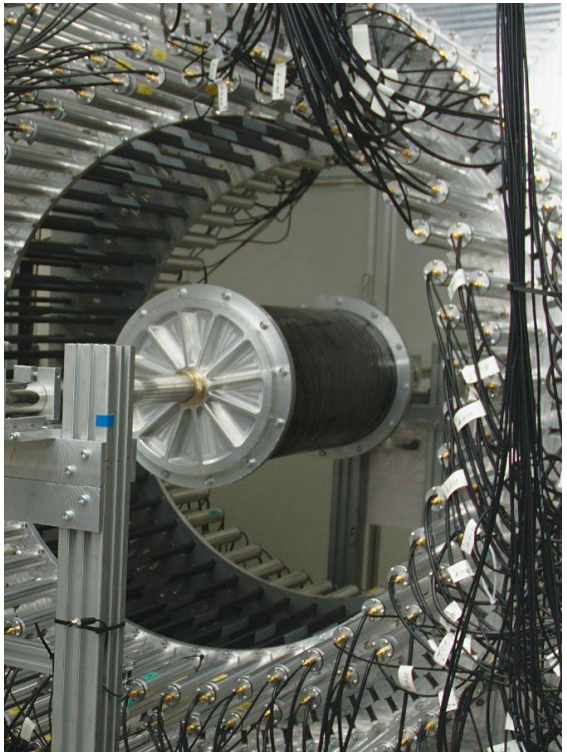
P : Analyzing power (dominated by polarization)

A.Gajos, NIM A 819 (2016), 54

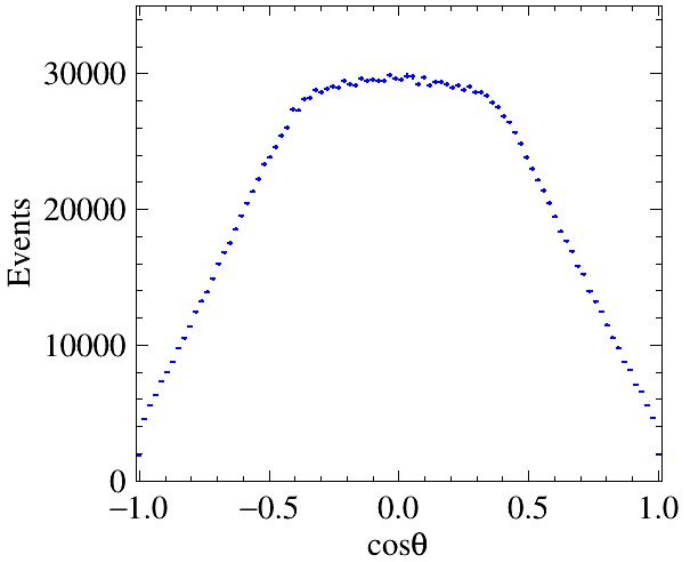
1st CPT test with J-PET



- **Cylindrical annihilation chamber**
- 10 MBq source activity
- 26 days of measurement



$$O_{CPT} = \hat{S}.\frac{(\vec{k_1}\times\vec{k_2})}{|\vec{k_1}\times\vec{k_2}|} = cos\theta$$

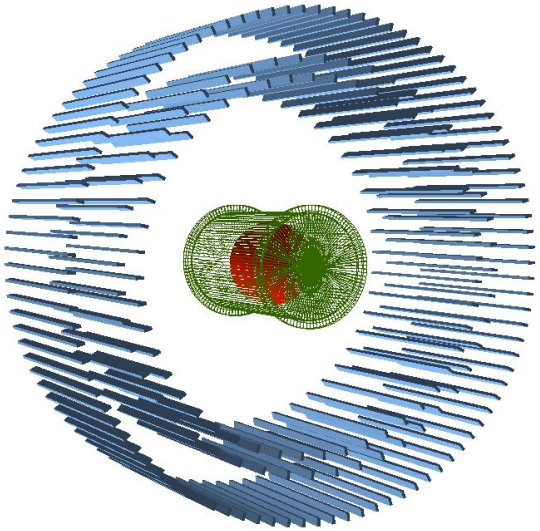


$$C_{CPT} = \frac{<O_{CPT}>}{P}$$

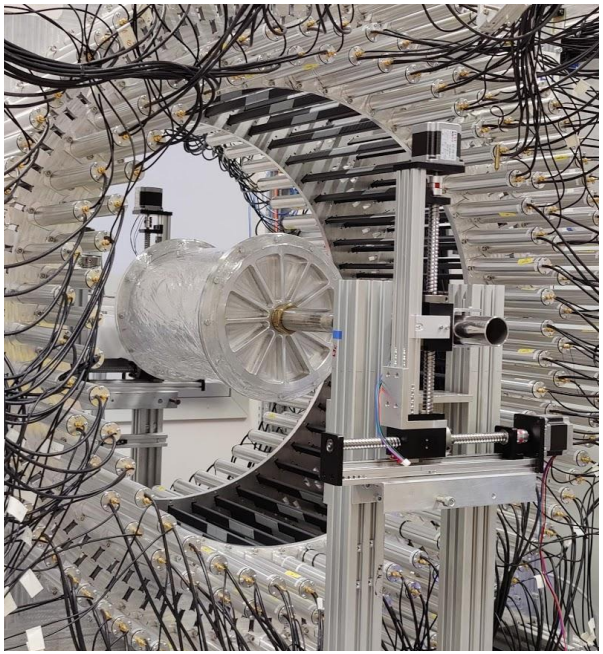
$$C_{CPT} = 0.00067 \pm 0.00095$$

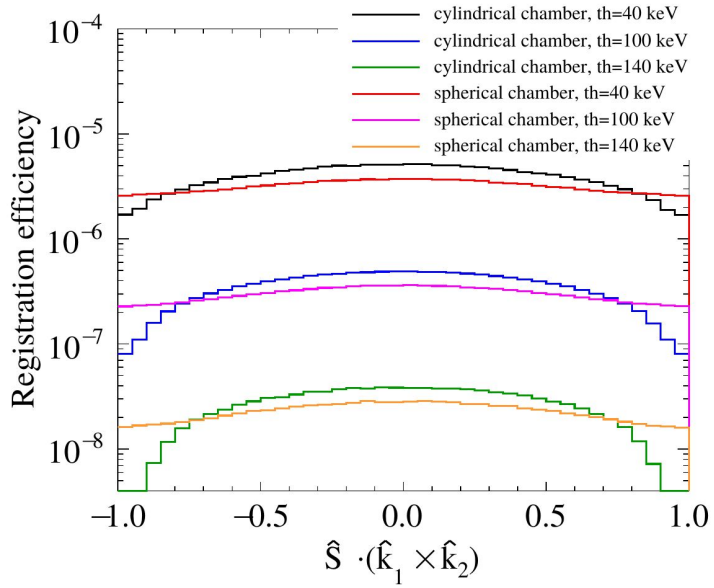
P. Moskal, A. Gajos et al., Nature Commun., 12, 5658 (2021)

Advancements in CPT test with J-PET



- **Spherical annihilation chamber** is used to increase positronium formation
- 1 and 4 MBq source activity
- 1.5 years of data taking

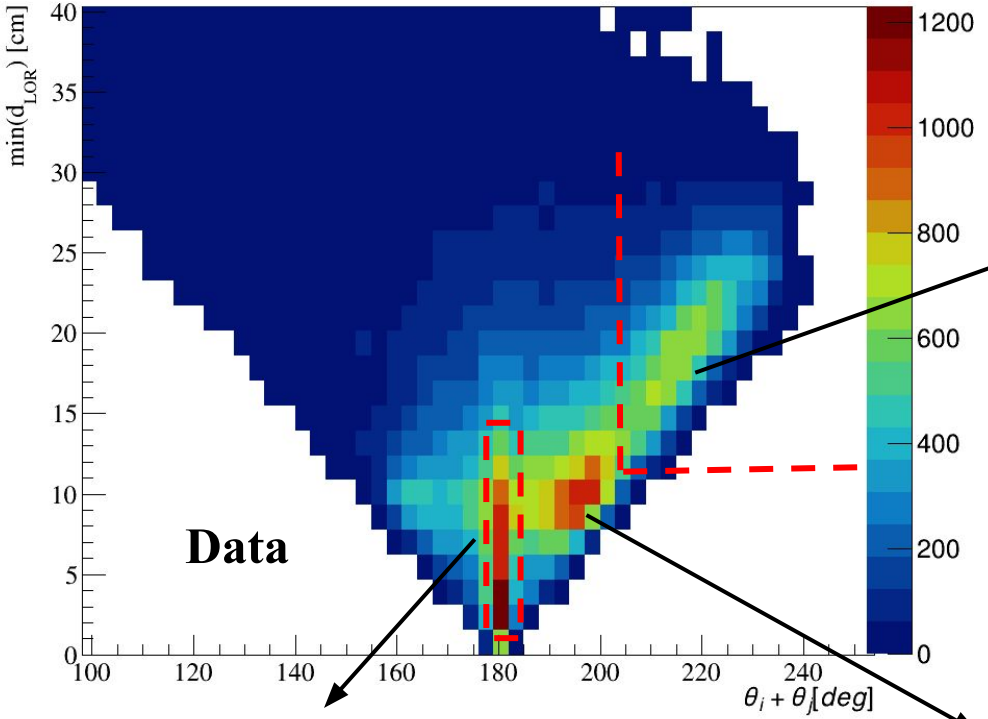


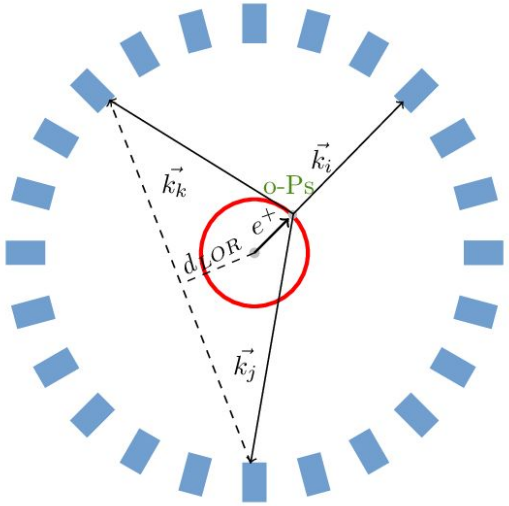


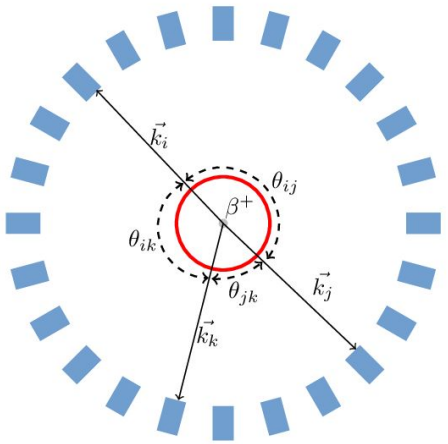
Total Efficiency of registration of o-Ps events in J-PET in case of using cylindrical and spherical annihilation chamber (MC simulations)

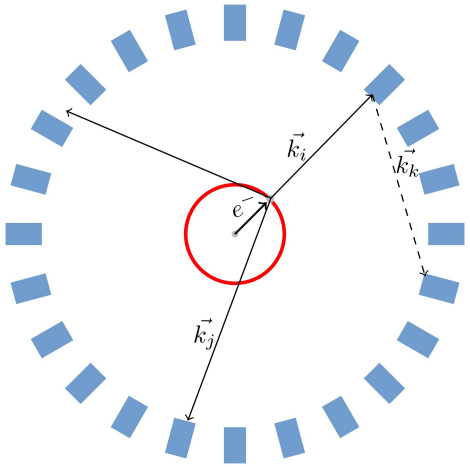
A. Gajos, *Symmetry* 2020, *12*(8), 1268

Identification of o-Ps→3γ events using spherical annihilation chamber

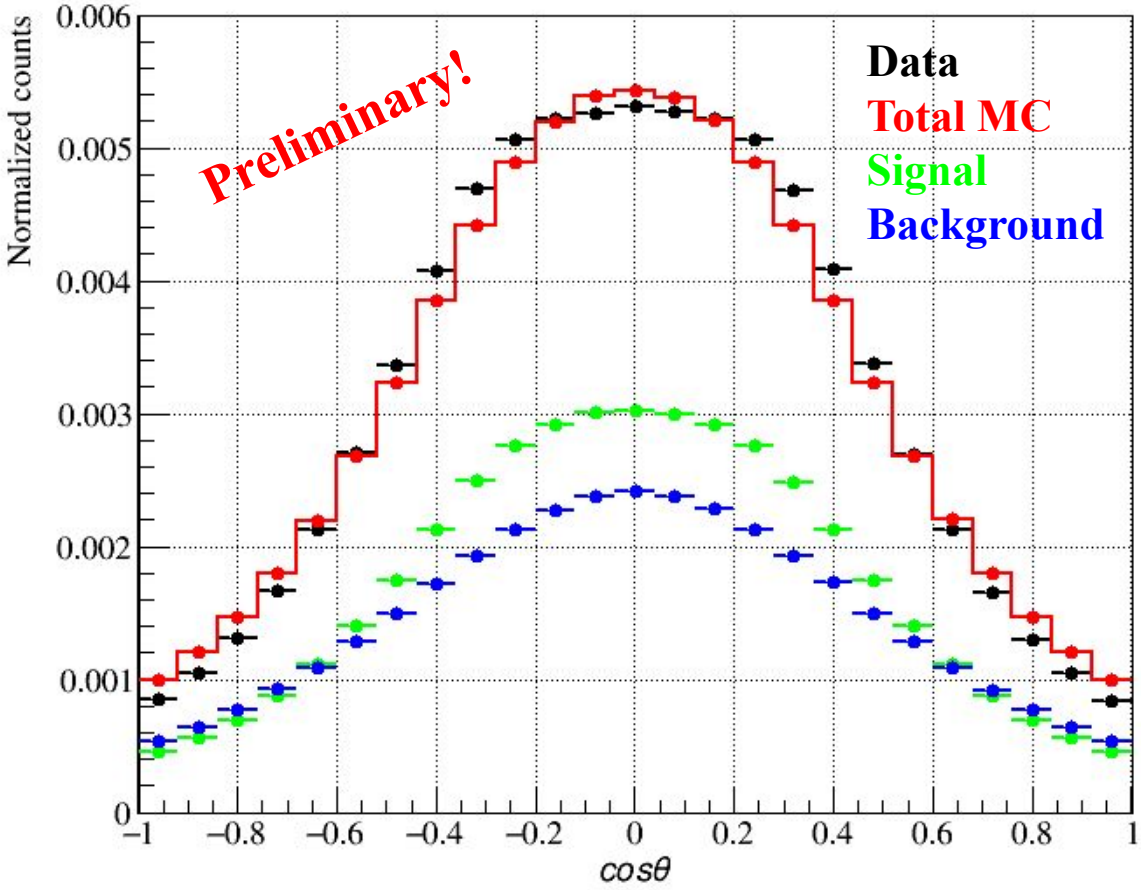








CPT-asymmetric angular correlation operator

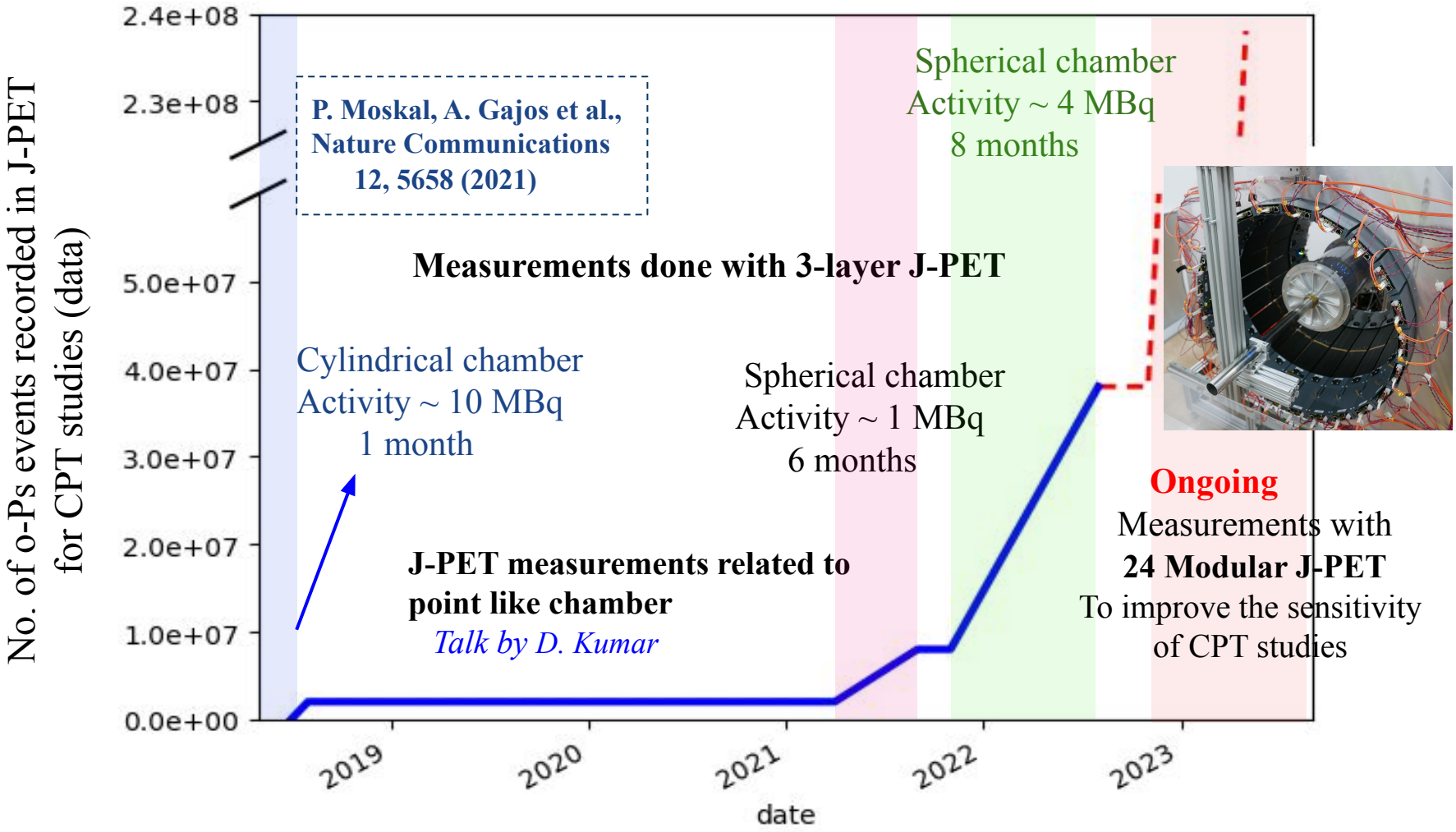


$$O_{CPT} = \hat{S}.\frac{(\vec{k_1}\times\vec{k_2})}{|\vec{k_1}\times\vec{k_2}|} = cos\theta$$

$< O_{CPT} > = -0.00033 +/- 0.00026$

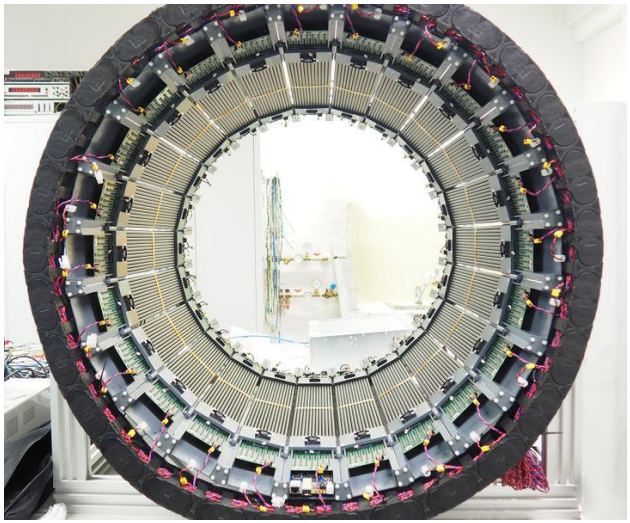
- The angular distribution between Spin and annihilation plane orientation of selected o-Ps event.
- Plotted for **2.8 * 10^6** identified o-Ps-3g events in data.
- Signal and Background is normalized to Total Monte Carlo.
- Presented data results is from 30% of the data collected for CPT symmetry test with J-PET and spherical annihilation chamber.

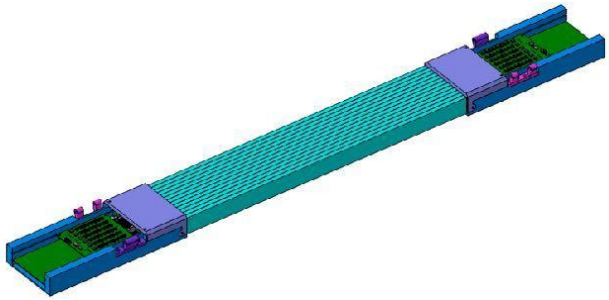
o-Ps events collected with J-PET so far



Towards improving the sensitivity to 10^{-5}

- **Modular J-PET Detector:** 24 modules of densely packed plastic scintillators with SiPM readout.
- Increase the **detection efficiency** for registration of annihilation photons from o-Ps.
- Reconfigured into **multiple layers**
- A **portable** device

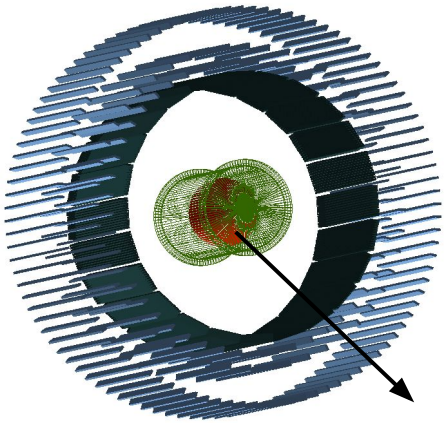




Towards improving the sensitivity to 10^{-5}

Optimization of different modular configurations for CPT symmetry test
(MC simulations)

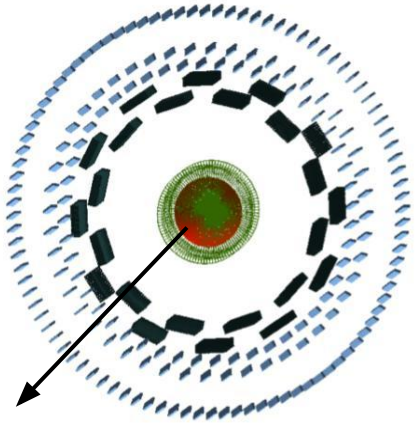
J-PET + 24 Modular J-PET



*Efficiency ~ 21
w.r.t present J-PET

*Scattering background: 37%

J-PET + (12 + 12) Modular J-PET

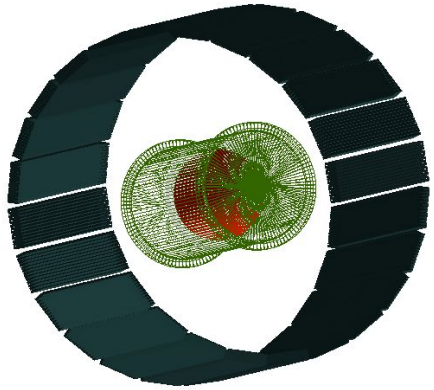


Spherical Chamber

Efficiency ~ 75
w.r.t present J-PET

Scattering background: 28%

24 Modular J-PET



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

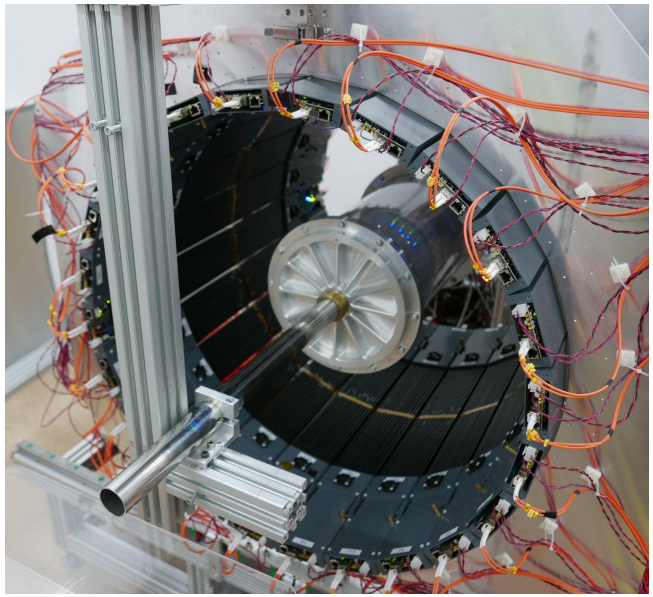
Scattering background: 7%

Best optimized geometry for CPT studies

*Secondary background: Fraction of secondary scattering events (MC)
*Efficiency of registration of o-Ps ➔ 3ɣ events in detector (MC)

Summary

- J-PET measured the CPT sensitive angular correlation $S.(k_1 \times k_2)$ in o-Ps $\rightarrow 3\gamma$ decays and found no CPT violation at the precision level of 10^{-4} .
- To further improve the sensitivity of CPT test, measurement with **24 Modular J-PET** and spherical annihilation chamber is ongoing.
- It is estimated that the **precision of 10^{-5}** can be achieved with 24 Modular J-PET.



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Thank You!