



# Precision tests of discrete symmetries in decays of positronium with the J-PET detector



E.C. on behalf of the J-PET Collaboration

4<sup>th</sup> Jagiellonian Symposium  
July 14<sup>th</sup>, 2022

# Positronium (Ps)

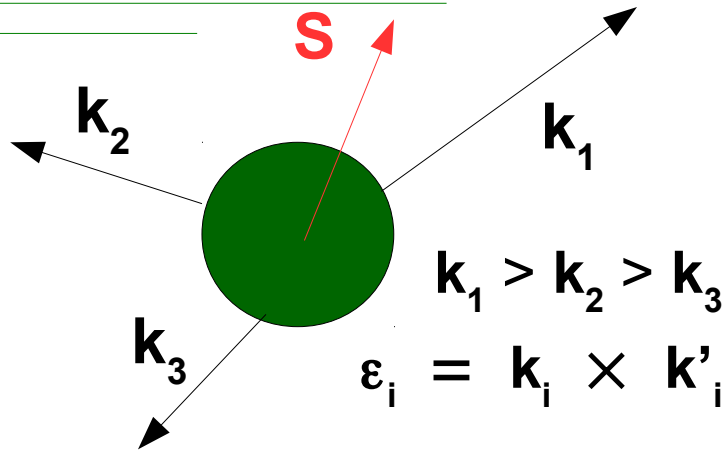
para-positronium (p-Ps)	$\uparrow\downarrow$	$2n\gamma$	CP = +1	$\tau \approx 0.125\text{ns}$
ortho-positronium (o-Ps)	$\uparrow\uparrow$	$(2n+1)\gamma$	CP = -1	$\tau \approx 142\text{ns}$

- ▶ purely leptonic (e<sup>+</sup>e<sup>-</sup>) bound state
- ▶ C, P, CP operators and  $\mathcal{H}$  eigenstate
- ▶ the lightest atom
- ▶ undergoes self-annihilation
- ▶ e<sup>+</sup> and e<sup>-</sup> do not decay into lighter particles via weak interaction,  $10^{-14}$  violation level due to the weak interaction

[ M. Sozzi, Discrete Symmetries and CP Violation, Oxford University Press (2008) ]

- ▶ no charged particles in the final state ( $2 \cdot 10^{-10}$  radiative corrections)
- ▶ upper limits  $10^{-3}$  for T, CP, ~~CPT~~ violation

# o-Ps



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



Unique @J-PET

[ J-PET: P. Moskal et al., Acta Phys. Polon. B 47 (2016) 509 ]

$$C_{\text{CPT}} = \langle \mathbf{S} \cdot (\mathbf{k}_1 \times \mathbf{k}_2) \rangle = 0.0026 \pm 0.0031$$

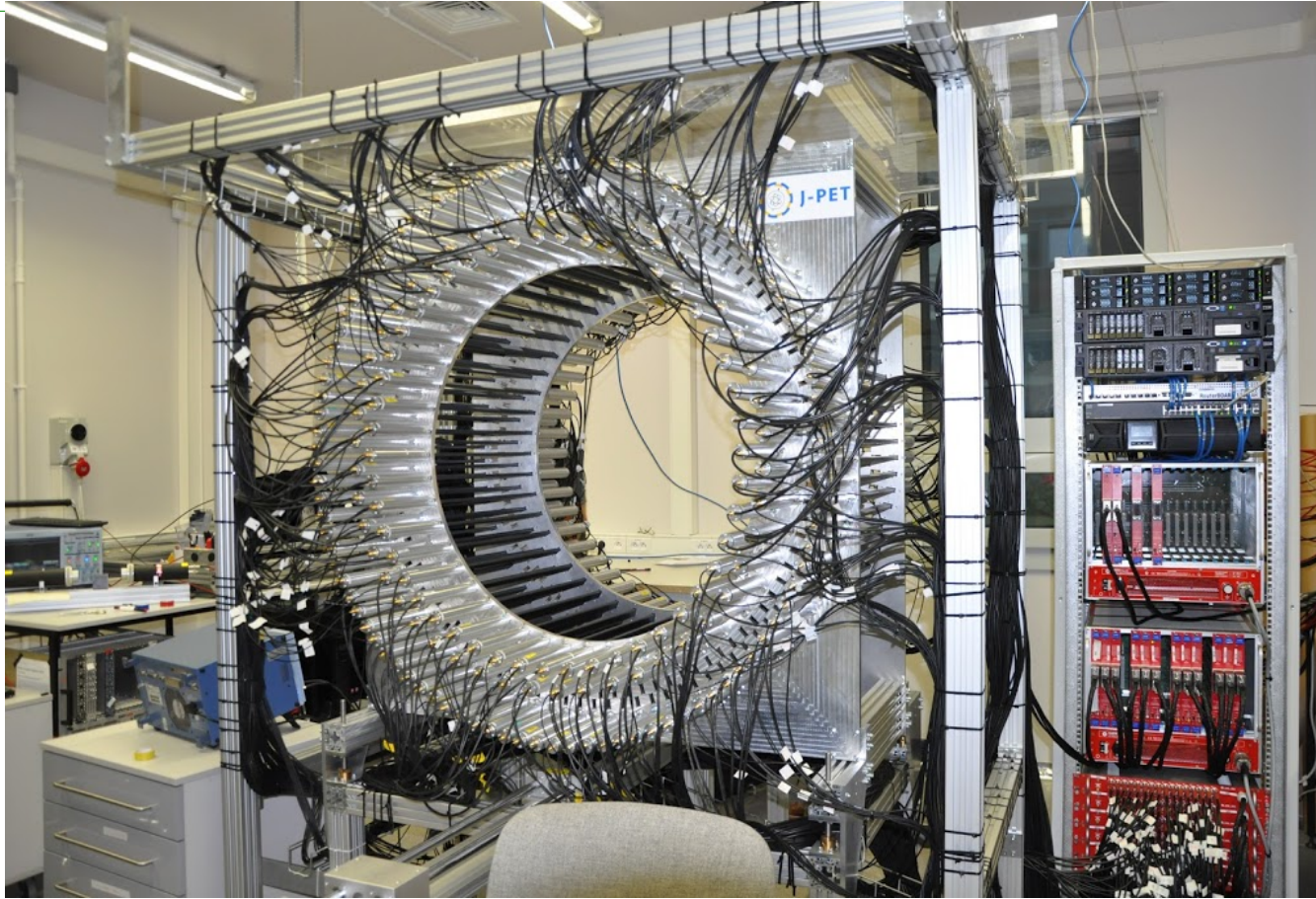
[ P.A. Vetter, S.J. Freedman, Phys. Rev. Lett. 91 (2003) 263401 ]

$$C_{\text{CP}} = \langle (\mathbf{S} \cdot \mathbf{k}_1) (\mathbf{S} \cdot (\mathbf{k}_1 \times \mathbf{k}_2)) \rangle = 0.0013 \pm 0.0022$$

[ T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401 ]

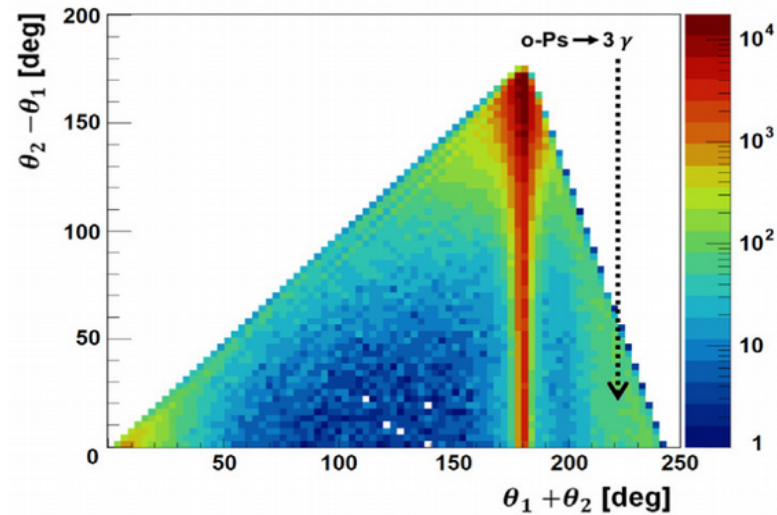
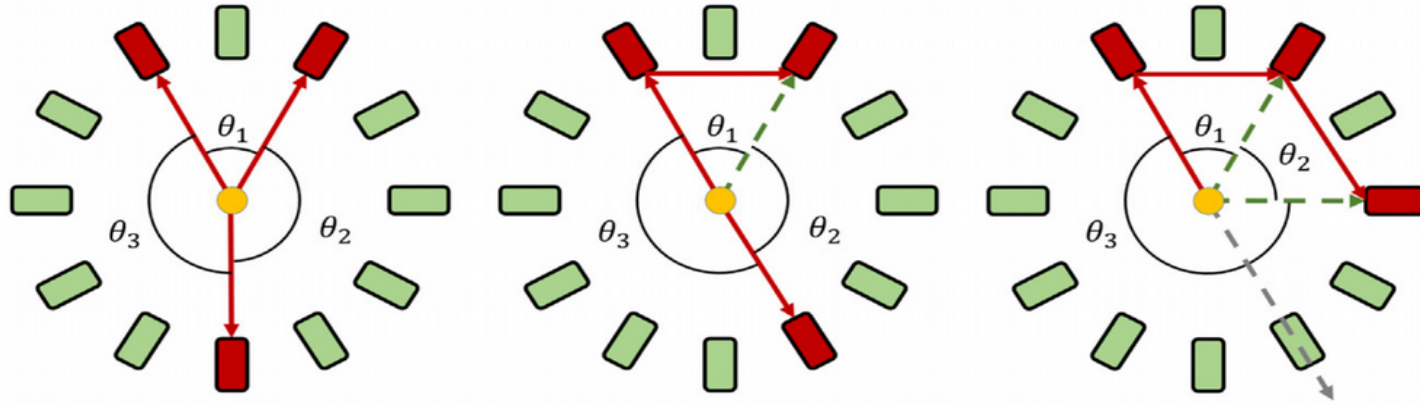
$$C_{\text{C}} \leq 2.8 \times 10^{-6} \text{ ( @68\% c.l. ) [ A.P. Mills, S. Berko, Phys. Rev. Lett. 18 (1967) 420 ]}$$

# Jagiellonian PET



First PET from plastic scintillators built at the Jagiellonian University in Poland

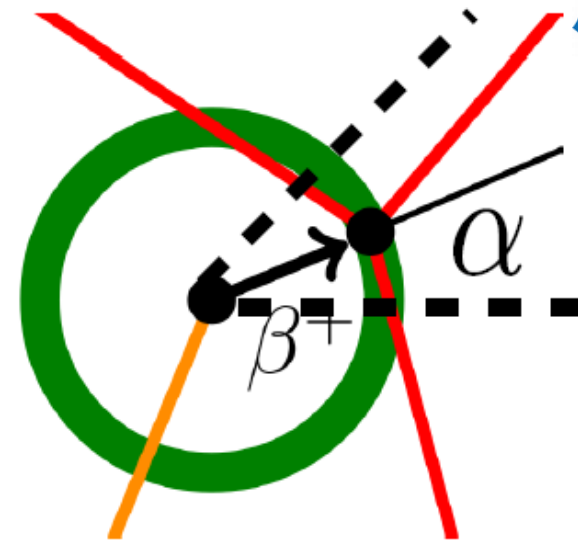
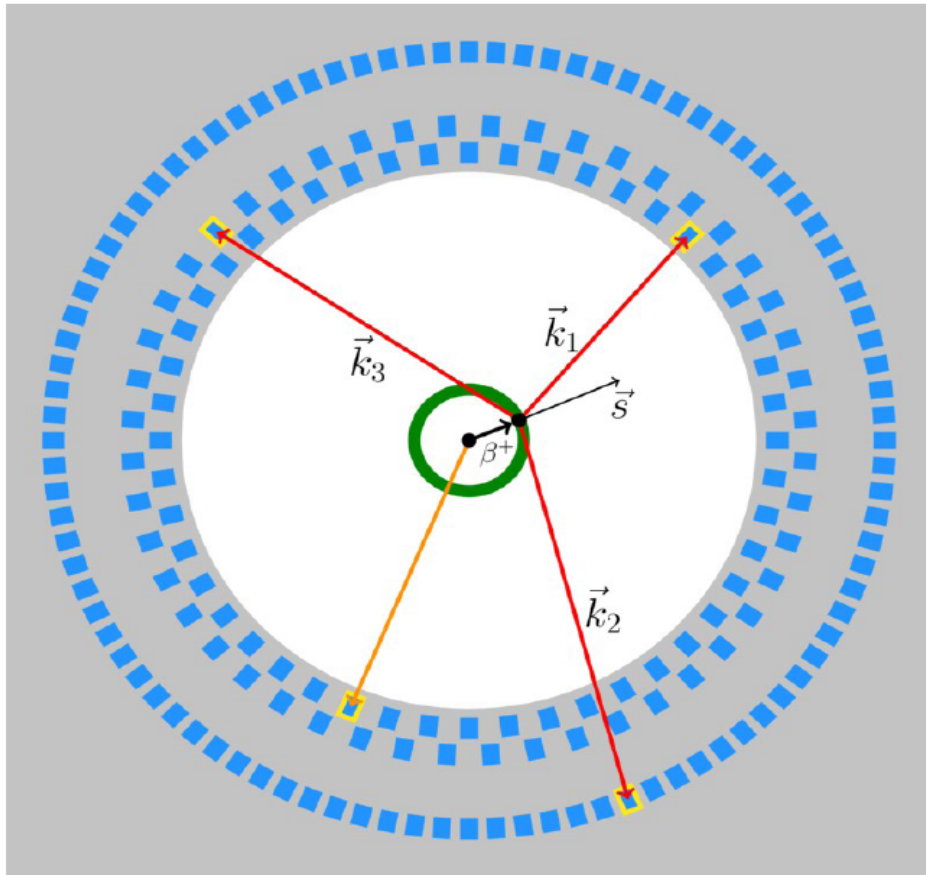
# o-Ps detection



# Determination of o-Ps polarization



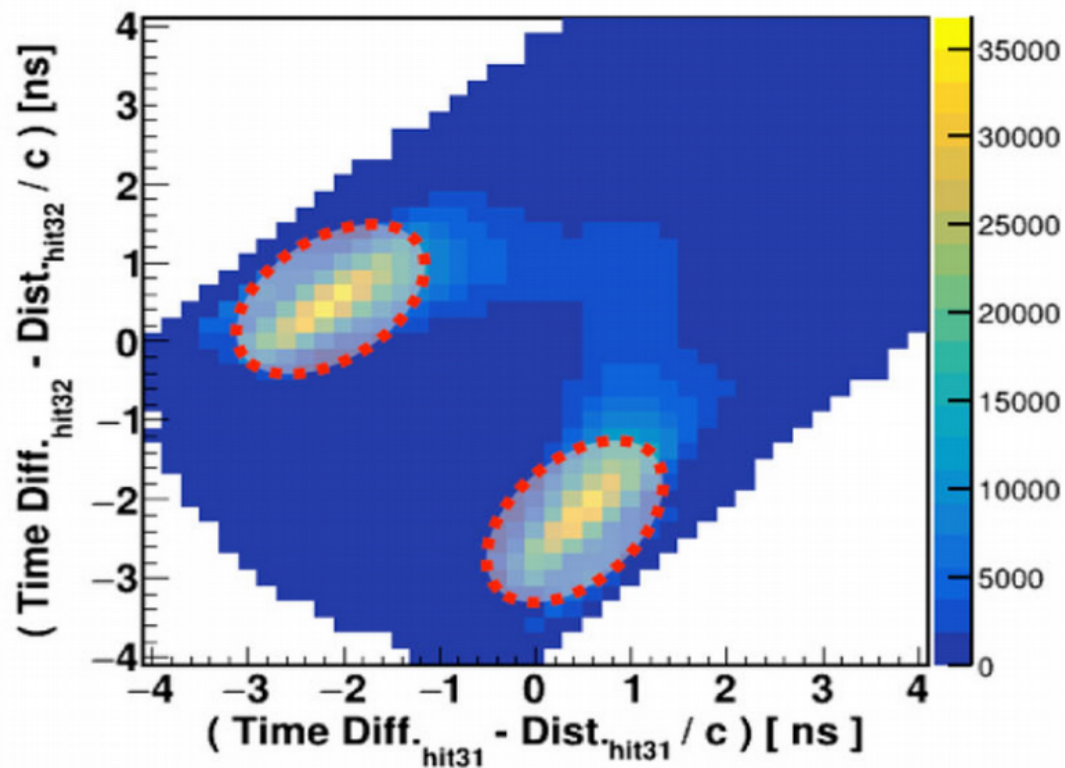
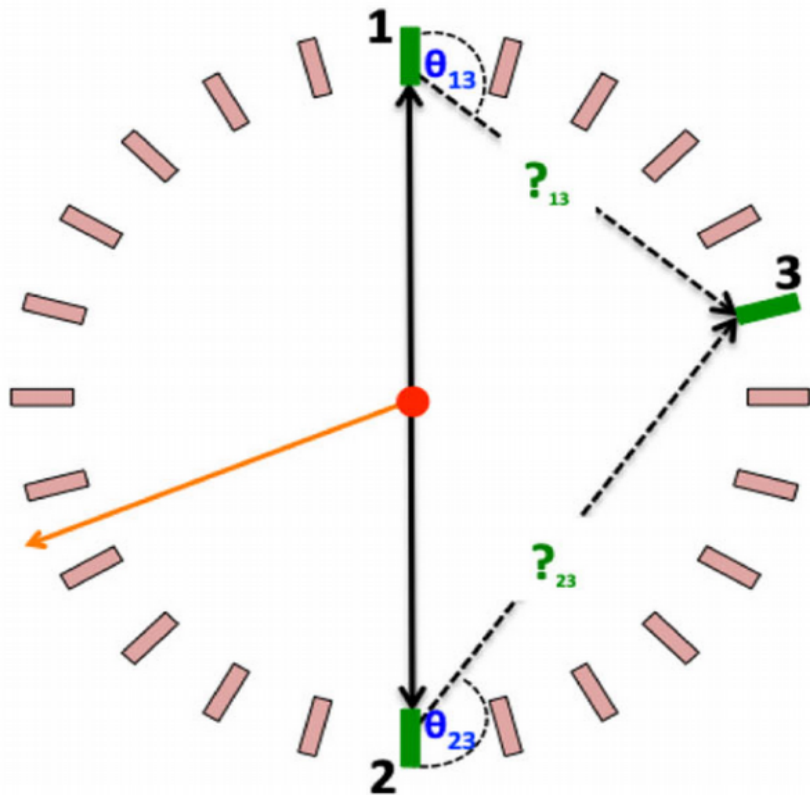
J-PET



$$P = \frac{v}{c}(1 + \cos\alpha)/2$$

J.PET: A. Gajos et al., Nucl. Inst. and Meth. A819 (2016) 54-59  
J-PET: P. Moskal et al., Acta Phys. Polon. B 47 (2016) 509

# Identification of scatterings



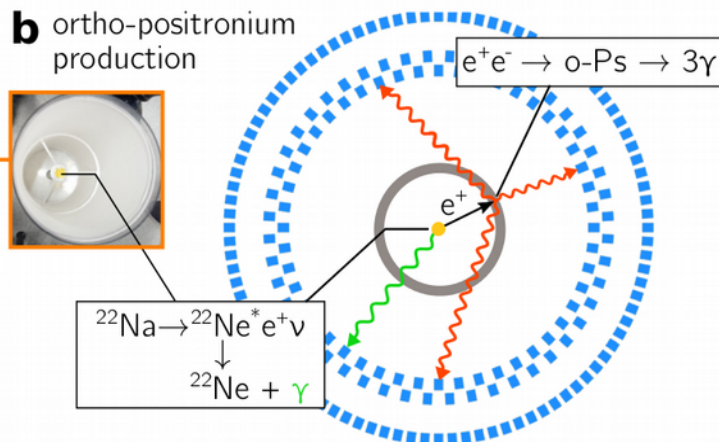
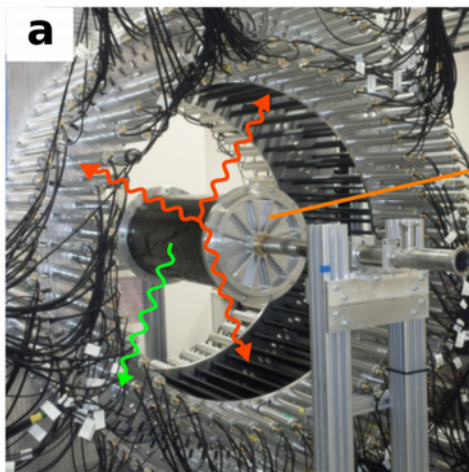
# CPT symmetry test



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

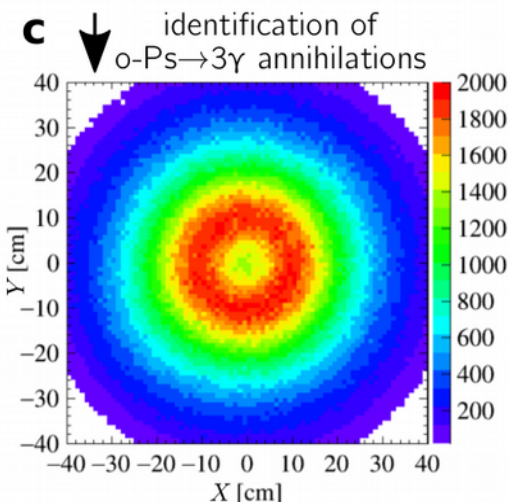


# CPT symmetry test

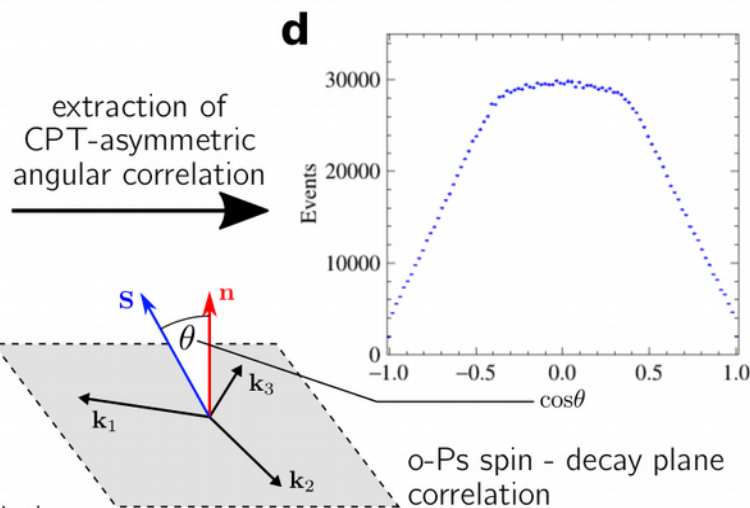


Schematic cross section of the J-PET detector

J-PET: P. Moskal et al.,  
Nature Communications  
12 (2021) 5658



distribution of ortho-positronium annihilations



o-Ps spin - decay plane correlation

# CPT symmetry test



Selection criteria for 26 days measurement:

- ▷ TOT and hit time windows
- ▷ rejection of secondary Compton scatterings
- ▷ cut on LOR, sum of 2D and 3D angles
- ▷ total effective polarisation 37.4 %
- ▷  $7.3 \times 10^6$  event candidates

$$\langle O_{\text{CPT}} \rangle = 0.00025 \pm 0.00036$$

$$C_{\text{CPT}} = \langle O_{\text{CPT}} \rangle / P = 0.00067 \pm 0.00095$$

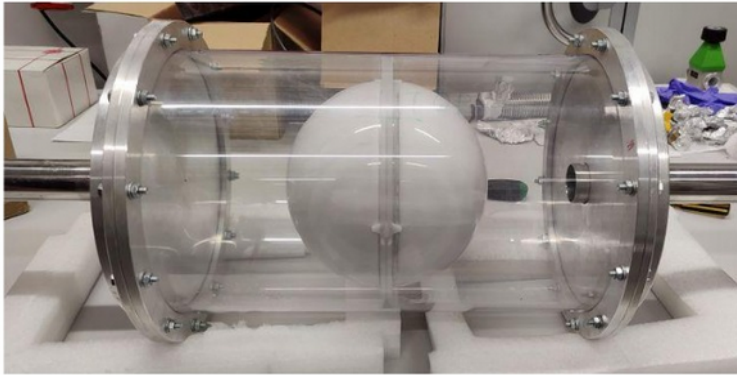
J-PET: P. Moskal et al., Nature Communications 12 (2021) 5658

$$C_{\text{CPT}} = \langle \mathbf{S} \cdot (\mathbf{k}_1 \times \mathbf{k}_2) \rangle = 0.0026 \pm 0.0031$$

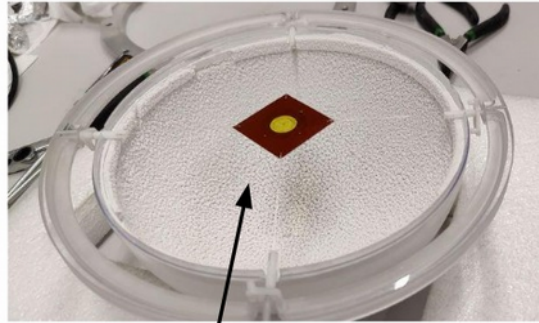
[ P.A. Vetter, S.J. Freedman, Phys. Rev. Lett. 91 (2003) 263401 ]

# CPT test – next generation

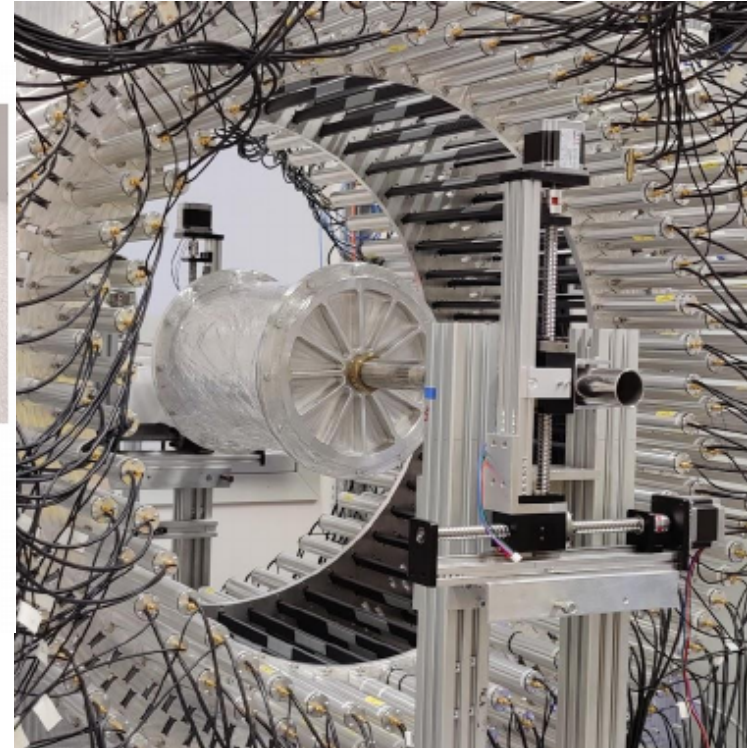
- 26 days → 9 months and still ongoing
- 10 MBq → 4 MBq of source activity
- cylindrical → spherical annihilation chamber



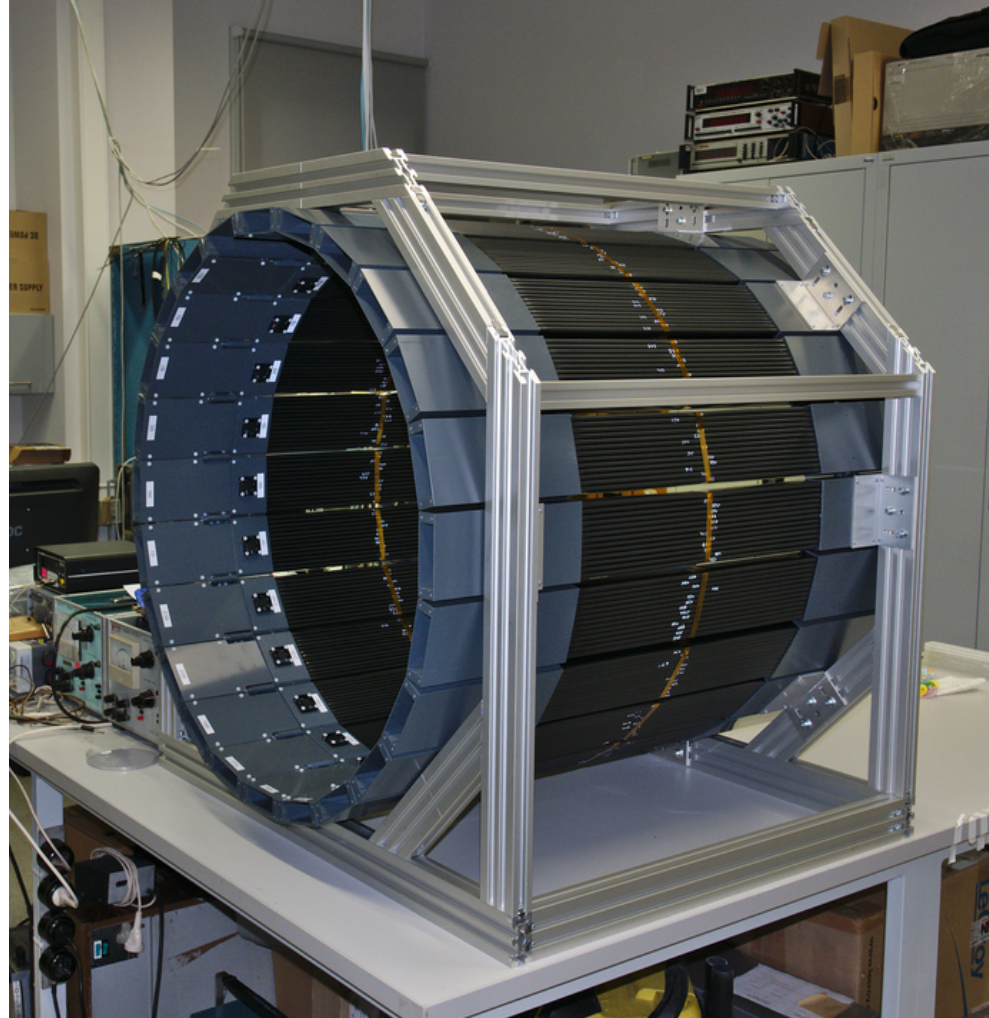
Setup of annihilation chamber



Placement of source inside spherical chamber



# Modular J-PET



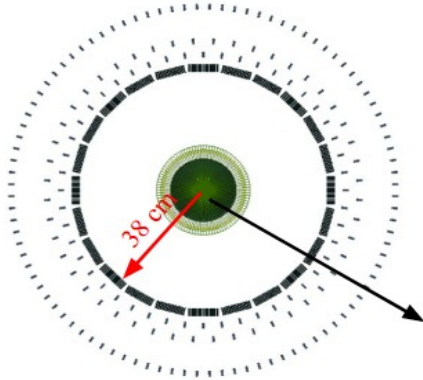
# CPT test – next<sup>2</sup> generation



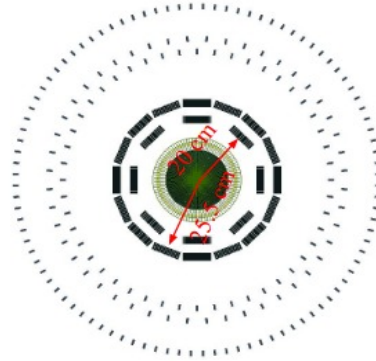
J-PET

N. Chug

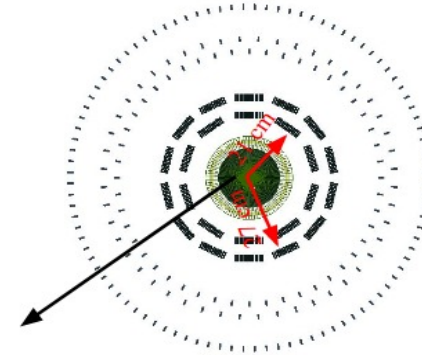
3 layer + 24 Modules



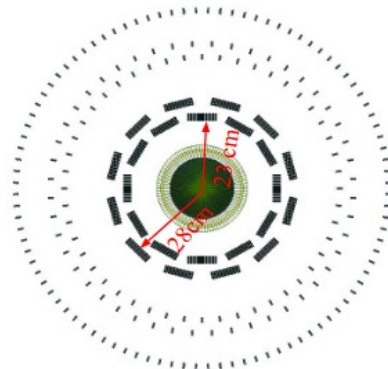
3 layer + (16 + 8) Modules



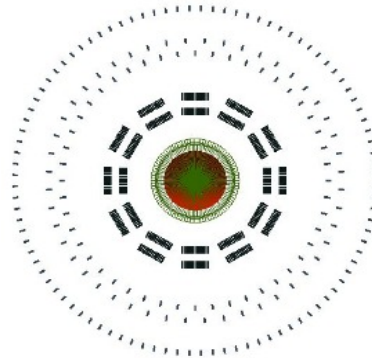
3 layer + (14 + 10) Modules



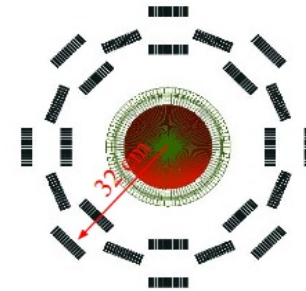
Spherical Chamber



3 layer + (12 + 12) Modules



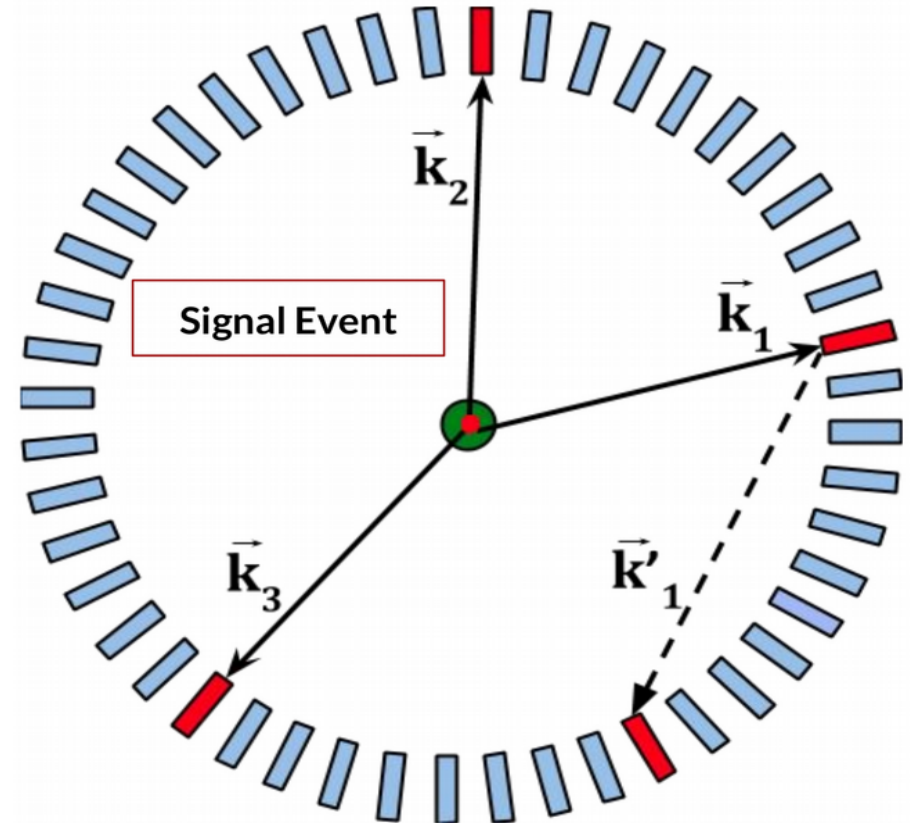
3 layer + (12 + 12) Modules v2



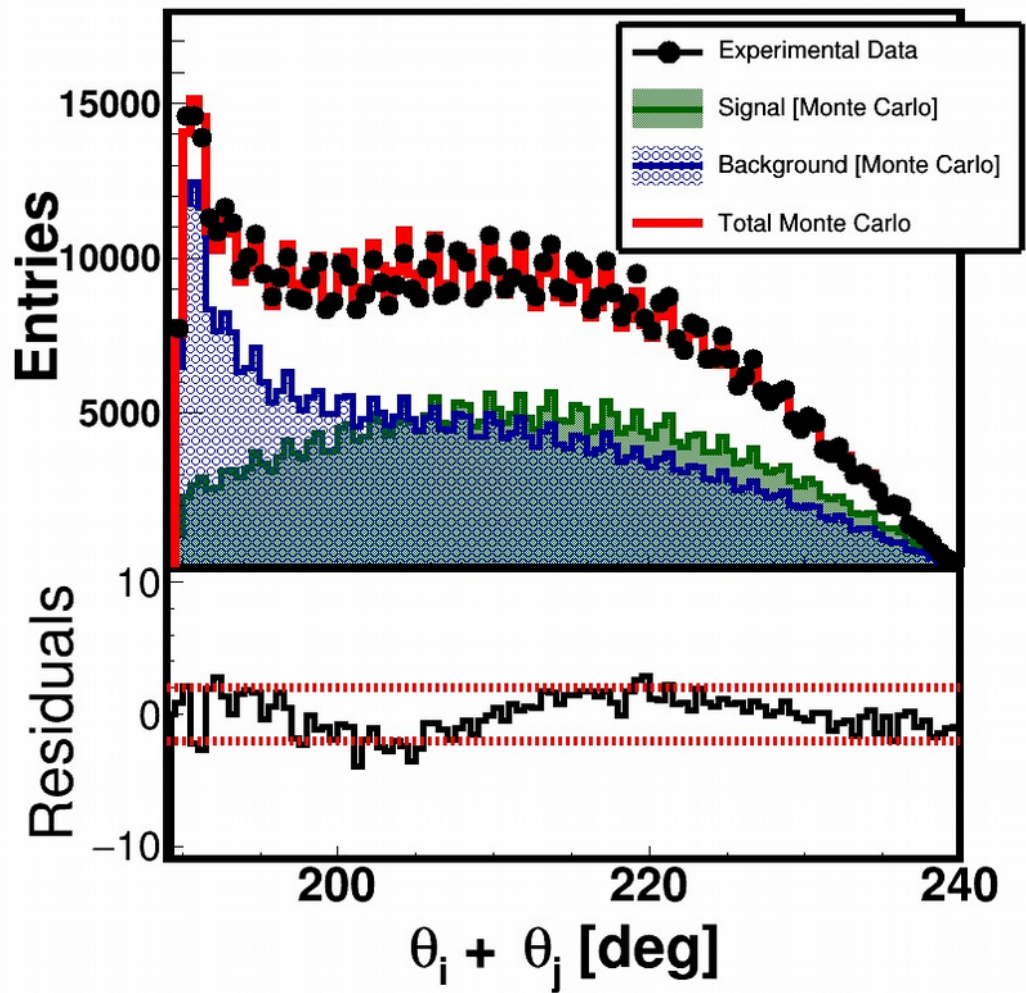
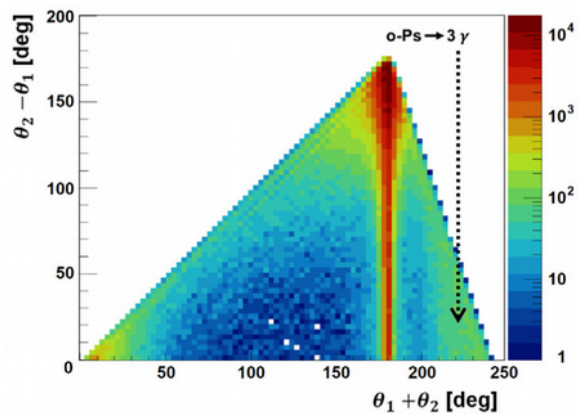
3 modular

# CP, P, T symmetry test

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



# CP, P, T symmetry test



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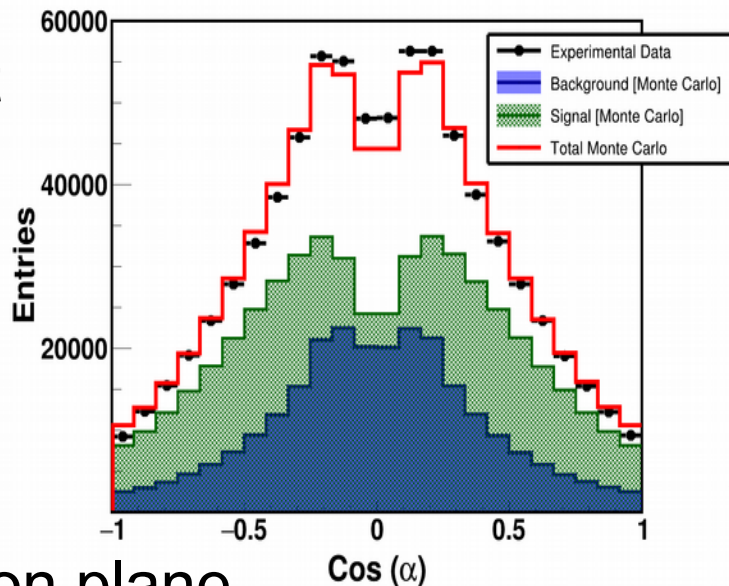
$$\text{J-PET: } C_{CP} = \langle \varepsilon_i \cdot \mathbf{k}_j \rangle = 0.00052 \pm 0.00067_{\text{stat}}$$

syst. error negligible

126 days of measurement

Selection based on:

- hit position
- TOT
- sum of 3D angles
- emission time of annihilation gammas
- distance of the annihilation plane



Error Composition:  
Background = 6 %  
Miss-Reco = 2 %  
Efficiency = 2 %  
Acceptance = 14 %  
Data = 76 %

$$C_{CP} = \langle (\mathbf{S} \cdot \mathbf{k}_1) (\mathbf{S} \cdot (\mathbf{k}_1 \times \mathbf{k}_2)) \rangle = 0.0013 \pm 0.0022$$

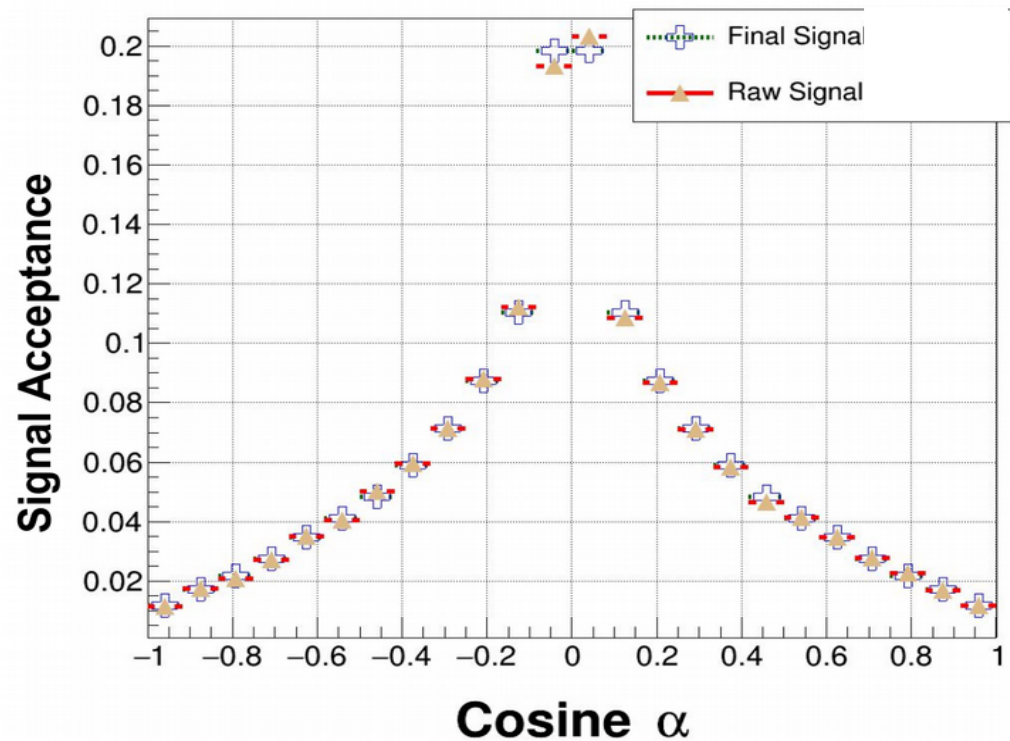
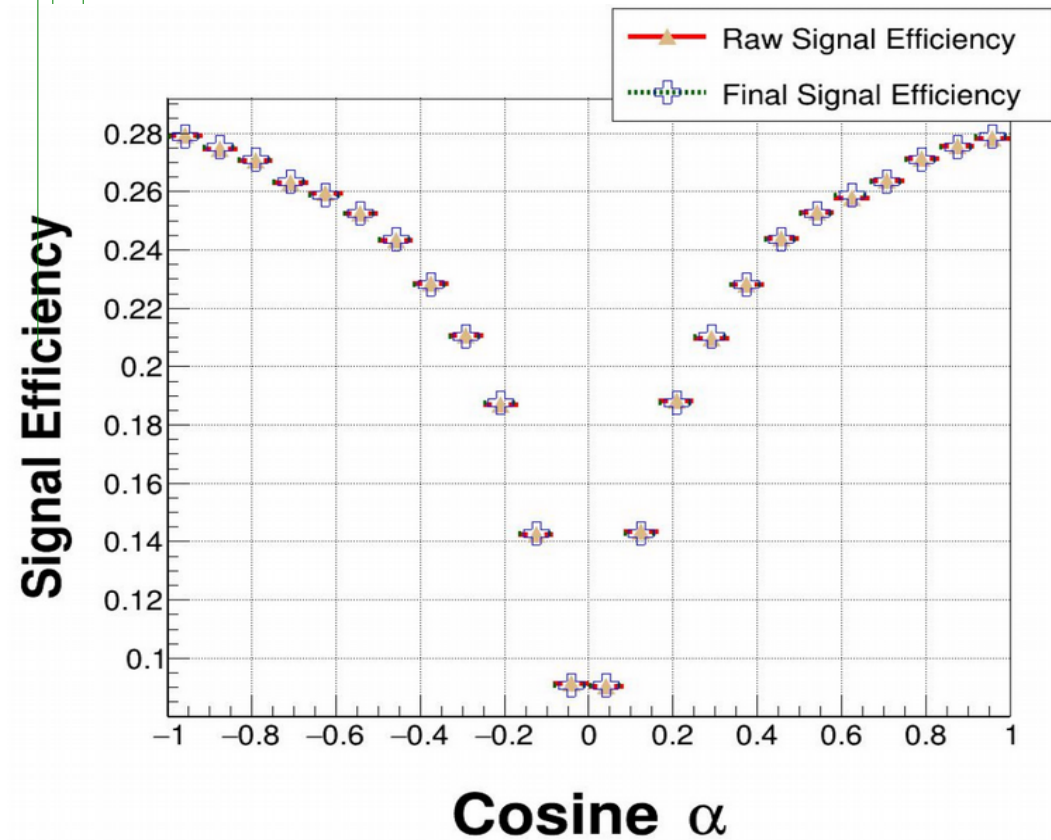
[ T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401 ]



# CP, P, T symmetry test



J-PET



# CP, P, T symmetry test



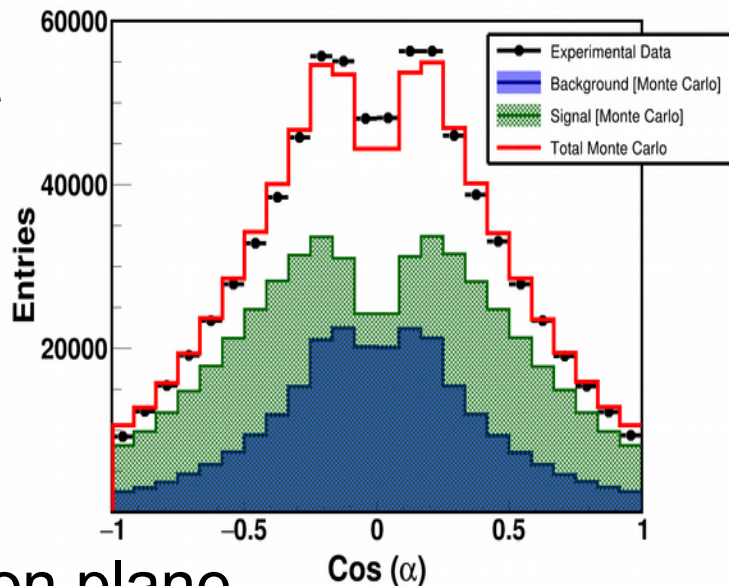
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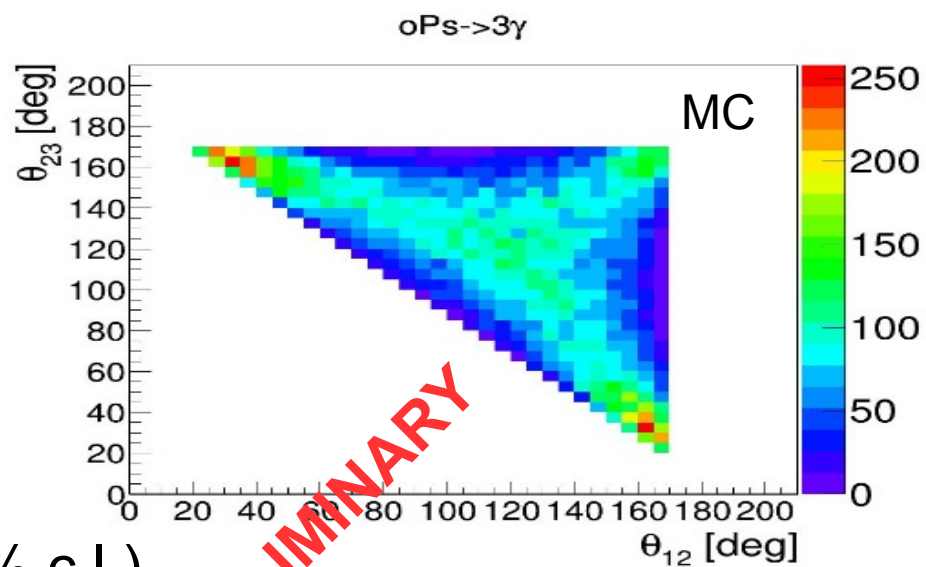
[ T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401 ]

# C test

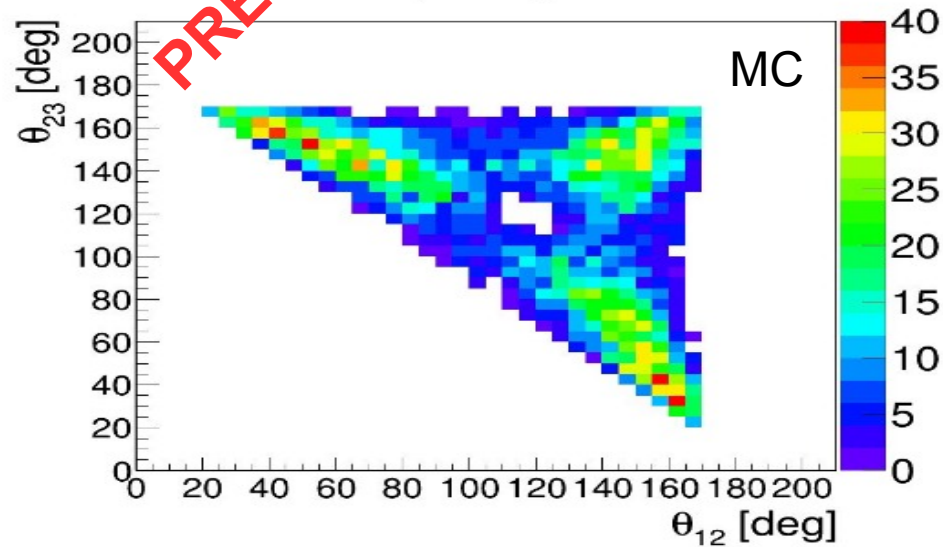


J-PET

M. Skurzok



PRELIMINARY



$$C_c \leq 2.8 \times 10^{-6} \text{ (@68\% c.l.)}$$

[ A.P. Mills, S. Berko,  
Phys. Rev. Lett.  
18 (1967) 420 ]

# SME@J-PET?



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

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

properties for the field operators  
in the SME lagrangian  
A. Kostelecky, C.D. Lane, A.G.M. Pickering,  
PhysRevD.65.056006 (2002)

	C	P	T	CP	CT	PT	CPT
$c_{00}, (k_F)_{0j0k},$							
$c_{jk}, (k_F)_{jklm}$	+	+	+	+	+	+	+
$b_j, g_{j0l}, g_{jk0}, (k_{AF})_j$	+	+	-	+	-	-	-
$b_0, g_{j00}, g_{jkl}, (k_{AF})_0$	+	-	+	-	+	-	-
$c_{0j}, c_{j0}, (k_F)_{0jkl}$	+	-	-	-	-	+	+
$a_0, e_0, f_j$	-	+	+	-	-	+	-
$H_{jk}, d_{0j}, d_{j0}$	-	+	-	-	+	-	+
$H_{0j}, d_{00}, d_{jk}$	-	-	+	+	-	-	+
$a_j, e_j, f_0$	-	-	-	+	+	+	-

# Summary



- ▶ J-PET detector determines o-Ps spin direction and polarization of annihilation  $\gamma$  on the event by event basis.
- ▶ Efficiency and acceptance of J-PET are non-zero for the whole phase-space of P, T, CP and CPT symmetry operators.

## Future:

- ▶ continuous data-taking
- ▶ configuration of modular J-PET for physics
- ▶ implementation of external magnetic field(?)
- ▶ SME(?)



*Thank you*