CP symmetry test at J-PET

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on behalf of the J-PET Collaboration

DISCRETE 2022

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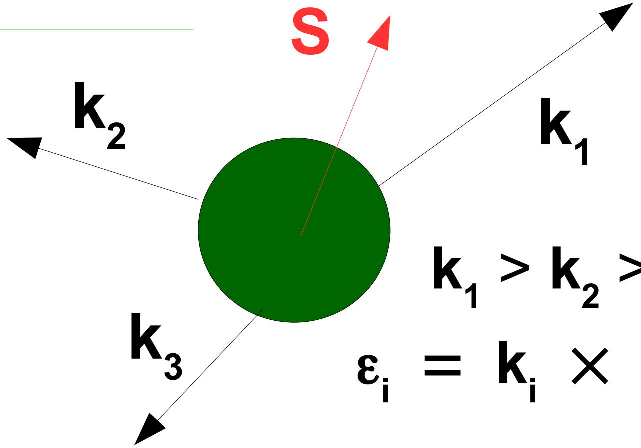
Positronium (Ps)

para-positronium (p-Ps)	↑↓	$2n\gamma$	CP = +1	$\tau \approx 0.125$ns
ortho-positronium (o-Ps)	↑↑	$(2n+1)\gamma$	CP = -1	$\tau \approx 142$ns

- purely leptonic (e+e-) bound state
- C, P, CP operators and $\mathcal{H}$ eigenstate
- the lightest atom
- undergoes self-annihilation
- e+ and e- 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 ($2*10^{-10}$ radiative corrections)
- upper limits 10^{-3} for T, CP, ~~CPT~~ violation

o-Ps



$k_1 > k_2 > k_3$

$\varepsilon_i = k_i \times k'_i$

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

J-PET

Unique @J-PET

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

~~$C_{CPT} = \langle \mathbf{S} \cdot (\mathbf{k}_1 \times \mathbf{k}_2) \rangle = 0.0026 \pm 0.0031$~~ see the next talk by N. Chug

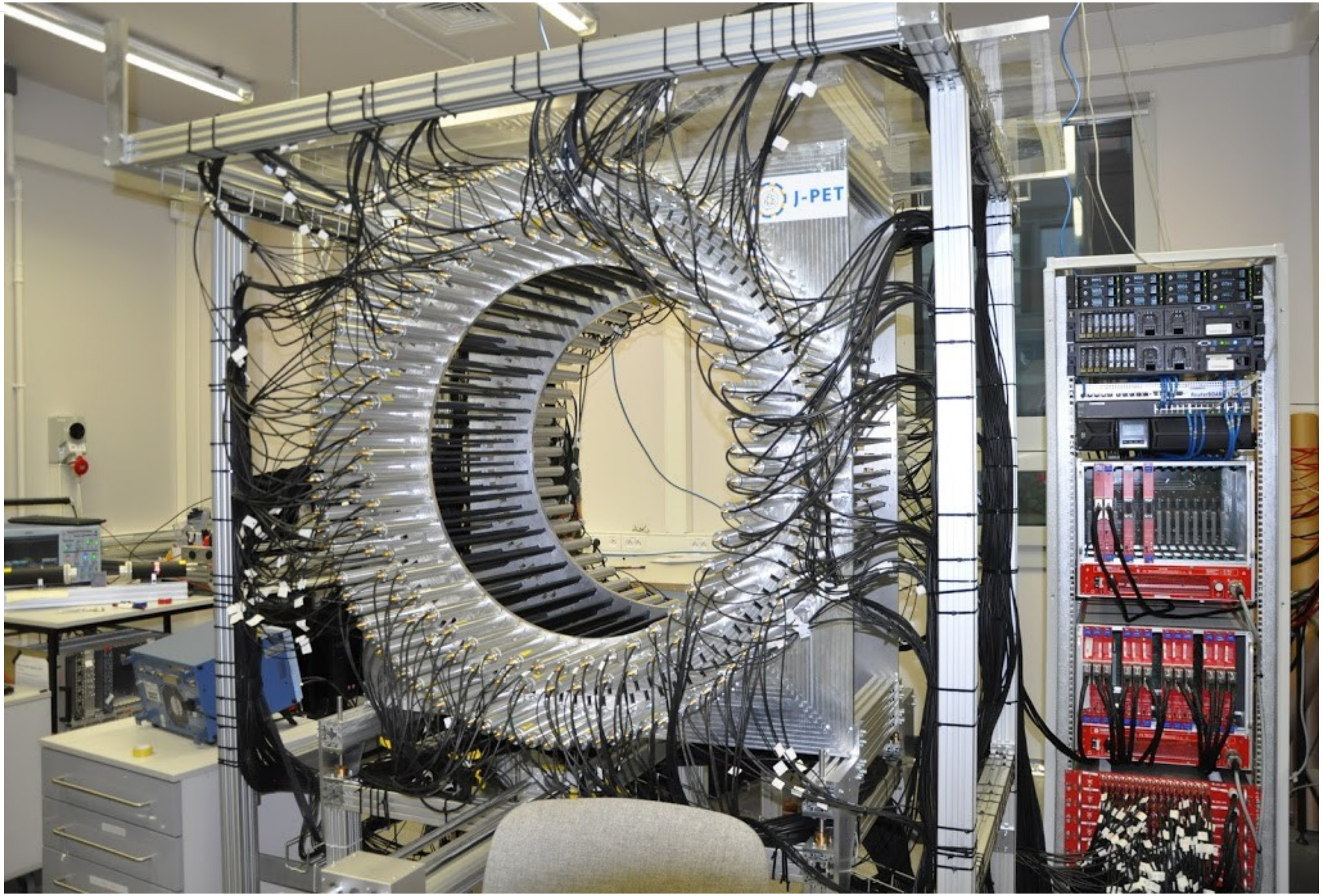
[P.A. Vetter, S.J. Freedman, Phys. Rev. Lett. 91 (2003) 263401]

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

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

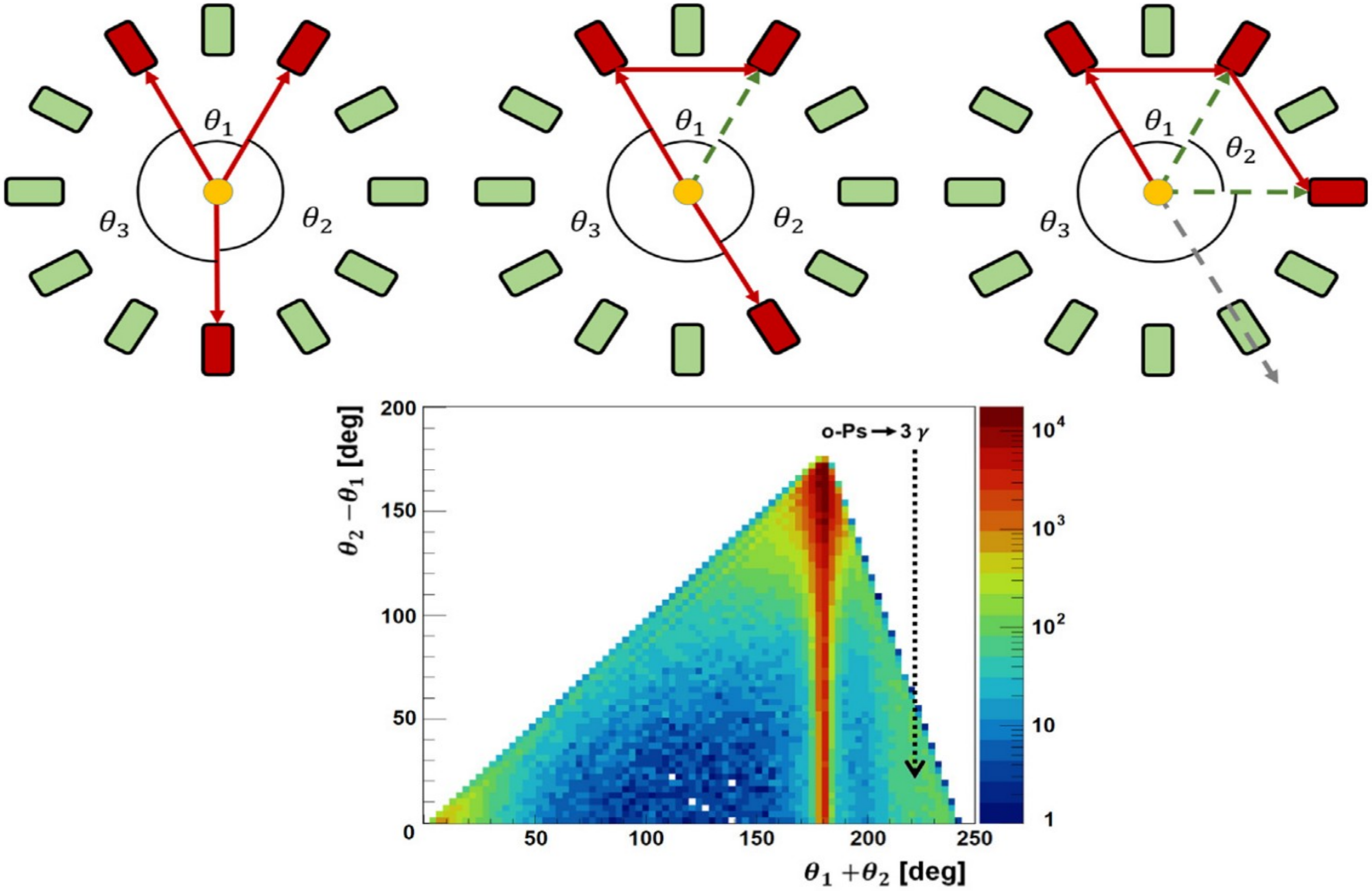
$C_C \leq 2.8 \times 10^{-6}$ (@68% c.l.) [A.P. Mills, S. Berko, Phys. Rev. Lett. 18 (1967) 420]

Jagiellonian PET



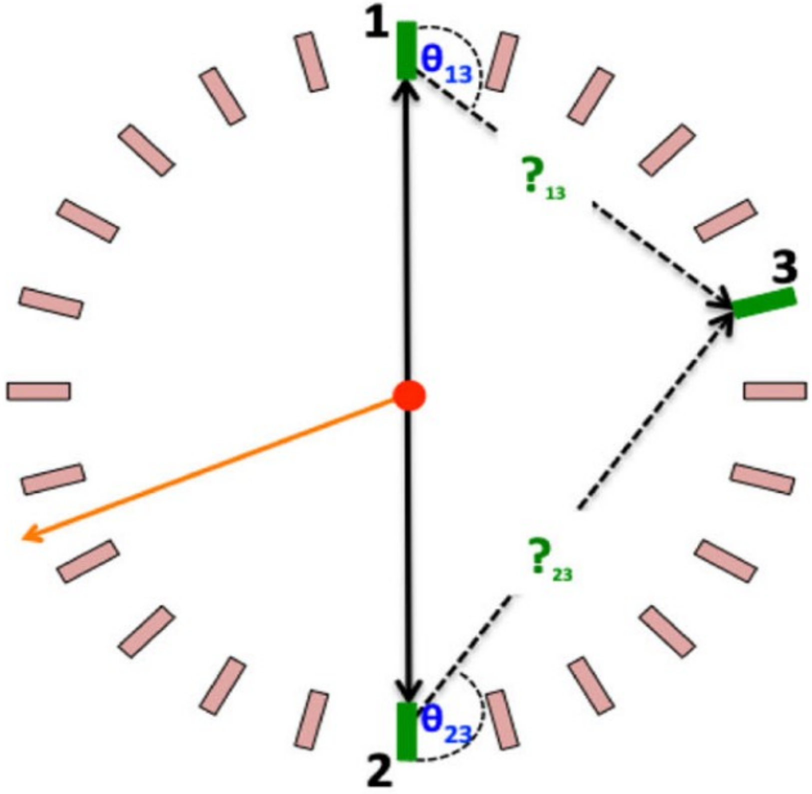
First PET from plastic scintillators built at the Jagiellonian University in Poland

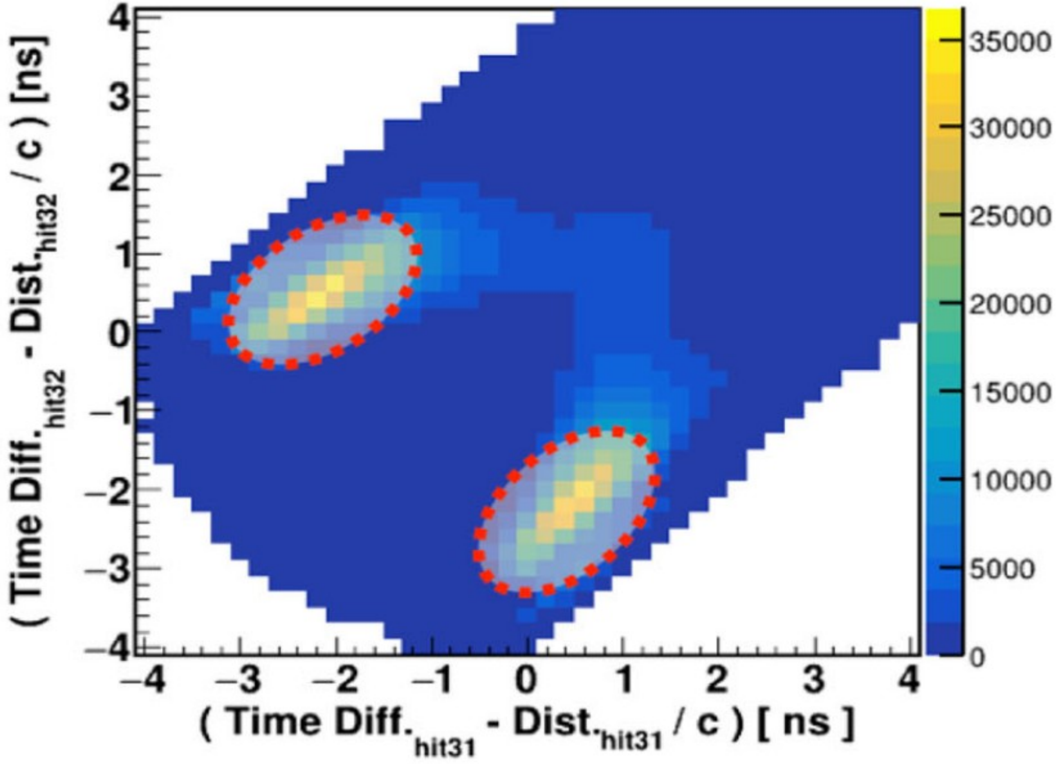
o-Ps detection



J-PET: K. Dulski et al., NIM A 1008 (2021) 165452

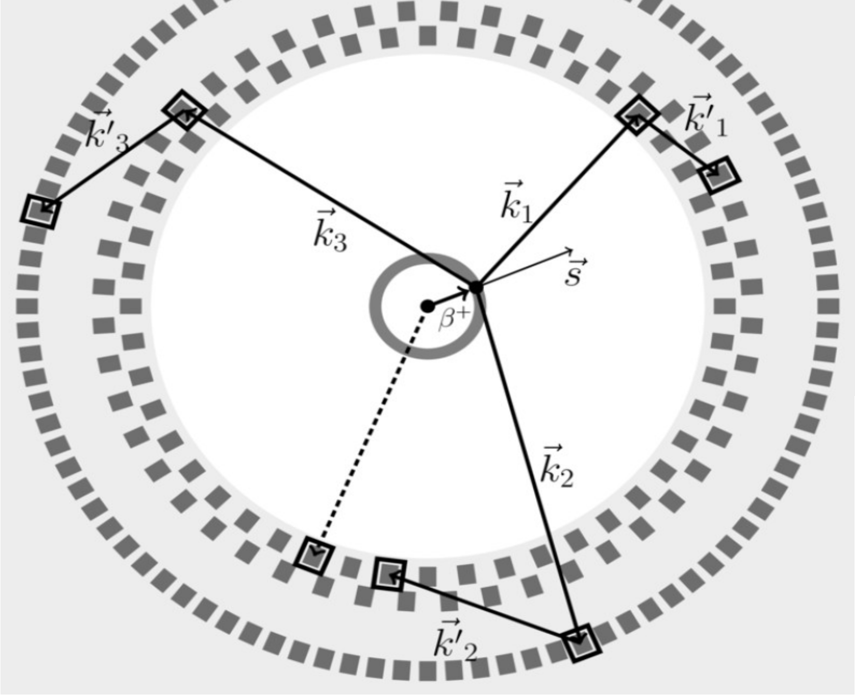
Identification of scatterings

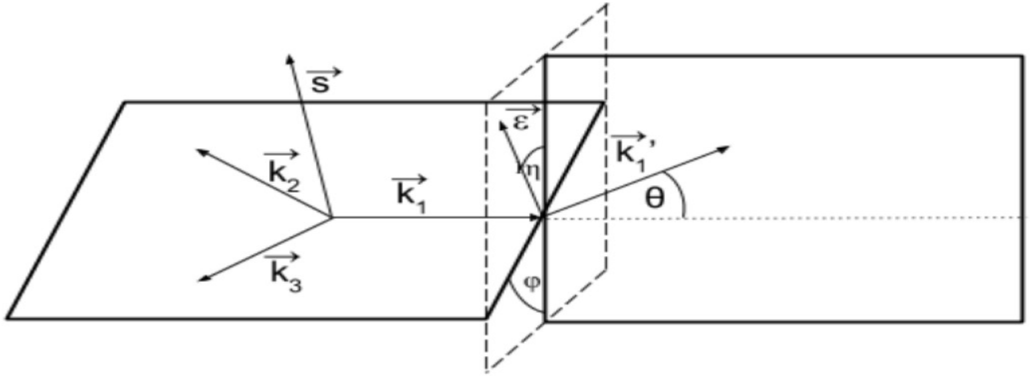




J-PET: S. Sharma et al., EJNMMI Phys. 7, 39 (2020)

Determination of polarization of anihilation γ





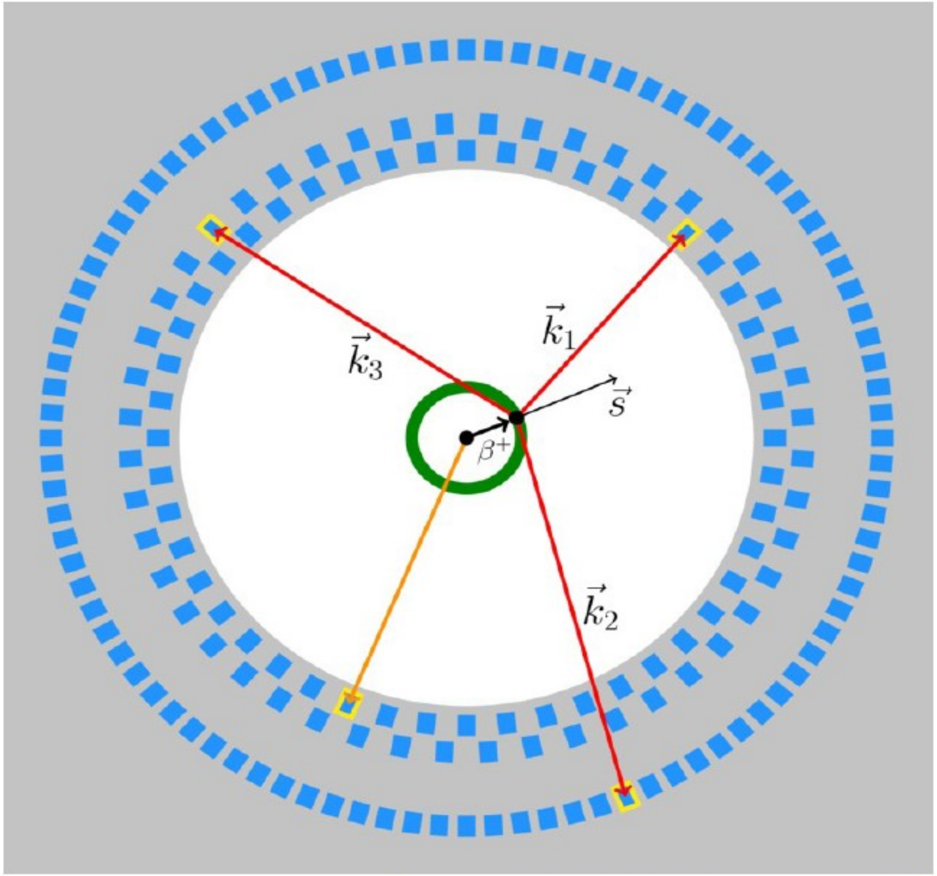
$$\frac{d\sigma}{d\Omega}(E,\theta,\eta) = \frac{r_0^2}{2}\left(\frac{E'}{E}\right)^2\left(\frac{E}{E'}+\frac{E'}{E}-2\sin^2\theta\cos^2\eta\right)$$

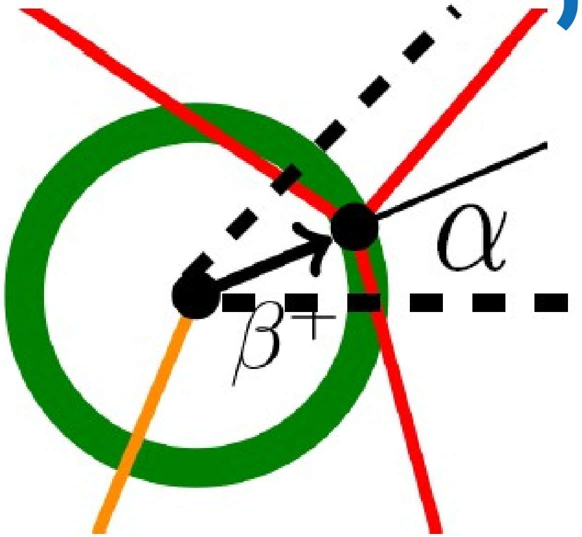
$$E'(E,\theta) = \frac{E}{1+\frac{E}{m_e c^2}(1-cos\theta)}$$

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

Determination of o-Ps polarization

J-PET





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

see the next talk by N. Chug

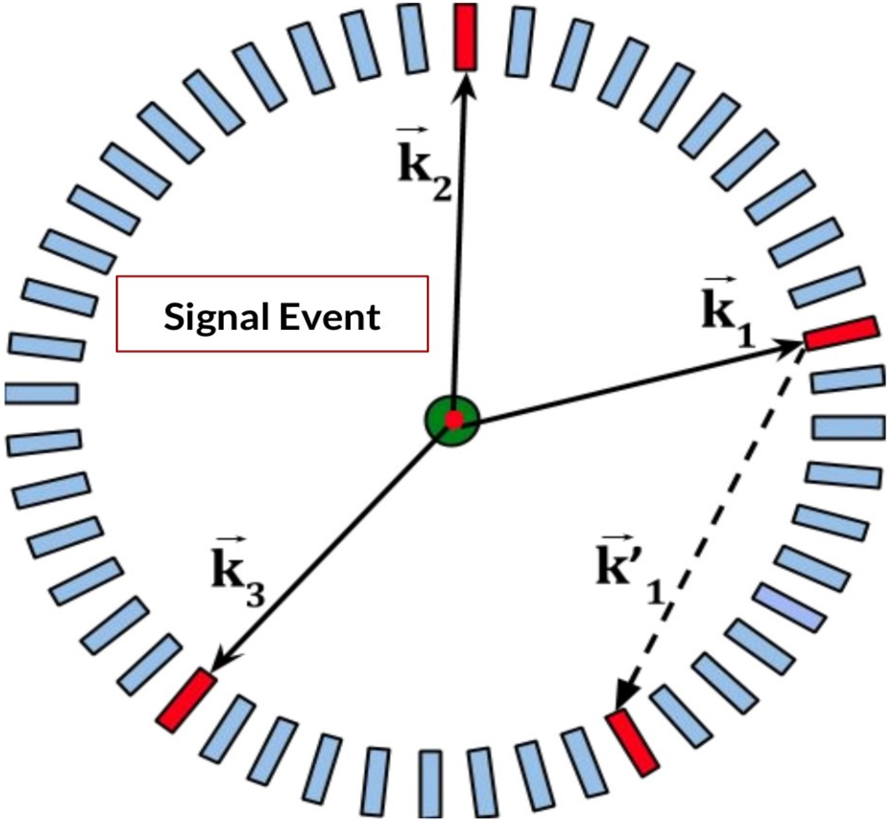
J.PET: A. Gajos al., Nucl. Inst. and Meth. A819 (2016) 54-59
J-PET: P. Moskal et al., Acta Phys. Polon. B 47 (2016) 509

CP, P, T symmetry test

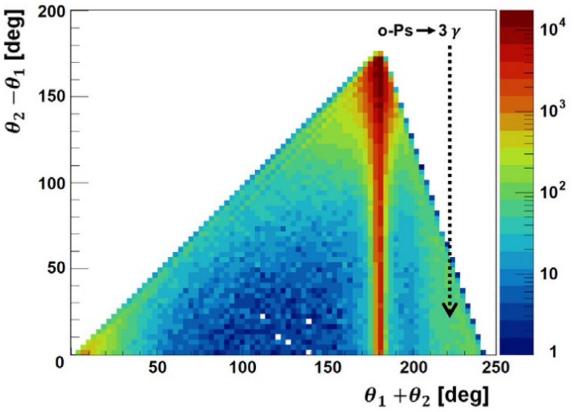
Operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	–	+	–	–
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	–	+	–
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))$	+	–	–	–	+
$\vec{k}_1 \cdot \vec{\varepsilon}_2$	+	–	–	–	+
$\vec{S} \cdot \vec{\varepsilon}_1$	+	+	–	+	–
$\vec{S} \cdot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

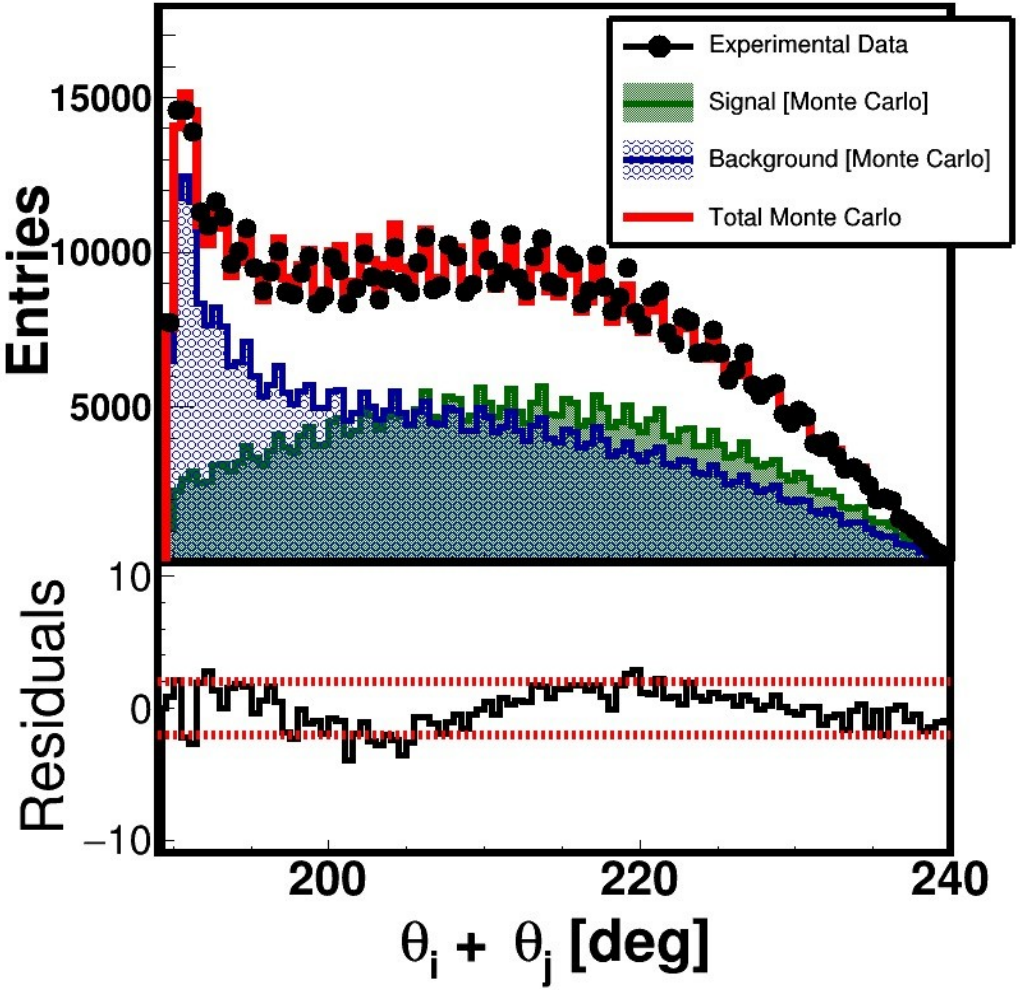
$\vec{k}_1 > \vec{k}_2 > \vec{k}_3$

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



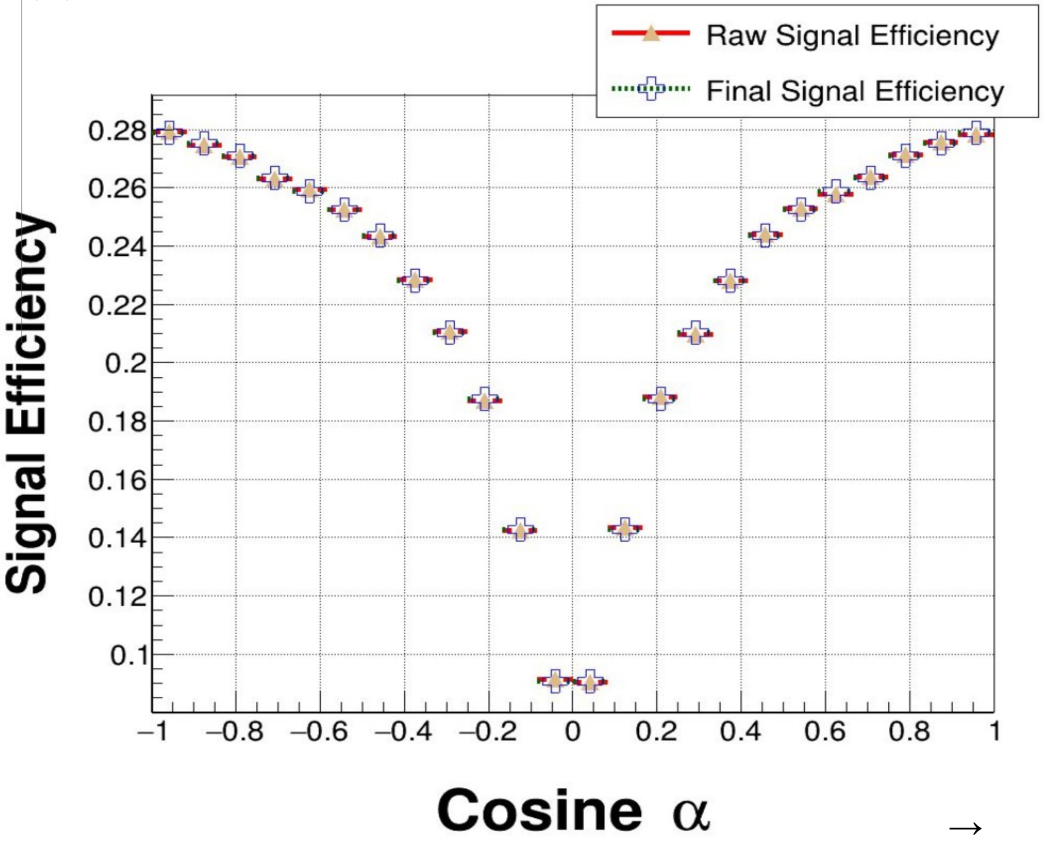
CP, P, T symmetry test

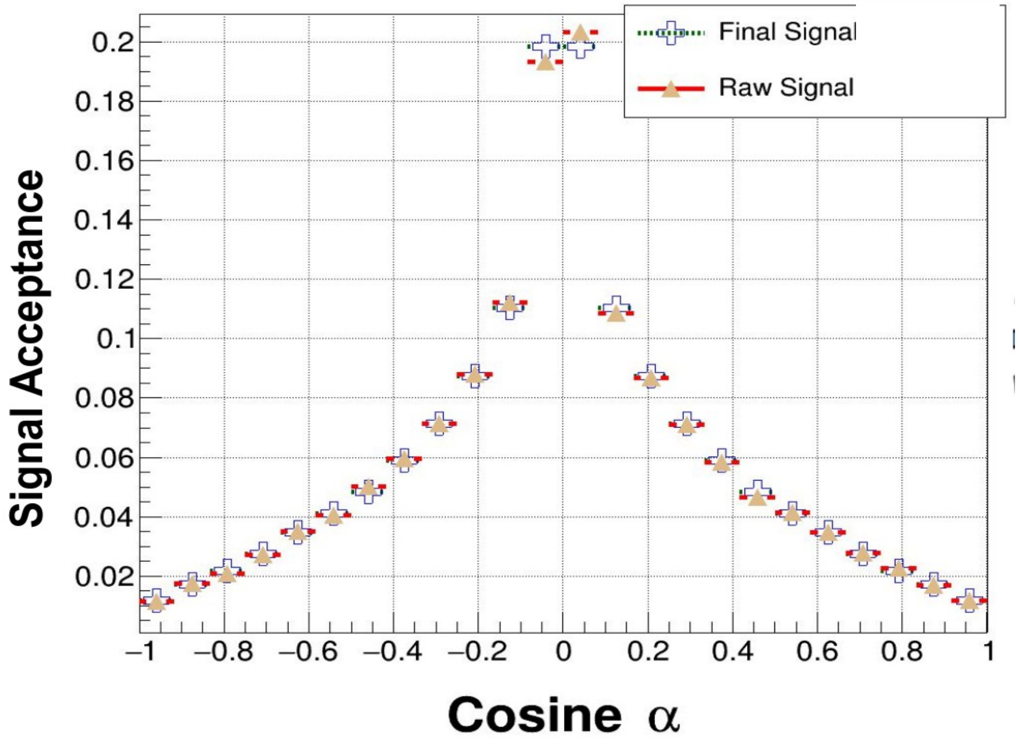




J. Raj

CP, P, T symmetry test





$$\vec{\varepsilon}_i \cdot \vec{k}_j = \cos(\alpha)$$

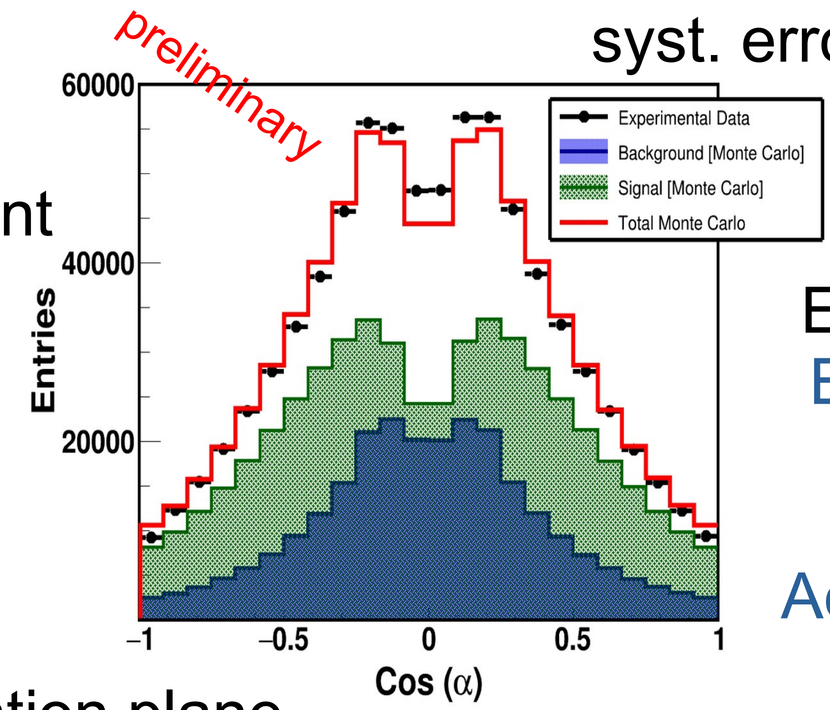
CP, P, T symmetry test

$\vec{\varepsilon}_i \bullet \vec{k}_j = \cos(\alpha)$

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

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]

Summary

► J-PET detector determines o-Ps spin direction and polarization of annihilation γ on the event by event basis.

► Efficiency and acceptance of J-PET are non-zero for the whole phase-space of operators sensitive to P, T, CP and CPT symmetry violations.

Future:

► continuous data-taking;

► configuration of modular J-PET for physics. see the next talk by N. Chug

Thank you