Status of o-Ps physics research @J-PET

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

Positronium Physics discussion day, UJ, 2022

Outline

- Positronium
- Discrete symmetries:
  - CPT
  - CP, P, T
  - C
  - SME
- Entanglement (talk by Beatrix)
- Dark Matter search (talk by Elena)

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

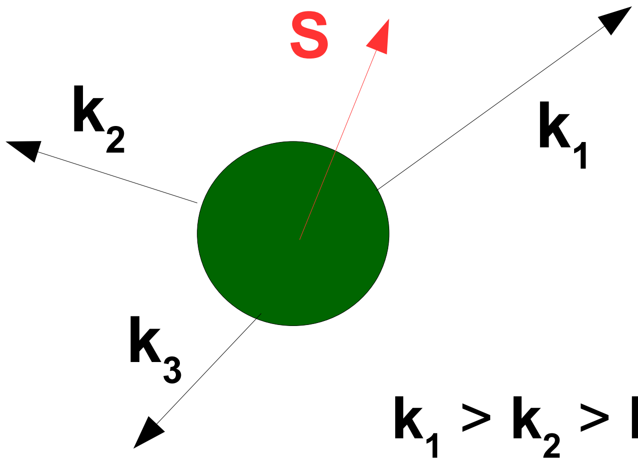
- purely leptonic (e+e-) bound state
- C, P, CP operators and $\mathcal{H}$ eigenstate
- the lightest atom
- undergoes self-annihilation
- e+ and e- do not decay into lighter particles via weak interaction, 10^{-14} violation level due to the weak interaction

  [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

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

$$^{22}Ne^{*} \rightarrow {}^{22}Ne + \gamma(1.247\ \mathrm{MeV}, \tau \approx 3.7\ \mathrm{ps})$$

o-Ps



$k_1 > k_2 > k_3$

$\varepsilon_i = k_i \times k'_i$

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

Unique @J-PET

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

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

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

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

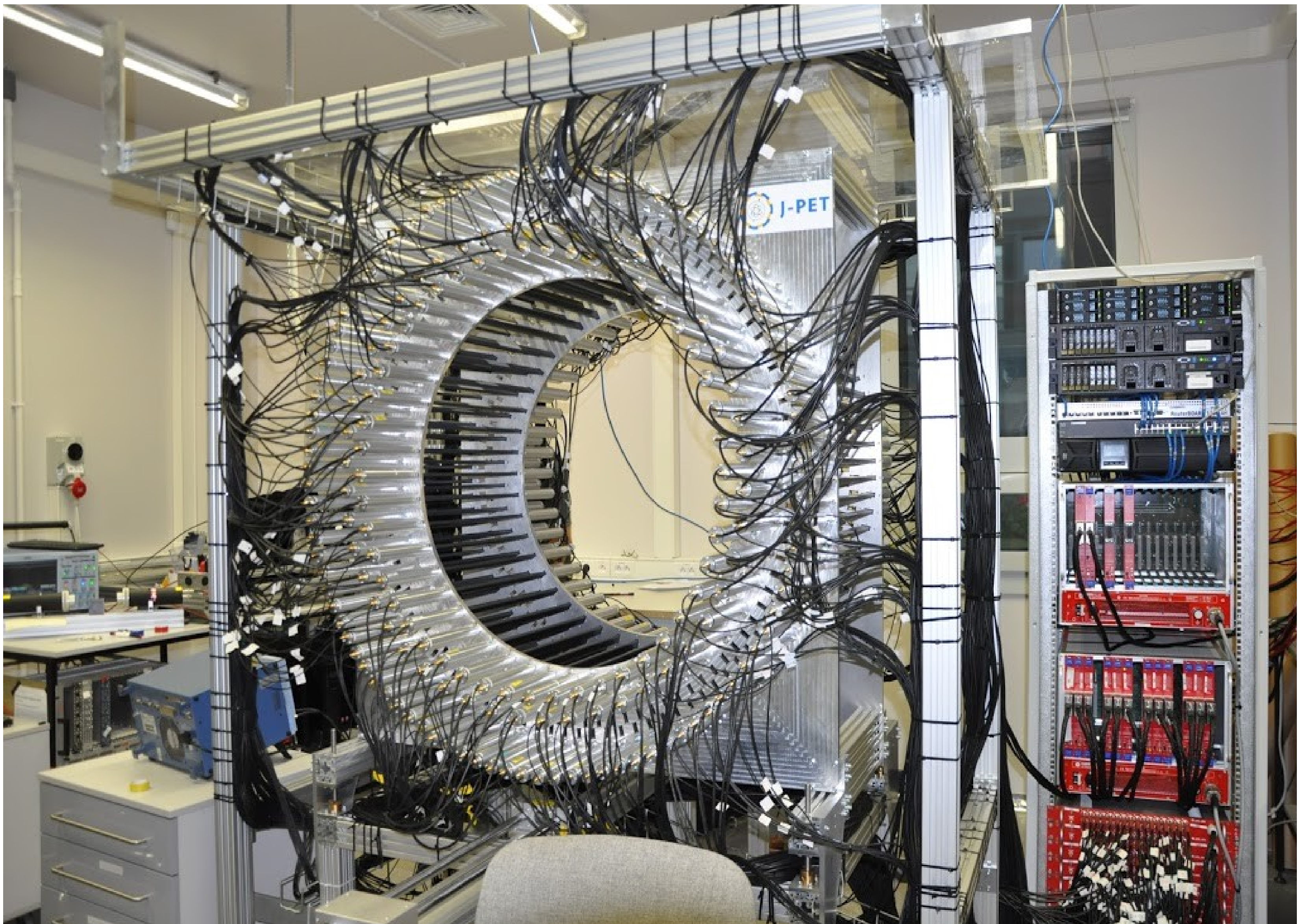
[T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401]

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

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

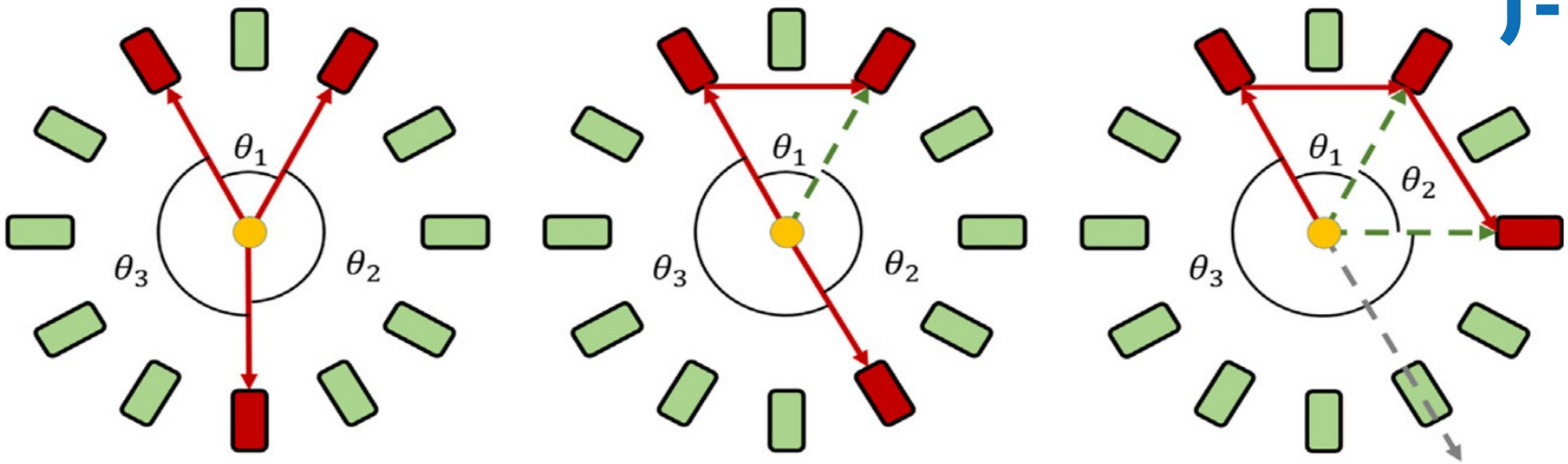
Jagiellonian PET

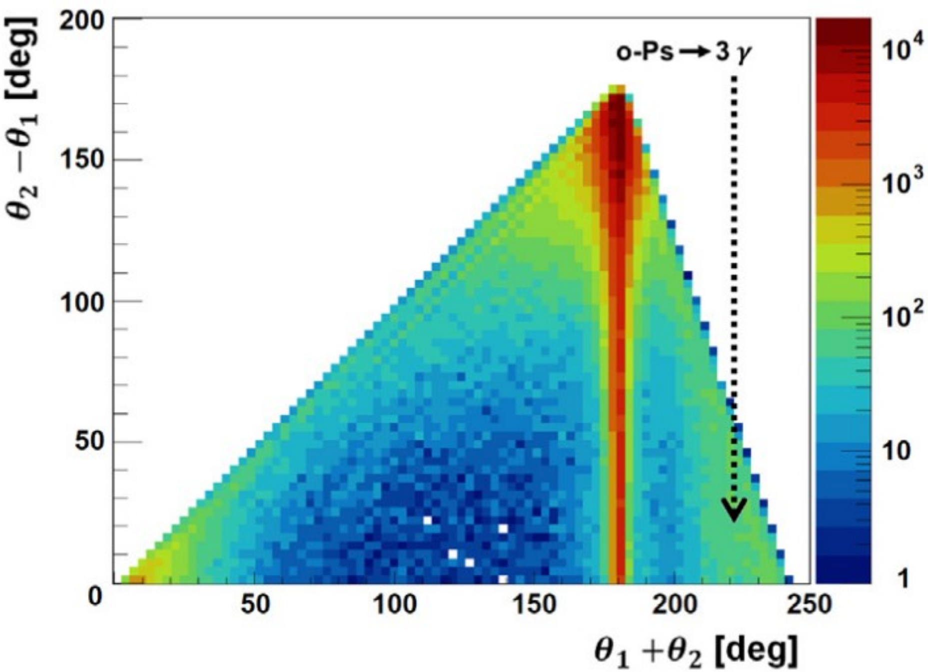
First PET from plastic scintillators
built at the Jagiellonian University in Poland



J-PET

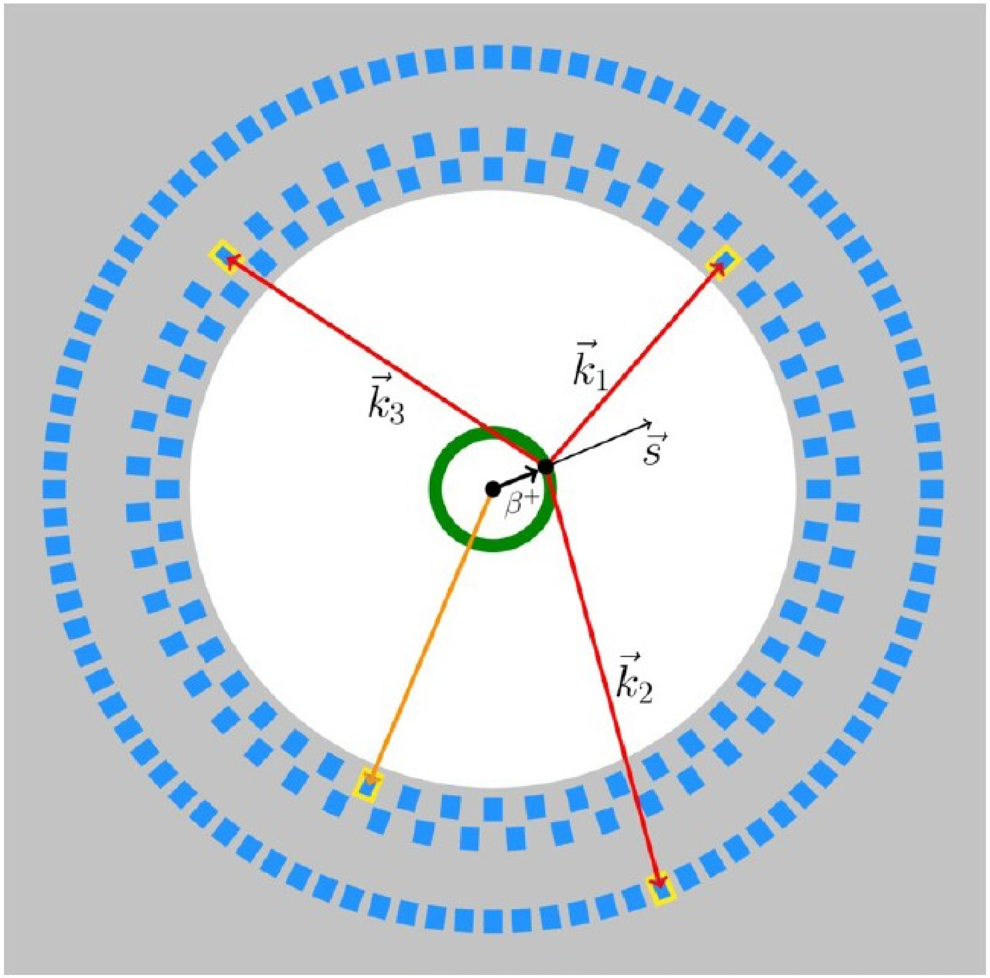
o-Ps detection

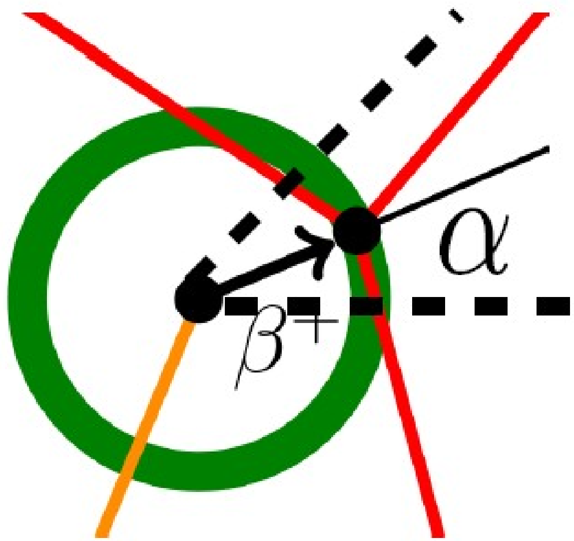




J-PET: K. Dulski et al., NIM A 1008 (2021) 165452

Determination of o-Ps polarization

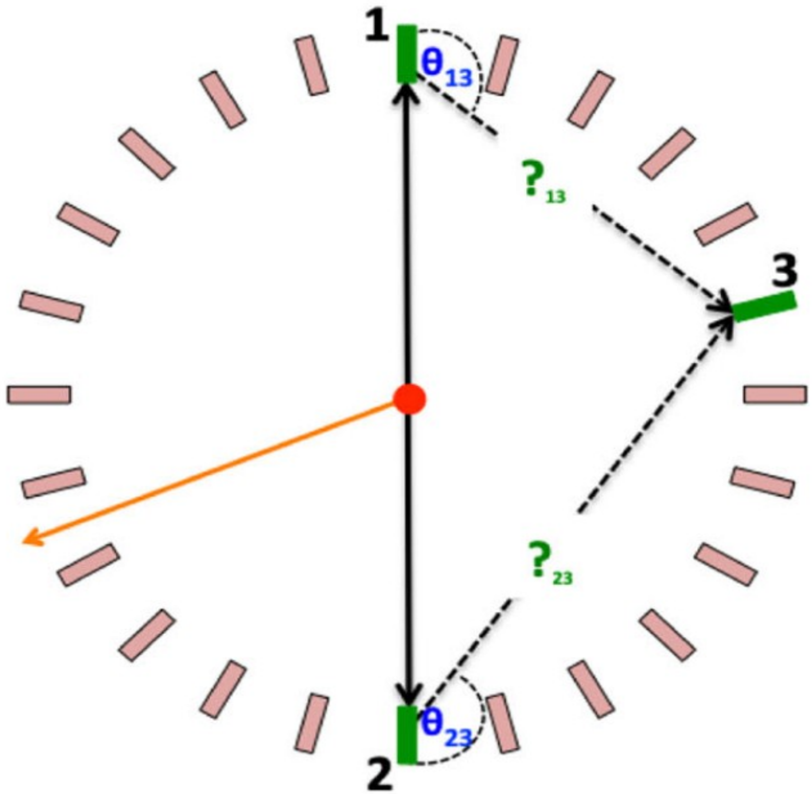


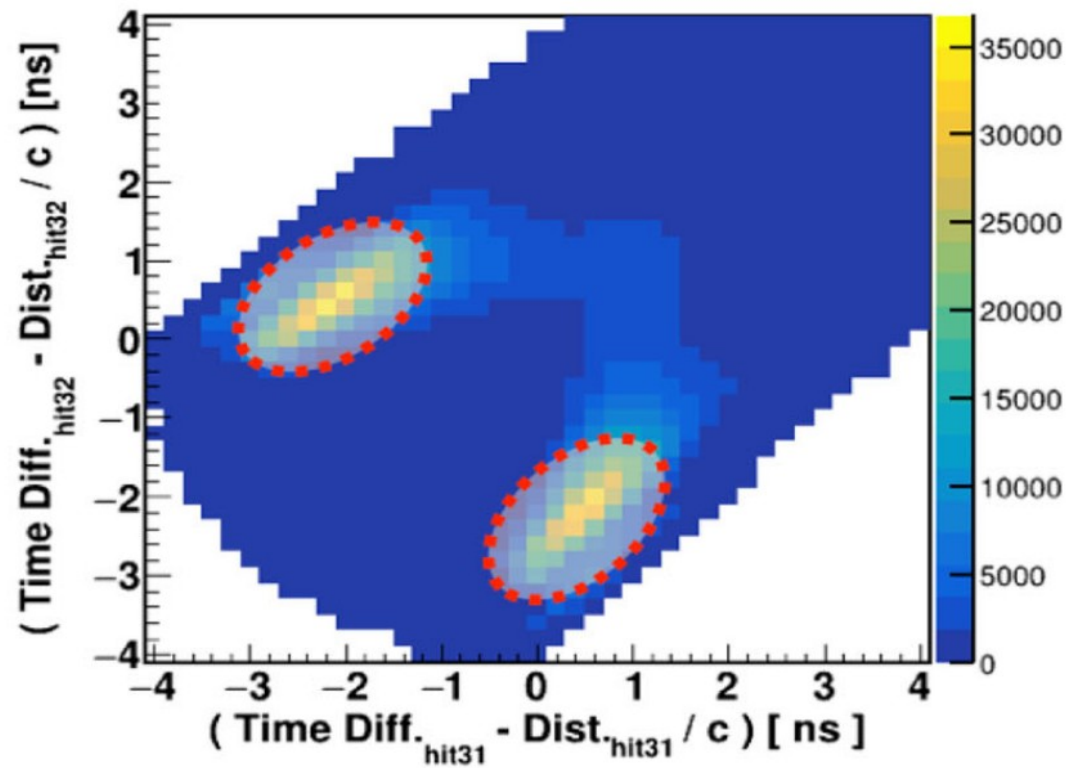


$$P = \frac{v}{c}(1 + \cos\alpha)/2$$

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

Identification/rejection of scatterings



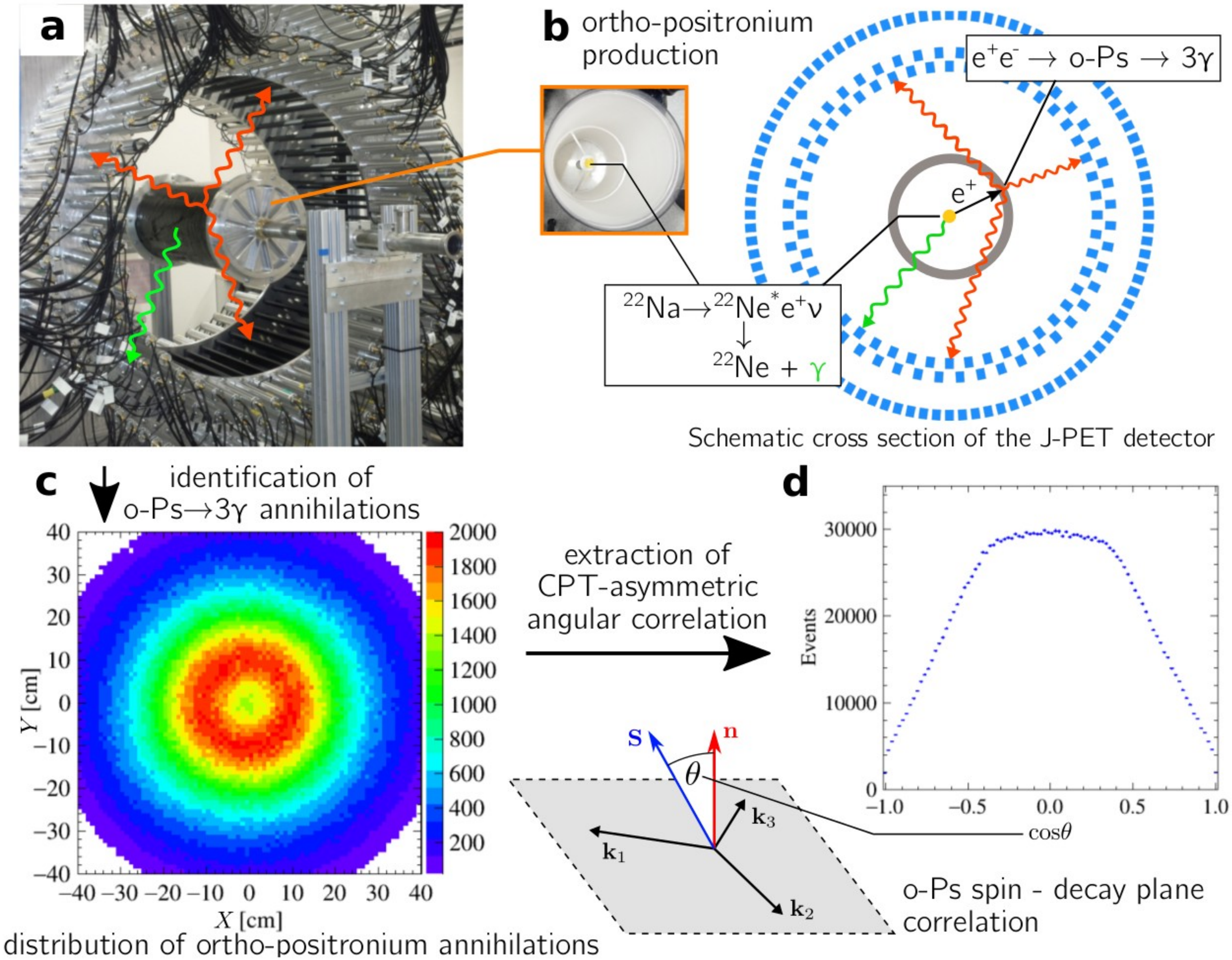


J-PET: S. Sharma et al., EJNMMI Phys. 7, 39 (2020)

CPT 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



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

CPT symmetry test

Selection criteria for 26 days measurement:

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

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

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

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

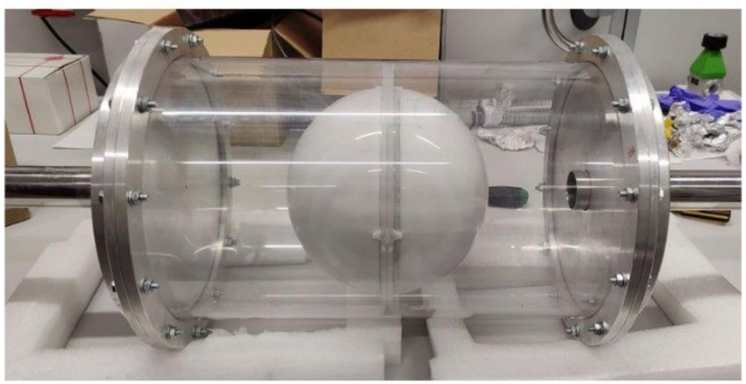
$$C_{CPT} = \langle \mathbf{S} \cdot (\mathbf{k}_1 \times \mathbf{k}_2) \rangle = 0.0026 \pm 0.0031$$

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

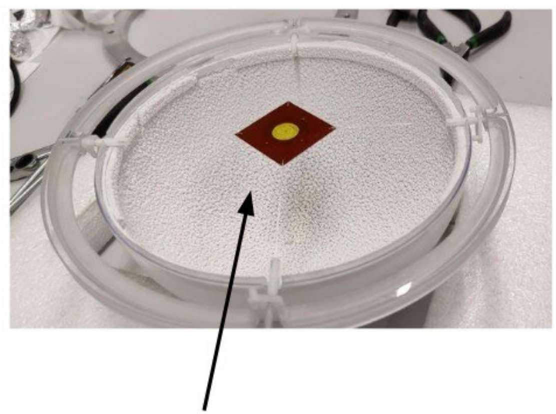
CPT test – next generation

N. Chug

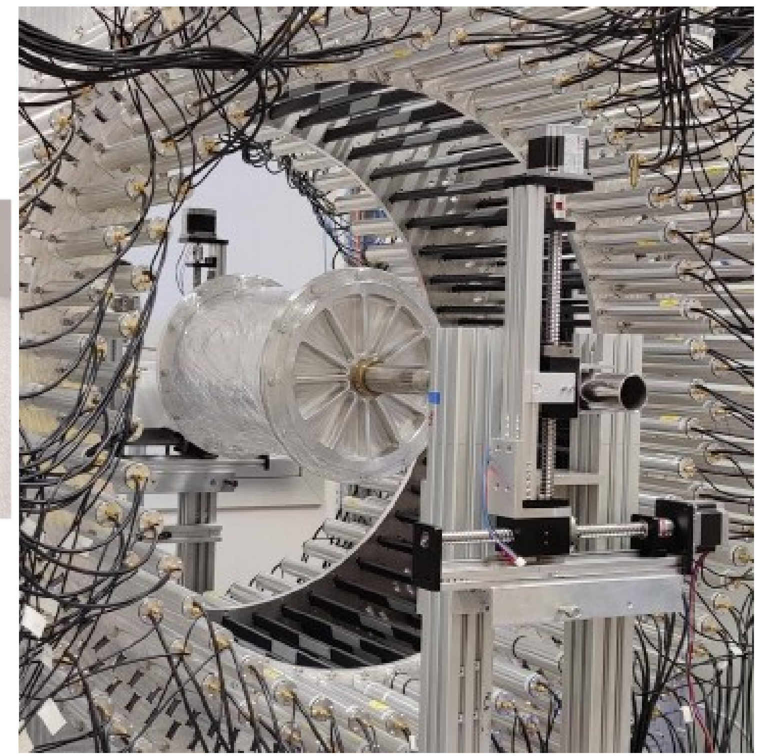
26 days → 3 months and still ongoing
10 MBq → 4 MBq of source activity
cylindrical → spherical annihilation chamber



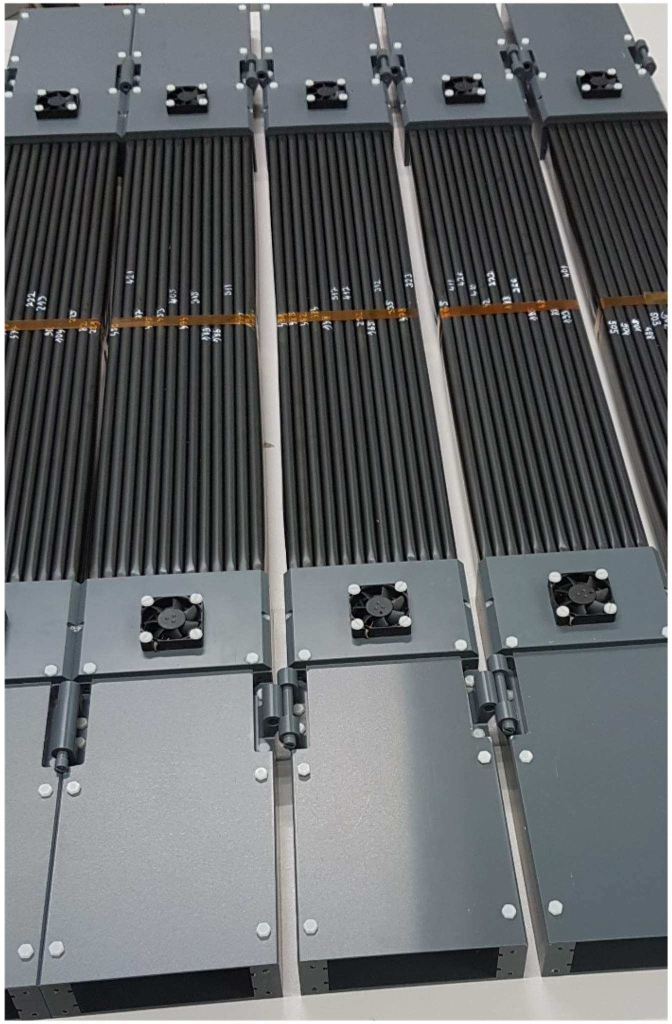
Setup of annihilation chamber

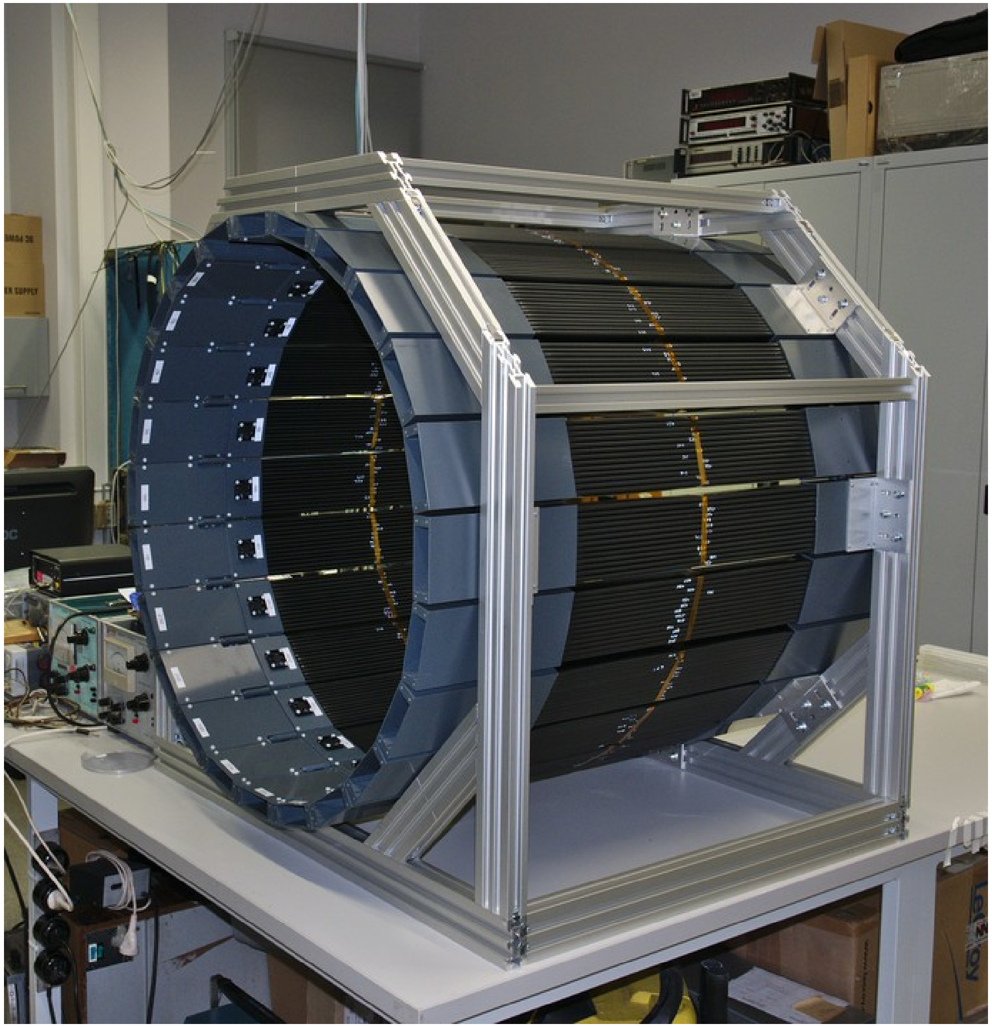


Placement of source inside spherical chamber



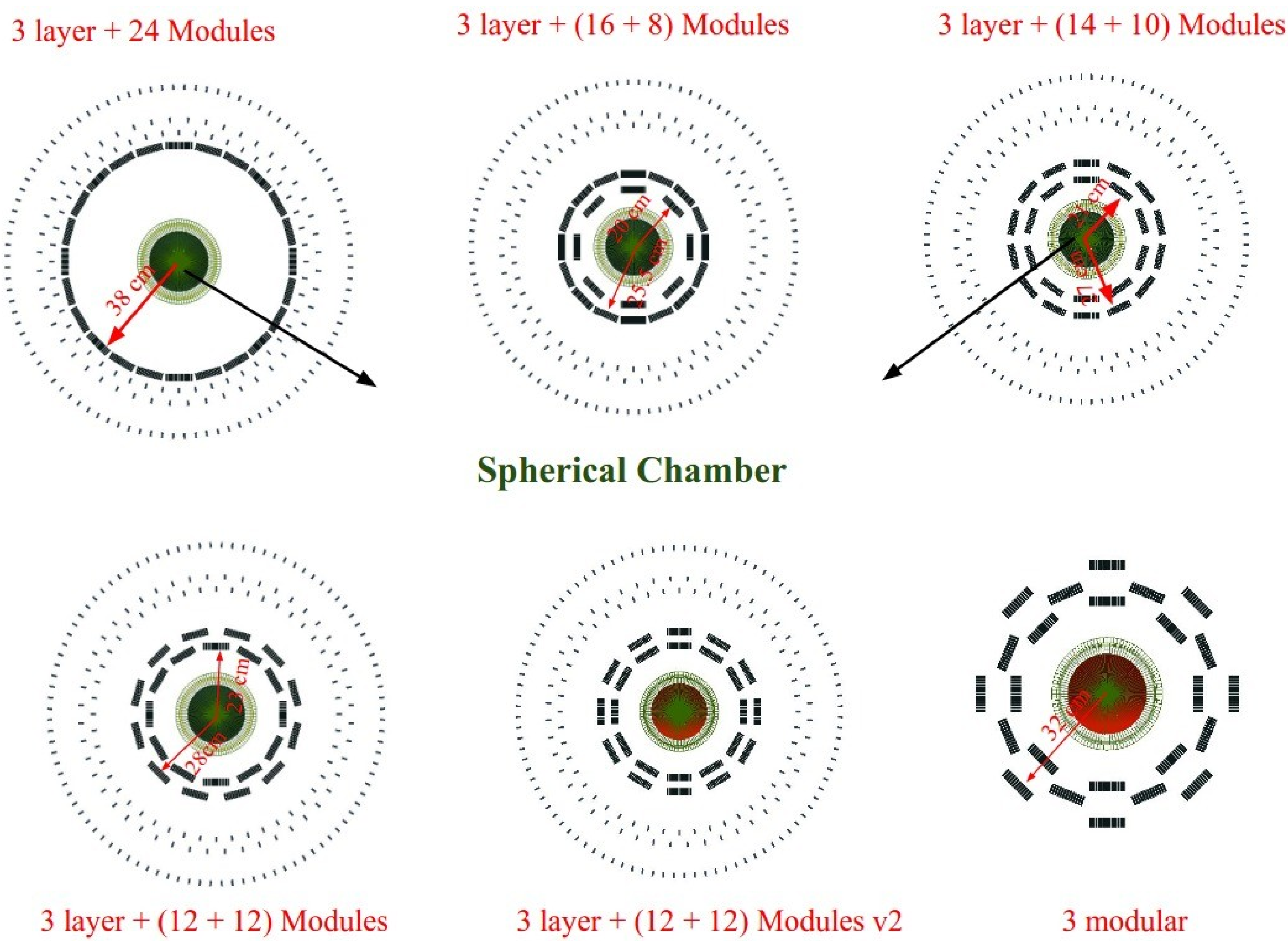
Modular J-PET





CPT test – next² generation

N. Chug

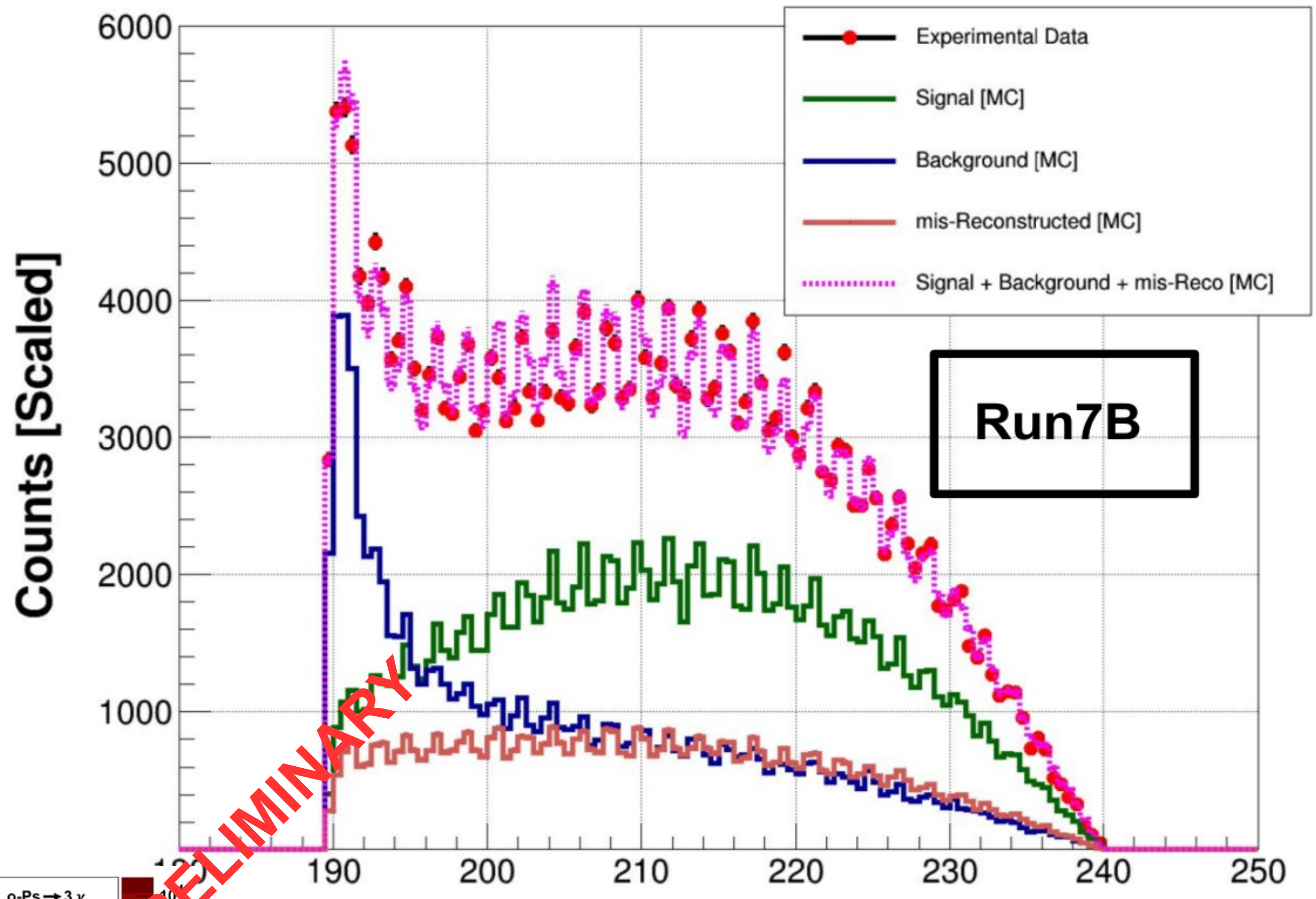


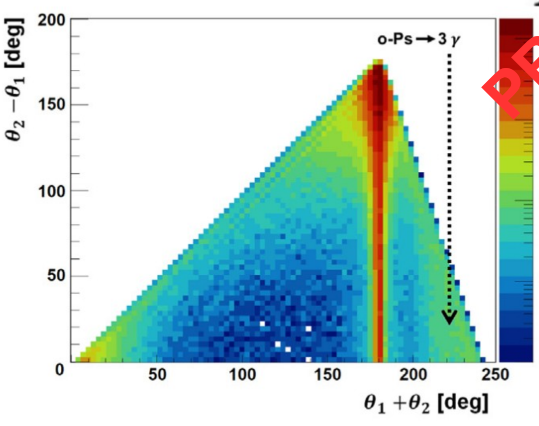
CP, P, T test

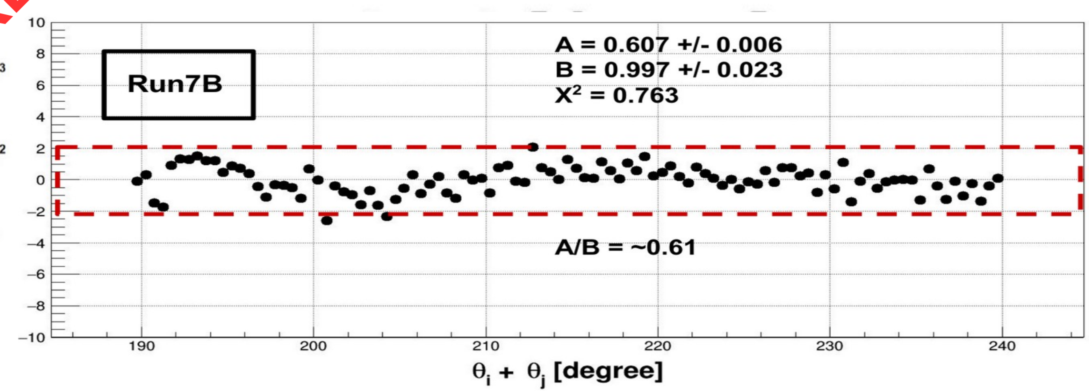
J. Raj

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

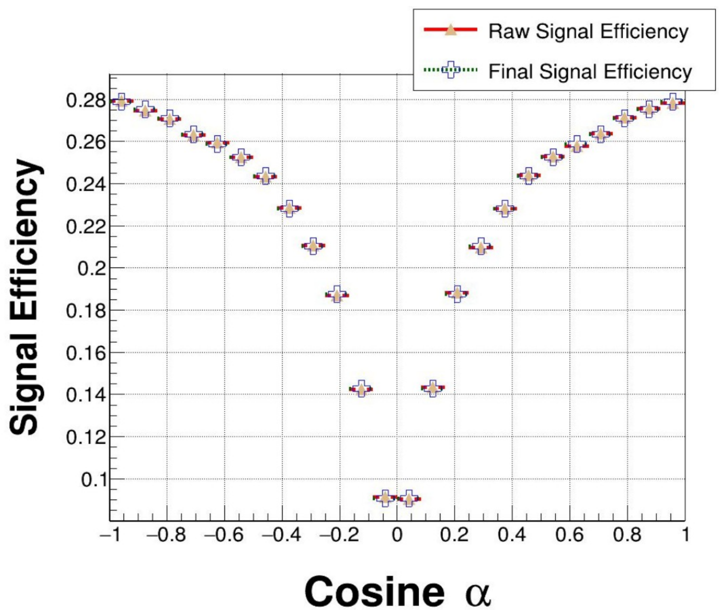
CP, P, T test

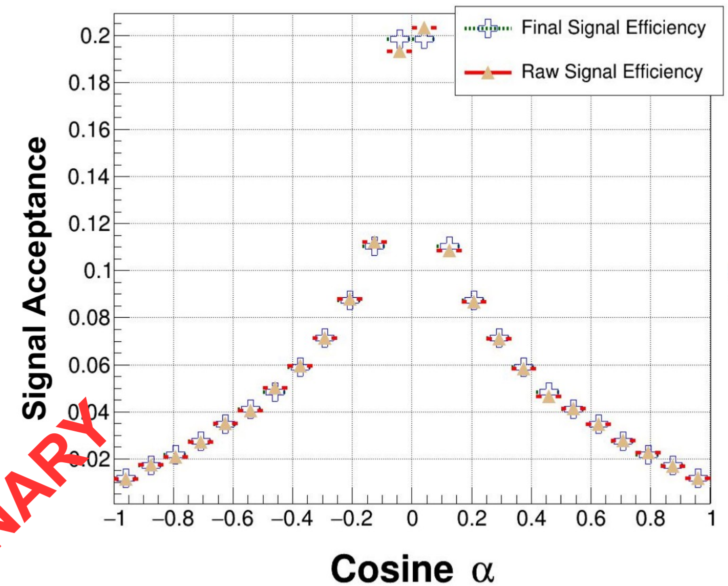

Counts [Scaled]
Experimental Data
Signal [MC]
Background [MC]
mis-Reconstructed [MC]
Signal + Background + mis-Reco [MC]
Run7B
PRELIMINARY

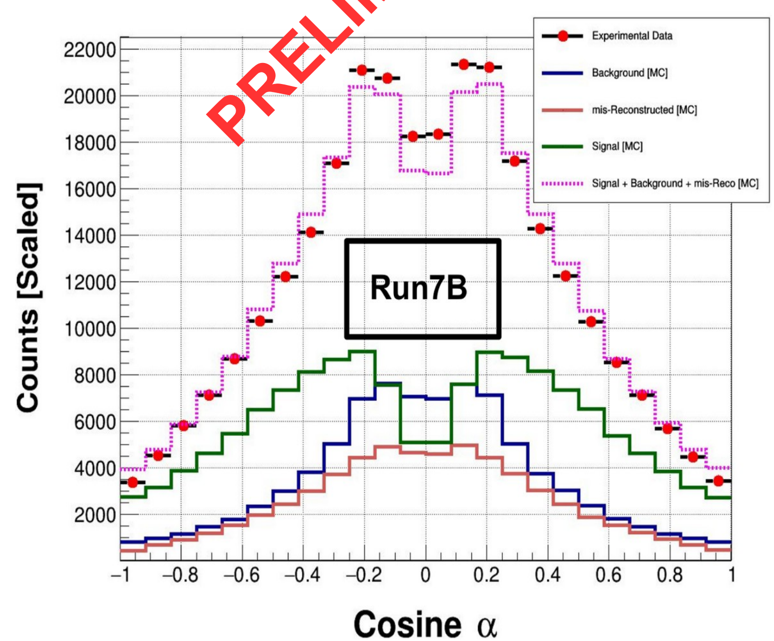

o-Ps → 3 γ
$\theta_2 - \theta_1$ [deg]
$\theta_1 + \theta_2$ [deg]


Run7B
A = 0.607 +/- 0.006
B = 0.997 +/- 0.023
X² = 0.763
A/B = ~0.61
$\theta_i + \theta_j$ [degree]

CP, P, T test


Raw Signal Efficiency
Final Signal Efficiency
Signal Efficiency
0.28
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
−1 −0.8 −0.6 −0.4 −0.2 0 0.2 0.4 0.6 0.8 1
Cosine α


Final Signal Efficiency
Raw Signal Efficiency
Signal Acceptance
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
−1 −0.8 −0.6 −0.4 −0.2 0 0.2 0.4 0.6 0.8 1
Cosine α


PRELIMINARY
Experimental Data
Background [MC]
mis-Reconstructed [MC]
Signal [MC]
Signal + Background + mis-Reco [MC]
Run7B
Counts [Scaled]
22000
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
−1 −0.8 −0.6 −0.4 −0.2 0 0.2 0.4 0.6 0.8 1
Cosine α

CP, P, T test

J-PET preliminary: $C_{CP} = \langle \boldsymbol{\varepsilon}_i \cdot \mathbf{k}_j \rangle = X \pm 0.0007_{stat}$

syst. error negligible

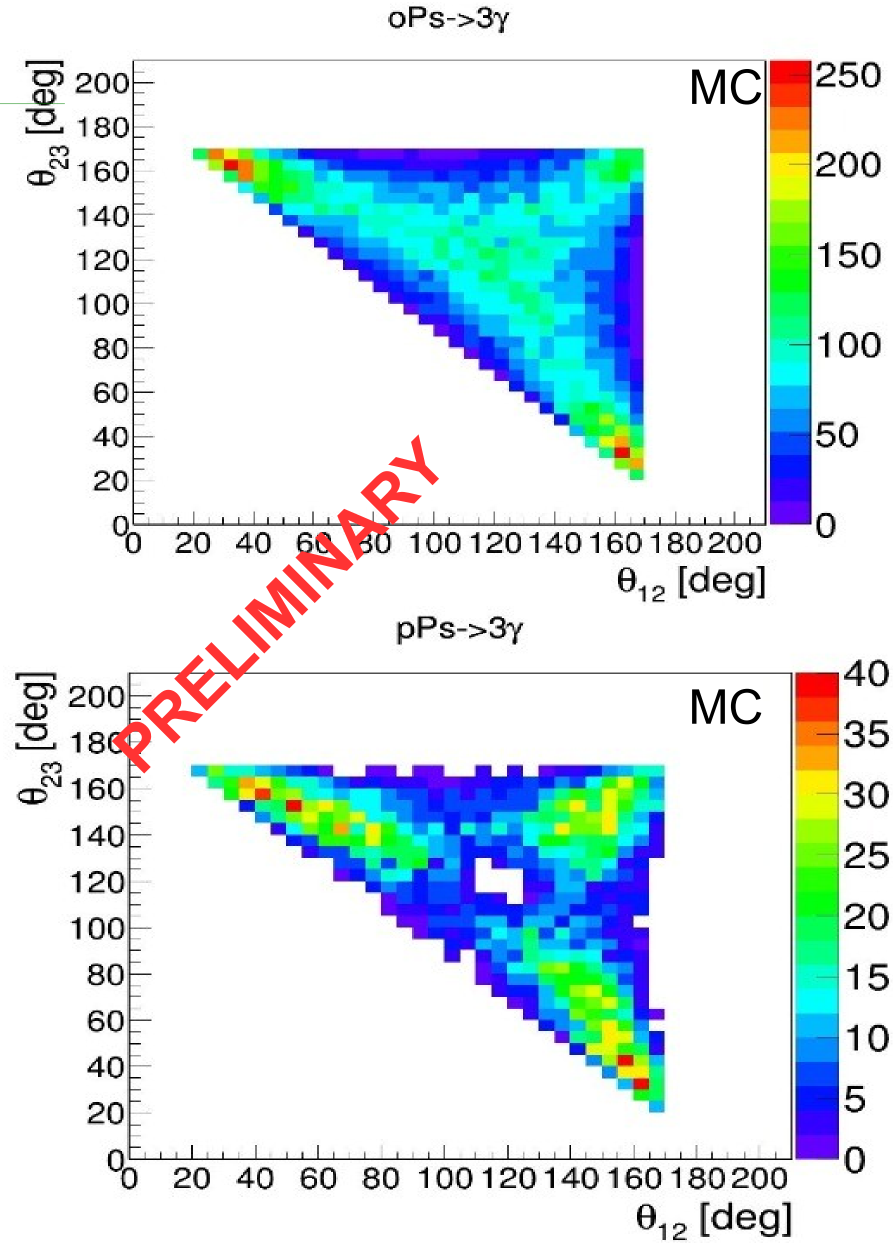
Error Composition:
Background = 6 %
Miss-Reco = 2 %
Efficiency = 2 %
Acceptance = 14 %
Data = 76 %

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

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

M. Skurzok

C test

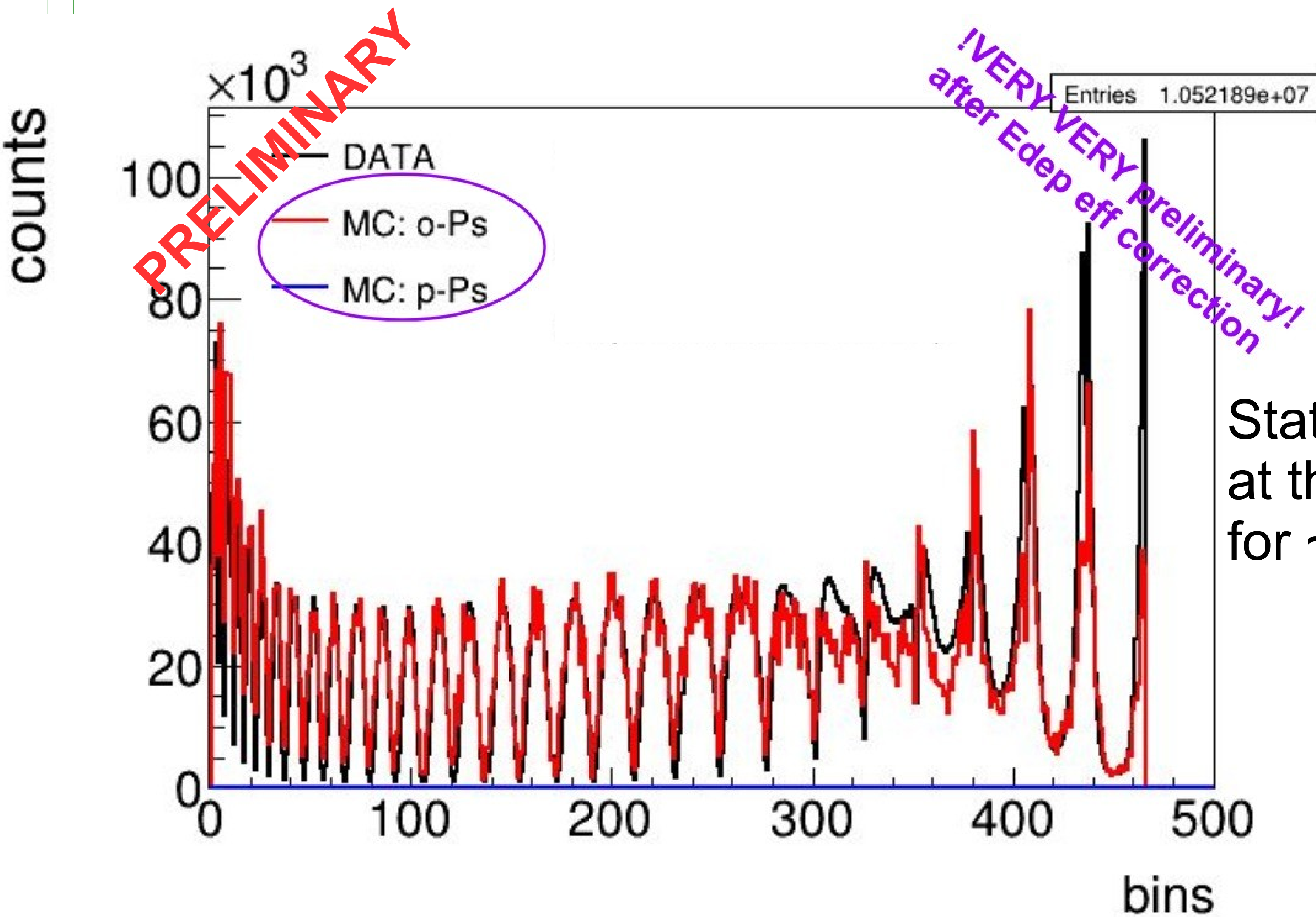


$C_C \leq 2.8 \times 10^{-6}$ (@68% c.l.)

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

M. Skurzok

C test



Statistical sensitivity at the level of $10^{-5}/10^{-6}$ for ~2% of Run 11

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

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

SME@J-PET?

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. Pol. B 47, 509 (2016)

	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	−	−	−	+	+	+	−

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

Future

- continous data-taking
- optimalization of source activity
- configuration of modular J-PET for physics
- implementation of external magnetic field

- SME

Thank you for attention