Testing CPT symmetry in ortho-positronium decays with the J-PET facility

Szymon Niedźwiecki
on behalf of the **J-PET** collaboration

Total-body J-PET and Theranstic Center group photo, 2021-04-26
In front of Faculty of Physics, Astronomy and Computer Science of Jagiellonian University

Motivation: discrete symmetry tests with o-Ps decays

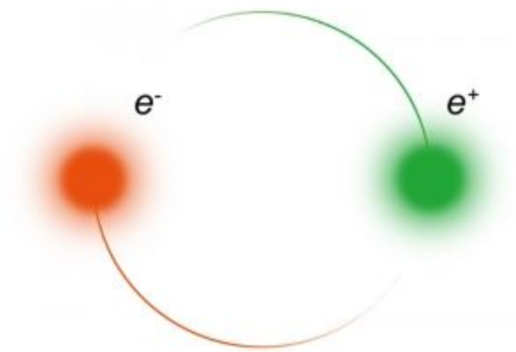
- **POSITRONIUM - the lightest purely leptonic object**

bound by a central potential

⇓

is eigenstate of the parity operator P

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



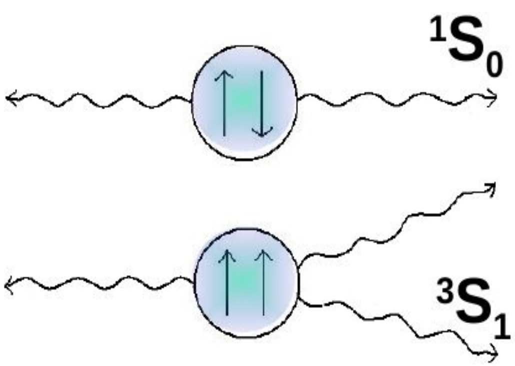
symmetric under the exchange of particles - anti-particles

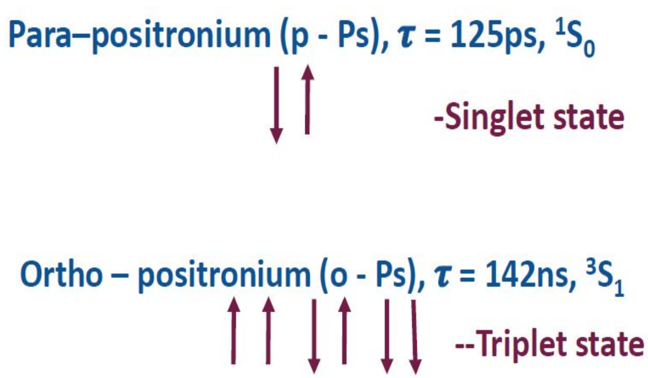
⇓

is eigenstate of the charge conjugation operator C

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

eigenstate of the CP operator





even number of photons

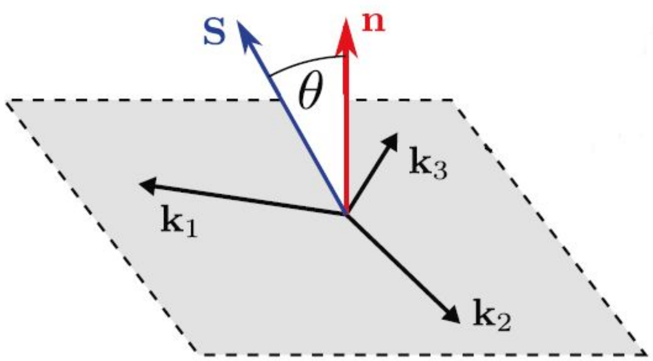
symm. of charge conjugation C

odd number of photons

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

Measurement the expectation value of the symmetry odd-operators

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



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

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

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

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

Required:

- the o-Ps spin determination
- of o-Ps→3γ decays selection

(determination of photons momenta)

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

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

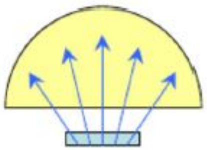
[P. Moskal et al., Acta Phys. Polon. B47 (2016) 509]

Previous measurements

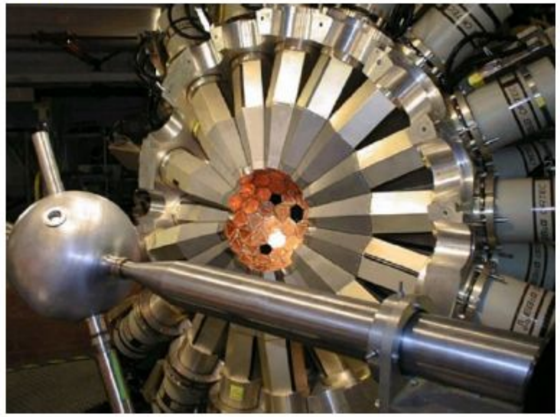
Gammasphere
PRL. 91 (2003) 263401

$$\vec{S} \cdot (\vec{k_1} \times \vec{k_2})$$

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



$$P_{e+} = \frac{v}{c} \cdot 0.686$$

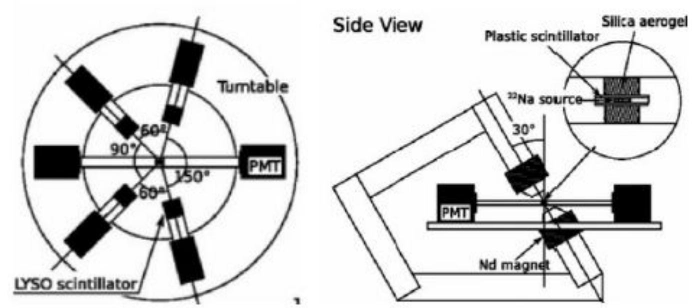


Limiting positron emission direction
1 Mbq β^+ emitter activity
4π detector but low angular resolution

Yamazaki et al.
PRL 104 (2010) 083401

$$(\vec{S} \cdot \vec{k_1})(\vec{S} \cdot (\vec{k_1} \times \vec{k_2}))$$

$C_{CP} = (1.3 \pm 2.1 \pm 0.6) \times 10^{-3}$

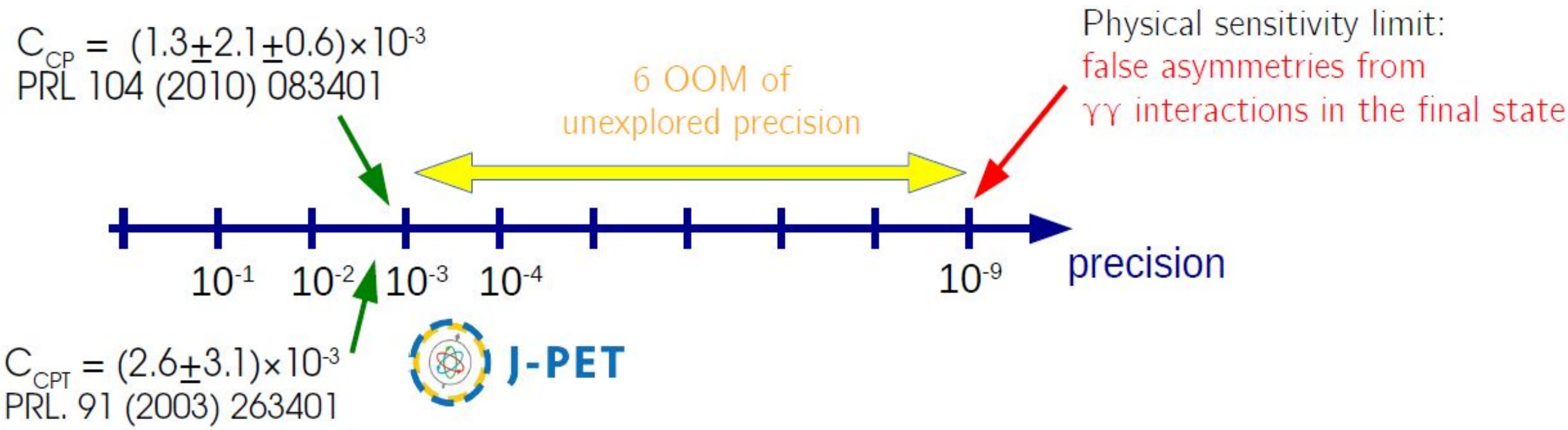


Polarized o-Ps using external B field
Inclusive measurement
Only certain angular configurations

Courtesy of A. Gajos

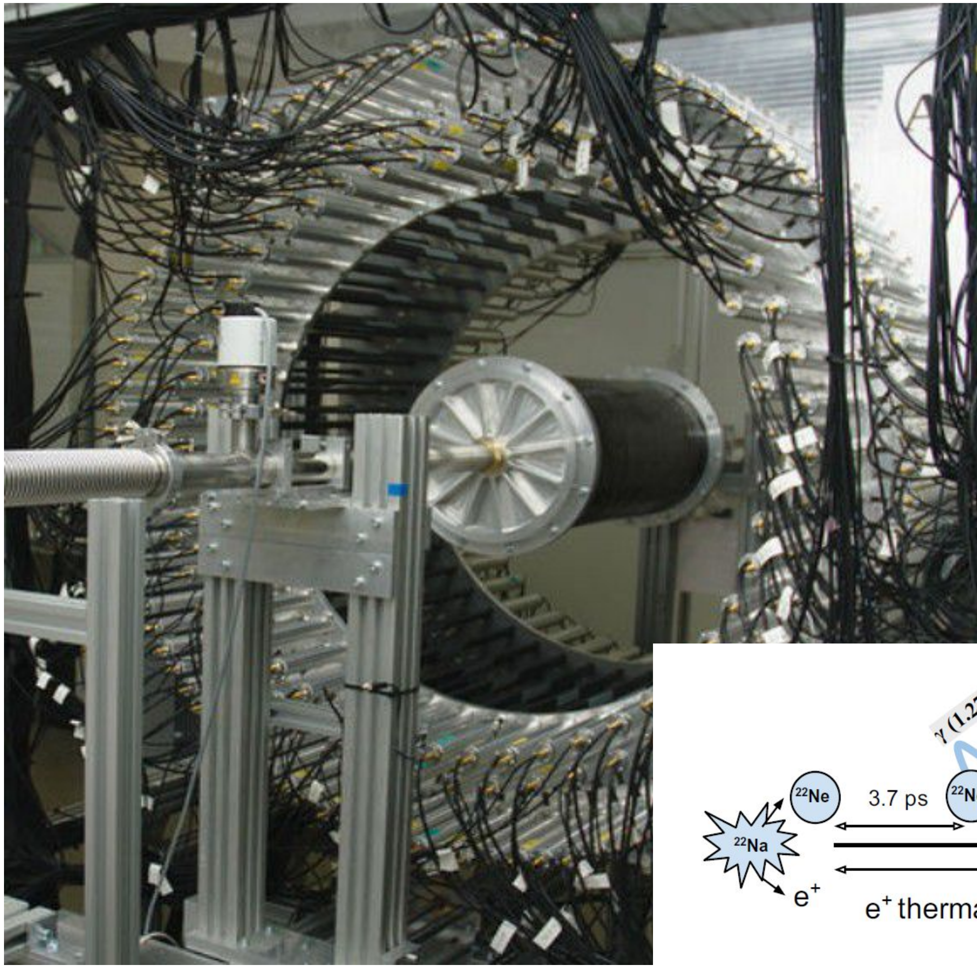
Motivation: discrete symmetry tests with o-Ps decays

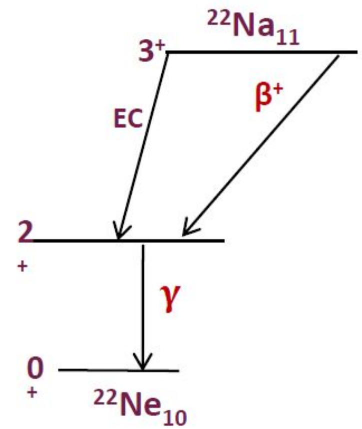
- Discrete symmetries are scarcely tested with leptonic systems:
  - Neutrino oscillations: Dirac phase, δCP ~3σ level [T2K, *Nature 580 (2020) 339*]
  - Electron EDM < 1.1×10^{-29} [ACME, *Nature 562 (2018) 355*]

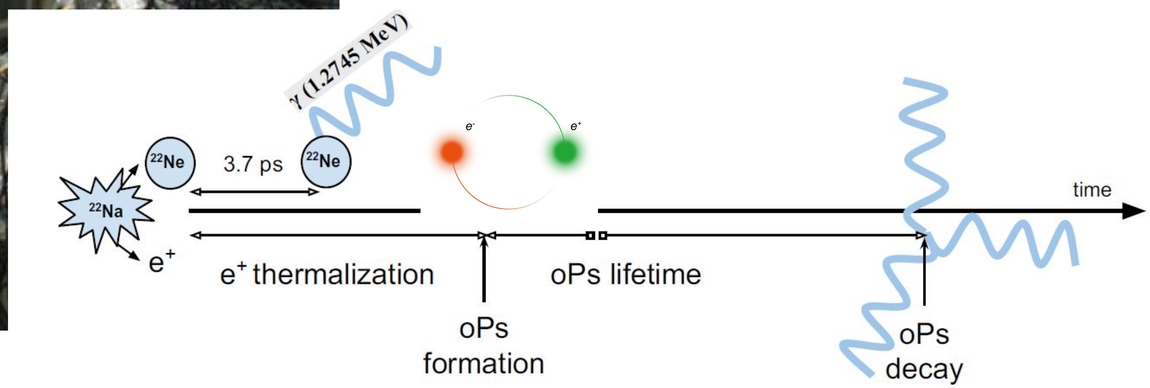


- symmetries tests can be made with a very high precision limited, only by the effects due to the weak interaction: 10^{-14} and photon-photon interaction: 10^{-9}. (Standard Model Calculations)
  [Phys. Rev. A 37, 3189 (1988), Z. Phys. C 41, 143 (1988), M. S Sozzi "Discreet Symmetries and CP violation"]

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







[D. Kaminska, et a.l., Eur. Phys. J. C (2016) 76:445]

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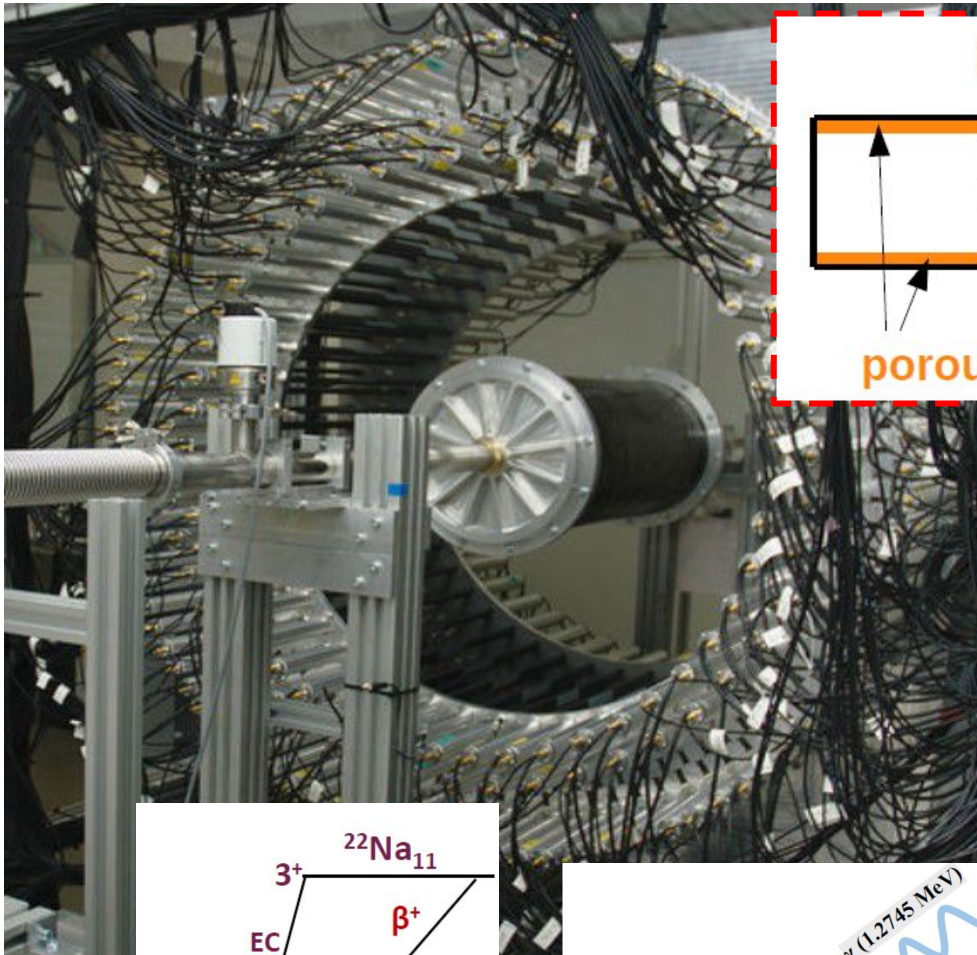
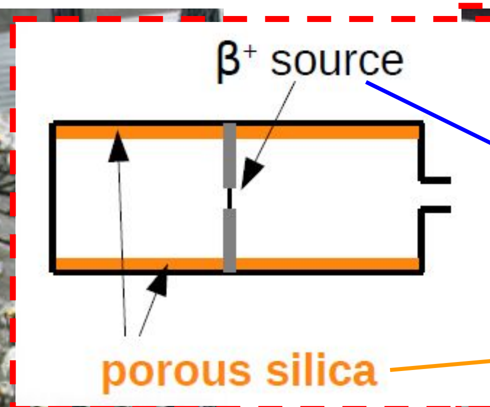
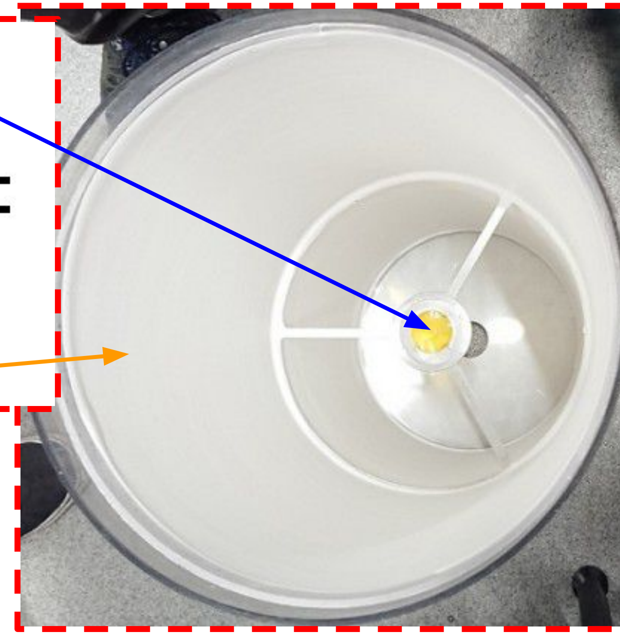
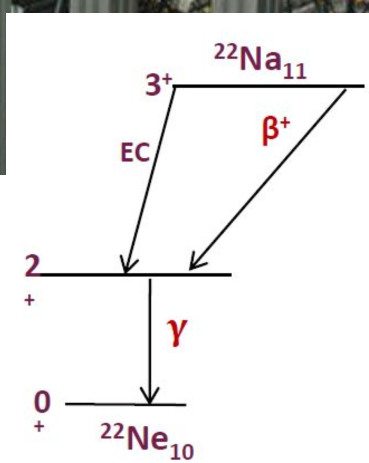
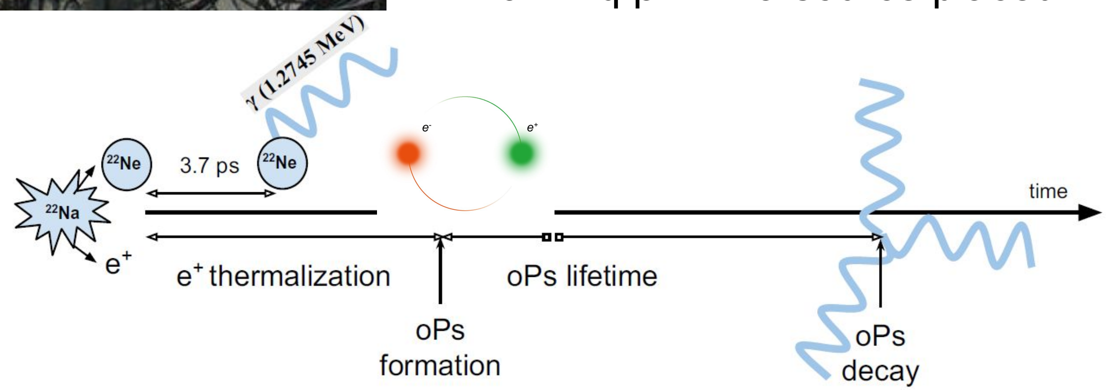






- Extensive-size chamber, R=12 cm
- Walls coated with porous silica material (o-P target)
- 10 MBq β+ ^{22}Na source placed in the center





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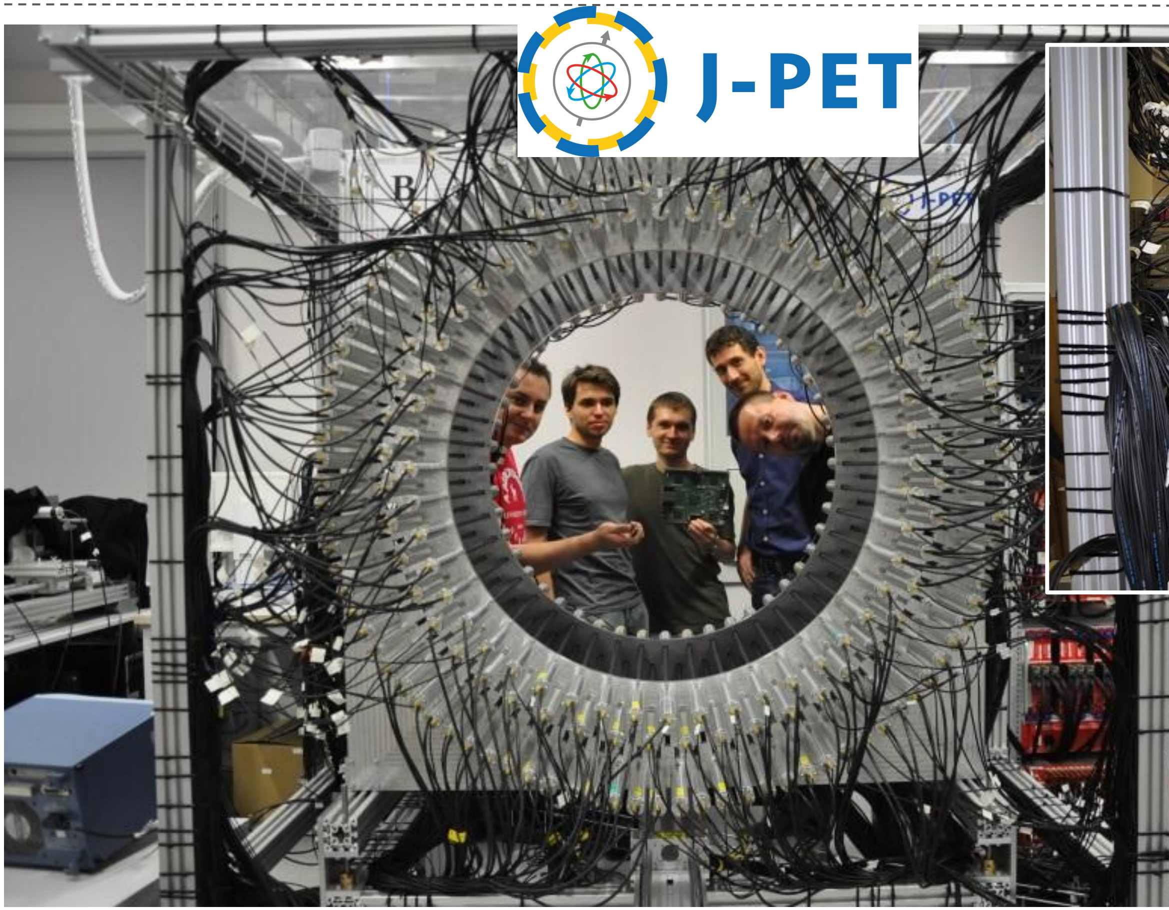
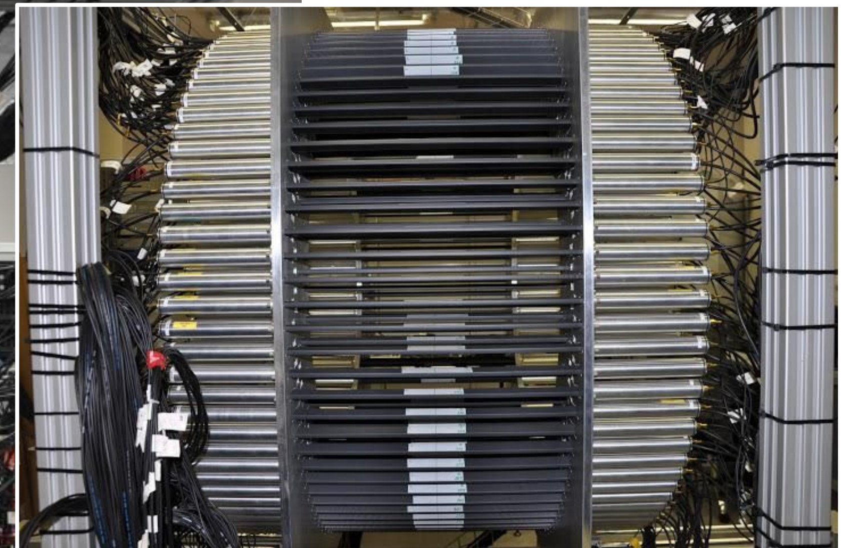
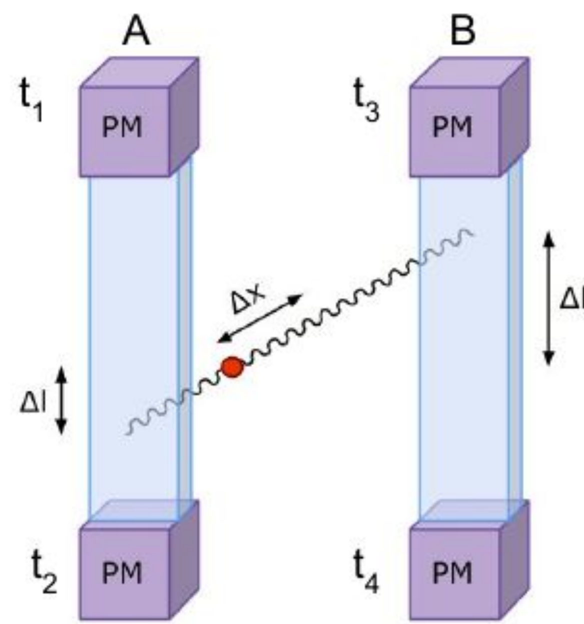
J-PET detector at Jagiellonian University in Kraków, Poland



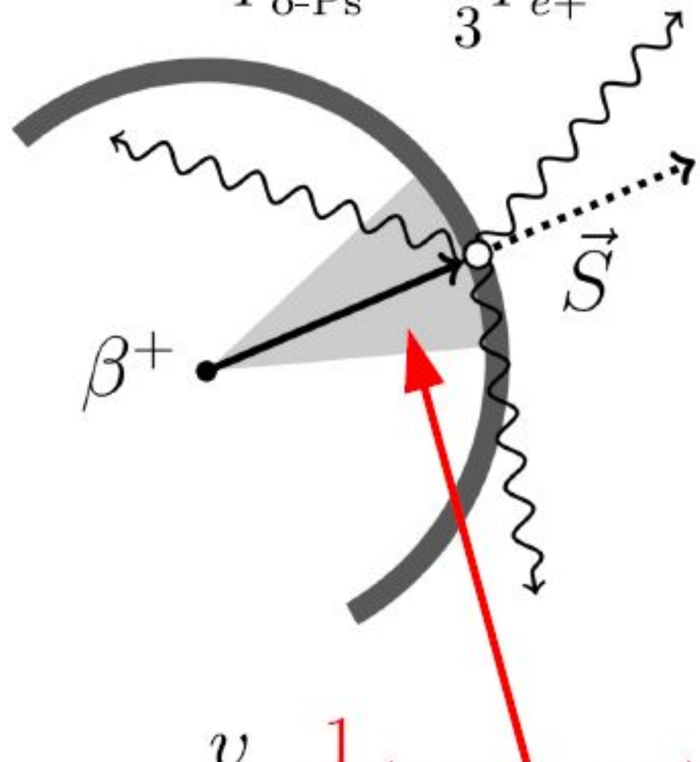




- 192 EJ-230 scintillators: 7x19x500 mm^3;
- 384 R9800 photomultipliers;
- 85 cm radius;
- 1536 channels;
- multithreshold digital electronics;
- the novel trigger-less DAQ;

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

$$P_{\text{o-Ps}} = \frac{2}{3} P_{e+}$$



<u>o-Ps spin estimation:</u>

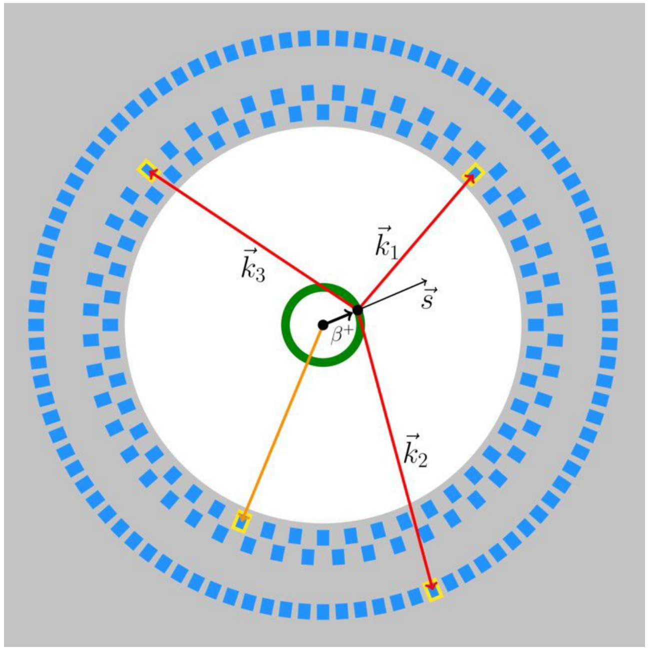
✶ e^+ spin estimated event-by-event recording multiple geometrical configurations
✶ effective polarization depends on o-Ps→3γ vertex resolution
✶ vacuum in the chamber assures that e^+ is not going to decay before reaching inner wall

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

$$P_{e+} = (N^{e+}_{+1/2} - N^{e+}_{-1/2}) \,/\, (N^{e+}_{+1/2} + N^{e+}_{-1/2})$$

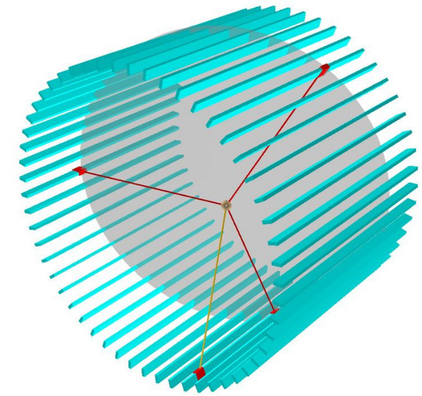
M. Mohammed, et al., Acta Phys. Pol. A 132, 1486 (2017)]

o-Ps spin determination and o-Ps→3γ decays reconstruction in J-PET

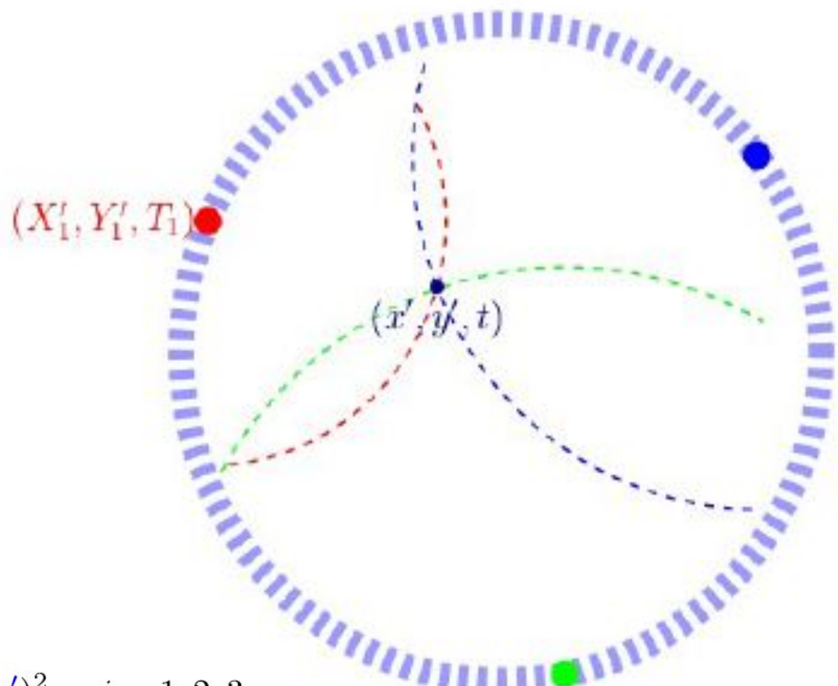


<u>o-Ps→3γ decays reconstruction:</u>

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



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



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

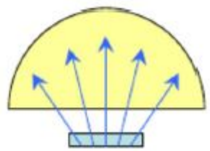
[A. Gajos et al., NIM A 819 (2016), 54-59]

J-PET vs previous measurements

Gammasphere
PRL. 91 (2003) 263401

C_{CPT} = (2.6±3.1)×10^{-3}

$$\vec{S} \cdot (\vec{k_1} \times \vec{k_2})$$



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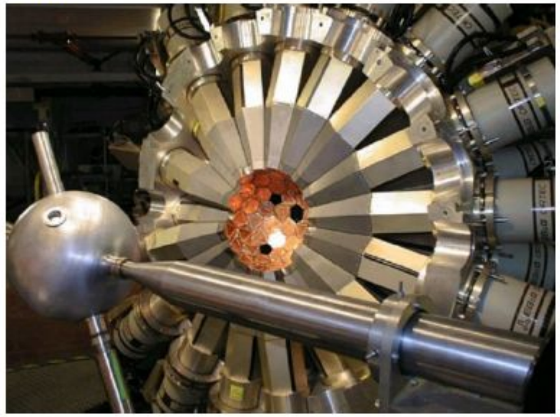

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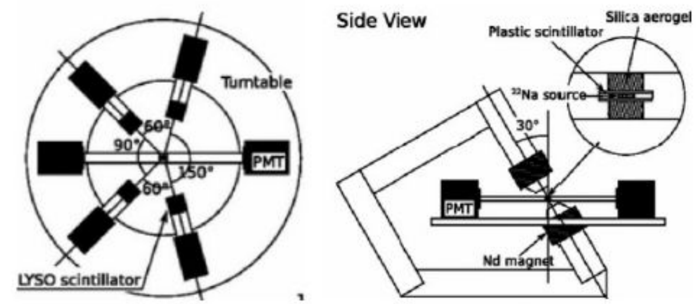

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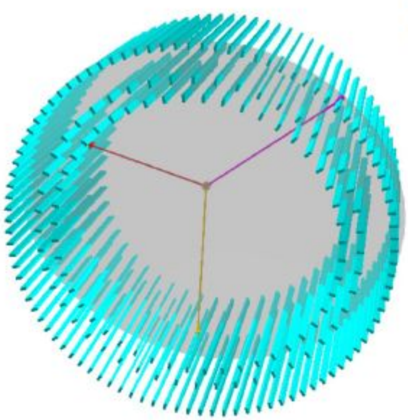
J-PET



Recording multiple geometrical configurations

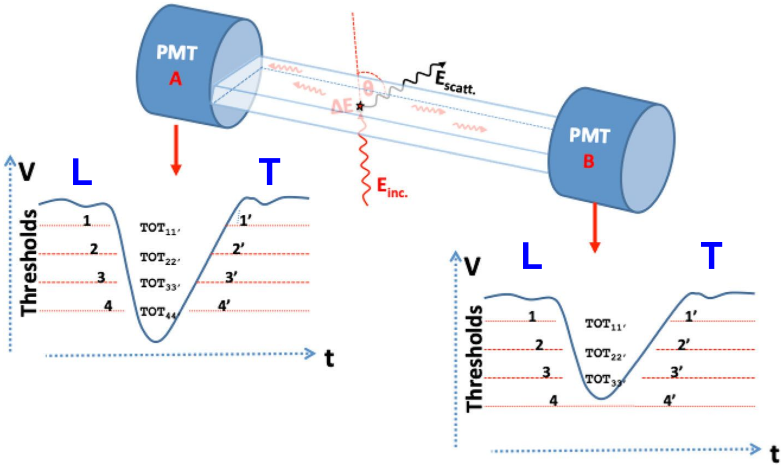
e+ spin estimated event-by-event

$$P_{e+} \approx \frac{v}{c} \cdot 0.91$$

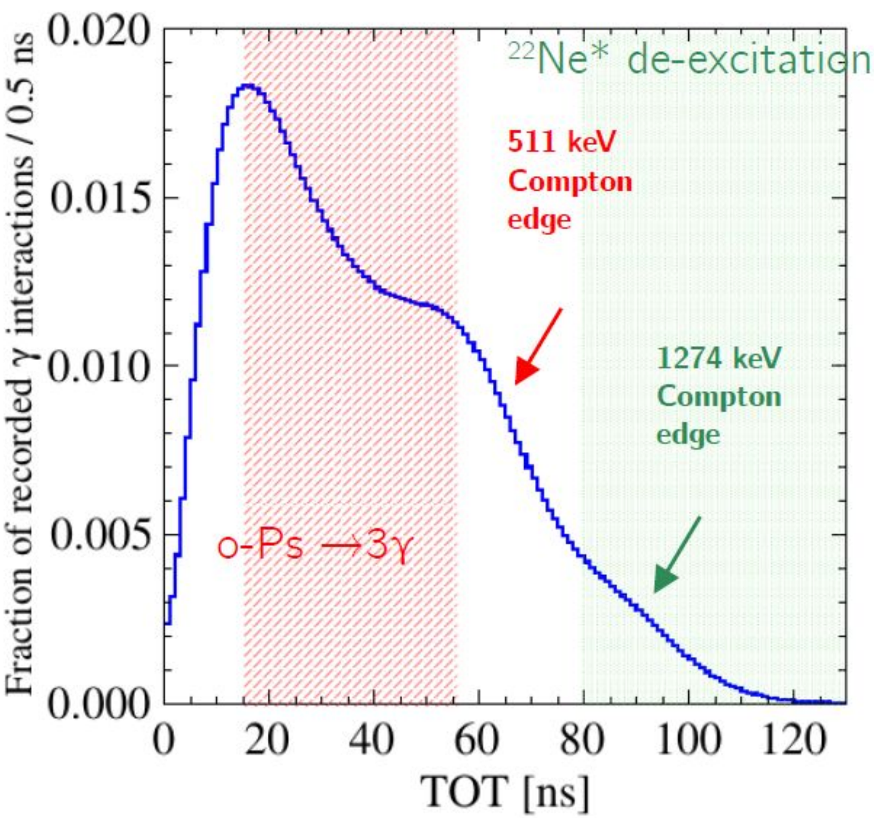
- Plastic scintillators = fast timing
  → using high β$^+$ emitter activity
  (tested up to 10 Mbq)
- Recording all 3 annihilation photons
- Angular resolution at 1° level

Courtesy of A. Gajos

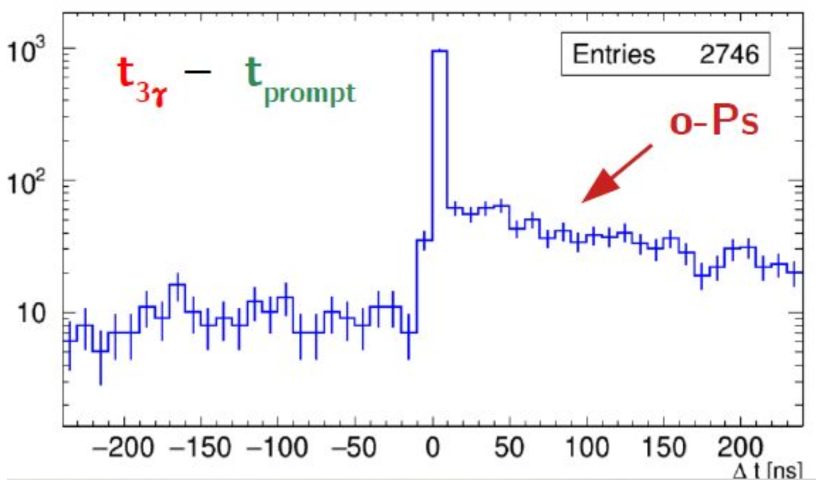
Identification of o-Ps→3γ annihilation events in J-PET



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



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



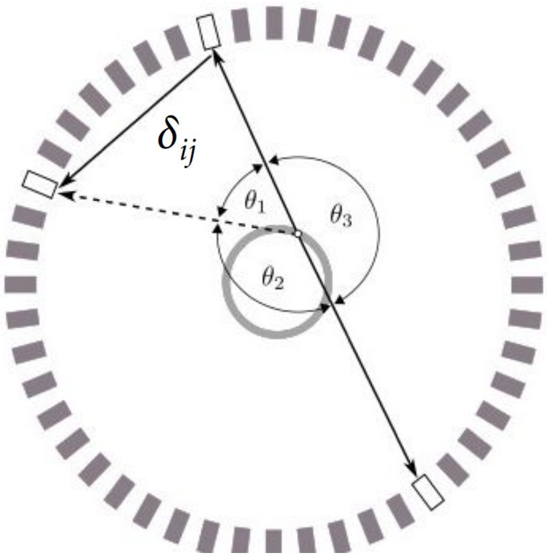
⇐ o-Ps presence in positron lifetime distribution

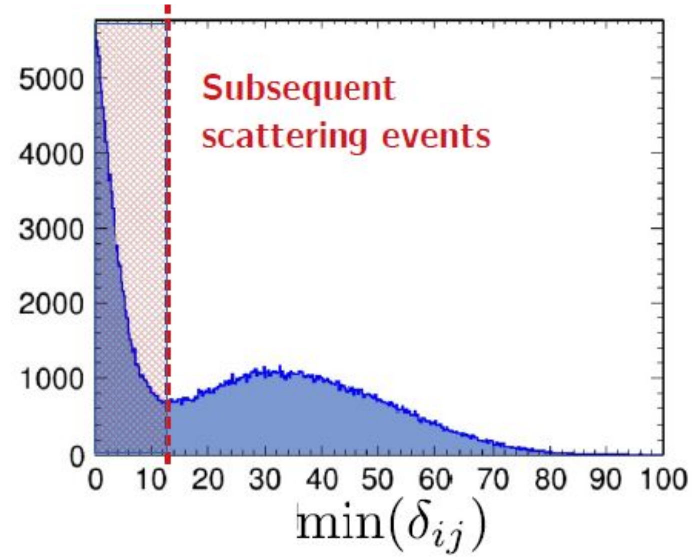
Background subtraction

Secondary Compton scatterings:

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

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

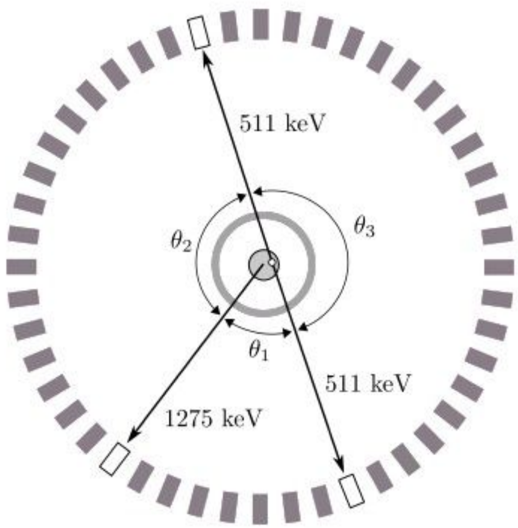


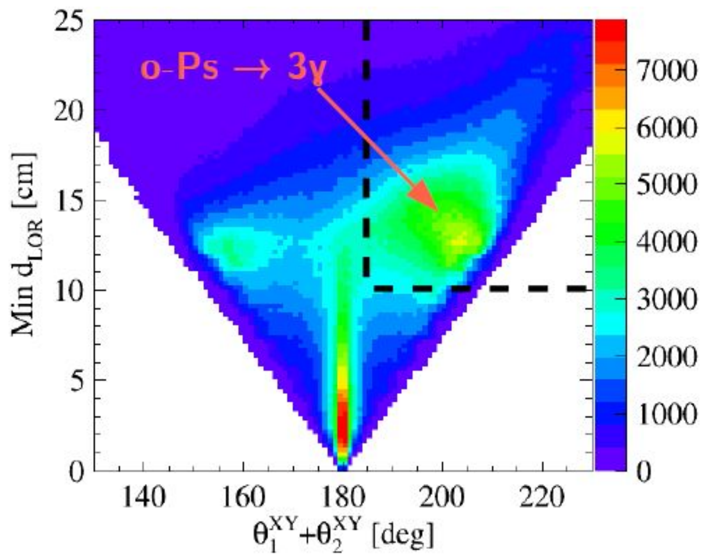


2γ from the β+ source setup coincident with de-excitation photon:

✶ 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



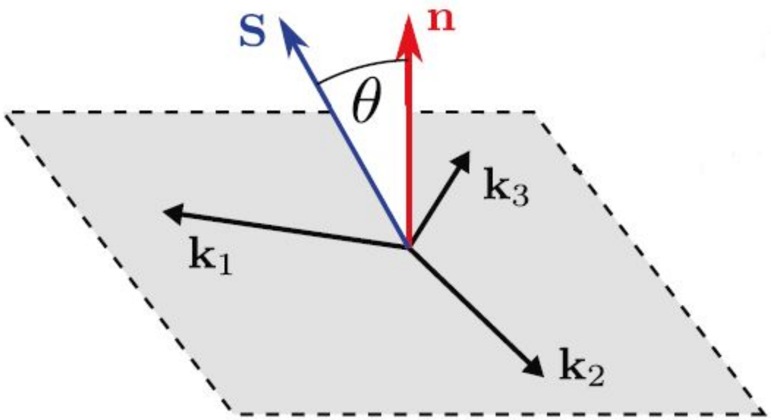


Determination of the CPT - asymmetric observable

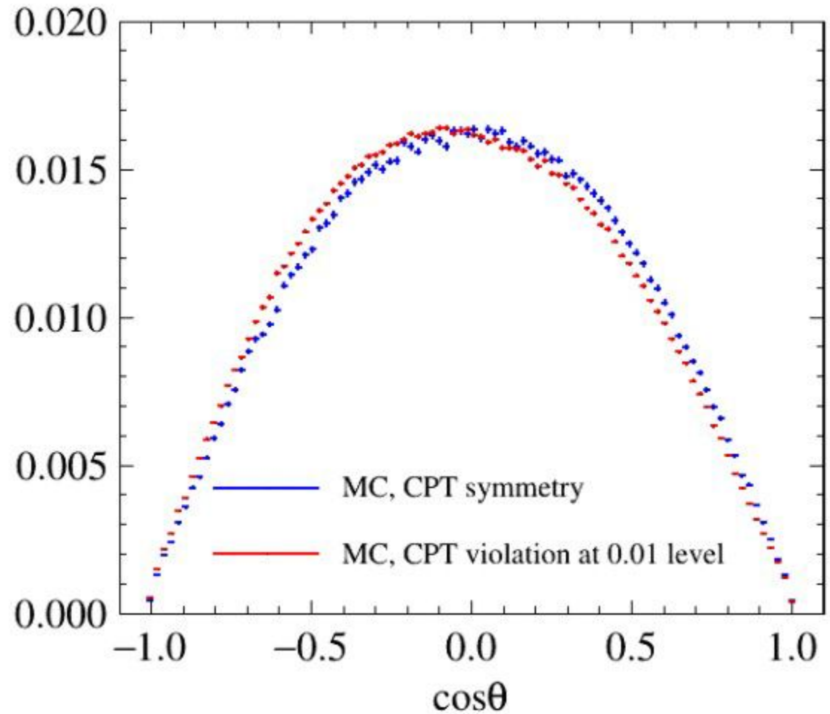
$$O_{CPT} = \hat{S} \cdot (\vec{k}_1 \times \vec{k}_2)/|\vec{k}_1 \times \vec{k}_2| = \cos\phi$$

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

J-PET is sensitive to the full range of this operator

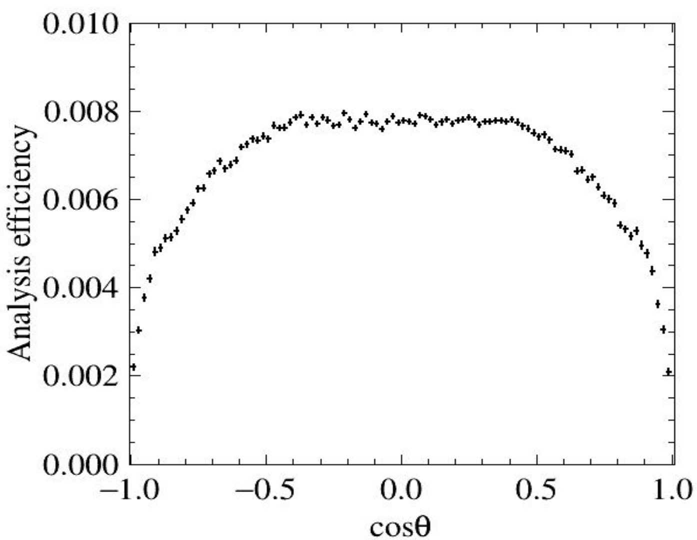


MC simulations



⇑

expected asymmetry in case of CPT violation



⇐ efficiencies evaluated with MC are symmetric in cosθ

Determination of the CPT - asymmetric observable

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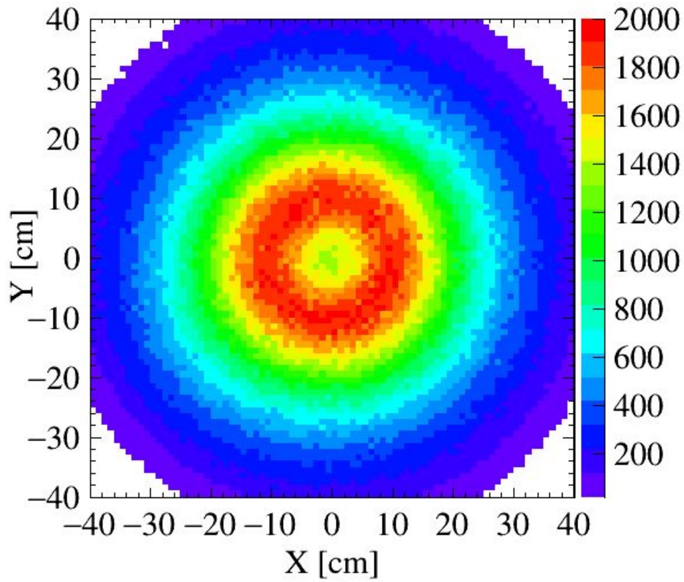
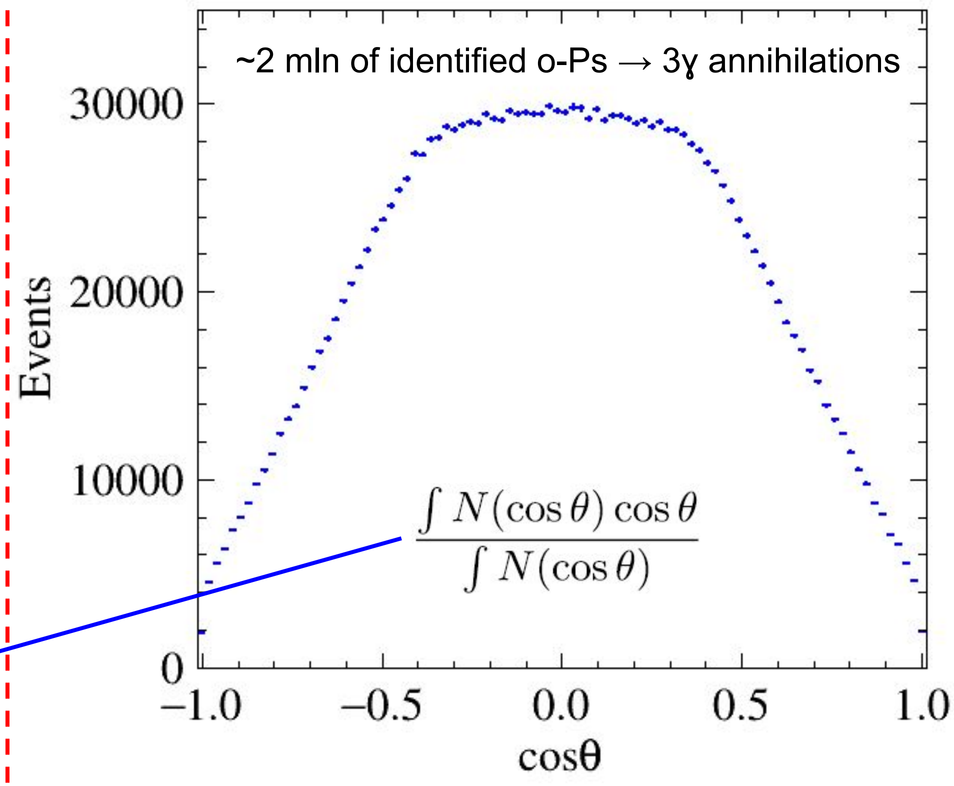
the angle between the direction of initial spin of the o-Ps atom and the normal to the decay plane

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





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

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

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

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

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

nature COMMUNICATIONS

ARTICLE

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https://doi.org/10.1038/s41467-021-25905-9 OPEN

Testing CPT symmetry in ortho-positronium decays with positronium annihilation tomography

P. Moskal[1,2]✉, A. Gajos[1,2]✉, M. Mohammed[1], J. Chhokar[1,2], N. Chug[1,2], C. Curceanu[3], E. Czerwiński[1,2], M. Dadgar[1,2], K. Dulski[1,2], M. Gorgol[4], J. Goworek[5], B. C. Hiesmayr[6], B. Jasińska[4], K. Kacprzak[1], Ł. Kapłon[1,2], H. Karimi[1,2], D. Kisielewska[1], K. Klimaszewski[7], G. Korcyl[1,2], P. Kowalski[7], N. Krawczyk[1,2], W. Krzemień[8], T. Kozik[1], E. Kubicz[1,2], S. Niedźwiecki[1,2], S. Parzych[1,2], M. Pawlik-Niedźwiecka[1,2], L. Raczyński[7], J. Raj[1,2], S. Sharma[1,2], S. Choudhary[1,2], R. Y. Shopa[7], A. Sienkiewicz[5], M. Silarski[1,2], M. Skurzok[1,3], E. Ł. Stępień[1,2], F. Tayefi[1,2] & W. Wiślicki[7]

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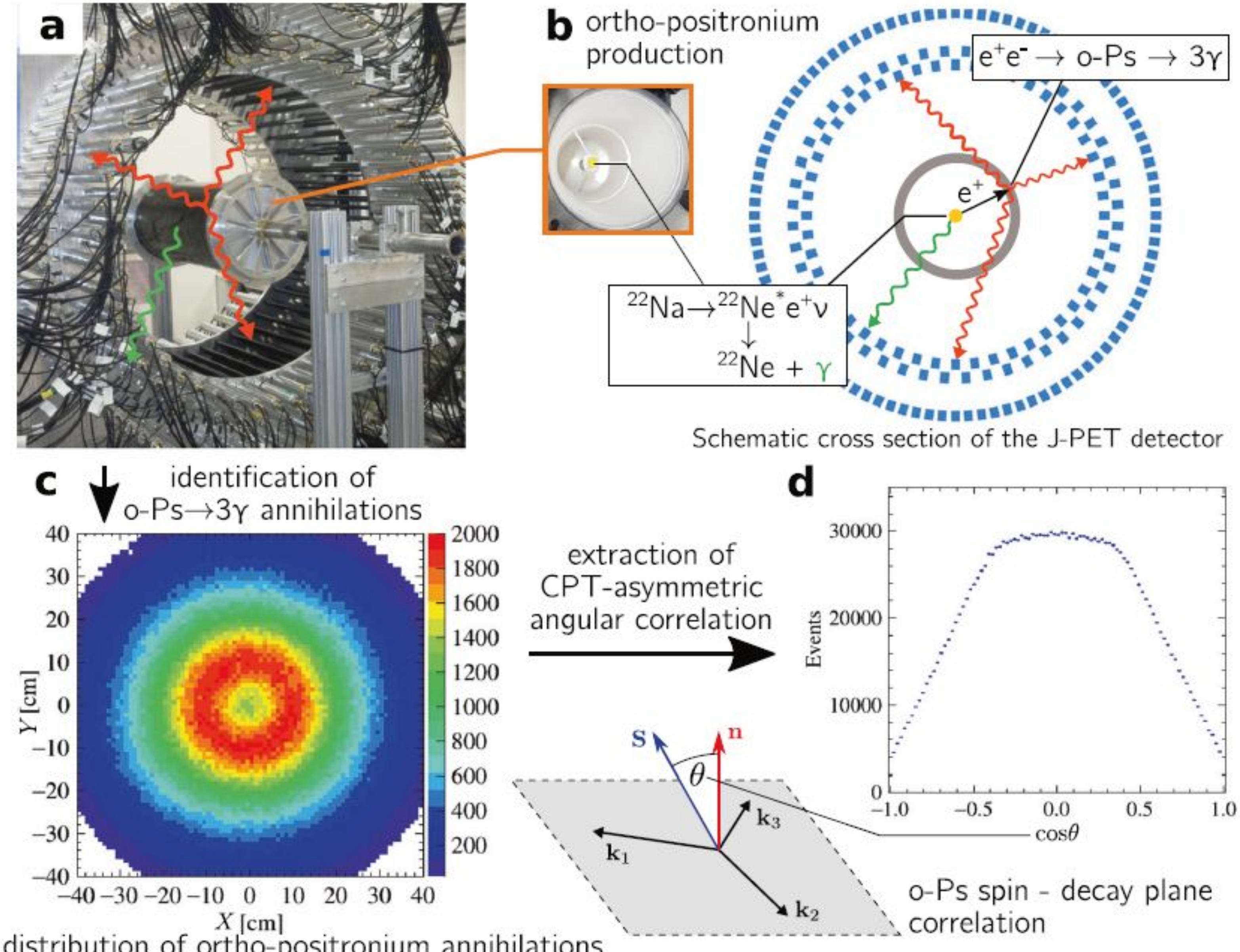
J-PET

Summary



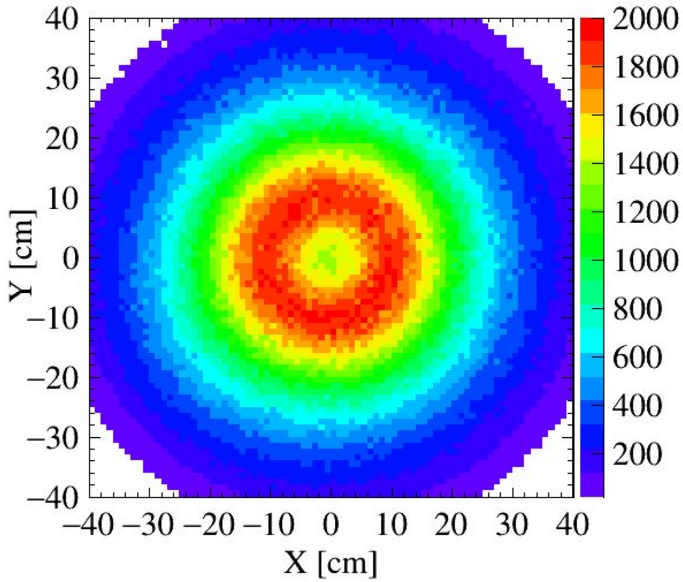
a
b ortho-positronium production
$e^+e^- \to$ o-Ps $\to 3\gamma$
e^+
$^{22}Na \to {}^{22}Ne^* e^+ \nu$
$^{22}Ne + \gamma$
Schematic cross section of the J-PET detector
c
identification of o-Ps→3γ annihilations
Y [cm]
X [cm]
distribution of ortho-positronium annihilations
extraction of CPT-asymmetric angular correlation
d
Events
cosθ
S
n
θ
k_1
k_2
k_3
o-Ps spin - decay plane correlation

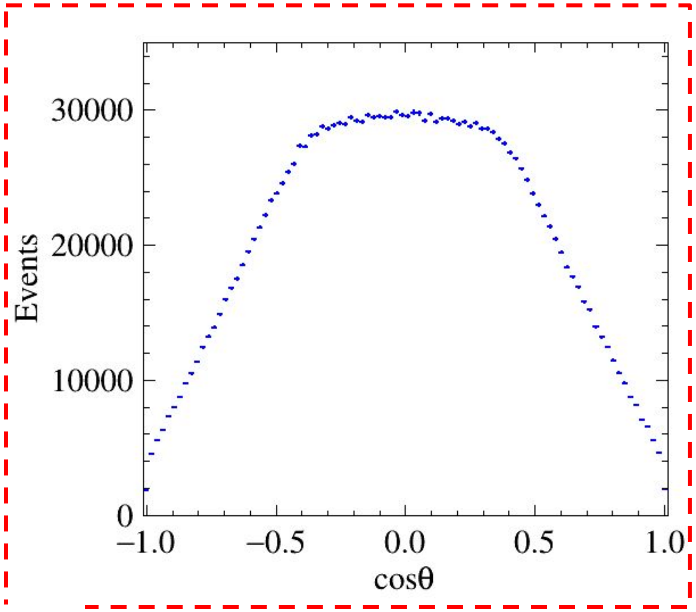
Summary and Perspectives

- 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

- **Sub-permil precision of the CPT test reached with the first J-PET measurement (26 days): over factor of 3 better** than the previous results

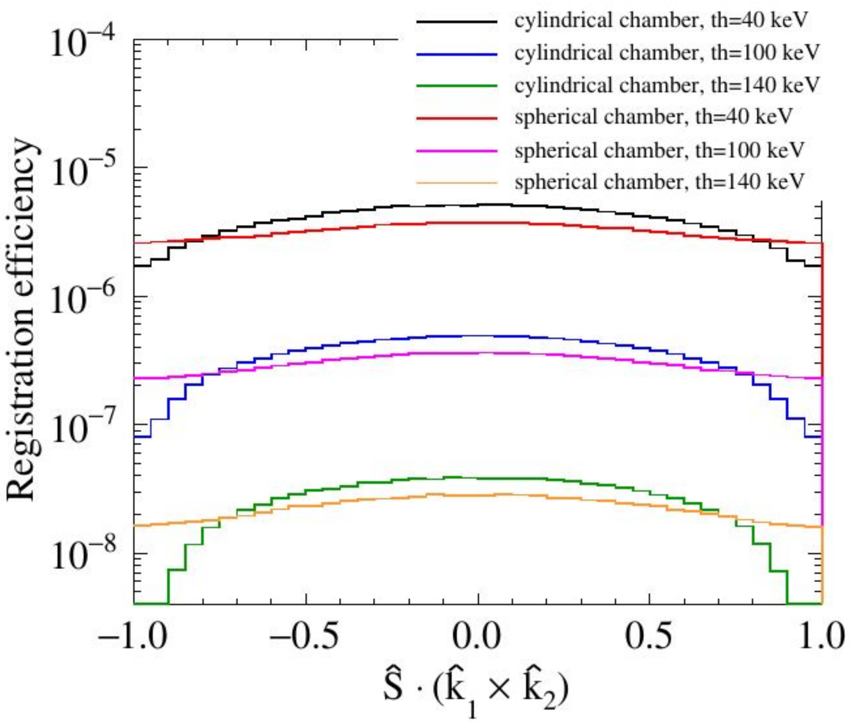
- J-PET aims at the sensitivity of the CP and CPT symmetry tests at the level of 10^{-5} with the pending improvements to the setup

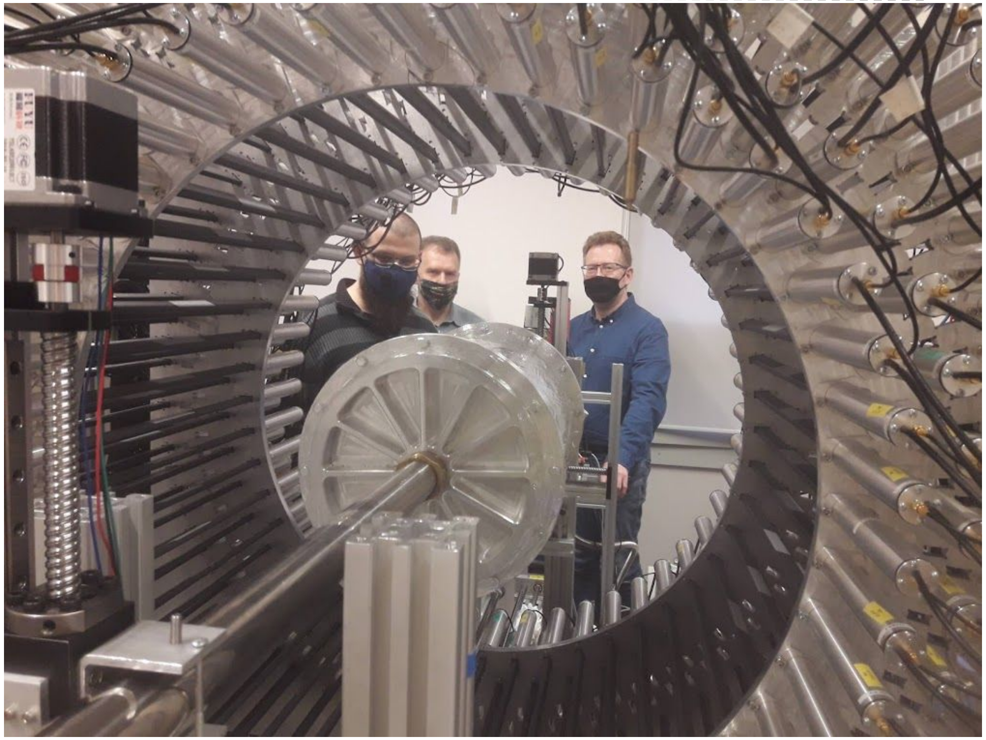




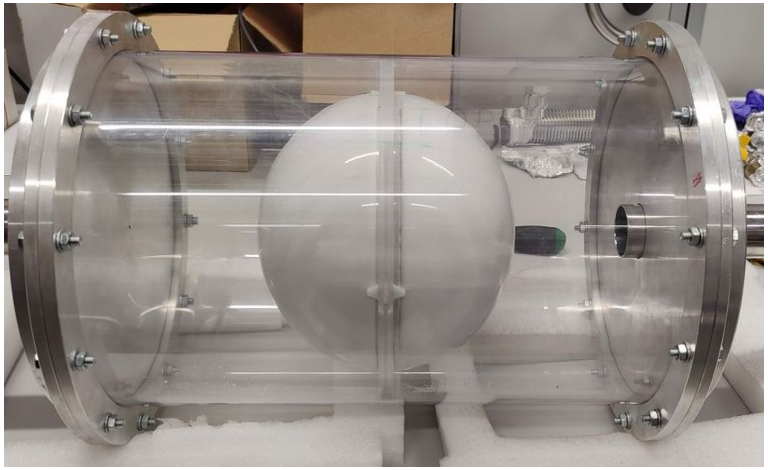
$$C_{\mathrm{CPT}} = \langle O_{\mathrm{CPT}} \rangle / P = 0.00067 \pm 0.00095$$

Summary and Perspectives





[Symmetry 12 (2020) 8, 1268]



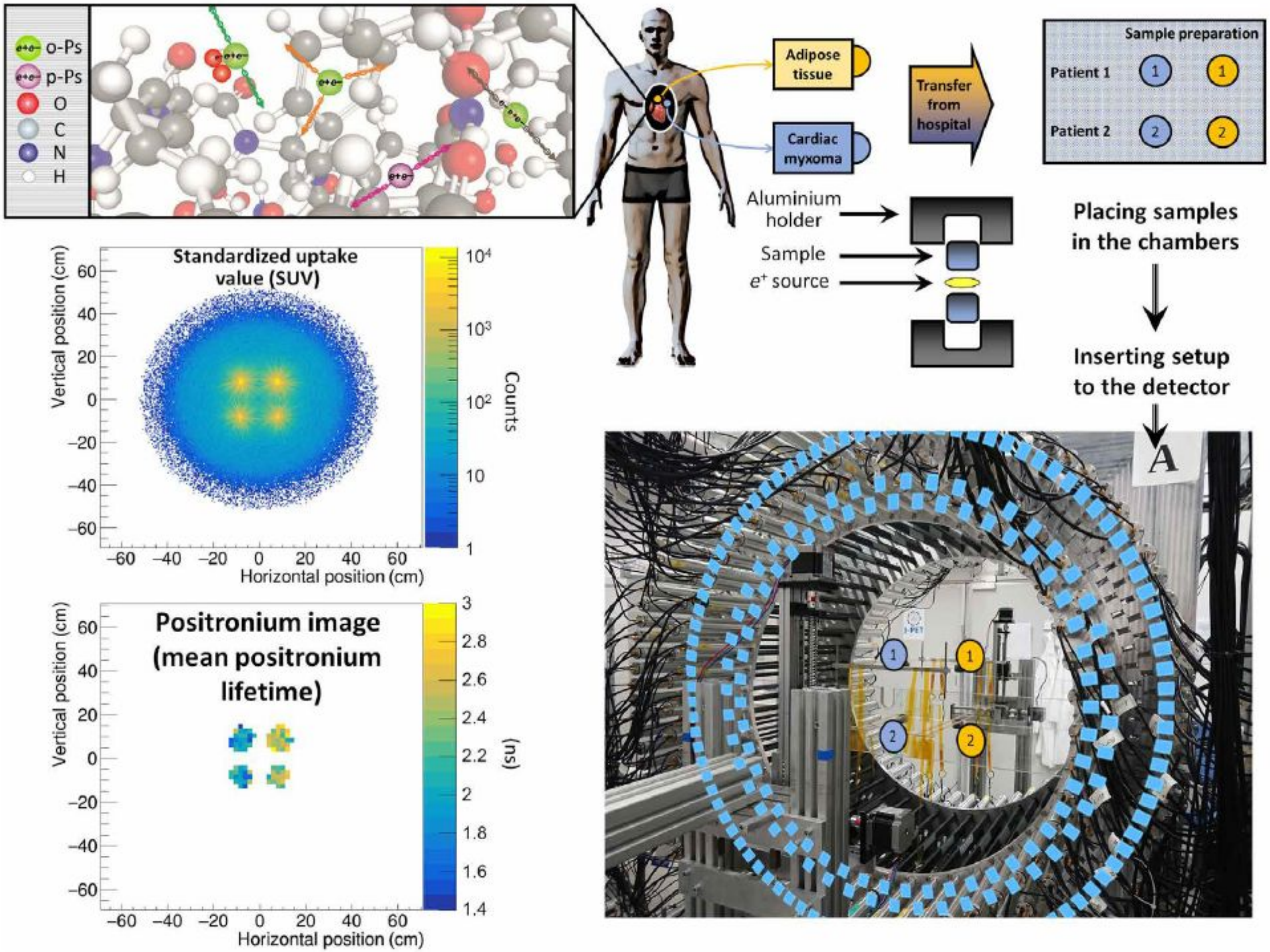
new design of the annihilation chamber with spherical geometry, increasing the o-Ps formation probability by a factor of ~1.5

Summary and Perspectives

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

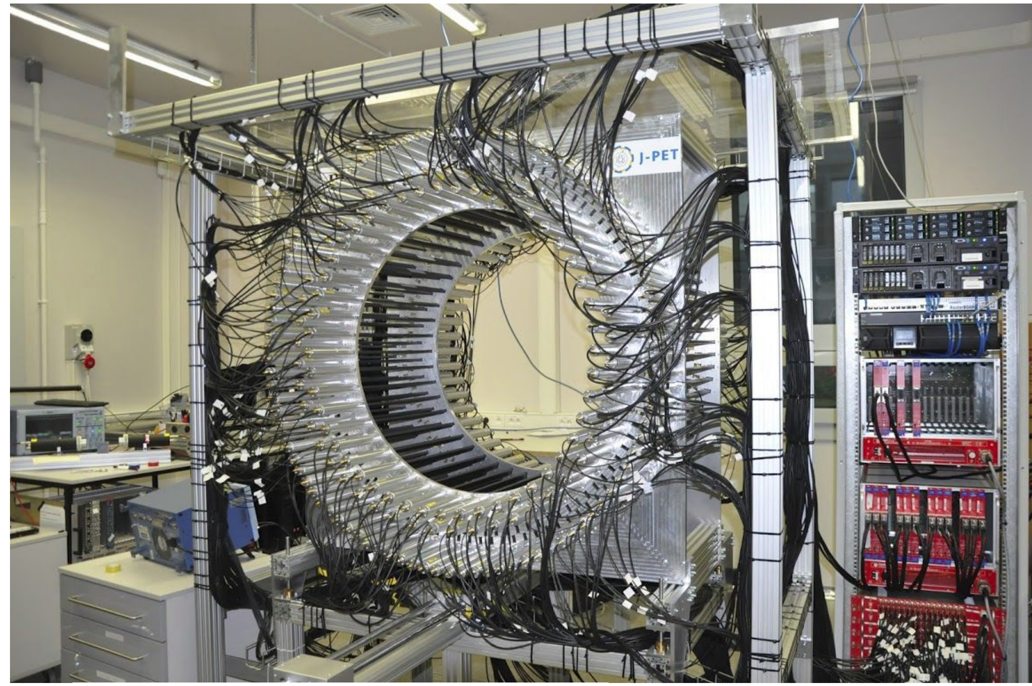
The first positronium imaging of a phantom built from cardiac myxoma and adipose tissue

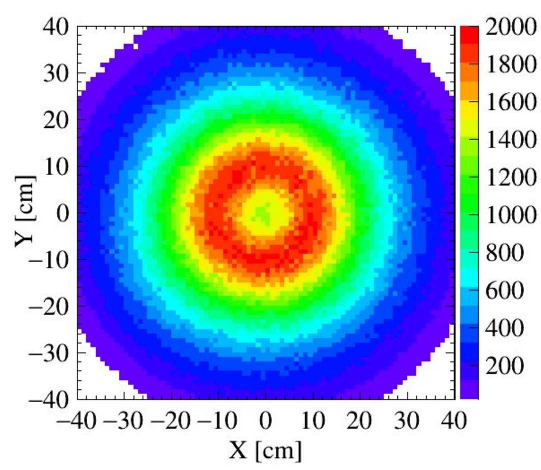
P. Moskal, et al., Science Advances 2021; 7 : eabh4394



Thank you for your attention

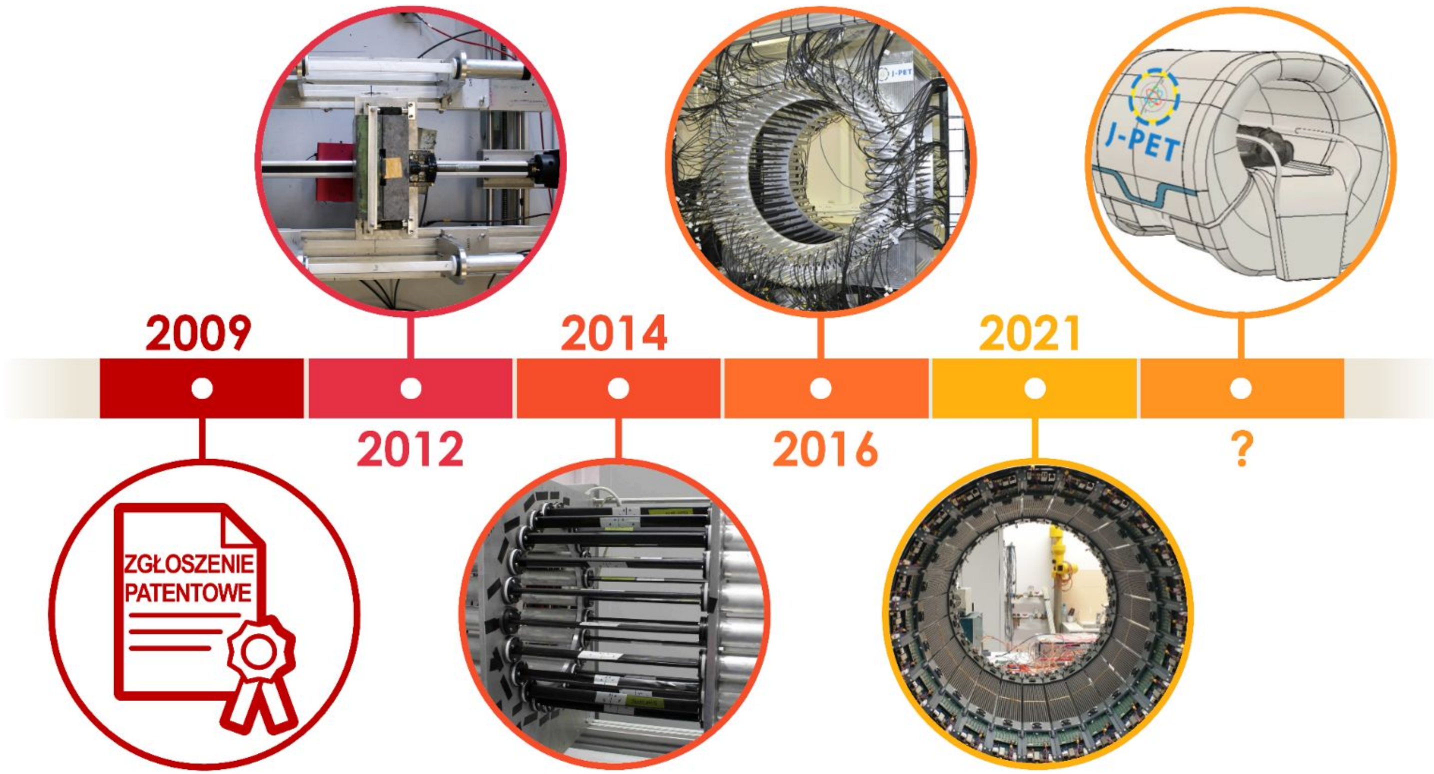
J-PET



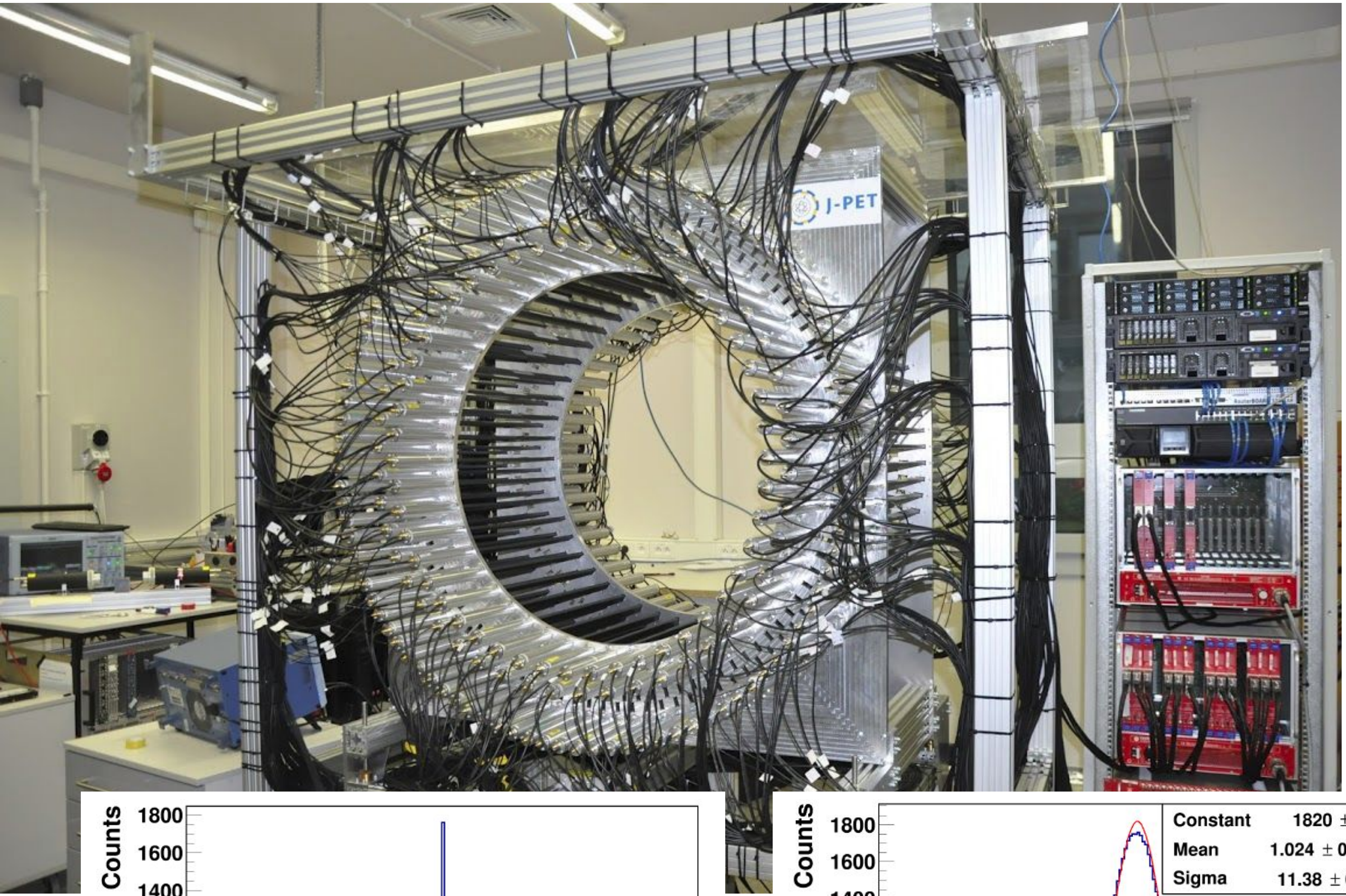


BACKUP SLIDES

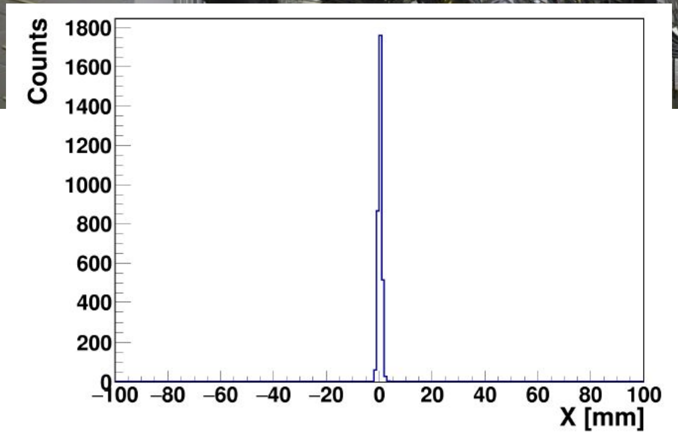
J-PET

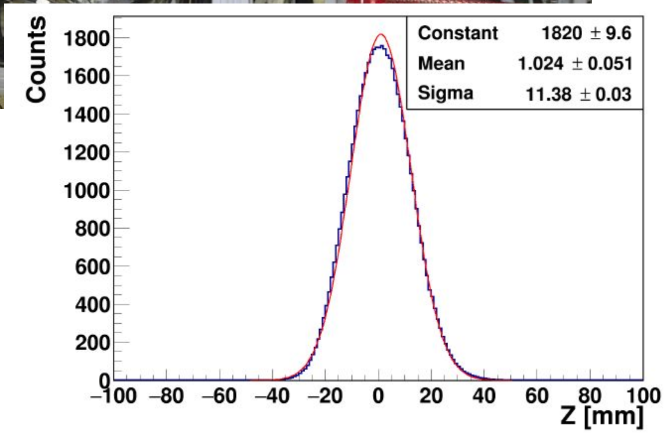


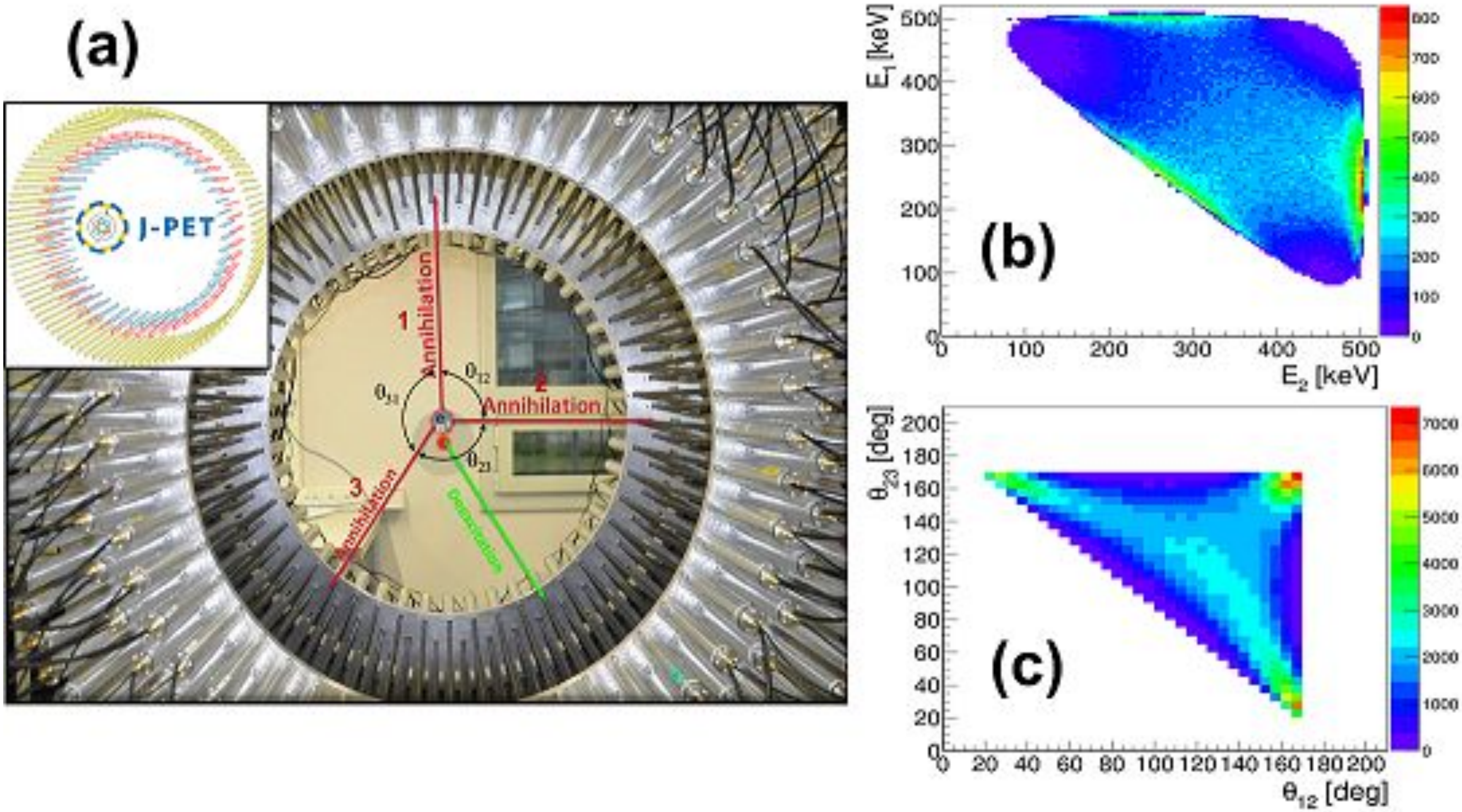
192 module prototype



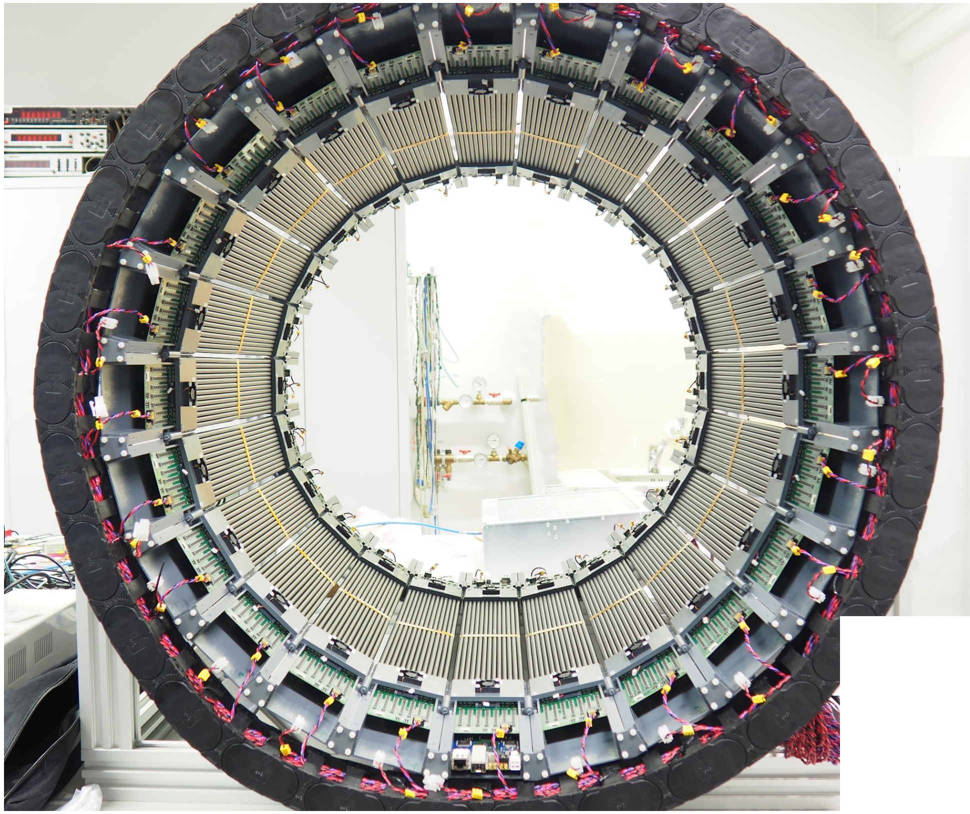
85 cm diameter,
50 cm FOV
4 constant threshold discrimination to determine time and energy of interaction



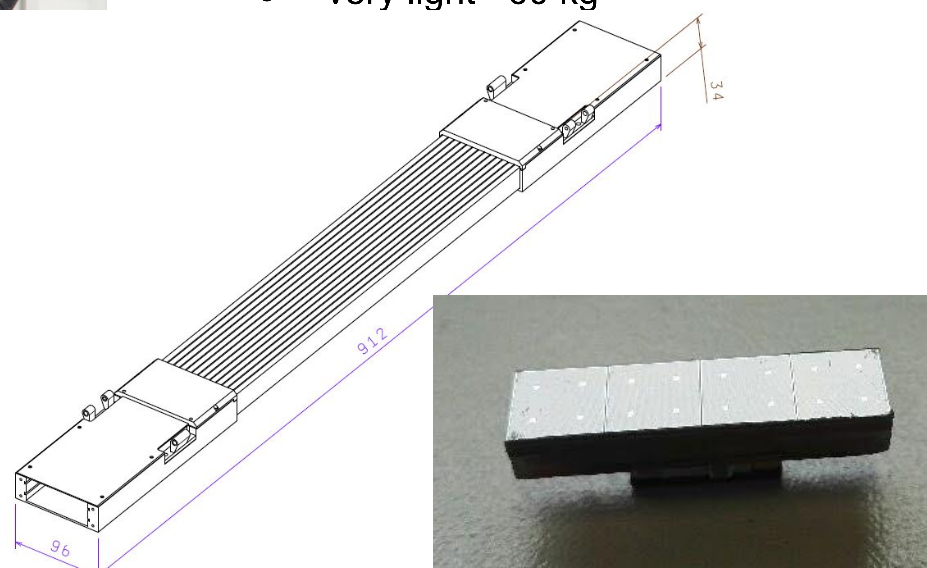



(a)
J-PET
1
Annihilation
2
Annihilation
3
Annihilation
Deexcitation
θ_{12}
θ_{31}
θ_{23}
(b)
E_1 [keV]
E_2 [keV]
(c)
θ_{23} [deg]
θ_{12} [deg]

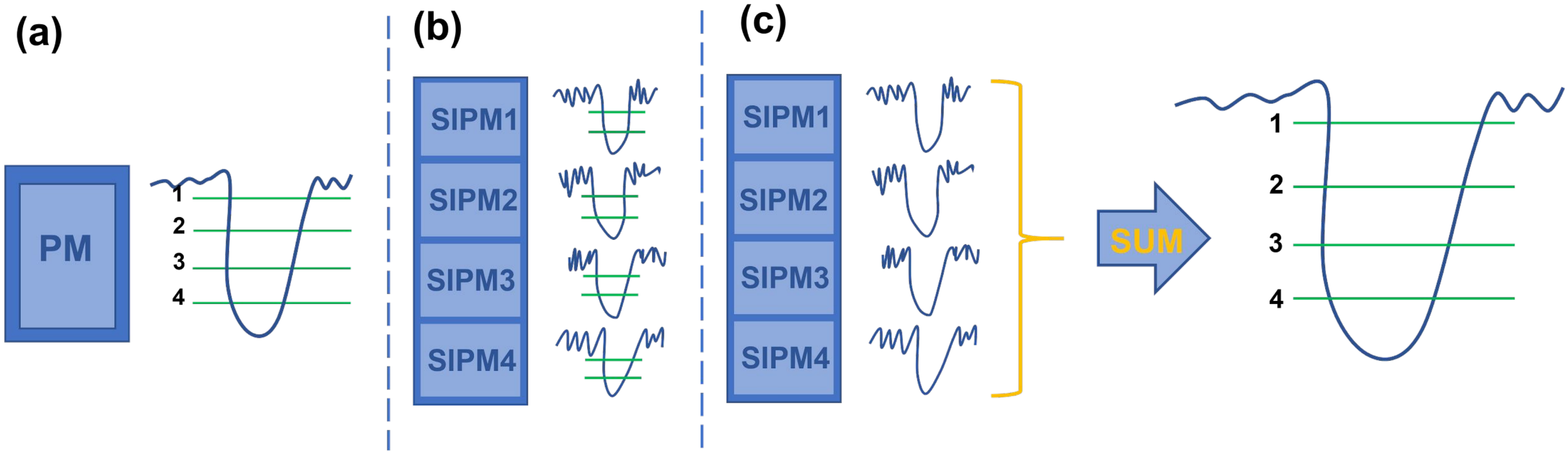
24 module prototype



- 74 cm diameter
- 50 cm FOV
- 4 SiPM per scintillator side
- 2 constant threshold per SiPM
- modular design 312 strips, 24 modules
- digital data at the module output
- very light ~60 kg



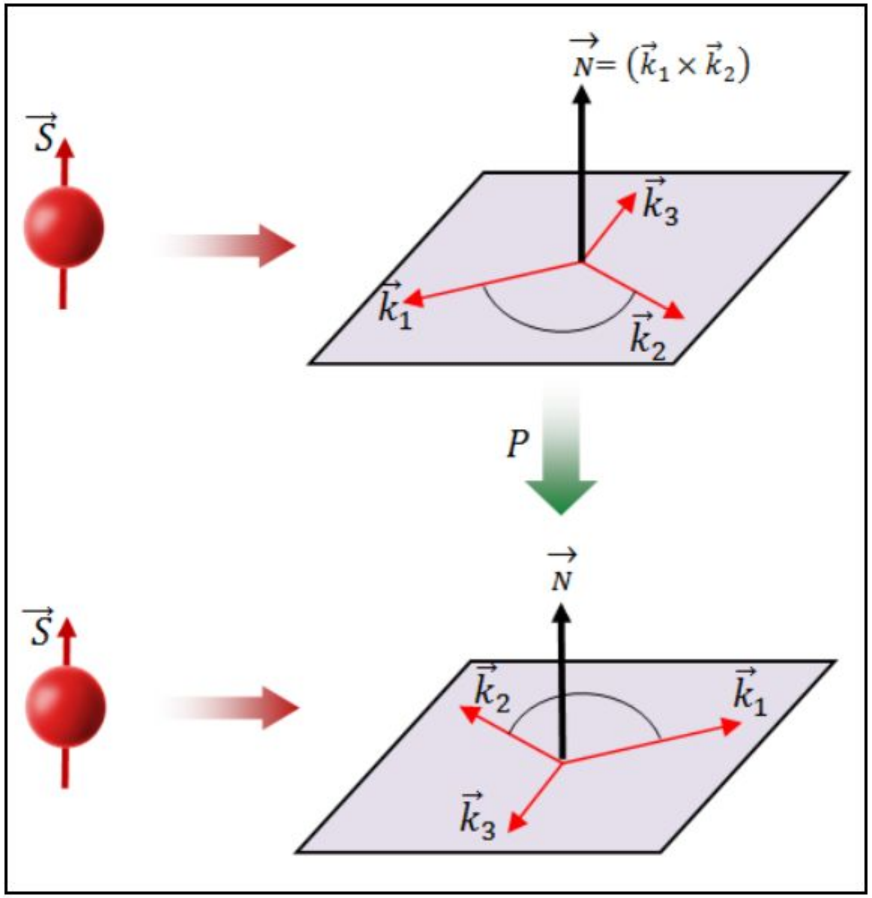
time and angular resolutions of 100 ps and 0.4

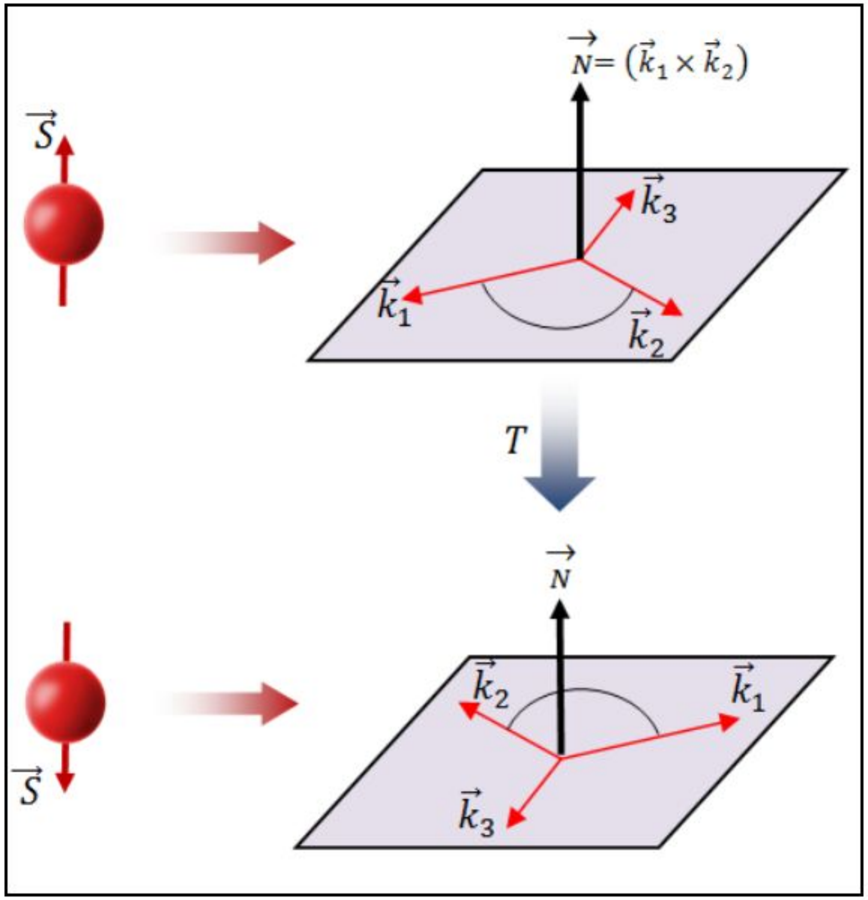


(a)
PM
1
2
3
4
(b)
SIPM1
SIPM2
SIPM3
SIPM4
(c)
SIPM1
SIPM2
SIPM3
SIPM4
SUM
1
2
3
4

Discrete symmetry tests in positronium decays

Measurement the expectation value of the symmetry odd-operators $\vec{S} \cdot \left(\vec{k}_1 \times \vec{k}_2\right)$ **example**





Charge conjugation (C)

The best limit in systems of quarks

$\pi^0 \to 3\gamma$ is forbidden $\quad \dfrac{\pi^0 \to 3\gamma}{\pi^0 \to 2\gamma} < \boxed{3.1 \times 10^{-8} \quad 90\%\ \text{cl}}$

CPT symmetry implies the equality of the masses, widths, etc.
of a particle and its antiparticle

$$2\,\frac{|m_{K^0} - m_{\overline{K}^0}|}{(m_{K^0} + m_{\overline{K}^0})} < 6 \times 10^{-19}\,, \qquad 2\,\frac{|\Gamma_{K^0} - \Gamma_{\overline{K}^0}|}{(\Gamma_{K^0} + \Gamma_{\overline{K}^0})} = (8 \pm 8) \times 10^{-18}$$

- CP violation is equivalent to T violation
- CP violation - asymmetry between matter and antimatter in our universe
- CP violation mechanism is introduced by the quark mixing described by the complex Cabibbo - Kobayashi - Maskawa matrix with none nonzero phase
- CP violation observed first for neutral kaons

CP violation
J. H. Christenson et al., Phys. Rev. Lett. 13, 138 (1964).

$$|K_S\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle + |\overline{K}^0\rangle\right] \text{ with } \mathcal{CP} = 1$$

$$|K_L\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle - |\overline{K}^0\rangle\right] \text{ with } \mathcal{CP} = -1$$

BR ($K_L \to \pi^+\pi^- / K_L \to$ all) $\approx 2\cdot 10^{-3}$

$$|K_L\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}\left(|K_2\rangle + \epsilon|K_1\rangle\right)$$

$$|K_S\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}\left(|K_1\rangle - \epsilon|K_2\rangle\right)$$