Tests of discrete symmetries with the J-PET detector

Wojciech Krzemień
On behalf of the J-PET collaboration

J-PET

September 8th 2021

NATIONAL CENTRE FOR NUCLEAR RESEARCH
ŚWIERK

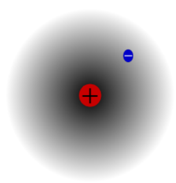
Outline

- Positronium properties and discrete symmetry tests
- J-PET detector setup
- Results
- Future prospects
  - Mirror Matter searches

Positronium

J-PET

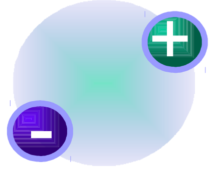
^1H

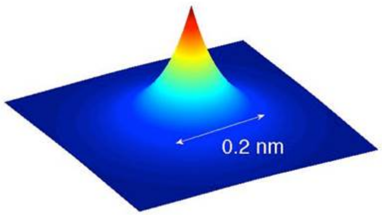


Ann. Rev. Nucl. Part. Sci 30,453 (1980)

Lightest purely leptonic object

Positronium (Ps)





$^1S_0$ Para-positronium
τ (p-Ps) ≈ 125 ps

$^3S_1$ Ortho-positronium
τ (o-Ps) ≈ 142 ns

S = 0 ↓↑ − ↑↓

S = 1 ↑↑ ; ↑↓ + ↓↑ ; ↓↓

	$^1S_0$	$^3S_1$
L	**0**	**0**
S	**0**	**1**
J	**0**	**1**

$C\,|Ps\rangle = (-1)^{L+S}\,|Ps\rangle$

$C\,|n\gamma\rangle = (-1)^{n}\,|n\gamma\rangle$

	$^1S_0$	$^3S_1$
C	+	-
P	-	-
CP	-	+

<u>Decay modes</u>

$^1S_0$ Para-positronium	**p-Ps → 2n γ**	**τ (p-Ps) ≈ 125 ps**
$^3S_1$ Ortho-positronium	**o-Ps → (2n+1) γ**	**τ (o-Ps) ≈ 142 ns**

S. D. Bass, Acta Physica Polonica B 50, 1319 (2019)

Discrete symmetry tests with o-Ps → 3γ decays

- Discrete symmetries are scarcely tested with leptonic systems
- Prominent results from neutrinos oscillation experiments
  - Dirac phase, δCP ~3σ level *[T2K, Nature 580 (2020) 339]*
- Electron EDM < 1.1×10^{-29} *[ACME, Nature 562 (2018) 355]*
- Positronium – the lightest leptonic state so far the only system of charged leptons used for test of CP and CPT

*courtesy A. Gajos MESON2021

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How to can we test discrete symmetries in the positronium system

- Searches for forbidden positronium decays

- Certain SME-based searches for CPT violation were proposed with **positronium spectroscopy** *[Phys. Rev. D92 (2015) 056002]*

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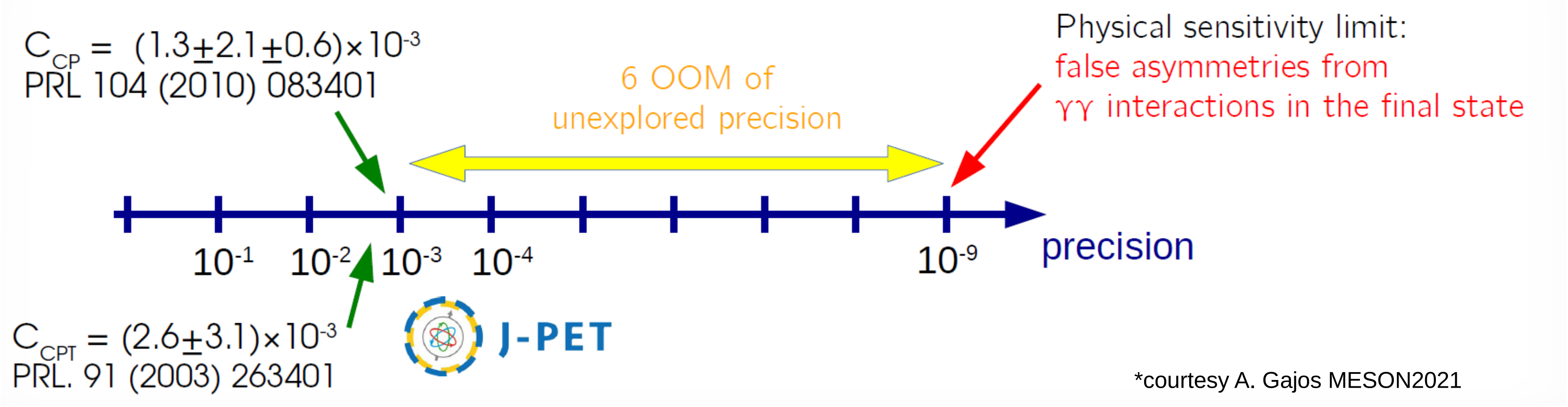
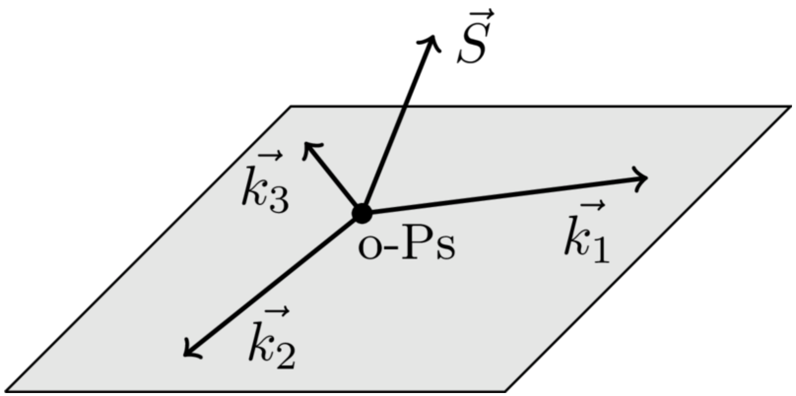
Searches for non-vanishing symmetry-odd correlations:



Discrete symmetry tests with angular correlations in o-Ps → 3γ decays



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

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

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

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

Using o-Ps spin →

Requires o-Ps tensor polarization →

Using photon polarization →

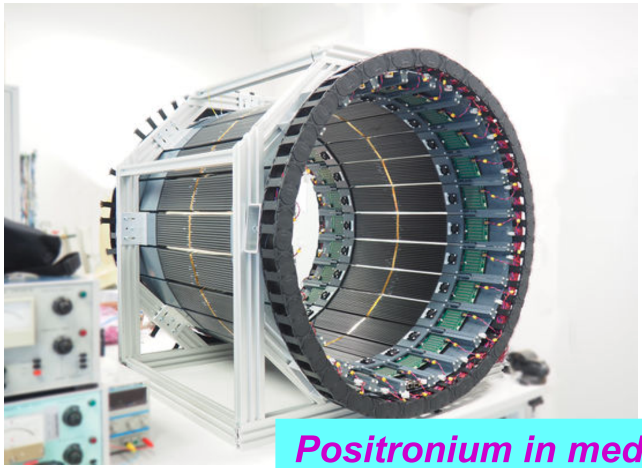
operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	-	+	-	-
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	-	+	-
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))$	+	-	-	-	+
$\vec{k}_2 \cdot \vec{\epsilon}_1$	+	-	-	-	+
$\vec{S} \cdot \vec{\epsilon}_1$	+	+	-	+	-
$\vec{S} \cdot (\vec{k}_2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

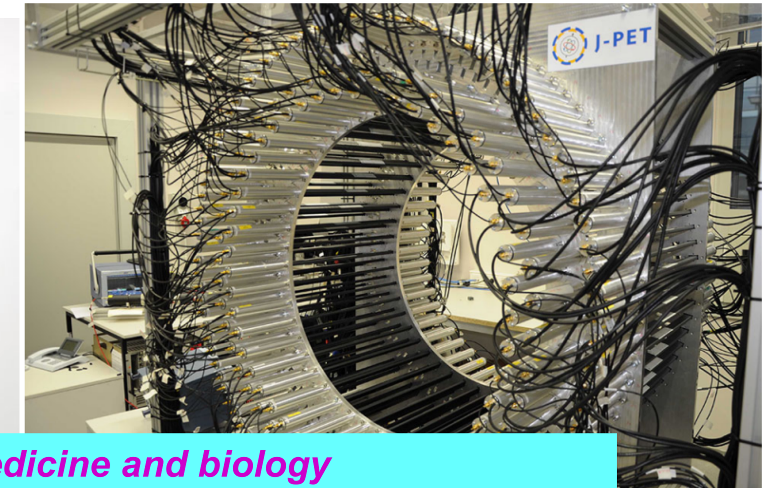
[W. Bernreuther *et al., Z. Phys. C41 (1988) 143*]

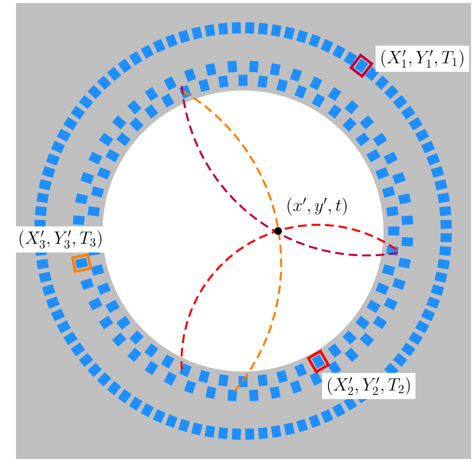
[P. Moskal et al., *Acta Phys. Polon. B47 (2016) 509*]

*courtesy A. Gajos MESON2021

J-PET (Jagiellonian-PET TOMOGRAPHY)







Positronium in medicine and biology
Moskal, P., Jasińska, B., Stępień, E.Ł., and S. Bass.
Nature Reviews Physics 1, pages 527-529 (2019)

A. Gajos et al. Nucl. Instrum. Methods. A819 (2016) 54

First Positron Emission Tomography scanner built from plastic scintillator

- Multidisciplinary detector
- Whole-body PET

•**3 + 1 layer arrangement**

- 192 scintillator modules 7 × 19 × 500 mm 3 arranged in 3 layers read out by vacuum tube photomultipliers (PMs) with radius of 42.5 cm and length of 50 cm
- 4-th layer modular JPET: 312 plastic scintillator strips in 24 modules with dimensions of 6 × 24 × 500 mm 3 read out by matrices of silicon photomultipliers (SiPM)

•**High timing resolution**
•High acceptance and angular resolution
•**Trigger-less** and reconfigurable DAQ system

- **Data has no filters: all data acquired is unfiltered**

•**GPS trilateration** reconstruction

prof. Paweł Moskal

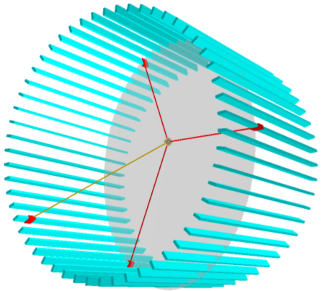
Session: Applications of nuclear and particle physics technology

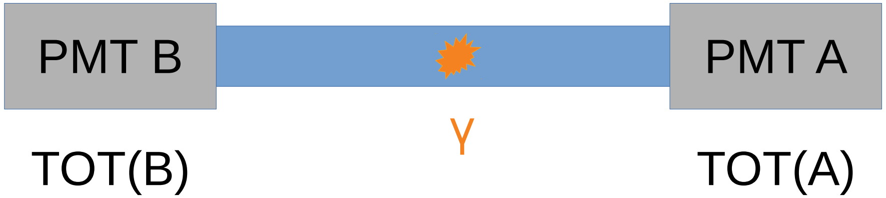
Date and time: 8 Sep 2021, 13:30

Talk: „From tests of discrete symmetries to medical imaging with J-PET detector"

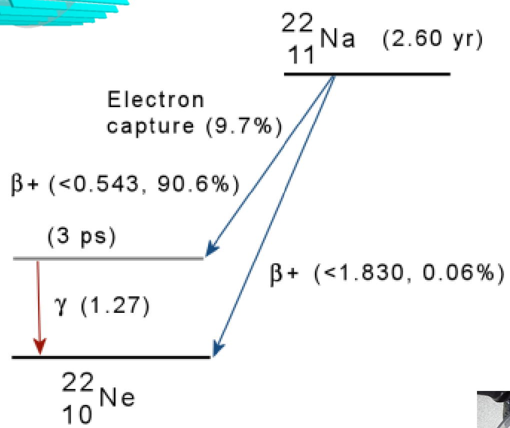
Positronium imaging for PET scanners → **P. Moskal, K. Dulski et al. Sciences Advances (in print)**

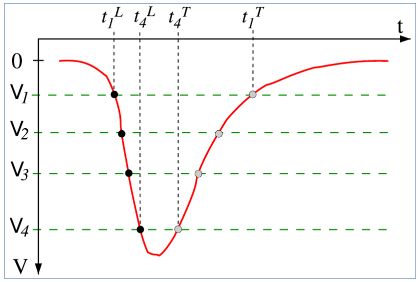
o-Ps in J-PET



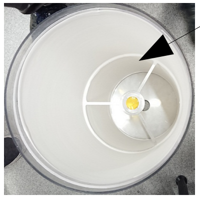


- 10 MBq β+ source **in annihilation chamber**
- Walls coated with porous silica to enhance o-Ps formation
- Extensive and small chamber measurements available
  - New spherical chamber added to the setup
- o-Ps decays are register using total Time-Over-Threshold (TOT)



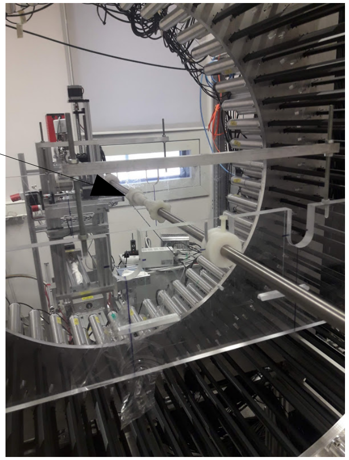


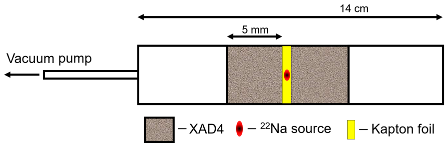
Extensive chamber



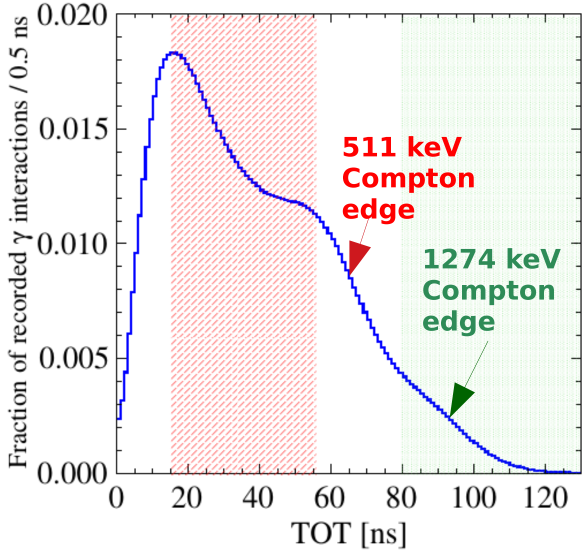
Acta Phys. Pol. B 48, 1567 (2017)

Small annihilation chamber

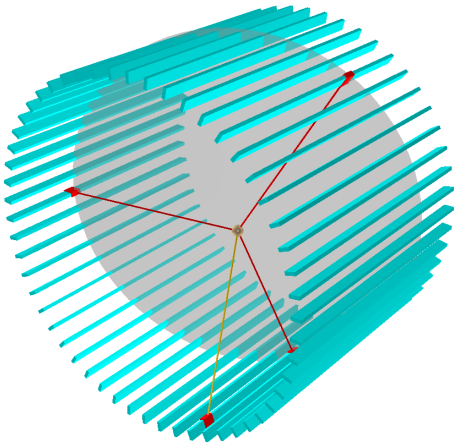




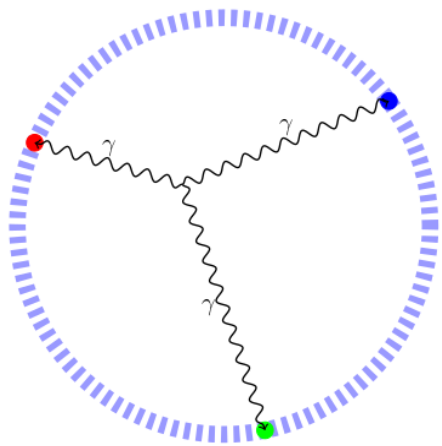
EJNMMI Phy 7 39 (2020)



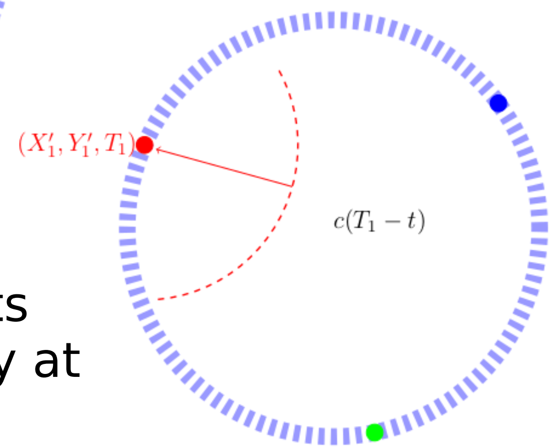
Reconstruction of o-ps decay vertex in J-PET



1. Find the decay plane containing the 3 hits in the J-PET barrel

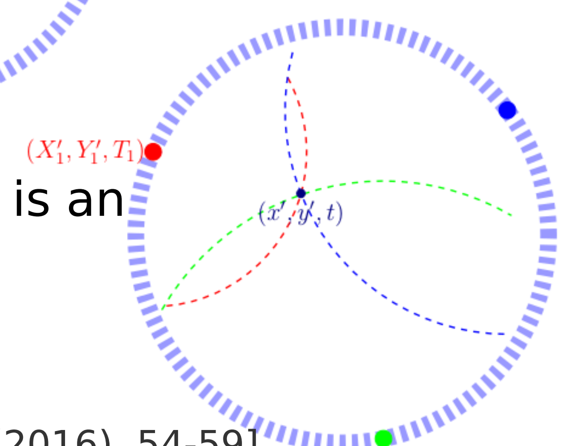


2. Transform the hit coordinates to a 2D coordinate system in the decay plane



3. For each of the recorded γ hits, define a circle of possible origin points of the incident γ assuming o-Ps decay at time *t*

4. The decay point (x',y') in the decay plane and time t is an intersection of 3 such circles:



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

Symmetry tests with CPT-odd operator

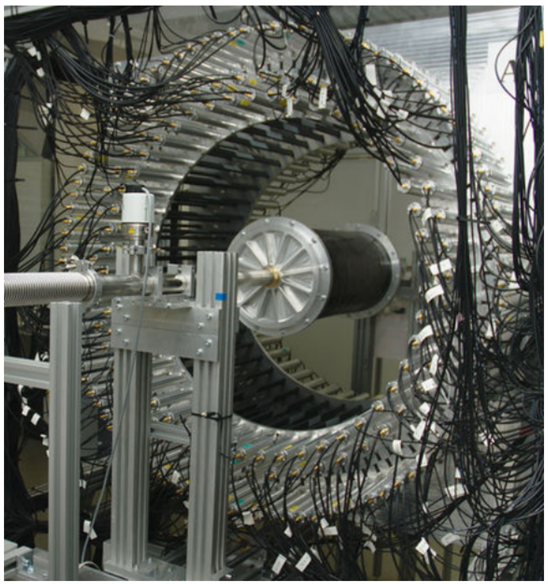
Using o-Ps spin

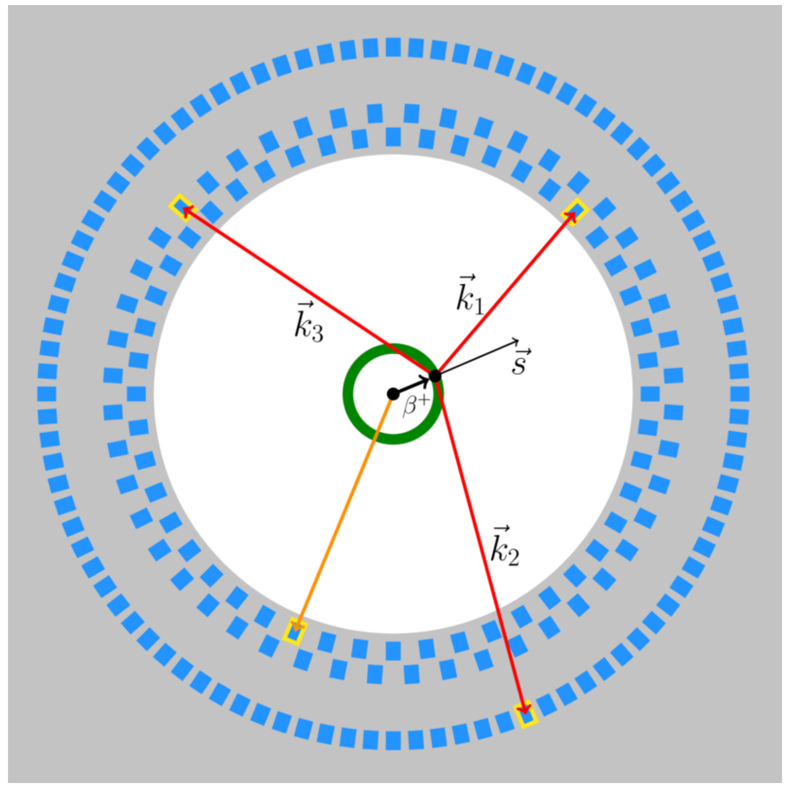
operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	-	+	-	-
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	-	+	-
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))$	+	-	-	-	+
$\vec{k}_2 \cdot \vec{\epsilon}_1$	+	-	-	-	+
$\vec{S} \cdot \vec{\epsilon}_1$	+	+	-	+	-
$\vec{S} \cdot (\vec{k}_2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

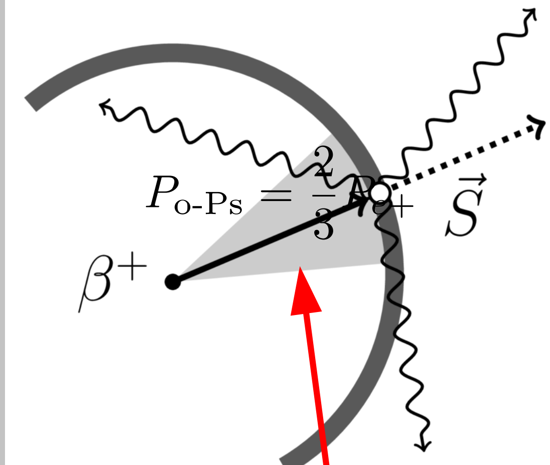
[W. Bernreuther *et al., Z. Phys. C41 (1988) 143*]

Event-by event spin estimation

Using an extensive-size o-Ps production and annihilation medium





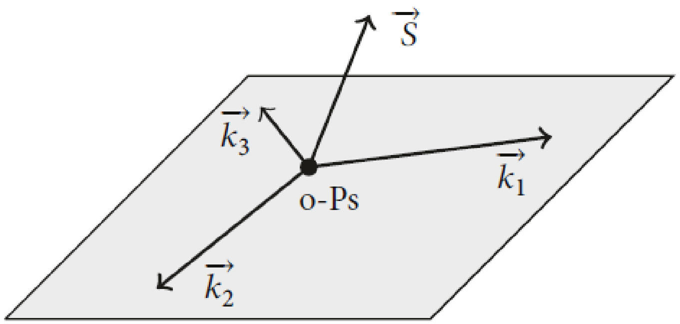


Effective polarization depends on o-Ps→3γ vertex resolution

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

*courtesy A. Gajos MESON2021

Evaluation of CPT-odd observable



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

Standard asymmetry:

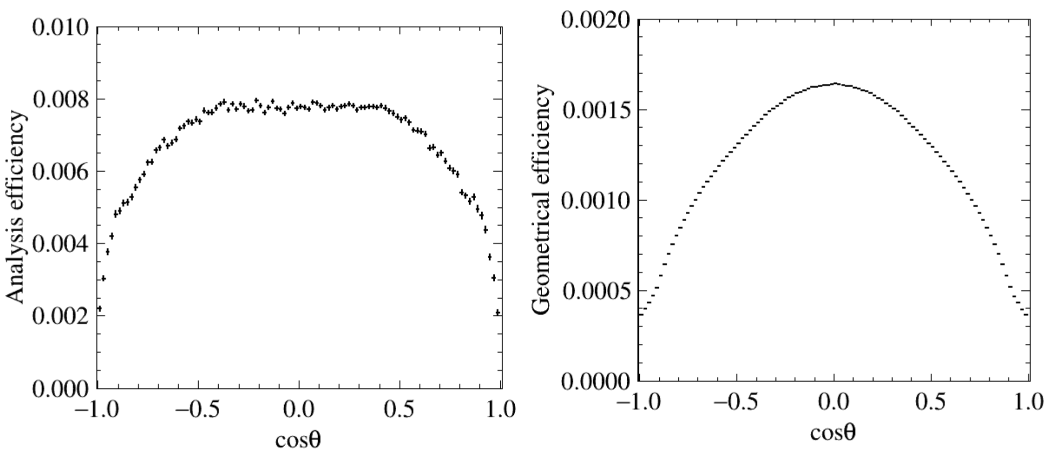
$$A = \frac{N_+ - N_-}{N_+ + N_-} \longrightarrow N_+ \Leftrightarrow cos\theta > 0$$

is generalized by the **mean value of cosθ**:

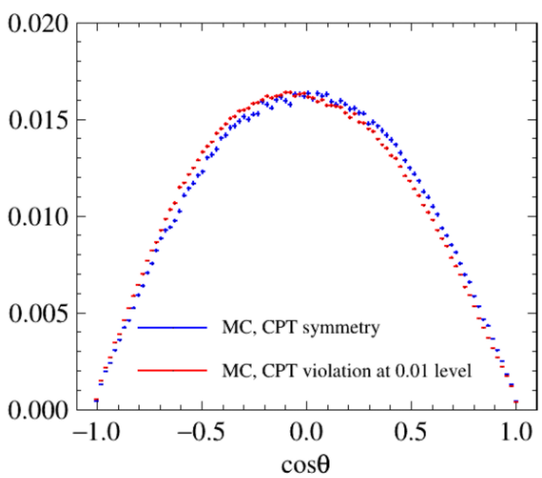
$$\frac{\int N(\cos\theta)\cos\theta}{\int N(\cos\theta)}$$

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

Evaluated efficiencies using MC are symmetric in cosθ

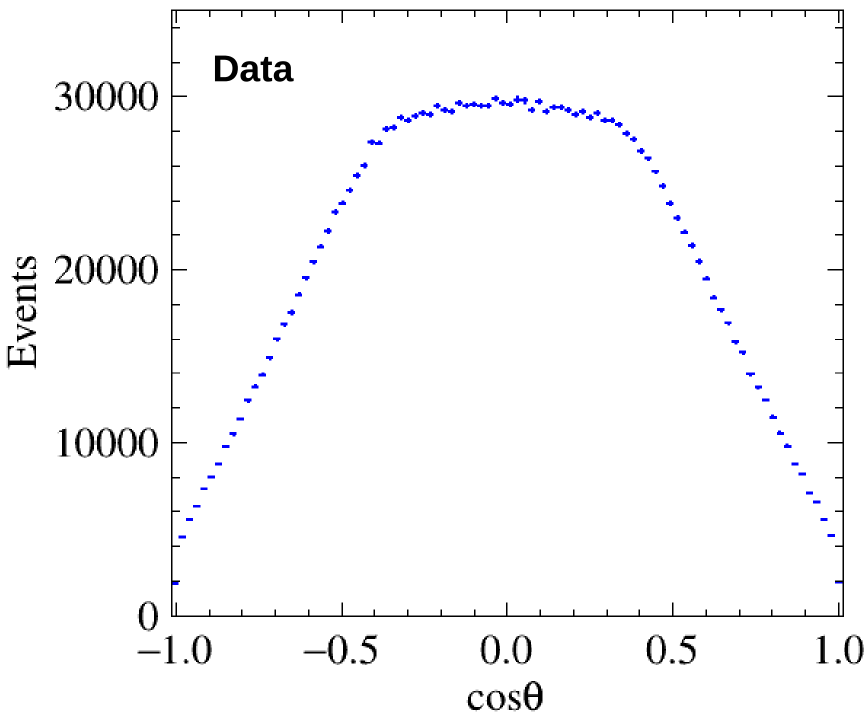


Expected effect with CPT-asymmetric simulations



Accepted to Nature Communications

7.3×10^6 o-ps candidates (26 days of data taking)



$$\mathbf{O}_{\mathrm{CPT}} = \hat{S} \cdot (\vec{k}_1 \times \vec{k}_2)/|\vec{k}_1 \times \vec{k}_2| = \cos\theta$$

$$< \mathbf{O}_{\mathrm{CPT}} > = 0.00025 \pm 0.00036$$

Over a factor of three improvement
Results limited by the statistical uncertainty

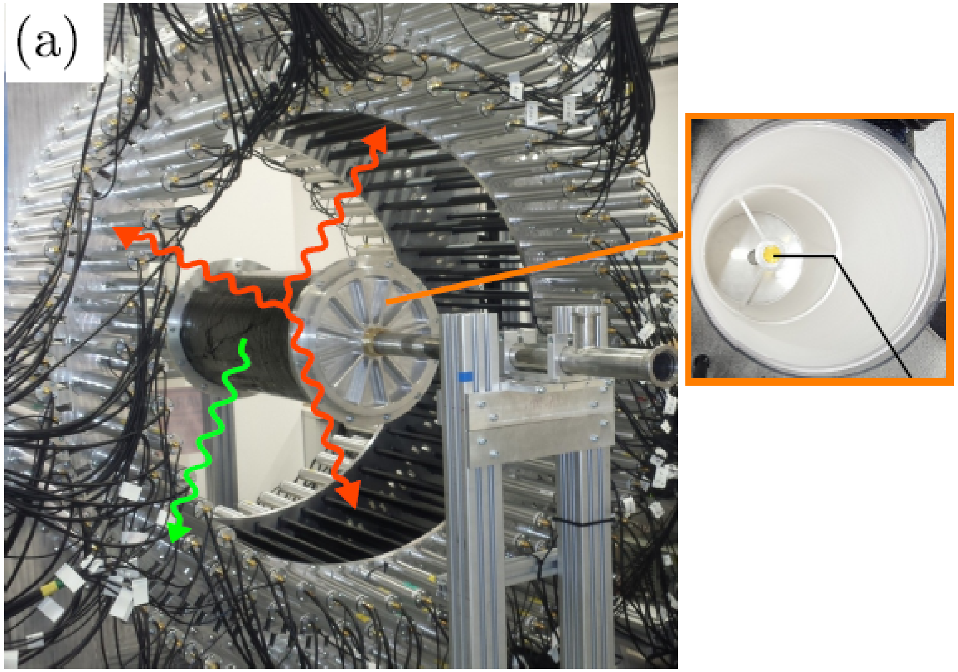
New data analysis ongoing

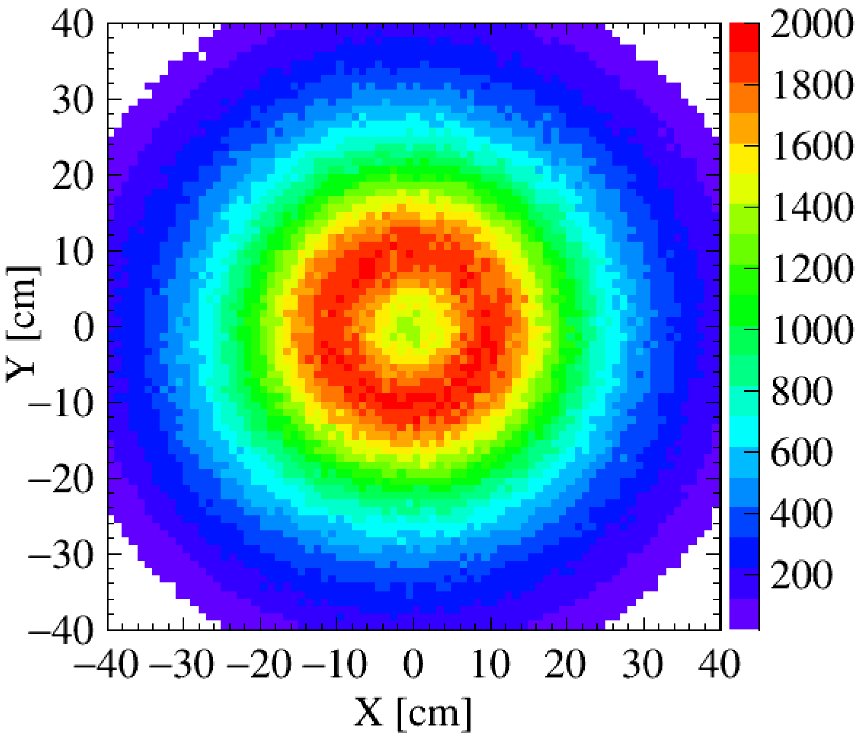
Neha Chug

Session: Poster Session II

Date and time: 7 Sep 2021, 18:10

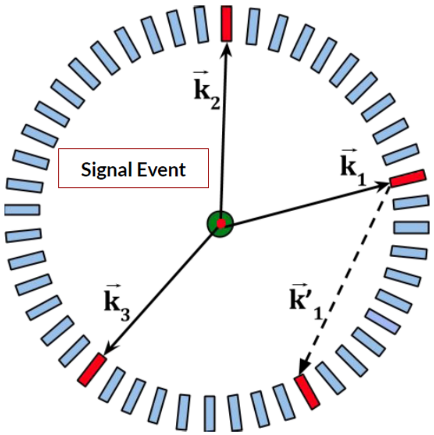
Poster: „CPT symmetry test in positronium annihilations with the J-PET detector"





As by-product: First tomographic image of an object (anihilation chamber) using o-ps decays

New operators with photon polarizations



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

[W. Bernreuther et al., Z. Phys. C41 (1988) 143]
[P. Moskal et al., Acta Phys. Polon. B47 (2016) 509]

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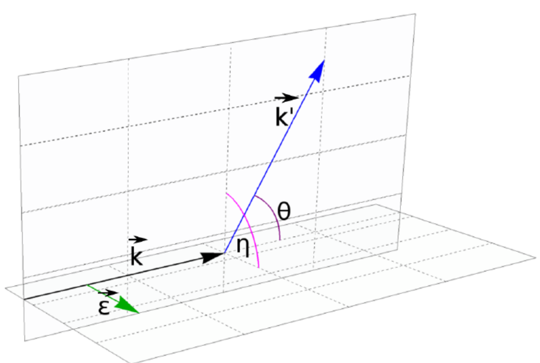
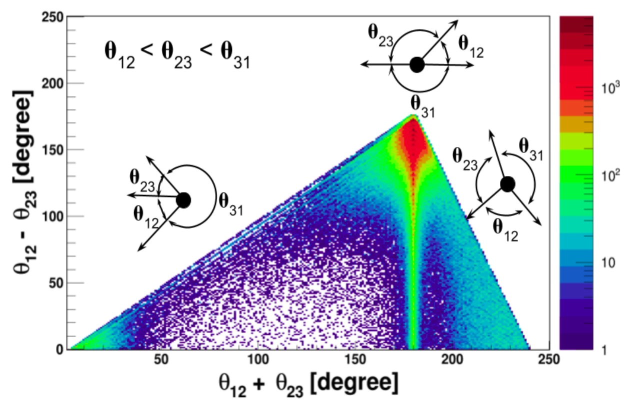
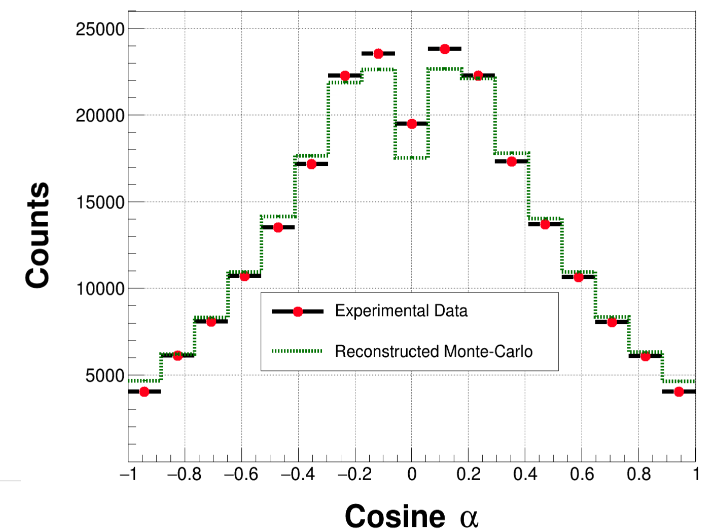
$\vec{k}_2\cdot\vec{\epsilon}_1$	+	-	-	-	+
$\vec{S}\cdot\vec{\epsilon}_1$	+	+	-	+	-
$\vec{S}\cdot(\vec{k}_2\times\vec{\epsilon}_1)$	+	-	+	-	-

So far, No CP- violation was observed with a sensitivity of 2.2×10^{-3} .
[T. Yamazaki et al., Phys. Rev. Lett. 104, 083401 (2010)]



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





Expectation Value = 0.0003 +/- 0.0003
PRELIMINARY

Precision o-ps lifetime measurments
and
Mirror Matter searches

Mirror Matter search in o-PS with J-PET

- Weak interactions violates parity (P).

  First experimental confirmations:

  - *C. S. Wu et al. Phys. Rev. 105 (1956) 1413*
  - *R. L. Garwin, L. Lederman and R. Weinrich Phys. Rev. 104 (1956) 254*

- Mirror Matter (or Alice Matter) was proposed as an explanation of Parity symmetry violation [T.D., Yang C. N. Phys. Rev. 1956. V. 104. P. 254.]
  - Each particle has a mirror partner with the same properties and opposite chirality (left/right - handed)
  - Mirror particles interact with normal matter mainly through gravity → **Dark Matter candidates**
  - γ − mirror γ' interaction via kinetic mixing

$$\mathcal{L}_{\gamma\gamma'} = -\epsilon F^{\mu\nu} F'_{\mu\nu}$$

Ps pure leptonic system:
•Clean experimental system (**no background**)
•**Lifetime accurately described** with Quantum Electrodynamics (QED) **theory**

$$\Gamma(\mathrm{o-Ps} \to 3\gamma, 5\gamma) = \frac{2(\pi^2-9)\alpha^6 m_e}{9\pi}\left[1 + A\frac{\alpha}{\pi} + \frac{\alpha^2}{3}\ln\alpha + B\left(\frac{\alpha}{\pi}\right)^2 - \frac{3\alpha^3}{2\pi}\ln^2\alpha + C\frac{\alpha^3}{\pi}\ln\alpha + D\left(\frac{\alpha}{\pi}\right)^3 + \ldots\right]$$

Acta Phys. Pol. B 50, 1319 (2019)

Theory prediction

$$\Gamma = 7.039979(11) \times 10^6\,\mathrm{s}^{-1}$$

Experimental values

$$\Gamma = 7.0401 \pm 0.0007 \times 10^6\,\mathrm{s}^{-1}$$ Tokyo group

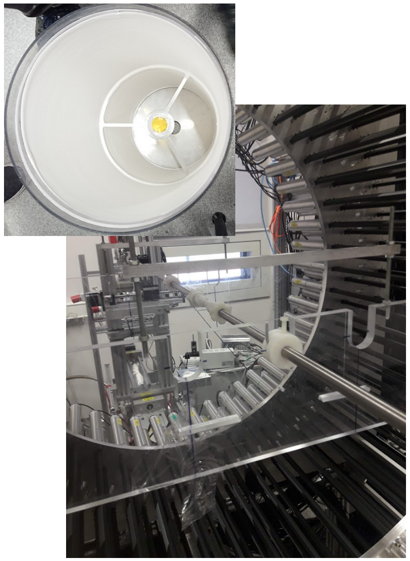
Phys. Lett. B 671 (2009), p. 219

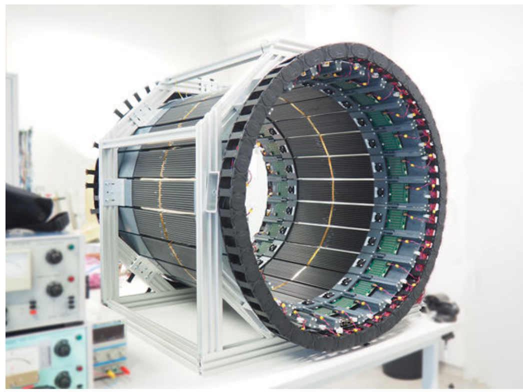
$$\Gamma = 7.0404 \pm 0.0010 \pm 0.0008 \times 10^6\,\mathrm{s}^{-1}$$ Ann Arbor group

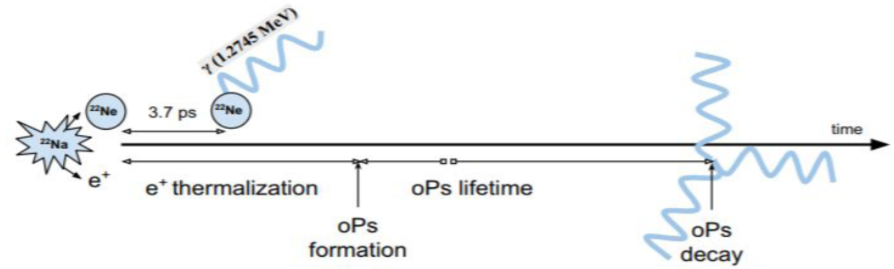
Phys. Rev. Lett. 90 (2003), p. 203402

Theory predictions 100 times more precise:
10^{-6} vs 10^{-4}

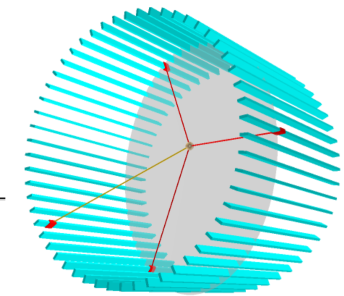
Precise measurement of the o-Ps lifetime looking for hints of new physic

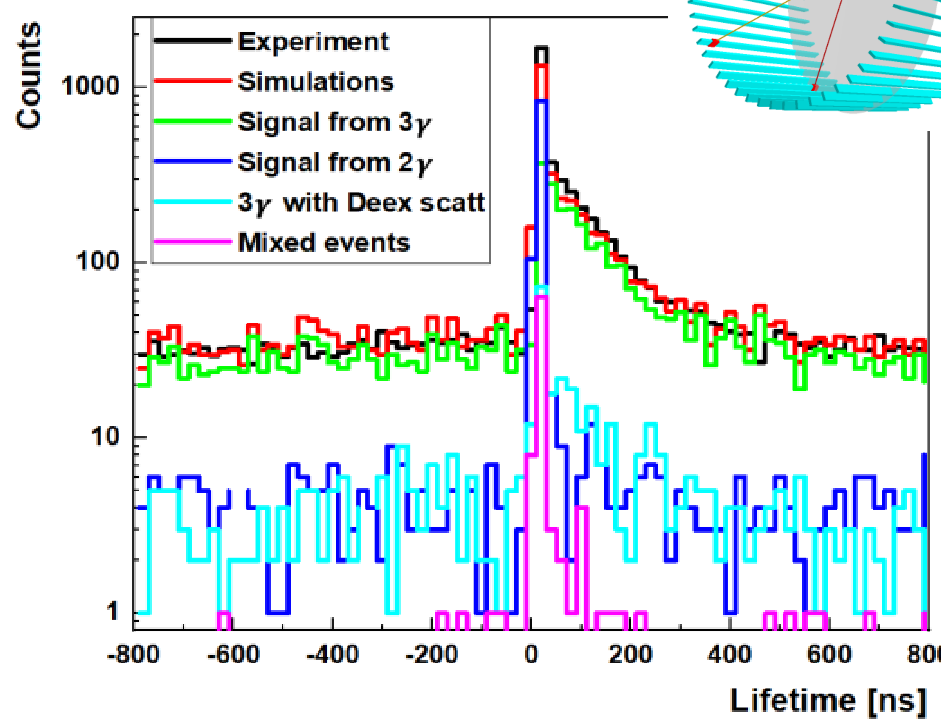






Acta Phys.Polon. B51 (2020) 165





- Source activity 1 MBq = **10^6 e^+/s**
- o-Ps formed in vacuum chamber with probability 29%
- Number of o-Ps after 2 years

10^{13} o-Ps formed

Sensitivity below O(10^{-5})

Photon mixing strength ε < O(10^{-7})

[arXiv:2006.07467 [physics.ins-det]]

Main competitor ETH Zurich

- [Phys. Rev. D 97, 092008]
  - Slow positron beam (1.5 x $10^4 e^+$/s)

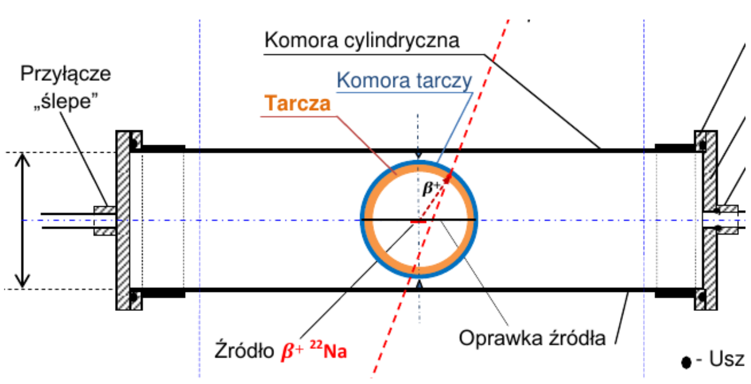
Summary and Outlook

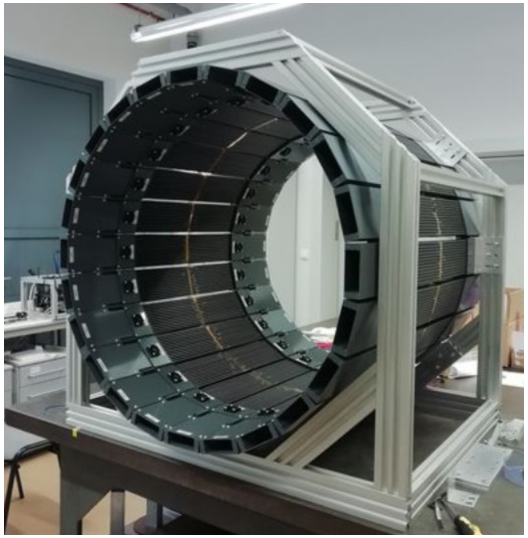
- Positronium atoms provide a good and clean test field for discrete symmetries in leptonic systems

- J-PET detector is capable of exclusive registration of o-Ps → 3γ annihilation events:
  - Full anihillation vertex reconstruction
  - Estimation of o-Ps spin on an event-by-event basis
  - o-Ps lifetime using the de-excitation photons emitted by the source

- Improvement of a factor more than 3 reached in CPT tests with the current data.
- Aims at an improved sensitivity for the CP and CPT symmetry tests (~10^{-5})
- Larger sensitivity reach with the inclusion of the modular 4th layer of the detector

- Precise measurement of the o-Ps lifetime in view of new Physics
  - Mirror matter as Dark Matter candidate





Thank you for your attention

prof. Paweł Moskal

Session: Applications of nuclear and particle physics technology

Date and time: 8 Sep 2021, 13:30

Talk: „From tests of discrete symmetries to medical imaging with J-PET detector”

J-PET

Neha Chug

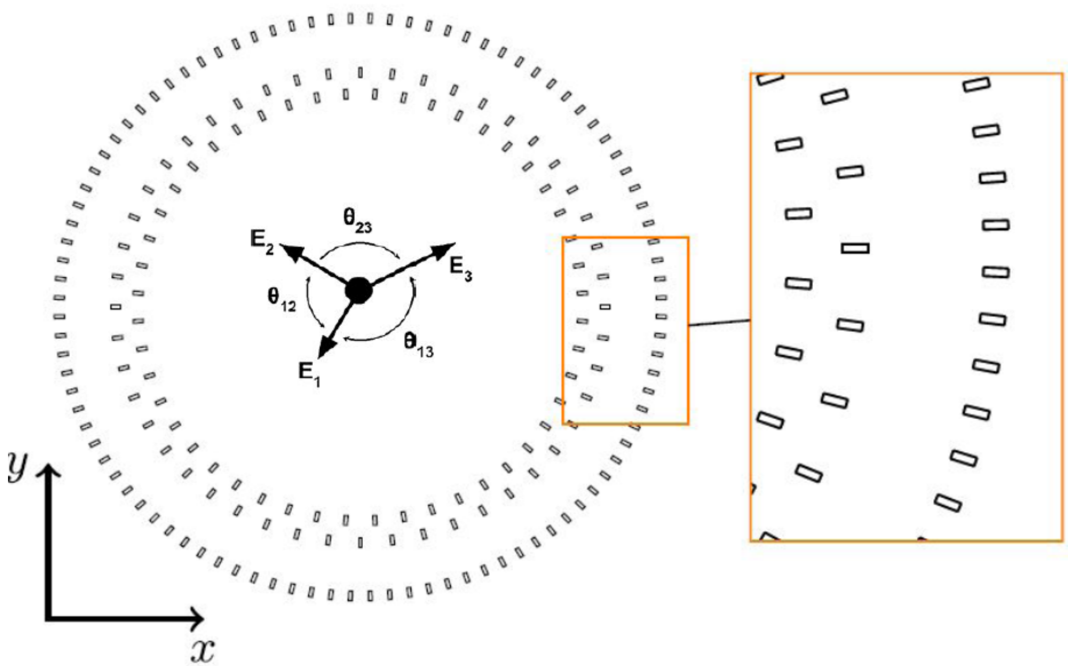
Session: Poster Session II

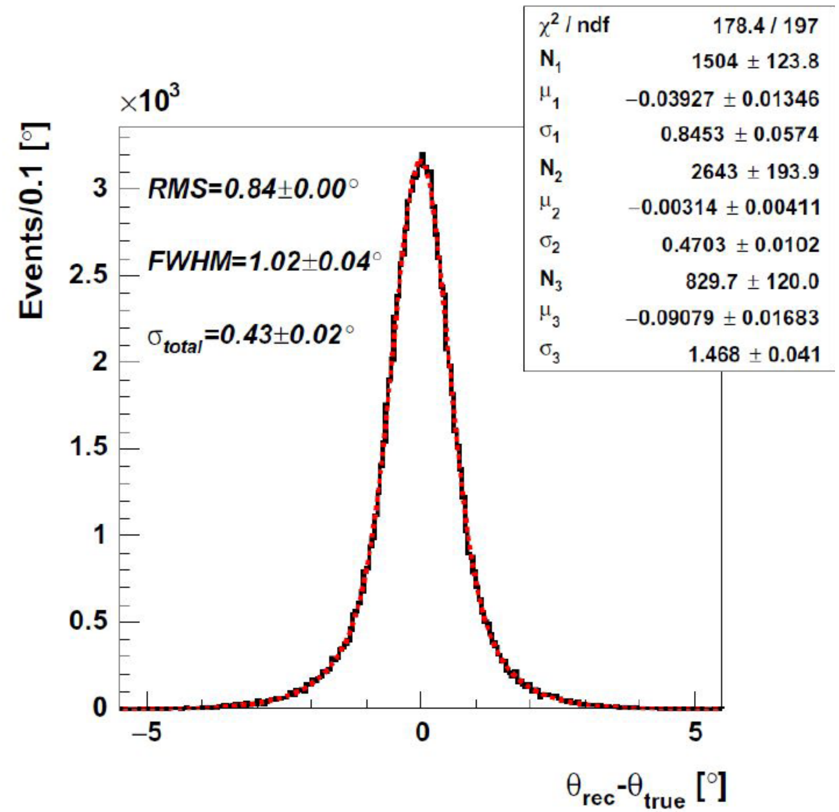
Date and time: 7 Sep 2021, 18:10

Poster: „CPT symmetry test in positronium annihilations with the J-PET detector”

Backup Slides

Detector performance: angular resolution (o-Ps)



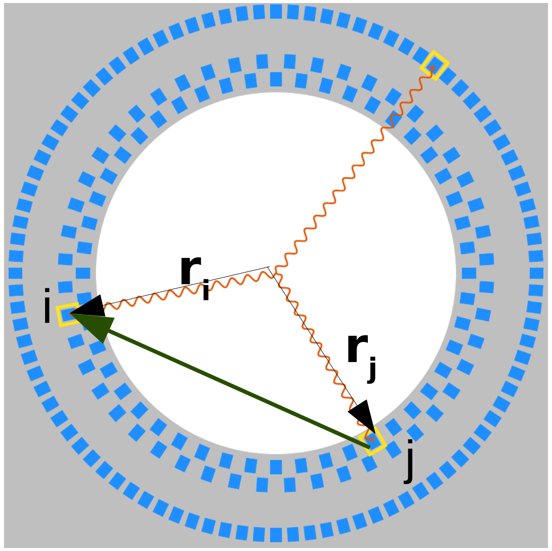


A feasibility study of ortho-positronium decays measurement with the J-PET scanner based on plastic scintillators
Eur. Phys. J. C (2016) 76:445
DOI 10.1140/epic/s10052-016-429

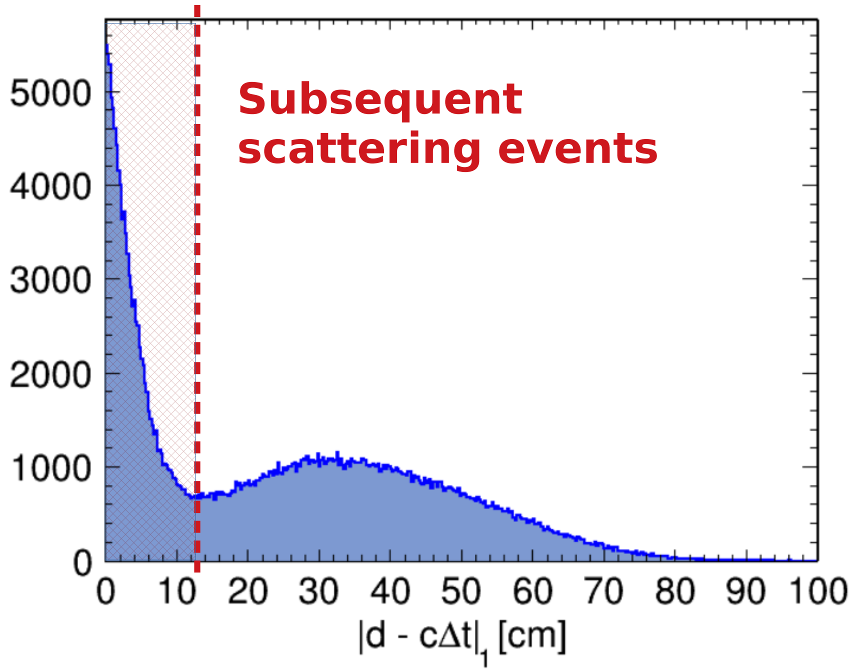
Rejection of subsequent scattering in the detector

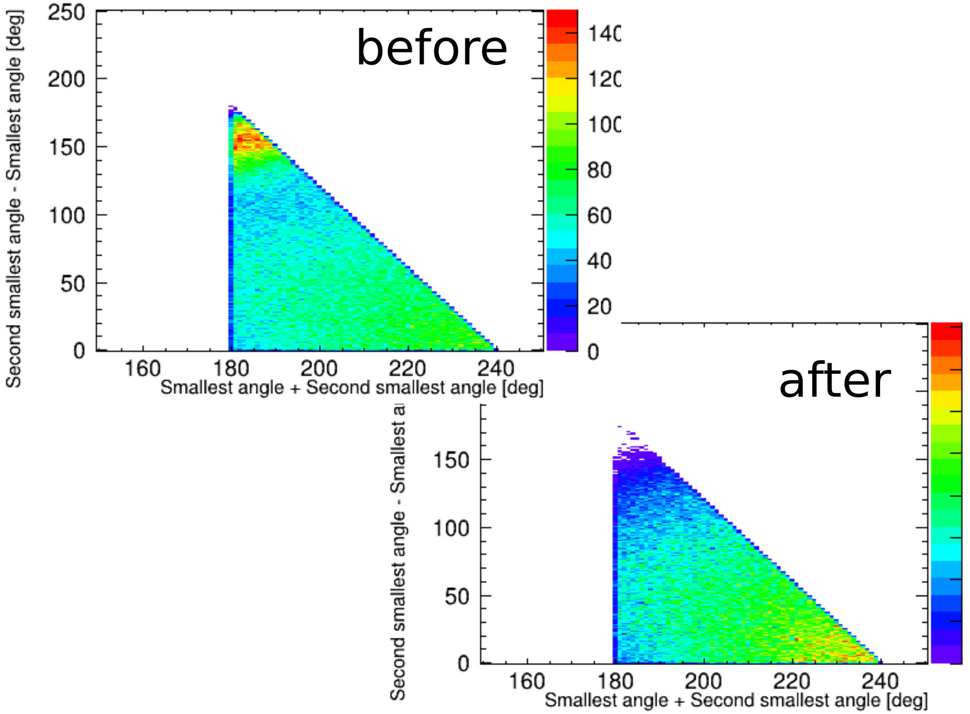
- Secondary Compton-scattered photons may be recorded by J-PET again
- For each pair of annihilation photon candidates *i* and *j* (*i*,*j*=1,2,3) the following figure is computed:

$$\delta t_{ij} = |d_{ij} - c\Delta t_{ij}| = ||\vec{r}_i - \vec{r}_j| - c(t_i - t_j)|$$



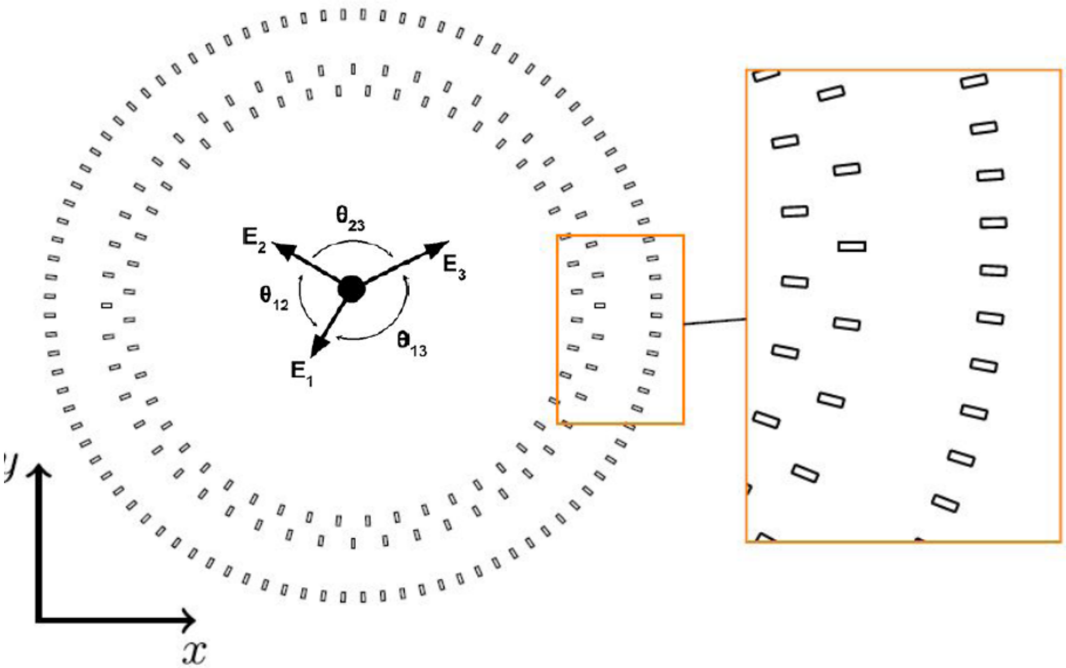
Distribution of the minimum δt_{ij} over all photon pair choices in a events:

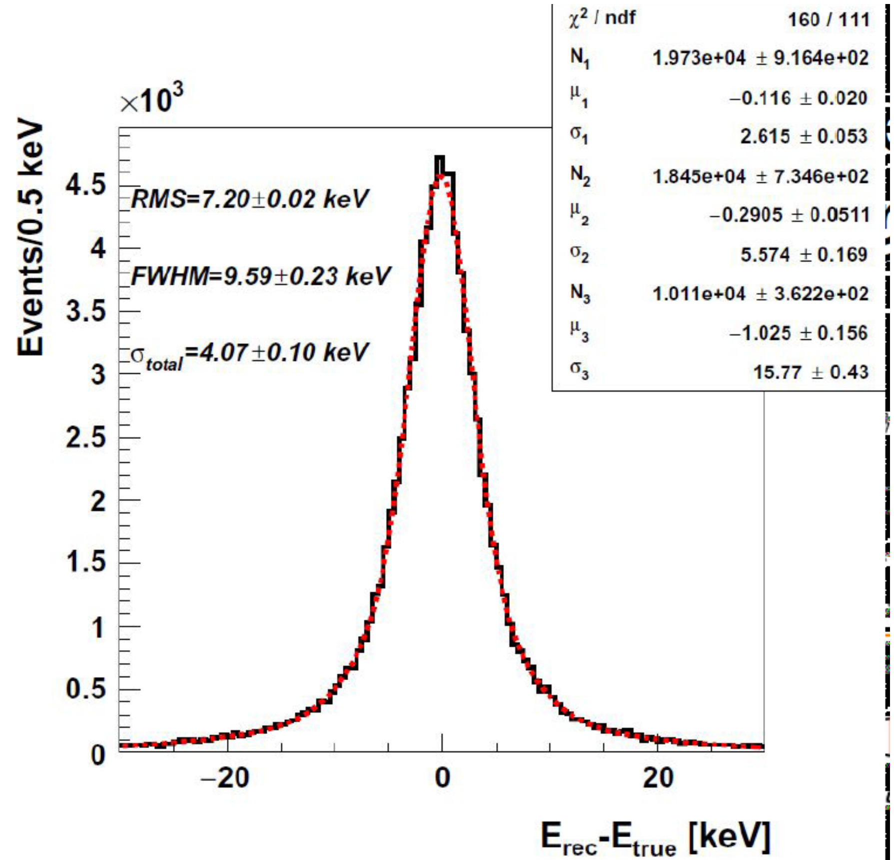




*courtesy A. Gajos MESON2021

Detector performance: energy resolution (o-Ps)





A feasibility study of ortho-positronium decays measurement with the J-PET scanner based on plastic scintillators
Eur. Phys. J. C (2016) 76:445
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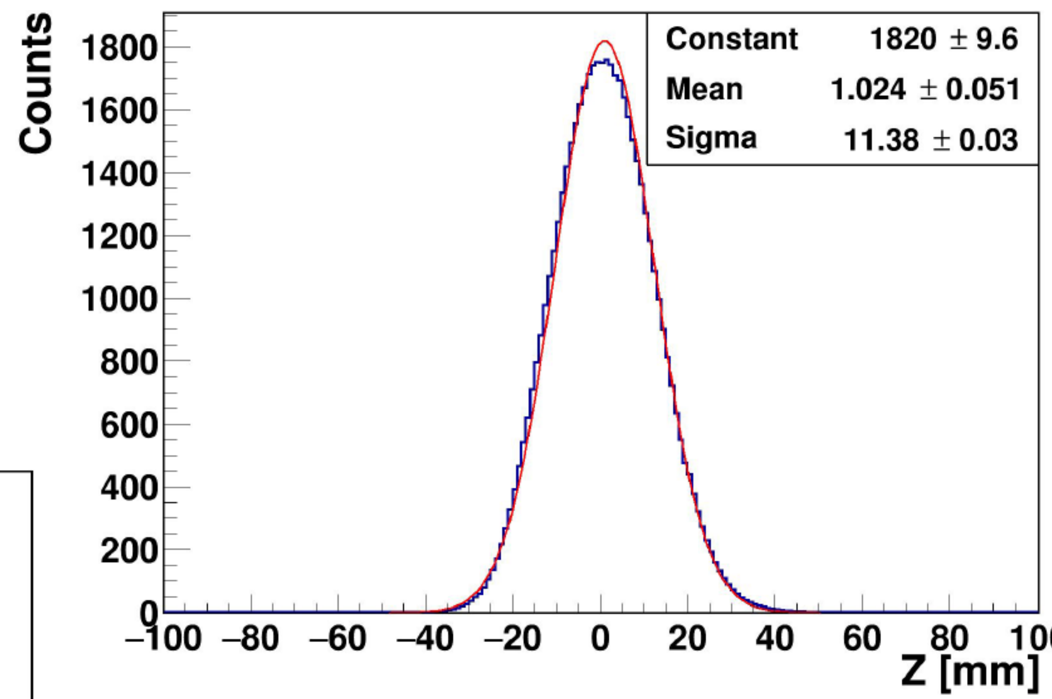
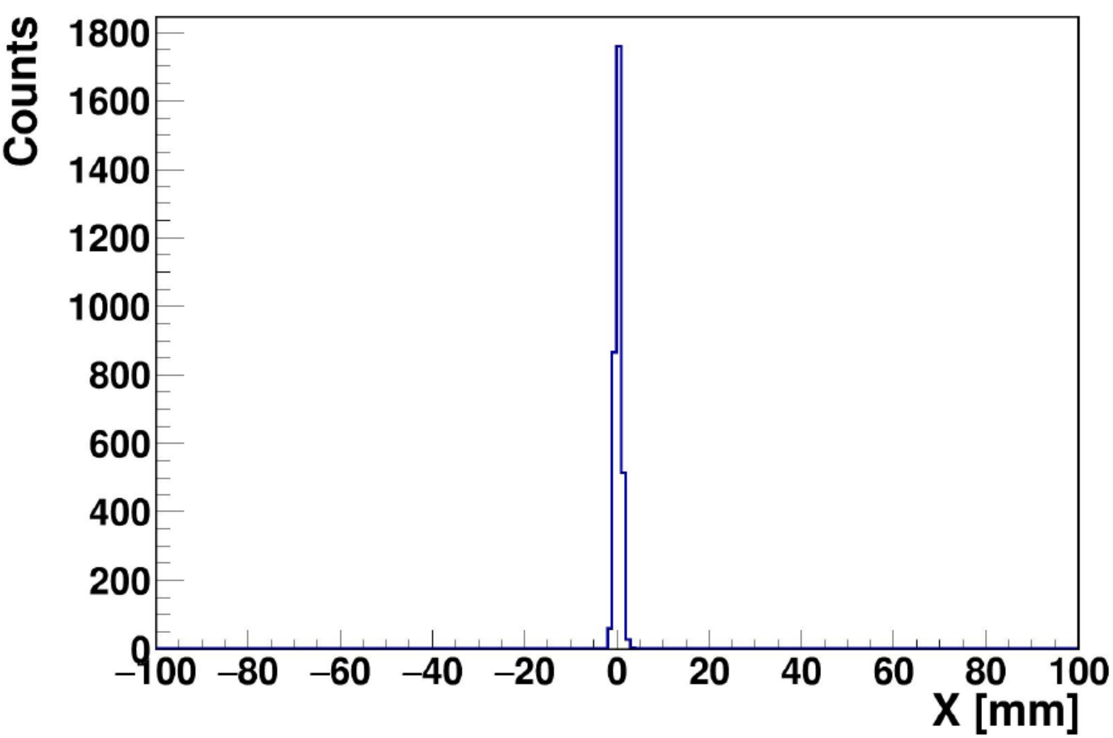
Detector performance: spatial resolution (p-Ps)





Resolution in XY in the order of source size (2-3 mm)
Resolution in Z ~ 1.2 cm

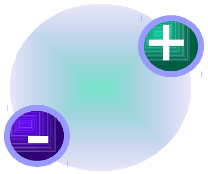
Preliminary Studies of J-PET Detector Spatial Resolution
Acta Phys. Polon. A 132, no. 5, 1645 (2017)

25

Positronium system

Acta Phys. Pol. B 50, 1319 (2019)

- Hamiltonian eigenstates of P, C, CP operators
- The lightest known atom and anti-atom
- The simplest atomic system with charge conjugation eigenstates.
- Electrons and positrons are the lightest leptons hence, they do not decay into lighter particles via weak interaction
- Weak interaction leads to the violation at the order of 10^{-14}.



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

- No charged particles in the final state (radiative corrections very small $2 * 10^{-10}$)
- Light by light contributions to various correlations are small

(B. K. Arbic et al., Phys. Rev. A 37, 3189 (1988)) (W. Bernreuther et al., Z. Phys. C 41, 143 (1988))

- Purely Leptonic state
- Breaking of T and CP was observed but only for processes involving quarks.
- So far, breaking of these symmetries was not observed for purely leptonic systems.
- 10^{-9} vs   upper limits of $3 *10^{-3}$ for T, CP, CPT

(P.A. Vetter and S.J. Freedman, Phys. Rev. Lett. 91, 263401 (2003))(T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401)

- 10^{-9} vs upper limits of $3*10^{-7}$ for C

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

Operators for the o-Ps→3γ process, and their properties with respect to the C, P, T, CP and CPT symmetries.

Using o-Ps spin →

Using photon polarization →

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

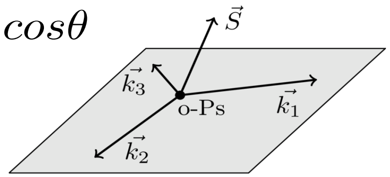
Operators involving spin used in J-PET
Event-by-event spin estimation using extensive annihilation medium

$\vec{S}\cdot(\vec{k}_1\times\vec{k}_2)$ T & CPT-violation sensitive

$\vec{S}\cdot\vec{k}_1$ CP-violation sensitive

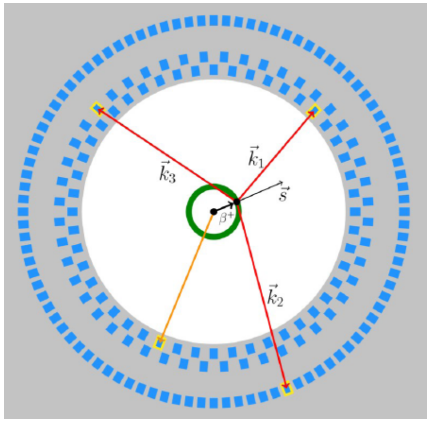
$$|\vec{k}_1| > |\vec{k}_2| > |\vec{k}_3|$$

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



Standard asymmetry:

$$A = \frac{N_+ - N_-}{N_+ + N_-} \quad N_+ \Leftrightarrow cos\theta > 0$$



Effective polarization depends on o-Ps vertex resolution

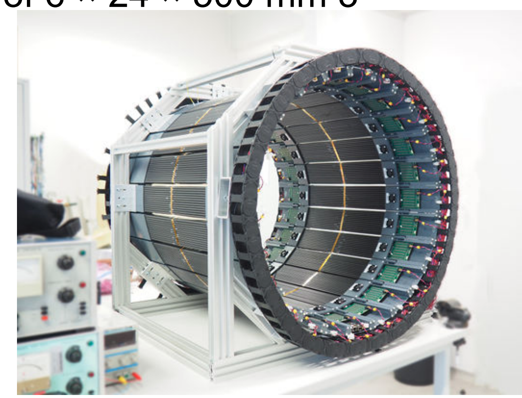
is generalized by the **mean value of cosϑ**:

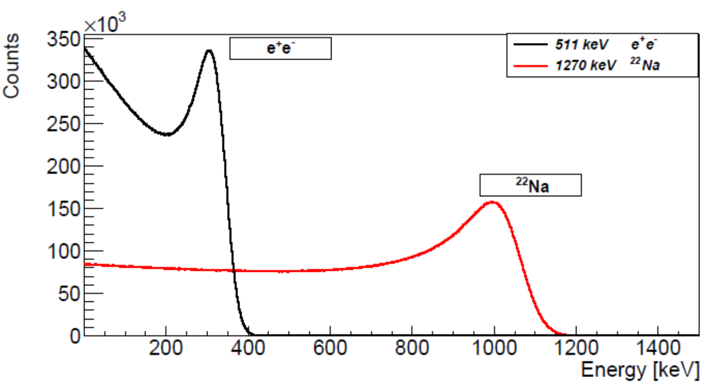
$$\frac{\int N(\cos\theta)\cos\theta}{\int N(\cos\theta)}$$

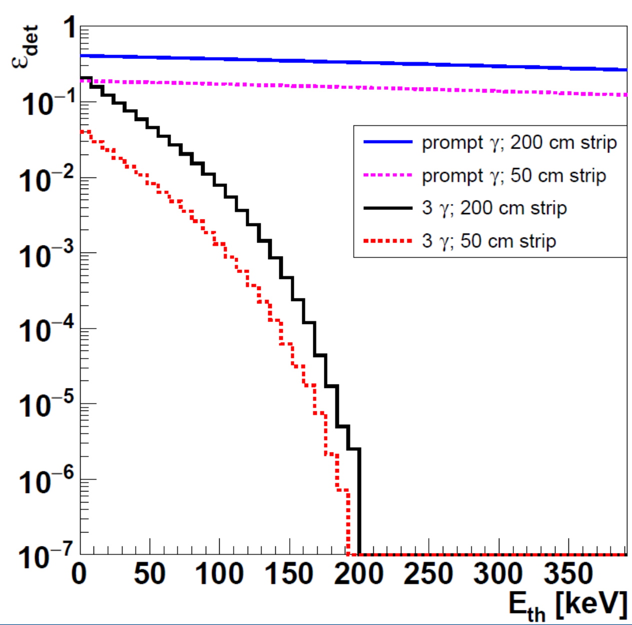
J-PET is sensitive to the full range of this operator

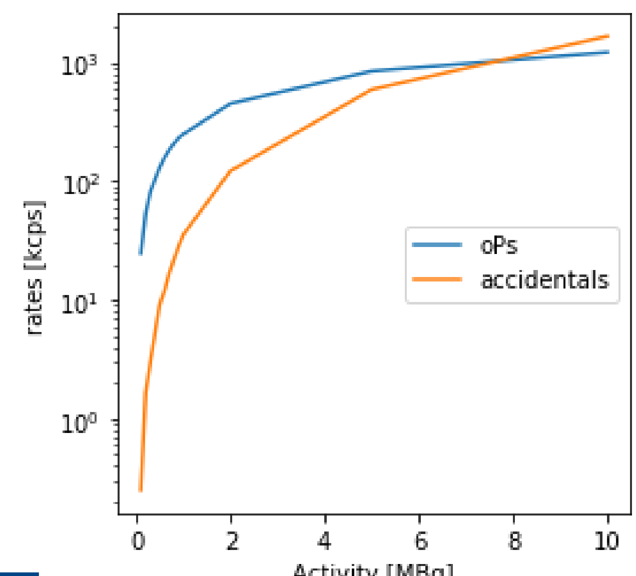
J-PET (Jagiellonian-PET TOMOGRAPHY)

- 3 + 1 layer arrangement
  - 192 scintillator modules 7 × 19 × 500 mm 3 arranged in 3 layers read out by vacuum tube photomultipliers (PMs) with radius of 42.5 cm and length of 50 cm
  - 4-th layer modular JPET: 312 plastic scintillator strips in 24 modules with dimensions of 6 × 24 × 500 mm 3 read out by matrices of silicon photomultipliers (SiPM)
- Novel digital front-end electronics probing signals at multiple thresholds
- Trigger-less and reconfigurable DAQ system
- Annihilation gamma quanta hit time measurement: σ_t (0.511 MeV) ~ 125 ps
- Gamma quanta energy resolution: $\sigma_E/E = 0.044/\sqrt{E(\mathrm{MeV})}$
- Resolution of photon relative angles measurement ~ 1°
- Possibility of o-Ps spin and photon polarization measurement
- Increased detection efficiency and improved time resolution with layer 4









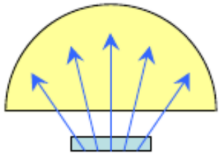
P. Moskal, D. Kisielewska et al. Phys. Med. Biol. 64 (2019) 055017

J-PET vs previous measurements

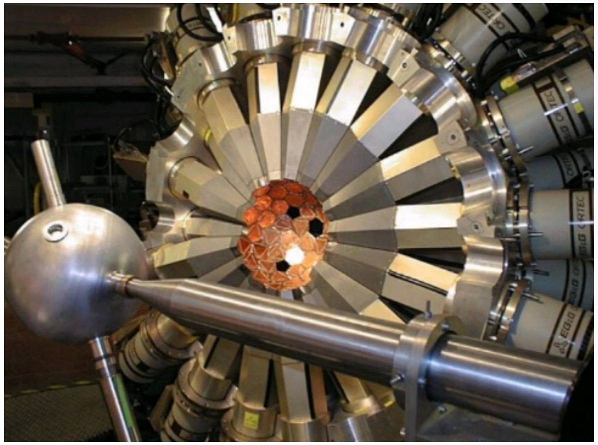
Gammasphere $C_{CPT} = (2.6 \pm 3.1) \times 10^{-3}$

PRL. 91 (2003) 263401

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



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



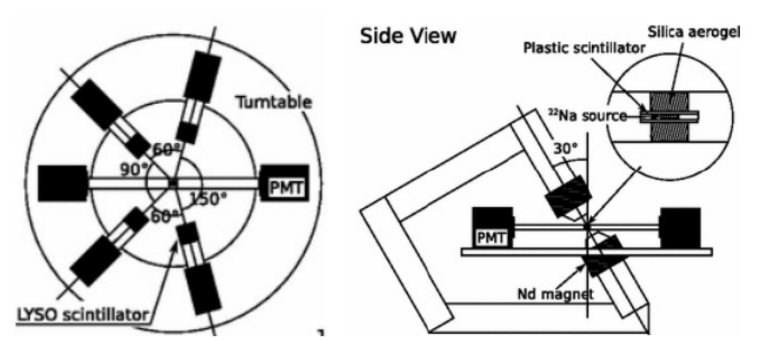
Limiting positron emission direction
1 Mbq β^+ emitter activity
4π detector but low angular resolution

Yamazaki et al.

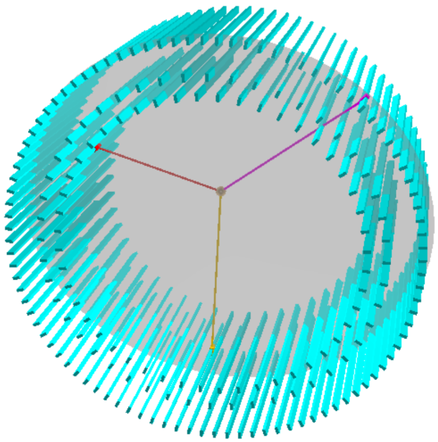
PRL 104 (2010) 083401

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

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



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



J-PET

Recording multiple geometrical configurations

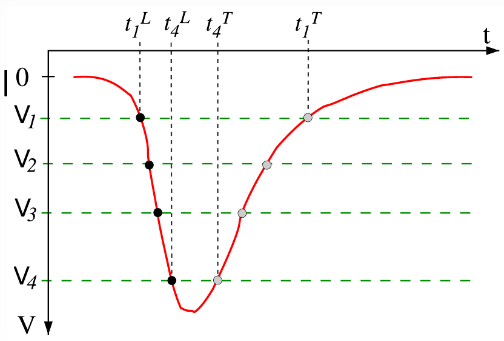
e+ spin estimated event-by-event

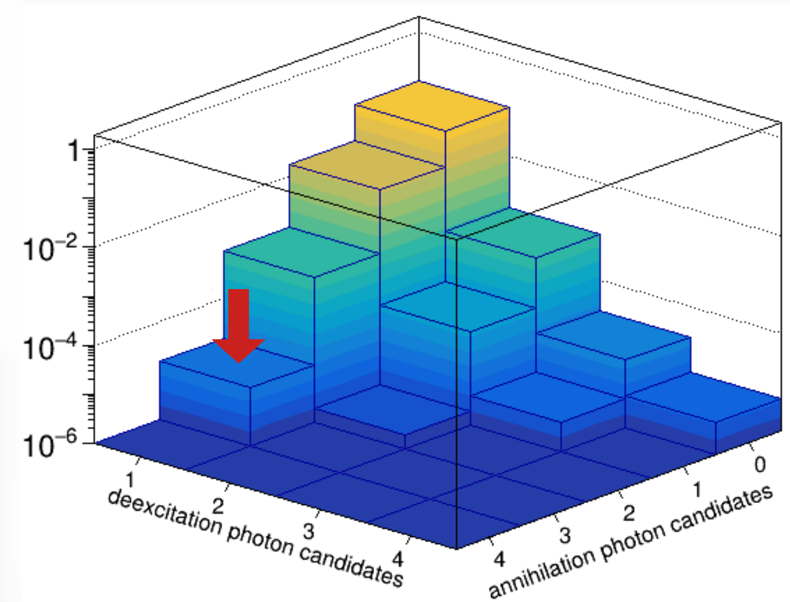
$$P_{e+} \approx \frac{v}{c} \cdot 0.91$$

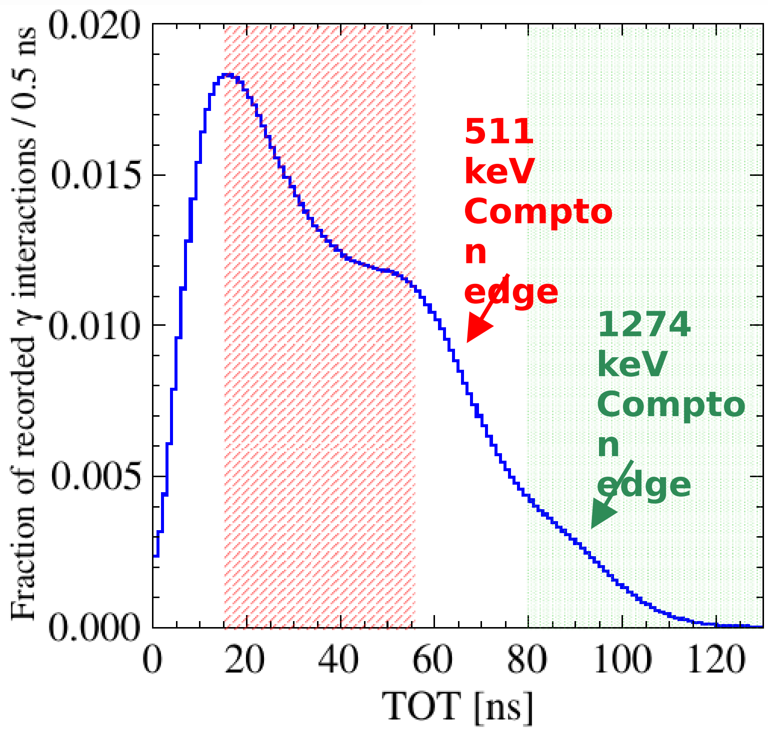
- Plastic scintillators = fast timing → using high β^+ emitter activity (tested up to 10 Mbq)
- Recording all 3 annihilation photons
- Angular resolution at 1° level

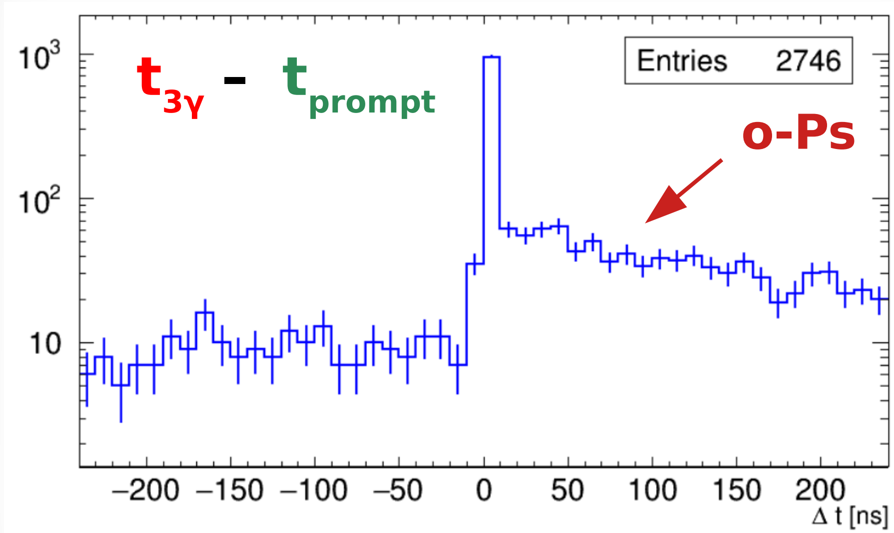
Identification of o-Ps → 3γ events in J-PET

Using total Time Over Threshold (TOT) of PMT signals from a scintillator strip









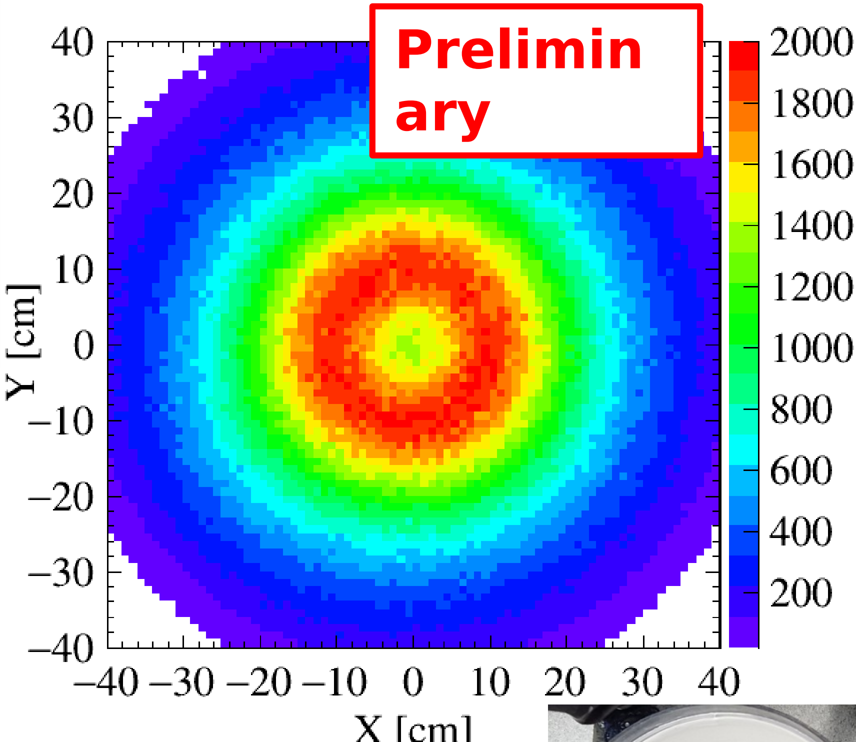
o-Ps →3γ annihilation (E<511 keV)

^{22}Ne* de-excitation (E=1274 keV)

Results of the CPT test

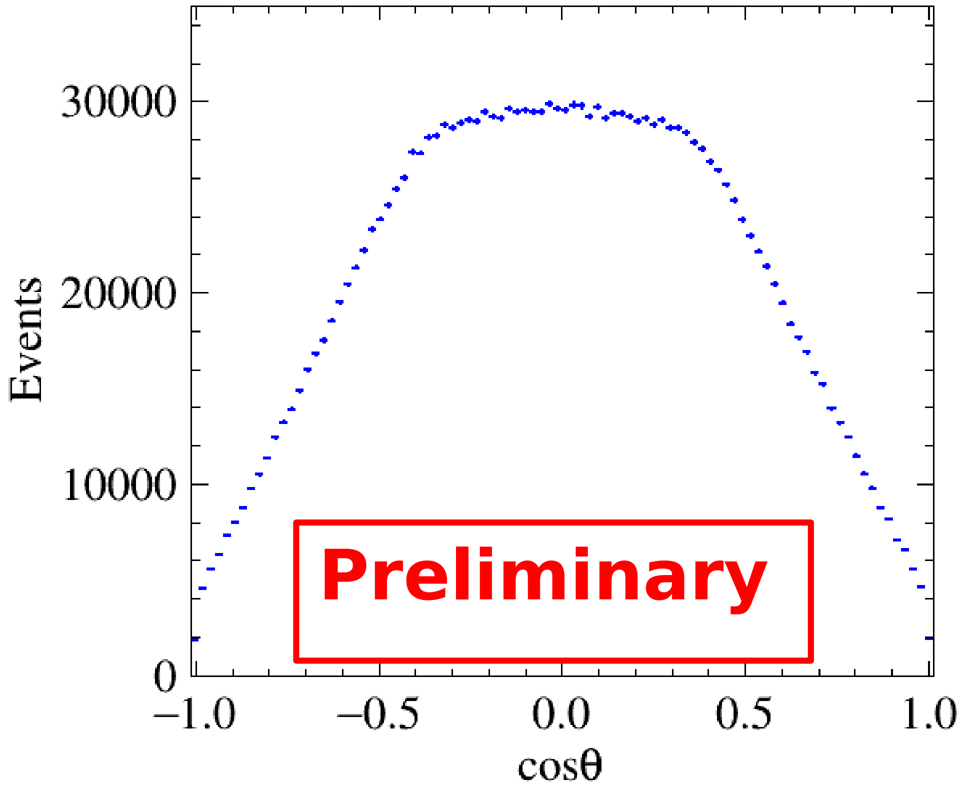
Using 2 x 10^6 of identified
o-Ps → 3ɣ annihilations

3ɣ image of the o-Ps production chamber
in the tranverse view of the detector



The first image of an extensive-size object obtained with o-Ps→3γ annihilations

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



<cosθ> statistical uncertainty: **3.3×10^{-4}**

systematic uncertainty **1.4×10^{-4}**

Analyzing power S = 37.4 %
(polarization-dominated)

oPs in JPET tomograph

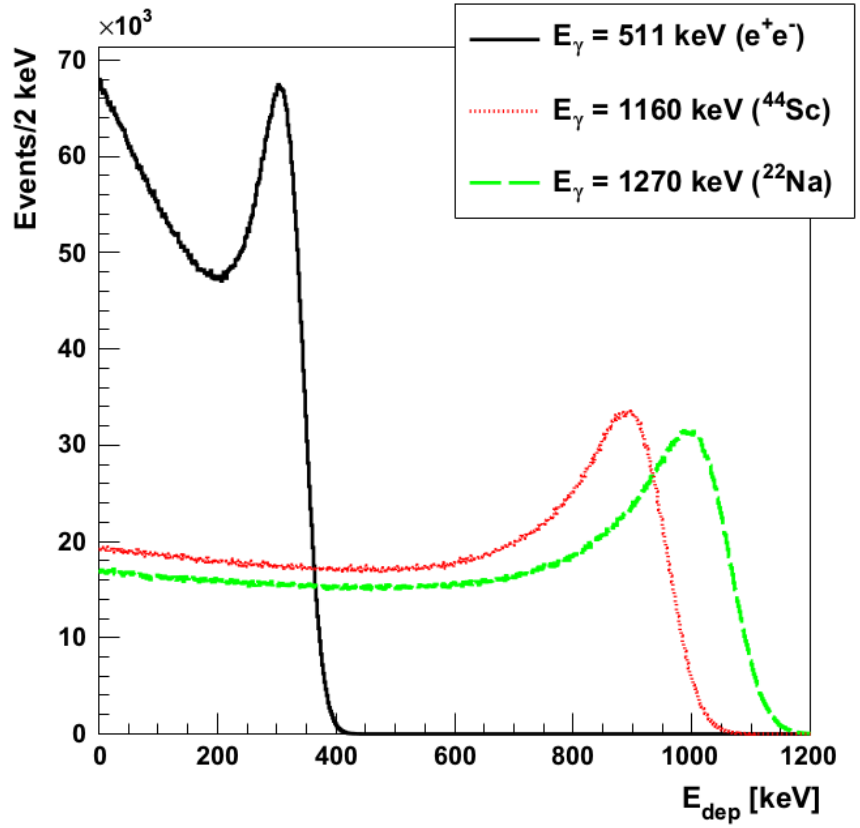
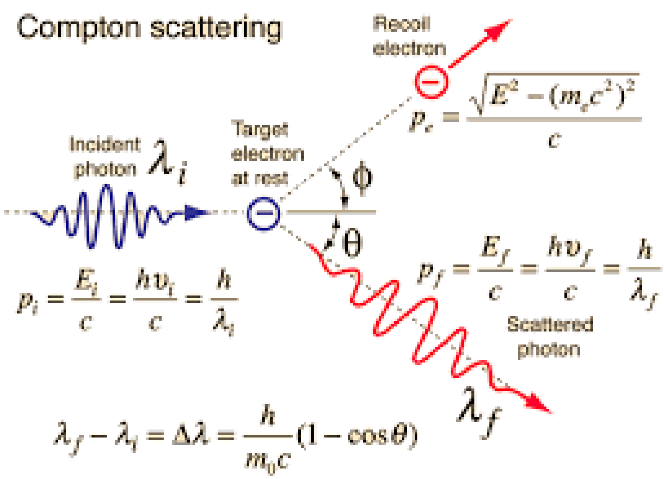
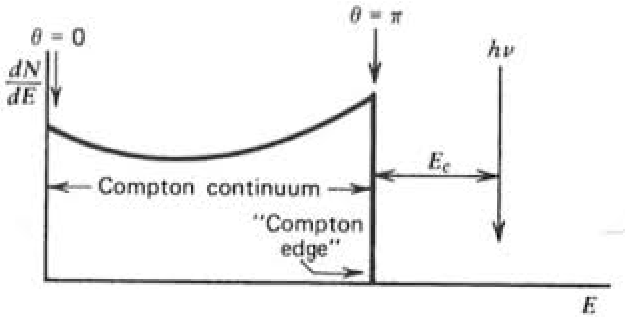


Fig. 3 Simulated spectra of deposited energy in plastic scintillators for gamma quanta from $e^+e^- \rightarrow 2\gamma$ annihilation and for de-excitation gamma quanta originating from isotopes indicated in the legend. The spectra were simulated including the energy resolution of the J-PET detector [20] and were normalized to the same number of events





GPS trilateration

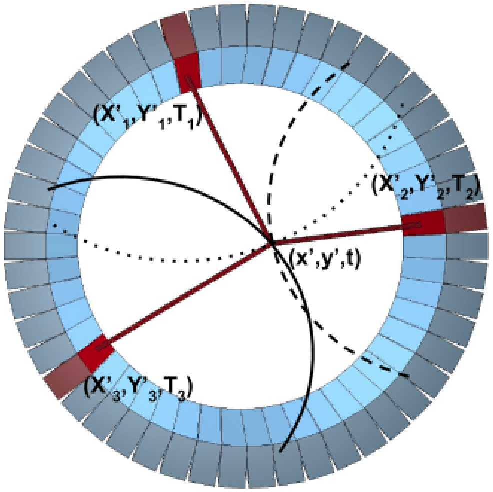
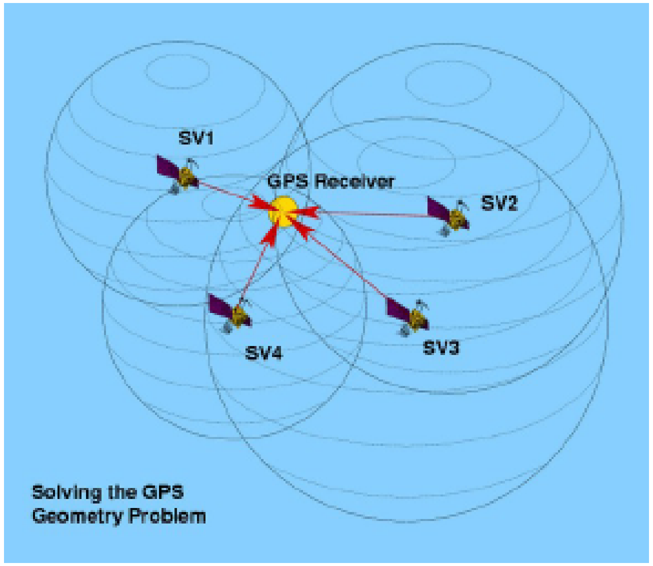


Figure 5: A scheme of the detector showing o-Ps $\rightarrow 3\gamma$ annihilation. For clarity only a single layer with registered hits is shown. Red lines represent the gamma photons from ortho-positronium annihilation. The trilateration method is used to determine the annihilation position and time (x', y', t) along the annihilation plane. For each recorded photon a circle, which is a set of possible photon origin points, centered in the hit-position and parameterised with the unknown o-Ps annihilation time is considered. The intersection of the three circles corresponds to the o-Ps $\rightarrow 3\gamma$ annihilation point.



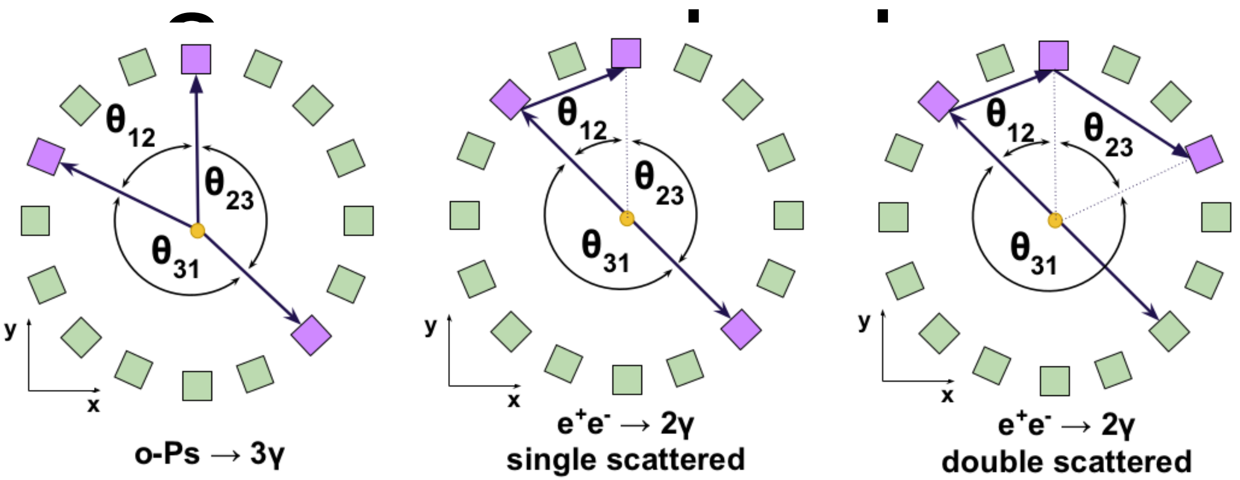
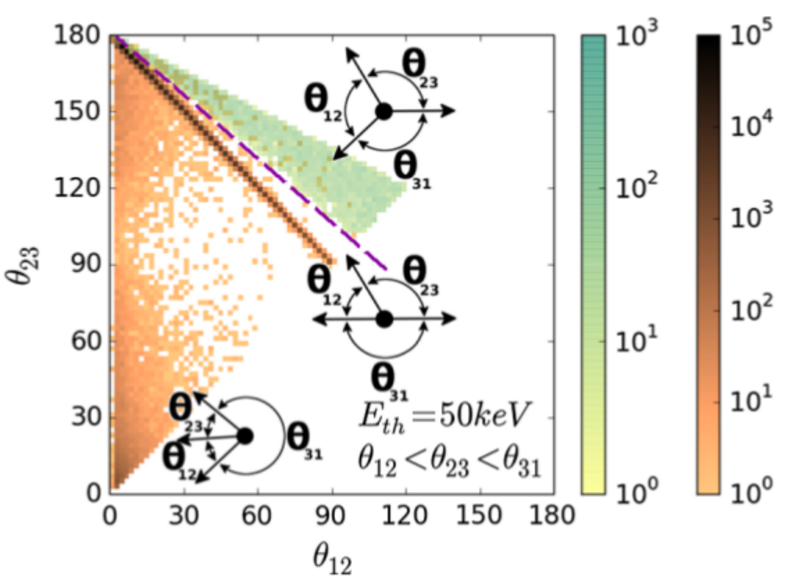
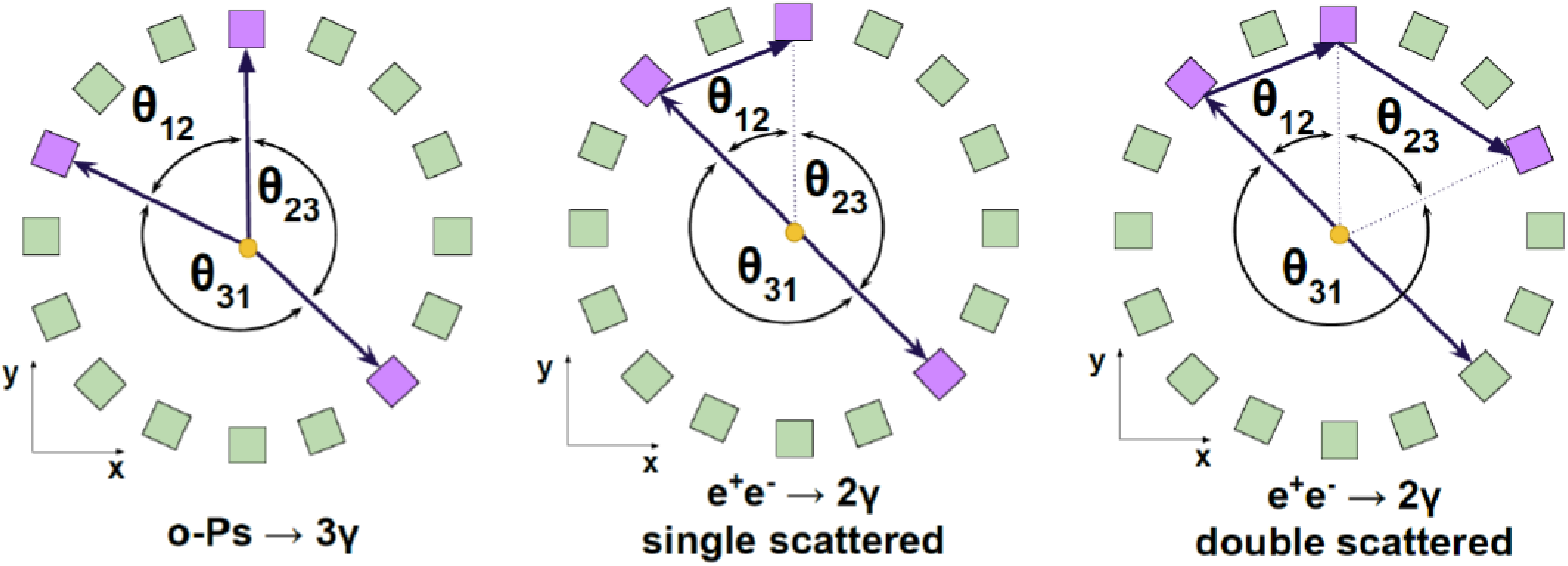


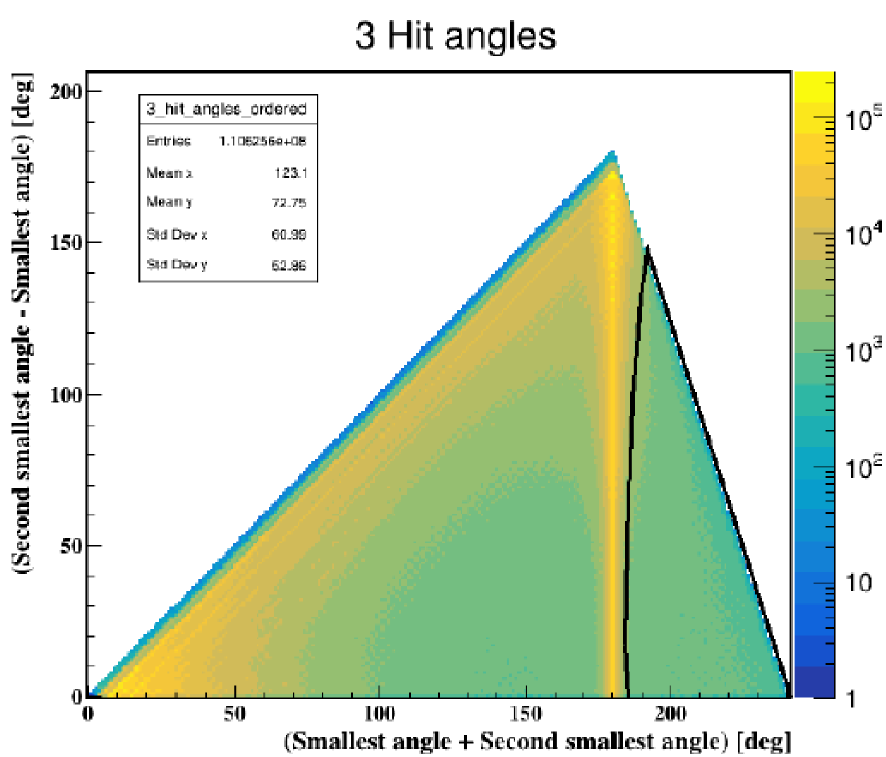
Fig. 13 Pictorial illustration of the possible response of the detector to o-Ps $\rightarrow 3\gamma$ and e^+e^- annihilation into 2γ. Arranged circularly *squares* represents scintillator strips—*purple* and *green* colors indicate strips where the gamma quanta were or were not registered, respectively. The *arrows* represents gamma quanta occurring in the events, while *dotted lines* indicate naively reconstructed gamma quanta. Examples of primary and secondary scatterings are depicted

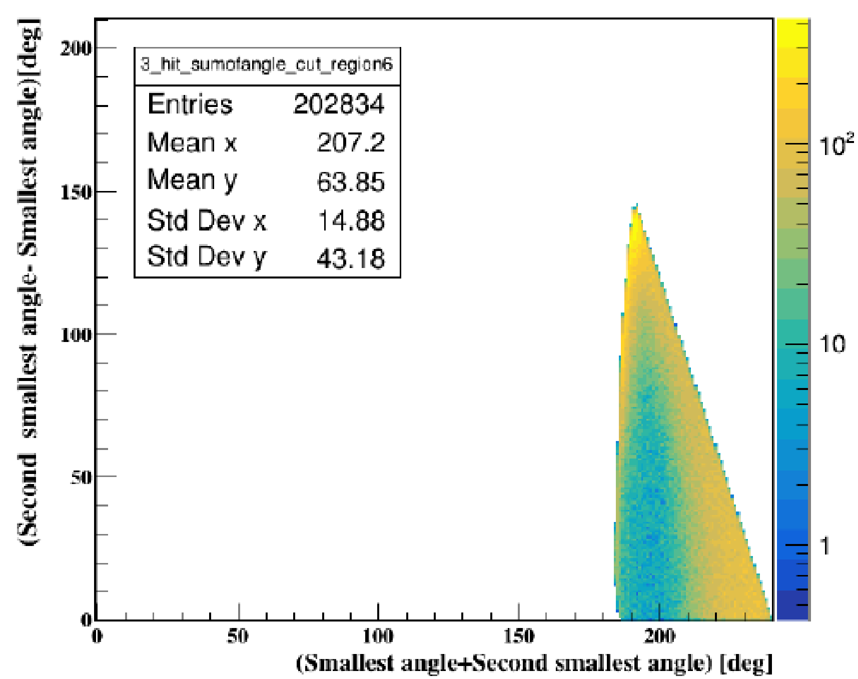


Eur. Phys. J. C (2016) 76 :445



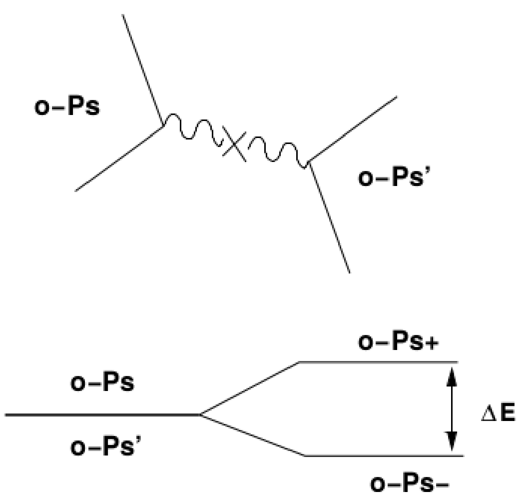
$\theta_{23} + \theta_{12} > 180$ $\theta_{23} + \theta_{12} = 180$ $\theta_{23} + \theta_{12} < 180$





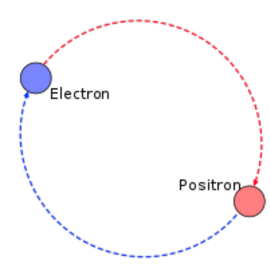
Mirror Matter in o-Ps

- o-Ps can be connected via one-photon annihilation to its mirror version (o-Ps’) and can be confirmed in experiments
  - o-Ps oscillates into its mirror partner o-Ps’
  - Only mimicked by very-rare decay from Standard Model Br(oPs→ $\nu\bar{\nu}$) < O(10^{-18})
  - **Precision measurements of the o-Ps decay rate and compare it to QED calculations.**



[P. Crivelli et al 2010 JINST 5 P08001]

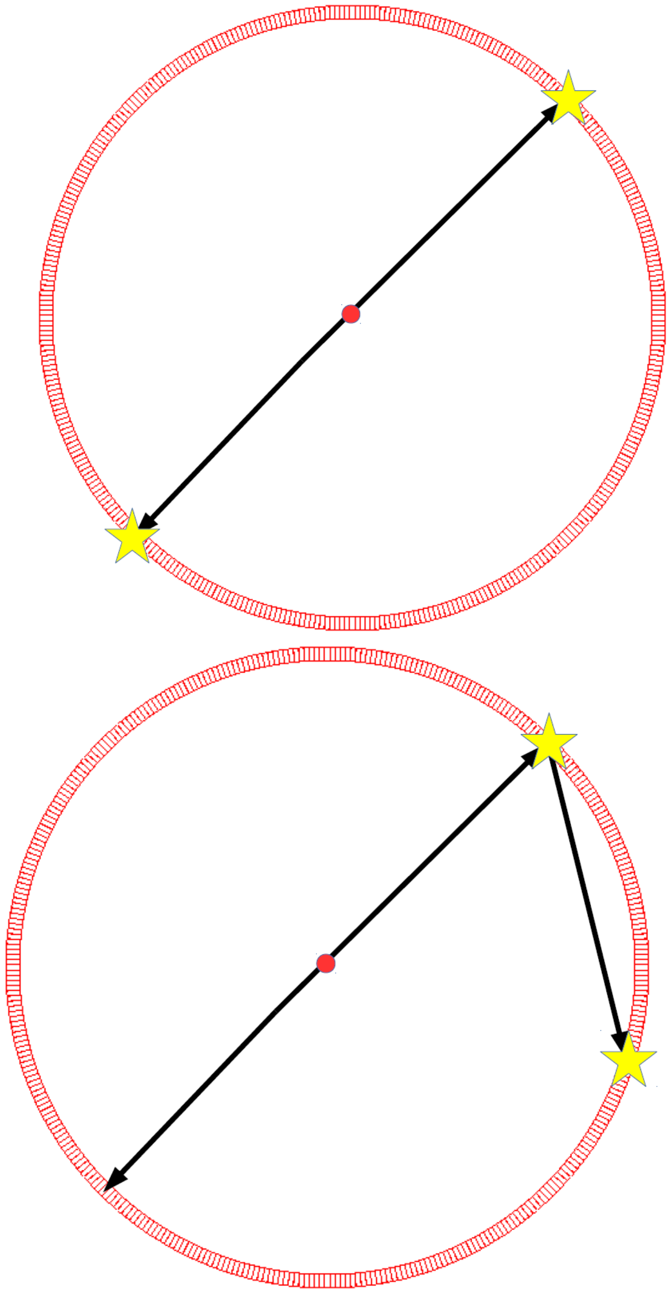
The o-Ps’ → invisible decay would manifest as an increase of the observed lifetime respect to the expected value → Precision measurement of the o-Ps lifetime

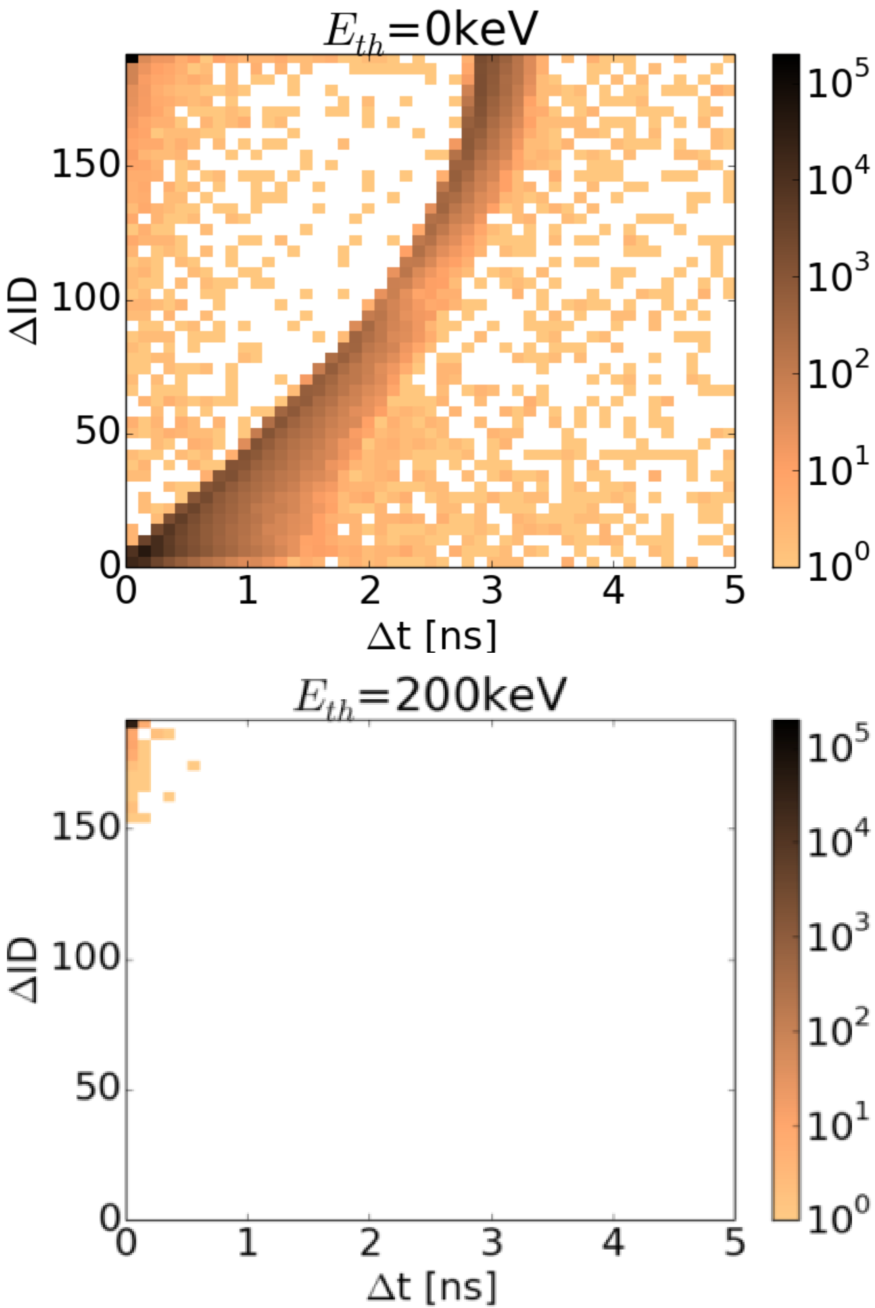


secondary scattering in the detector

J-PET: P. Kowalski et al., Phys. Med. Biol. submitted

J-PET: P. Kowalski et al., Acta Phys. Pol. A127 (2015) 1505 and Acta Phys. Pol. B47 (2016) 549



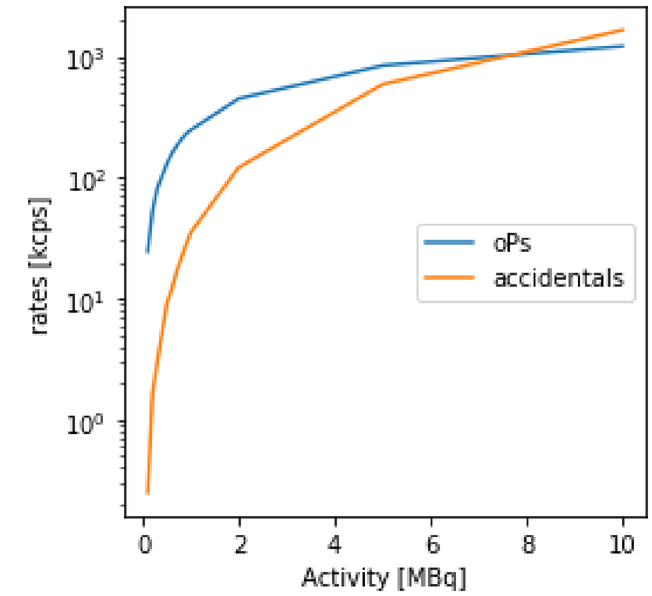


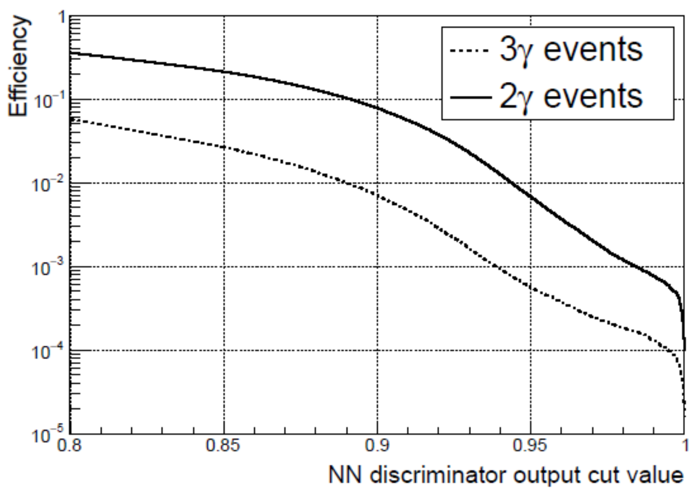
Systematic Uncertainties

Accidental events

-
-

Acta Phys.Polon. B51 (2020) 165



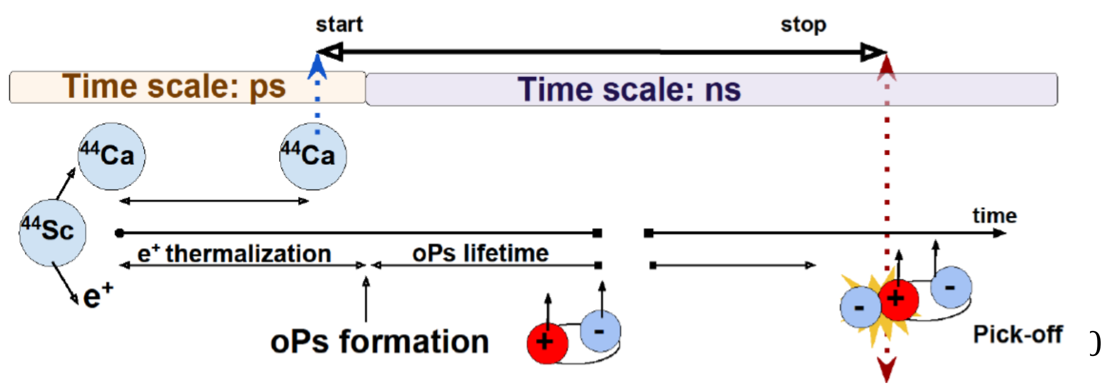


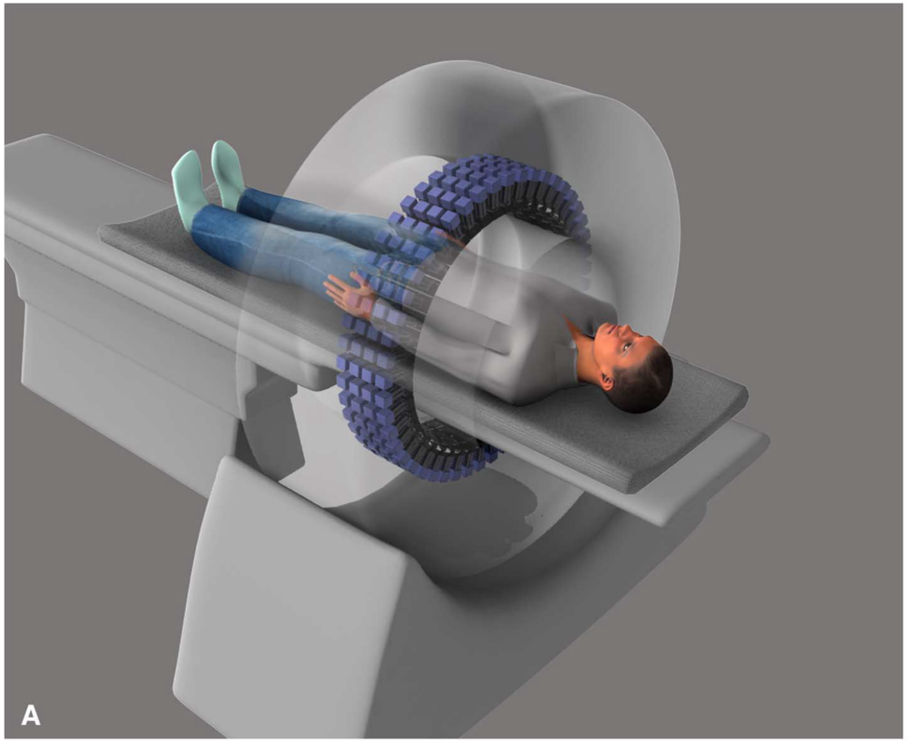
C. Vigo et al. (2019) [805.06384v]

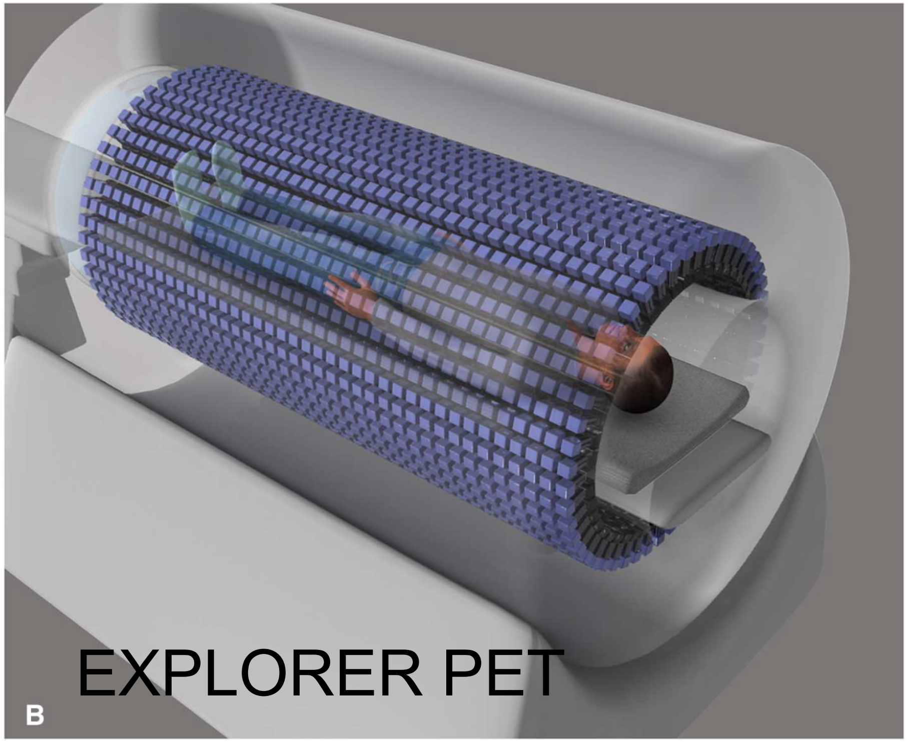
J. of Phys.: Conf. Series, Vol. 1138, conf 1

oPs interacting with the material

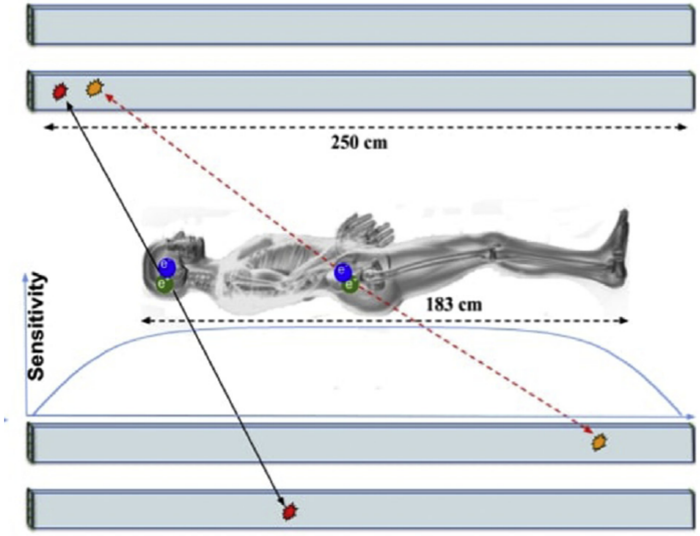
-
-

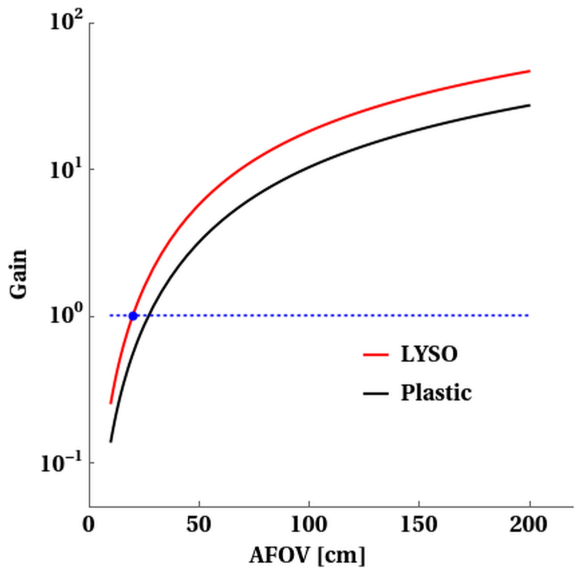






J. Nucl. Med. 60 (2019) 299–303.



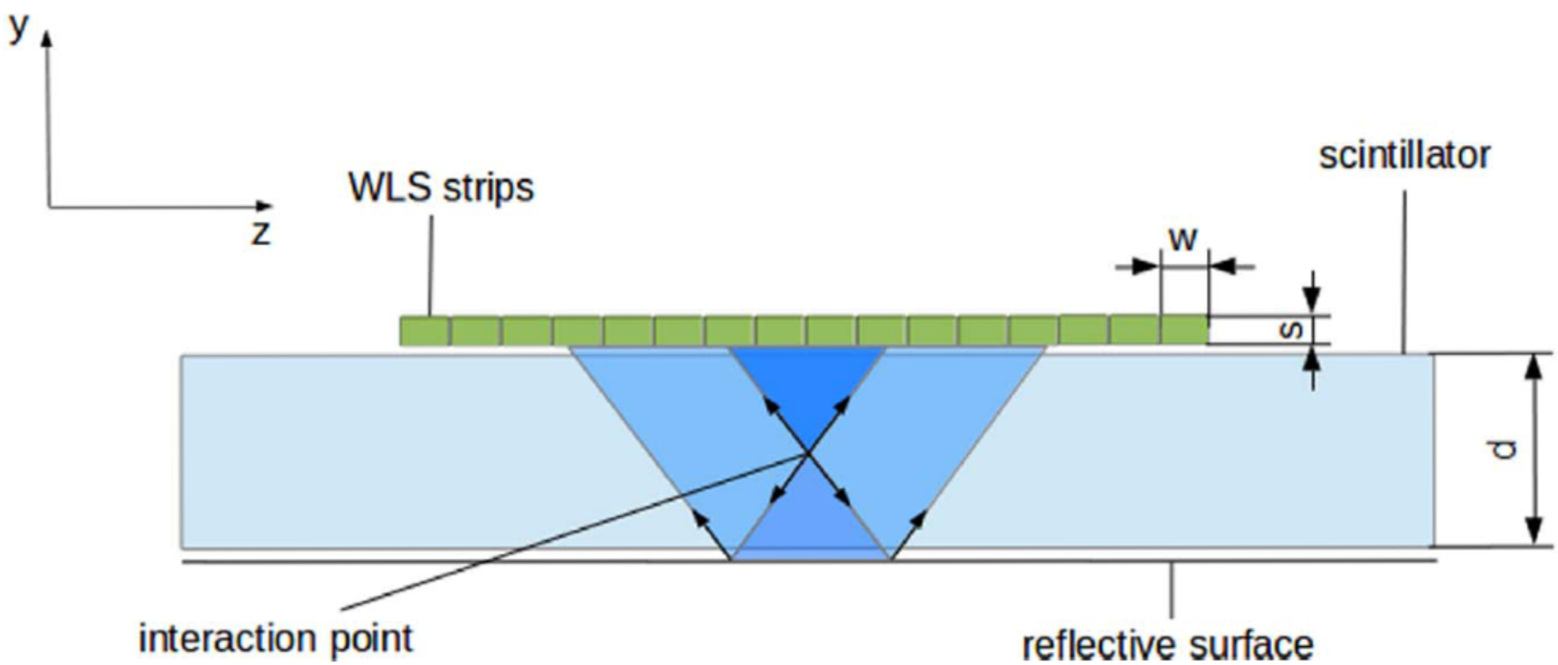


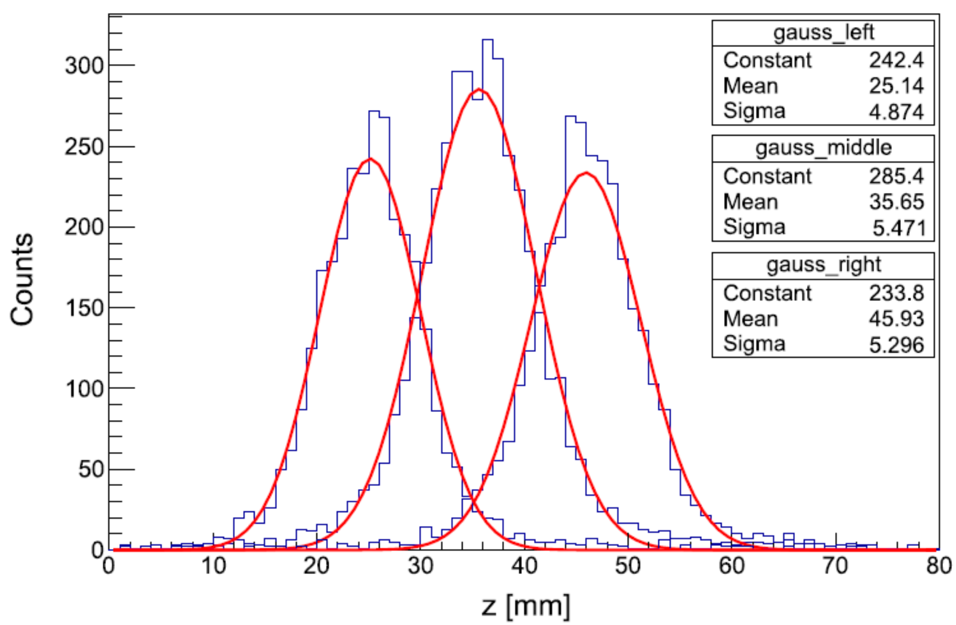
P. Moskal, E. Ł. Stępień,
PET Clinics 15 (2020) 439

Application of WLS

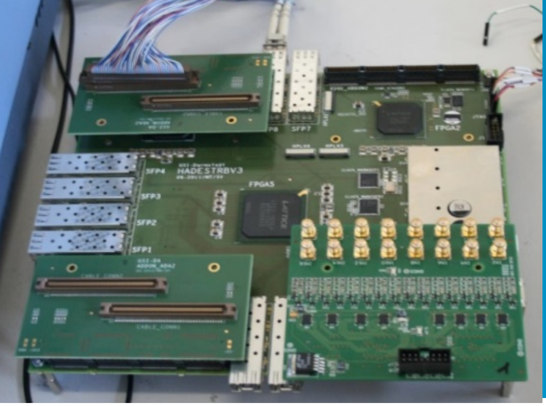
2

2





J. Smyrski et al Nuclear Instruments and Methods in Physics Research A 851 (2017) 39–42



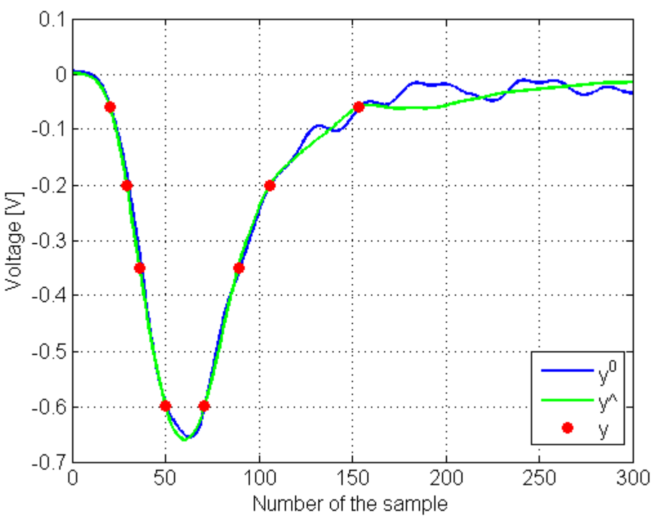
ONLY DIGITAL in triggerless mode

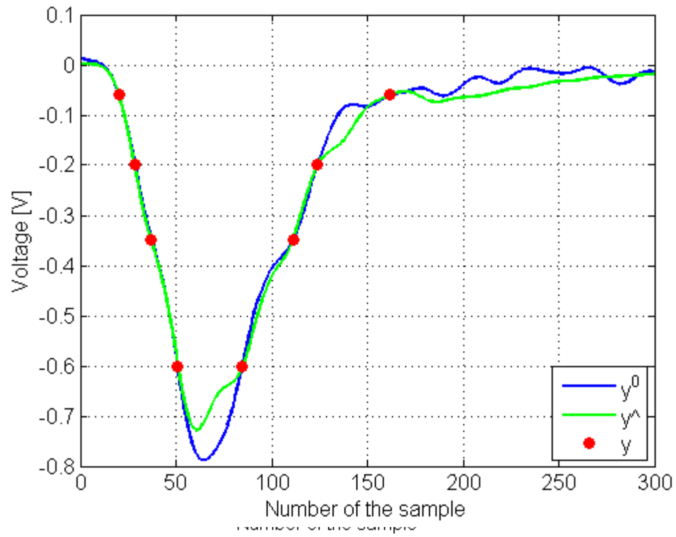
FFE sampling & Readout electronics

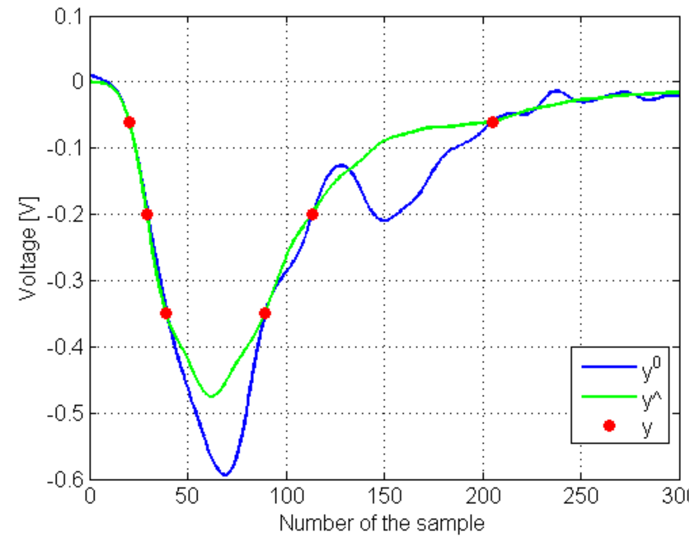
precision of 20ps (sigma) for 10 Euro per sample

M.Pałka, P.M., **PCT/EP2014/068367**

G. Korcyl, P. M., M. Kajetanowicz, M. Pałka, **PCT/EP2014/068352**







Library of signals; Principal Component Analysis; Compressive Sensing;
J-PET: L. Raczyński et al., Nucl. Instr. Meth. A786 (2015) 105
J-PET: P. M. et al., Nucl. Instrum. Meth. A775 (2015) 54

Reconstruction

Detector | **FrontEnd electronics** | **Electronics controller** | **Hit along strip** | **Annihilation point** | **Image**

J-PET: M.Palka et al., JINST 12 (2017) P08001 J-PET: W. Krzemień et al., Acta Phys. Pol. B47 (2016) 561 J-PET: G. Korcyl et al., IEEE TMI 2018 in press J-PET: P. Bialas et al., Bio-Alg. and Med-Sys. 10 (2014) 12

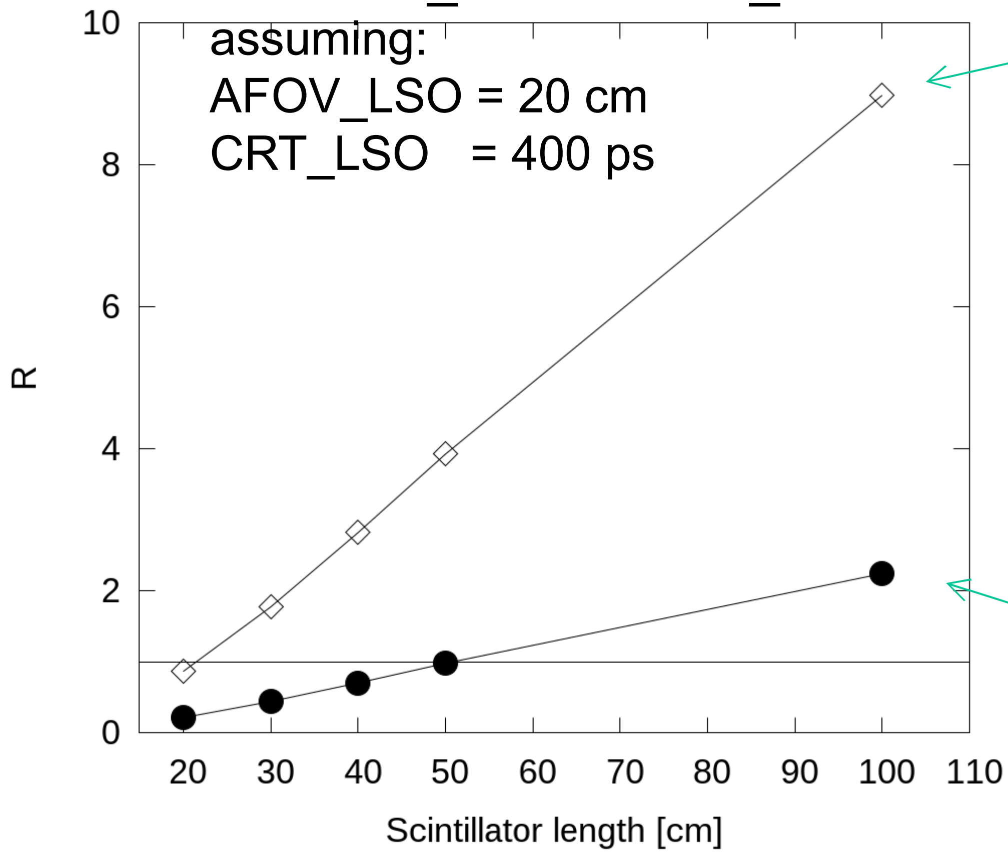
G. Korcyl -> poster session

for the 2.5 cm layer the efficiency for the registration of events selected to reconstruct the image is for the plastic scintillator by

a factor of about 20 smaller in relation to the BGO crystals and about 40 times less compared to the LSO crystals

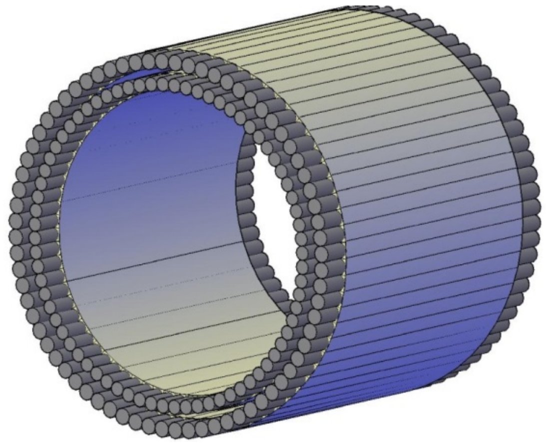
name	type	density [g/cm^3]	decay time [ns]	photons/ MeV	mean free path [cm]
BGO	crystal	7.13	300	6000	1.04
GSO	crystal	6.71	50	10000	1.49
LSO	crystal	7.40	40	29000	1.15
NE102A	polymer	1.032	2.4	10000	10.2
BC404	polymer	1.032	1.8	10000	10.2
RP422	polymer	1.032	1.6	10000	10.2

R = FOM_JPET / FOM_LSO
assuming:
AFOV_LSO = 20 cm
CRT_LSO = 400 ps

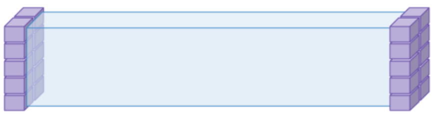


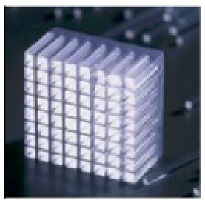
N_JPET_layers = 2

N_JPET_layers = 1



$$R = \frac{FOM\_JPET}{FOM\_LSO}$$





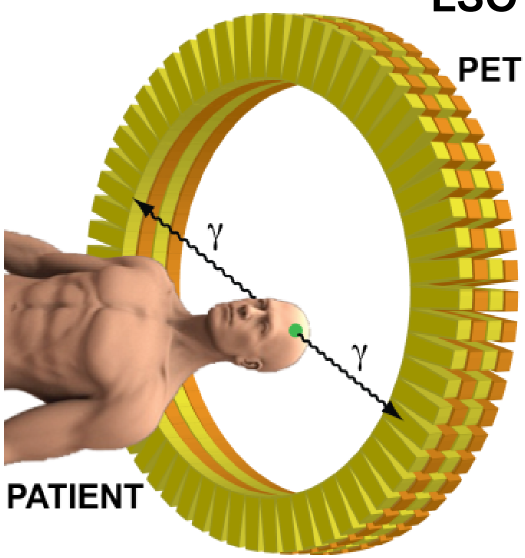
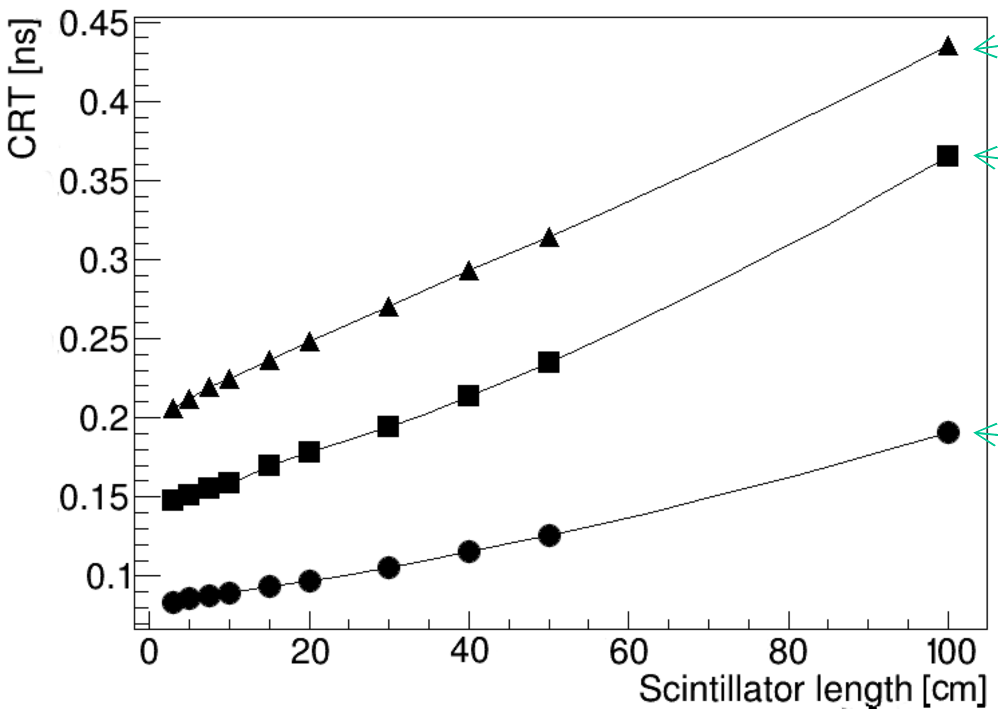
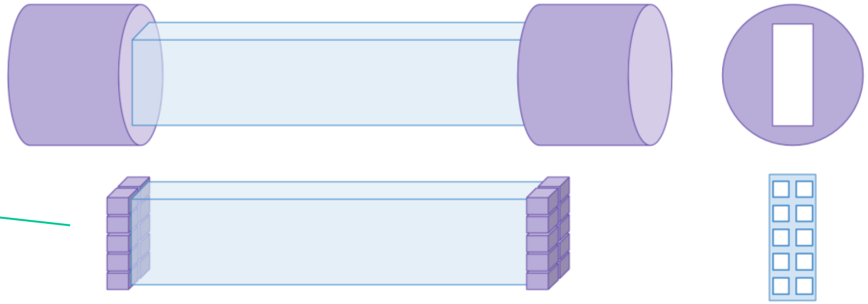


Figure of Merit for whole body imaging (FOM):

$$FOM \cong \frac{(\text{detection effi.})^2 \bullet (\text{selection effi.})^2 \bullet \text{acceptance}}{CRT \bullet \text{Number\_of\_bed\_positions}}$$

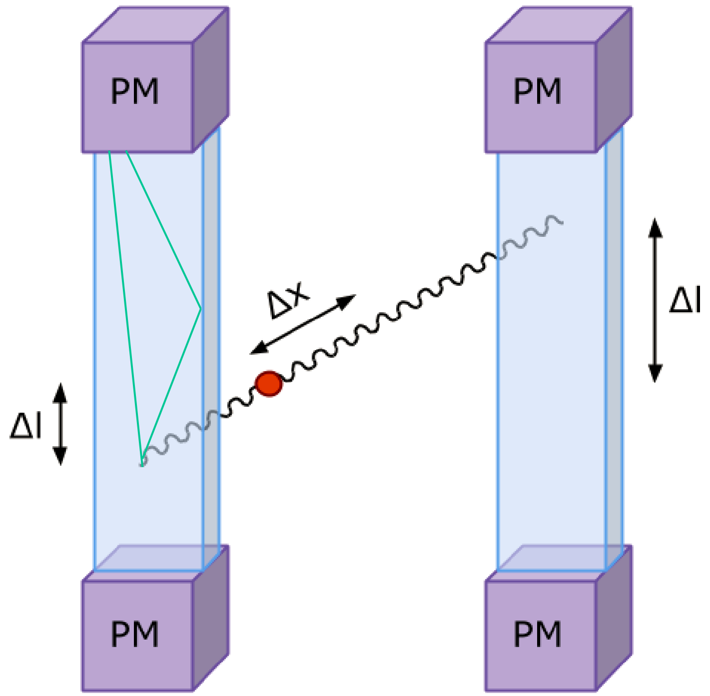
J-PET: P.M. et al., Phys. Med. Biol. 61 (2016) 2025; arXiv:1602.02058

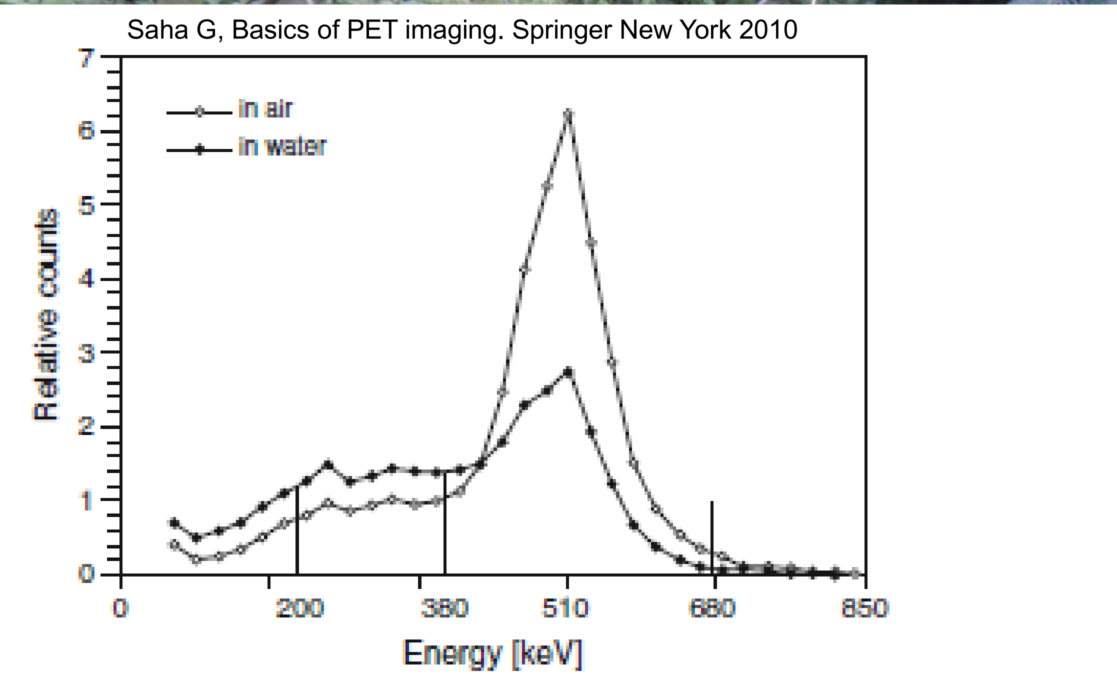


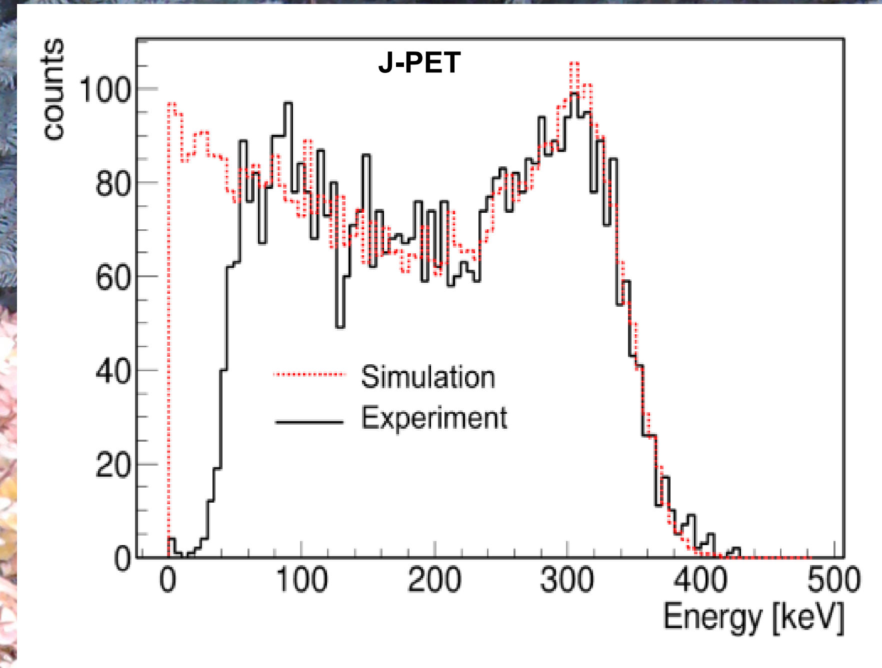


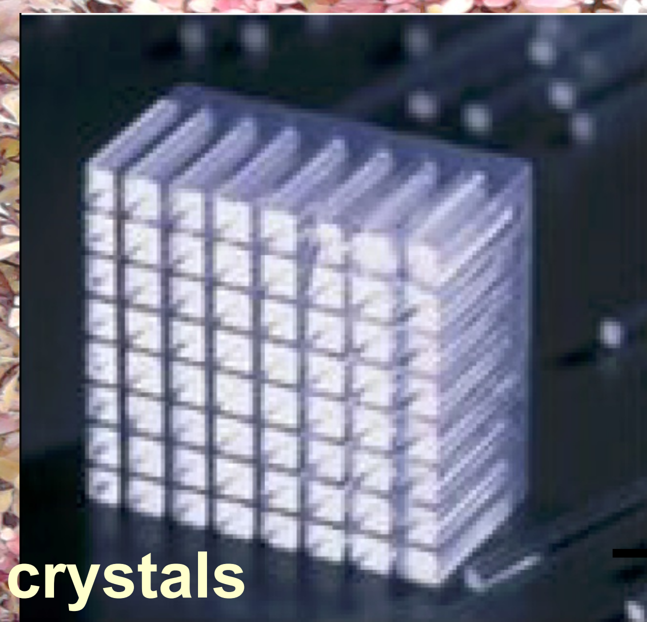
J-PET: P.M. et al., Phys. Med. Biol. 61 (2016) 2025

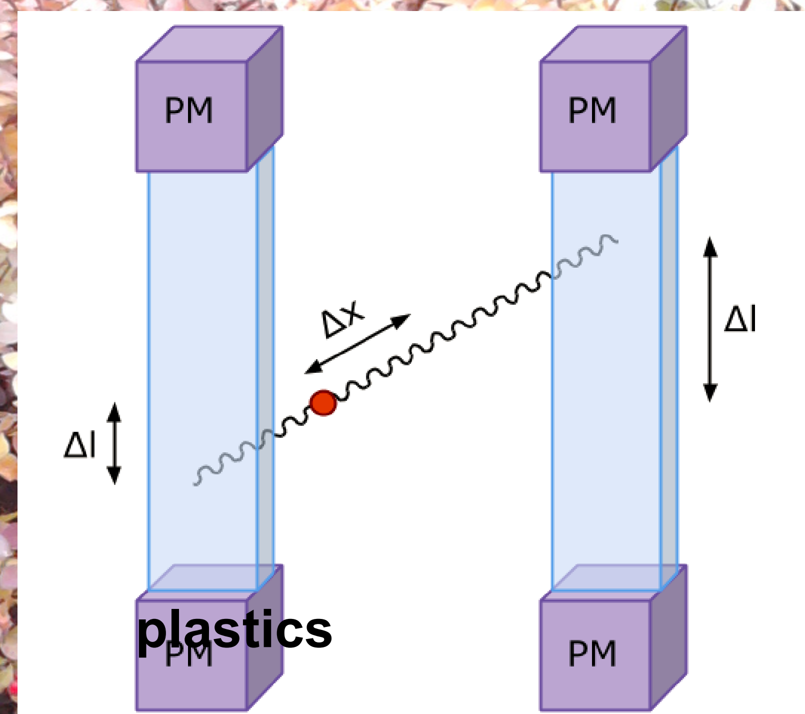
Limit of the J-PET




Saha G, Basics of PET imaging. Springer New York 2010
in air
in water
Relative counts
Energy [keV]
0
200
380
510
680
850
0
1
2
3
4
5
6
7

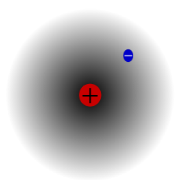

J-PET
counts
Simulation
Experiment
Energy [keV]
0
100
200
300
400
500
0
20
40
60
80
100

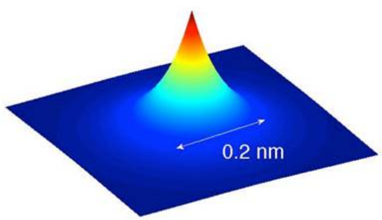

crystals


PM
PM
PM
PM
Δx
Δl
Δl
plastics

Positronium

^1H

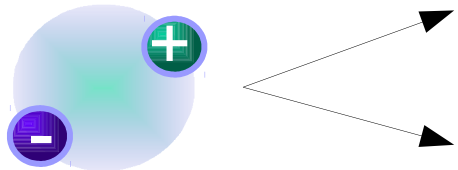




Ann. Rev. Nucl. Part. Sci 30,453 (1980)

Lightest purely leptonic system

Positronium (Ps)



$^1S_0$ Para-positronium
τ (p-Ps) ≈ 125 ps

$^3S_1$ Ortho-positronium
τ (o-Ps) ≈ 142 ns

$S = 0 \quad \downarrow\uparrow - \uparrow\downarrow$

$S = 1 \quad \uparrow\uparrow, \quad \uparrow\downarrow + \downarrow\uparrow, \quad \downarrow\downarrow$

Symmetric under exchange of particles and anti-particles → eigenstate of the charge conjugation operator C

$C\,|Ps\rangle = (-1)^{L+S}\,|Ps\rangle$

$C\,|n\gamma\rangle = (-1)^{n}\,|n\gamma\rangle$

	$^1S_0$	$^3S_1$
C	+	-
P	-	-
CP	-	+

Due to charge conjugation both states of the Ps decays are even or odd in the number of decay photons

<u>Decay modes</u>

p-Ps → 2n γ

o-Ps → (2n+1) γ

$|^1S_0\rangle \rightarrow 2\gamma, 4\gamma, \ldots \qquad |^3S_1\rangle \rightarrow 3\gamma, 5\gamma, \ldots$

Even number of photons

Odd number of photons