Physics Beyond the Standard Model with the J-PET detector

EPS-HEP2021 online conference

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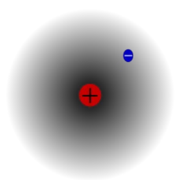
on behalf of the J-PET Collaboration
Jagiellonian University

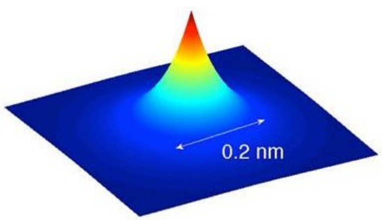
Outline

- Positronium (Ps) system
  - The Ps properties
- The J-PET (Jagiellonian PET) detector setup
  - Tomography scanner for medicine, physics and more
- Studies with J-PET
  - CPT- and CP-symmetry tests
  - Mirror matter

Positronium

^1H

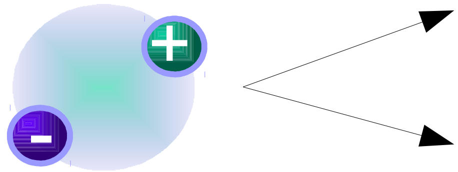




Ann. Rev. Nucl. Part. Sci 30,453 (1980)

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 ↑↑, ↑↓ + ↓↑, ↓↓

Symmetric under exchange of particles and anti-particles → eigenstate of the charge congugation 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 isospin states of the Ps decays are even or odd in the number of decay photons

Decay modes

p-Ps → 2n γ

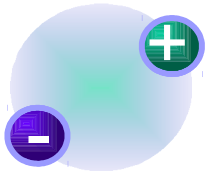
o-Ps → (2n+1) γ

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

Even number of photons Odd number of photons

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

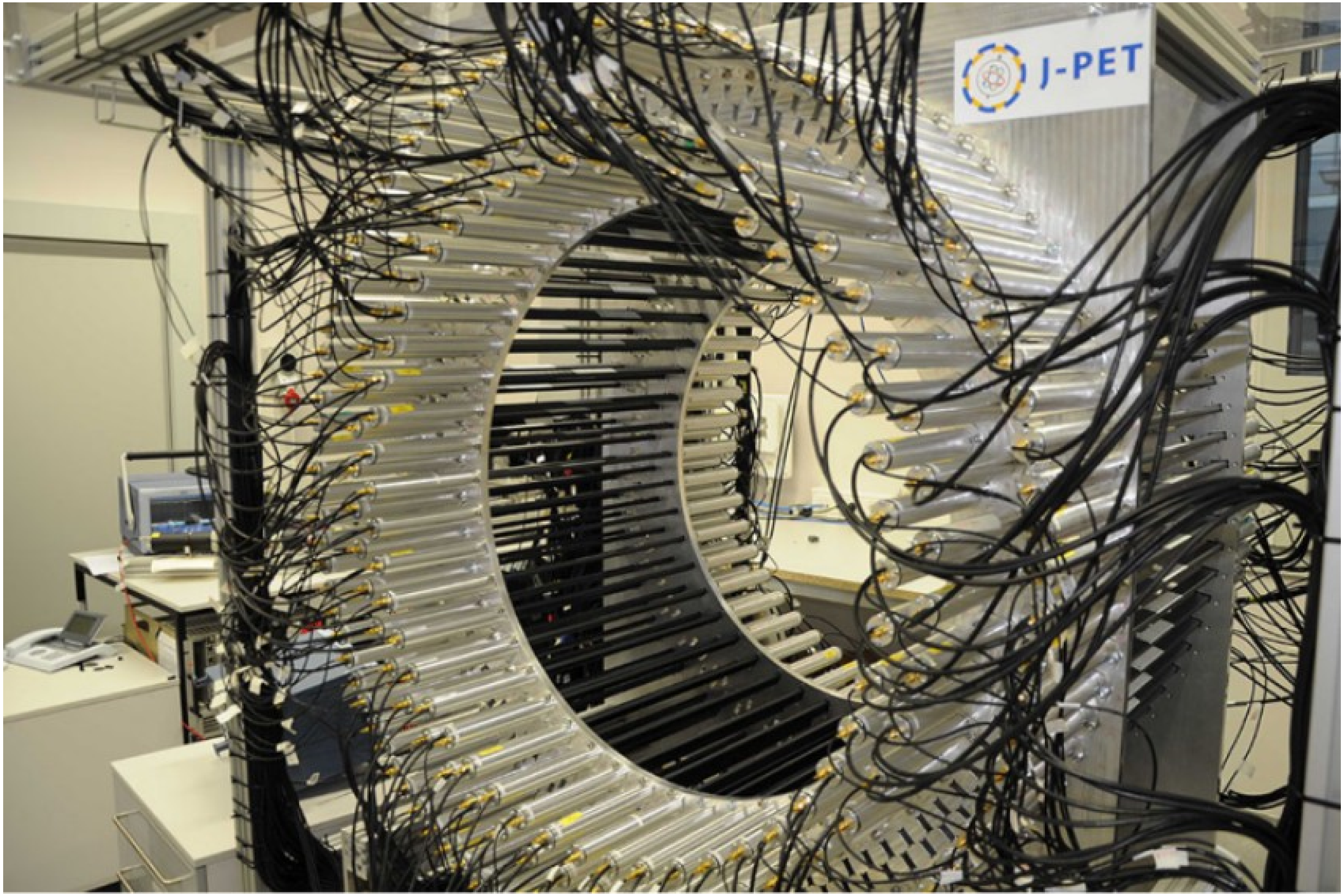
(B. K. Arbic et al., Phys. Rev. A 37, 3189 (1988)) (W. Bernreuther et al., Z. Phys. C 41, 143 (1988))

- 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

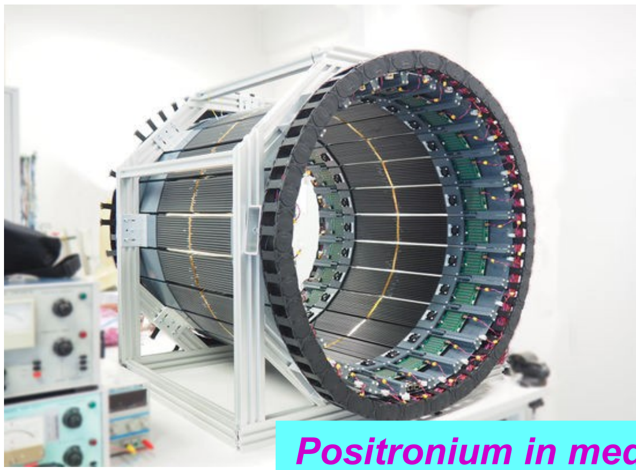
(P.A. Vetter and S.J. Freedman, Phys. Rev. Lett. 91, 263401 (2003))(T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401)

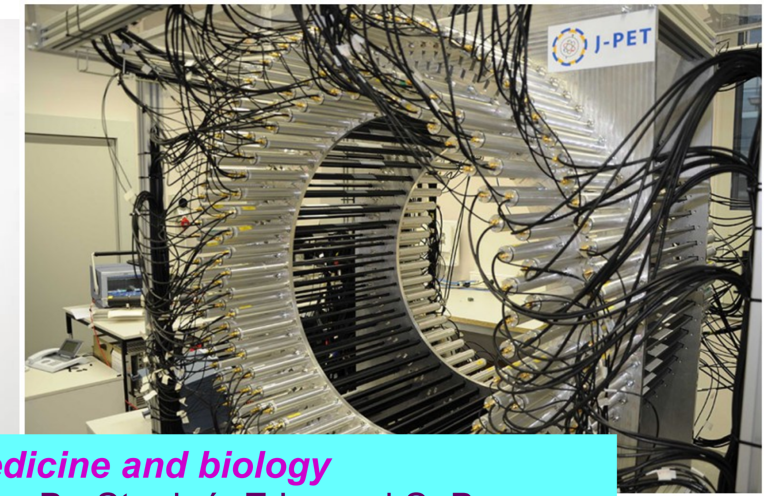
- 10^{-9} vs upper limits of $3*10^{-7}$ for C

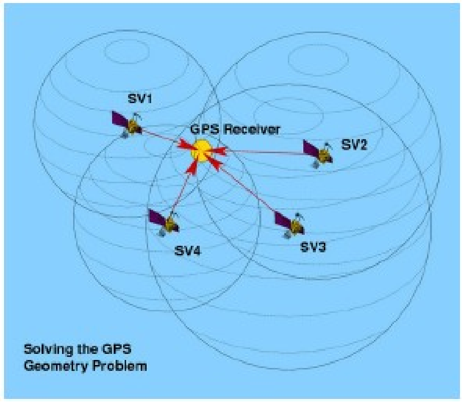
J-PET scanner at the Jagiellonian University



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)

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

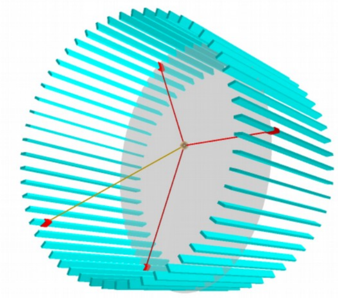
•**Trigger-less** and reconfigurable DAQ system

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

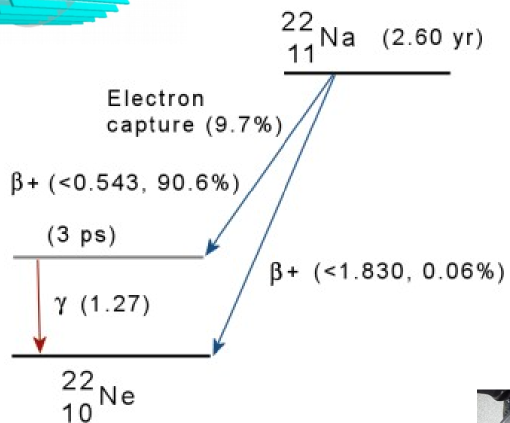
•**GPS trilateration** reconstruction

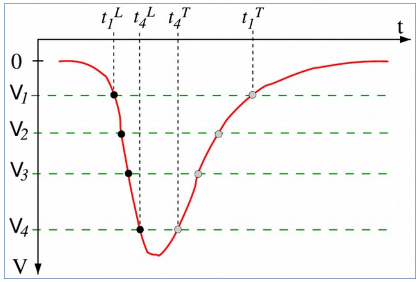
A. Gajos et al. Nucl. Instrum. Methods. A819 (2016) 54

ortho-Ps in J-PET

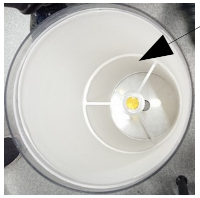


- 10 MBq β+ source **in annihilation chamber**
- Walls coated with porous silica to enhance o-Ps formation
- Extensive and small chamber measurements available
  - New spherical chamber added to the setup
- o-Ps decays are register using total Time-Over-Threshold (TOT) of PMT signals from a scintillator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



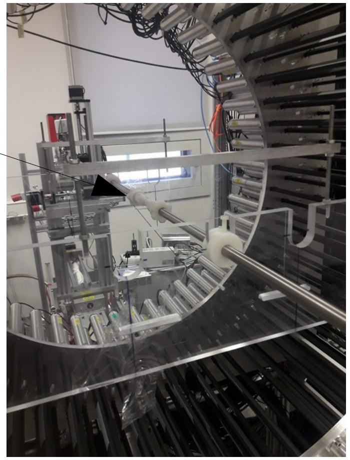


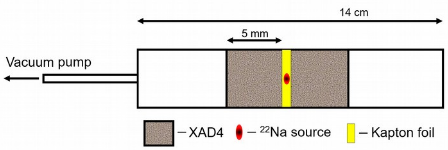
Extensive chamber



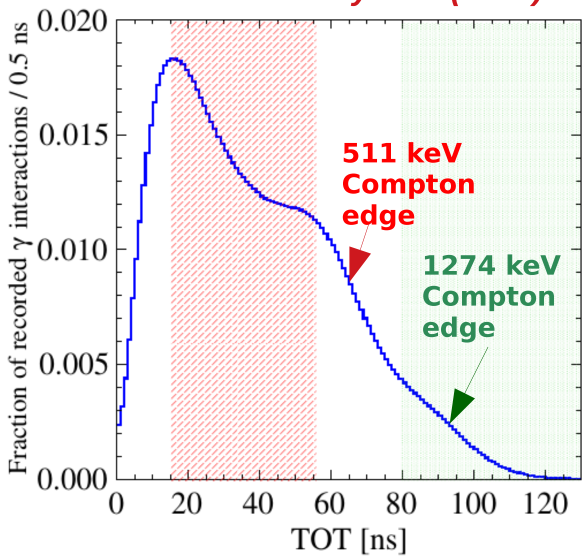
Acta Phys. Pol. B 48, 1567 (2017)

Small annihilation chamber





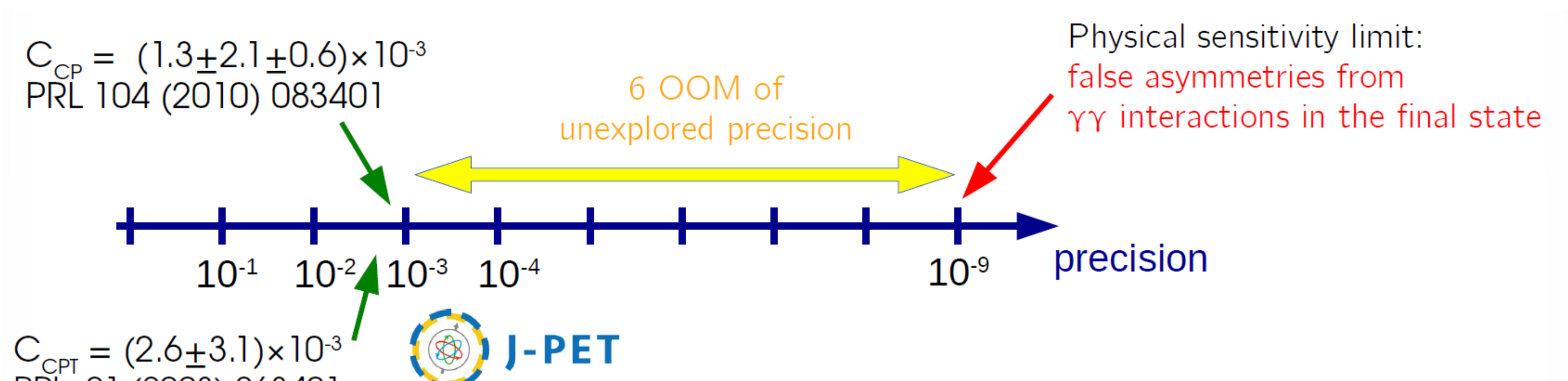
EJNMMI Phy 7 39 (2020)



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 – so far the only system of charged leptons used for test of CP and CPT
- Certain SME-based searches for CPT violation were proposed with **positronium spectroscopy** *[Phys. Rev. D92 (2015) 056002]*

Searches for non-vanishing symmetry -odd correlations:



*courtesy A. Gajos MESON2021

Discrete symmetry tests with o-Ps → 3γ decays

[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 →

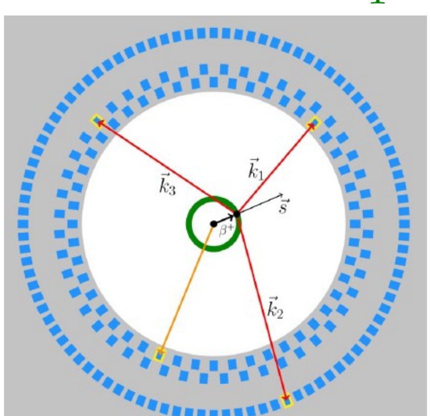
Using photon polarization →

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

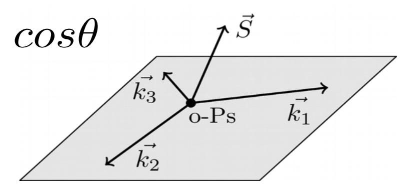
$\vec{S}\cdot\vec{k}_1$ CP-violation sensitive



Effective polarization depends on o-Ps vertex resolution

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

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



Standard asymmetry:

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

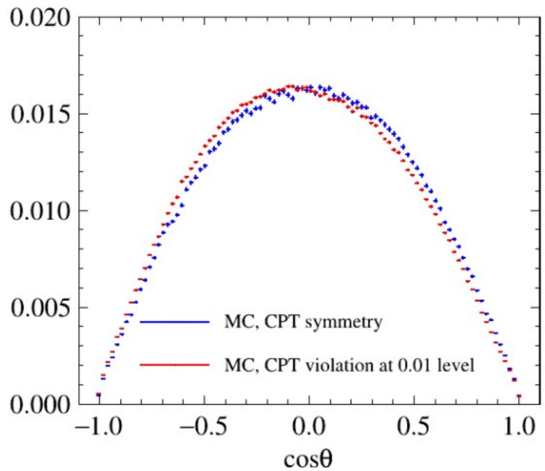
is generalized by the **mean value of cosθ**:

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

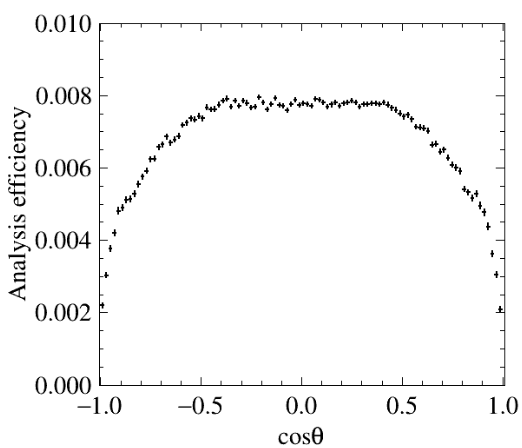
J-PET is sensitive to the full range of this operator

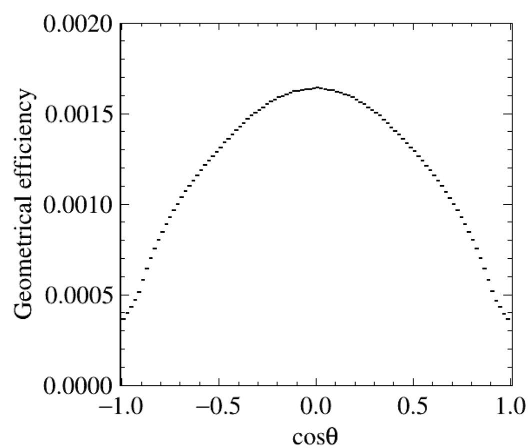
Evaluation CPT-asymmetric observable

Expected effect with CPT-asymmetric simulations



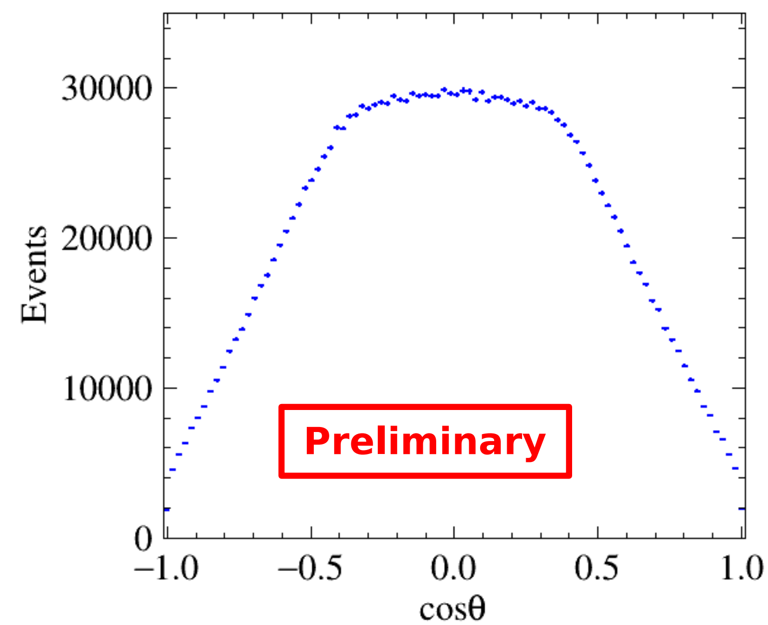
Evaluated efficiencies using MC are symmetric in cosθ





Result using 2 x 10^6 of identified o-Ps → 3γ

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

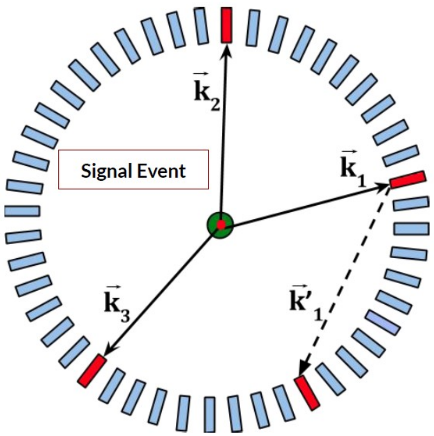


<cosθ> statistical uncertainty: 3.3×10^{-4}
systematic uncertainty 1.4×10^{-4}

Analyzing power S = 37.4 %
(polarization-dominated)

Precision test in CP- and T-symmetry in the leptonic sector

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

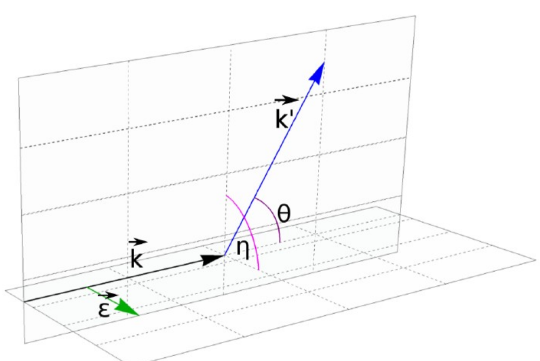


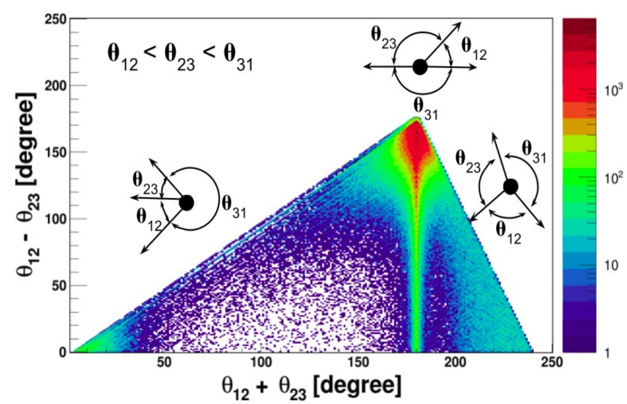
$|\vec{k}_1| > |\vec{k}_2| > |\vec{k}_3|$

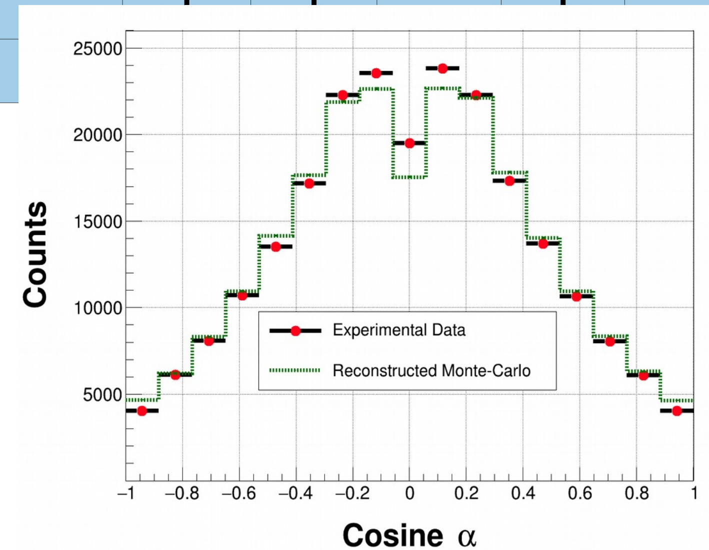
Using photon polarization

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

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)]







Expectation Value = 0.0003 +/- 0.0003
PRELIMINARY

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

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

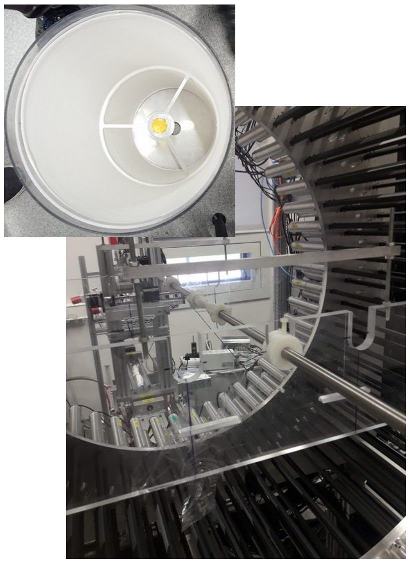
Phys. Lett. B 671 (2009), p. 219

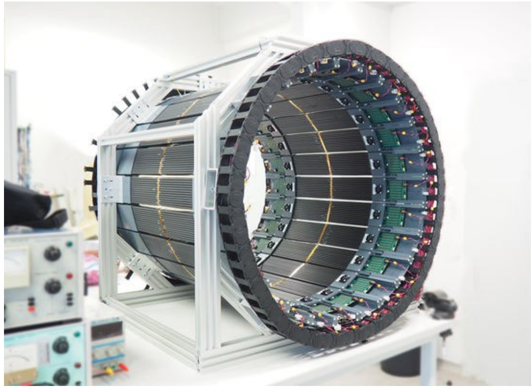
$$\Gamma = 7.0404 \pm 0.0010 \pm 0.0008 \times 10^6\,\mathrm{s}^{-1}$$ Ann Arbor group

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

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

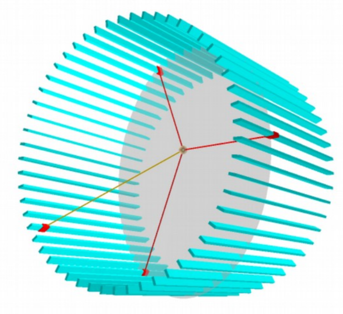
ortho-Ps in J-PET

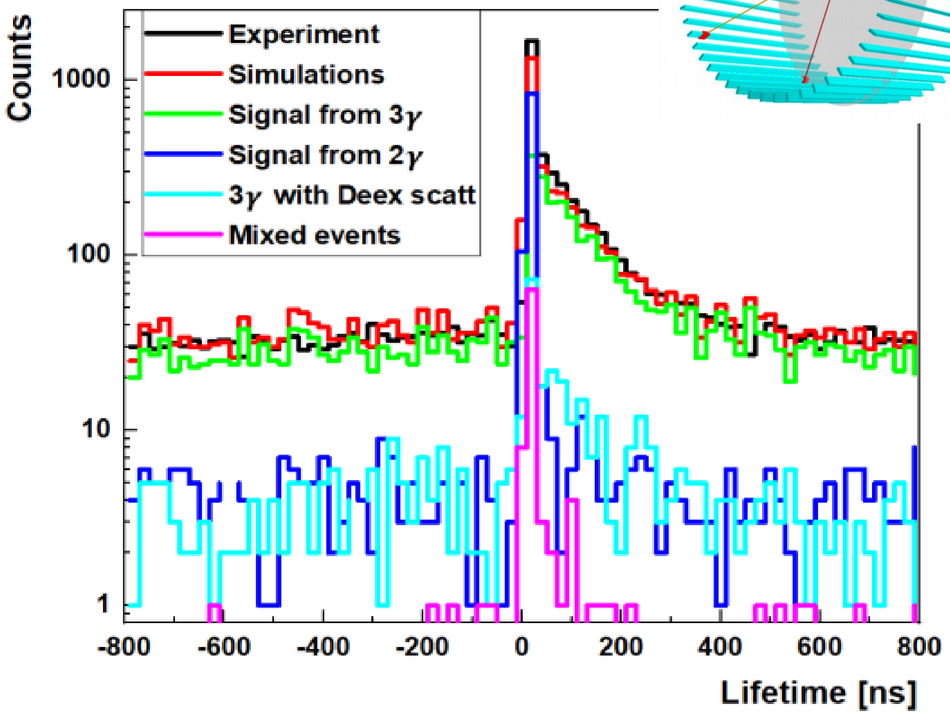




Precise measurement of the o-Ps lifetime looking for hints of new physics

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})

Main competitor ETH Zurich

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

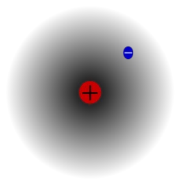
[arXiv:2006.07467 [physics.ins-det]]

Conclusions

- The J-PET tomography scanner of the Jagiellonian University is a multipurpose detector with applications in fundamental physics, medicine, biology …
- It is the first plastic-based scintillator PET tomography scanner
  - High timing resolution with large acceptance
  - Cost-effective solution for whole-body PET imaging
- 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 $\rightarrow$ 3γ annihilation events
  - Full event reconstruction including the annihilation point
  - Estimation of o-Ps spin on an event-by-event basis
  - Precise determination of the o-Ps lifetime using the de-excitation photons emitted by the source
- Sub-permil precision of the CPT test reached with the first J-PET measurement
- J-Pet aims at an improved sensitivity for the CP and CPT symmetry tests at the level of 10^{-5} with setup improvements
- 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
  - Sensitivity after two years of experiment below 10^{-5}

Backup Slides

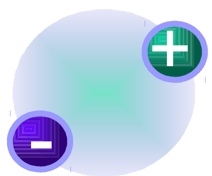
^1H

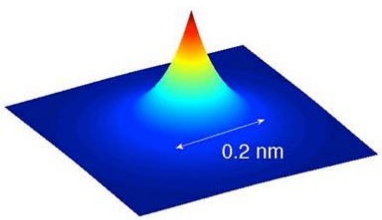


Ann. Rev. Nucl. Part. Sci 30,453 (1980)

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**

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

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

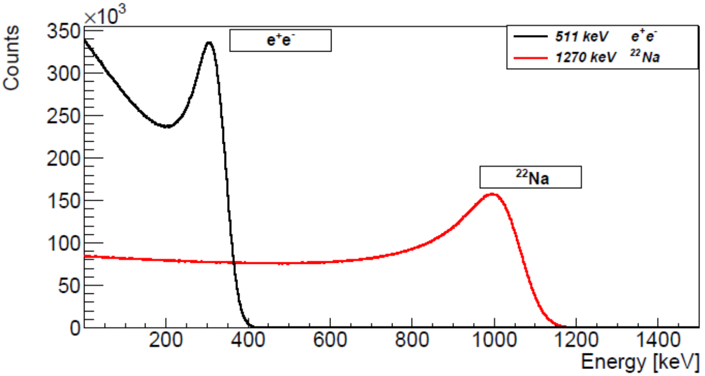
	$^1S_0$	$^3S_1$
C	+	-
P	-	-
CP	-	+

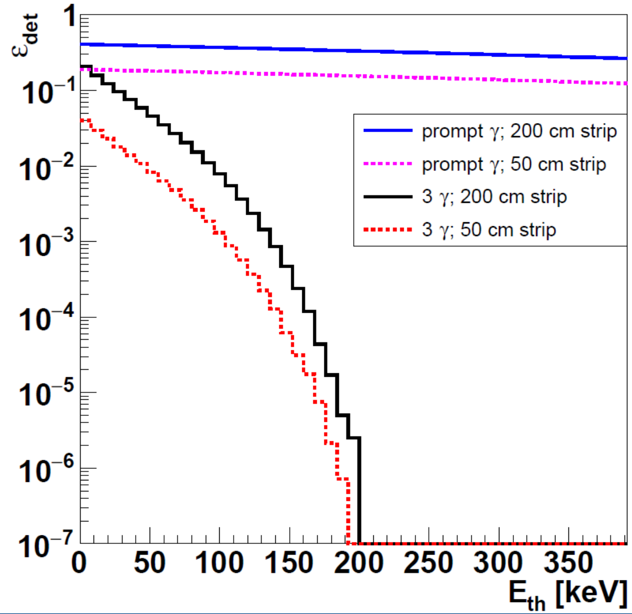
<u>Decay modes</u>

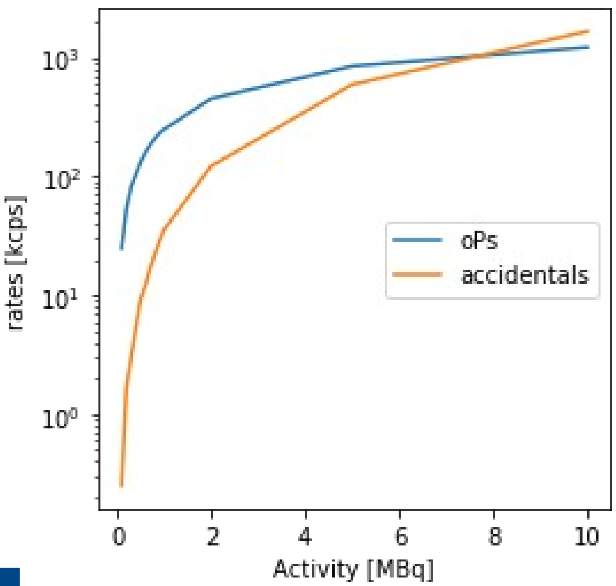
$^1S_0$ Para-positronium	**p-Ps → 2n γ**	**τ (p-Ps) ≈ 125 ps**
$^3S_1$ Ortho-positronium	**o-Ps → (2n+1) γ**	**τ (o-Ps) ≈ 142 ns**

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: $\sigma_E/E = 0.044/\sqrt{E(MeV)}$
- 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







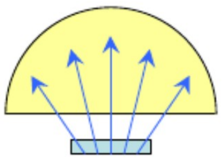
P. Moskal, D. Kisielewska et al. Phys. Med. Biol. 64 (2019) 055017

J-PET vs previous measurements

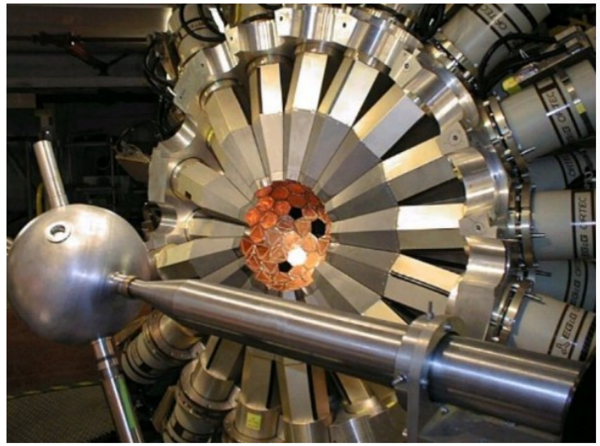
Gammasphere $C_{CPT} = (2.6\pm3.1)\times10^{-3}$

PRL. 91 (2003) 263401

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



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



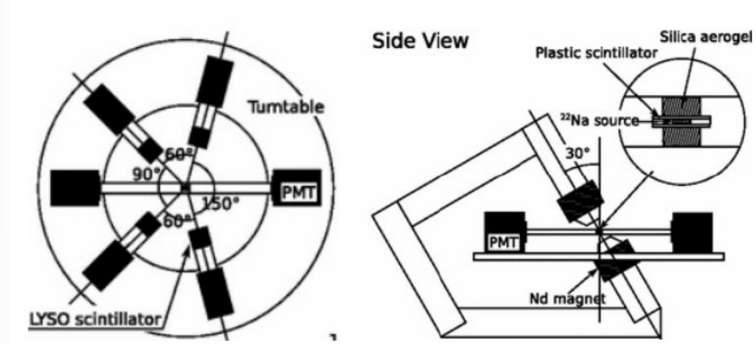
Limiting positron emission direction
1 Mbq β^+ emitter activity
4π detector but low angular resolution

Yamazaki et al.

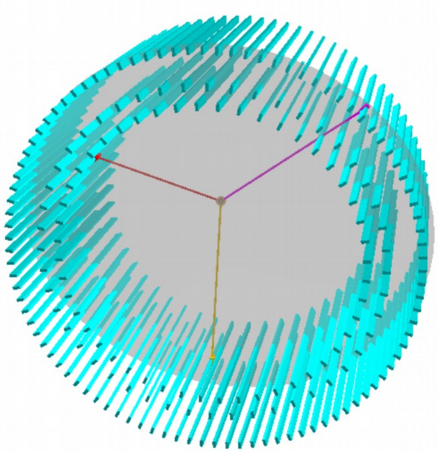
PRL 104 (2010) 083401

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

$C_{CP} = (1.3\pm2.1\pm0.6)\times10^{-3}$



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



J-PET

Recording multiple geometrical configurations

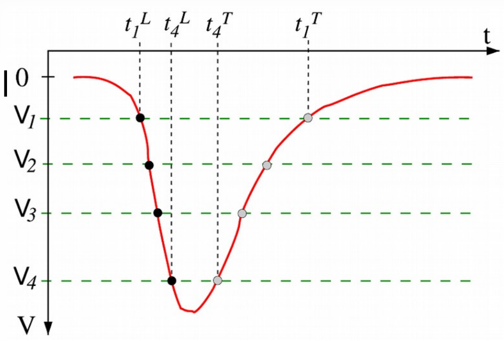
e+ spin estimated event-by-event

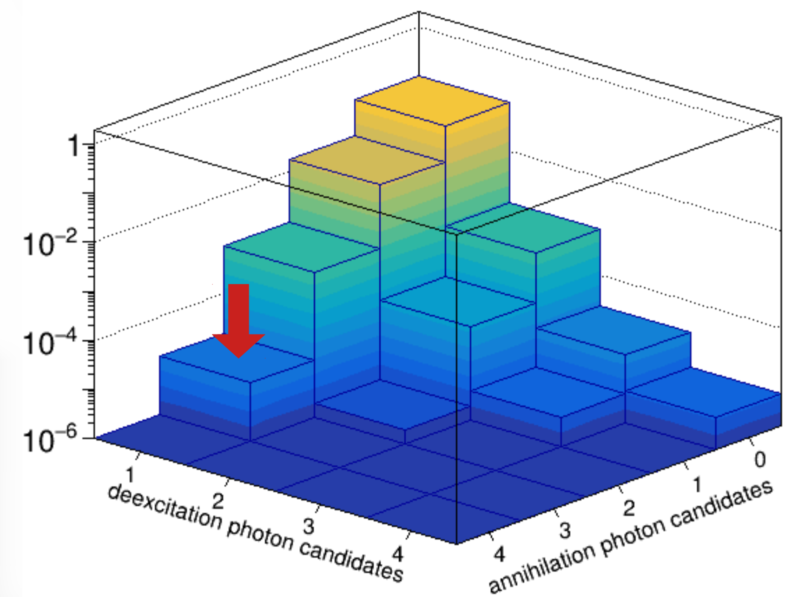
$$P_{e+} \approx \frac{v}{c}\cdot 0.91$$

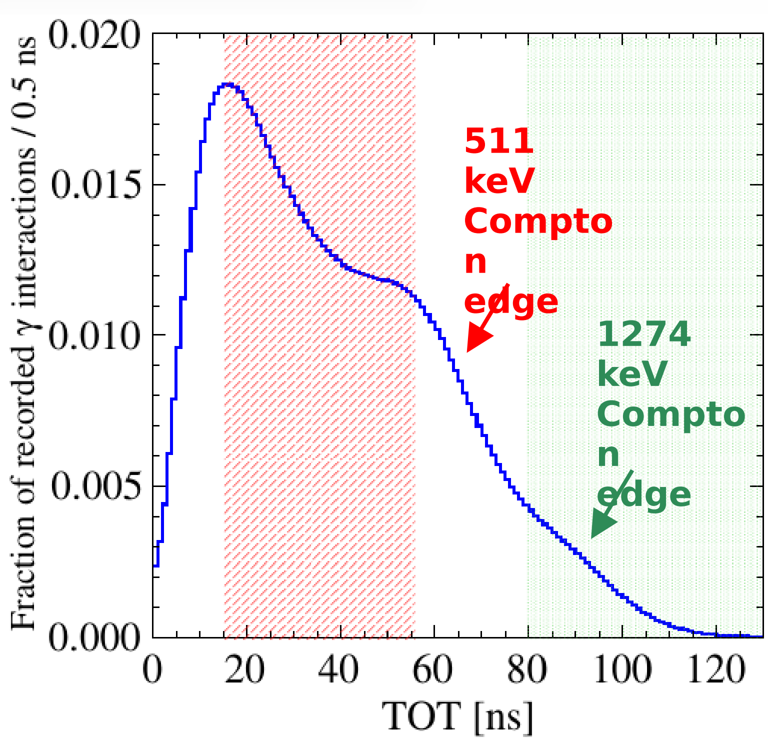
- Plastic scintillators = fast timing → using high β^+ emitter activity (tested up to 10 Mbq)
- Recording all 3 annihilation photons
- Angular resolution at 1° level

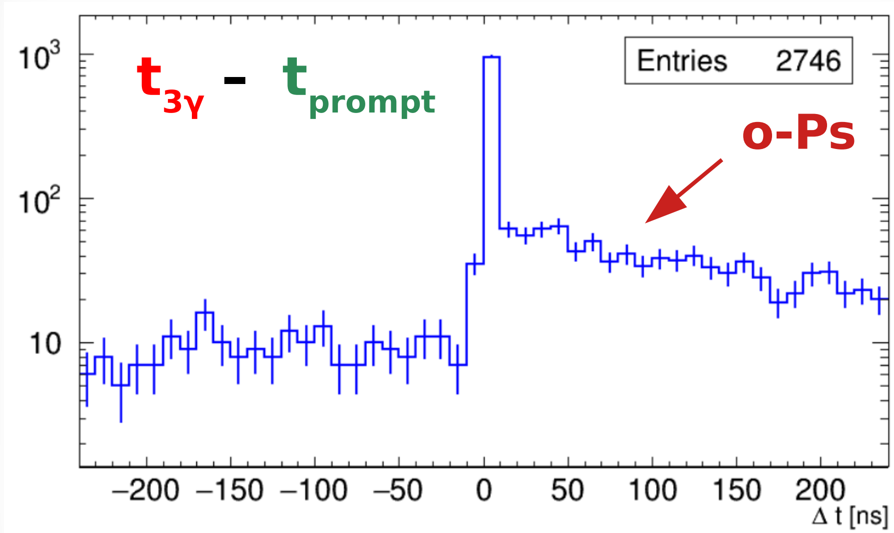
Identification of o-Ps → 3γ events in J-PET

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









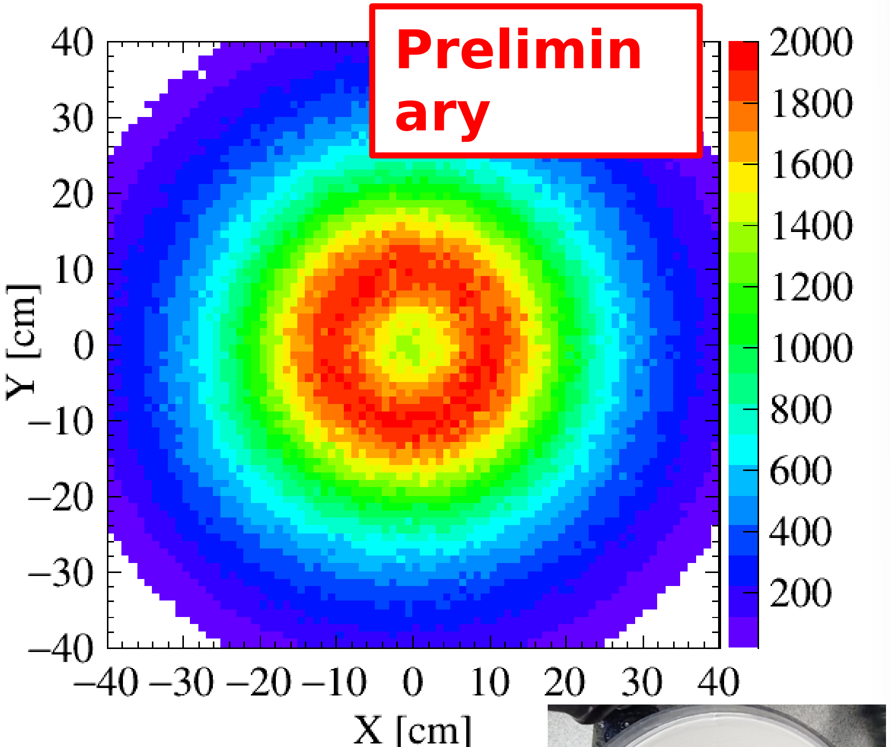
o-Ps →3γ annihilation (E<511 keV)

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

Results of the CPT test

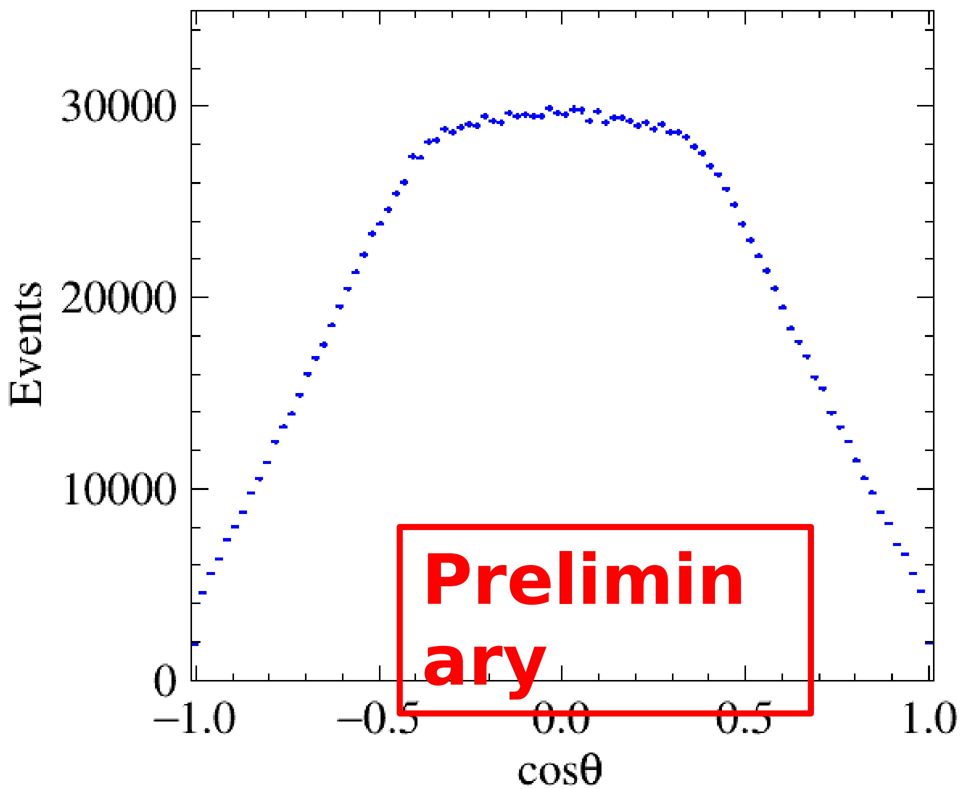
Using 2 x 10^6 of identified
o-Ps → 3ɣ annihilations

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 x 10^{-4}**

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

Analyzing power S = 37.4 %
(polarization-dominated)

oPs in JPET tomograph

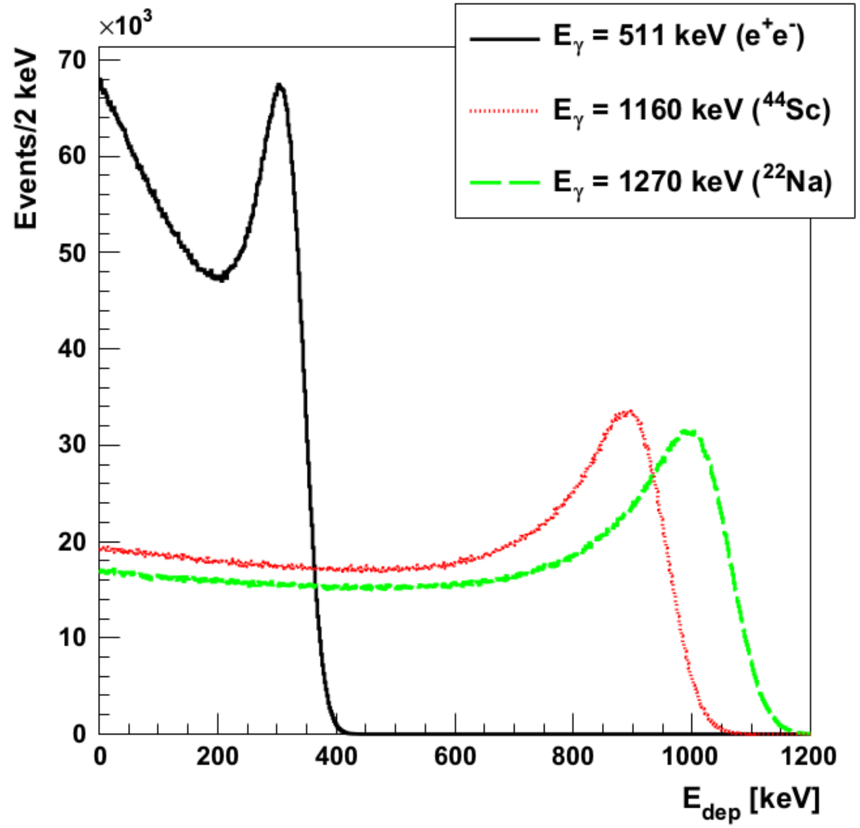
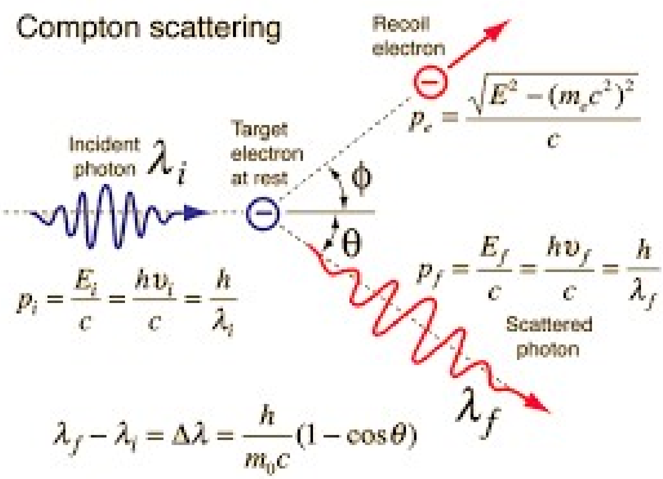
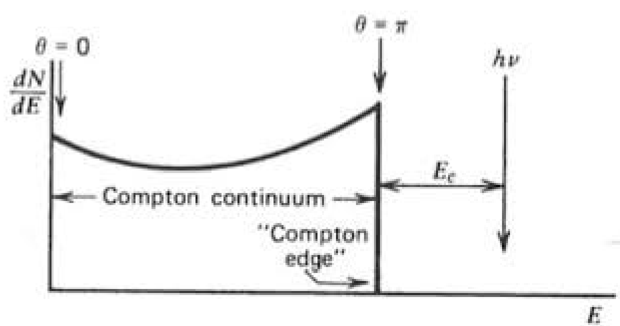


Fig. 3 Simulated spectra of deposited energy in plastic scintillators for gamma quanta from $e^+e^- \rightarrow 2\gamma$ annihilation and for de-excitation gamma quanta originating from isotopes indicated in the legend. The spectra were simulated including the energy resolution of the J-PET detector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

Gamma quanta interact in detector via Compton scattering





GPS trilateration

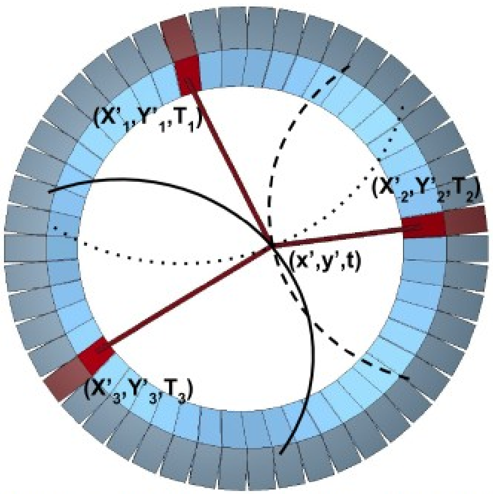
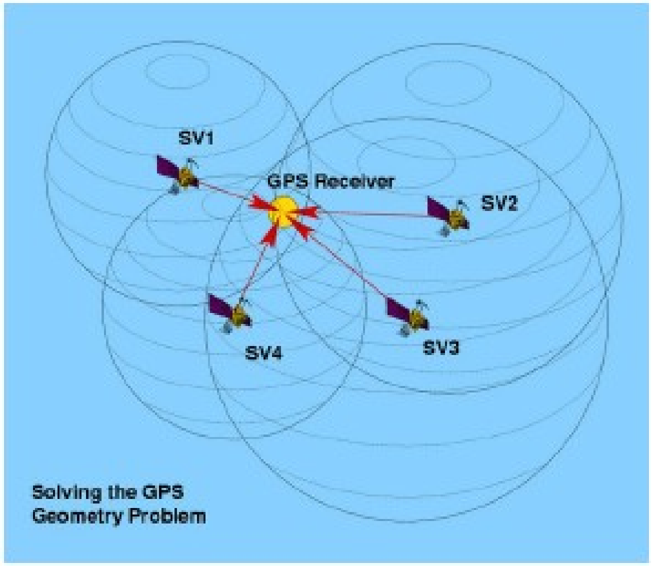


Figure 5: A scheme of the detector showing o-Ps $\rightarrow 3\gamma$ annihilation. For clarity only a single layer with registered hits is shown. Red lines represent the gamma photons from ortho-positronium annihilation. The trilateration method is used to determine the annihilation position and time (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.



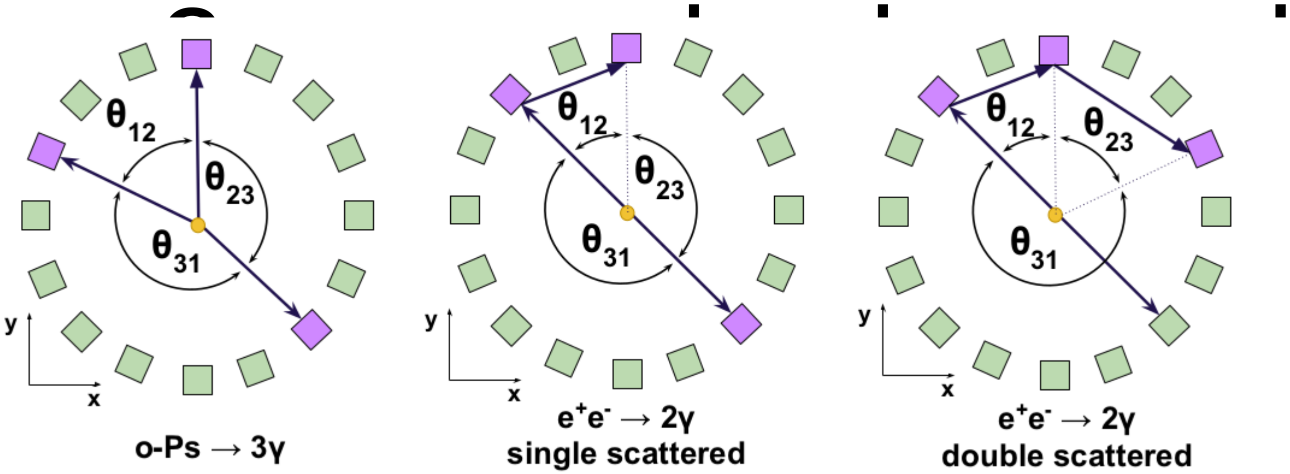
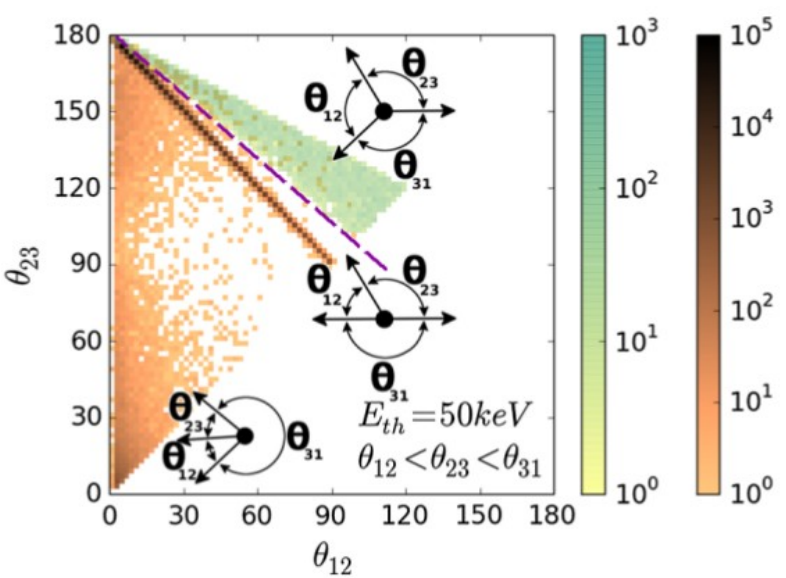
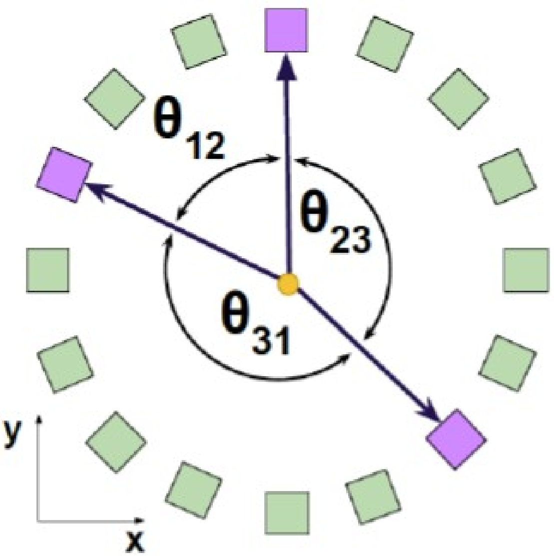


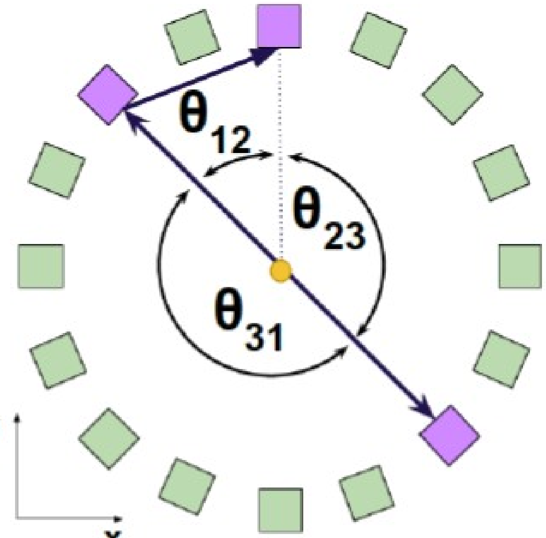
Fig. 13 Pictorial illustration of the possible response of the detector to o-Ps $\rightarrow 3\gamma$ and e^+e^- annihilation into 2γ. Arranged circularly *squares* represents scintillator strips—*purple* and *green* colors indicate strips where the gamma quanta were or were not registered, respectively. 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



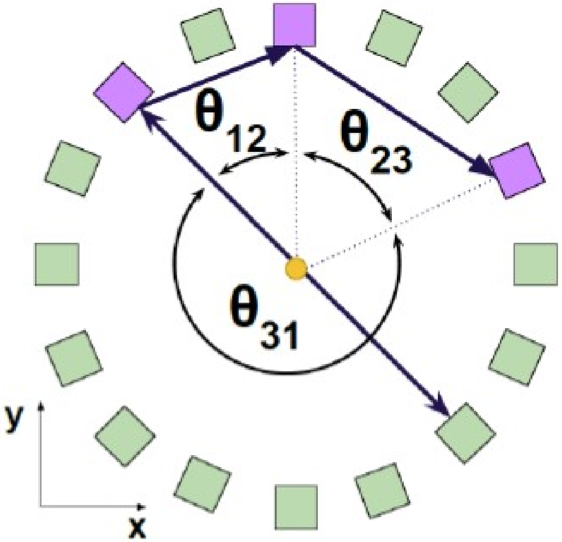
Eur. Phys. J. C (2016) 76 :445



o-Ps → 3γ

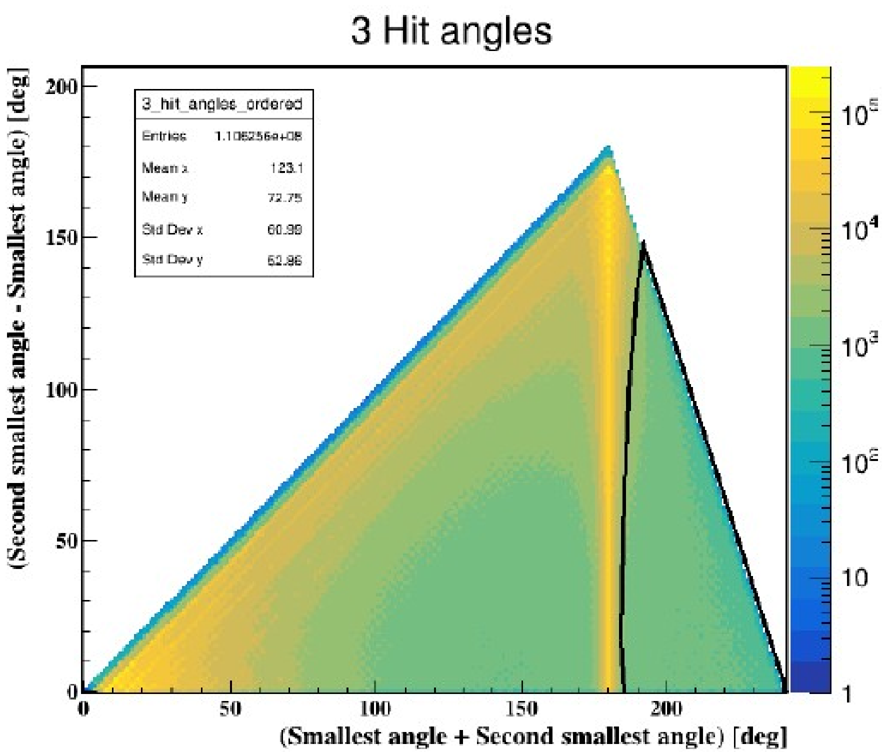


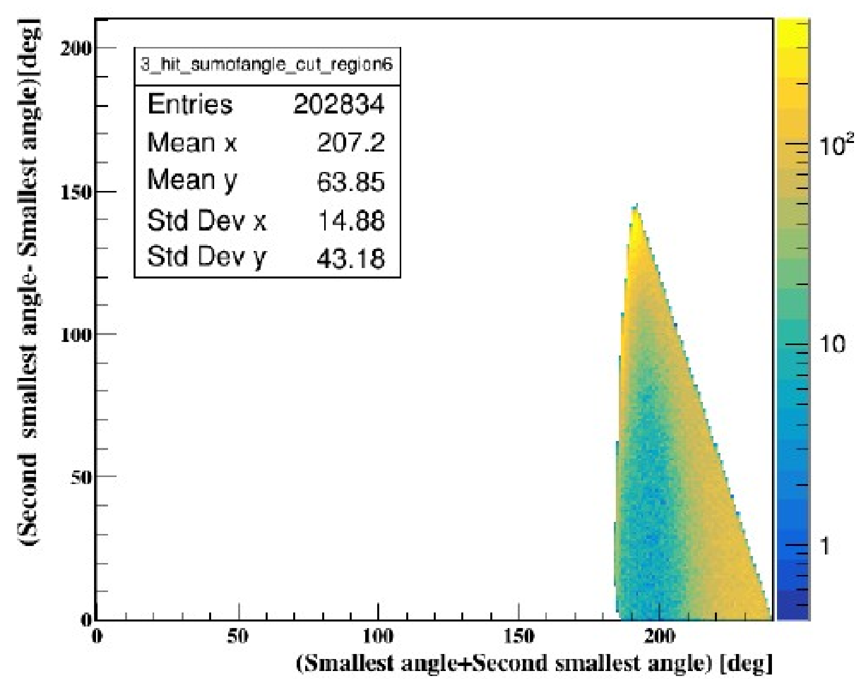
$e^+e^- \rightarrow 2\gamma$
single scattered



$e^+e^- \rightarrow 2\gamma$
double scattered

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

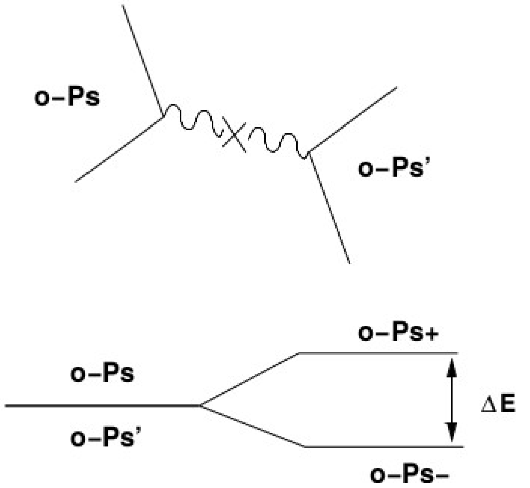




Mirror Matter in o-Ps

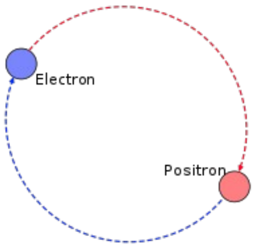
•o-Ps can be connected via one-photon annihilation to its mirror version (o-Ps’) and can be confirmed in experiments

- o-Ps oscillates into its mirror partner o-Ps’
- Only mimicked by very-rare decay from Standard Model $Br(oPs \to \nu\bar{\nu}) < O(10^{-18})$
- **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



Systematic Uncertainties

- **Accidental events**: events in coincidence but not correlated
  - Can be controlled with source activity
  - Evaluation performed in 2020 article

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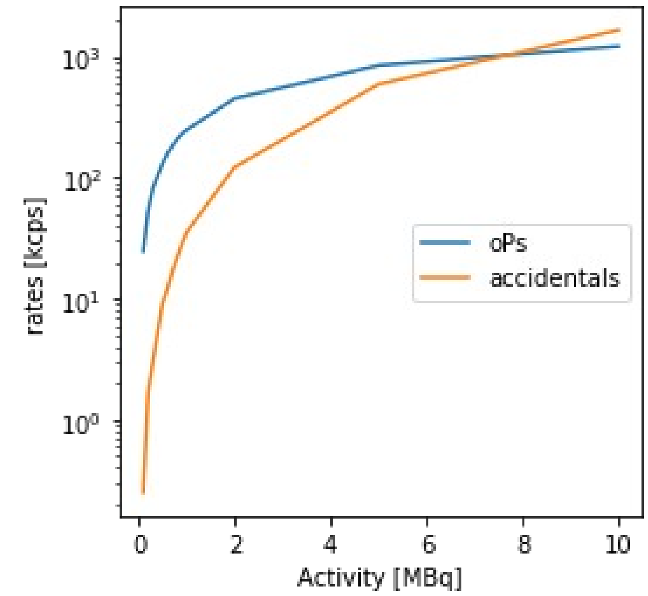
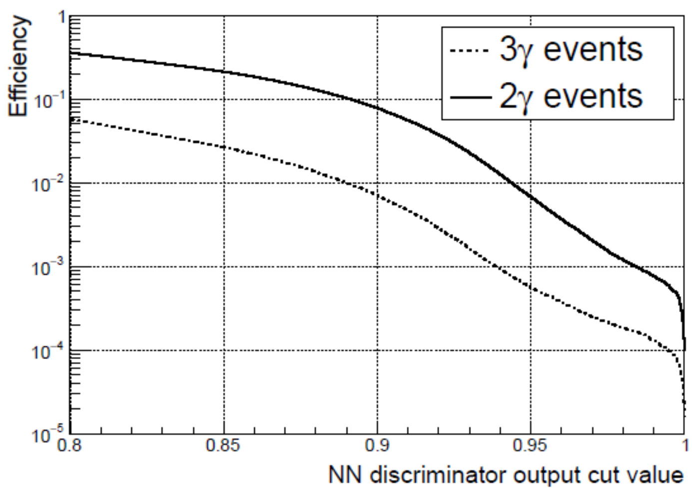
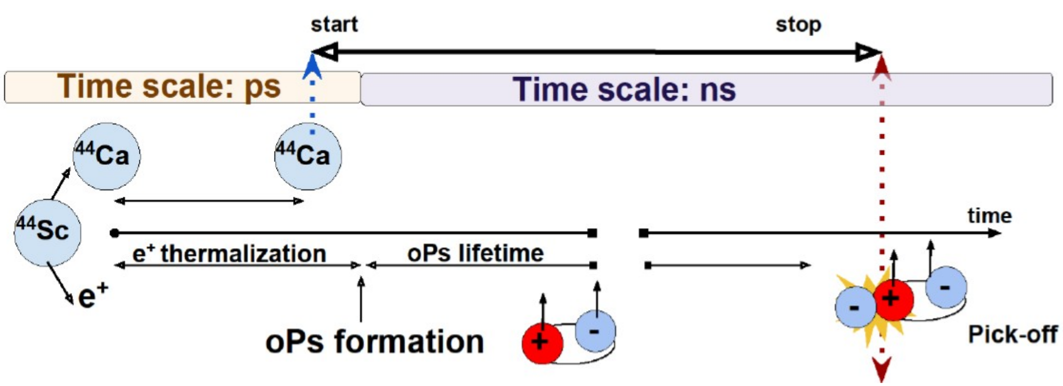




C. Vigo et al. (2019) [805.06384v]

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

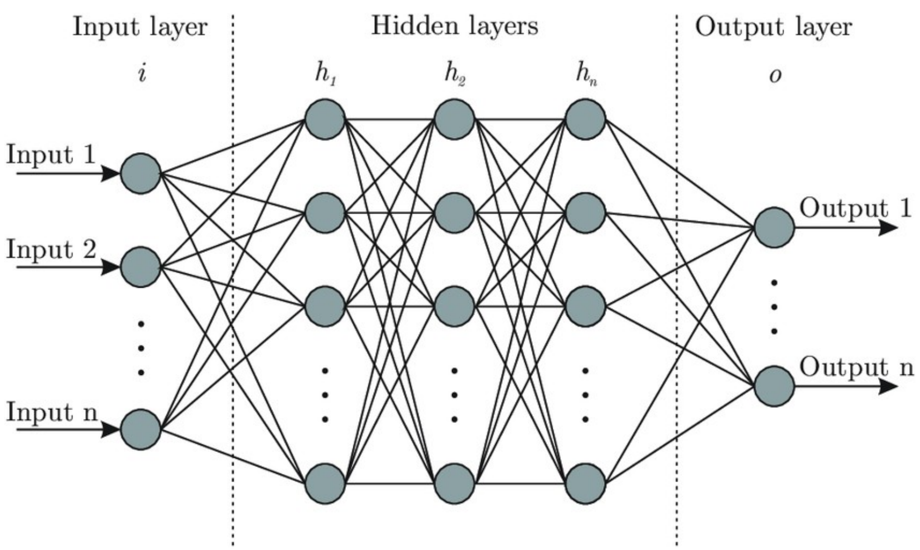
- **oPs interacting with the material**:
  - Can be directly evaluated from data
  - Can be used to train Machine Learning algorithms to reject the events (below 12 ppm level)



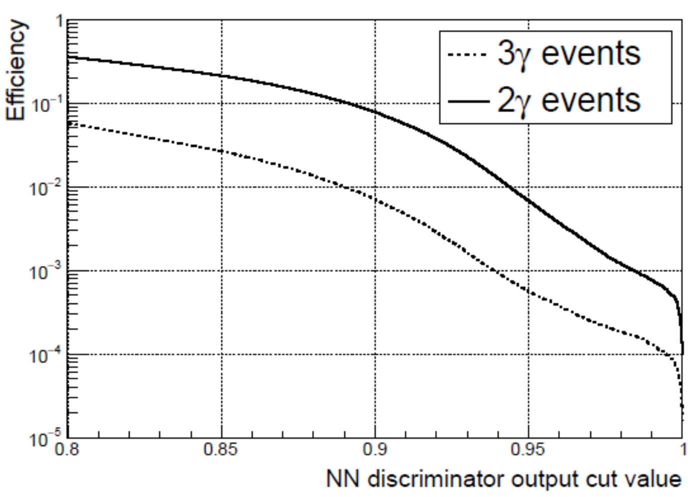
Machine Learning for background reduction

Byron P. Roe et al. Nucl.Instrum.Meth. A 543 (2005), 577–584.

Machine learning techniques, like Boosted Decision Trees and Artificial Neural Networks for background reduction



Development of **Neural Network** algorithms to profit of the the excellent timing and reconstruction capabilities of the JPET detector → can be adapted in future to ***medical imaging***.



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

Journal of Physics: Conference Series, Vol. 1138, conference 1