Test of discrete symmetries with spin observables at J-PET

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On behalf of the J-PET collaboration

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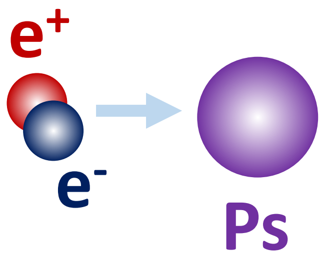
Outline

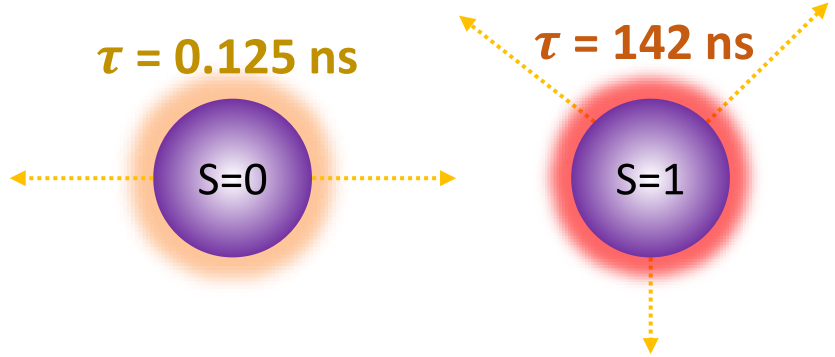
- Positronium and discrete symmetries
- J-PET detector and the experimental details
- Analysis procedure
- Treatment of the background events
- Results of three-photon imaging and the CPT test
- Future development and conclusions

Positronium

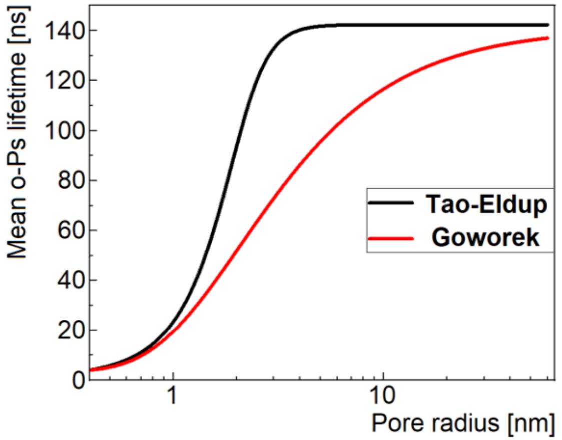
Positronium (Ps) –
the lightest purely leptonic bound state



Depending on the total spin (S) Ps can be in one of two states – **para** and **ortho**



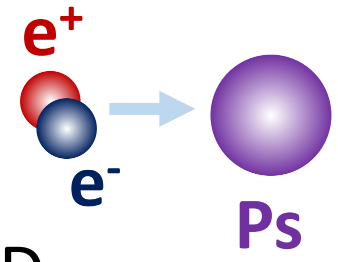
Mean ortho-positronium lifetime is a valid indicator of the volume of the defects (pores) in the matter



Motivation

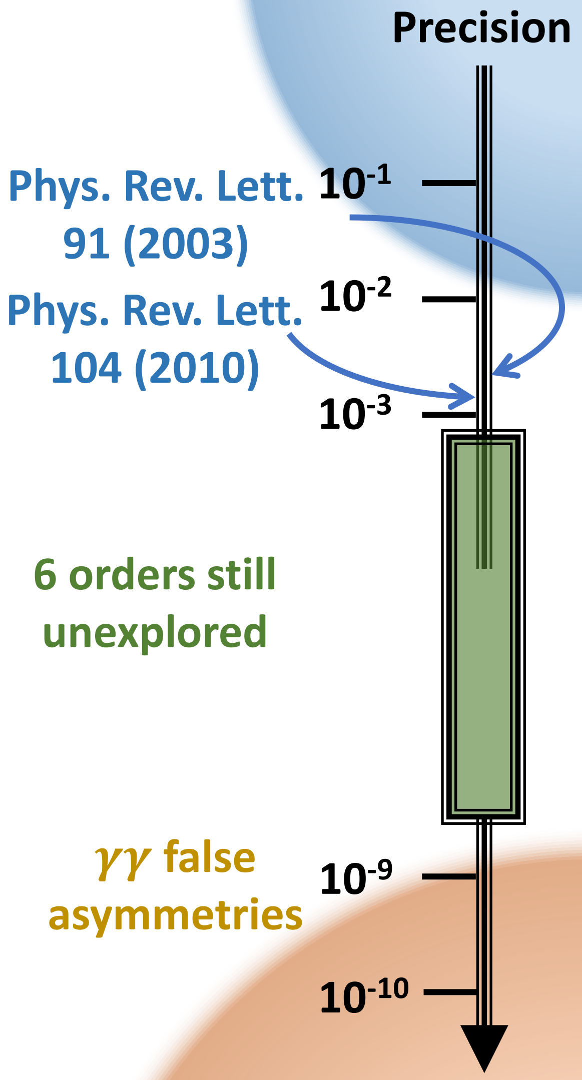
Pushing the limits for the test of the discrete symmetries on leptonic systems

Positronium (Ps) –
the lightest purely leptonic bound state



Positronium physics – almost entirely QED
Assuming CPT conservation up to 10^{-12} level

Some deviations from QED were found in positronium fine structure – L. Gurung et al., Phys. Rev. Lett. (2020)



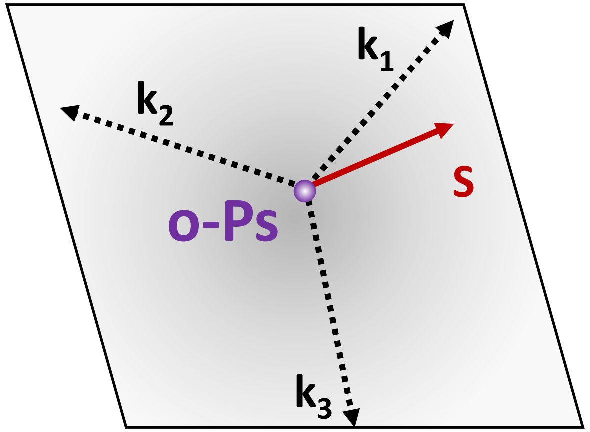
Motivation

The focus was on the study of angular correlations with positronium decays

Using such operators requires determination of the photons momenta and spin of the o-Ps

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

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



Other operators

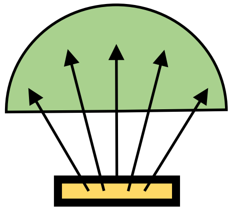
Operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	-	+	-	-
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	-	+	-
$(\vec{S} \cdot \vec{k}_1)\left(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)\right)$	+	-	-	-	+
$\vec{k}_2 \cdot \vec{\epsilon}_1$	+	-	-	-	+
$\vec{S} \cdot \vec{\epsilon}_1$	+	+	-	+	-
$\vec{S}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

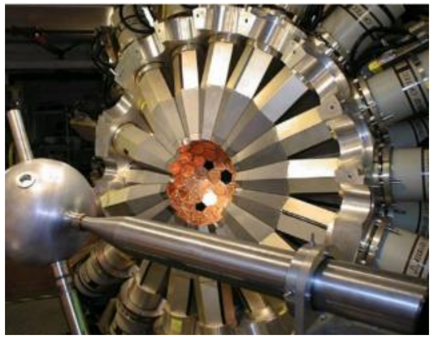
Using photon polarization (applies to the last three rows)

Motivation

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

Phys. Rev. Lett. 91 (2003)





$P_{e+} = 0,686\ v/c$

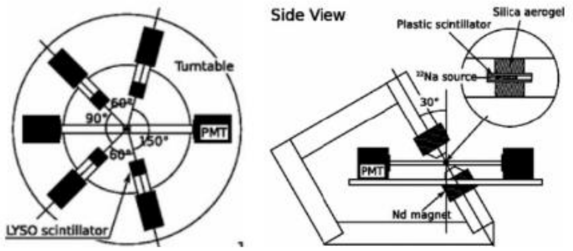
Limiting positron emission direction
1 Mbq β+ emitter activity
4π detector but low angular resolution

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

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

Phys. Rev. Lett. 104 (2010)

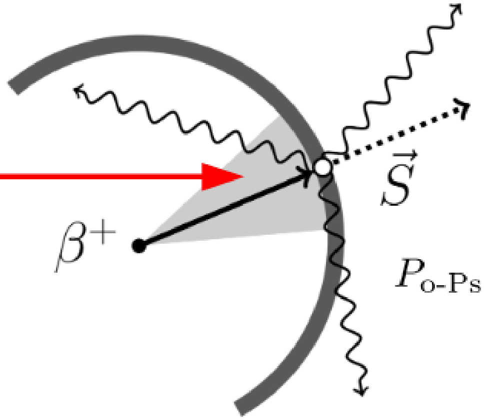
Polarized o-Ps using external B field
Inclusive measurement
Only certain angular configurations



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

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

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



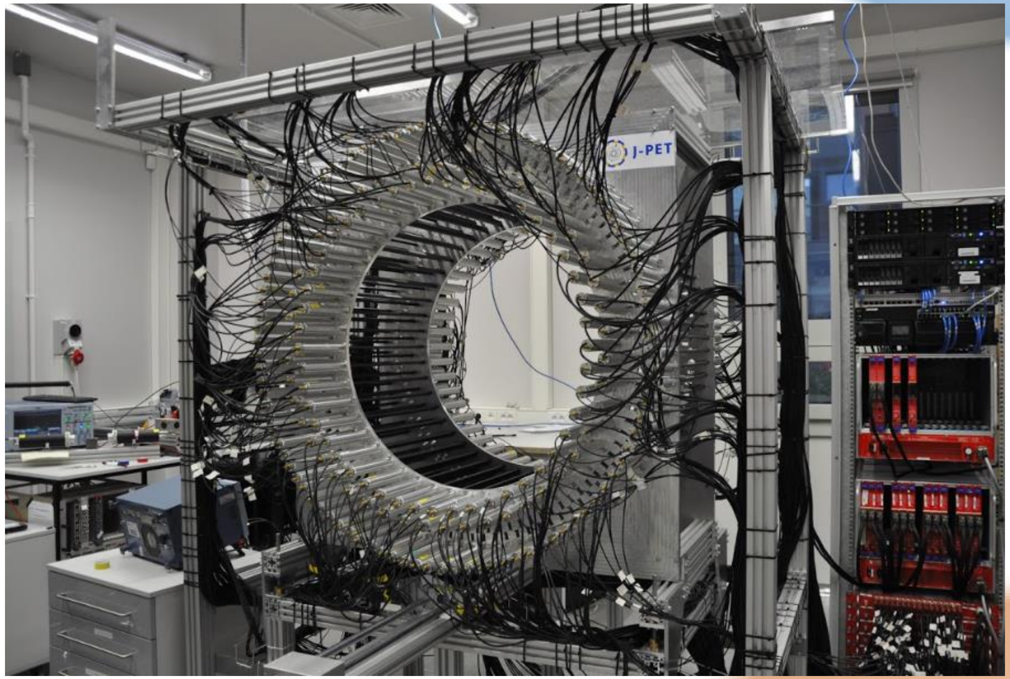
$$P_{\text{o-Ps}} = \frac{2}{3} P_{e+}$$

J-PET detector and experimental details

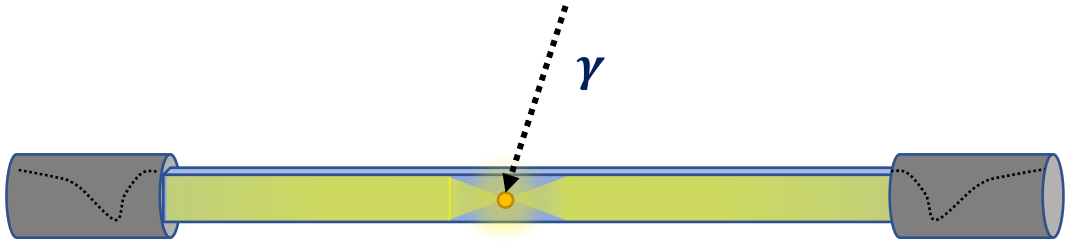
Device for detection of the photons from positronium annihilation (~ 0.5 MeV) and nucleus deexcitation (~ 1 MeV)

Detection based on Compton effect in long plastic scintillator

Energy estimated as a Time-over-Threshold value



P. Moskal et al., IEEE Trans. Instrum. Meas. 70 (2021) 2000810
S. Niedźwiecki et al., Acta Phys. Pol. B 48 (2017) 1567



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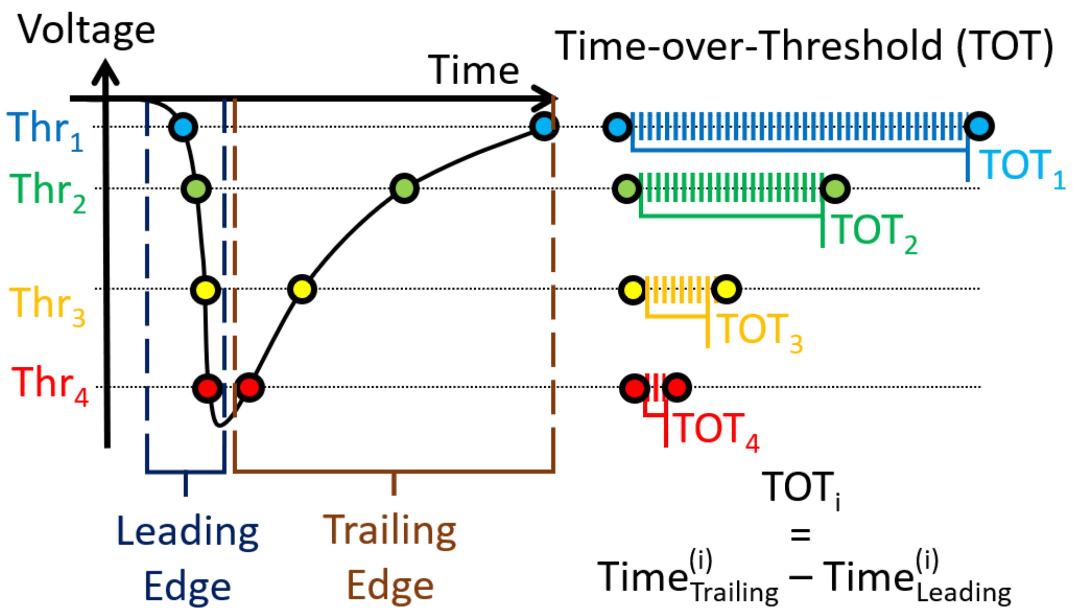

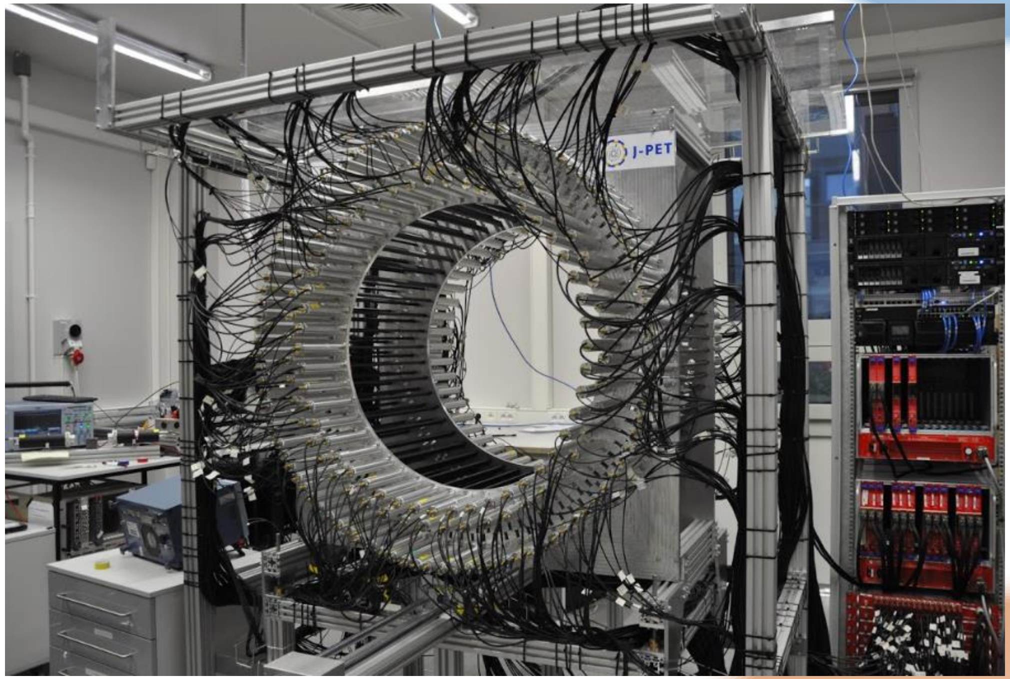

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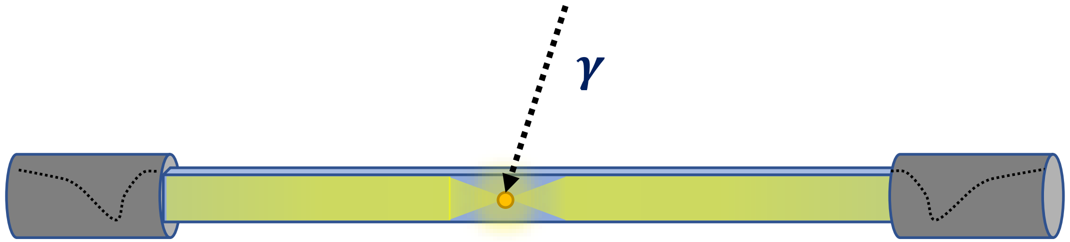

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Device for detection of the photons from positronium annihilation ($\sim$0.5 MeV) and nucleus deexcitation ($\sim$1 MeV)

Energy estimated as a Time-over-Threshold value

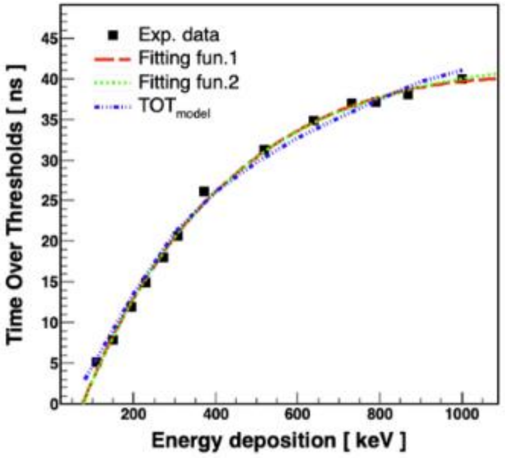
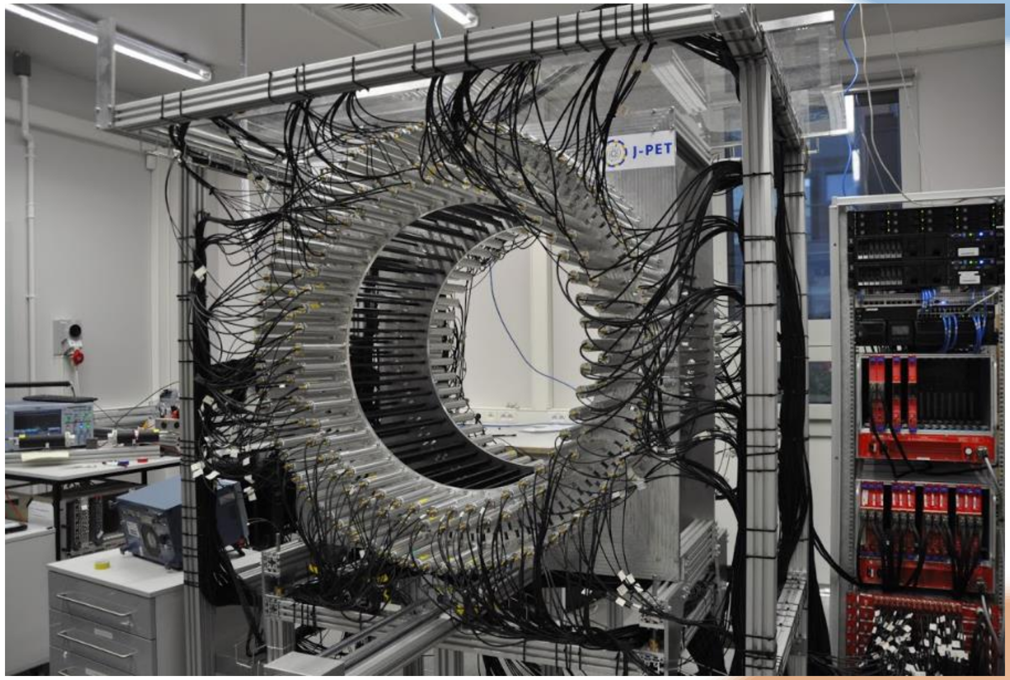


Figure adapted from S. Sharma et al., EJNMMI Phys. 7(2020) 39



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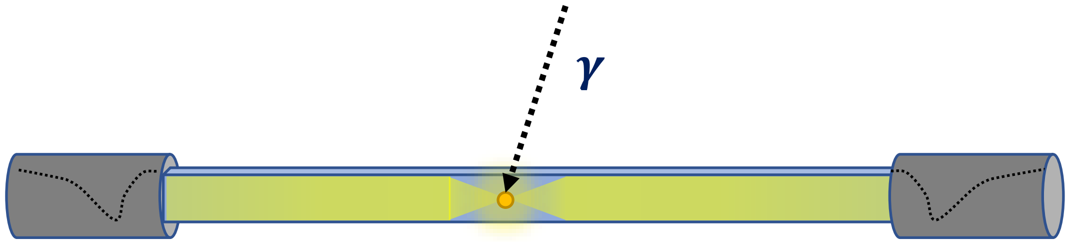
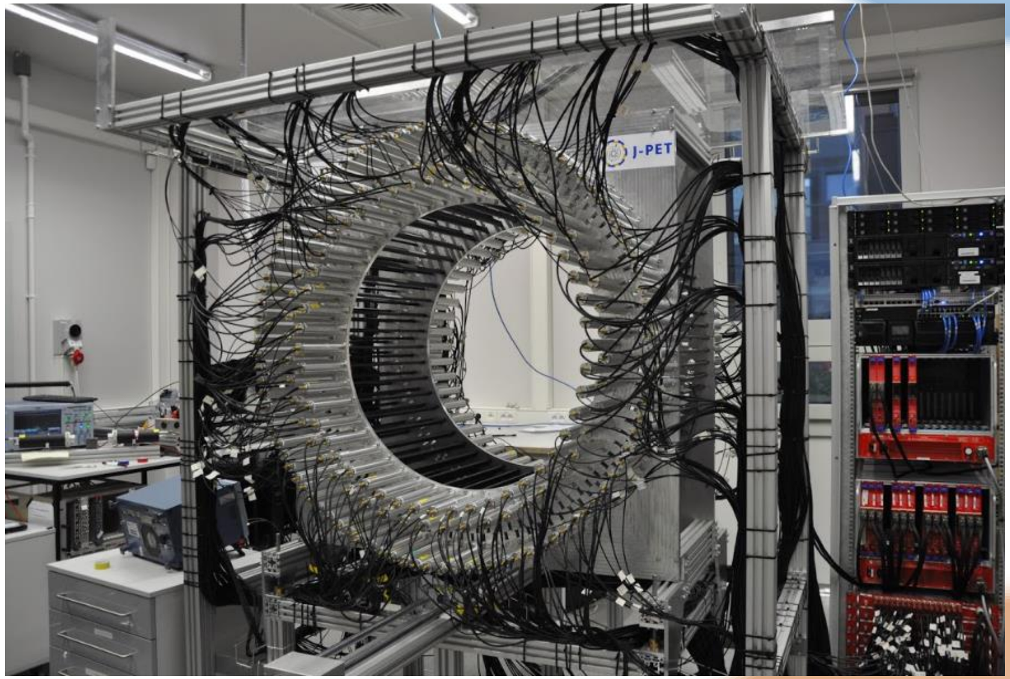


J-PET detector and experimental details

Both energy and position of the hit reconstructed based on the measured times (resolution ~350 ps in FWHM)

Annihilation position reconstruction based on multi-photon coincidences



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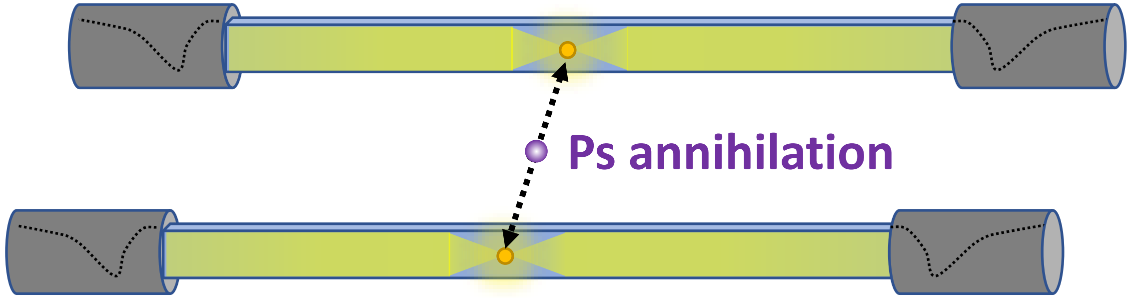
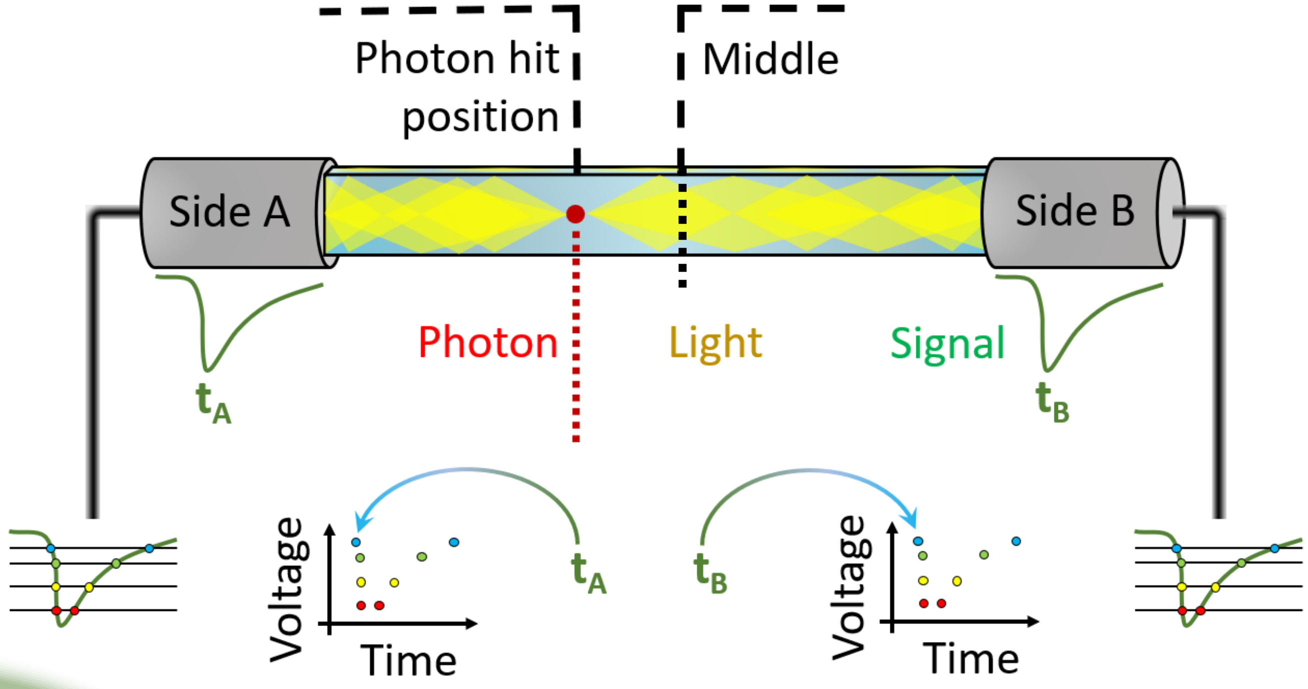


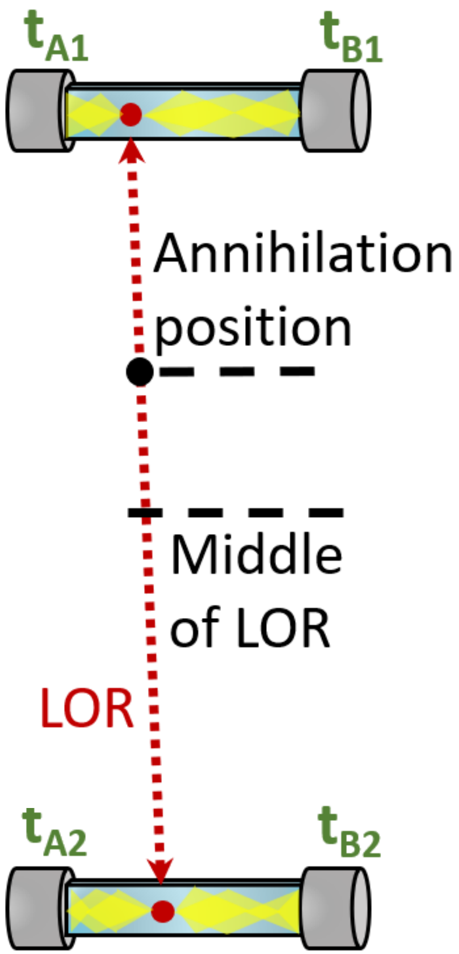
J-PET detector and experimental details



Photon hit position – Middle = $\mathbf{v} \cdot (t_B - t_A) / 2$

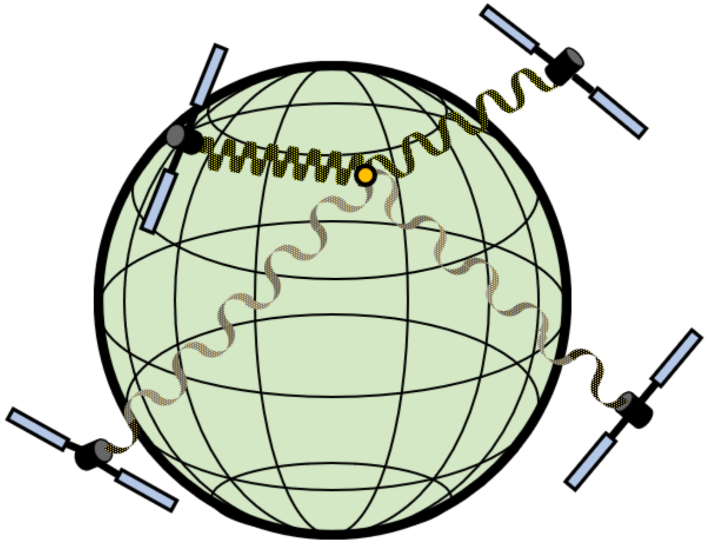
Annihilation position – Middle of LOR

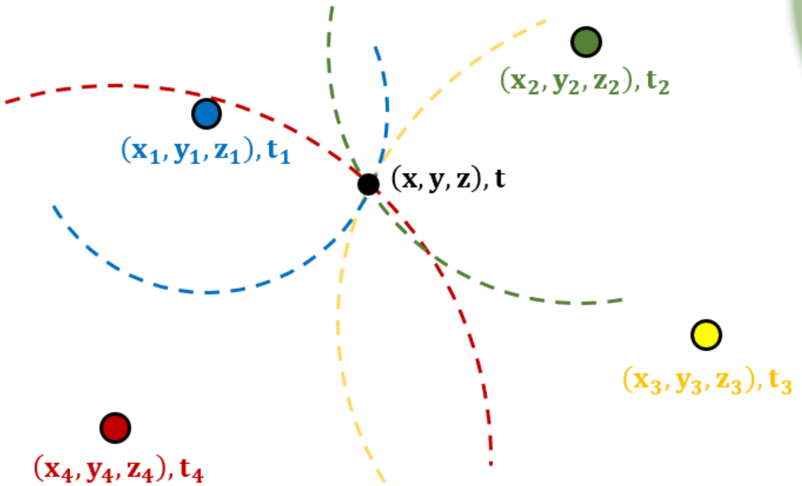
= $\mathbf{c} \cdot (t_{Hit2} - t_{Hit1}) / 2$

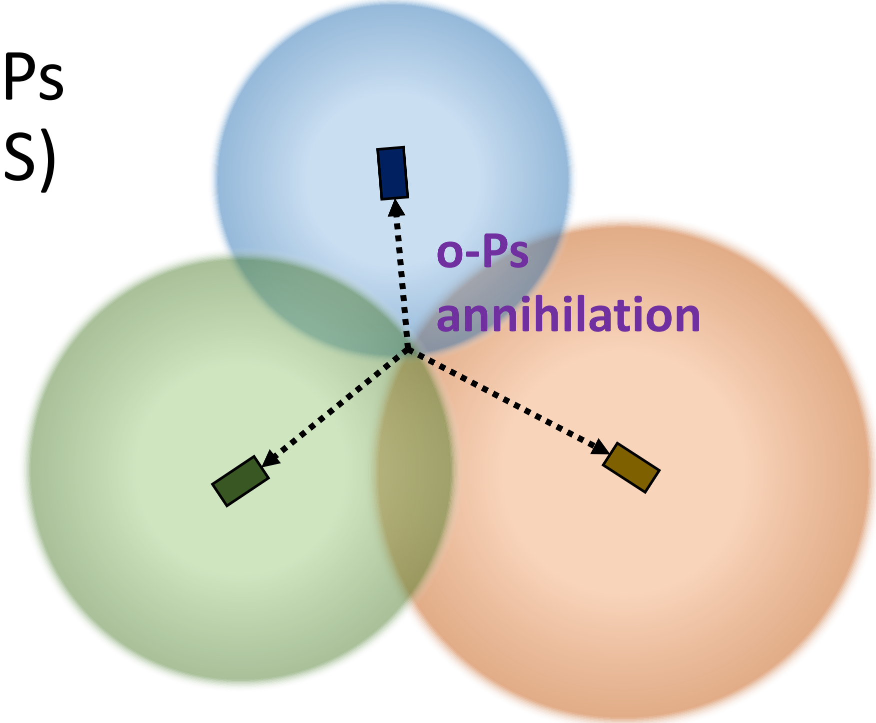


Trilateration method

It is also possible to reconstruct annihilation position based on the annihilation of the ortho-Ps into 3 photons – trilateration method (like in GPS)
A. Gajos et al., NIM A 819 (2016) 54-59

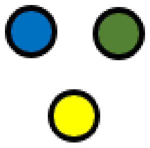




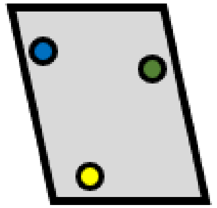


Trilateration method

3 signals



co-planarity



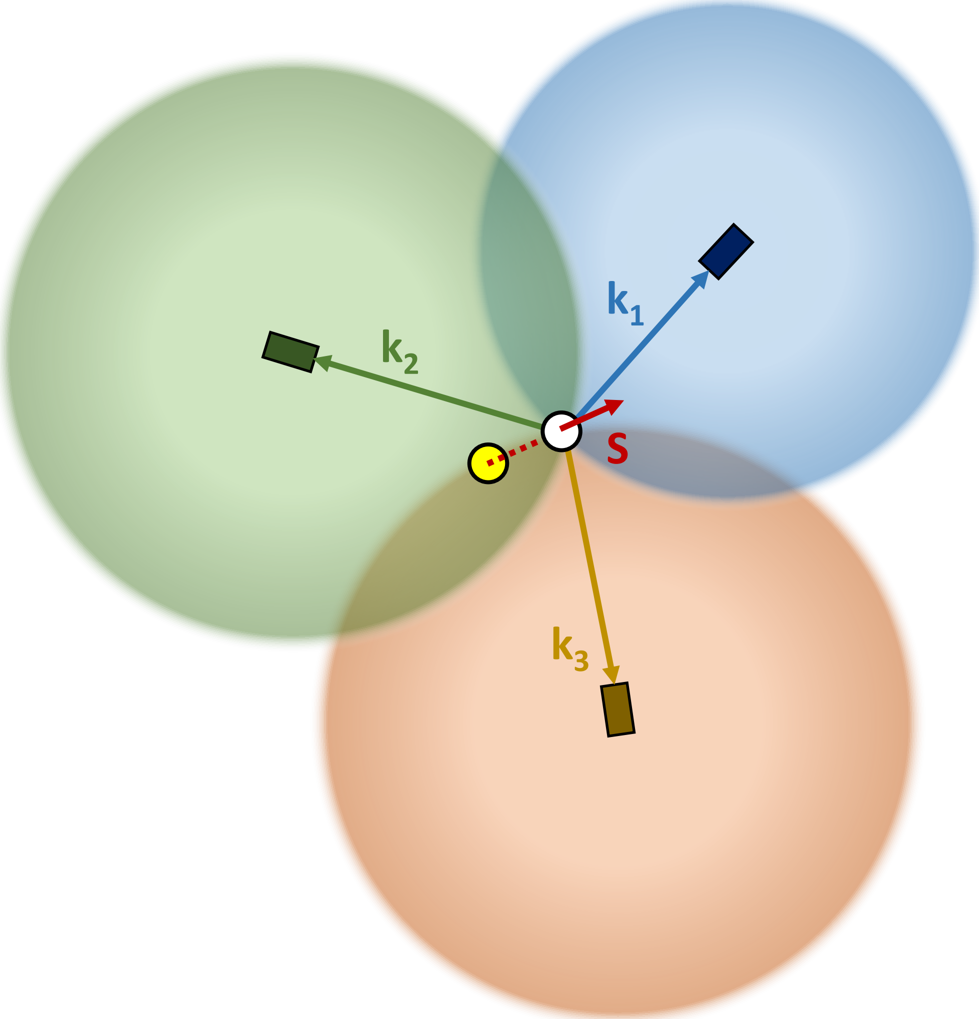
3 equations
3 variables

position of the source on the decay plane
$(\mathbf{x}', \mathbf{y}')$

time of emission
$\mathbf{t}$

$$
\begin{cases}
(\mathbf{x}' - \mathbf{x}'_1)^2 + (\mathbf{y}' - \mathbf{y}'_1)^2 = \mathbf{v}(\mathbf{t}' - \mathbf{t}'_1)^2 \\
(\mathbf{x}' - \mathbf{x}'_2)^2 + (\mathbf{y}' - \mathbf{y}'_2)^2 = \mathbf{v}(\mathbf{t}' - \mathbf{t}'_2)^2 \\
(\mathbf{x}' - \mathbf{x}'_3)^2 + (\mathbf{y}' - \mathbf{y}'_3)^2 = \mathbf{v}(\mathbf{t}' - \mathbf{t}'_3)^2
\end{cases}
$$

$\mathbf{v}$ – velocity of the signal



J-PET detector and experimental details

Large cylindrical chamber with walls from the mesoporous silica -> high fraction of the o-Ps production

Vacuum inside the chamber – 10^{-3} Pa -> reduction of the positron scatterings before entering walls of the chamber

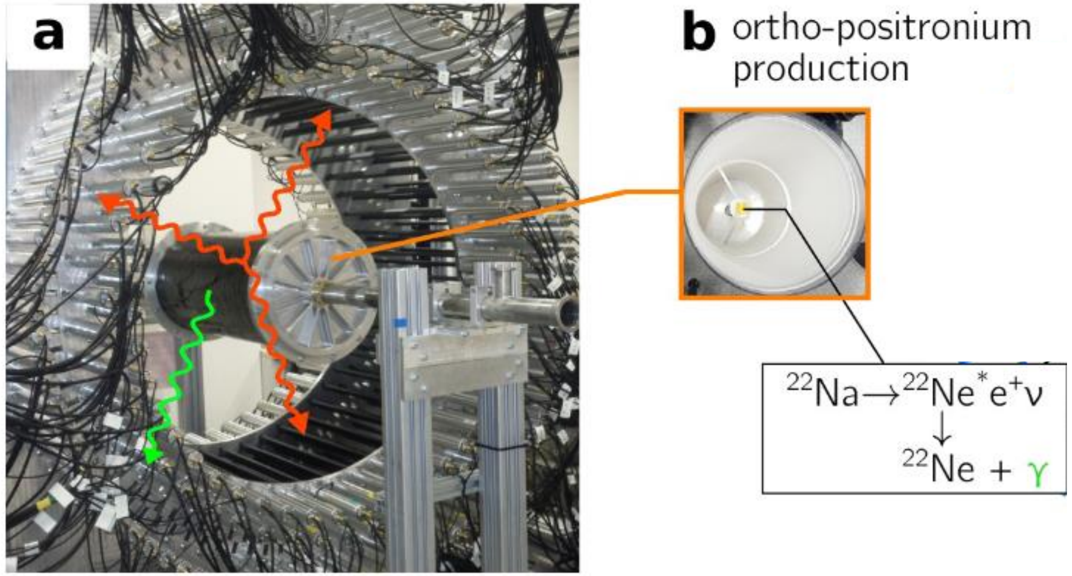
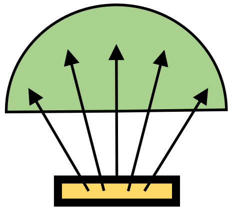


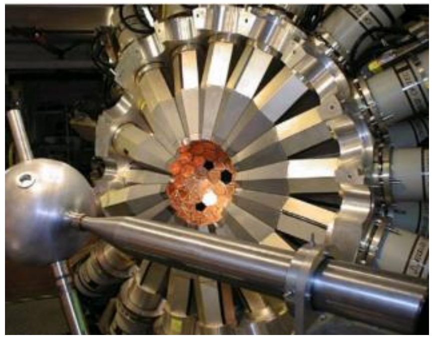
Figure from P. Moskal, A. Gajos et al., Nature Comm. 12 (2021) 5658

JPET vs previous measurements

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

Phys. Rev. Lett. 91 (2003)





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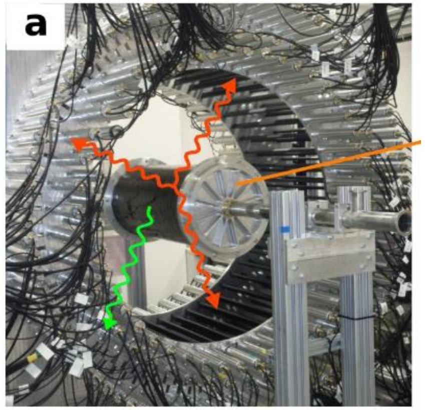

$P_{e+} \approx 0{,}98$ v/c

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

$(\vec{S} \cdot \vec{k}_1)\left(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)\right)$

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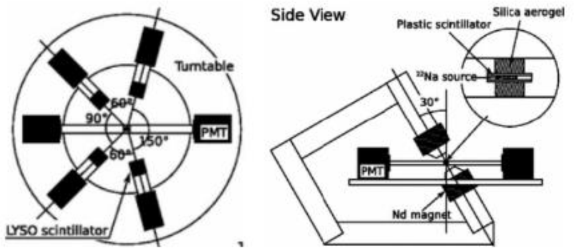
Polarized o-Ps using external B field
Inclusive measurement
Only certain angular configurations



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

Multiple geometrical configurations
e+ spin estimated event-by-event
Plastic scintillators = fast timing
Recording all 3 annihilation photons

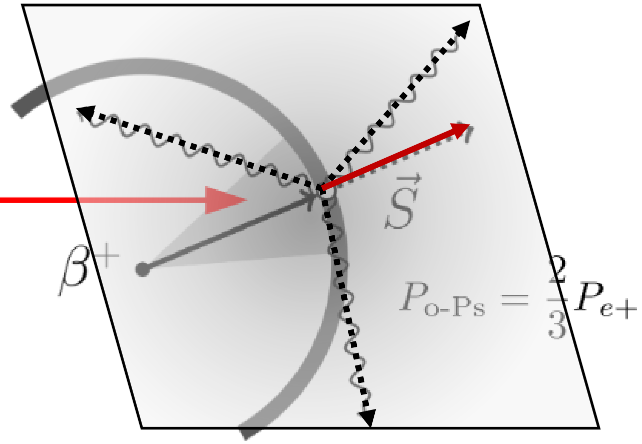
Analysis procedure

Extensive medium in which o-Ps is formed and annihilated, along with the position reconstruction algorithm, allowed for the formulation of the positron polarization (spin) estimation on the event-by-event basis

Knowledge of the o-Ps annihilation position and the hit positions allows for the determination of the annihilation photon momenta

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

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



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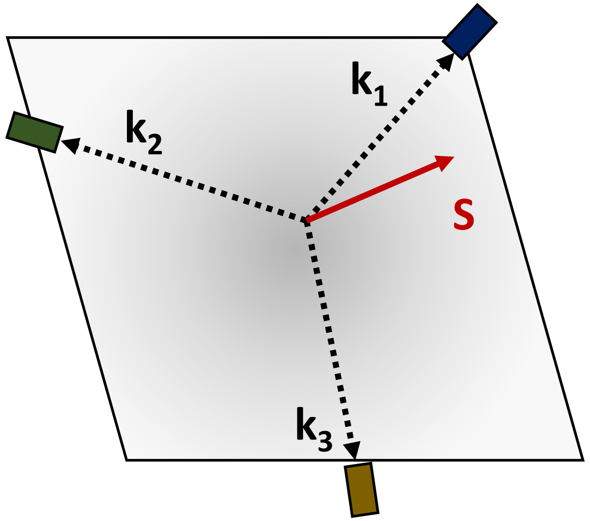

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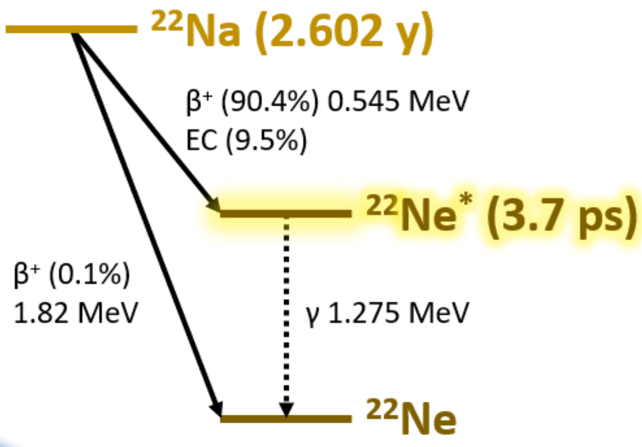


Main requirements for an event:

Only 3 Hits in the 2.5 ns event time window

All hits with TOT such, that 15 ns < TOT < 55 ns

Data

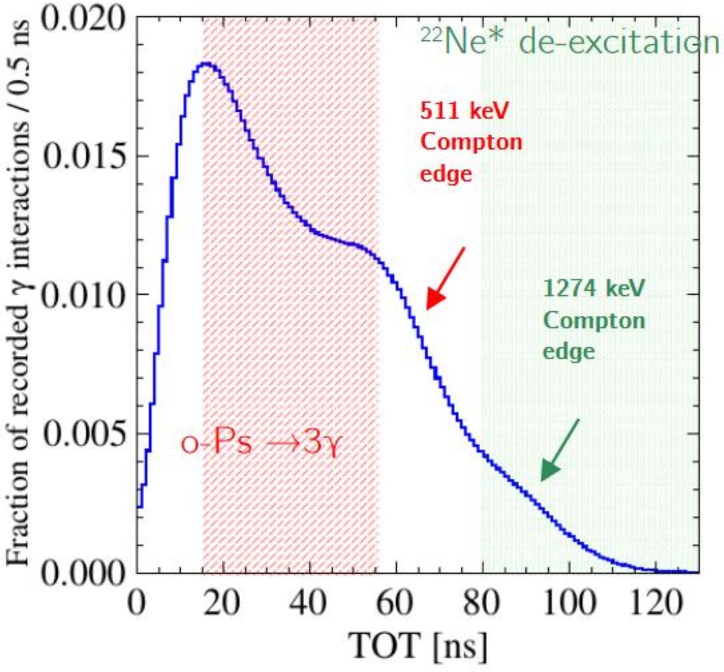
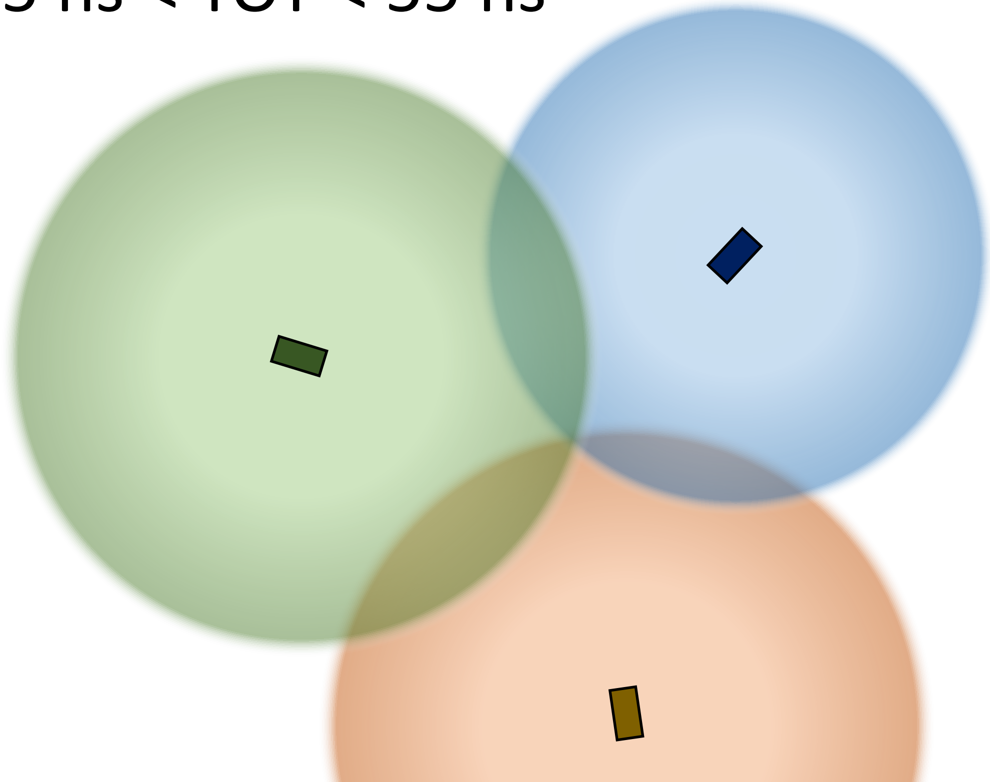


Figure from P. Moskal, A. Gajos et al., Nature Comm. 12 (2021) 5658



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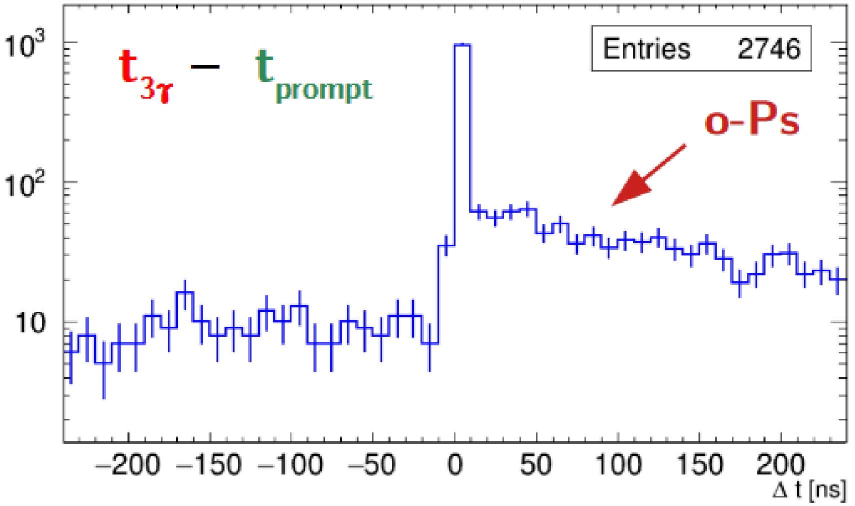
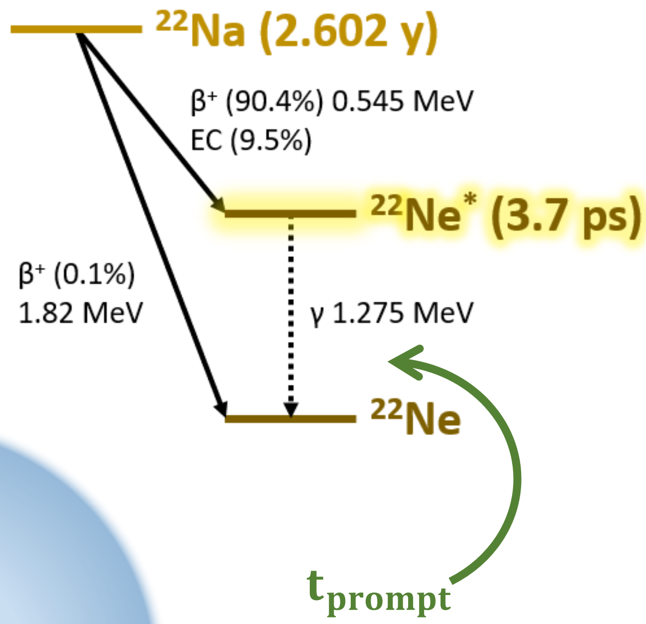
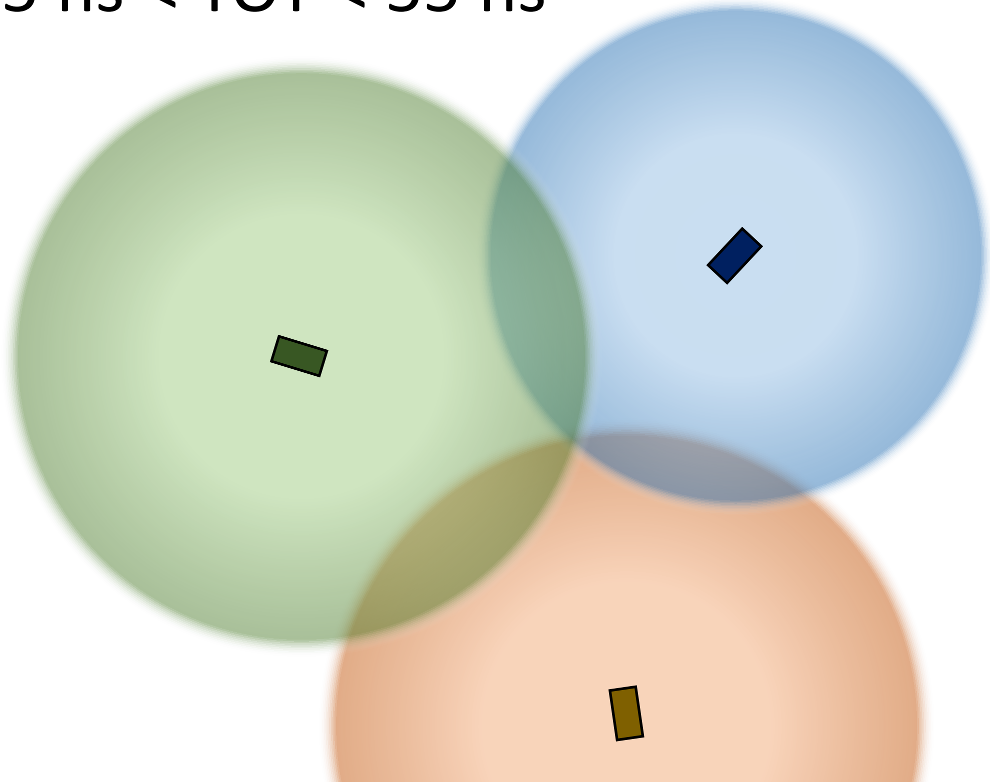
Proof of measuring o-Ps -> 3G from another measurement

Data



$t_{3\gamma}$ - Time of o-Ps annihilation into 3 photons





Analysis procedure

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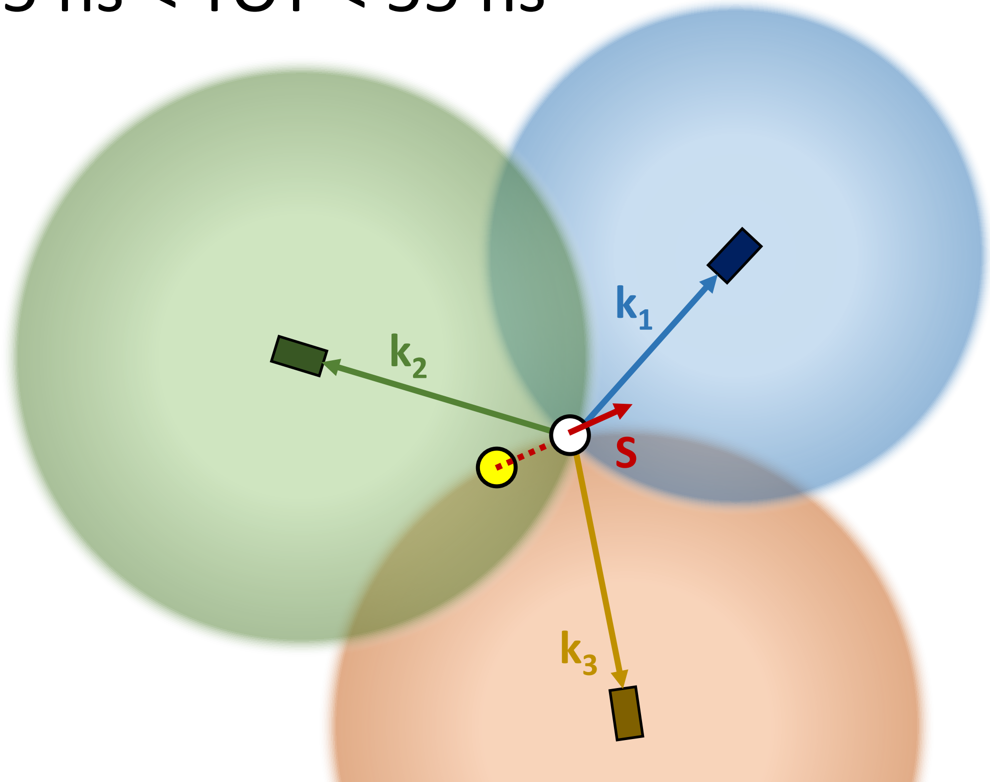
Annihilation position (○) –> Trilateration

Position (○) -> $\vec{k}_1 \times \vec{k}_2$

Adding position of the source (●) -> $\vec{S}$



Treatment of the background events

Possible configurations of events

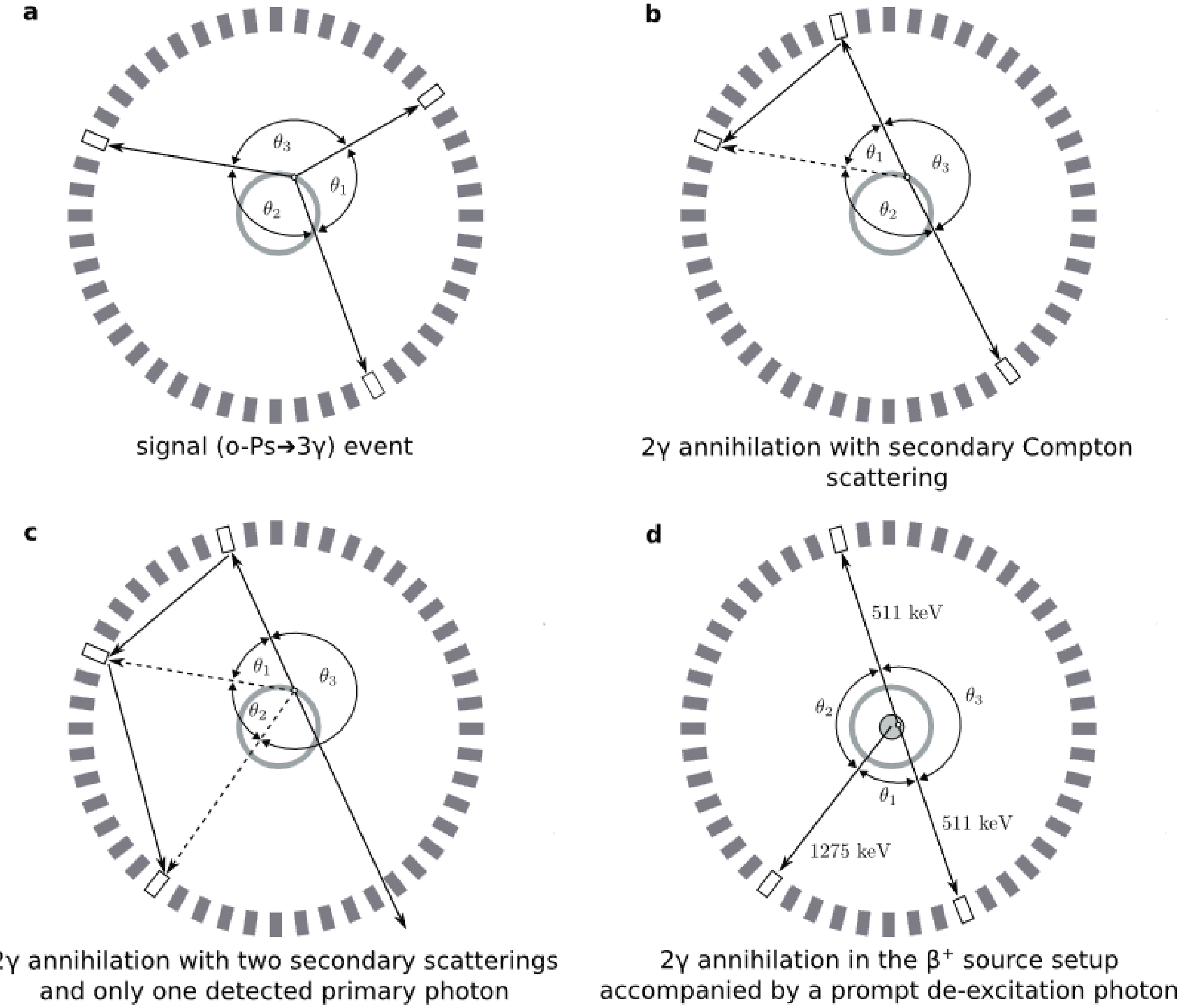


Figure from P. Moskal, A. Gajos et al., Nature Comm. 12 (2021) 5658

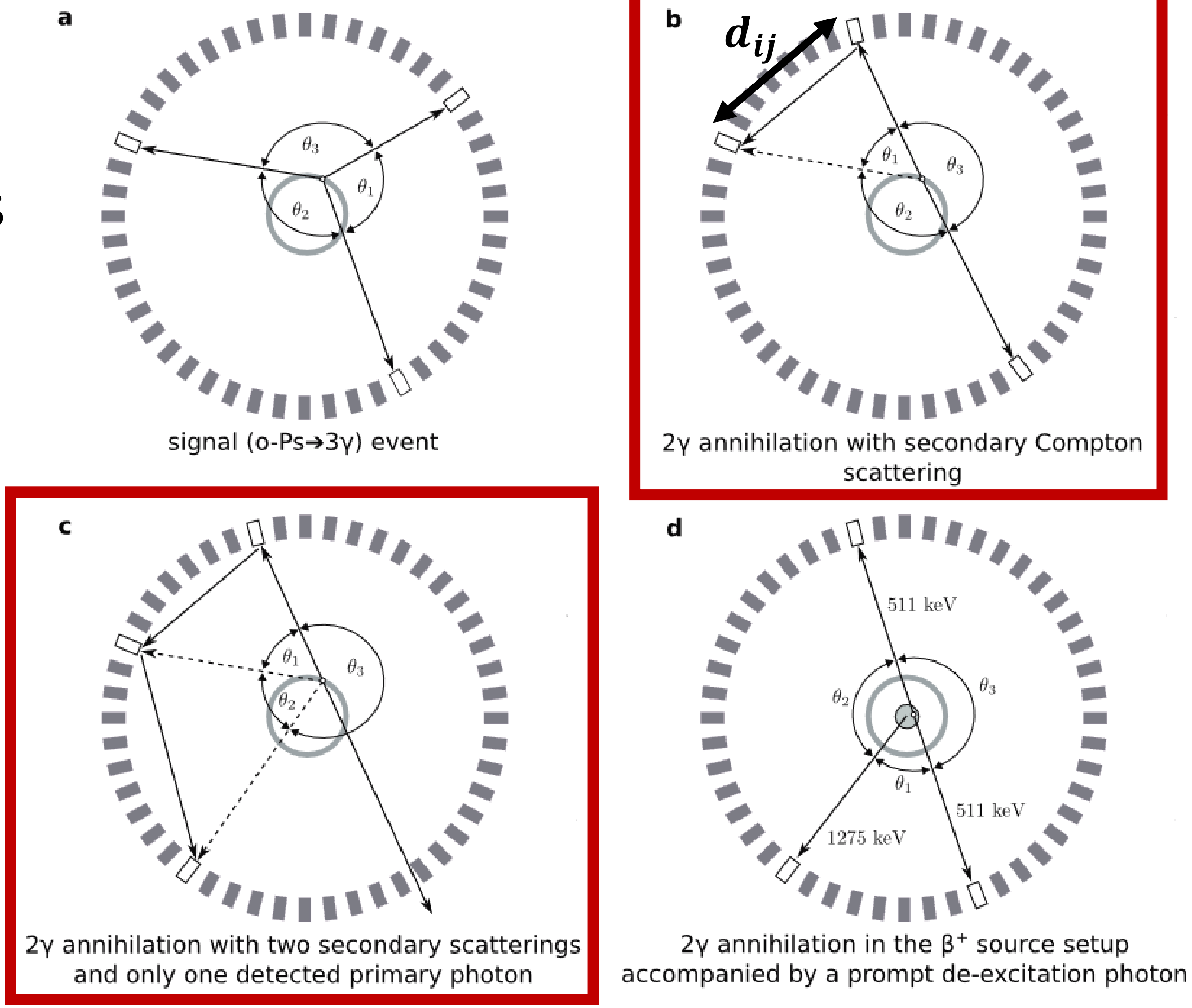
Treatment of the background events

Rejection of the scatterings

For a given pair of hits i-j

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

$$\boldsymbol{\delta_{min} = \min \delta_{ij}}$$



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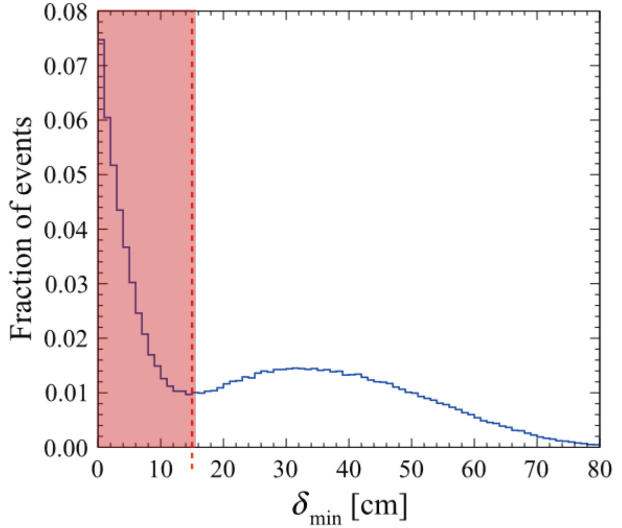
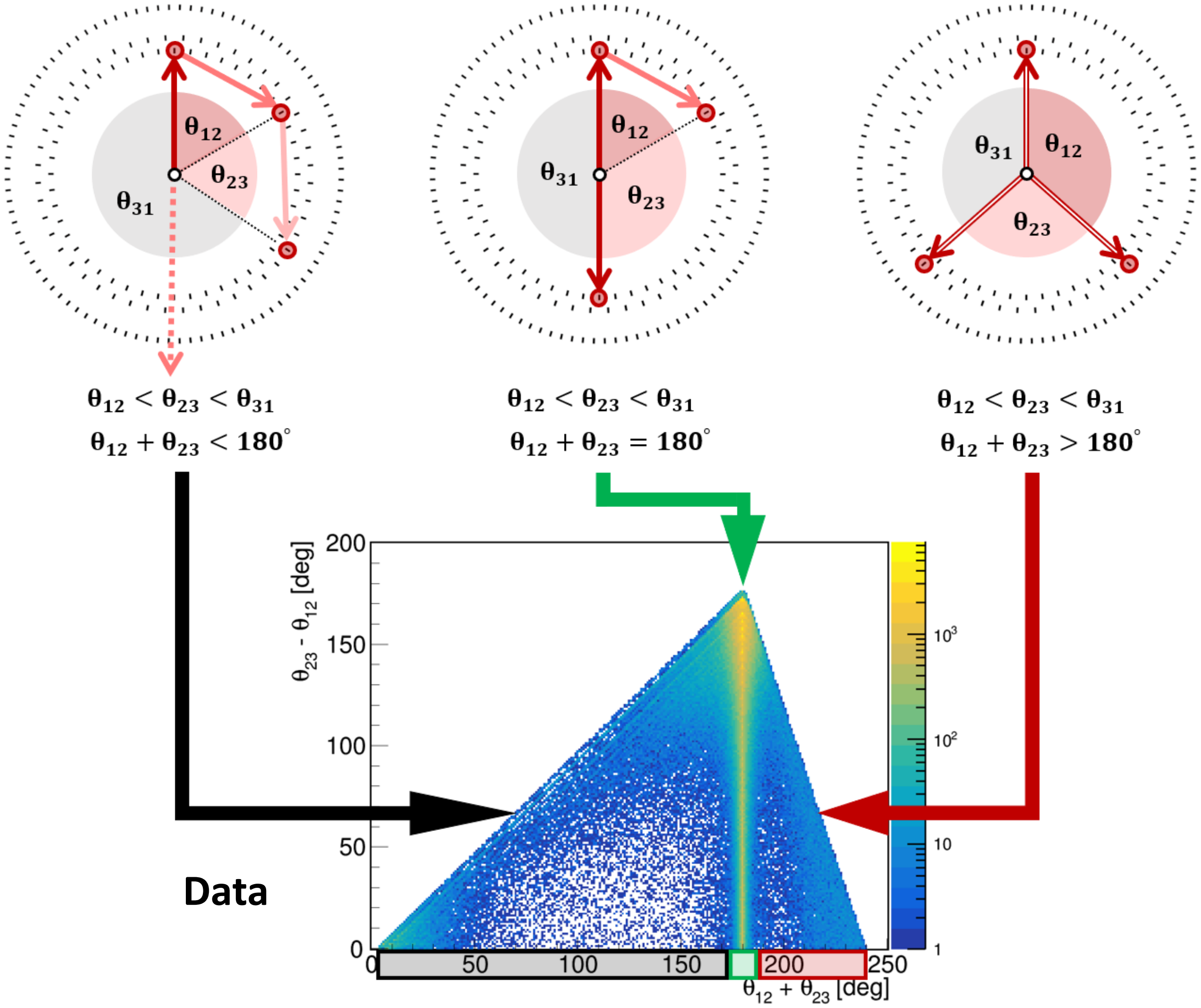


Figures from P. Moskal, A. Gajos et al., Nature Comm. 12 (2021) 5658

Treatment of the background events

One can distnguish three area with different area based on angular correlations



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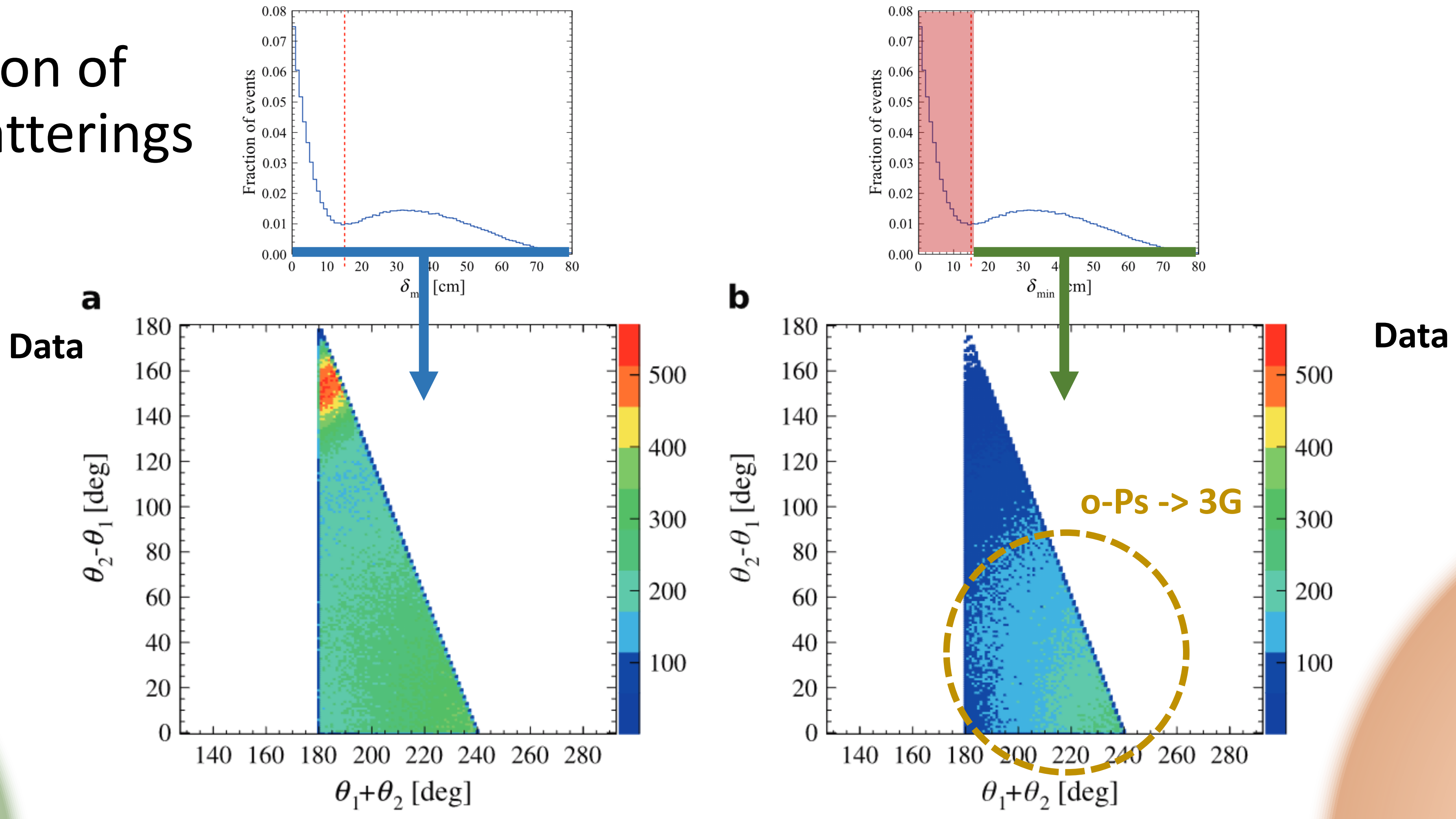


Figures from P. Moskal, A. Gajos et al., Nature Comm. 12 (2021) 5658

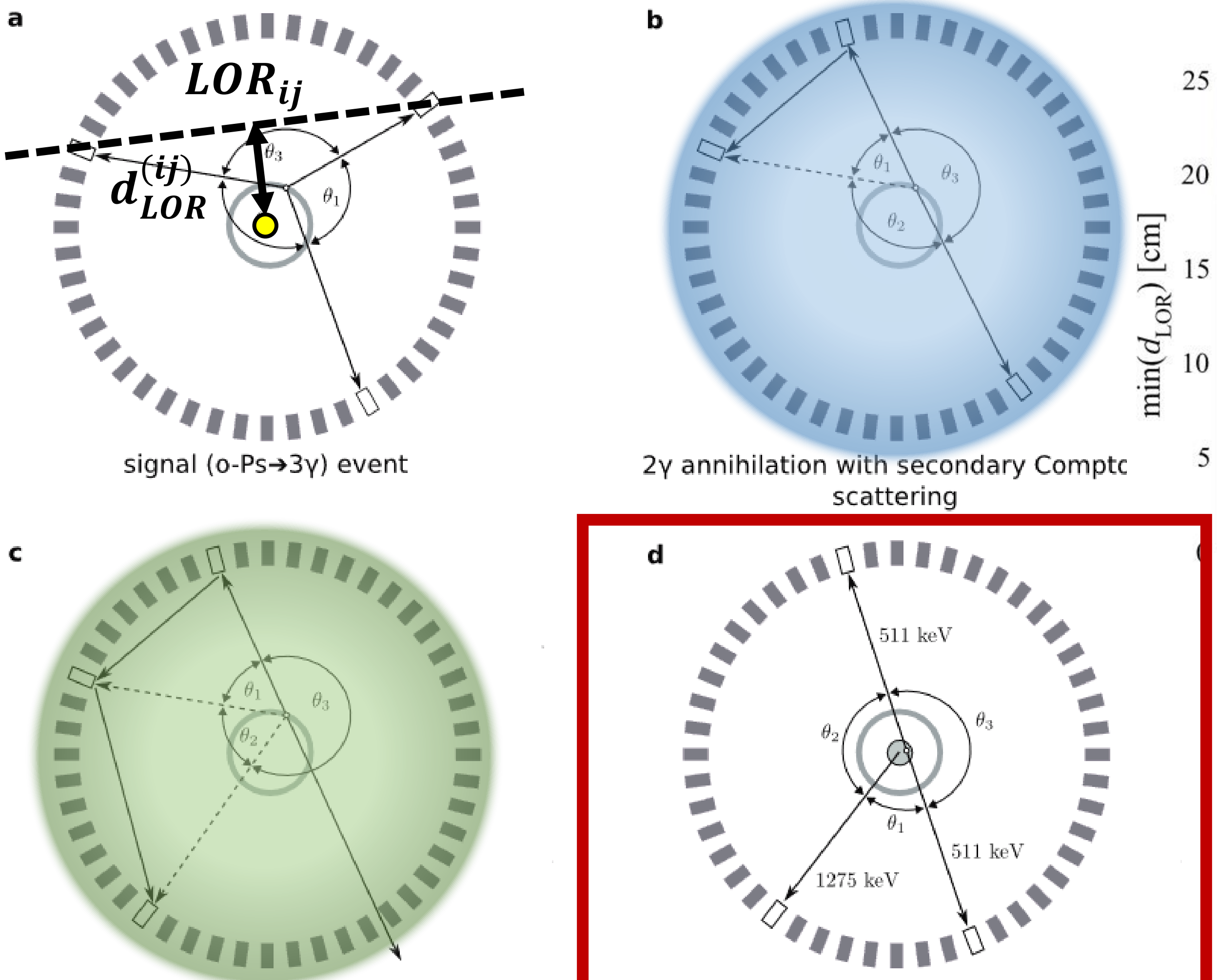
Treatment of the background events

Rejection of the 2G decays

For a given pair of hits i-j

$$d_{LOR}^{(ij)} = d(source, LOR_{ij})$$

$$\min(d_{LOR}) = \min d_{LOR}^{(ij)}$$

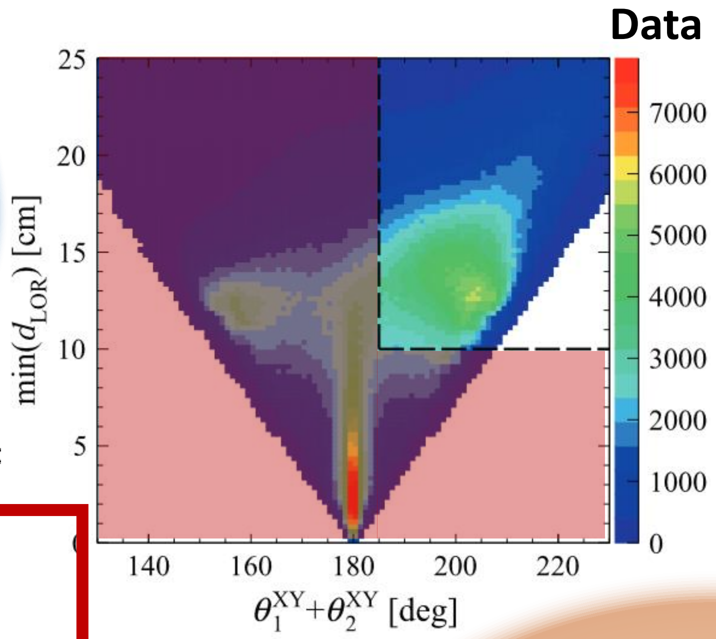


a: signal (o-Ps→3γ) event

b: 2γ annihilation with secondary Comptc scattering

c: 2γ annihilation with two secondary scatterings and only one detected primary photon

d: 2γ annihilation in the β^+ source setup accompanied by a prompt de-excitation photon



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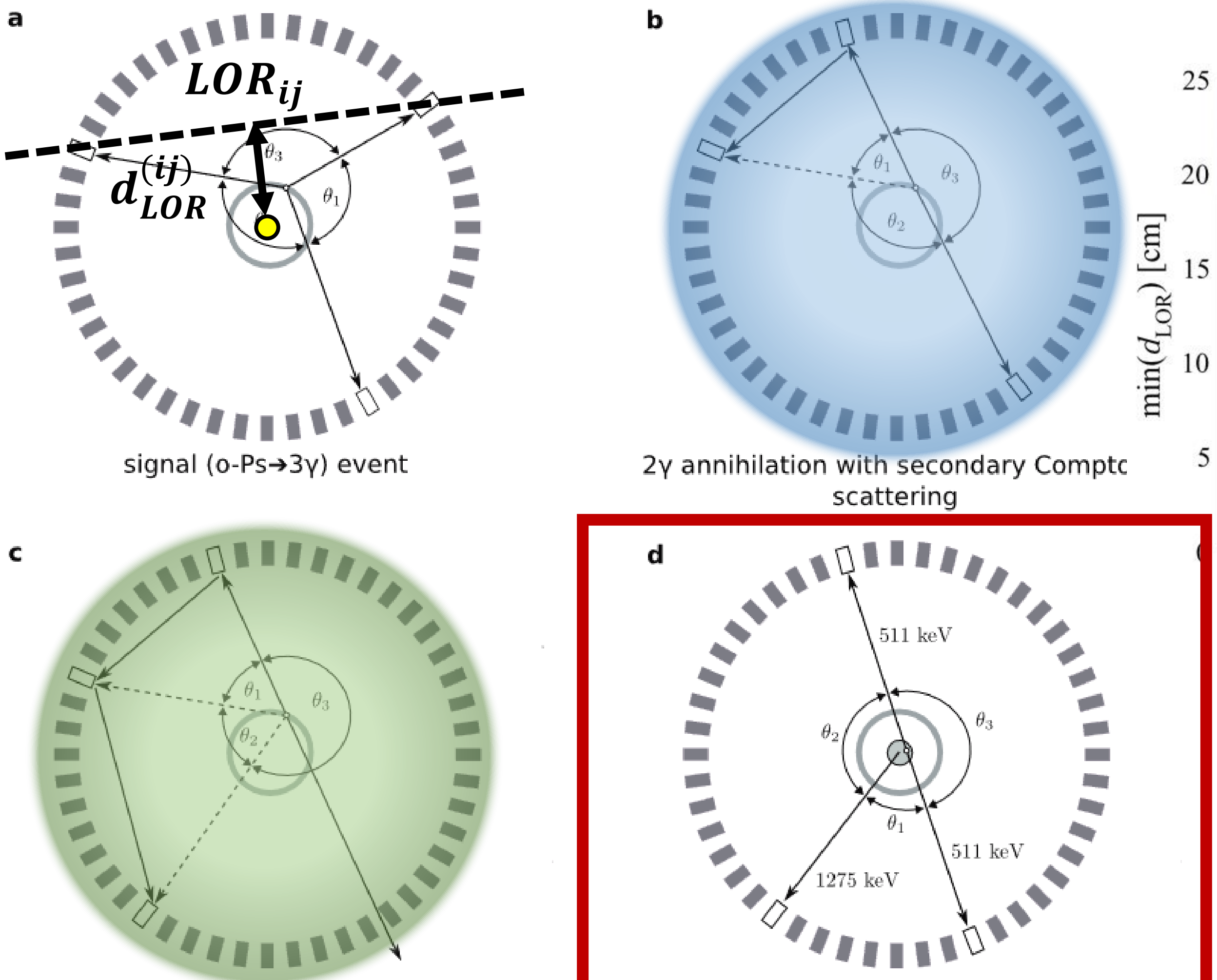
For a given pair of hits i-j

$$d_{LOR}^{(ij)} = d(source, LOR_{ij})$$

$$\min(d_{LOR}) = \min d_{LOR}^{(ij)}$$



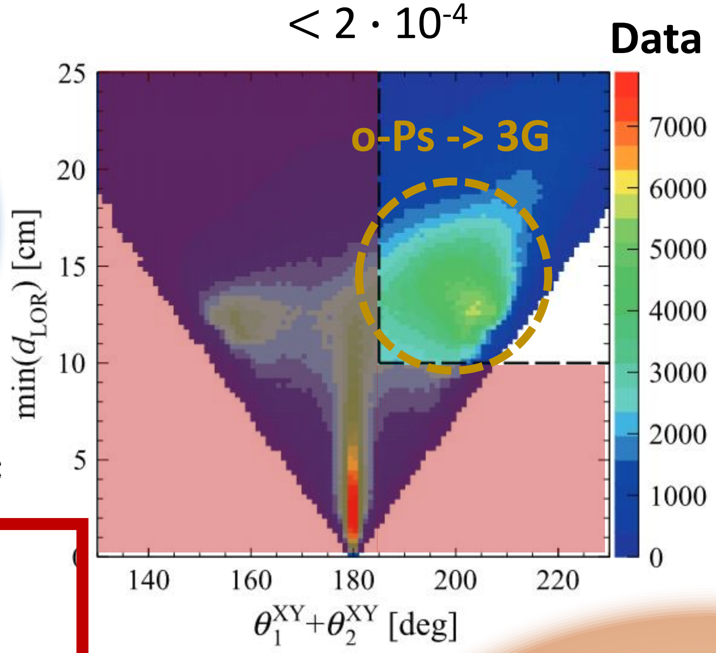
signal (o-Ps→3γ) event

2γ annihilation with secondary Comptc scattering

2γ annihilation with two secondary scatterings and only one detected primary photon

2γ annihilation in the β⁺ source setup accompanied by a prompt de-excitation photon

p-Ps contamination fraction $< 2 \cdot 10^{-4}$



Figures from P. Moskal, A. Gajos et al., Nature Comm. 12 (2021) 5658

Results of the three-photon imaging

The **first 3G image** of the **o-Ps** from the extensive-size object

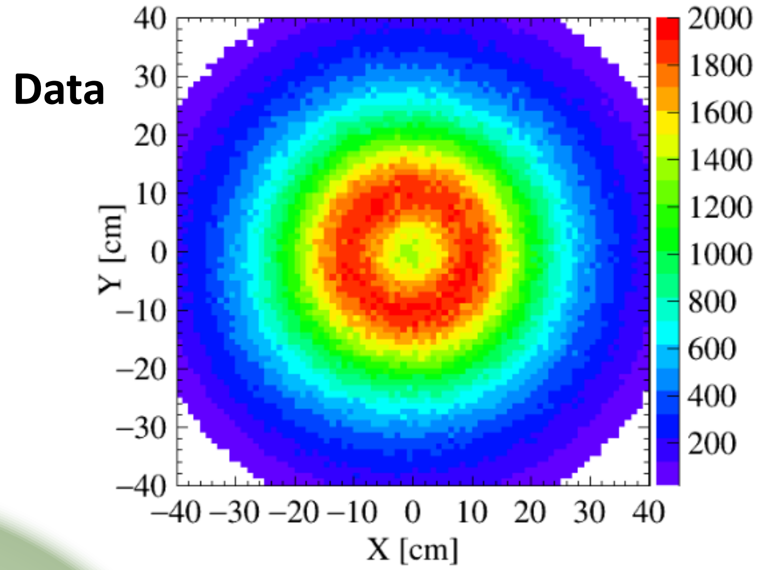
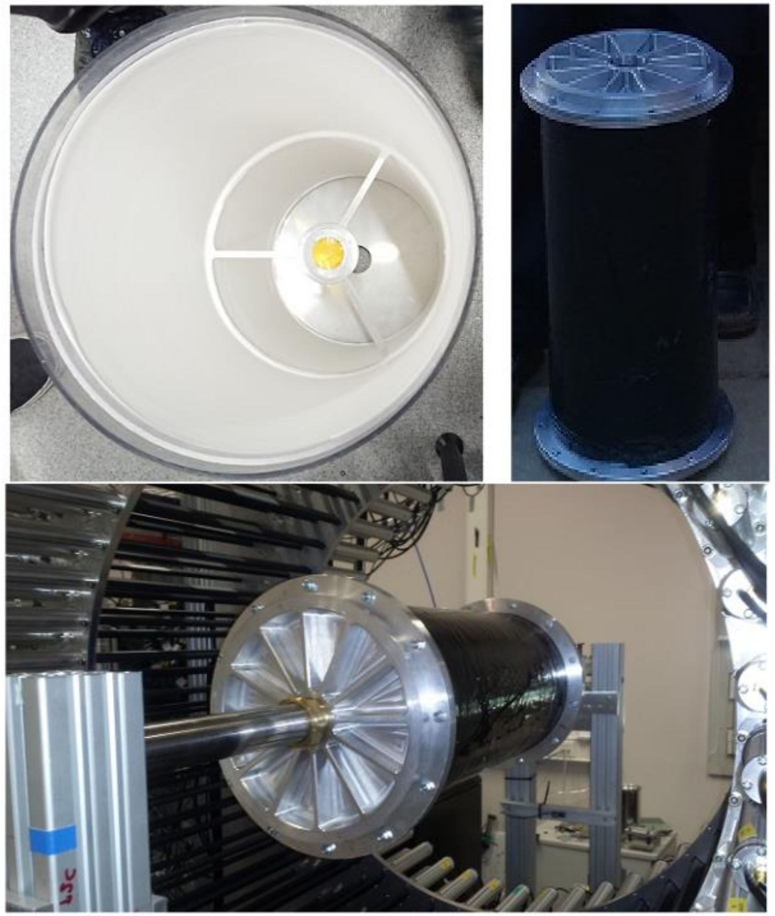
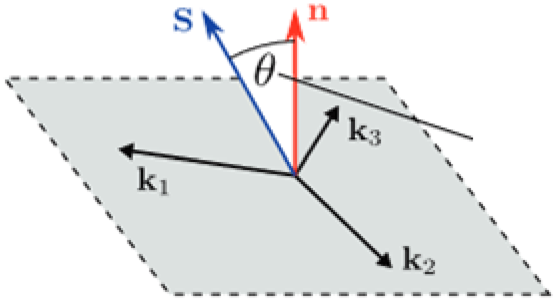


Figure from P. Moskal, A. Gajos et al.,
Nature Comm. 12 (2021) 5658



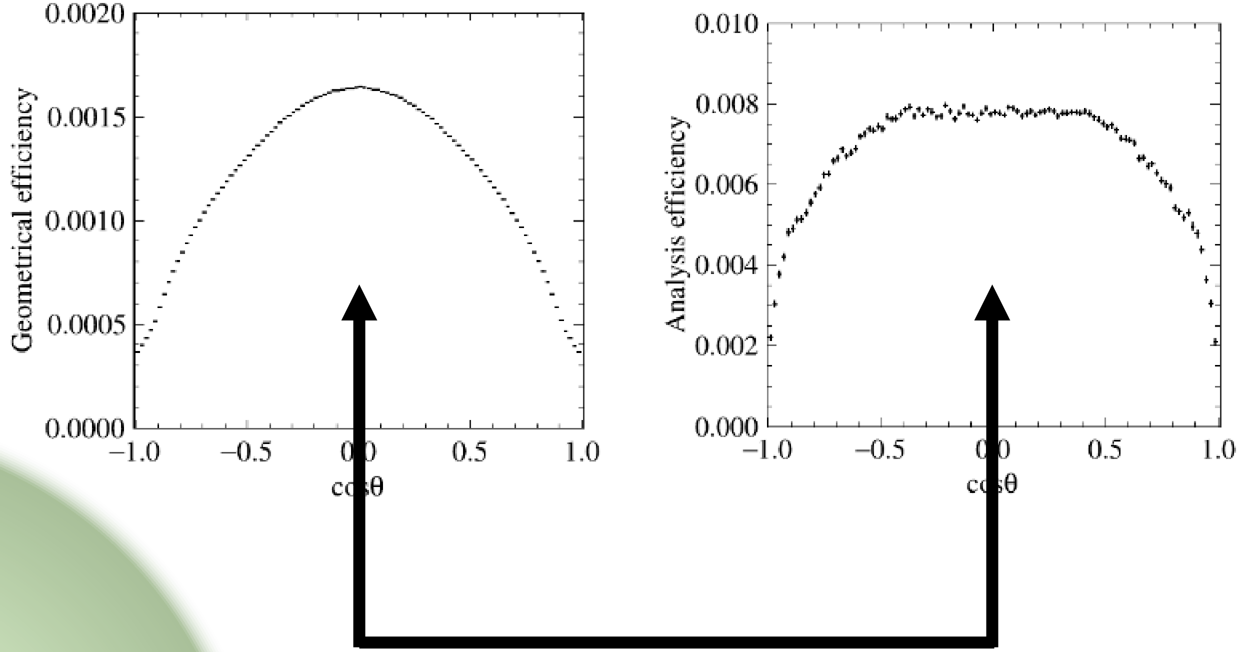
Results of the CPT test



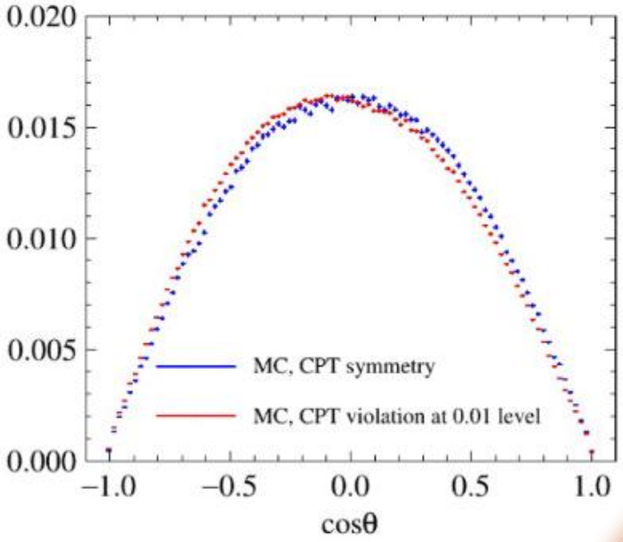
Simulation data were generated in order to estimate efficiencies: geometrical and analysis

MC

MC

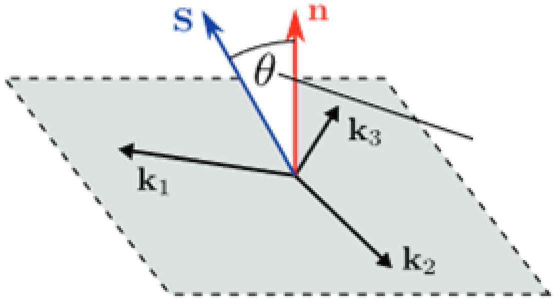


Symmetric in $\cos\theta$



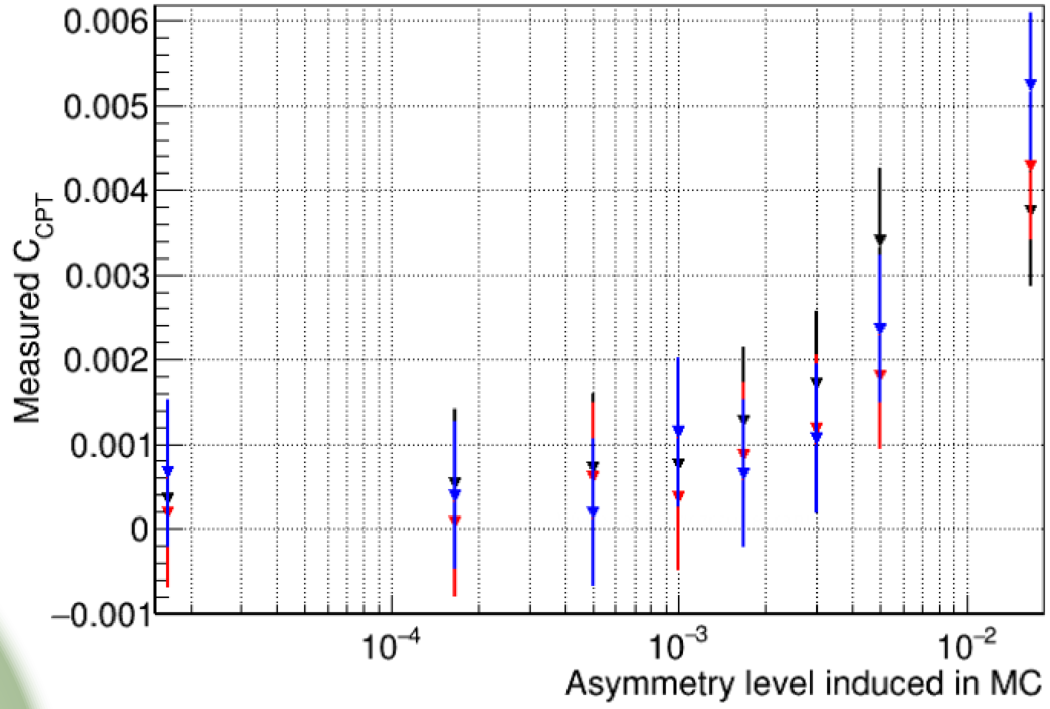
A. Gajos Symmetry 12 (2020) 8, 1268

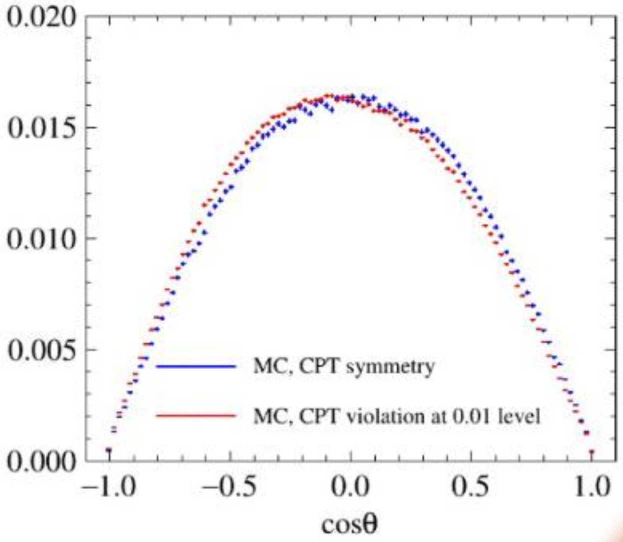
Results of the CPT test



Simulation data were generated in order to estimate efficiencies and to check how induced assymetry will affect observable

MC

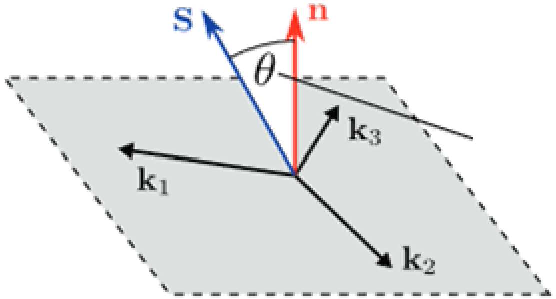




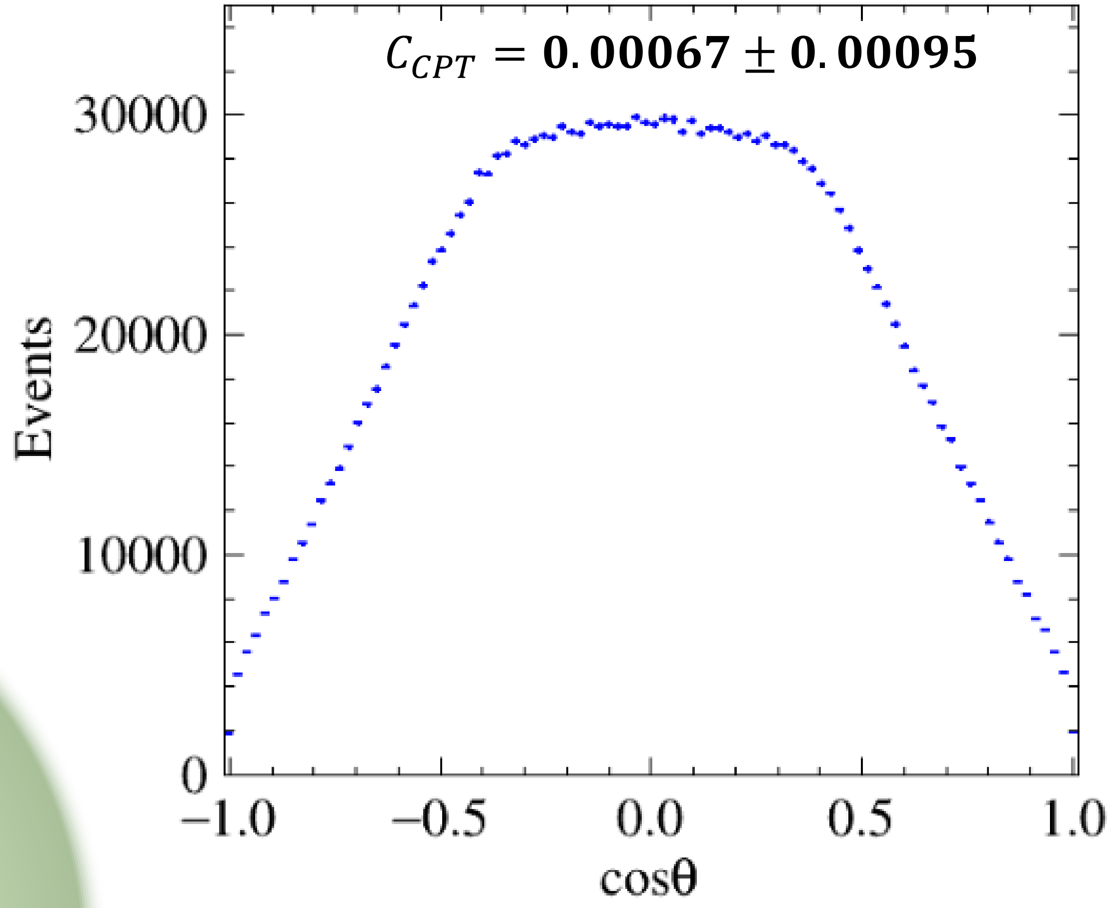
Courtesy of A. Gajos

$C_{CPT} = \langle \cos\theta \rangle / P$

Results of the CPT test



Data Total number of events ~2x10^6



Statistical uncertainty = 0.00033
Systematic uncertainty = 0.00014
Analyzing power P = 37.4%

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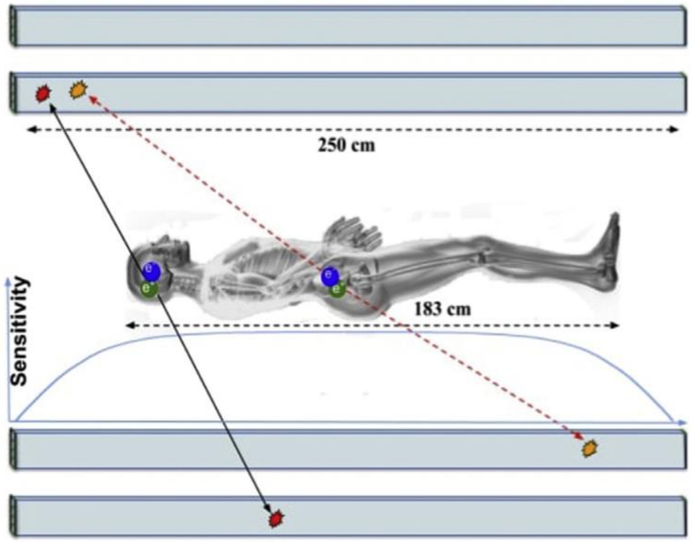
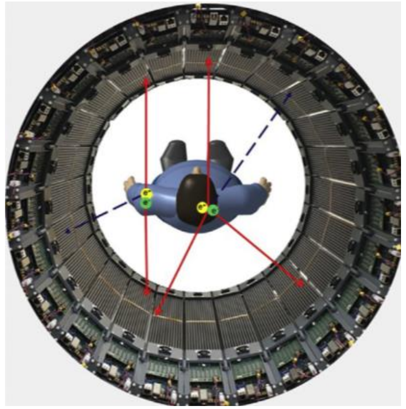
Testing CPT symmetry in ortho-positronium decays with positronium annihilation tomography

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

Nature Communications **12**, Article number: 5658 (2021) | Cite this article

Future developments





Total-body J-PET

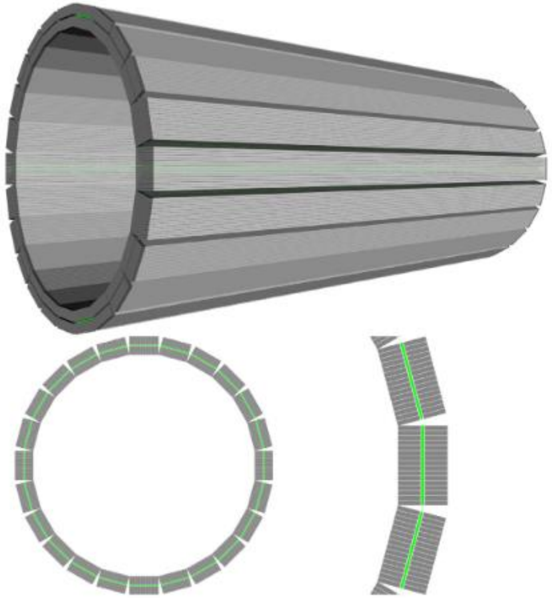
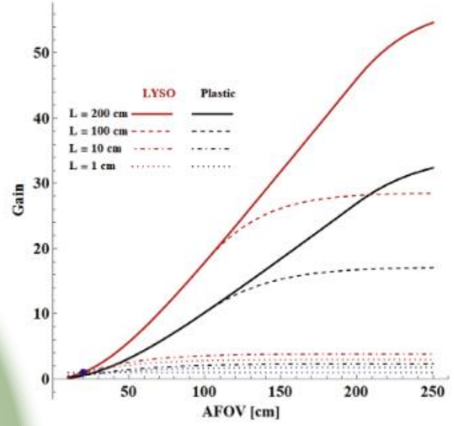
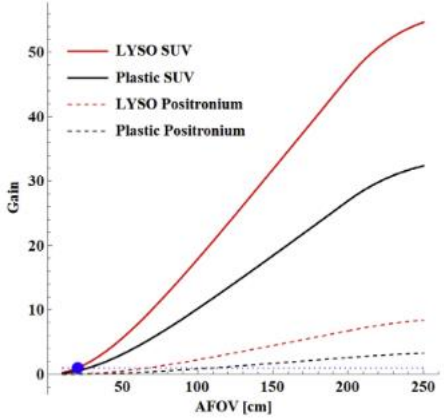


Figure from P. Moskal et al.., Phys. Med. Biol. 66 (2021) 175015





Figures from P. Moskal, E. Stępień, PET Clin. 15 (2020) 439

Conclusions

- The first test of the CPT symmetry with angular correlations in ortho-positronium annihilations at prevision below per-mil level was performed by J-PET. Results was obtained from the only 27-day measurement, leaving a lot of field to improvements in future
- The first image of an object extensive in size was obtained using three-photon annihilations of ortho-positronium.
- Properties of the 3γ reconstruction are being studied further in view of multi-photon imaging

Acknowledgment

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Smart Growth

Foundation for
Polish Science

European Union
European Regional
Development Fund

Thank you

for your

attention

Results of the CPT test and three-photon imaging

Evaluation of the CPT-asymmetric observable

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

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

$$\frac{N_+ - N_-}{N_+ + N_-} \rightarrow \frac{\int N(\cos\theta)\cos\theta}{\int N(\cos\theta)}$$

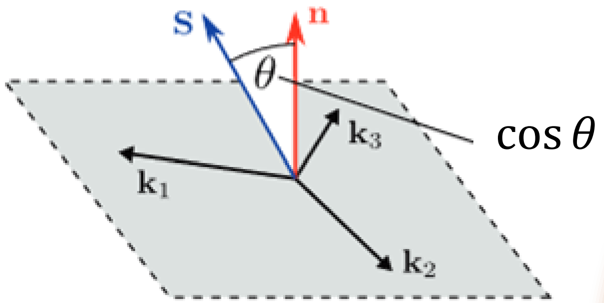
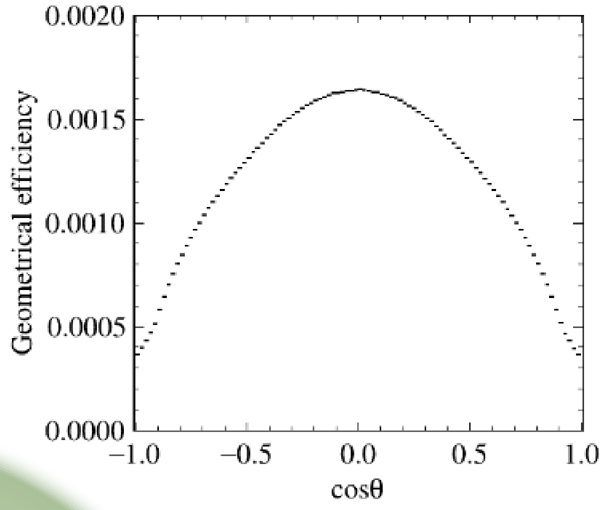
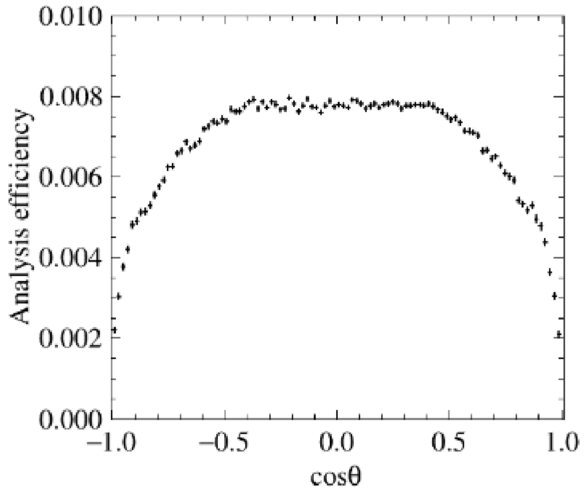


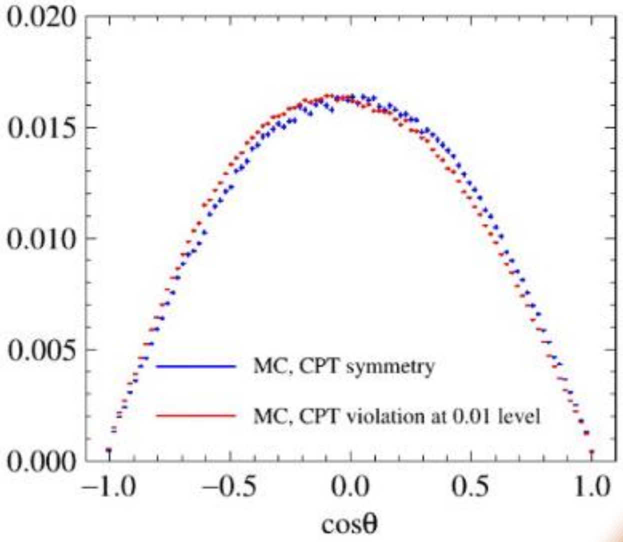
Figure from P. Moskal, A. Gajos et al., Nature Comm. 12 (2021) 5658

Results of the CPT test

Simulation data were generated in order to estimate efficiencies: geometrical and analysis







The same statistic as for the data and after the same cuts

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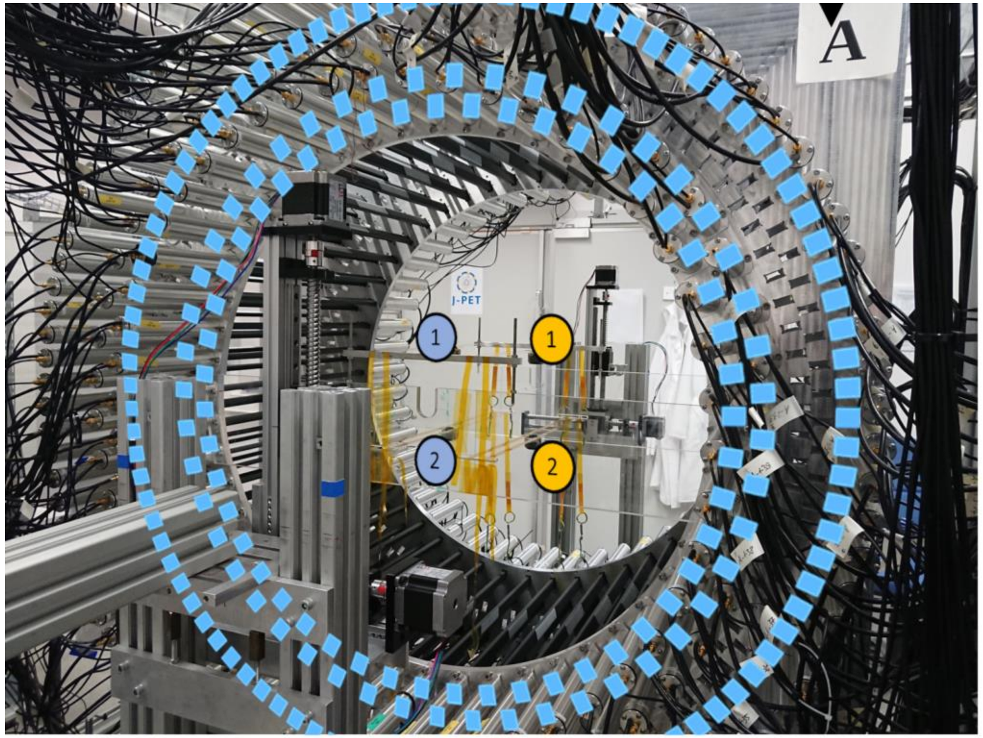
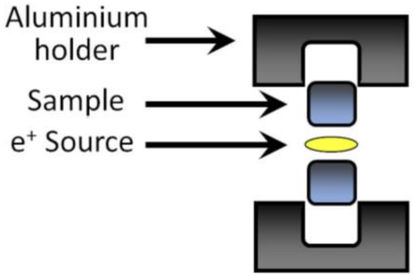
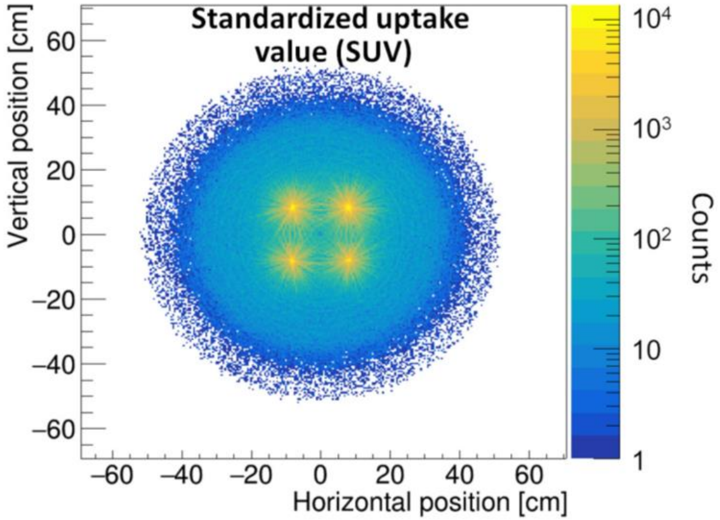
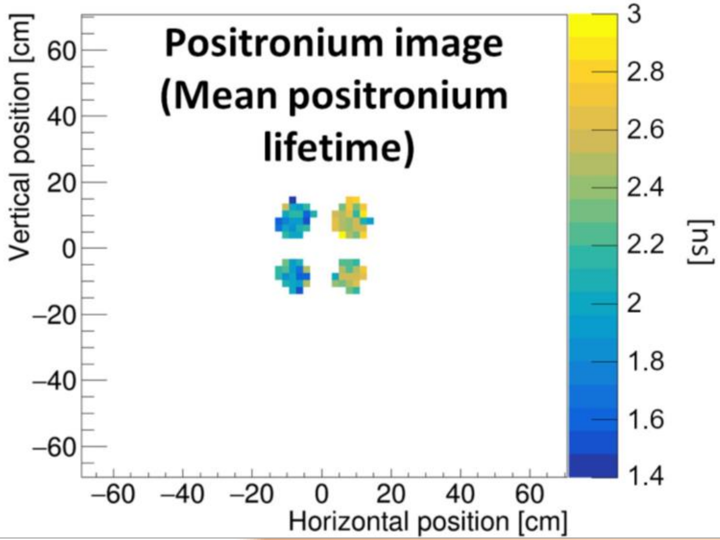
Future developments

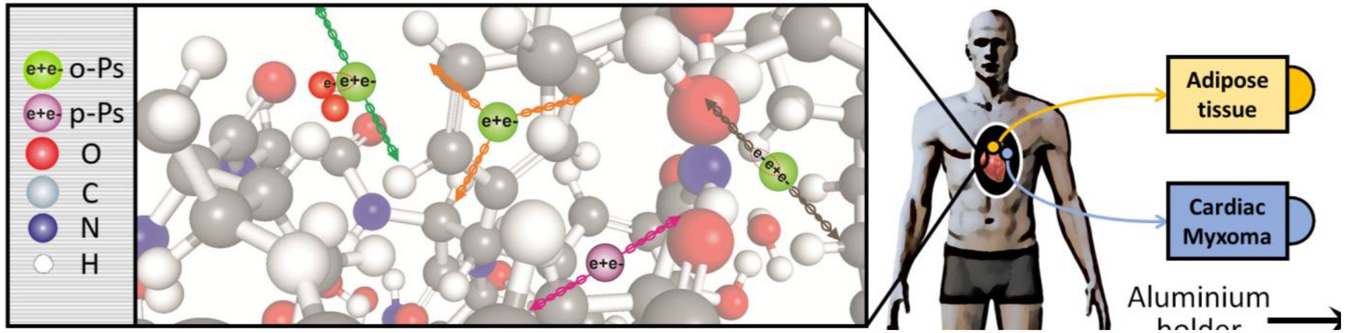




Positronium imaging



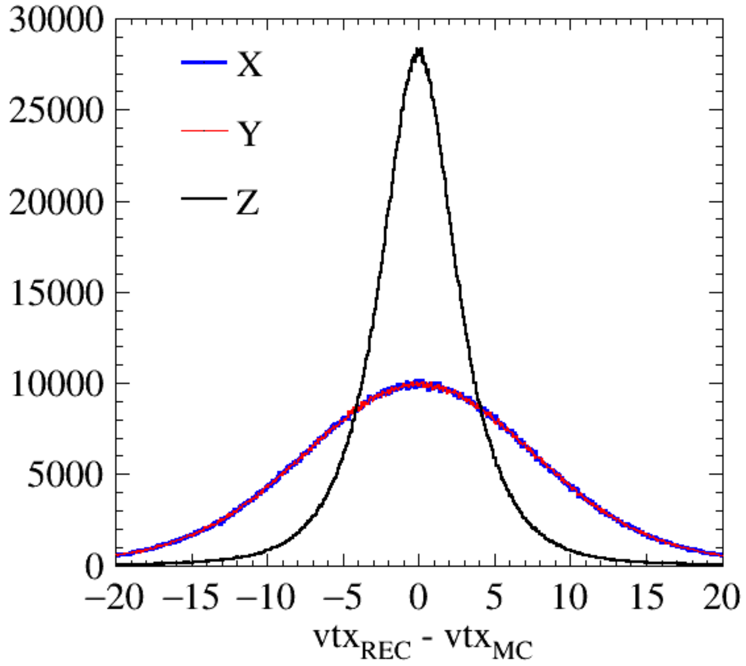




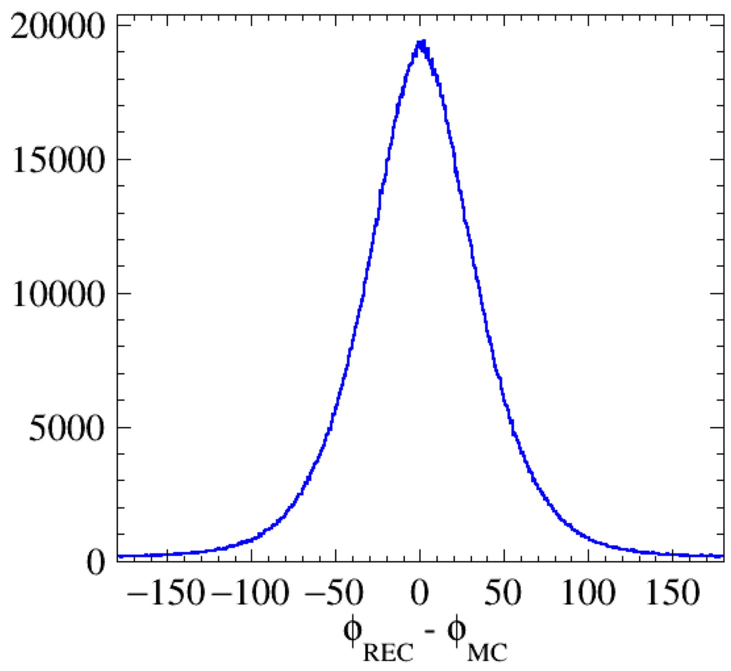
Figures from P. Moskal, K. Dulski et al.., Science Adv. 7 (2021) 10.1126/sciadv.abh4394

Resolutions from o-Ps 3G annihilation point

Cartesian



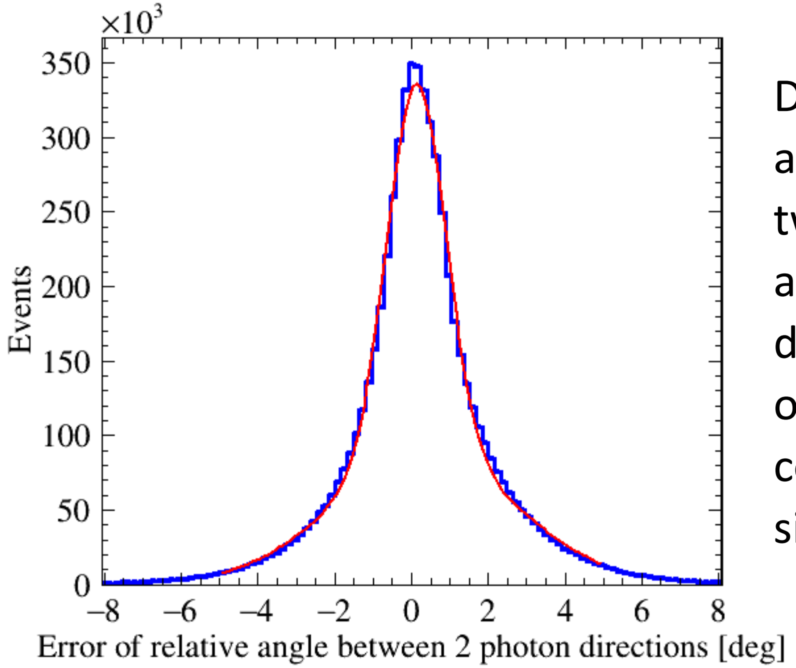
Azimuthal



σ(X) = σ(Y) = 8.0 cm and σ(Z) = 3.2

σ(ϕ) = 35^{o} -> Polarization 37.4%

Angular resolution



Distribution of the error of the relative angle between momentum directions of two photons originating from the same annihilation event (blue) and a fit of a double Gaussian function (red), average σ of which amounts to 1.18 degree, corresponding to angular resolution of a single photon interaction of 0.83 degree.

Energy Smearing in MC

$$\sigma(t) = \frac{\sigma_0(t)}{\sqrt{E_{dep}/E_0}}$$

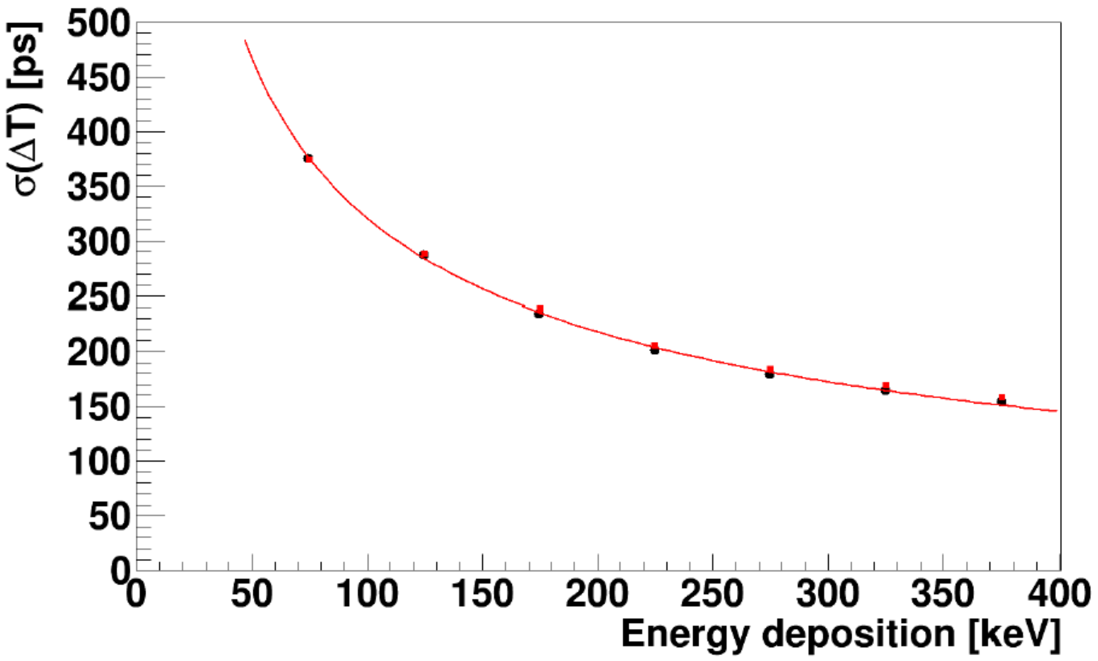
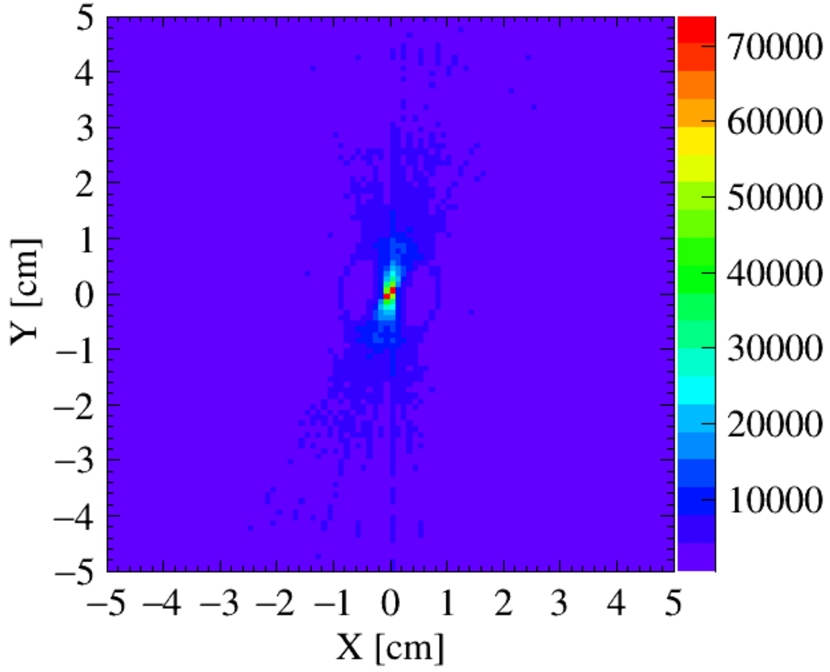


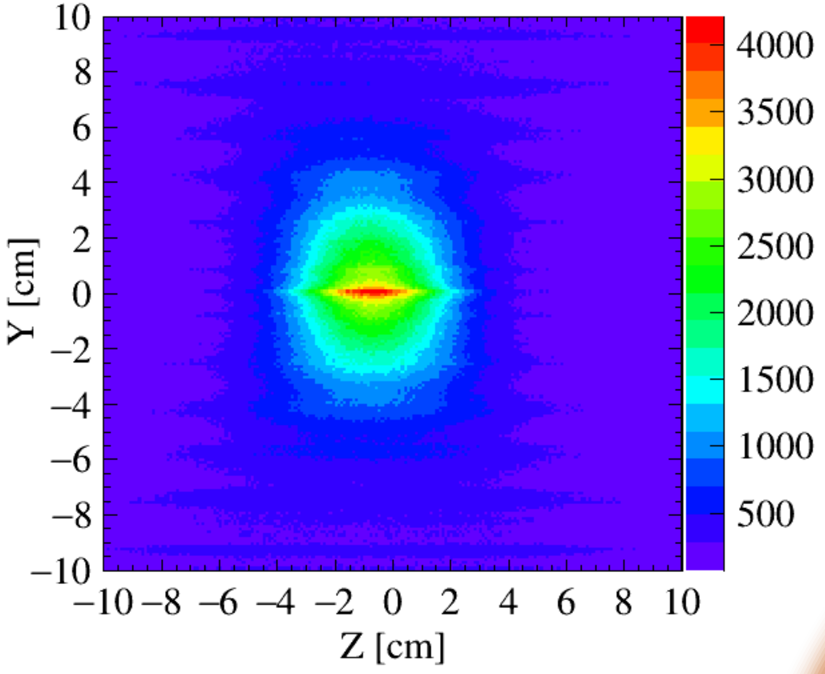
Figure from S. Niedźwiecki PhD thesis,
http://koza.if.uj.edu.pl/files/be8d72b864fb25187429a881d600d3b4/main.pdf

Position shift effect

Annihilation positions from 2G annihilations



7 mm shift from zero in 0



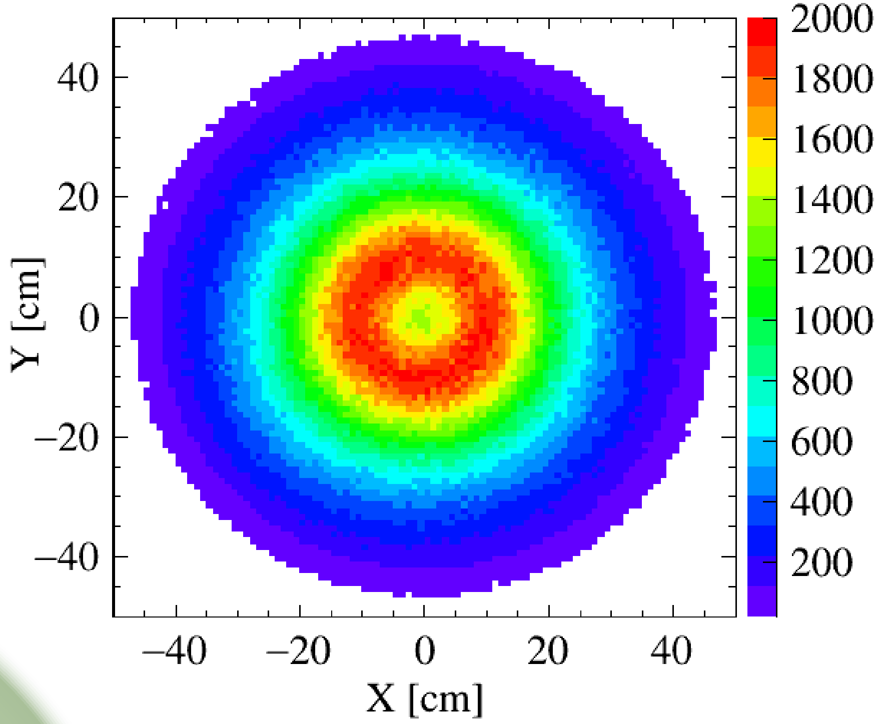
5 mm shift in MC -> systematic error = 4.5×10^{-5} for X,Y and 2.8×10^{-5}

↓

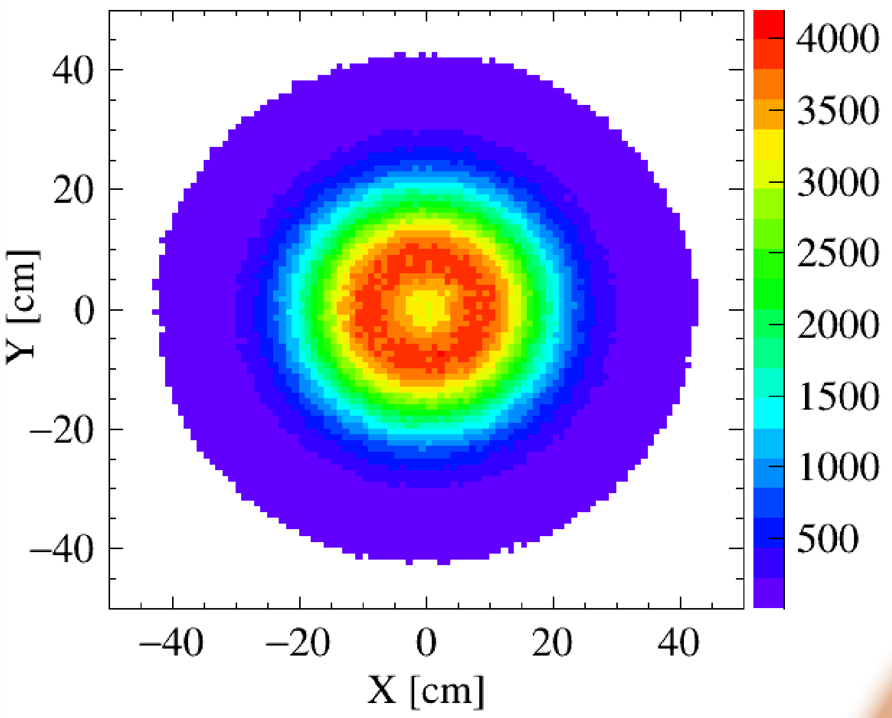
more than order of magnitude larger error than the real precision of the source position determination

Image reconstruction comparison with MC

Data



MC



Polarization estimate

The positron source is prepared as a micro-droplet of liquid 22NaCl, evaporated and closed in a very thin 7 µm Kapton foil with density of ~1.5 g/cm3 resulting in areal density of ~1 mg/cm2. Therefore, the scattering and depolarization of positrons in the source material is negligible with respect to the 8% of polarisation loss estimated for the 3 mm thick target material with the density of 0.32 g/cm3 resulting in areal density of ~100 mg/cm2.

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

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