Test of discrete symmetries with spin observables at J-PET

K. Dulski[a], A. Gajos[a], P. Moskal[a]

On behalf of the J-PET collaboration

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High Energy Physics Seminar,
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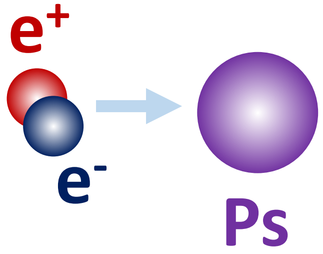
J-PET

Outline

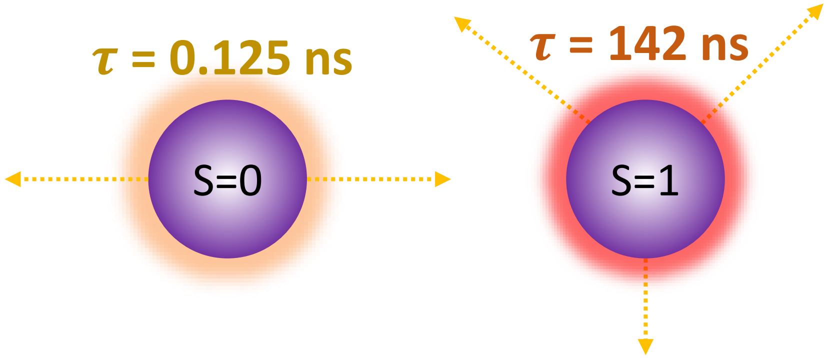
- Positronium and discrete symmetries
- J-PET detector and the image reconstruction
- Experimental and analysis procedures
- Treatment of the background events
- Results of three-photon imaging and the CPT test
- Positronium imaging and future development
- Conclusions

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**



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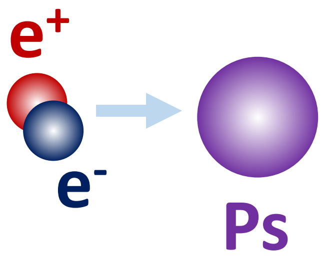
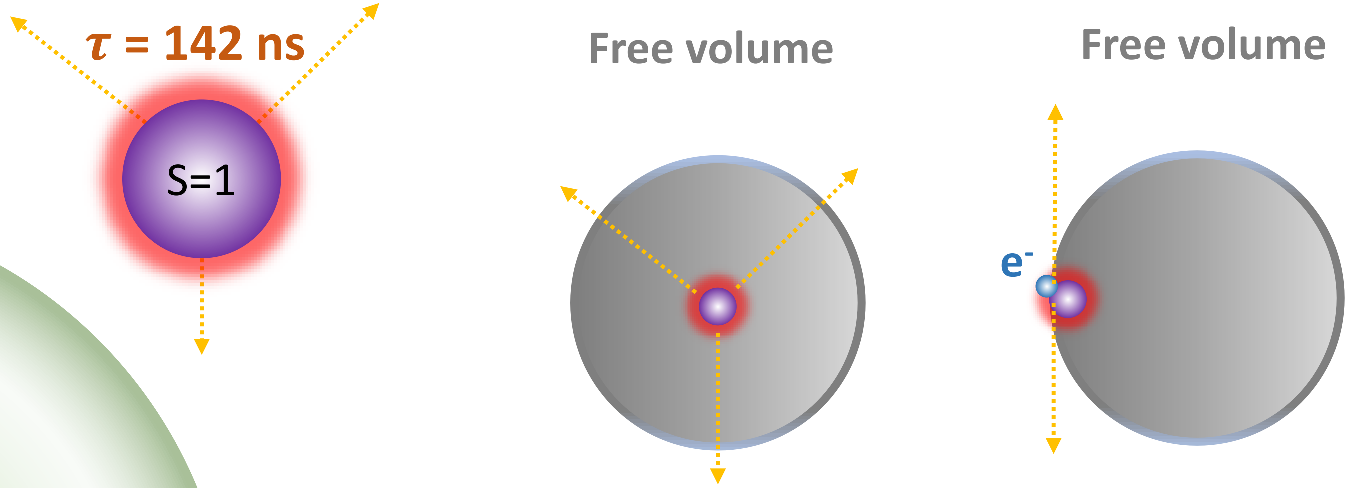
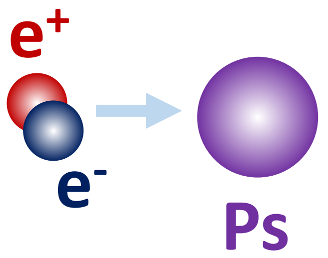


In matter **ortho-Ps** mean lifetime can be shorten mainly due to the pick-off proces and ortho-para conversion



It also decreases number of the o-Ps decays into 3 photons

Positronium



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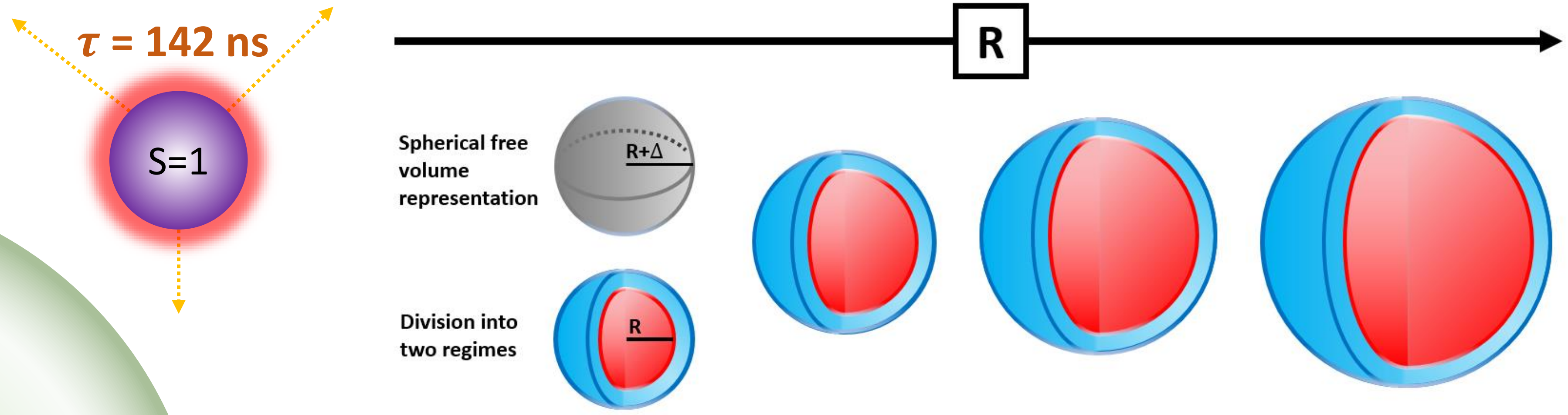

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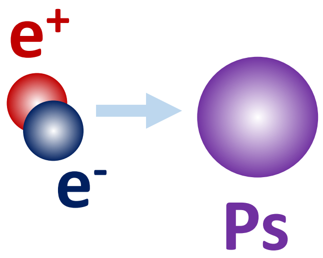

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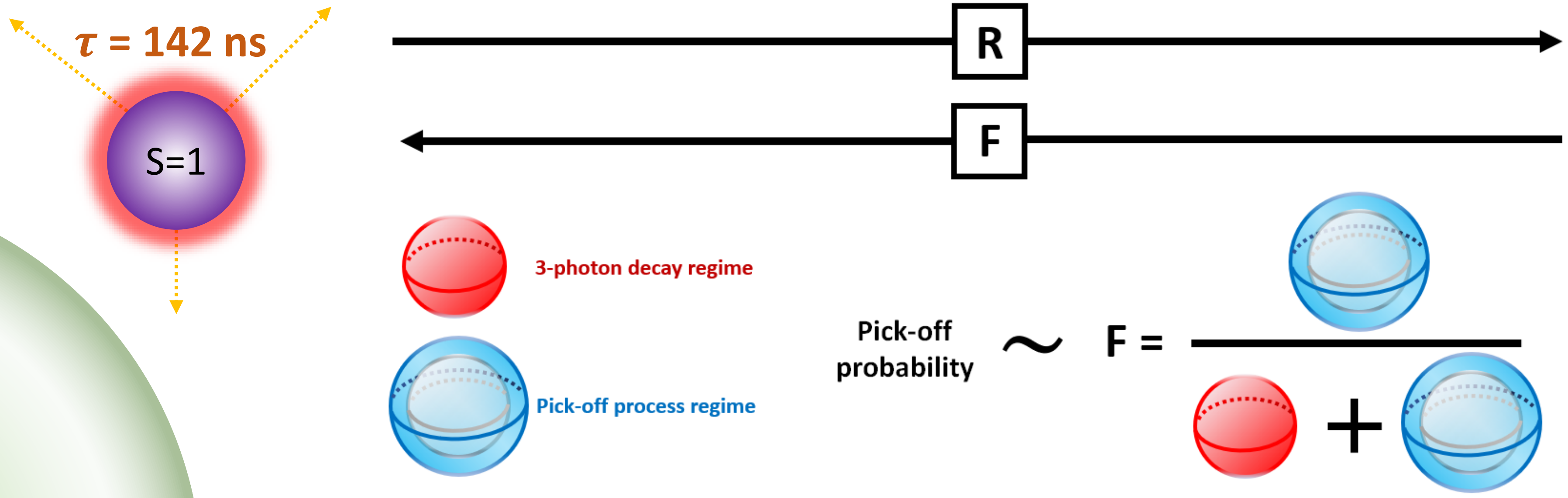

Positronium

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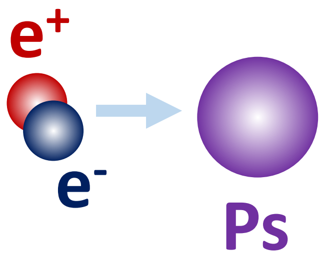

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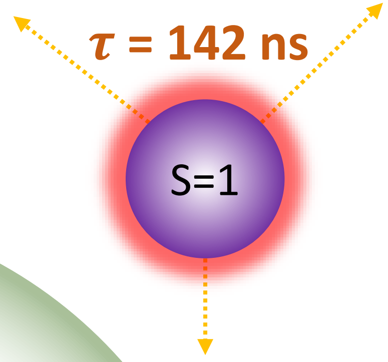
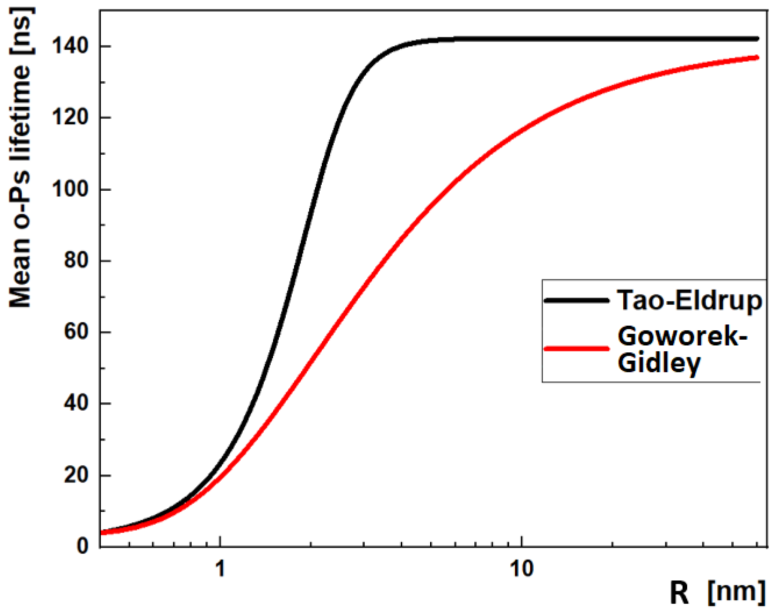


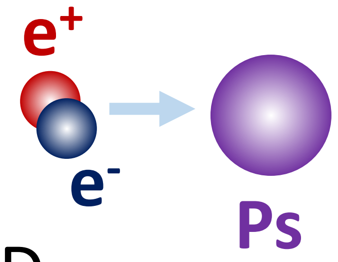


Mean o-Ps lifetime can be translated into the free volume size

Motivation

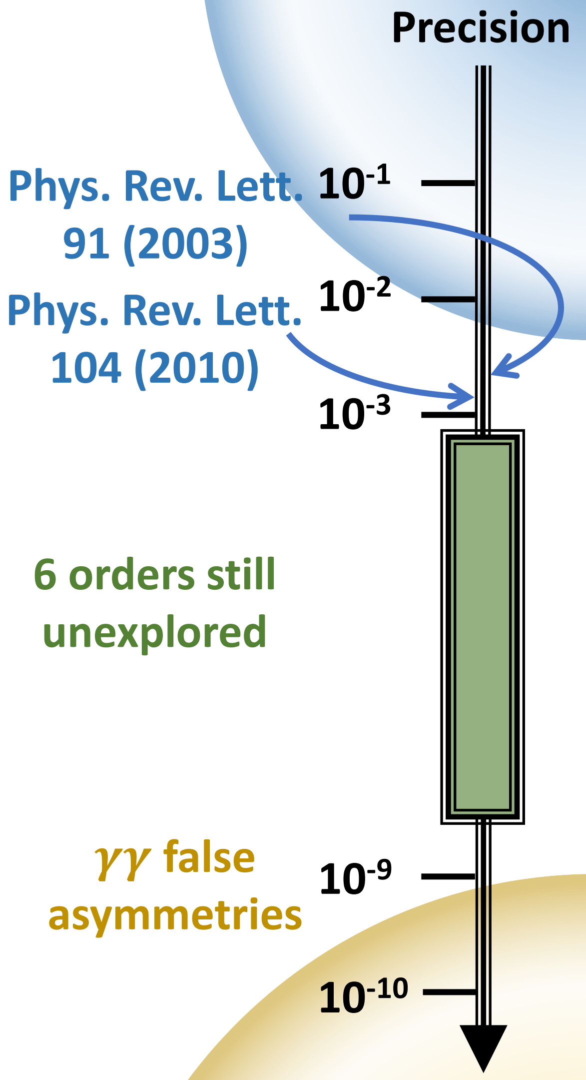
Pushing the limits for the test of the discrete symmetries on leptonic systems

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)



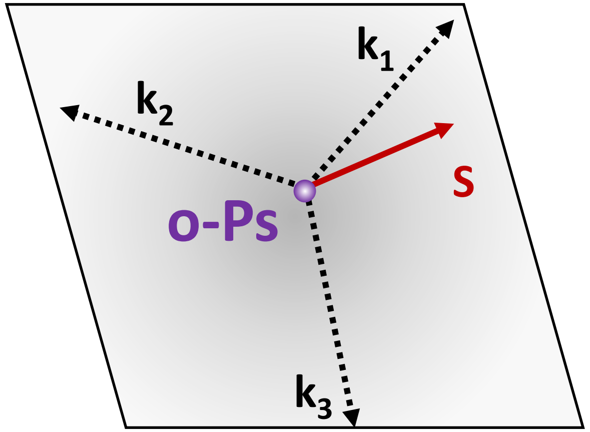
Motivation

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



Other operators

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

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

Using photon polarization

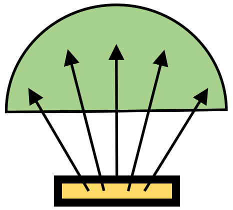
$\vec{k}_2 \cdot \vec{\epsilon}_1$	**+**	**-**	**-**	**-**	**+**
$\vec{S} \cdot \vec{\epsilon}_1$	+	+	-	+	-
$\vec{S} \cdot (\vec{k}_2 \times \vec{\epsilon}_1)$	+	-	+	-	-

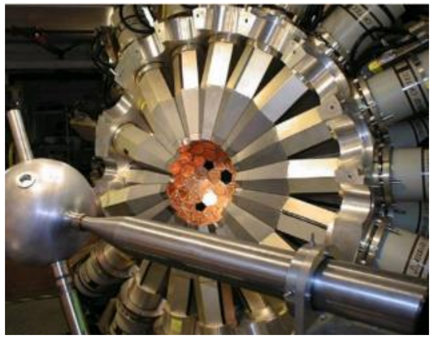
P. Moskal et al., Acta Phys. Polon. B47 (2016) 509

Motivation

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

Phys. Rev. Lett. 91 (2003)





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

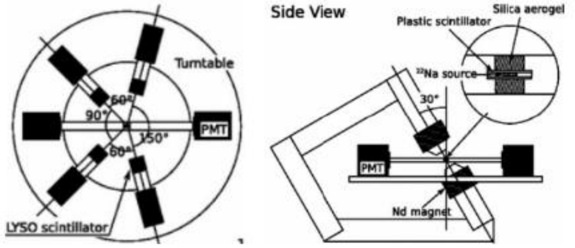
Limiting positron emission direction
1 Mbq β+ emitter activity
4π detector but low angular resolution

C_{CPT} = (2.6±3.1)×10-3

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

Phys. Rev. Lett. 104 (2010)

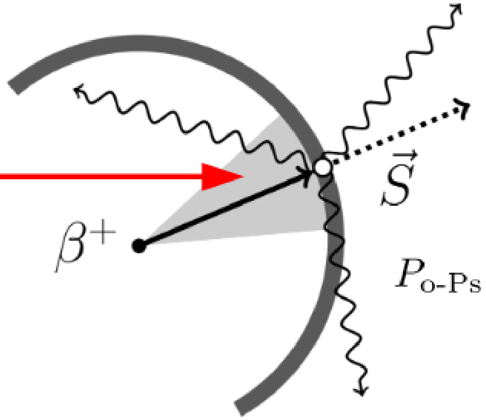
Polarized o-Ps using external B field
Inclusive measurement
Only certain angular configurations



C_{CP} = (1.3±2.1±0.6)×10-3

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

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



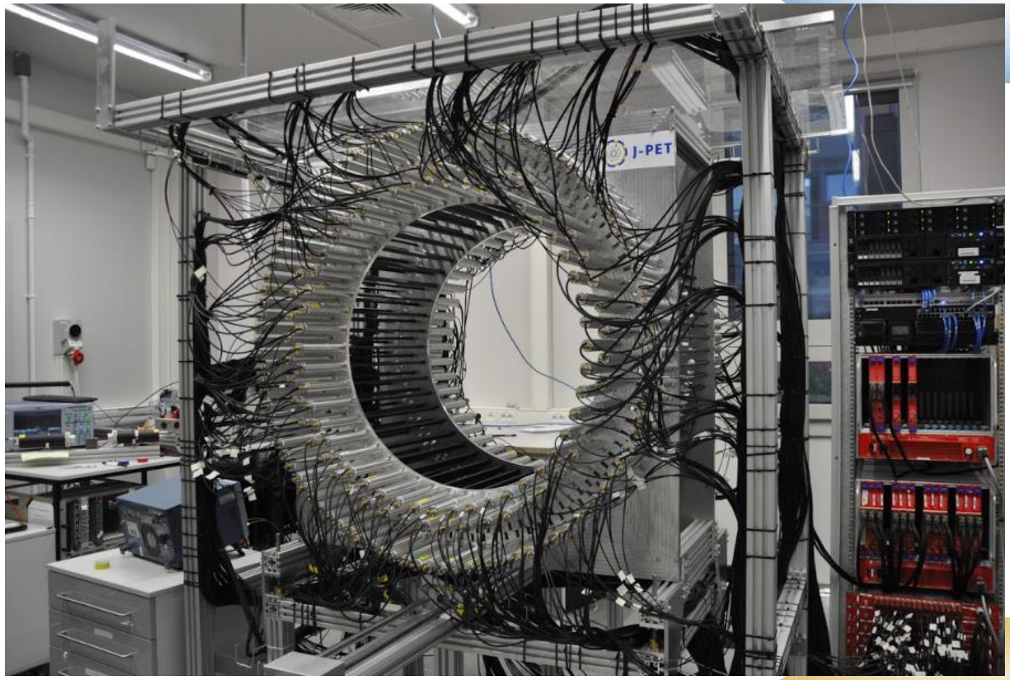
$$P_{\text{o-Ps}} = \frac{2}{3} P_{e+}$$

J-PET detector

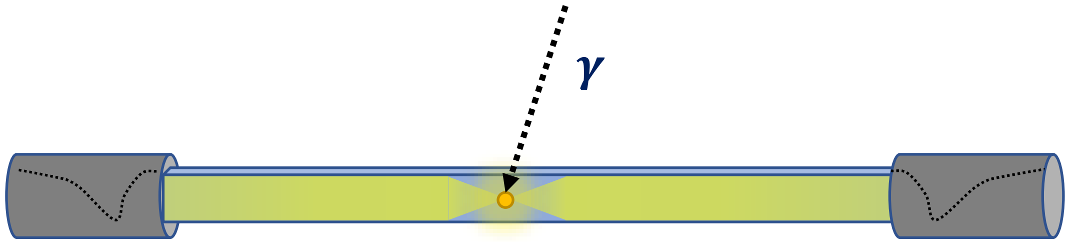
Device for detection of the photons from positronium annihilation (~0.5 MeV) and nucleus deexcitation (~1 MeV)

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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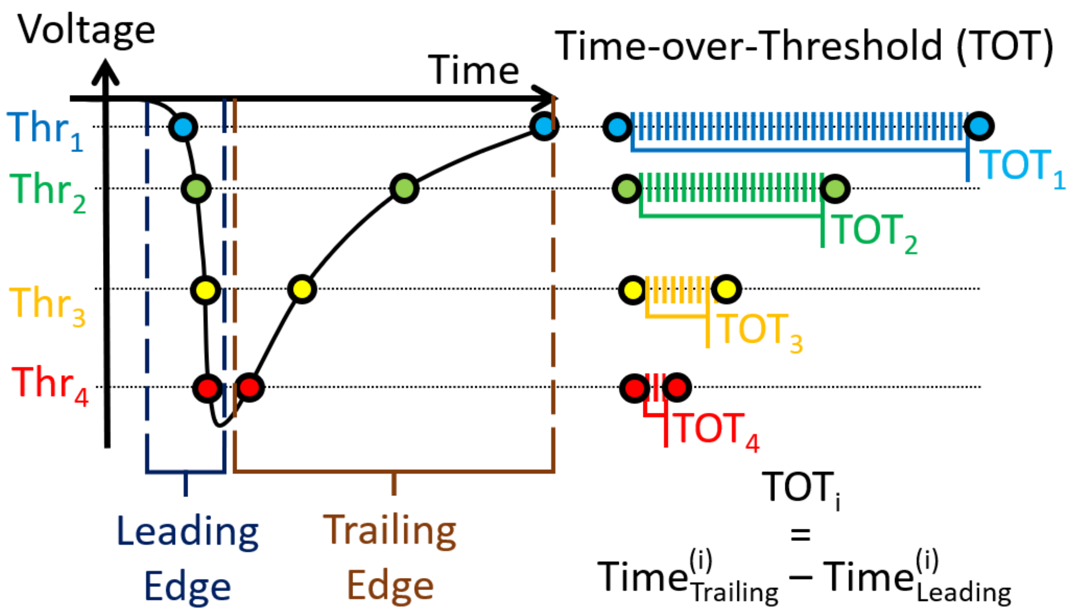

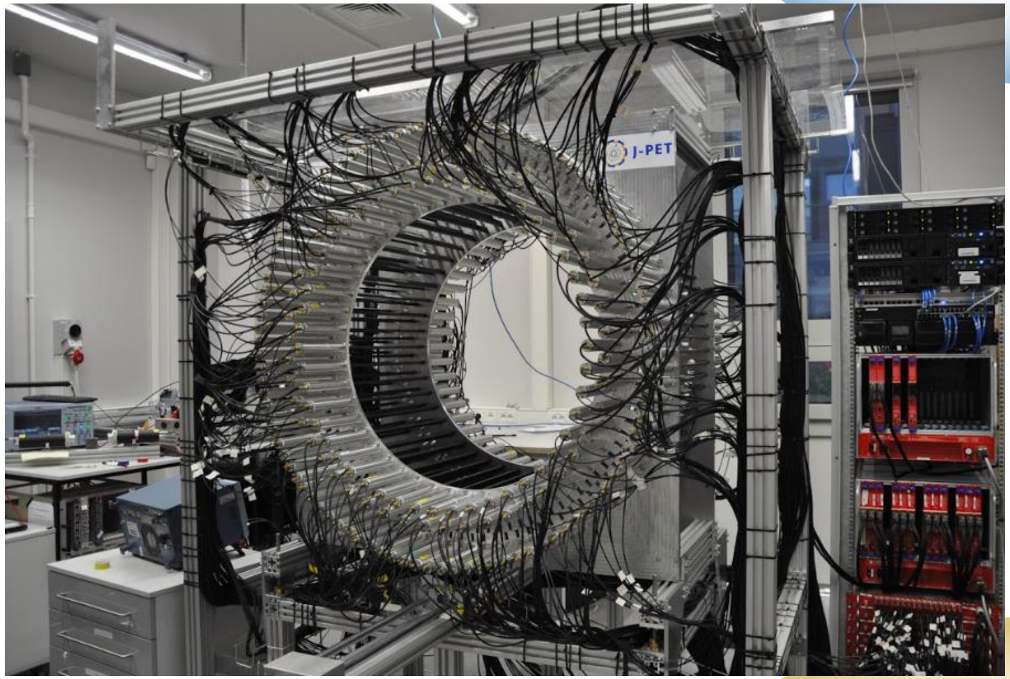

P. Moskal et al., IEEE Trans. Instrum. Meas. 70 (2021) 2000810
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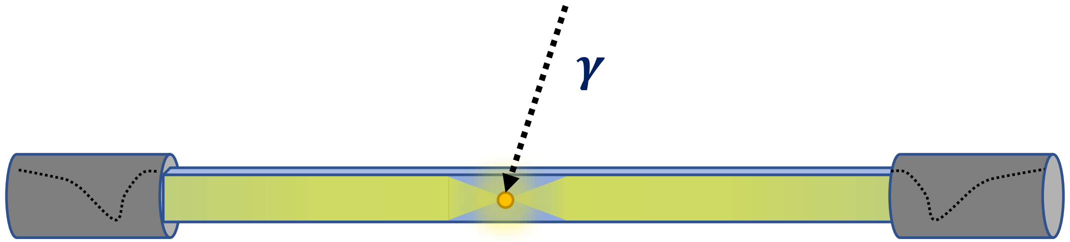


J-PET detector

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

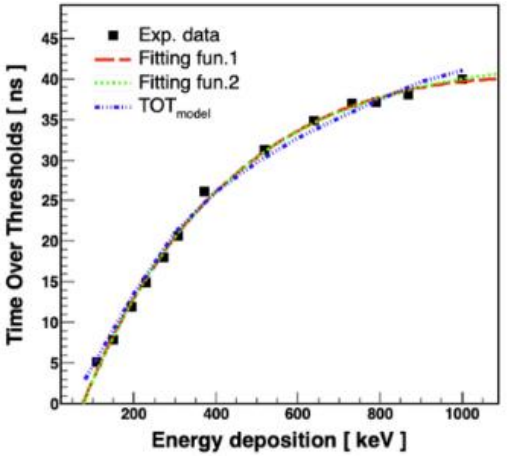
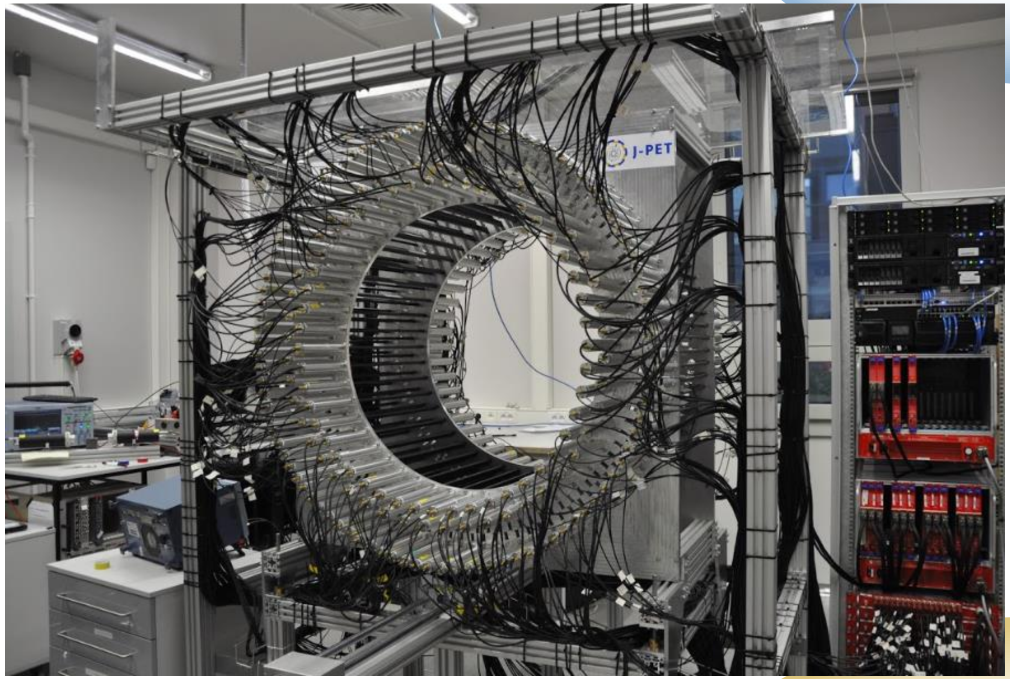


Figure adapted from S. Sharma et al., EJNMMI Phys. 7(2020) 39



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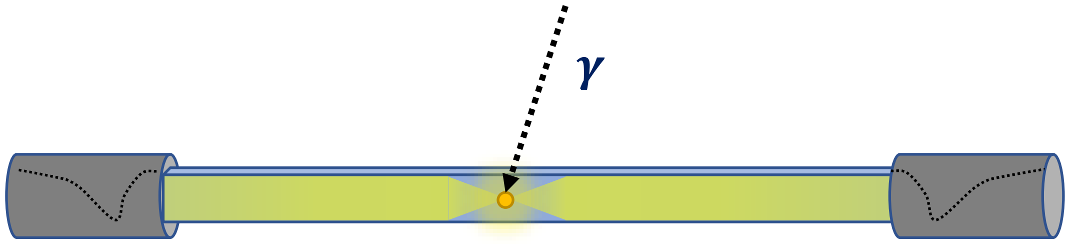
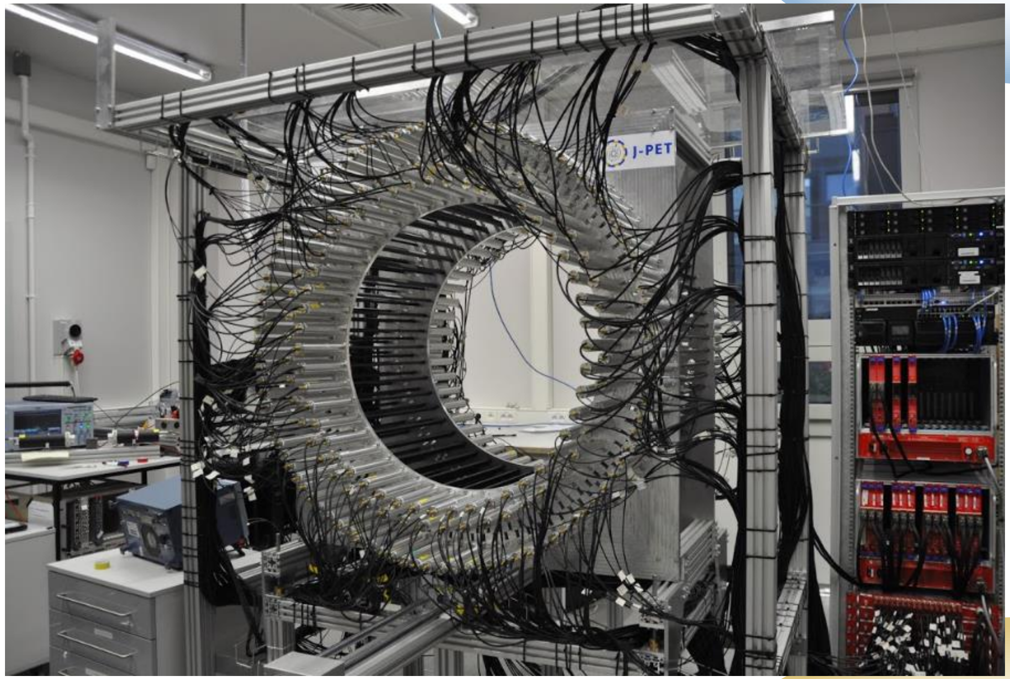


J-PET detector

Both energy and position of the hit reconstructed based on the measured times (resolution ~350 ps in FWHM[1])

Annihilation position reconstruction based on multi-photon coincidences

[1]K. Dulski et al., NIM A 1008 (2021) 165452



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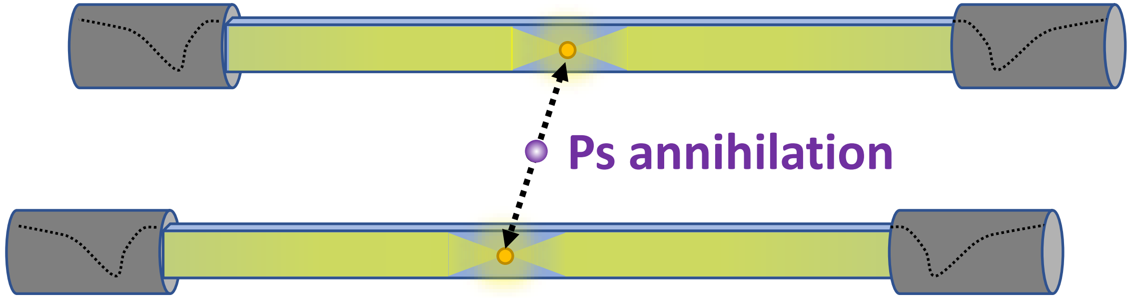
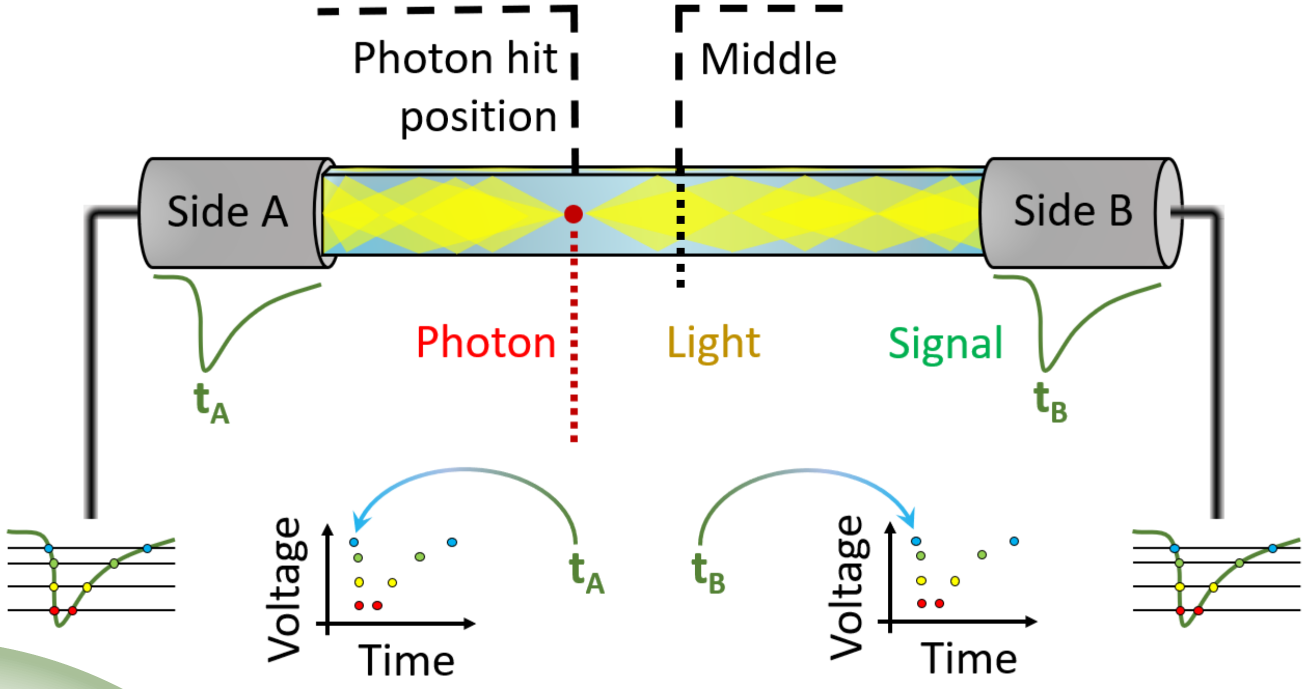
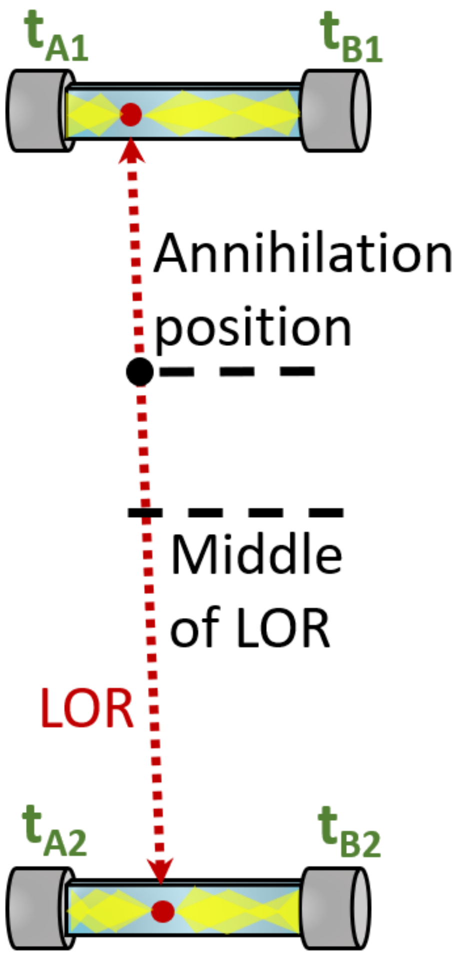


J-PET detector – image reconstruction





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

Annihilation position – Middle of LOR

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

J-PET detector – image reconstruction

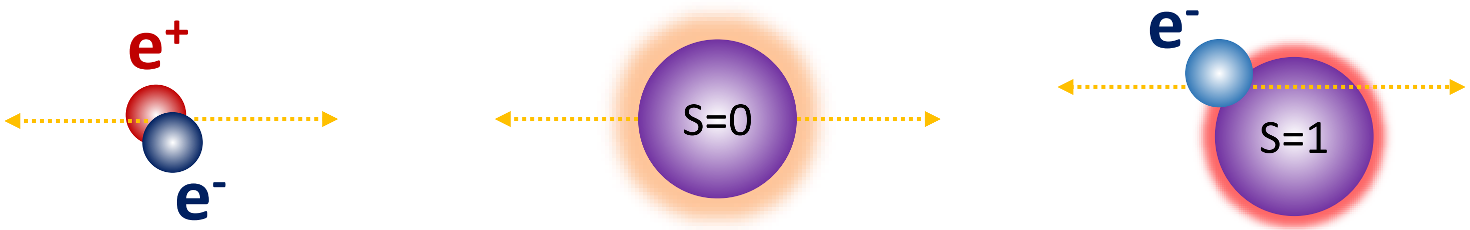


Image from the 2-photon annihilation can be reconstructed using specific algorithms

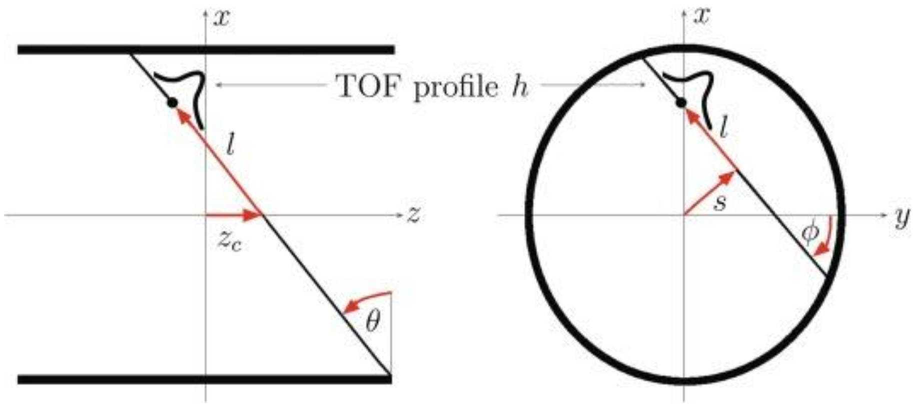


Figure from L. Raczyński et al., Physica Medica 80 (2020) 230

TOF-BPTV
(TOF Back Projection Total Variation regularization)

TOF-FBP
(TOF Filtered Back Projection)

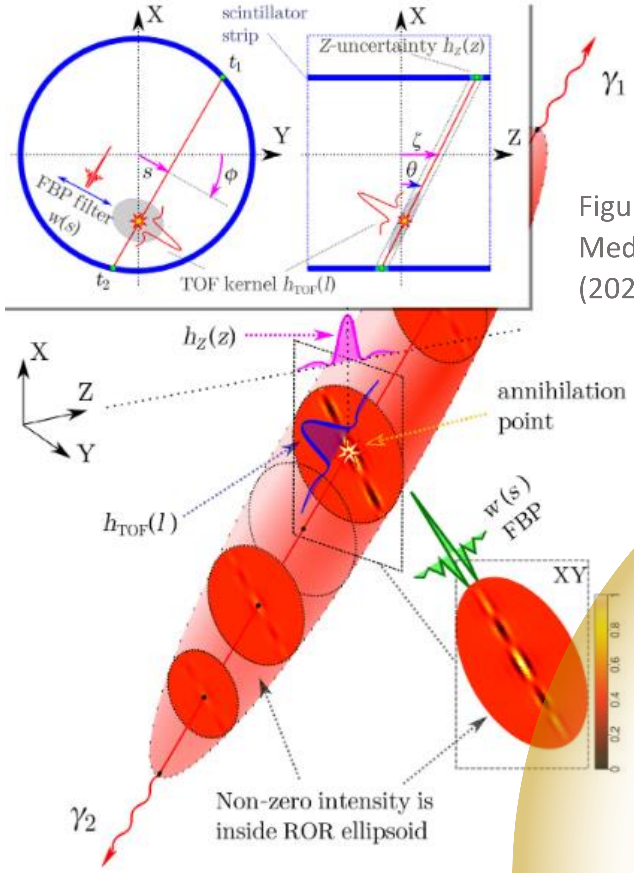


Figure from R.Y. Shopa et al., Medical Image Analysis 73 (2021) 102199

J-PET detector – image reconstruction

We have also developed our own image reconstruction algorithms

Thanks to K. Klimaszewski, P. Kopka, P. Kowalski, W. Krzemień, L. Raczyński, R.Y. Shopa, W. Wiślicki

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Physica Medica
Volume 80, December 2020, Pages 230-242

Original paper

3D TOF-PET image reconstruction using total variation regularization

L. Raczyński [a], W. Wiślicki [a], K. Klimaszewski [a], W. Krzemień [b], P. Kopka [a], P. Kowalski [a], R.Y. Shopa [a], M. Bała [c], J. Chhokar [c], C. Curceanu [d], E. Czerwiński [c], K. Dulski [c], J. Gajewski [e], A. Gajos [c], M. Gorgol [f], R. Del Grande [f], B. Hiesmayr [g], B. Jasińska [f], K. Kacprzak [c], L. Kapłon [c], D. Kisielewska [c], G. Korcyl [c], T. Kozik [c], N. Krawczyk [c], E. Kubicz [c], M. Mohammed [c, h], S.z. Niedźwiecki [c], M. Pałka [c], M. Pawlik-Niedźwiecka [c], J. Raj [c], K. Rakoczy [c], A. Ruciński [e], S. Sharma [c], S. Shivani [c], M. Silarski [c], M. Skurzok [c, d], E.L. Stepień [c], B. Zgardzińska [f], P. Moskal [c]

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[c] Marian Smoluchowski Institute of Physics, Jagiellonian University, 31-348 Cracow, Poland
[d] INFN, Laboratori Nazionali di Frascati, 00044 Frascati, Italy
[e] Institute of Nuclear Physics PAN, Cracow, Poland
[f] Institute of Physics, Maria Curie-Skłodowska University, 20-031 Lublin, Poland
[g] Faculty of Physics, University of Vienna, 1090 Vienna, Austria
[h] Department of Physics, College of Education for Pure Sciences, University of Mosul, Mosul, Iraq

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Medical Image Analysis
Volume 73, October 2021, 102199

Challenge Report

Optimisation of the event-based TOF filtered back-projection for online imaging in total-body J-PET

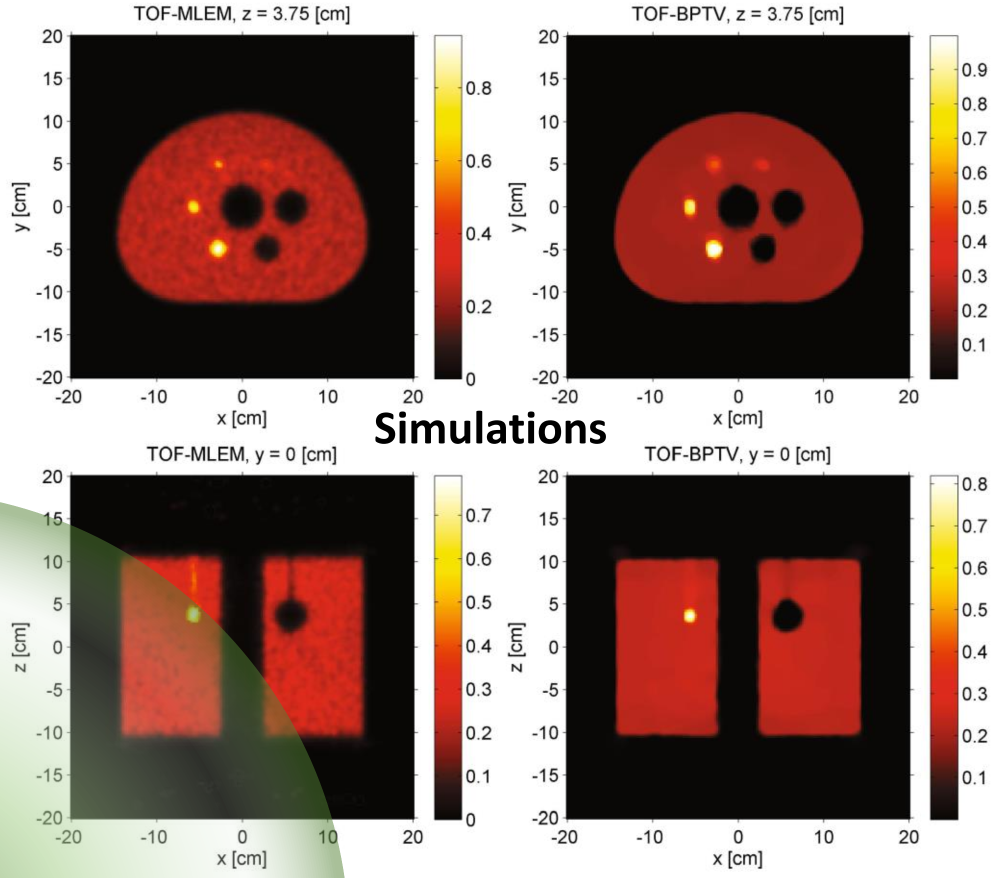
R.Y. Shopa [a], K. Klimaszewski [a], P. Kopka [a], P. Kowalski [a], W. Krzemień [b], L. Raczyński [a], W. Wiślicki [a], N. Chug [c, d], C. Curceanu [e], E. Czerwiński [c, d], M. Dadgar [c, d], K. Dulski [c, d], A. Gajos [c, d], B.C. Hiesmayr [f], K. Kacprzak [c, d], Ł. Kapłon [c, d], D. Kisielewska [c, d], G. Korcyl [c, d], N. Krawczyk [c, d], E. Kubicz [c, d], Sz. Niedźwiecki [c, d], J. Raj [c, d], S. Sharma [c, d], Shivani [c, d], E.Ł. Stępień [c, d], F. Tayefi [c, d], P. Moskal [1, c, d]

[a] Department of Complex Systems, National Centre for Nuclear Research, 05–400 Otwock-Świerk, Poland
[b] High Energy Physics Division, National Centre for Nuclear Research, 05–400 Otwock-Świerk, Poland
[c] Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University, prof. Stanisława Łojasiewicza 11, 30–348 Cracow, Poland
[d] Total-Body Jagiellonian-PET Laboratory, Jagiellonian University, Poland
[e] INFN, Laboratori Nazionali di Frascati, Frascati 00044, Italy
[f] Faculty of Physics, University of Vienna, Vienna 1090, Austria

J-PET detector – image reconstruction

Image reconstruction for NEMA IEC phantom

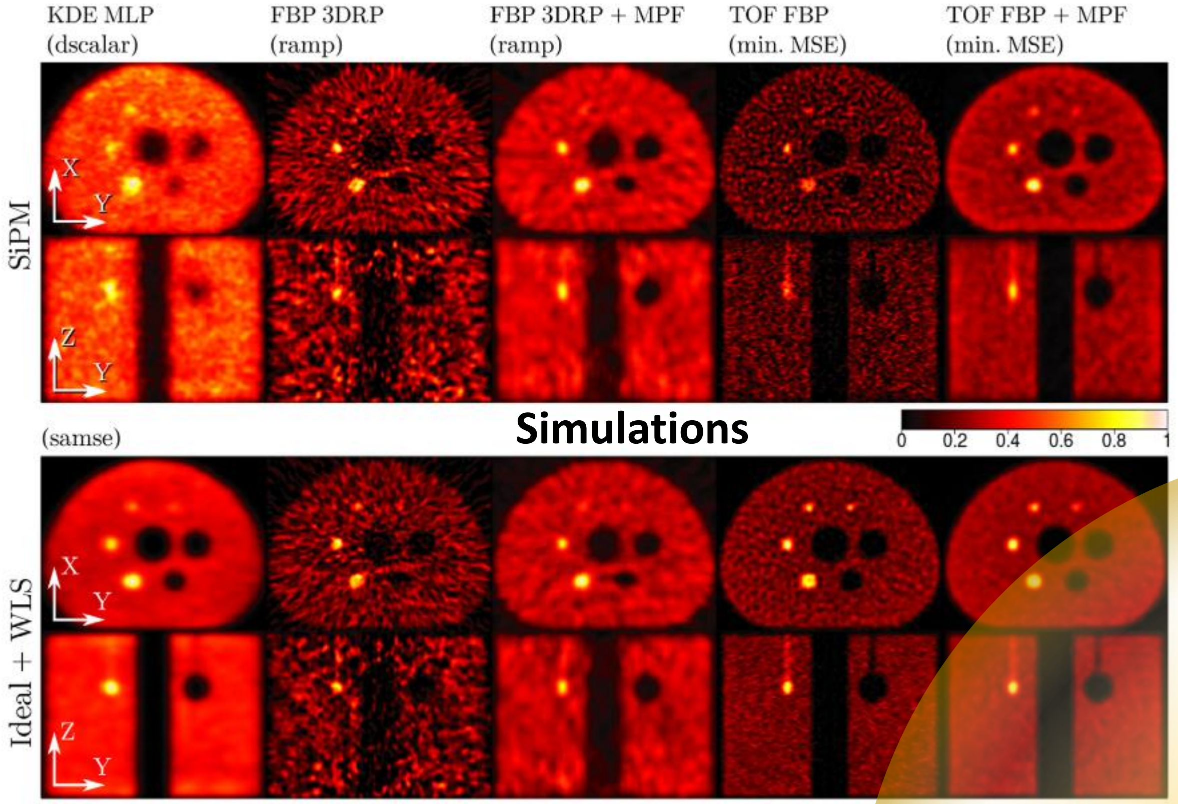
$FWHM_t$ = 230 ps, $FWHM_Z$ = 2 cm



Simulations

Figure L. Raczyński et al., Physica Medica 80 (2020) 230

KDE – Kernel Density Estimator, RP – Reprojection, MPF – Median Post Filter



Simulations

$FWHM_t$ = 235 ps

$FWHM_Z$ = 2.6 cm

$FWHM_t$ = 50 ps

$FWHM_Z$ = 2.6 cm

Figure from R.Y. Shopa et al., Medical Image Analysis 73 (2021) 102199

J-PET detector – image reconstruction

Their performance was compared with the most commonly used algorithms

CRC - Contrast recovery coefficient, BV – Background Variability

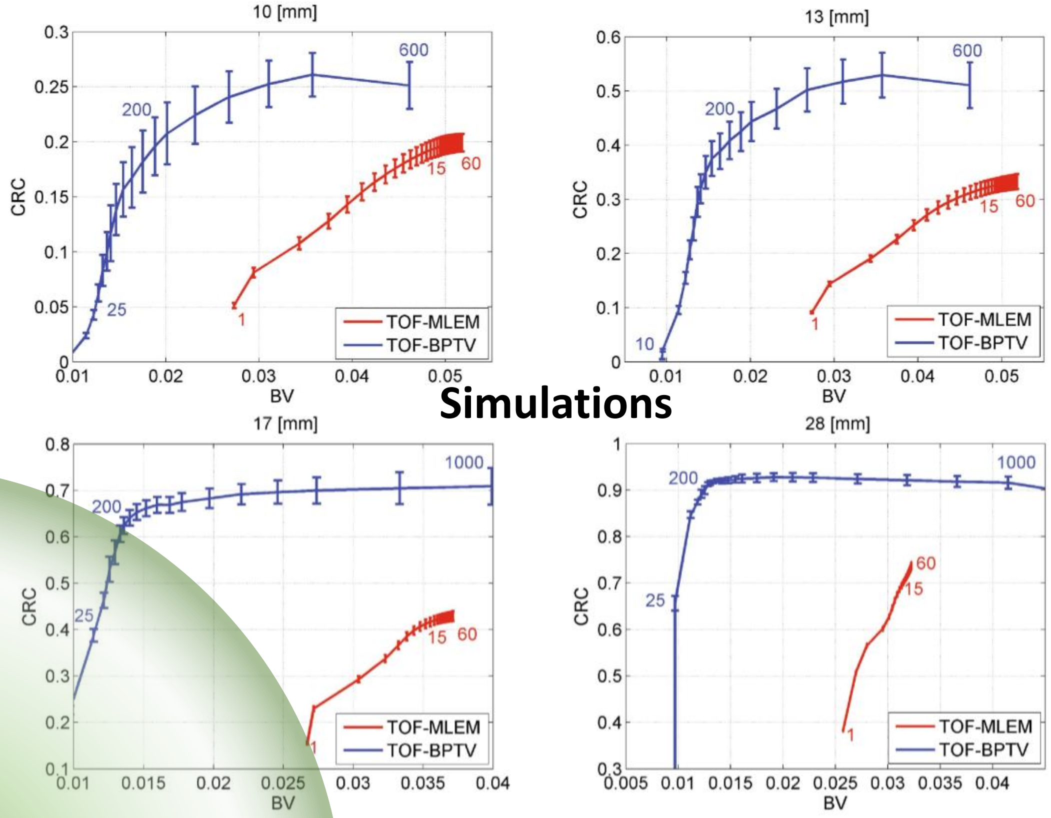


Figure L. Raczyński et al., Physica Medica 80 (2020) 230

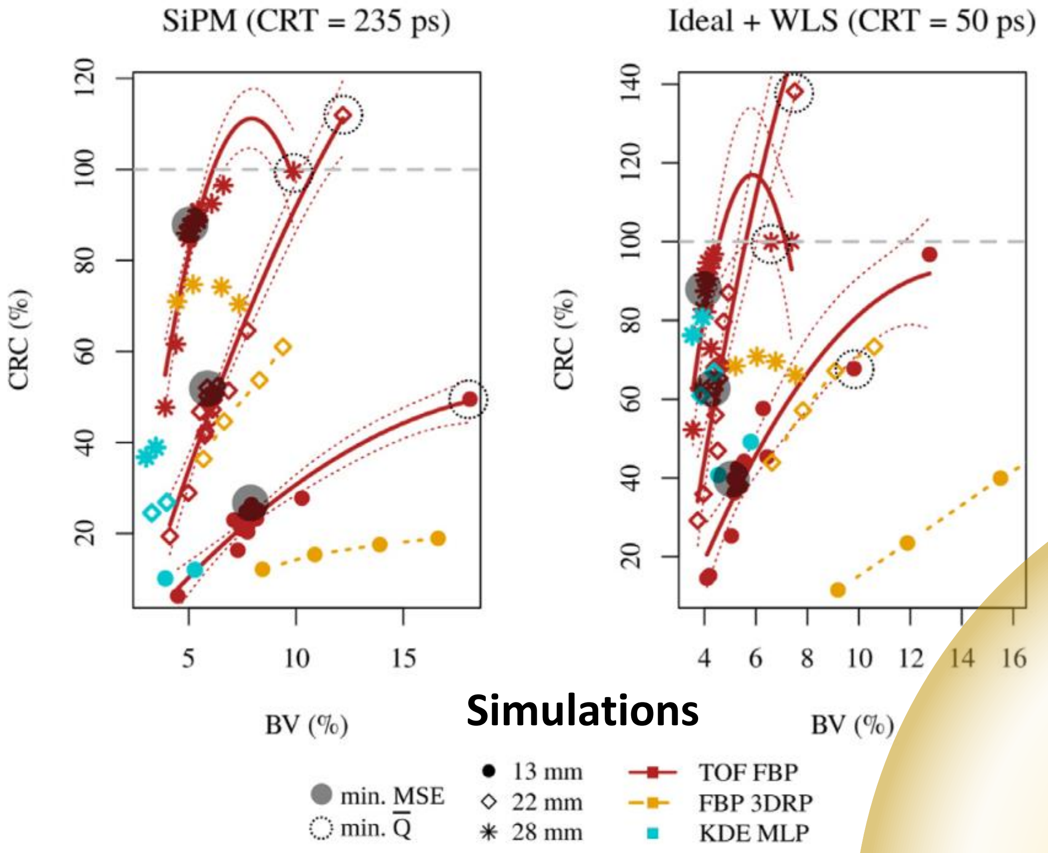
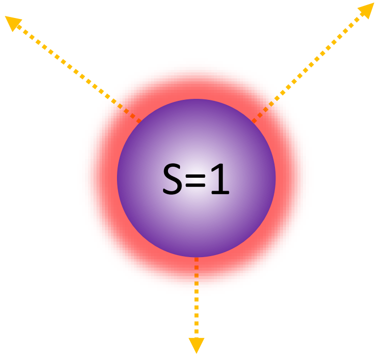
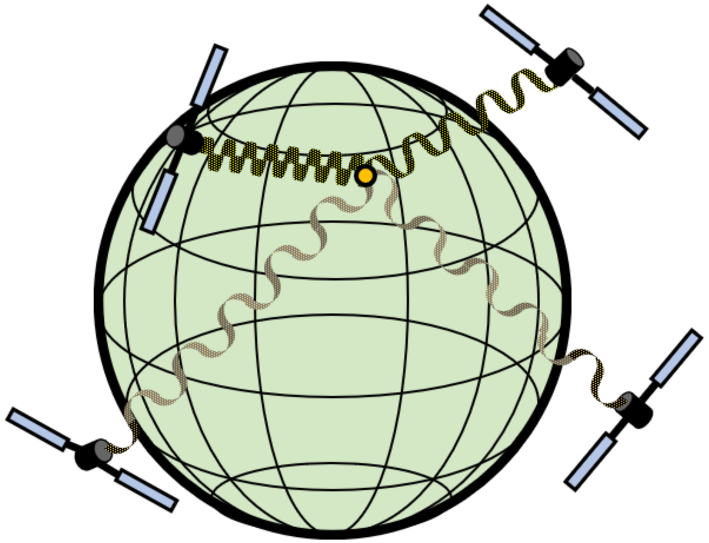


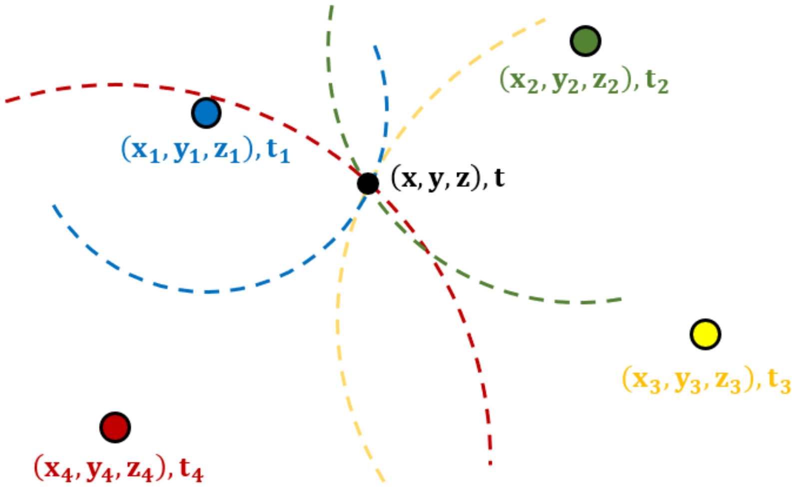
Figure from R.Y. Shopa et al., Medical Image Analysis 73 (2021) 102199

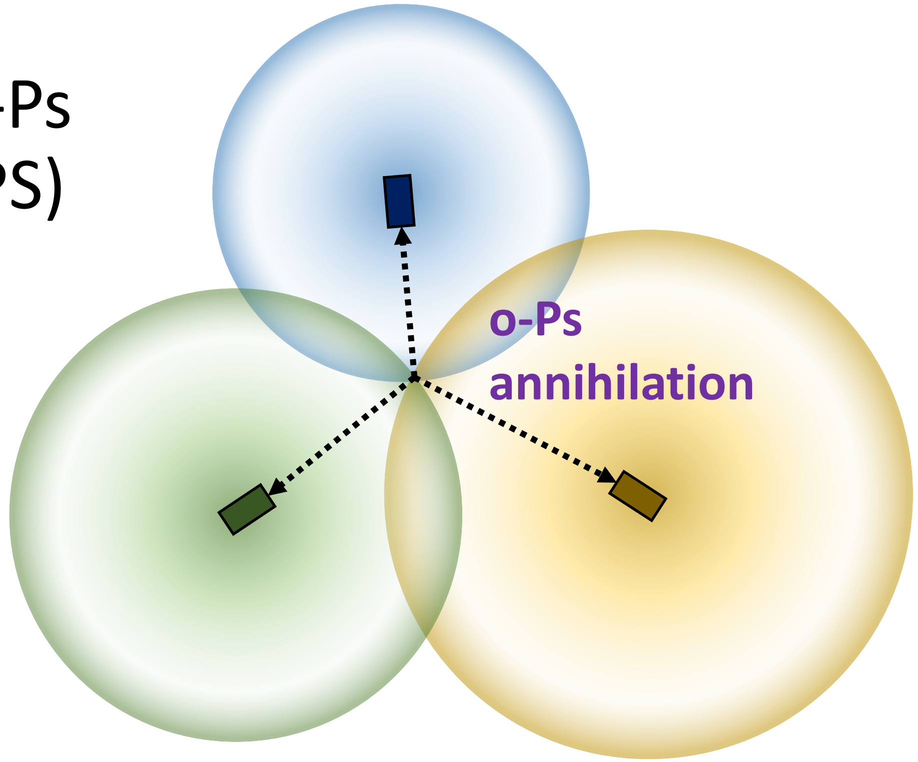
Trilateration method



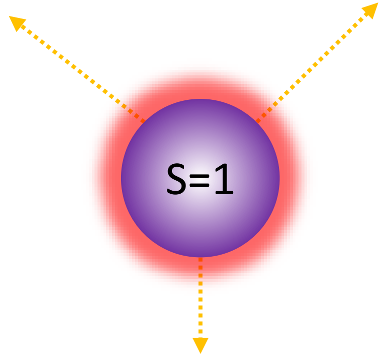
It is also possible to reconstruct annihilation position based on the annihilation of the ortho-Ps into 3 photons – trilateration method (like in GPS)
A. Gajos et al., NIM A 819 (2016) 54-59





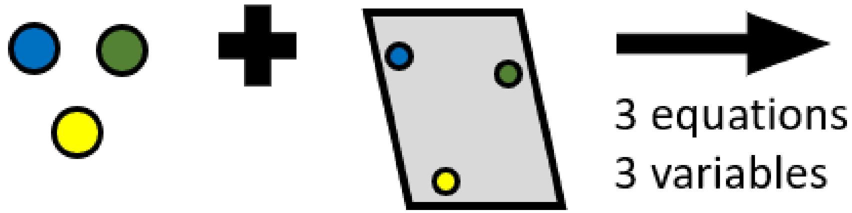


Trilateration method



3 signals

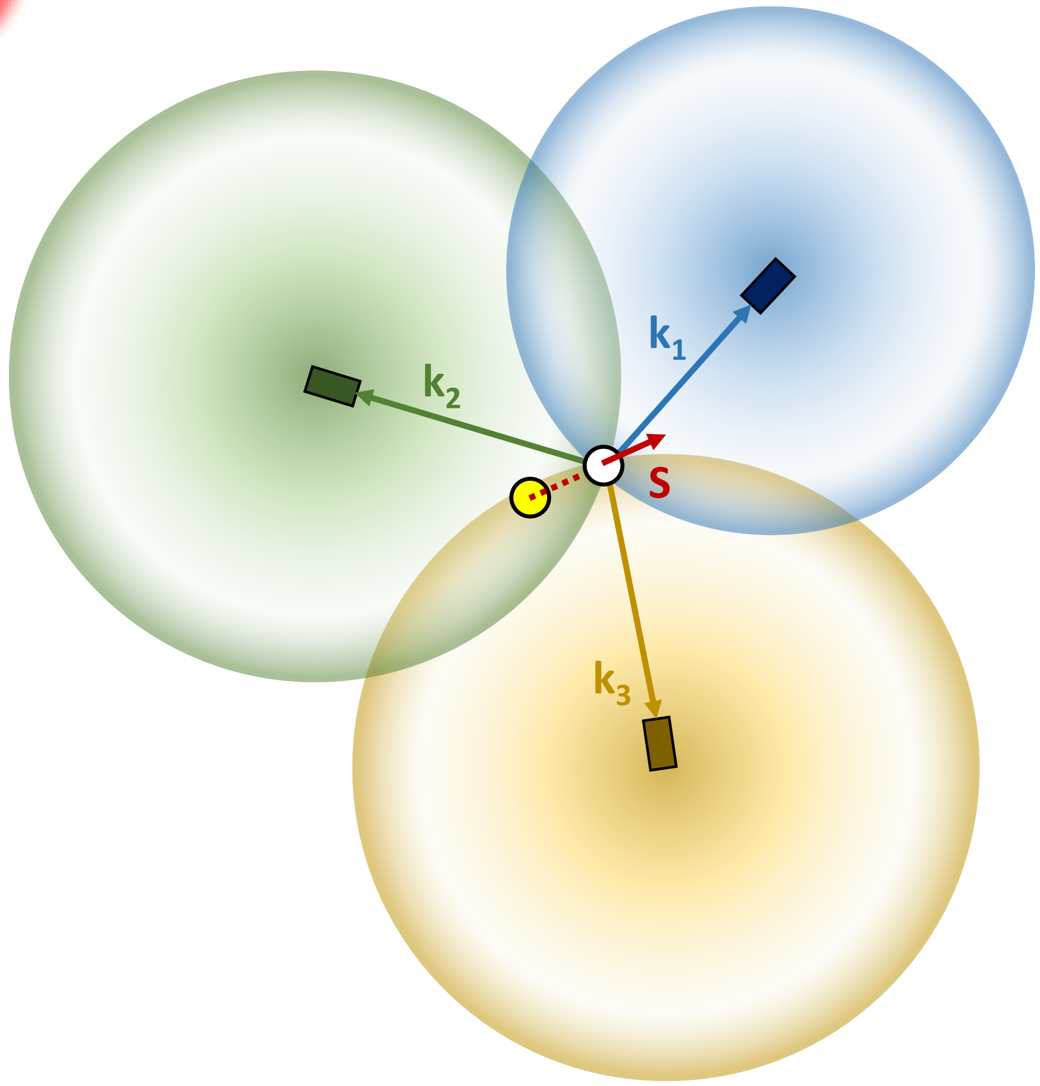
co-planarity



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

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

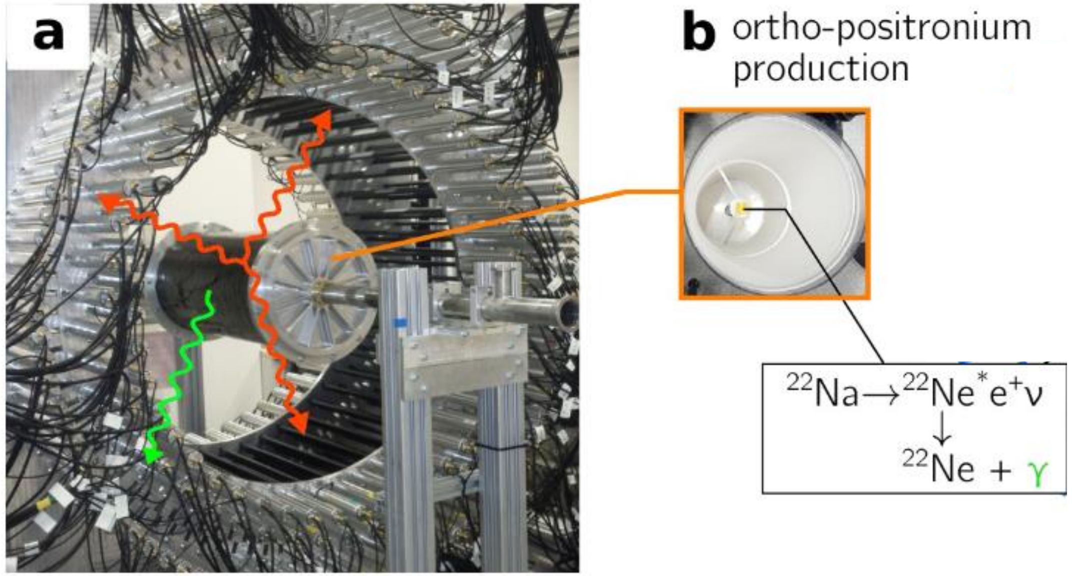
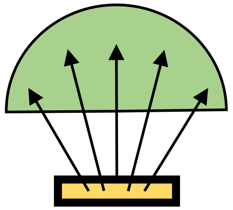


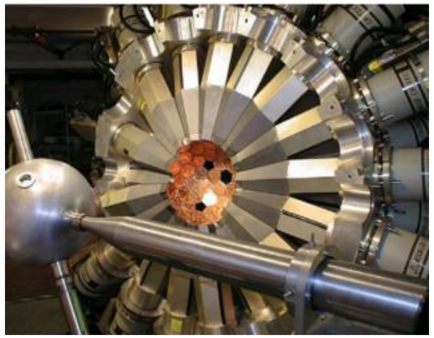
Figure from P. Moskal, A. Gajos et al., Nature Comm. 12 (2021) 5658

JPET vs previous measurements

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

Phys. Rev. Lett. 91 (2003)

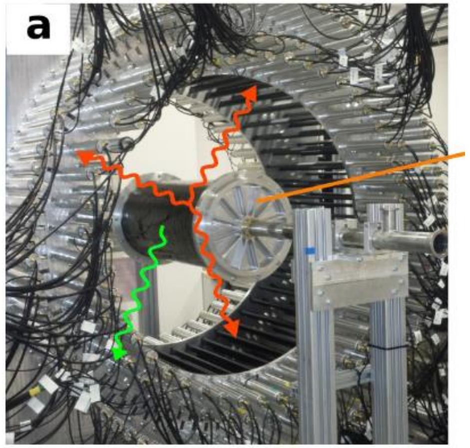




P_{e+} = 0,686 v/c

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

C_{CPT} = (2.6±3.1)×10-3



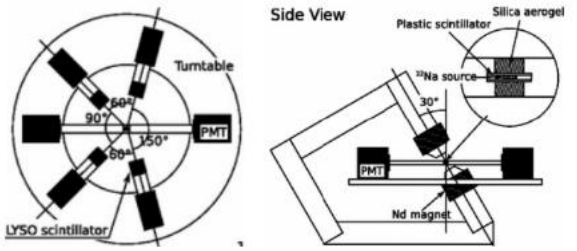
$P_{e+} \approx$ 0,98 v/c

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

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

Phys. Rev. Lett. 104 (2010)

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



C_{CP} = (1.3±2.1±0.6)×10-3

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

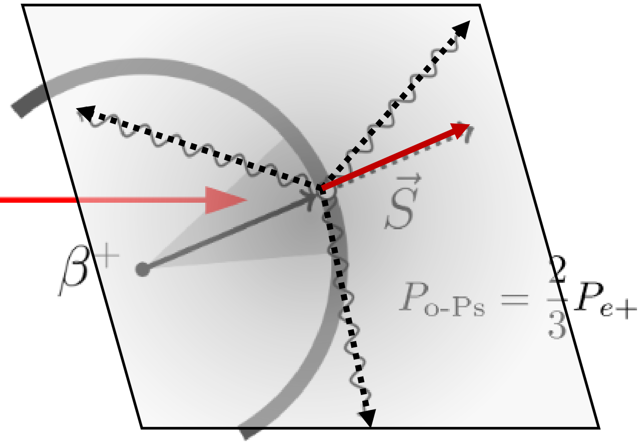
Analysis procedure

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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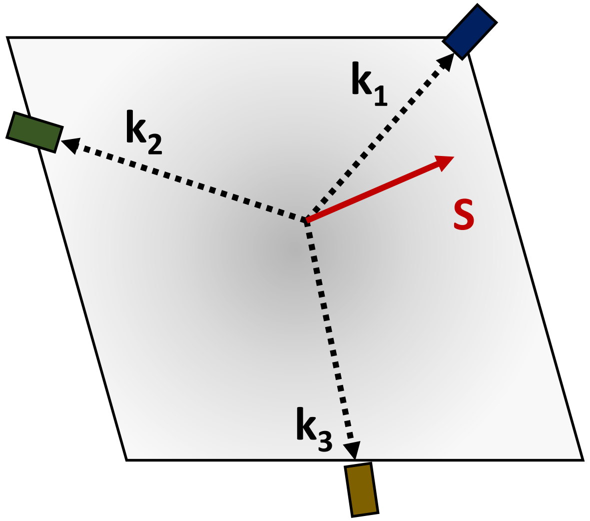
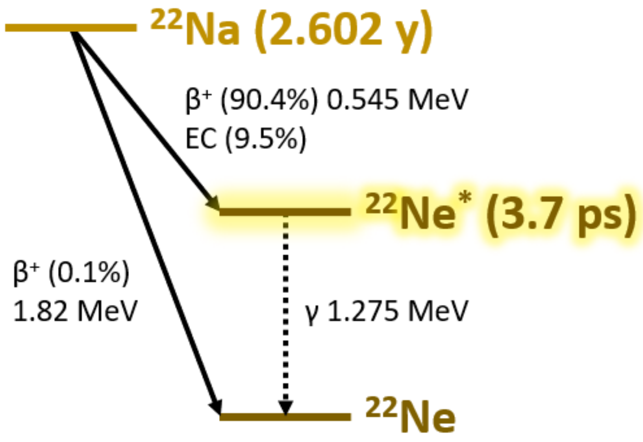


Analysis procedure



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

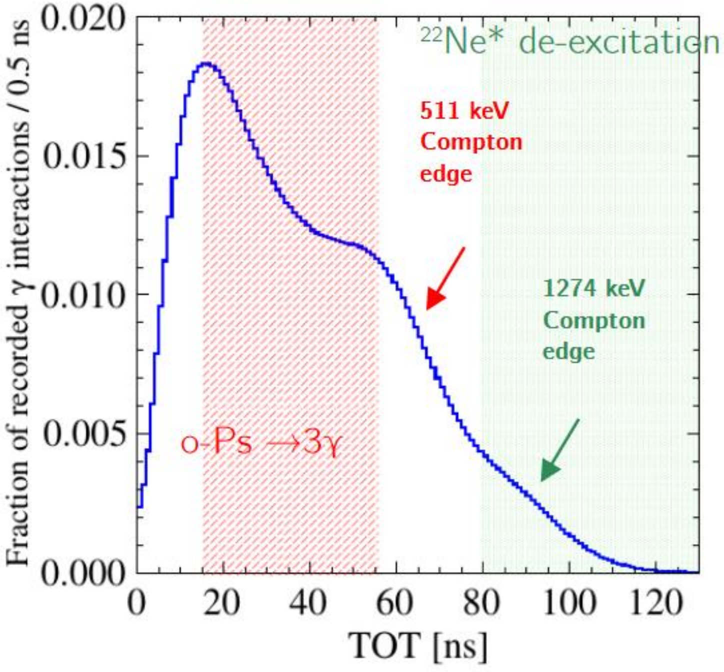
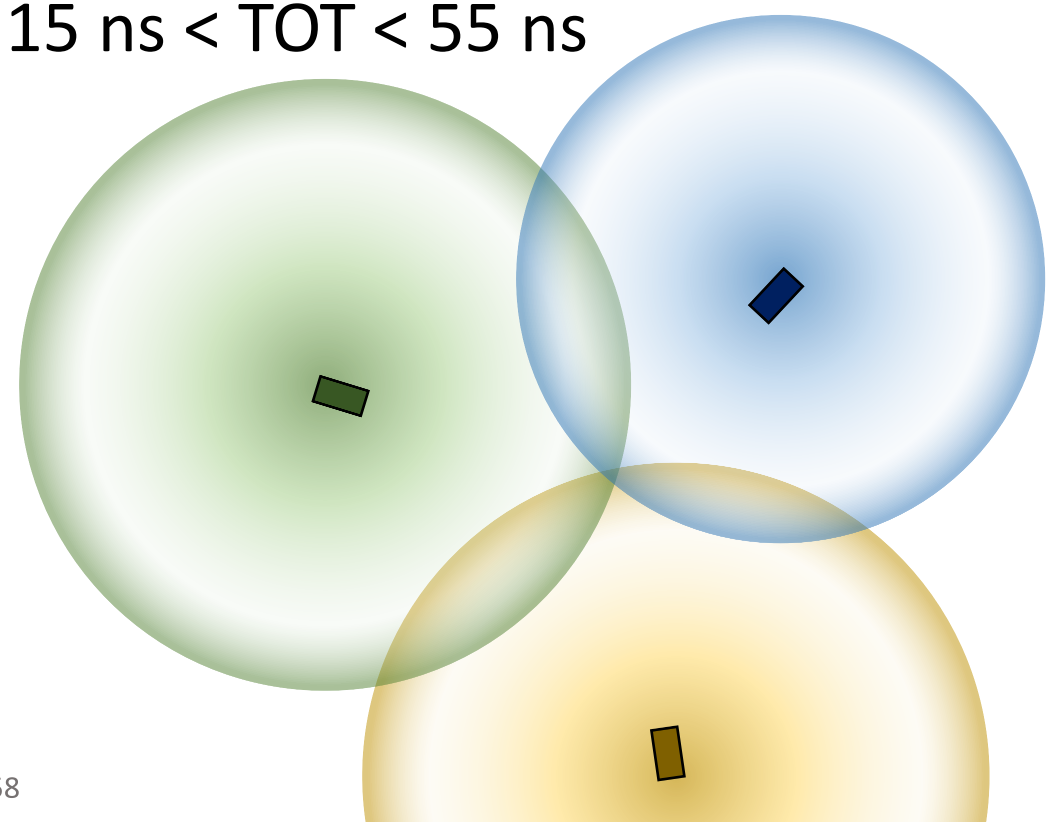


Figure from P. Moskal, A. Gajos et al., Nature Comm. 12 (2021) 5658



Analysis procedure

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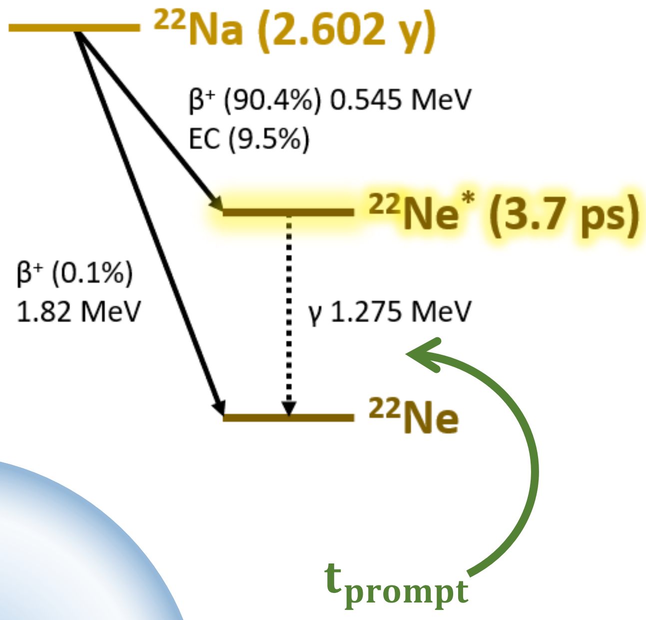
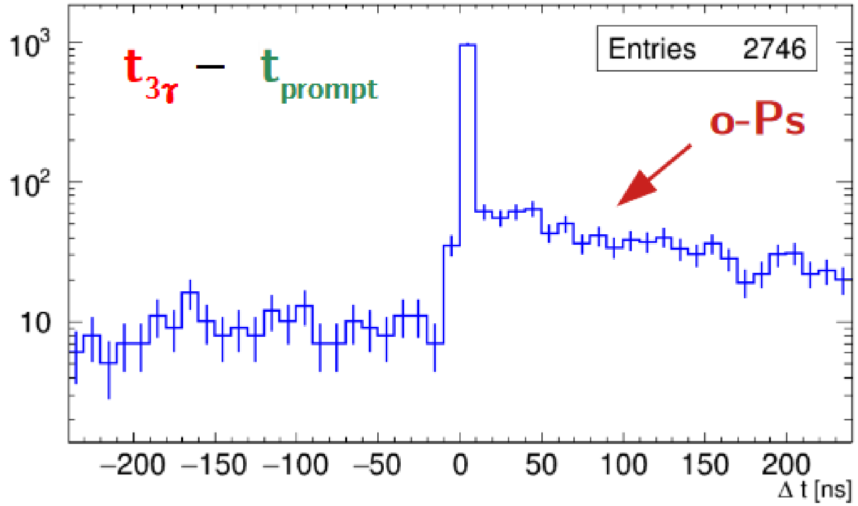
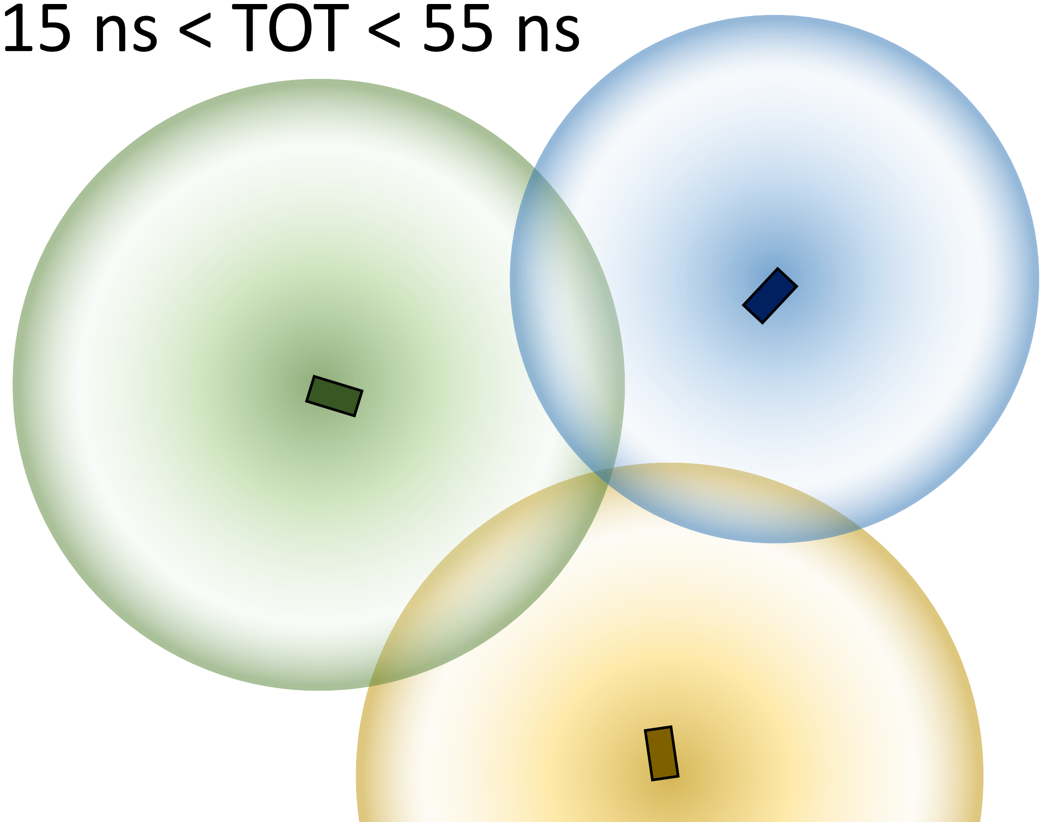


Proof of measuring o-Ps -> 3G
from another measurement

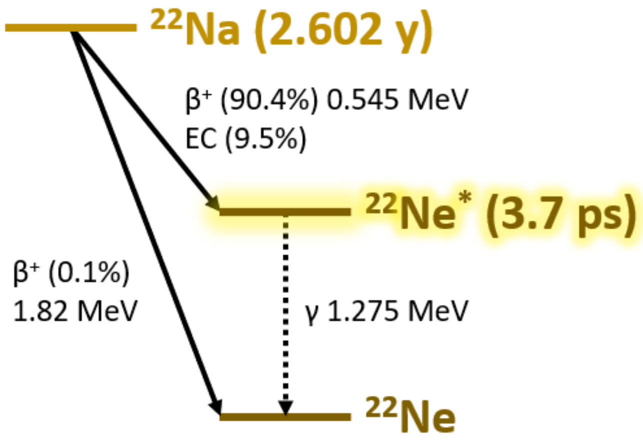
Data



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



Analysis procedure



Main requirements for an event:

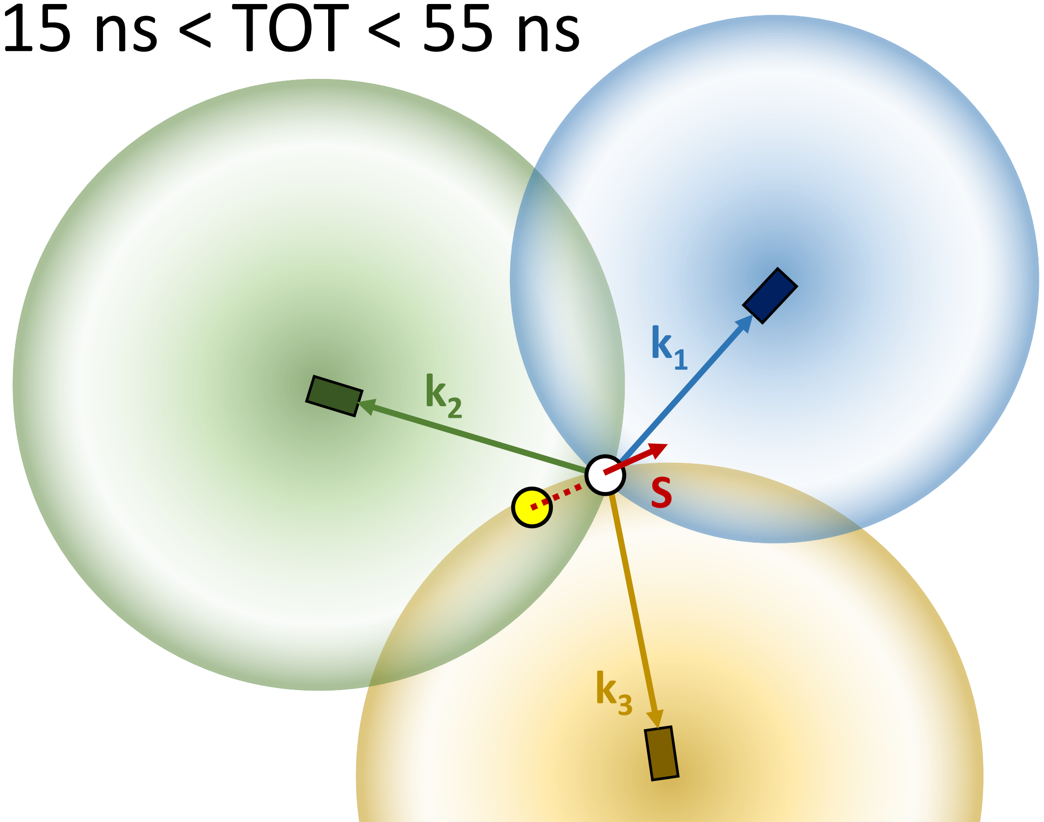
Only 3 Hits in the 2.5 ns event time window

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

Annihilation position (○) –> Trilateration

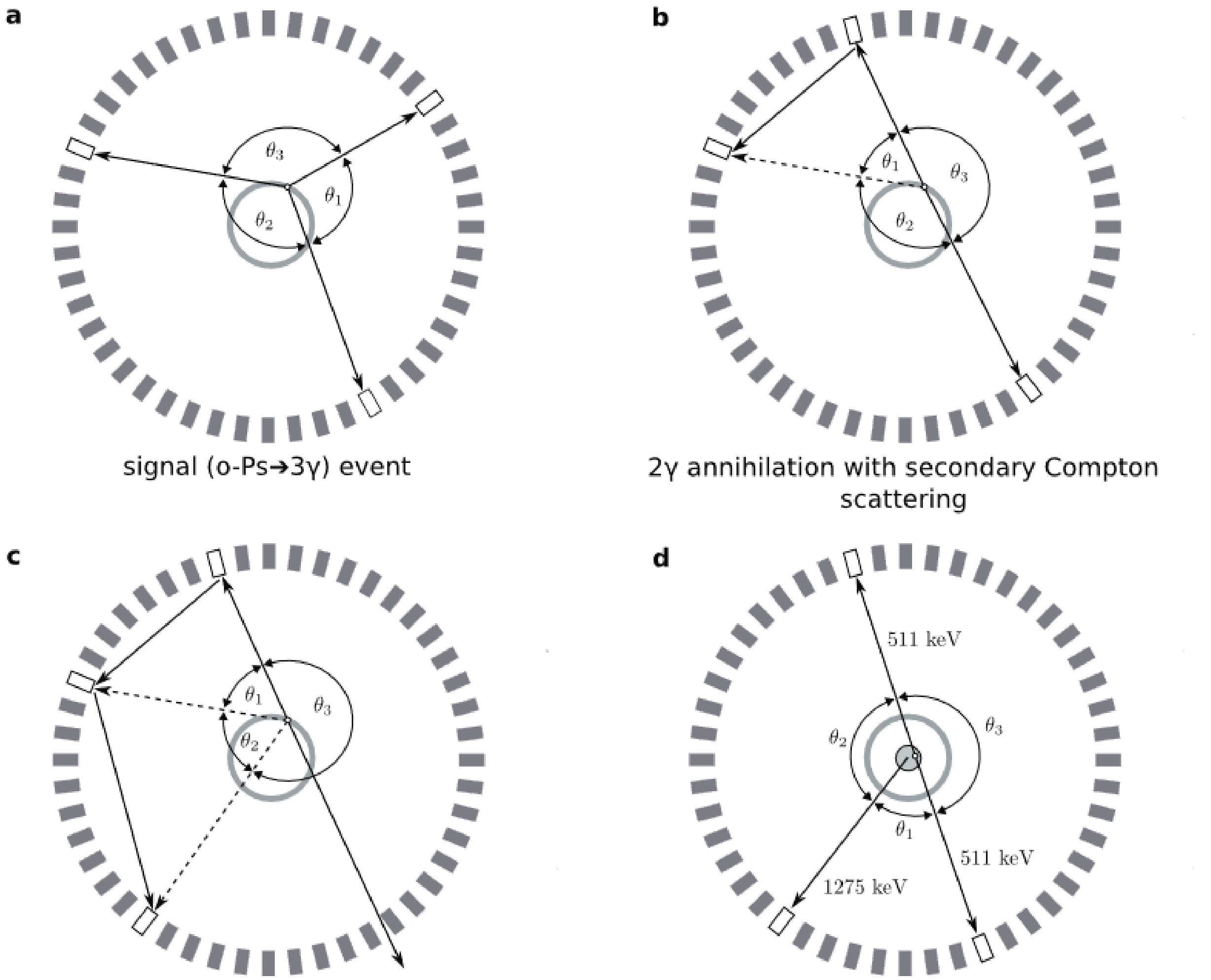
Position (○) -> $\vec{k}_1 \times \vec{k}_2$

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



Treatment of the background events

Possible configurations of events



a: signal (o-Ps→3γ) event

b: 2γ annihilation with secondary Compton 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

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

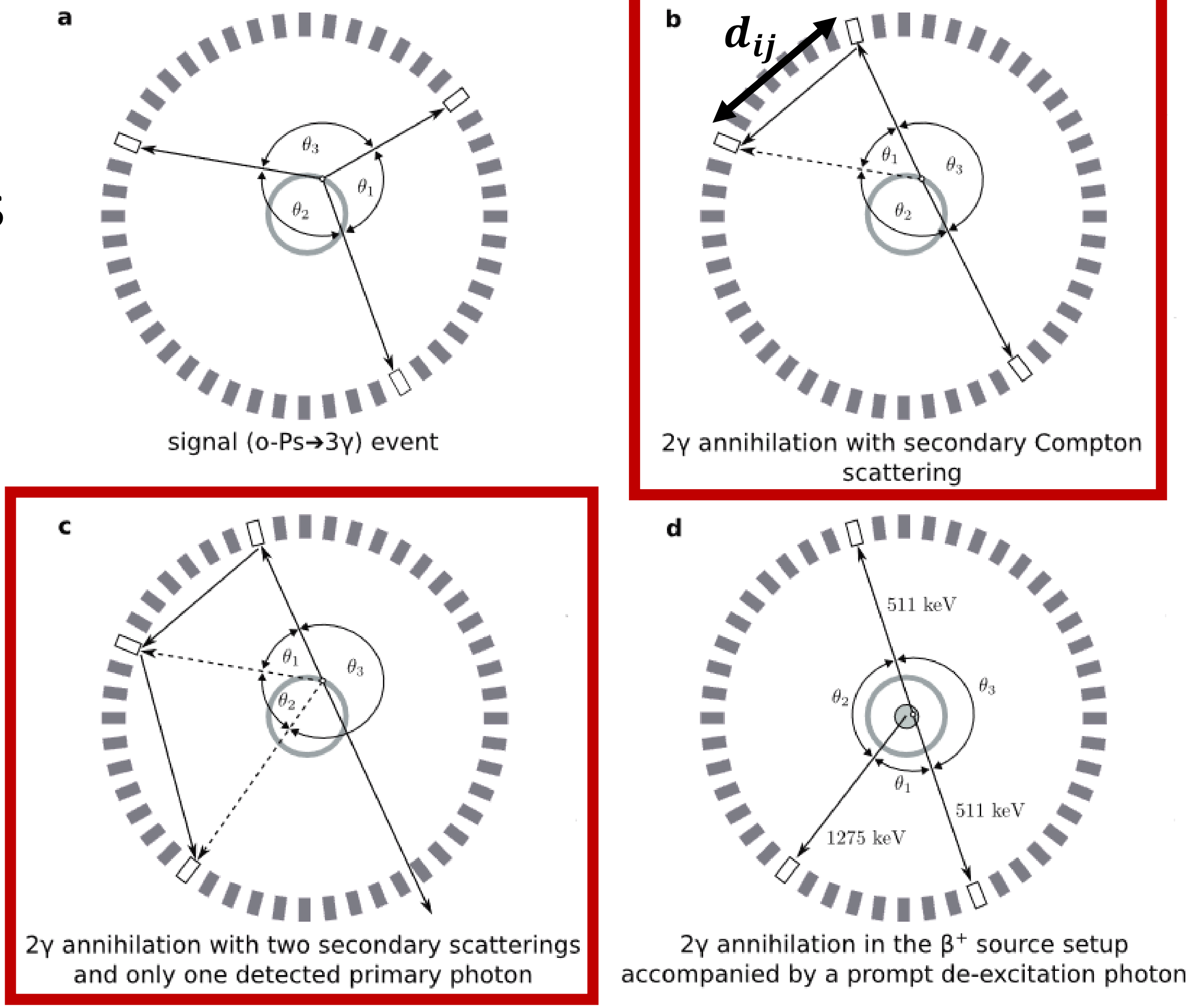
Treatment of the background events

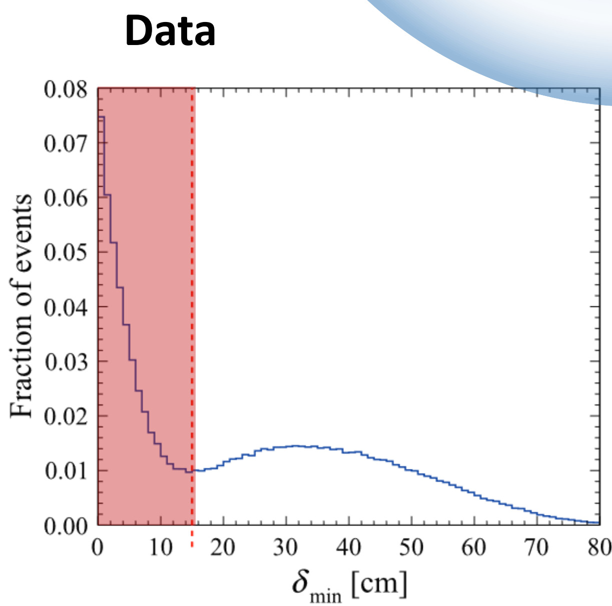
Rejection of the scatterings

For a given pair of hits i-j

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

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

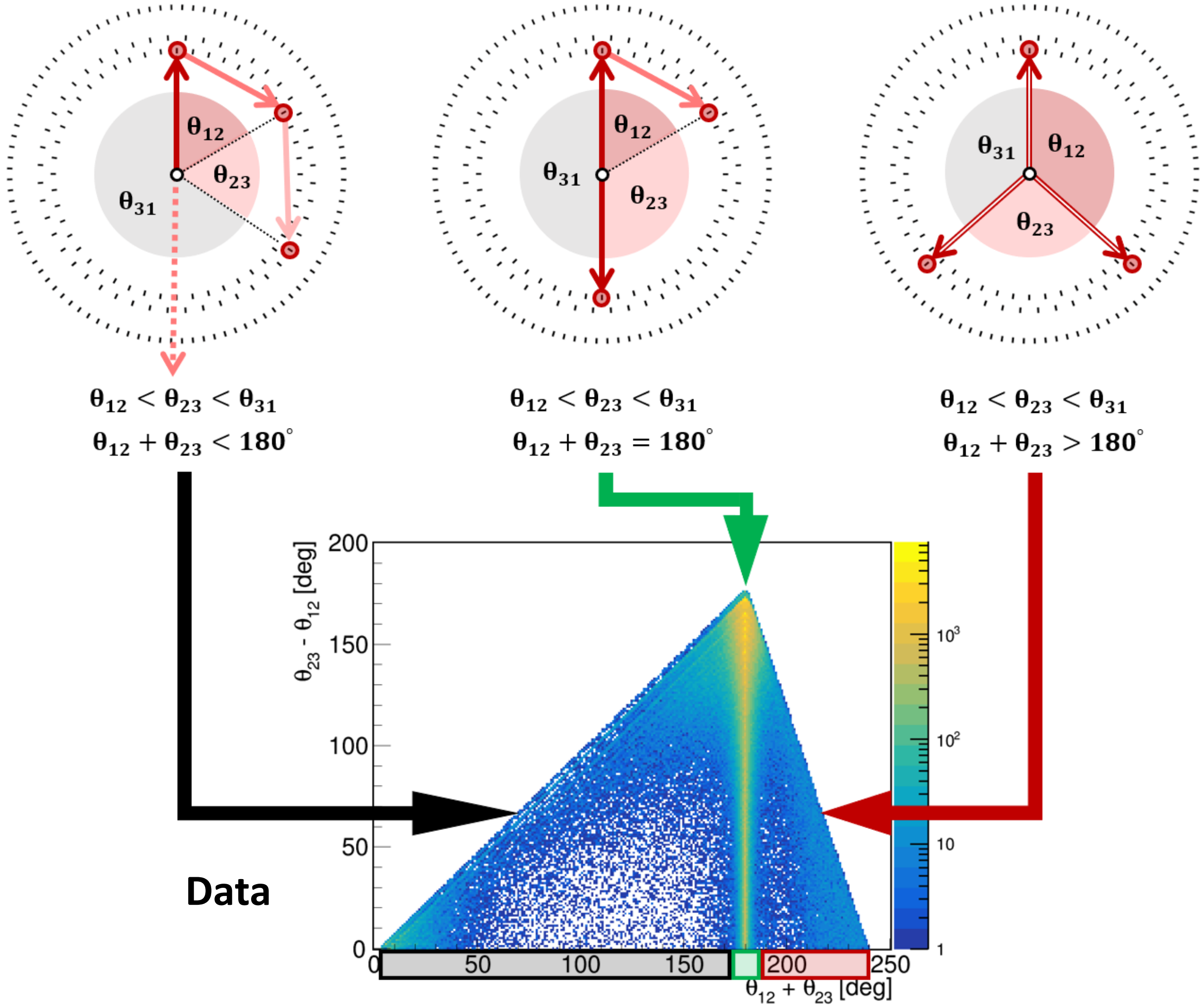




Figures from P. Moskal, A. Gajos et al., Nature Comm. 12 (2021) 5658

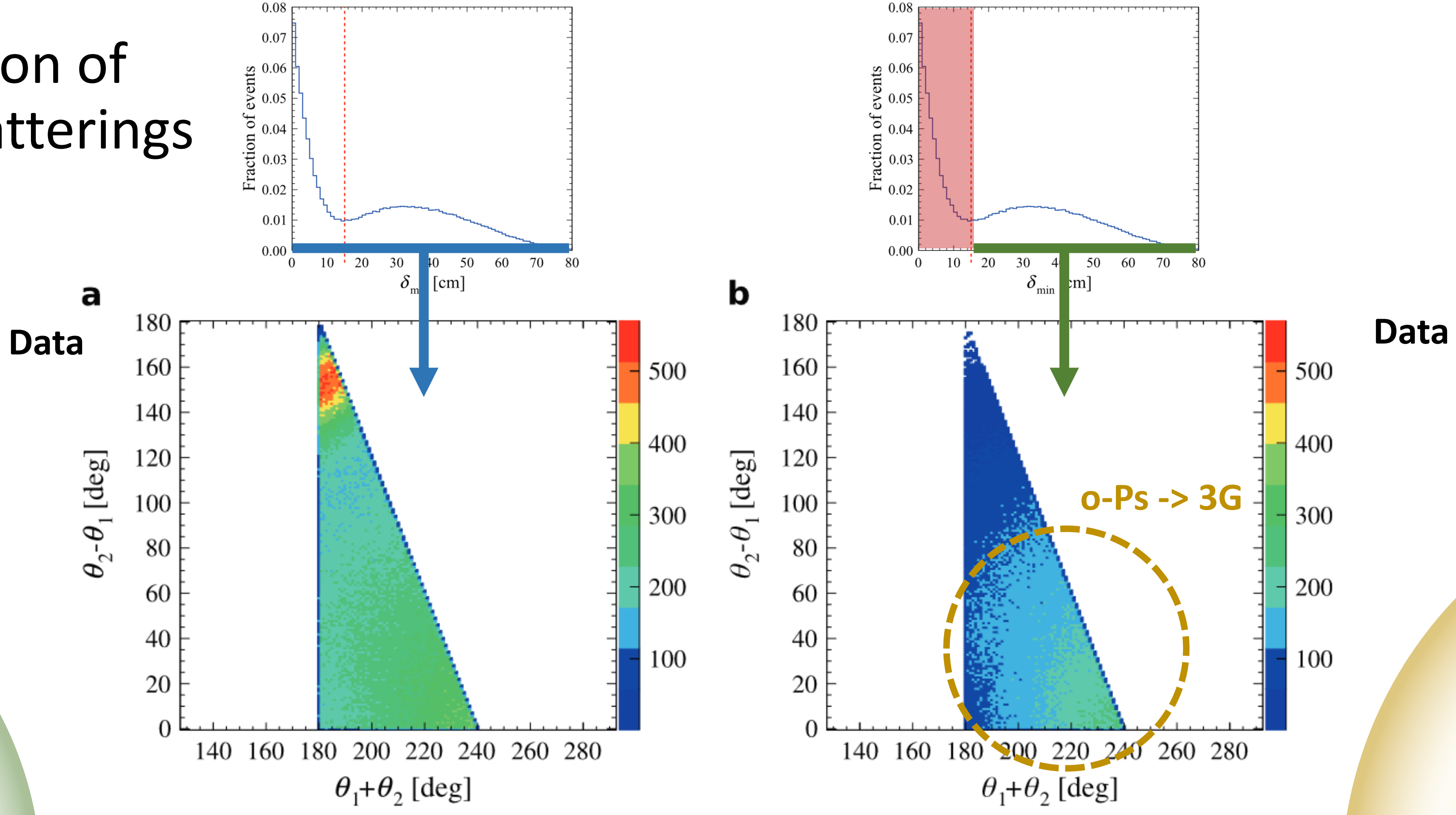
Treatment of the background events

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



Treatment of the background events

Rejection of the scatterings



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

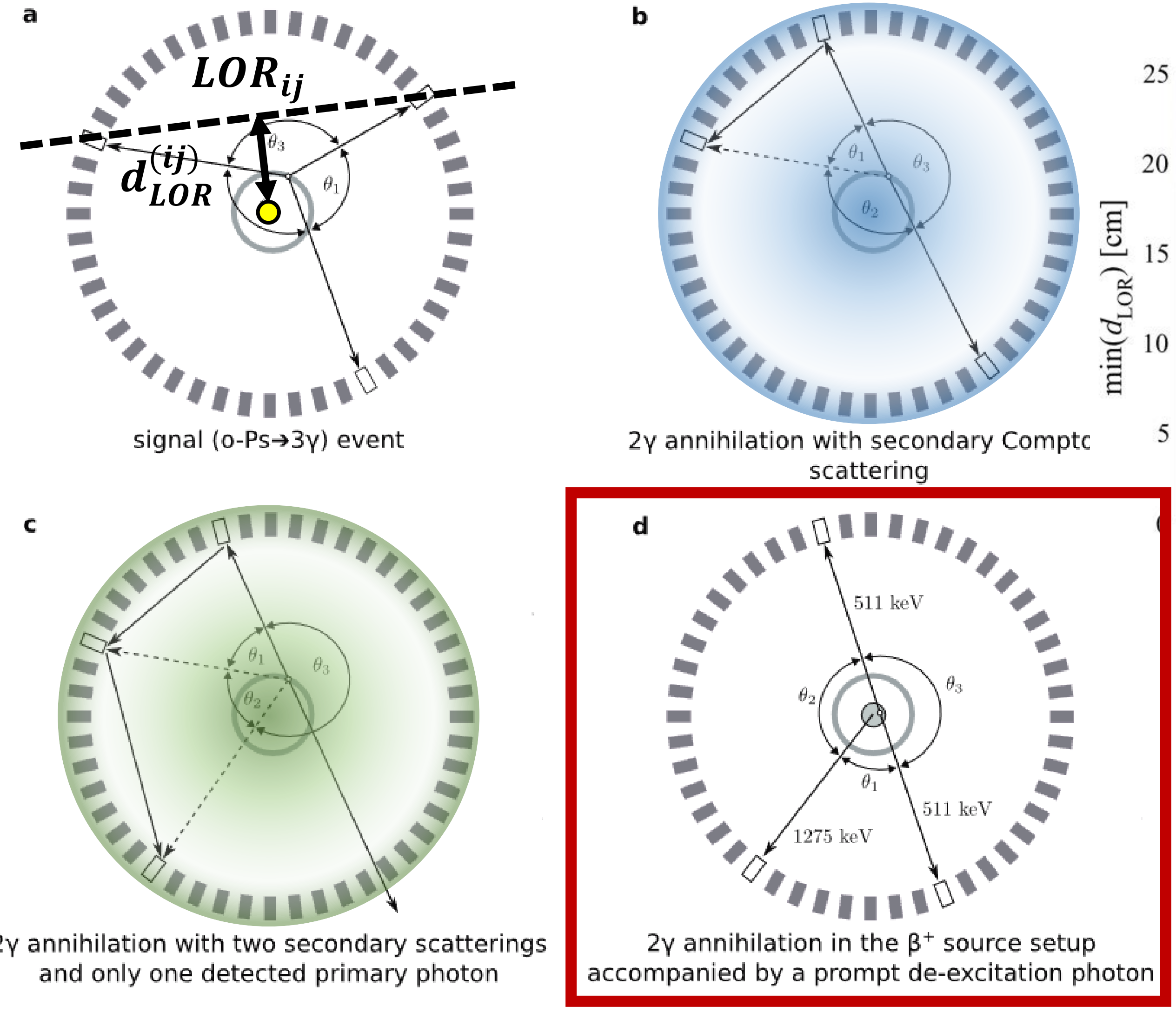
Treatment of the background events

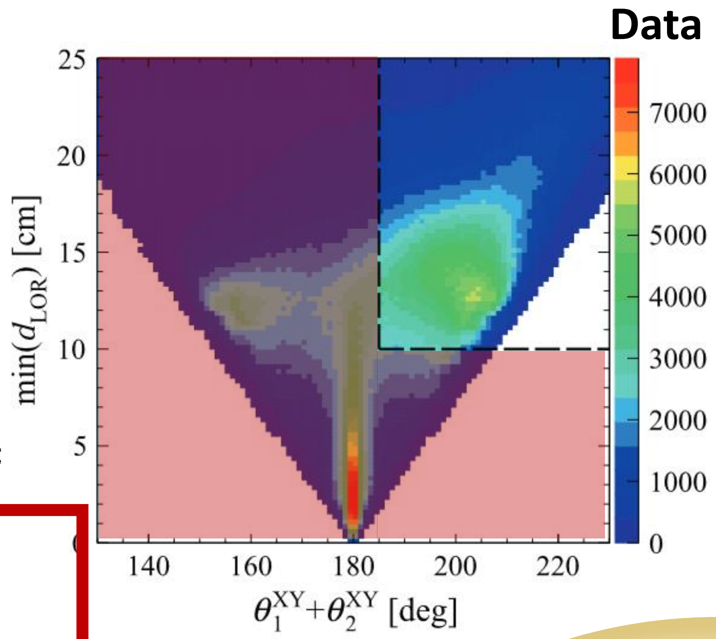
Rejection of the 2G decays

For a given pair of hits i-j

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

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





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

Treatment of the background events

Rejection of the 2G decays

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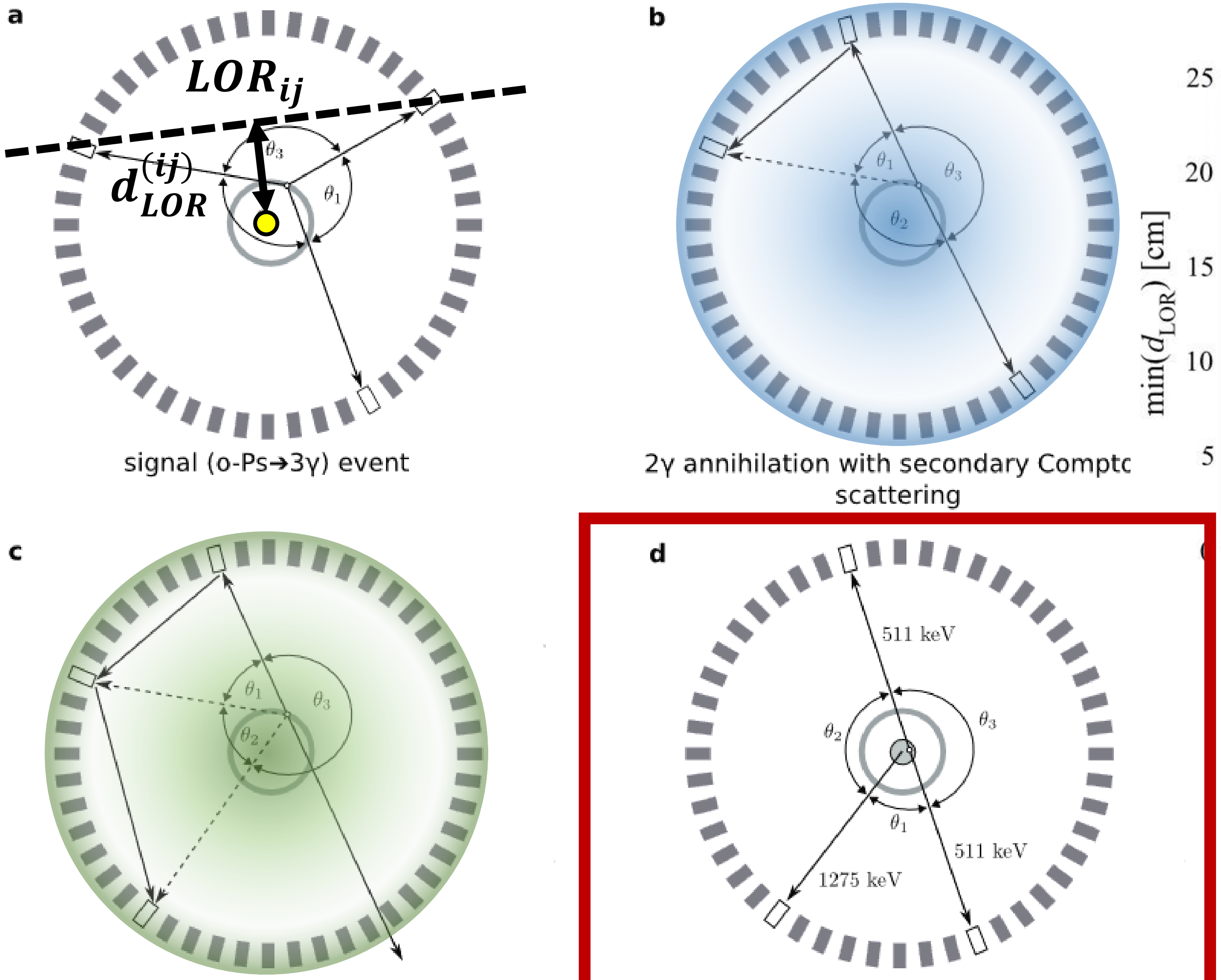


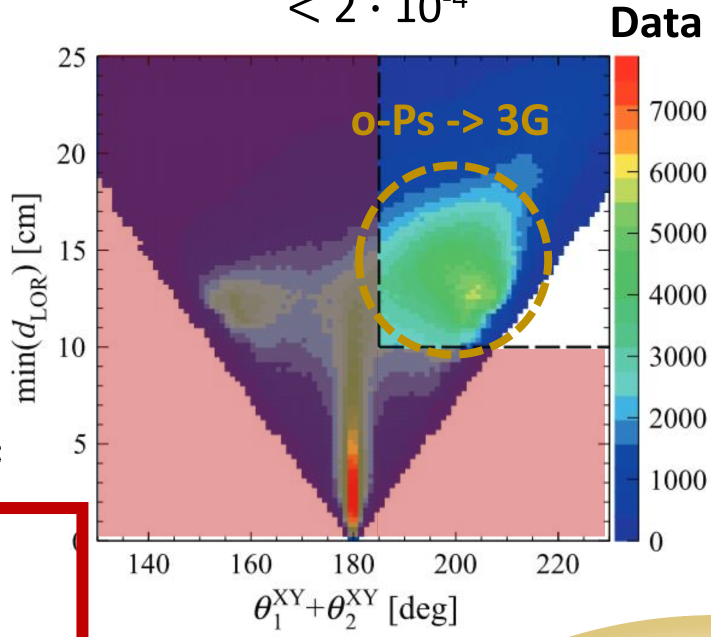
signal (o-Ps→3γ) event

2γ annihilation with secondary Comptc scattering

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

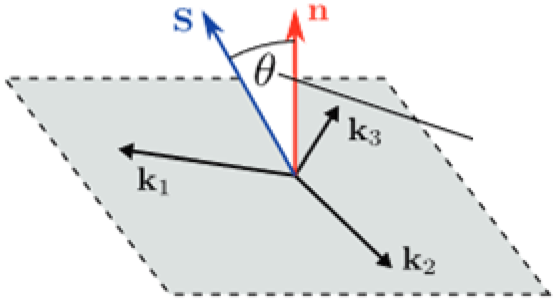
2γ annihilation in the β⁺ source setup accompanied by a prompt de-excitation photon

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



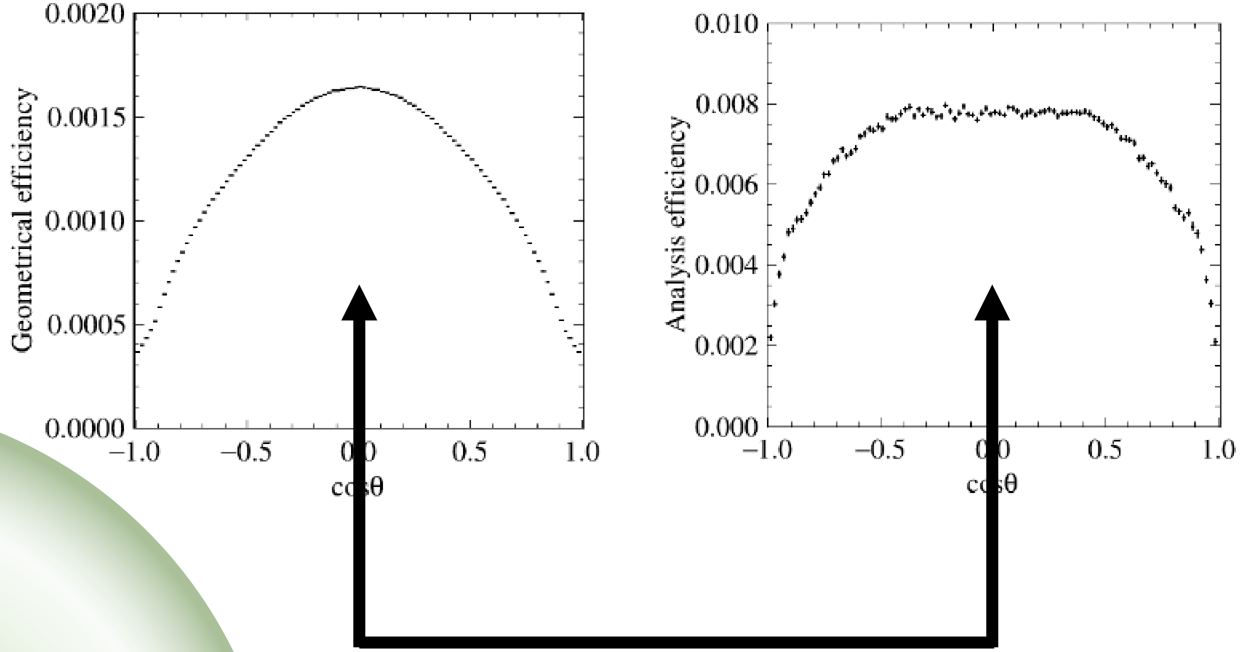
Figures from P. Moskal, A. Gajos et al., Nature Comm. 12 (2021) 5658

Results of the CPT test

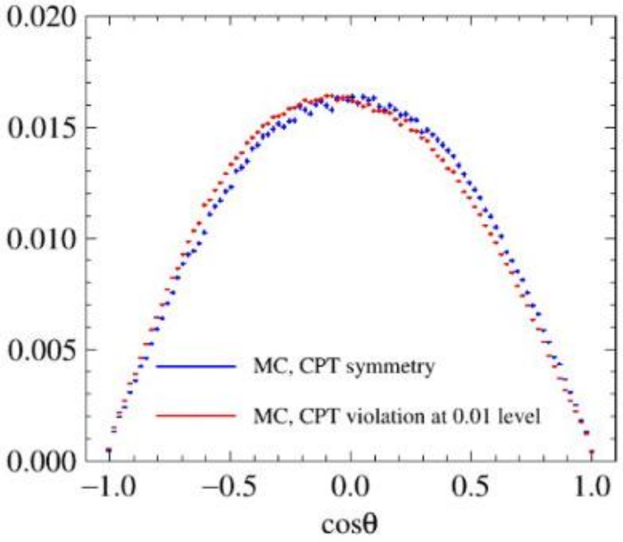


Simulation data were generated in order to estimate efficiencies: geometrical and analysis

MC

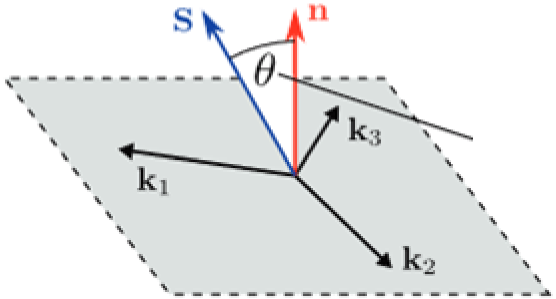


Symmetric in $\cos\theta$



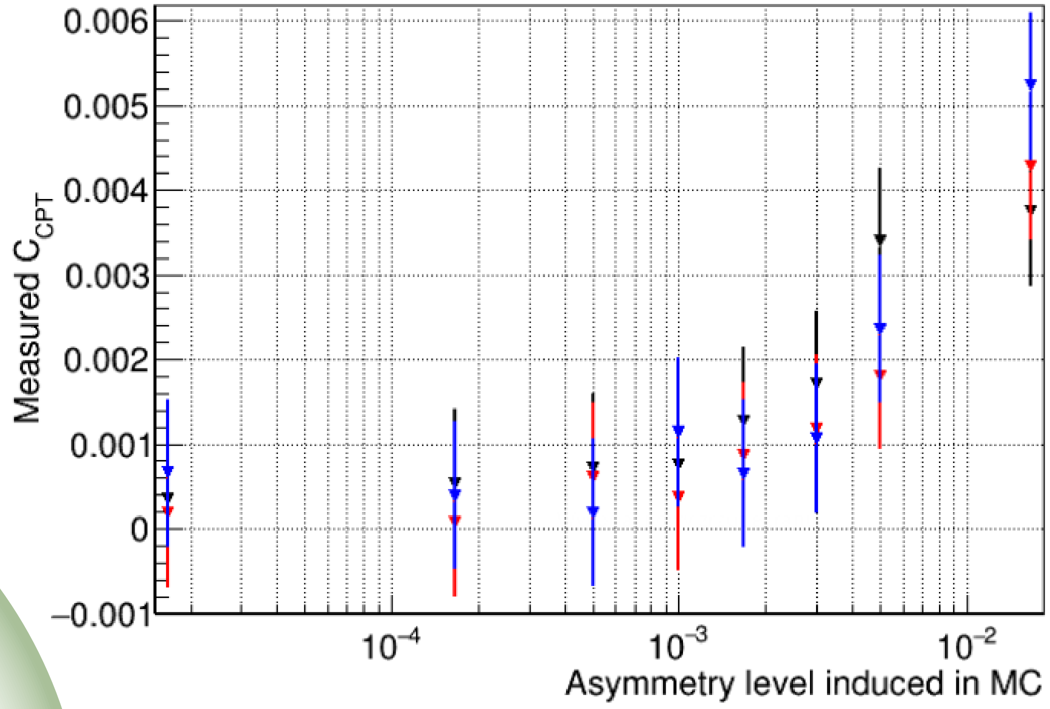
A. Gajos Symmetry 12 (2020) 8, 1268

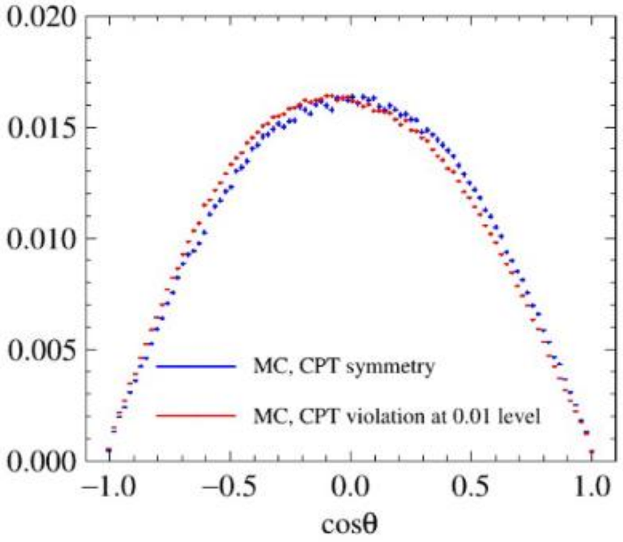
Results of the CPT test



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

MC

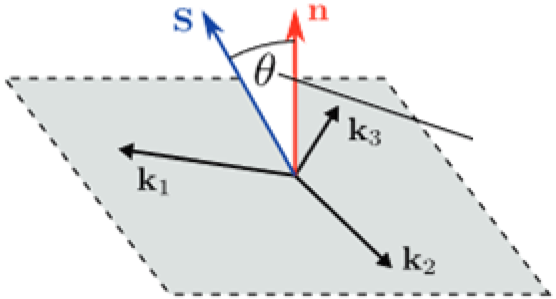




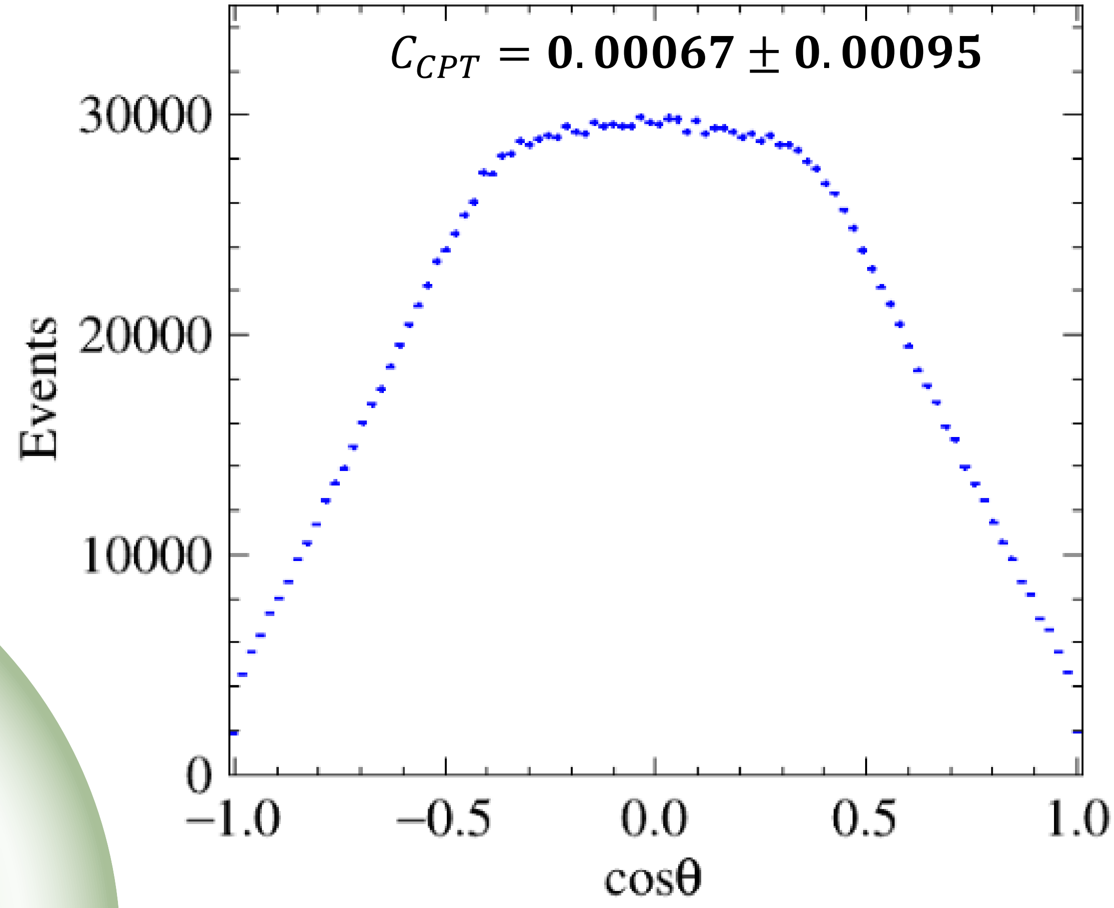
Courtesy of A. Gajos

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

Results of the CPT test



Data Total number of events ~2x10⁶



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

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Results of the three-photon imaging

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

Data

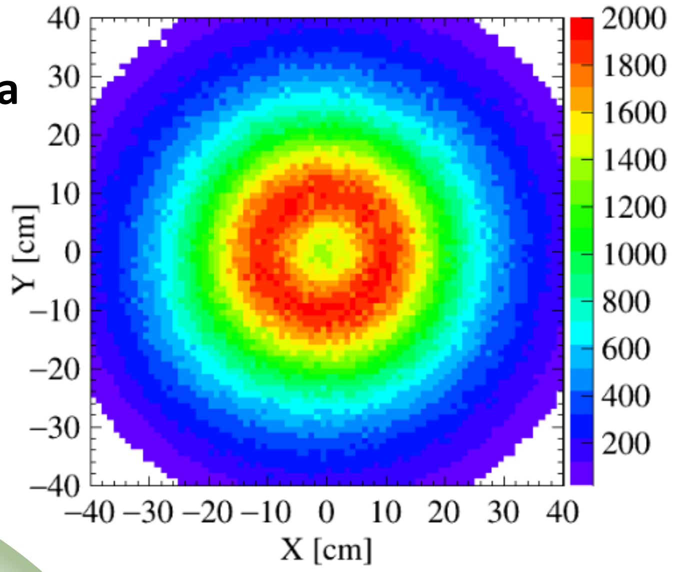
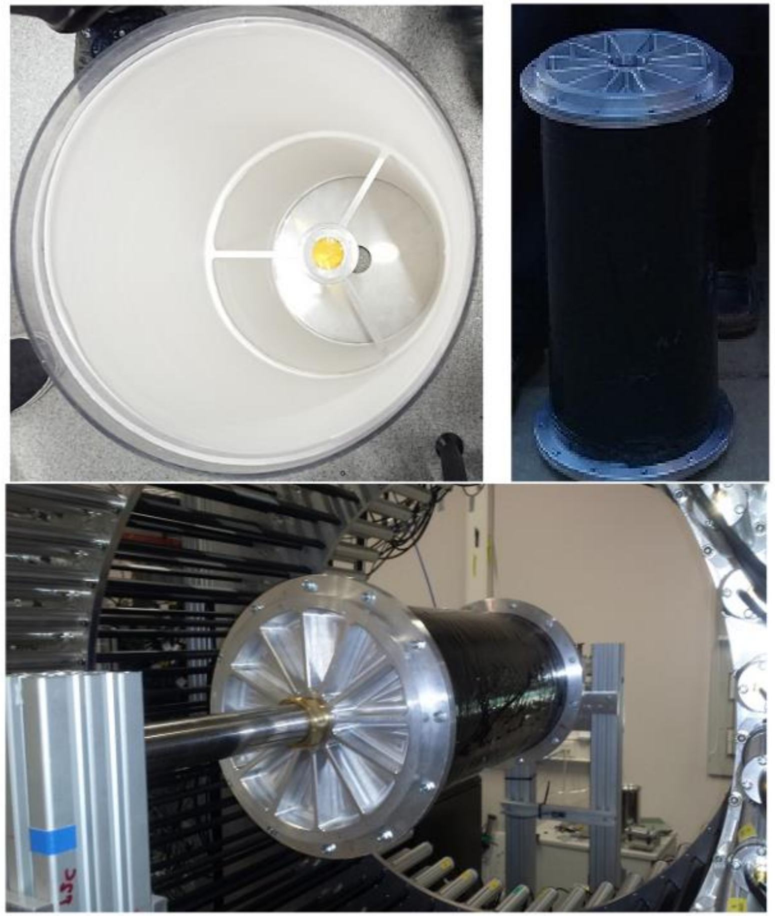
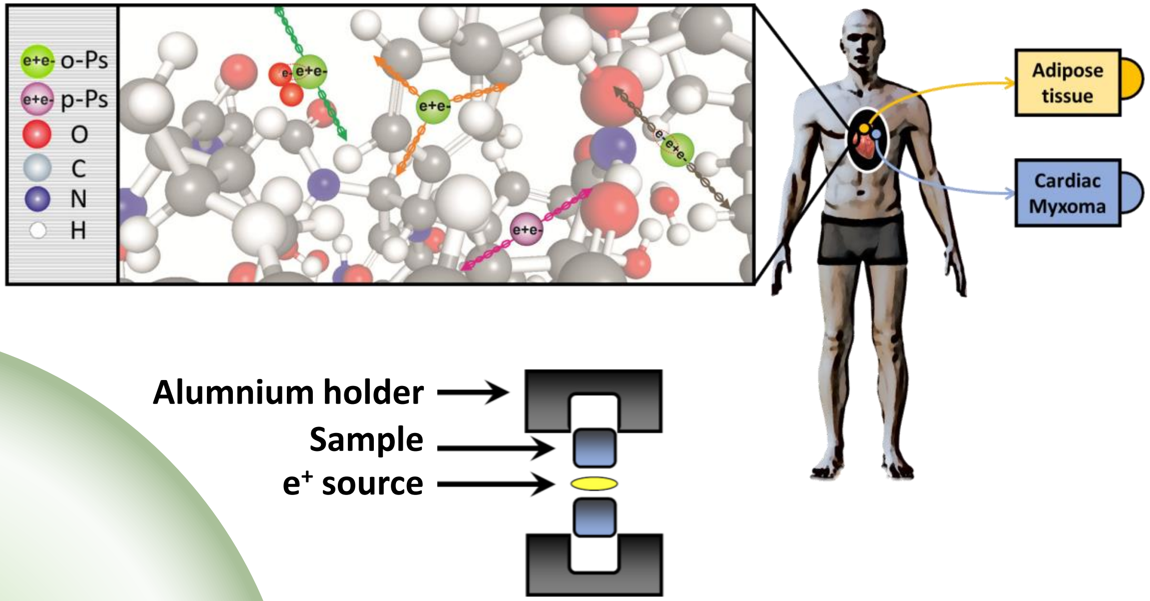


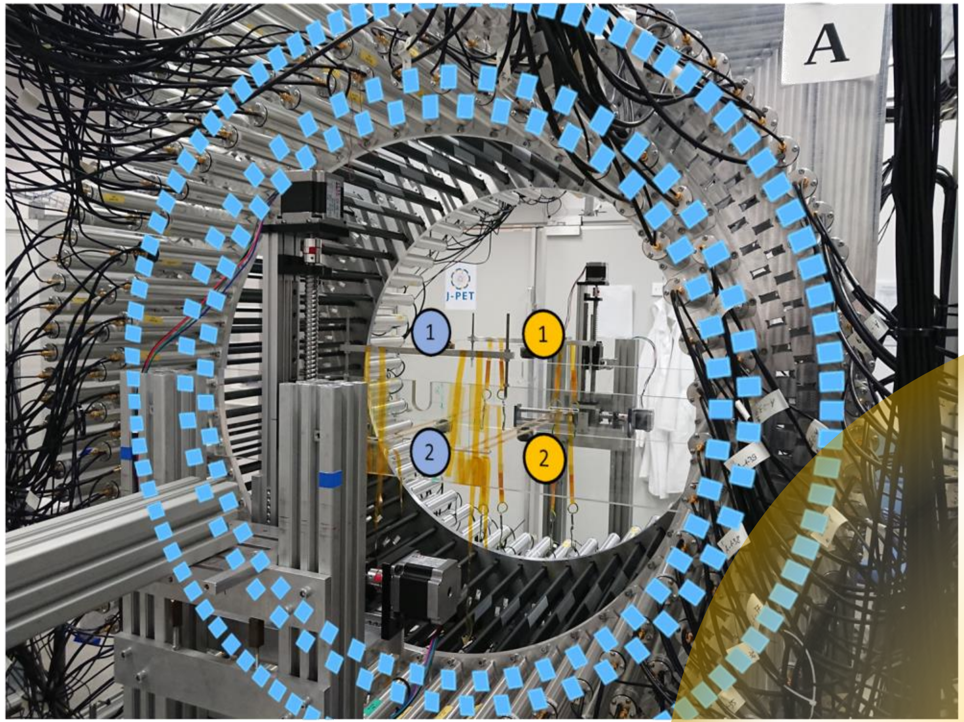
Figure from P. Moskal, A. Gajos et al., Nature Comm. 12 (2021) 5658



Positronium Imaging

Different type of the image that also focuses on o-Ps is positronium image. It is based on the mean o-Ps lifetime studies in every voxel.





Figures from P. Moskal, K. Dulski et al., Sci. Adv. 7 (2021) eabh4394

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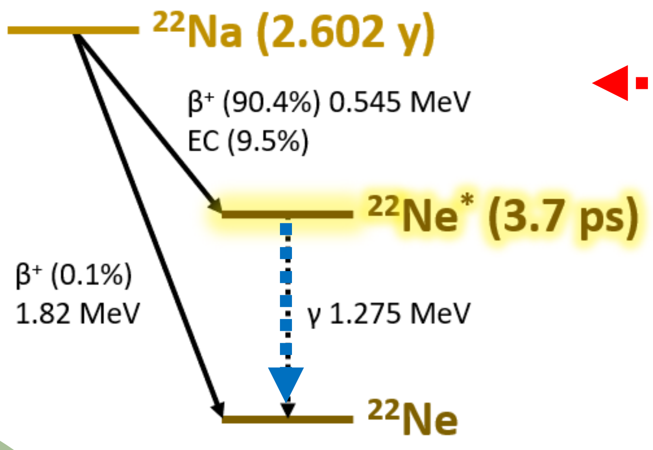

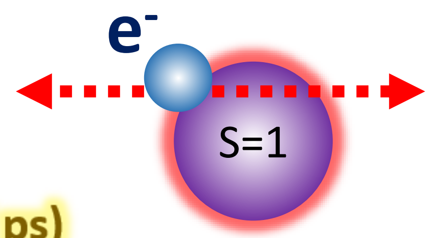

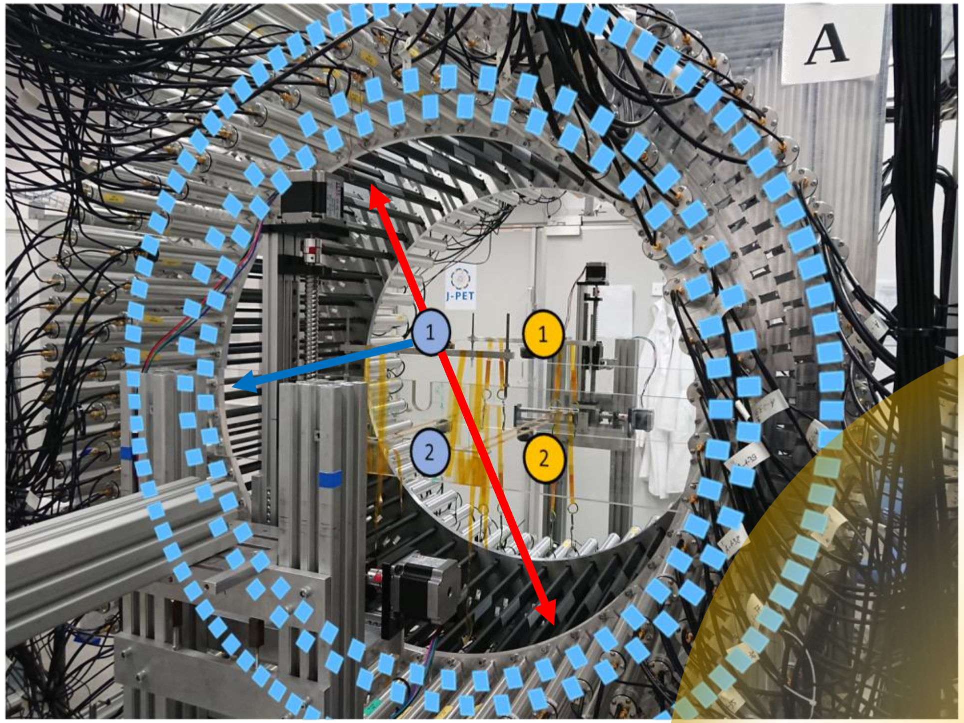

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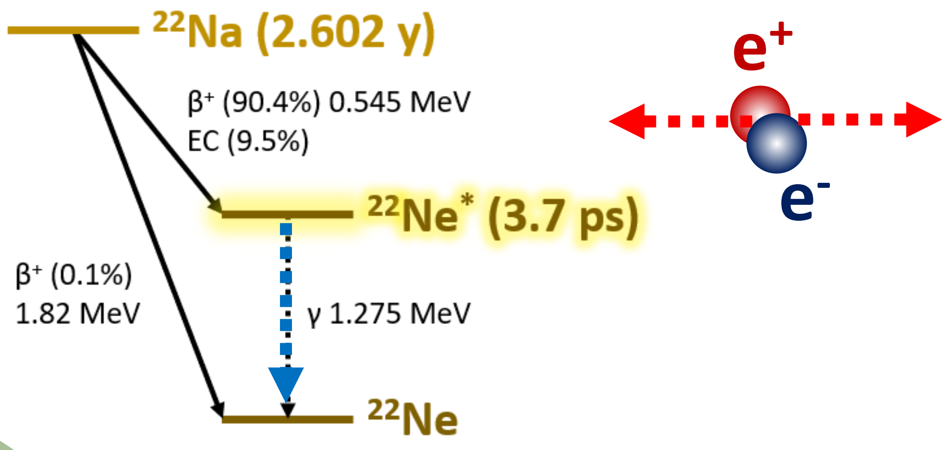

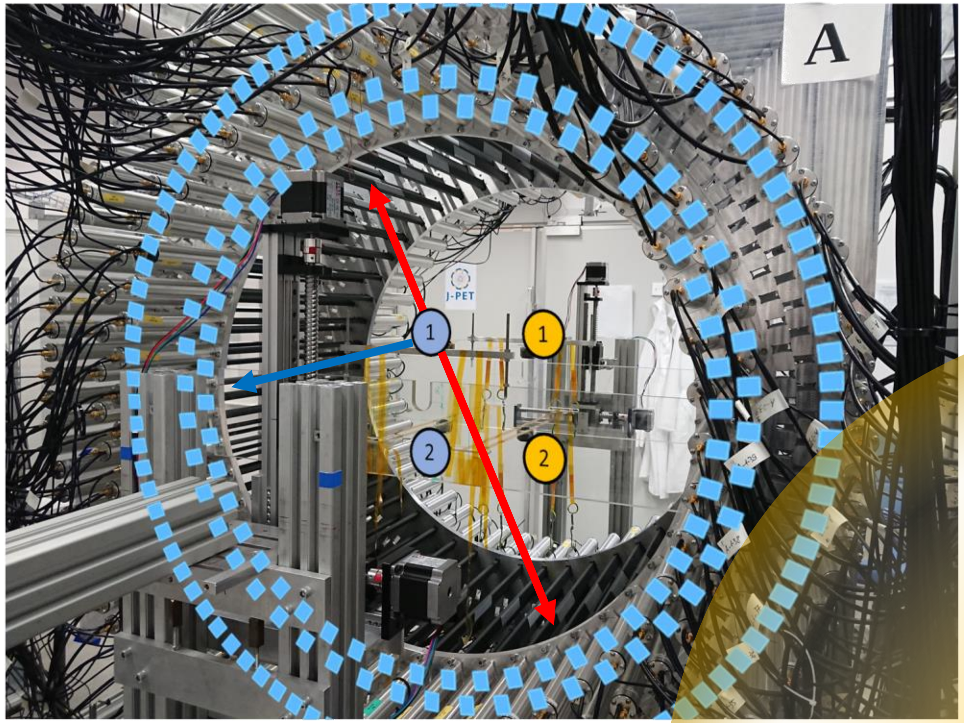

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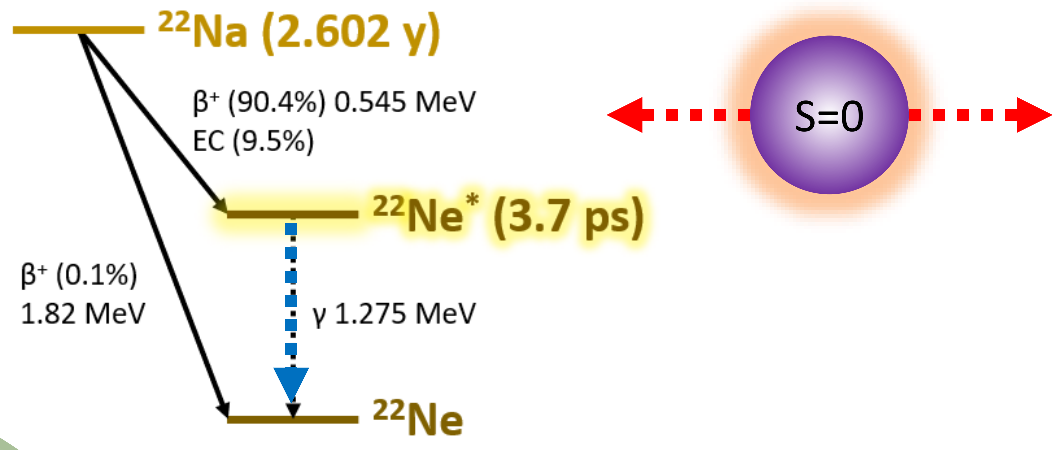


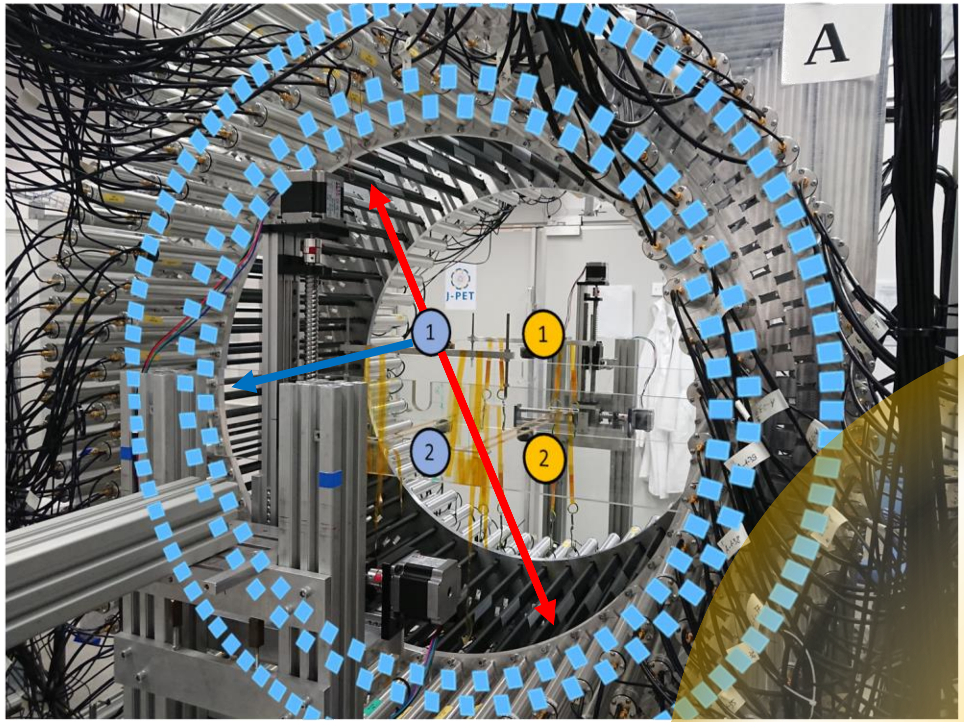
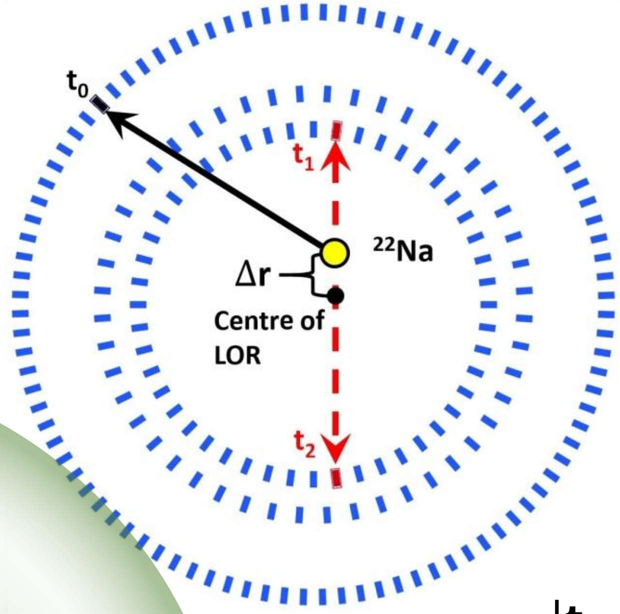


Figure from P. Moskal, K. Dulski et al., Sci. Adv. 7 (2021) eabh4394

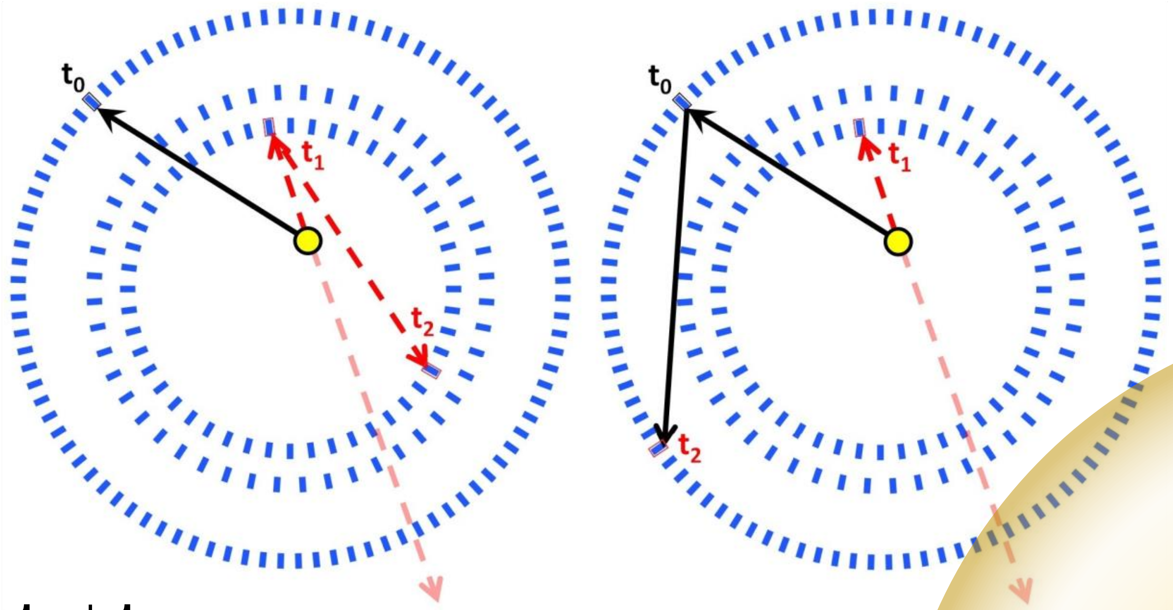
Positronium Imaging – event selection

There can be different background events for such events (2+1)

Proper event for analysis



Possible sources of background



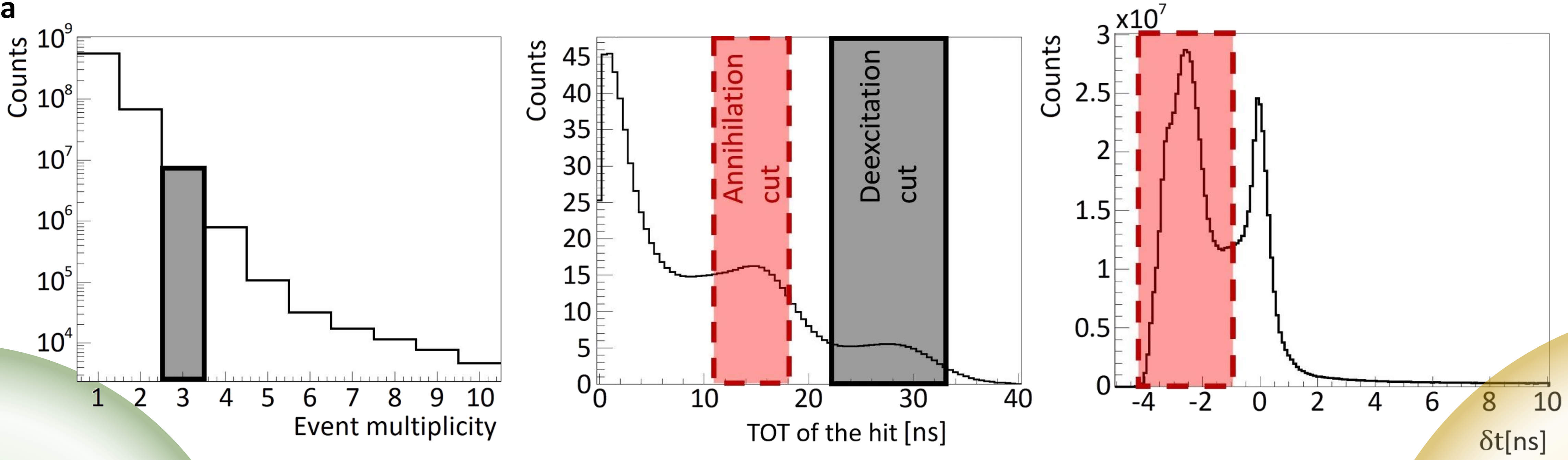
$$\Delta \mathbf{r} = \frac{|\mathbf{t_2} - \mathbf{t_1}|}{2}\mathbf{c} \qquad \Delta \mathbf{t} = \frac{\mathbf{t_1} + \mathbf{t_2}}{2} - \mathbf{t_0}$$

Figure from P. Moskal, K. Dulski et al., Sci. Adv. 7 (2021) eabh4394

Positronium Imaging – event selection

Set of selection criteria were applied to reduce background from the data

Data



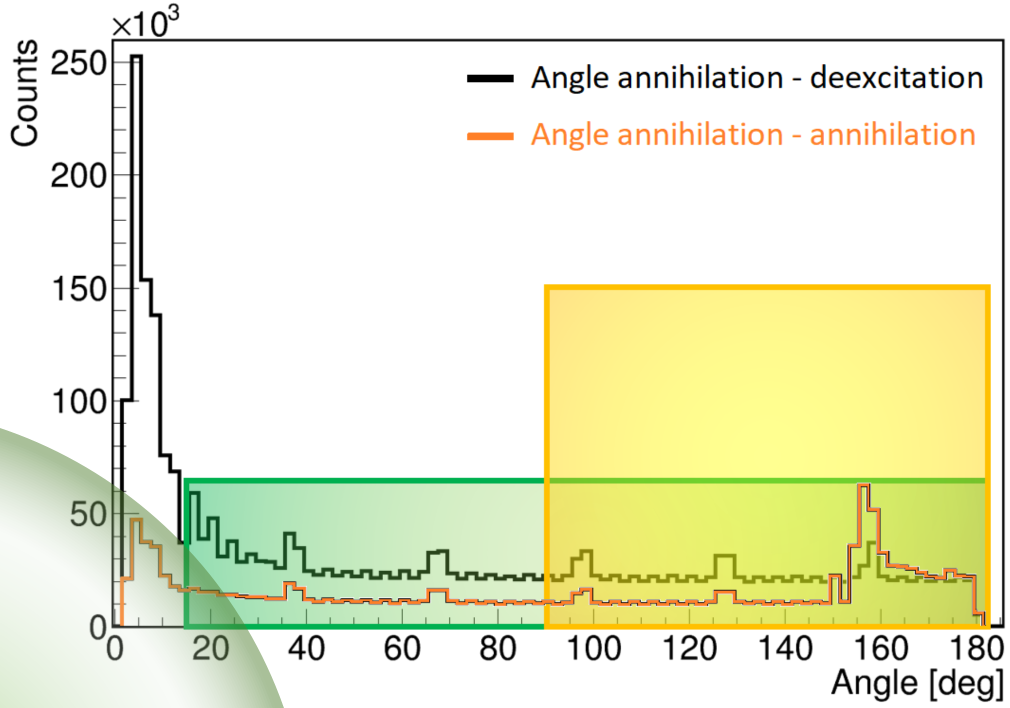
$$\boldsymbol{\delta t = \Delta t - \frac{\Delta Distance}{c}}$$

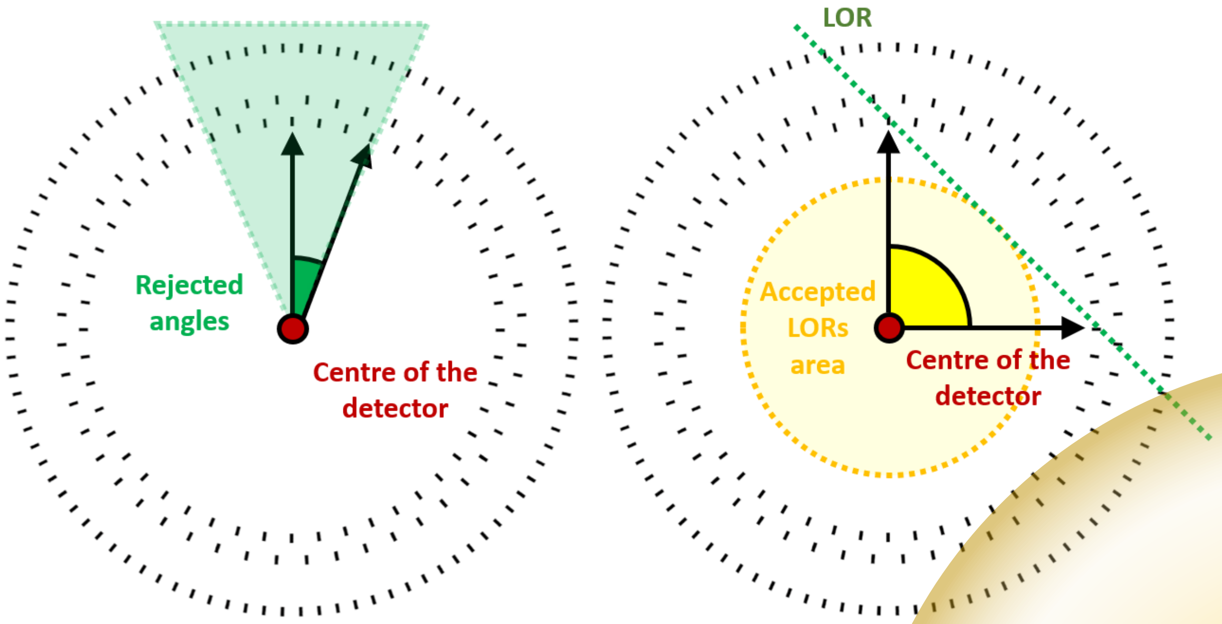
Figures from P. Moskal, K. Dulski et al., Sci. Adv. 7 (2021) eabh4394

Positronium Imaging – event selection

Additional geometric cuts were applied to limit potential annihilation positions inside the detection chamber

Data





Positronium Imaging

In every voxel positron lifetime spectrum can be collected and decomposed onto different component – p-Ps, o-Ps, direct annihlation

Data

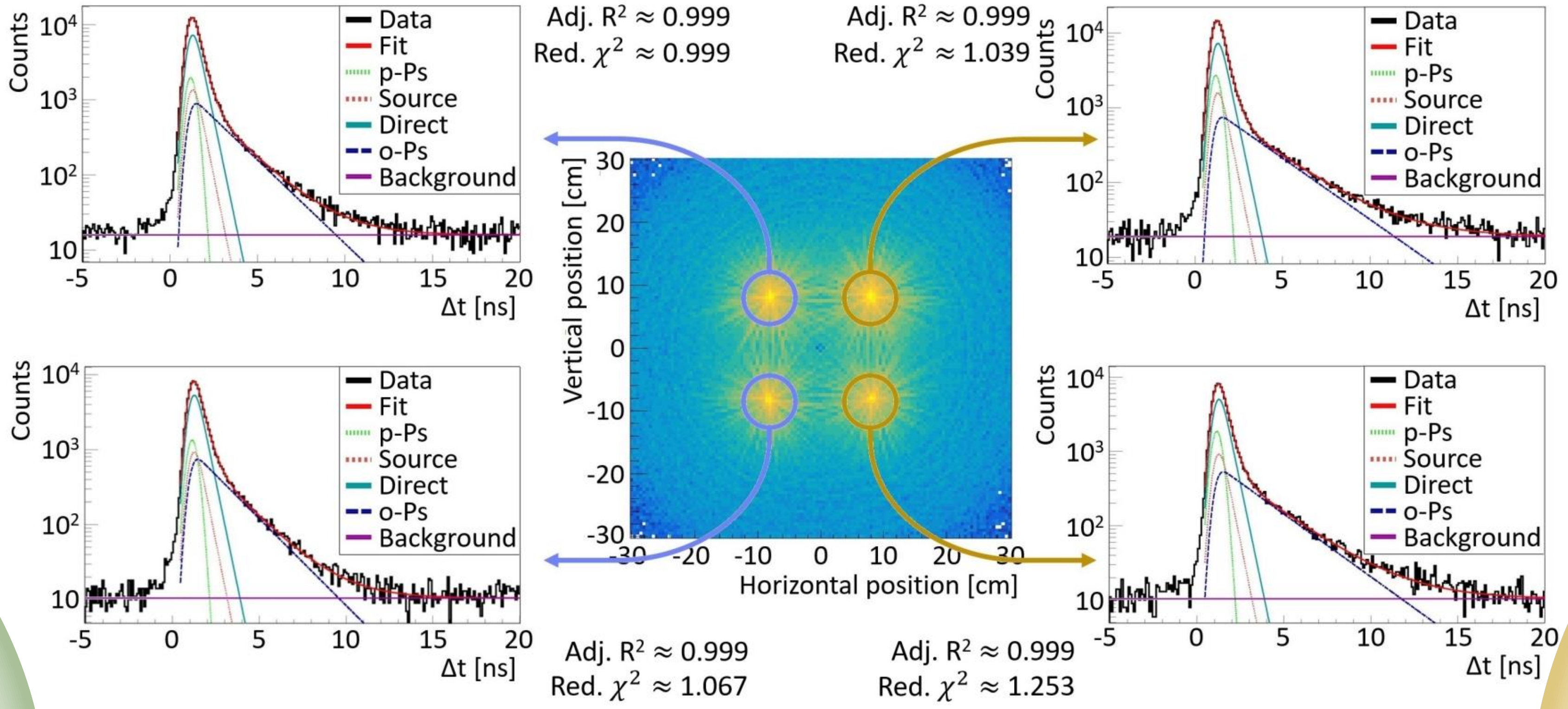


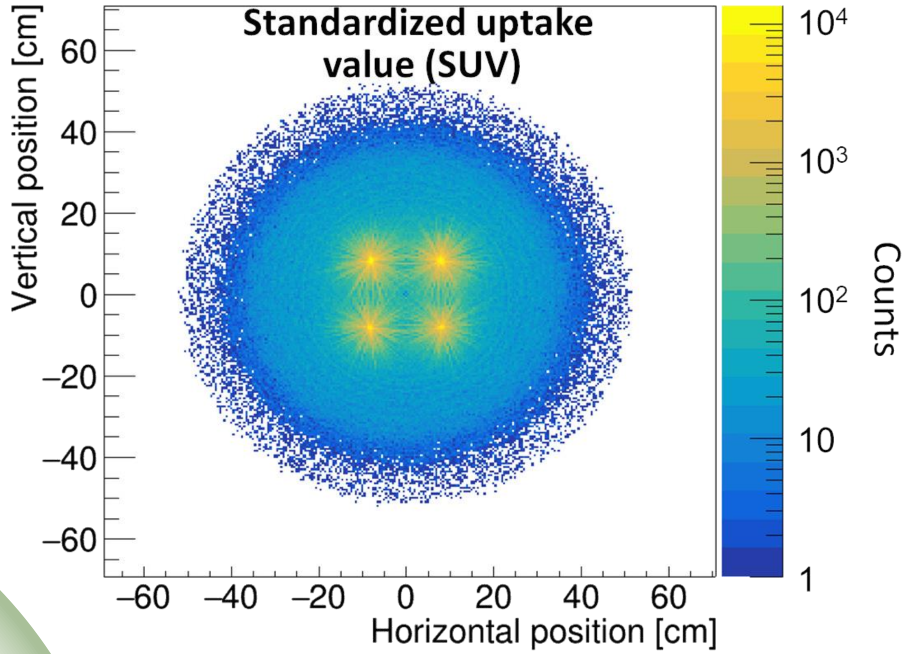
Figure from P. Moskal, K. Dulski et al., Sci. Adv. 7 (2021) eabh4394

Fitting by PALS Avalanche software – K. Dulski, Acta. Phys. Pol. A, 137 (2020) 167

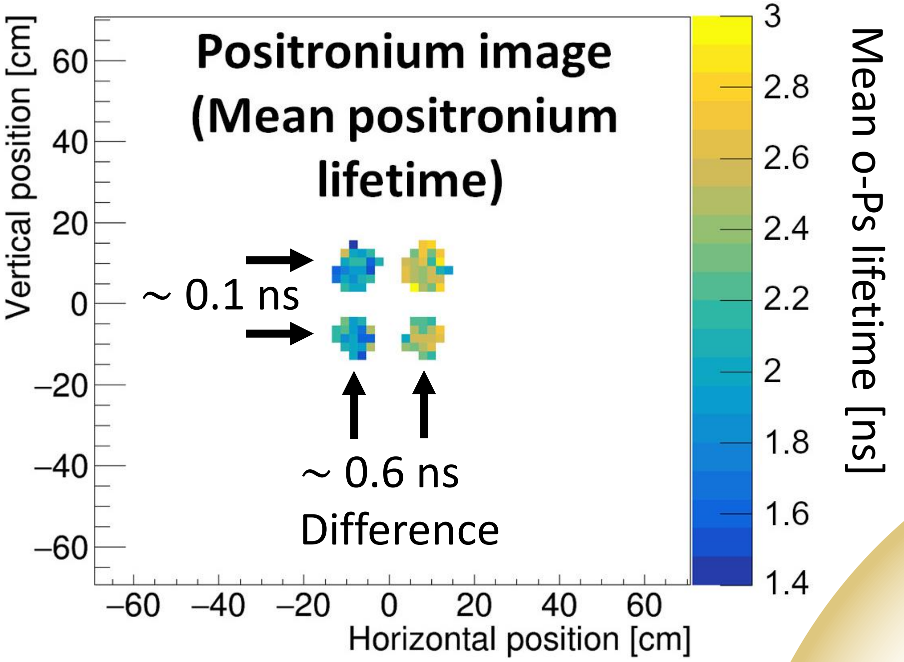
Positronium Imaging – final result

It resulted in the first positronium image of biological samples

Data



Data



Figures from P. Moskal, K. Dulski et al., Sci. Adv. 7 (2021) eabh4394

Positronium Imaging – final result

It resulted in the first positronium image of biological samples

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RESEARCH ARTICLE | BIOPHYSICS

Positronium imaging with the novel multiphoton PET scanner

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Info & Affiliations

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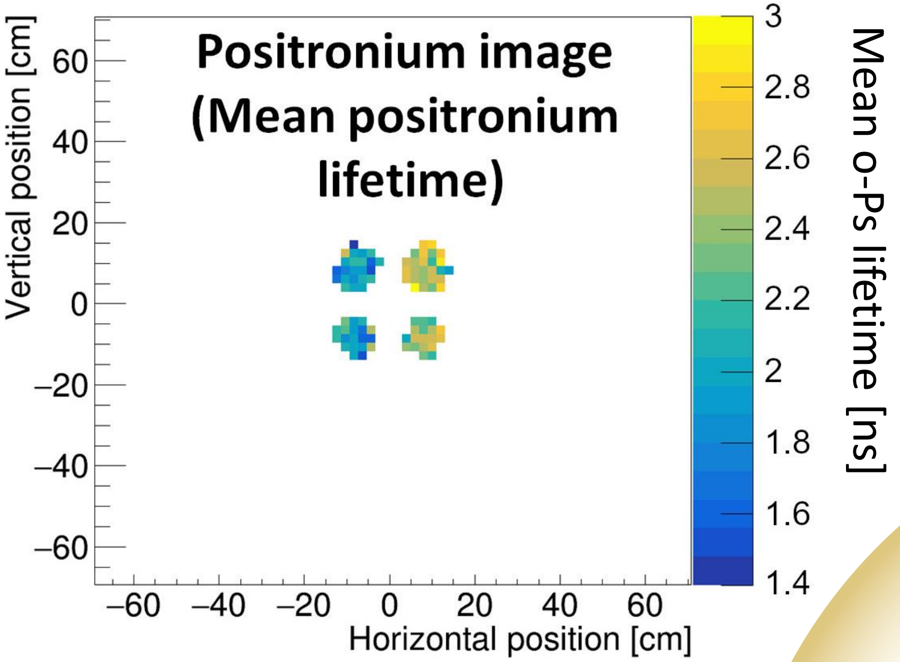
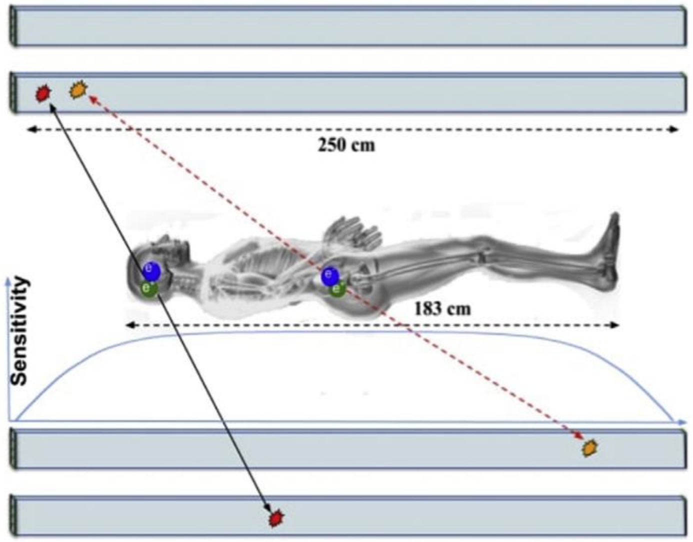
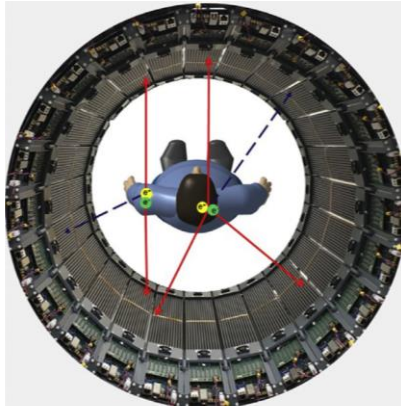
Data



Future developments





Total-body J-PET

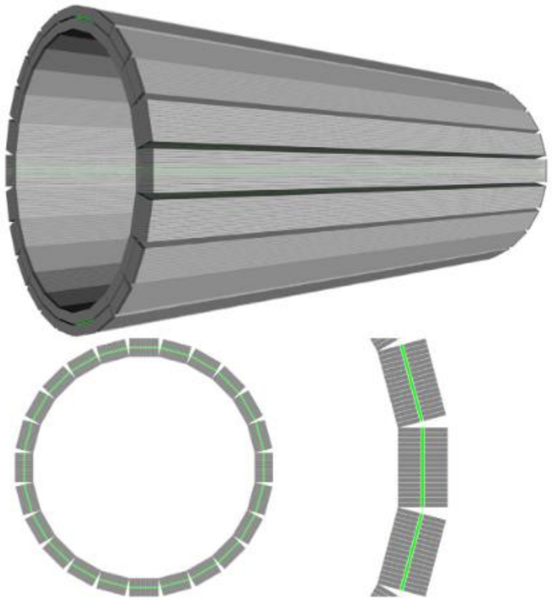
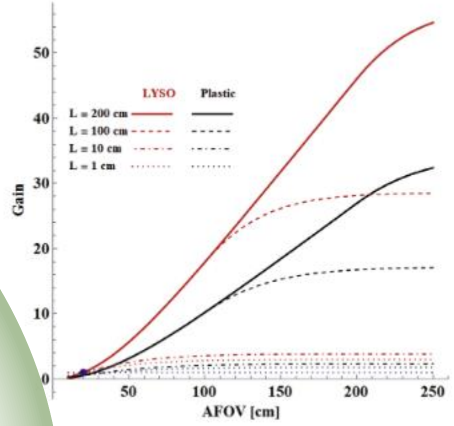
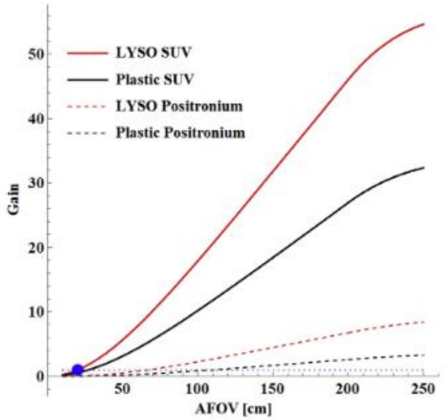


Figure from P. Moskal et al.., Phys. Med. Biol. 66 (2021) 175015





Simulations

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.
- 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.
- Positronium imaging proof of concept was presented by the J-PET detector. The first positronium image shown visible differences between two types of the tissues – Cardiac Myxoma and Adipose tissue.

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Thank you for your attention