Analysis of positronium decays by the J-PET detector for the medical and fundamental studies

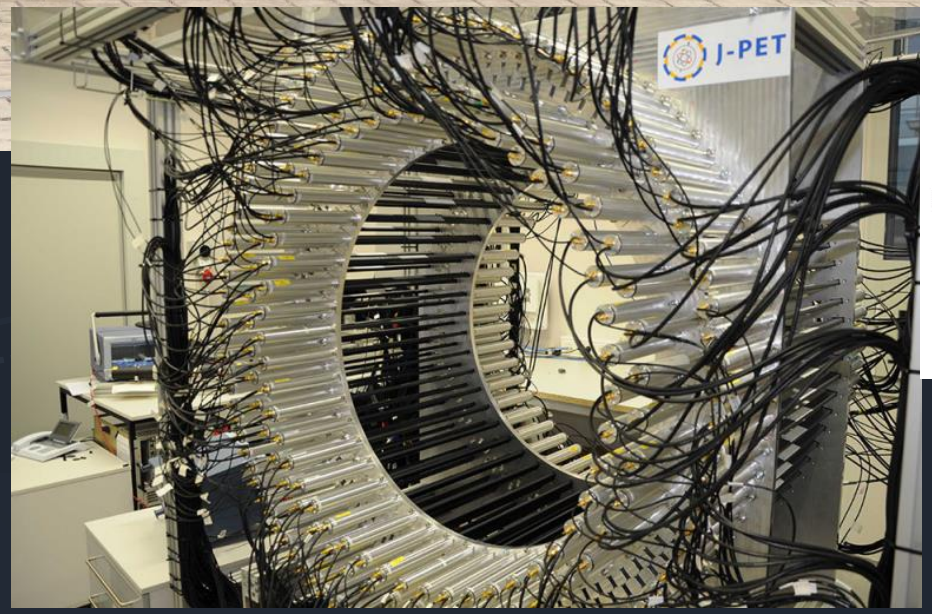
K. Dulski
on behalf of the J-PET collaboration

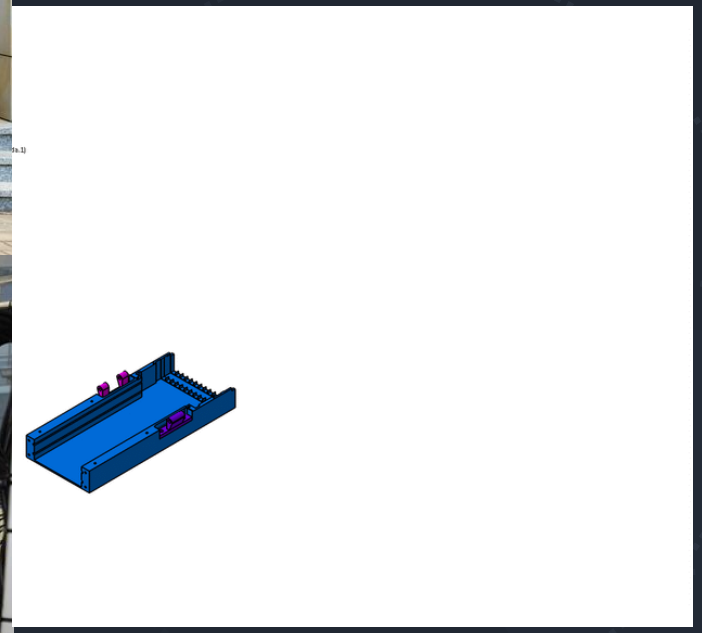
20.11.2023

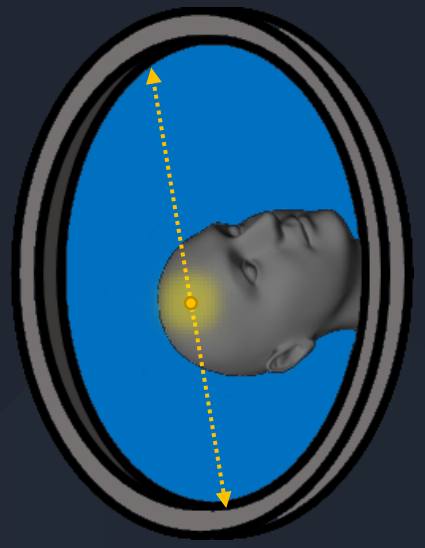
ALPACA: modern algorithms in machine learning and data analysis: from medical physics to research with accelerators and in underground laboratories

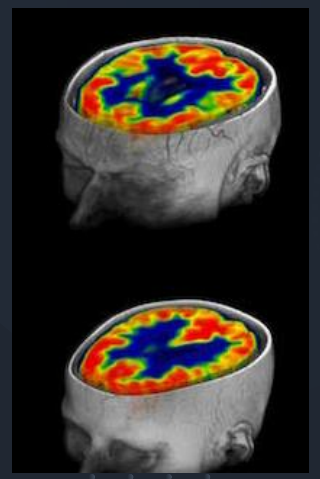
J-PET

Jagiellonian Positron Emission Tomography (J-PET)

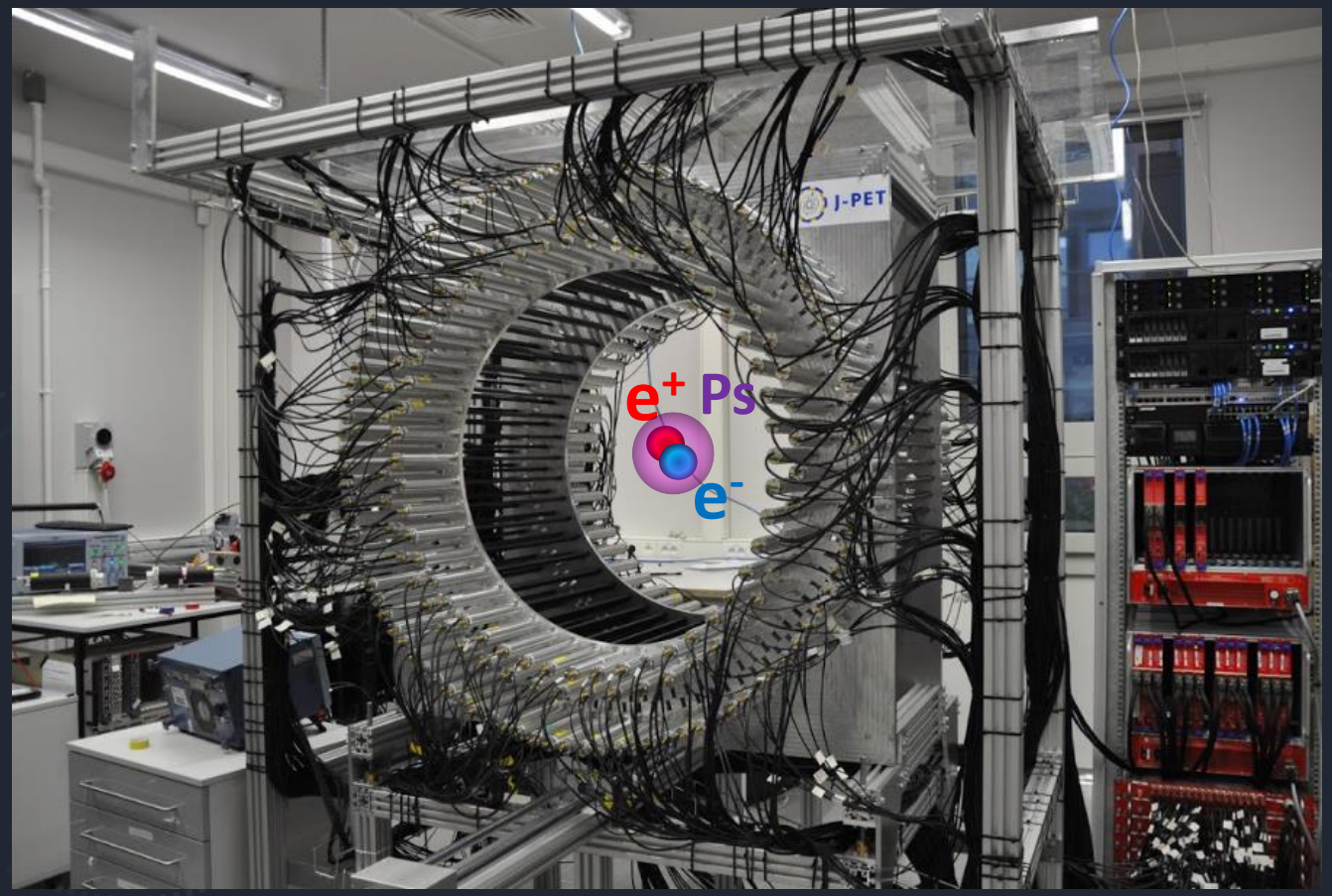


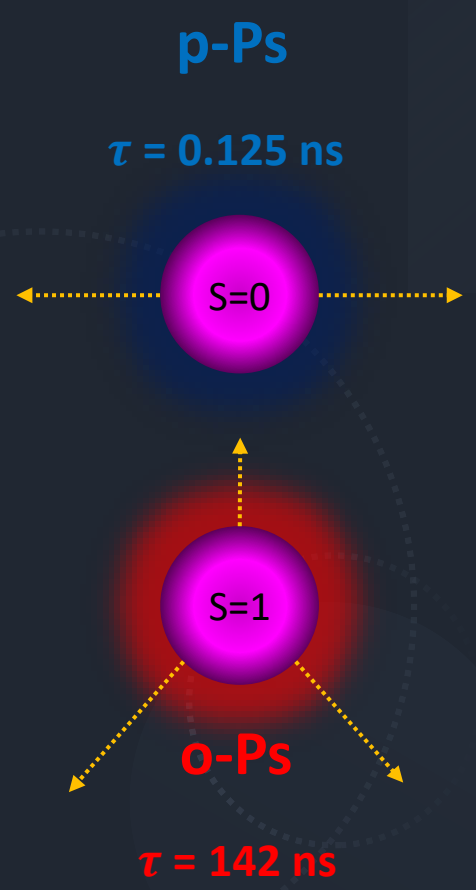


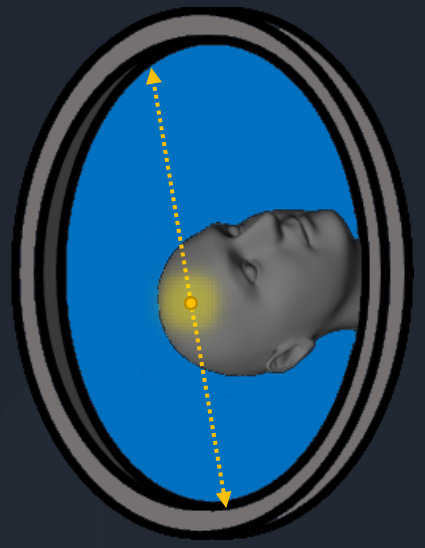


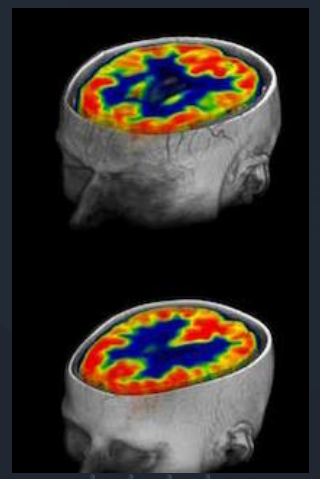


https://sciencebasedmedicine.org/pet-scans-predict-coma-outcome/
DOI: 10.1016/j.cub.2016.04.024





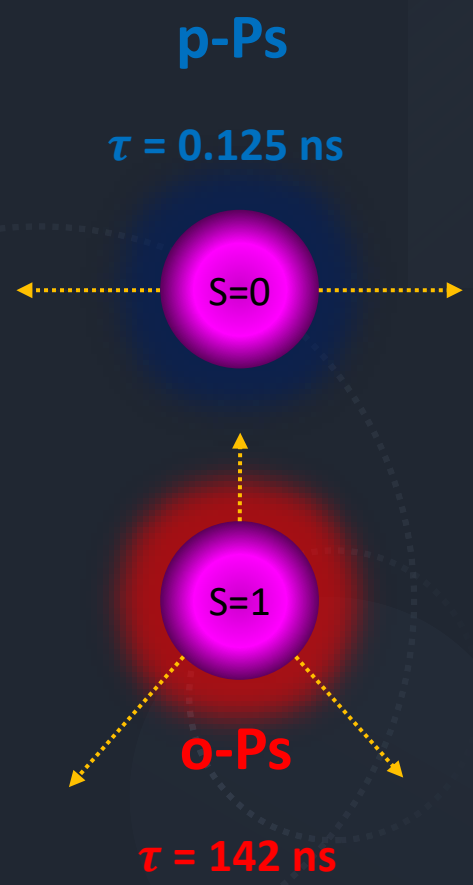




https://sciencebasedmedicine.org/pet-scans-predict-coma-outcome/
DOI: 10.1016/j.cub.2016.04.024

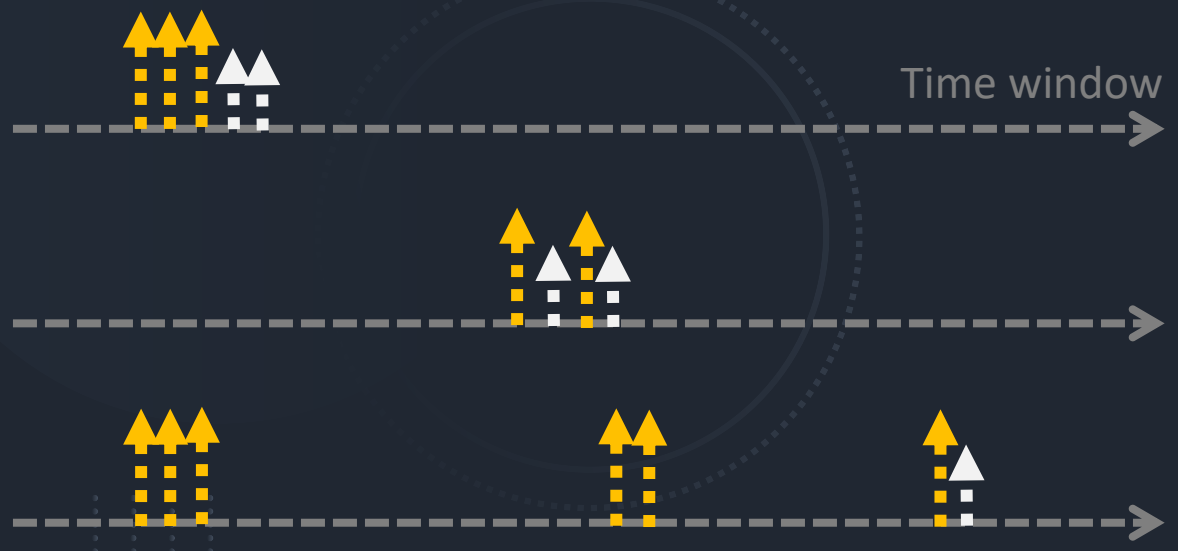
Analysis procedure:

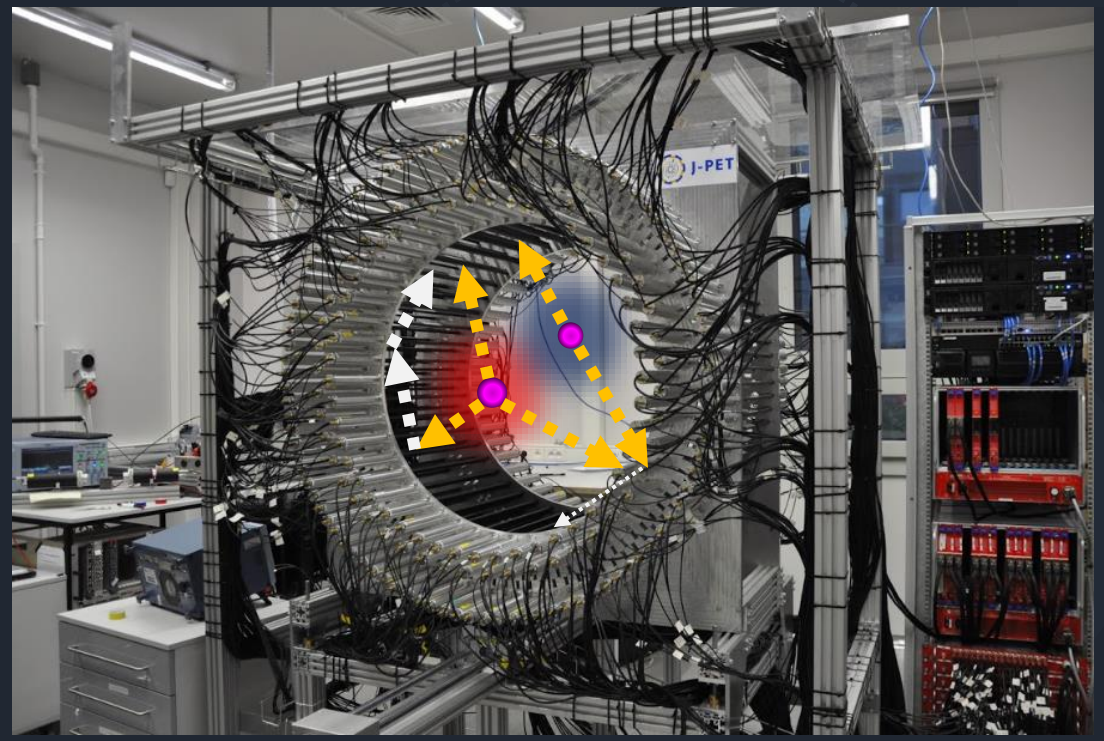
- Data reconstruction
- Data selection
- Advanced refinements



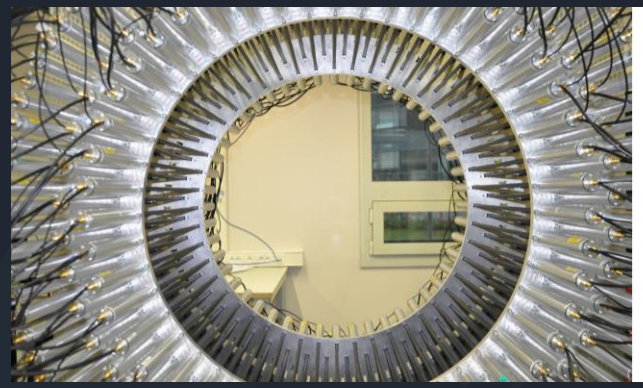
Triggering?

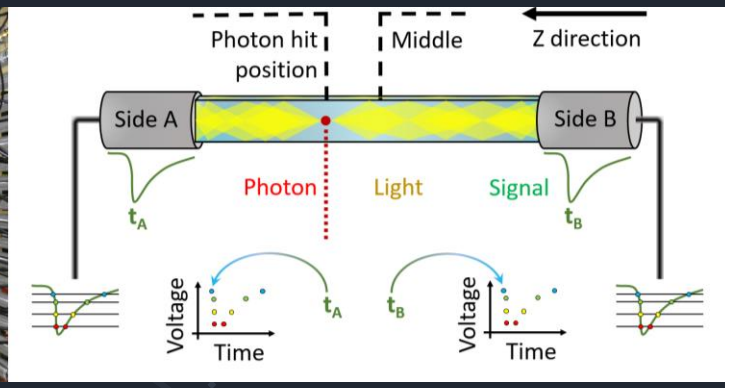
The J-PET DAQ based on FPGA works in a trigger-less mode in order to maximize potential of measurements into different types of analysis



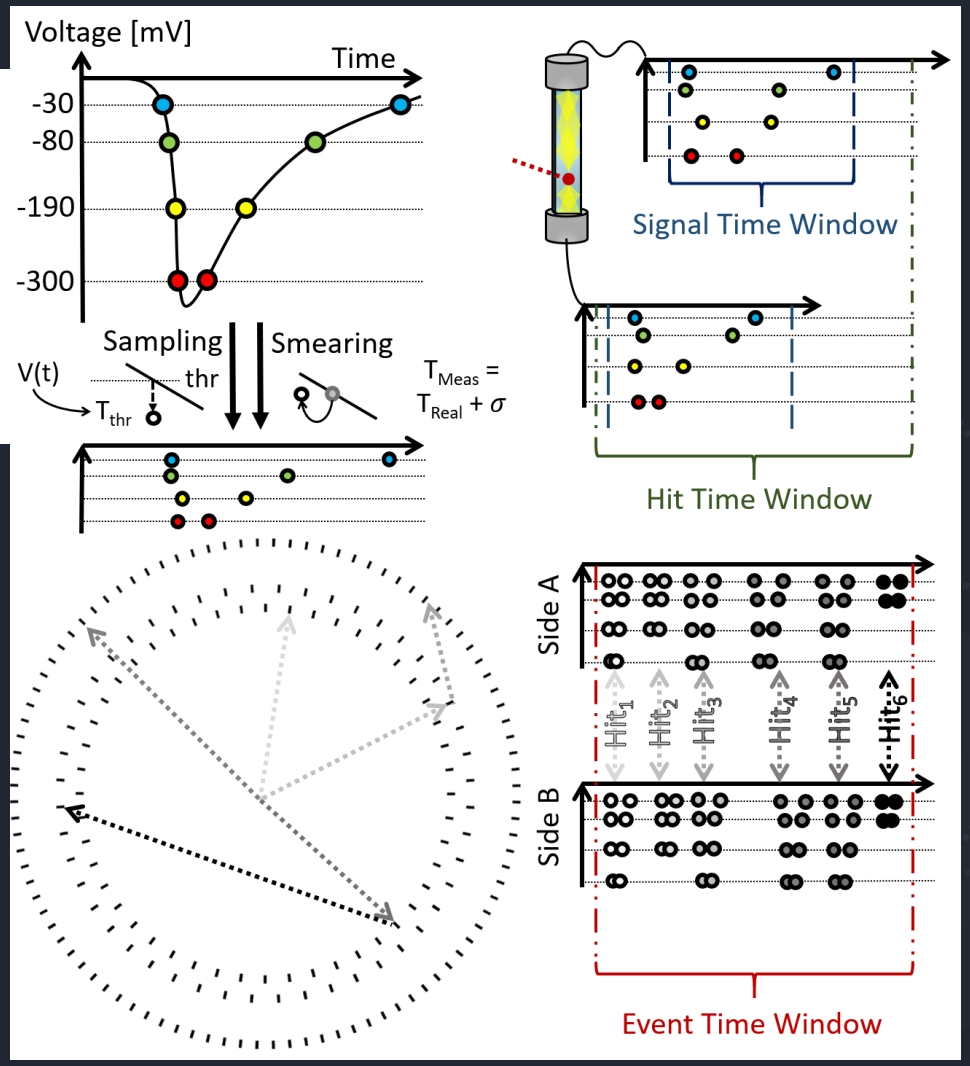


Data reconstruction

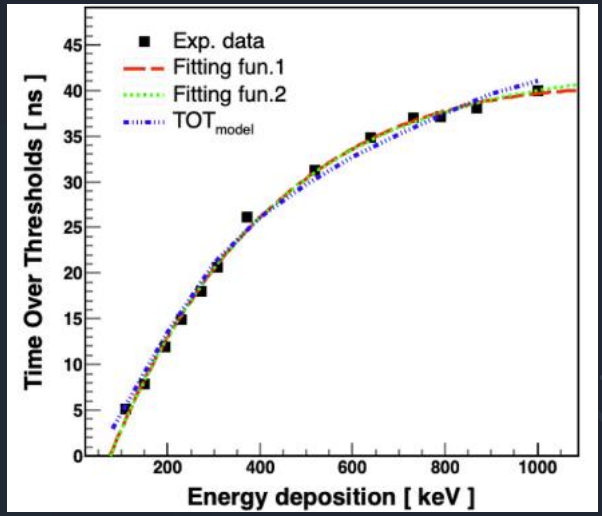




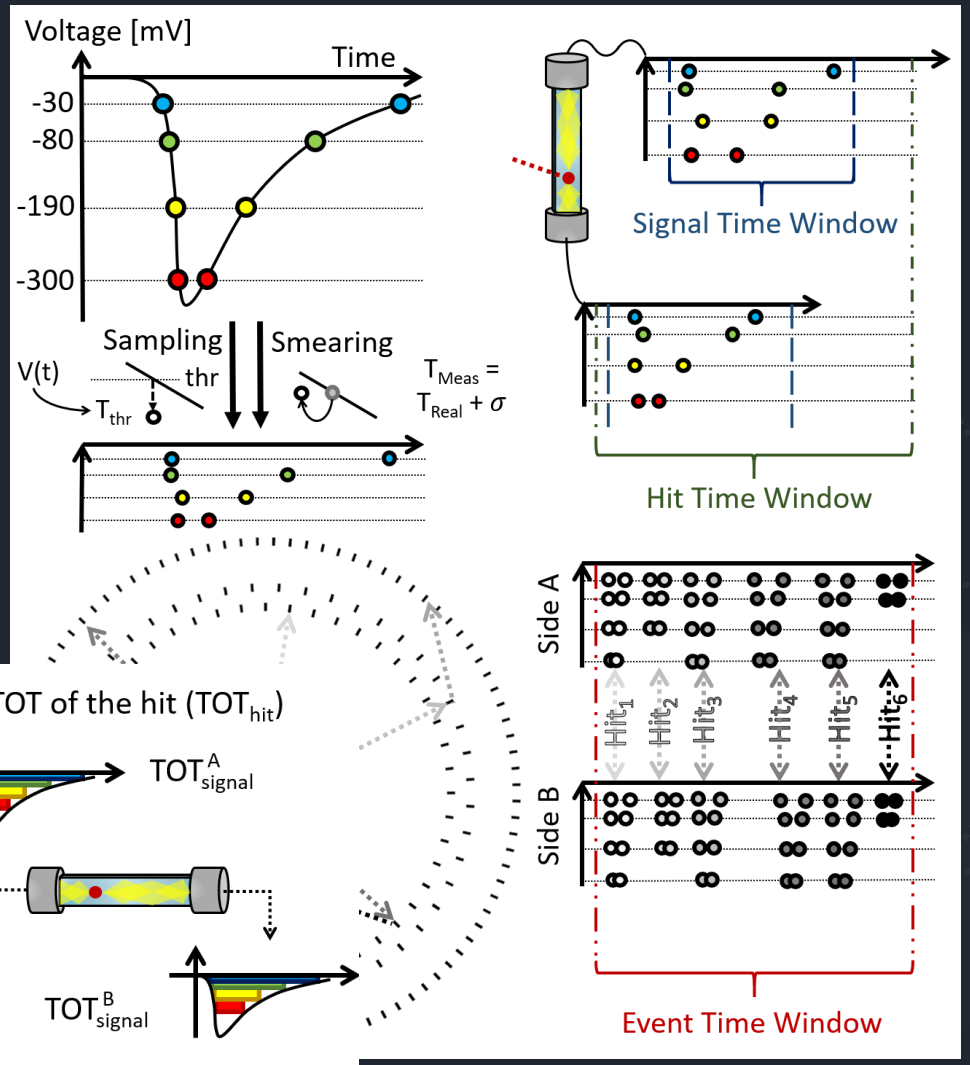
K. Dulski, PhD thesis
S. Niedźwiecki et al., Acta Phys. Polon. B 48 (2017) 1567

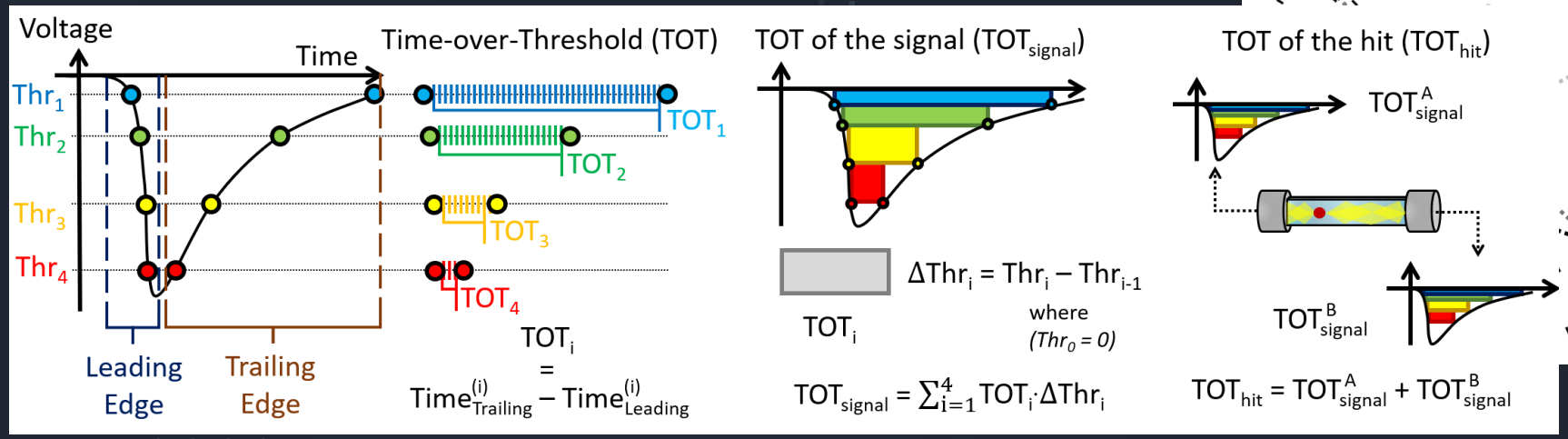


Data reconstruction



S.Sharma ... K. Dulski et al. EJNMMI Phys. 7 (2020) 39





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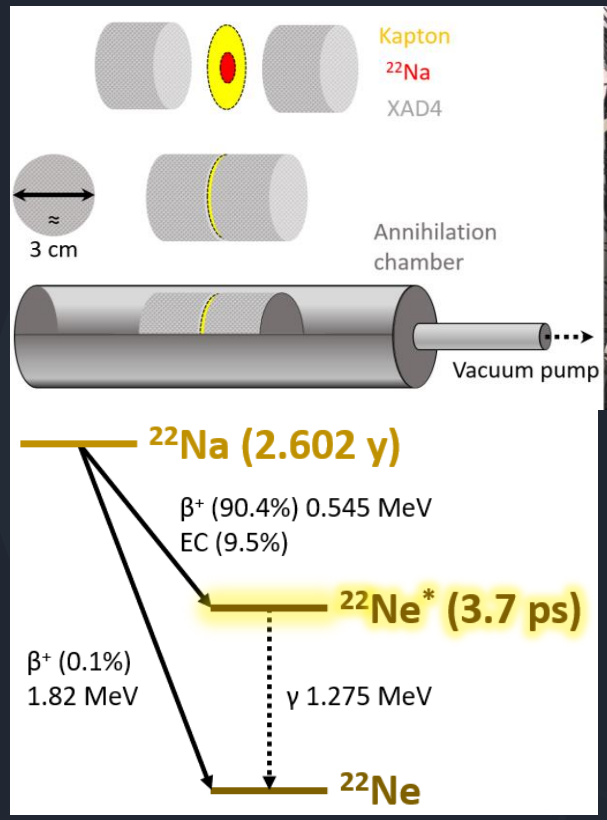
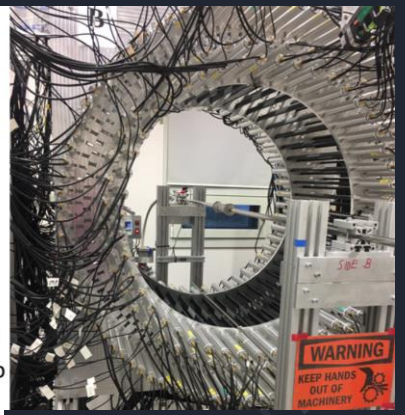
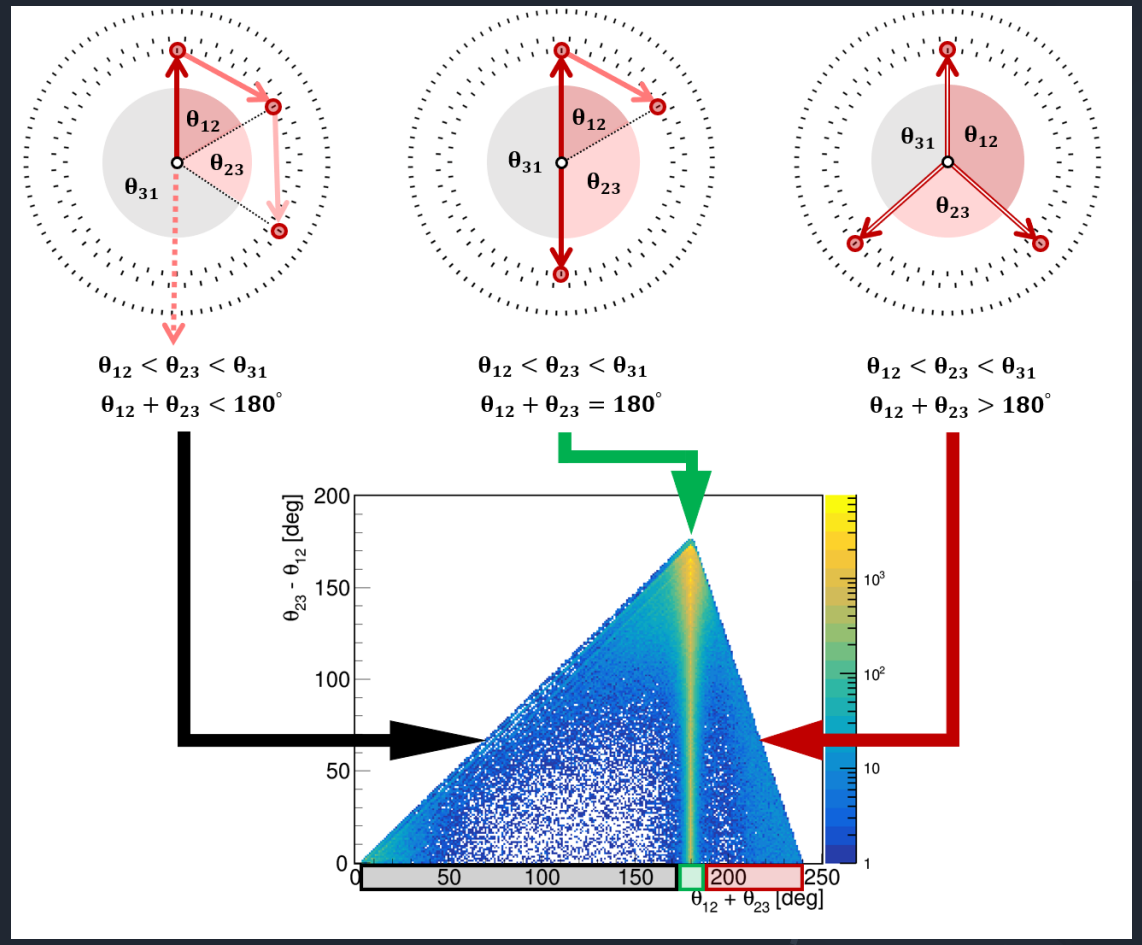
Data selection



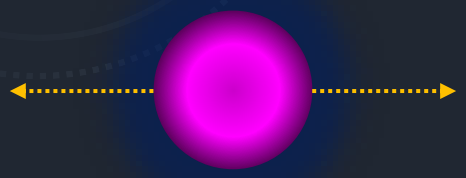


Chamber in the centre (0,0,0) of the detector



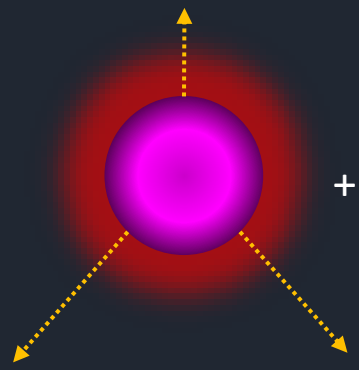
K. Dulski, PhD thesis
K. Dulski et al., Nuclear Inst. and Methods in Physics Research, A 1008 (2021) 165452
K. Dulski et al., Hyperfine Interact. 239 (2018) 40

(2G)



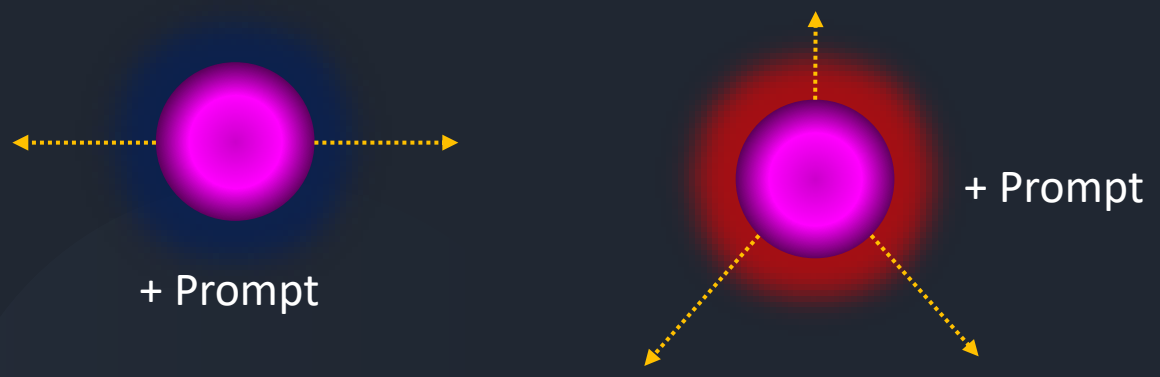
+ Prompt

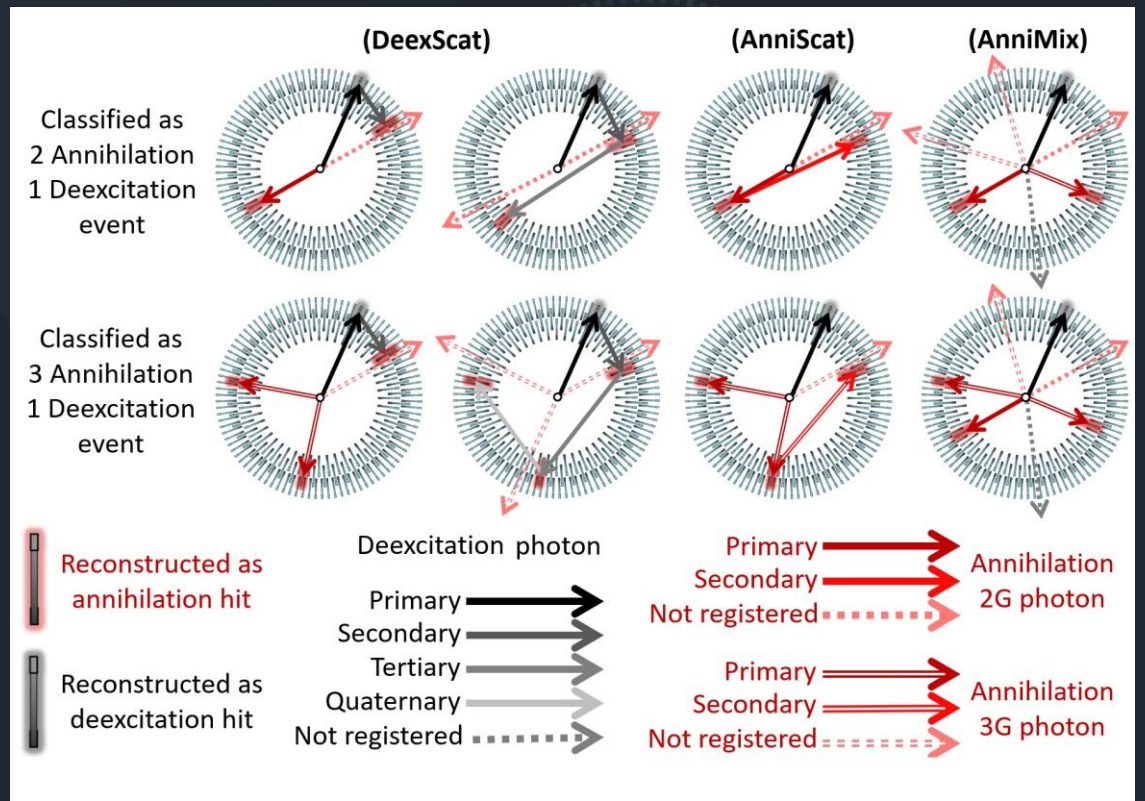
(3G)

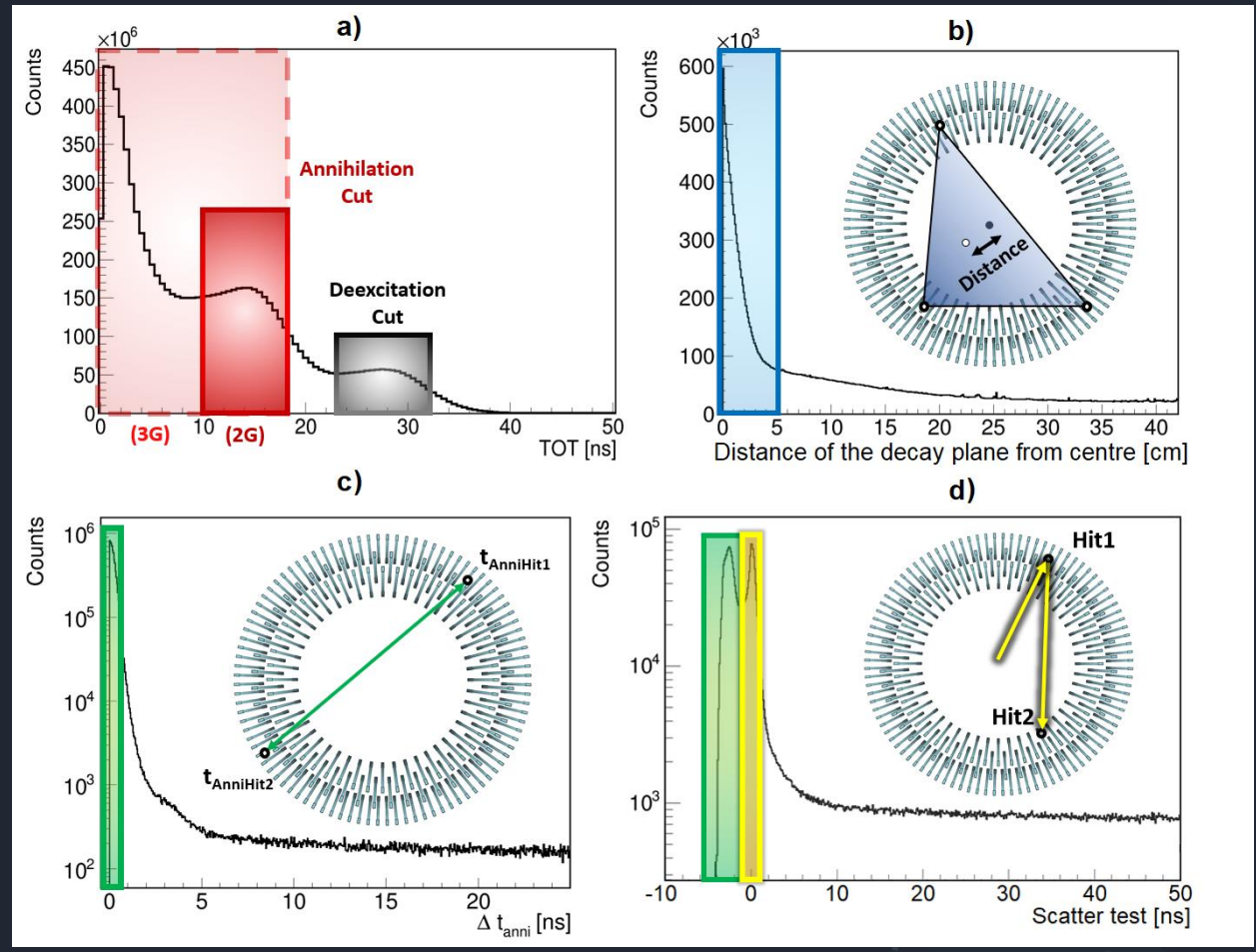


+ Prompt

Data selection







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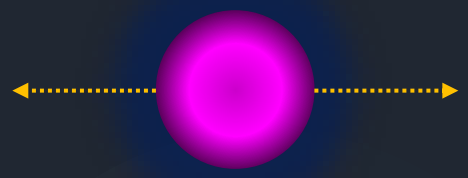
K. Dulski et al., Nuclear Inst. and Methods in Physics Research, A 1008 (2021) 165452
K. Dulski et al., Hyperfine Interact. 239 (2018) 40

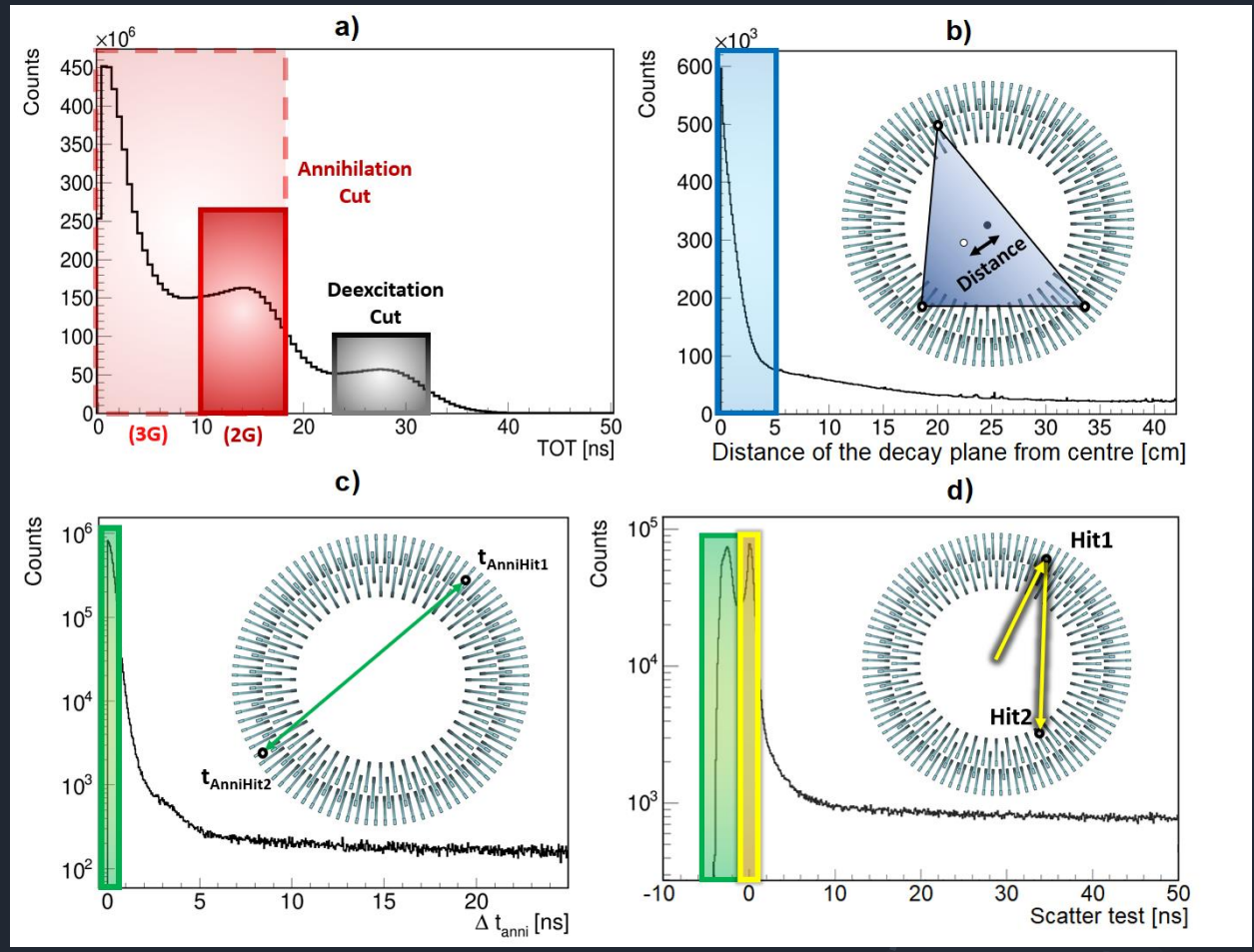
$$Scatter\ test = \Delta t - \frac{distance}{c}$$

Data selection



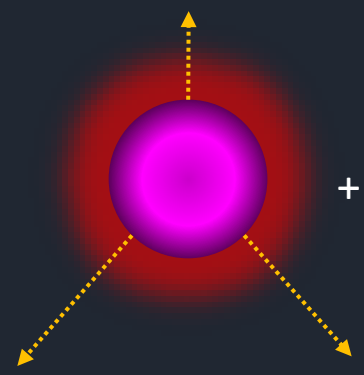
+ Prompt

Stage of the analysis		(2G) Sensitivity [$\cdot 10^{-6}$]	Purity [%]	(DeexScat) [%]	(AnniScat) [%]	(AnniMix) [%]	(3G) [%]
Hit selection	TOT cut	15.59	34.62	7.89	13.63	41.80	2.06
Data selection	Distance	7.21	61.73	3.90	7.11	23.44	3.82
	Time difference	4.76	54.28	7.04	7.17	27.02	4.50
	Scater test	5.40	55.13	5.44	11.38	27.82	0.22
After selection		**1.17**	**94.71**	0.44	1.84	2.10	0.90



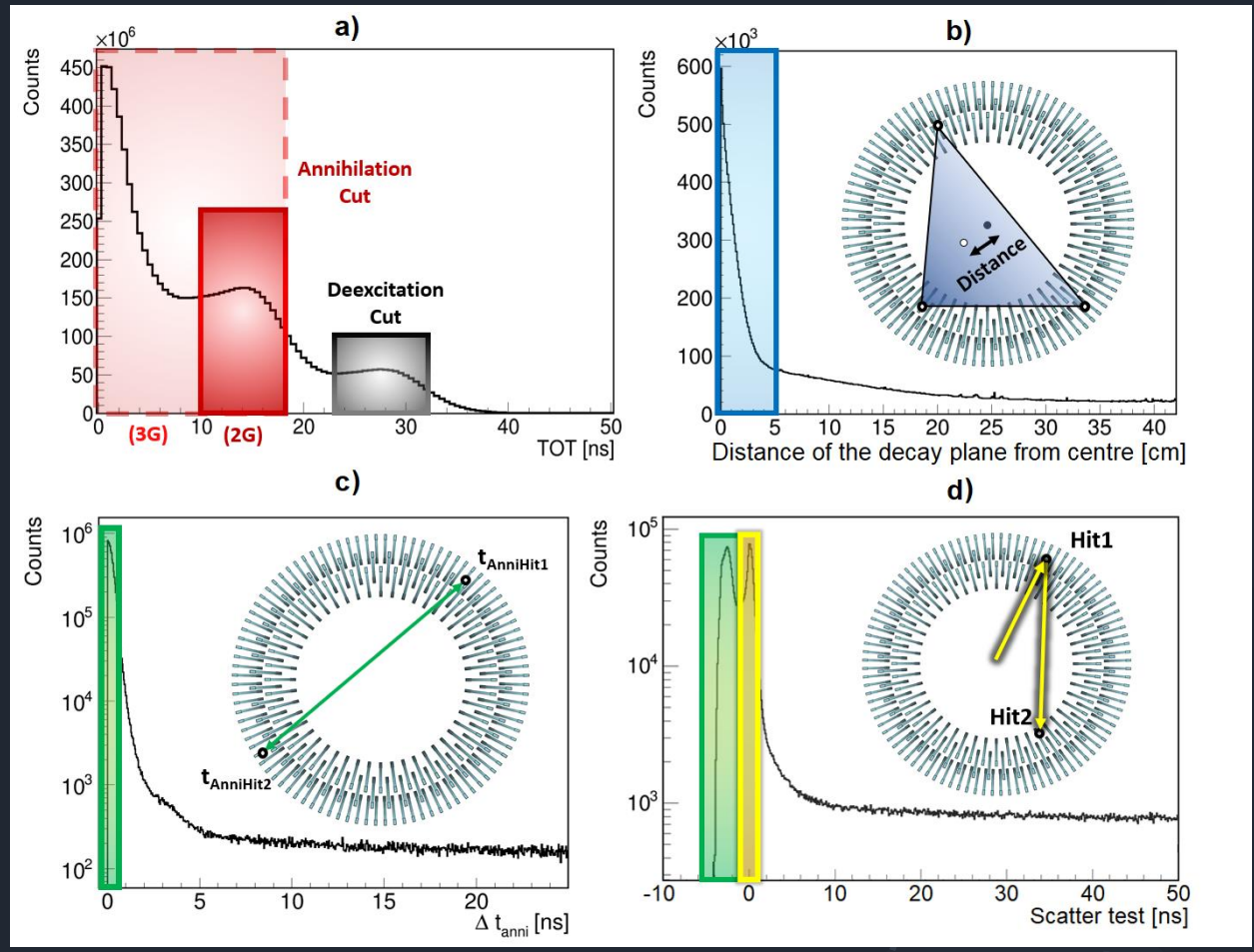
K. Dulski, PhD thesis
K. Dulski et al., Nuclear Inst. and Methods in Physics Research, A 1008 (2021) 165452
K. Dulski et al., Hyperfine Interact. 239 (2018) 40

Data selection



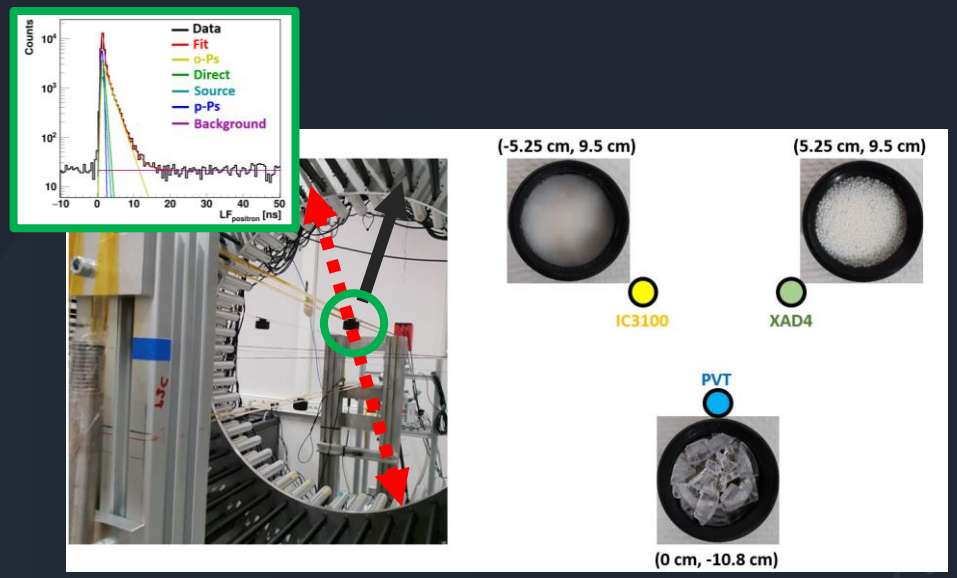
+ Prompt

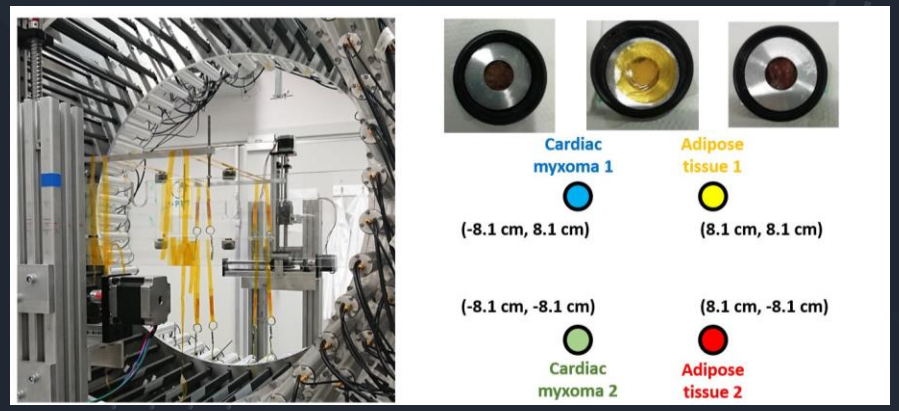
Stage of the analysis		(3G) Sensitivity [$\cdot 10^{-6}$]	Purity [%]	(DeexScat) [%]	(AnniScat) [%]	(AnniMix) [%]	(2G) [%]
Hit selection	TOT cut	12.36	21.04	11.99	6.74	34.02	26.22
Data selection	Distance	3.26	33.20	5.29	5.44	32.90	23.17
	Time difference	4.08	17.73	10.00	18.02	22.20	32.08
	Scater test	3.26	11.53	10.14	2.11	39.06	37.15
After selection		**0.41**	**56.27**	4.73	14.46	10.88	13.66

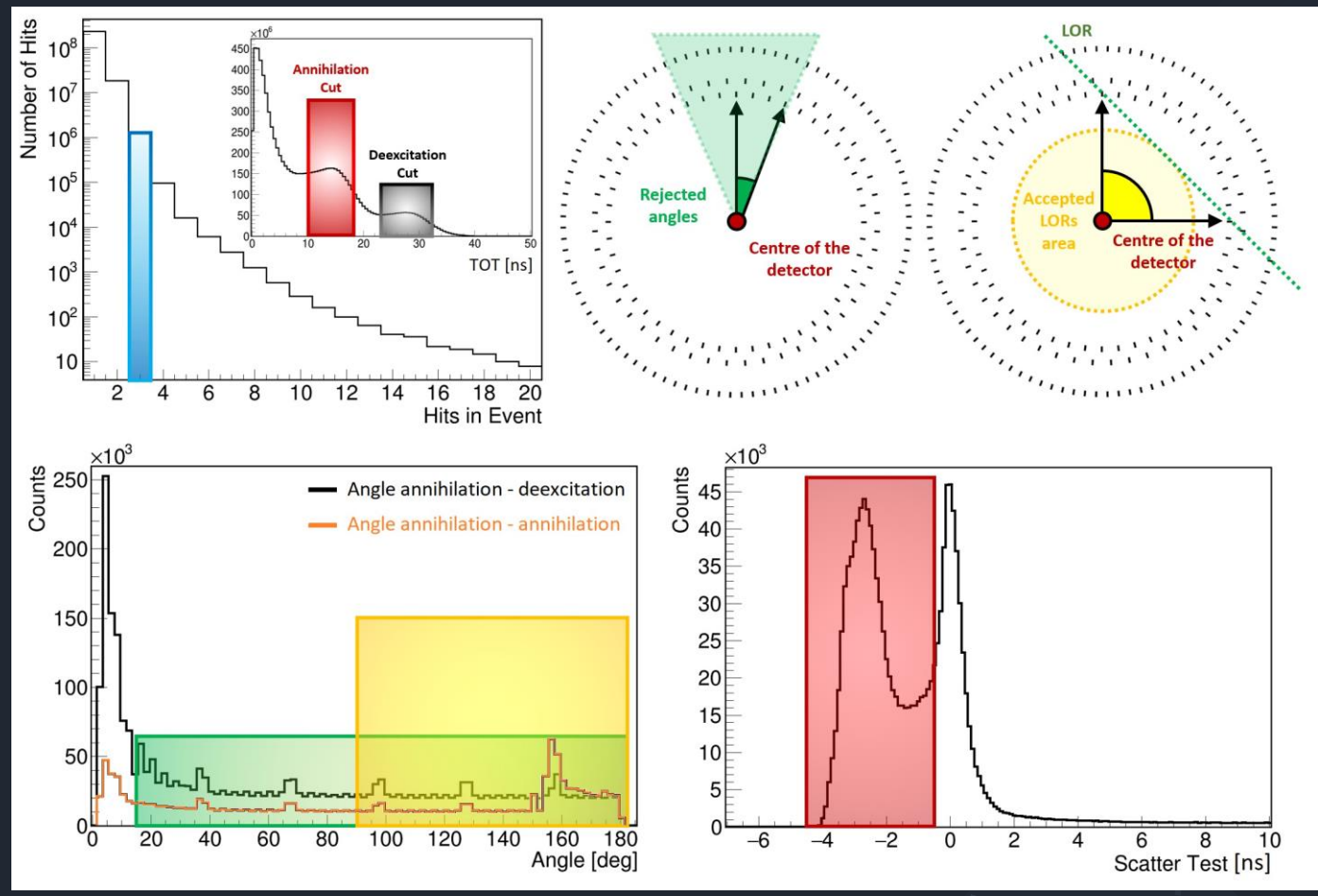


K. Dulski, PhD thesis
K. Dulski et al., Nuclear Inst. and Methods in Physics Research, A 1008 (2021) 165452
K. Dulski et al., Hyperfine Interact. 239 (2018) 40

Data selection – positronium imaging



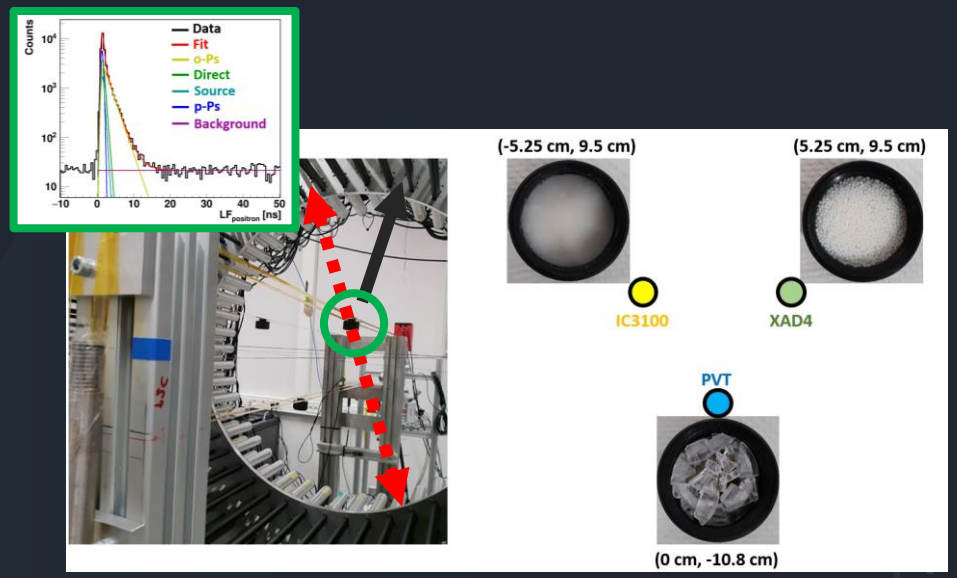


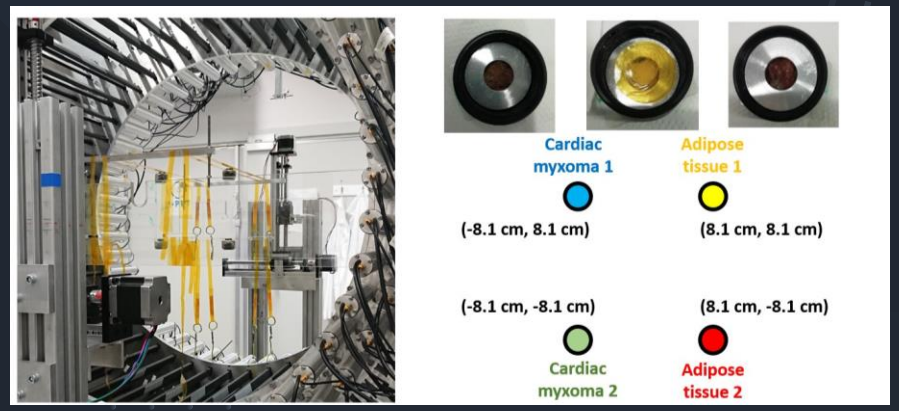


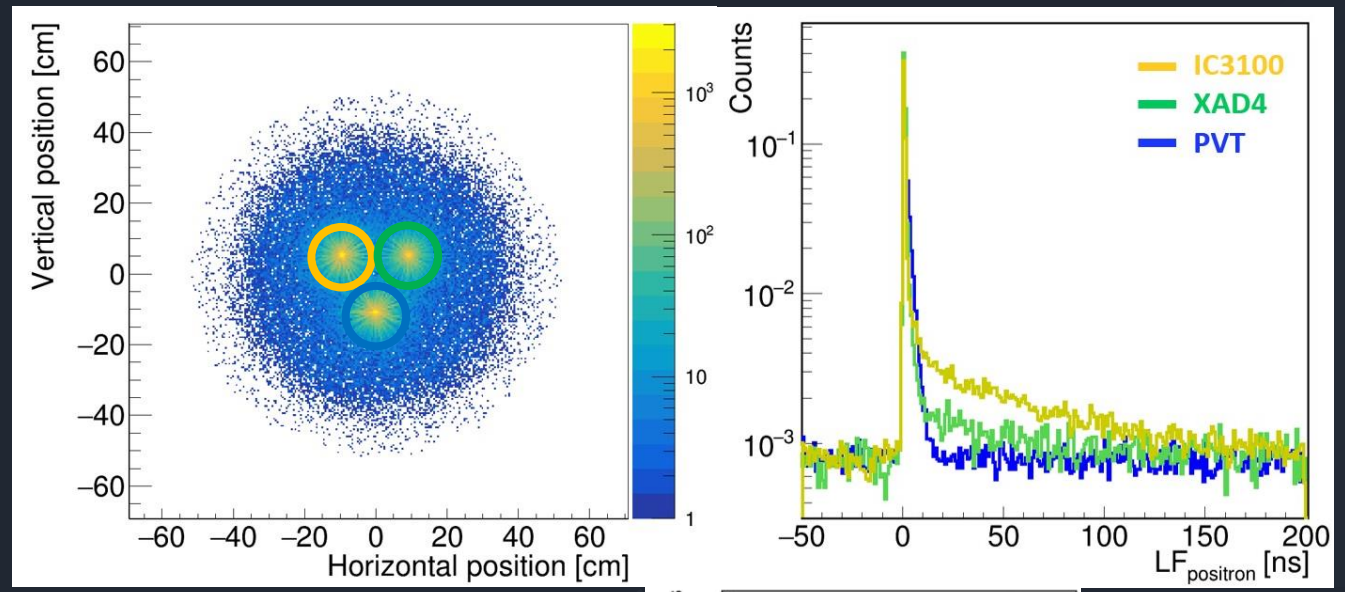
K. Dulski, PhD thesis
K. Dulski et al., Nuclear Inst. and Methods in Physics Research, A 1008 (2021) 165452
K. Dulski et al., Hyperfine Interact. 239 (2018) 40

$$LF = \frac{t_{anni1} + t_{anni2}}{2} - t_{deex}$$

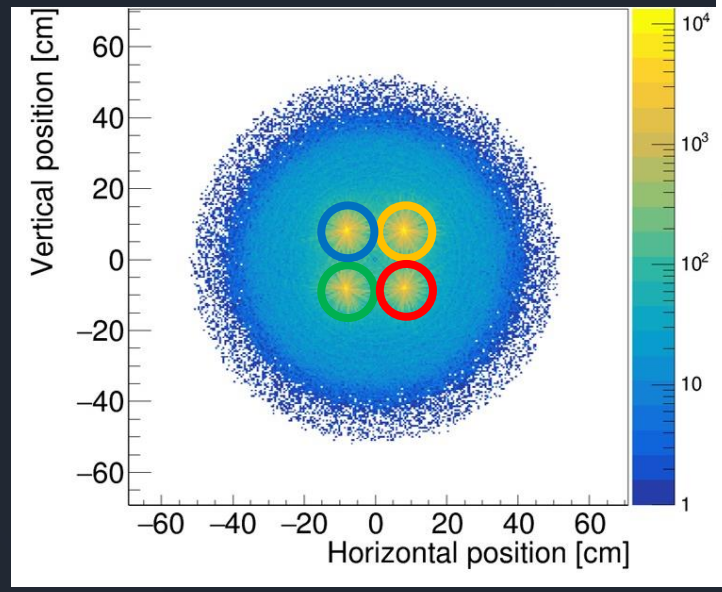
Data selection – positronium imaging

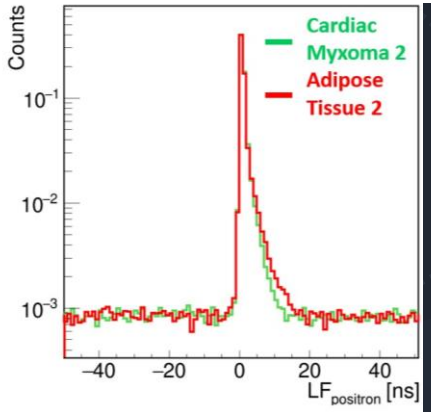


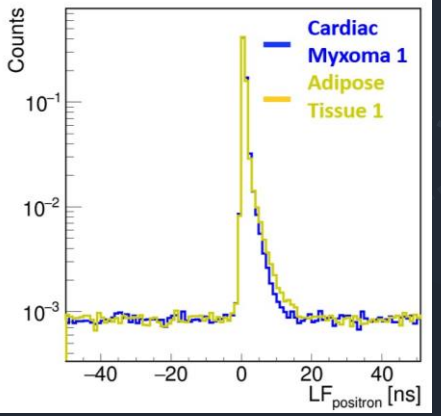




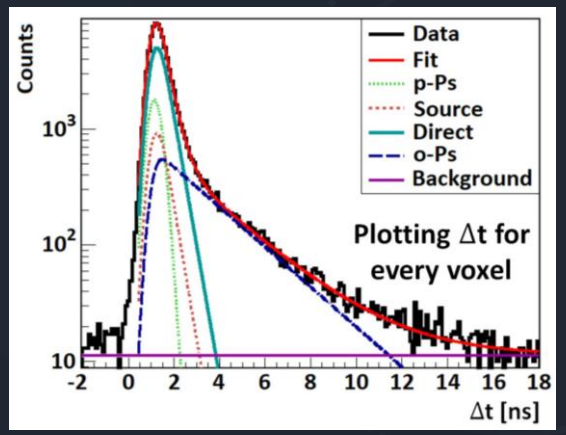
K. Dulski, PhD thesis
K. Dulski et al., Hyperfine Interact. 239 (2018) 40
P. Moskal, K. Dulski et al., Science Advances 7 (2021) eabh4394

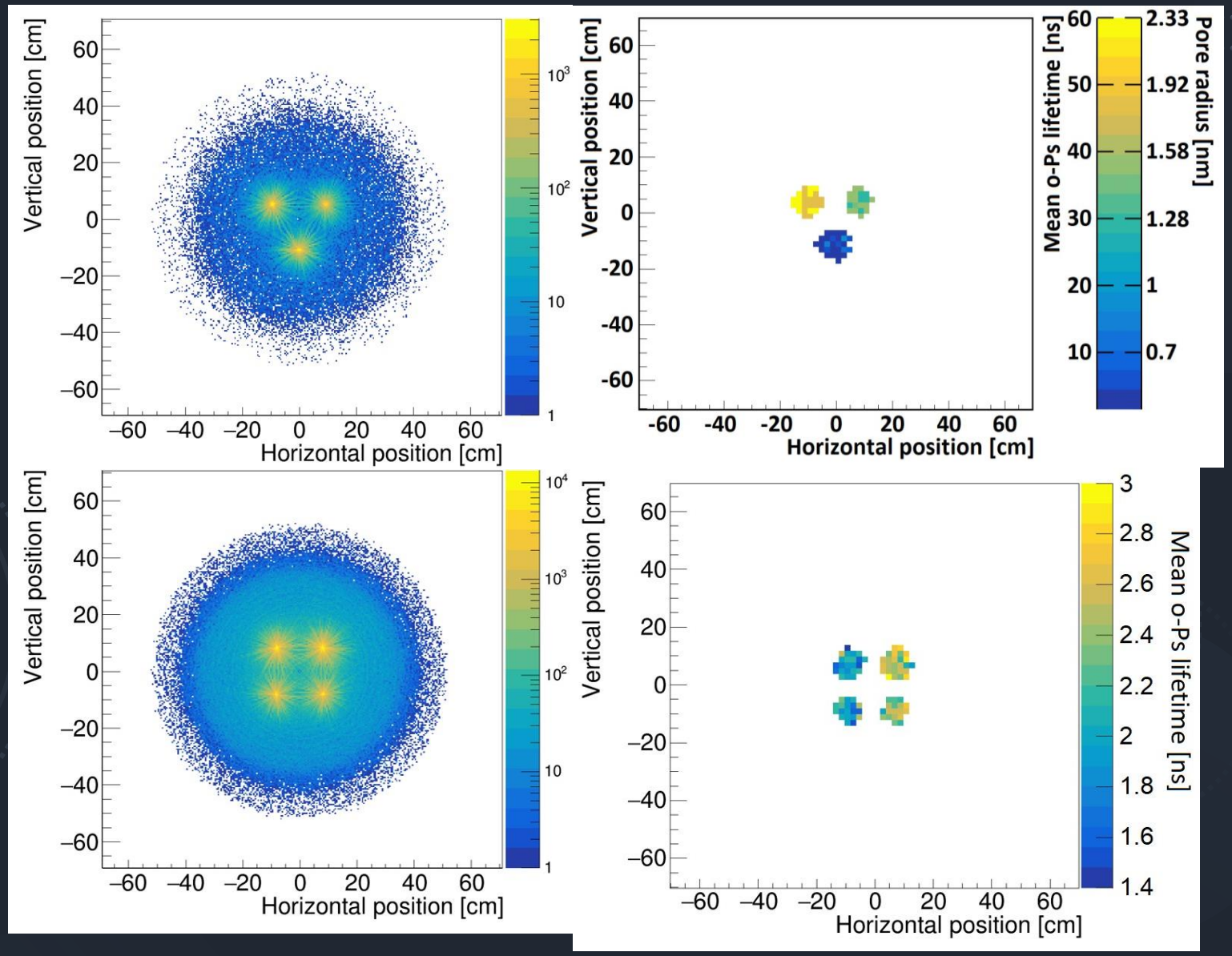






Advanced refinements – positronium imaging



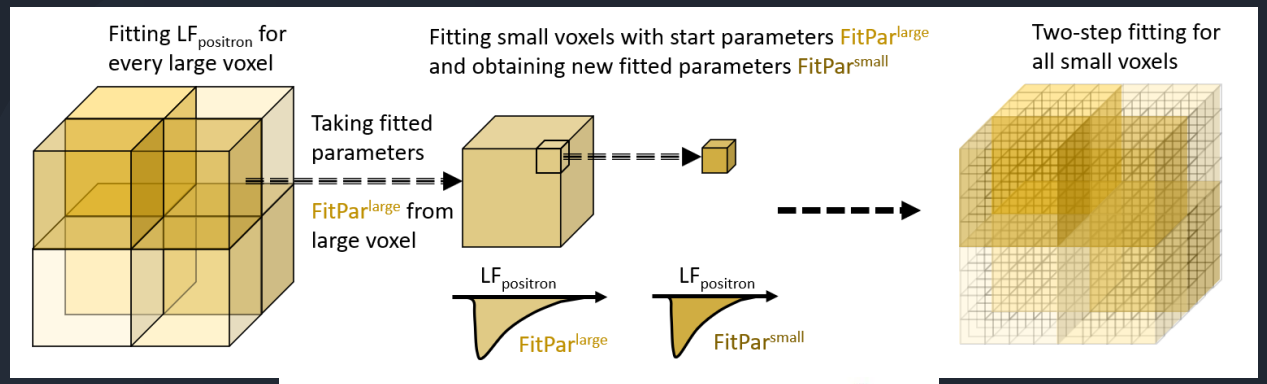


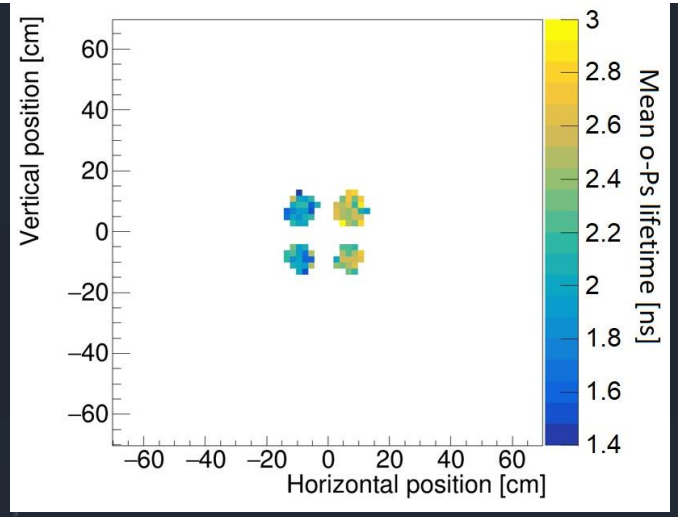
K. Dulski, PhD thesis
K. Dulski et al., Hyperfine Interact. 239 (2018) 40
P. Moskal, K. Dulski et al., Science Advances 7 (2021) eabh4394
Fitting with PALS Avalanche:
K. Dulski et al., Acta Phys. Pol. A 132 (2017) 1637
K. Dulski, Acta. Phys. Pol. A 137 (2020) 167

Study of positronium lifetime in different tissues:
P. Moskal et al., EJNMMI Phys. 10 (2023) 22

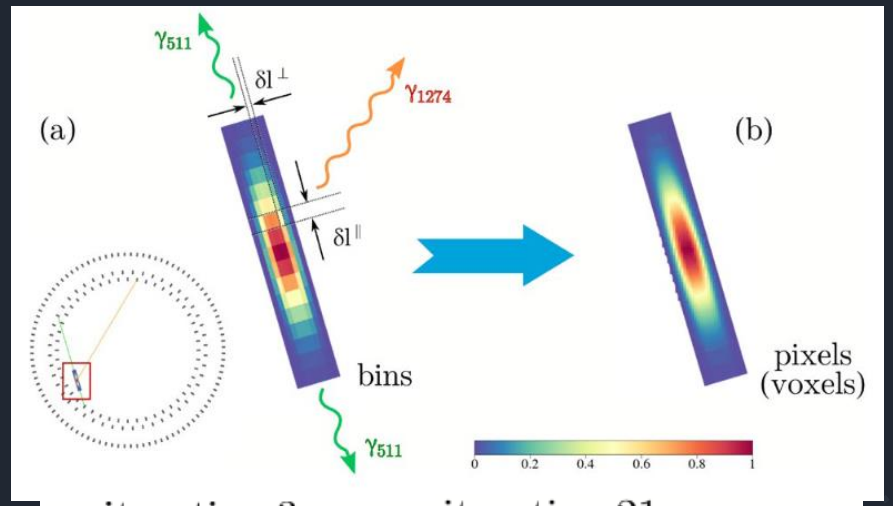
Advanced refinements – positronium imaging

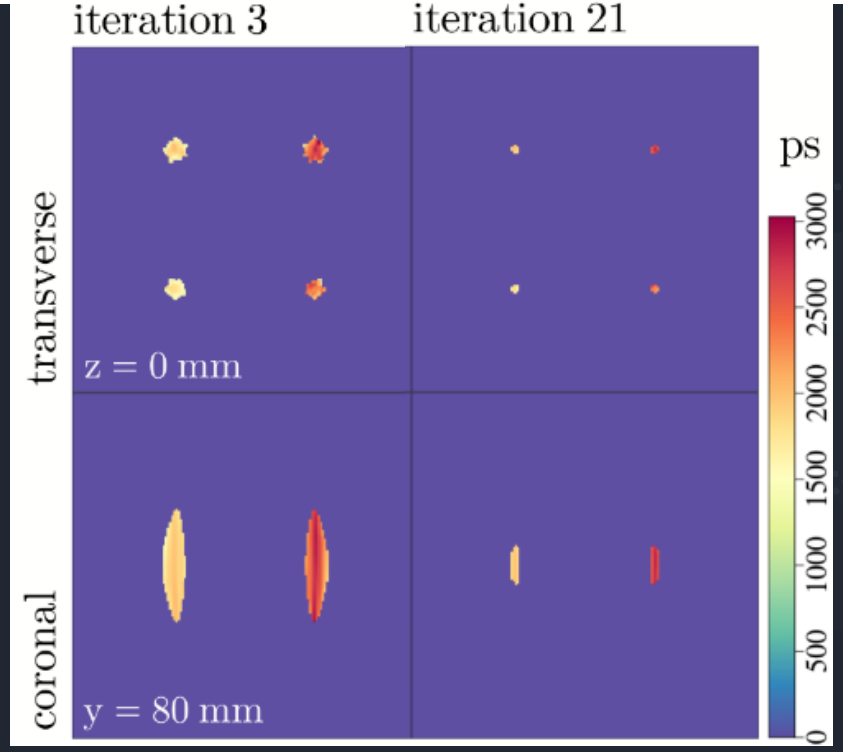
K. Dulski PhD thesis



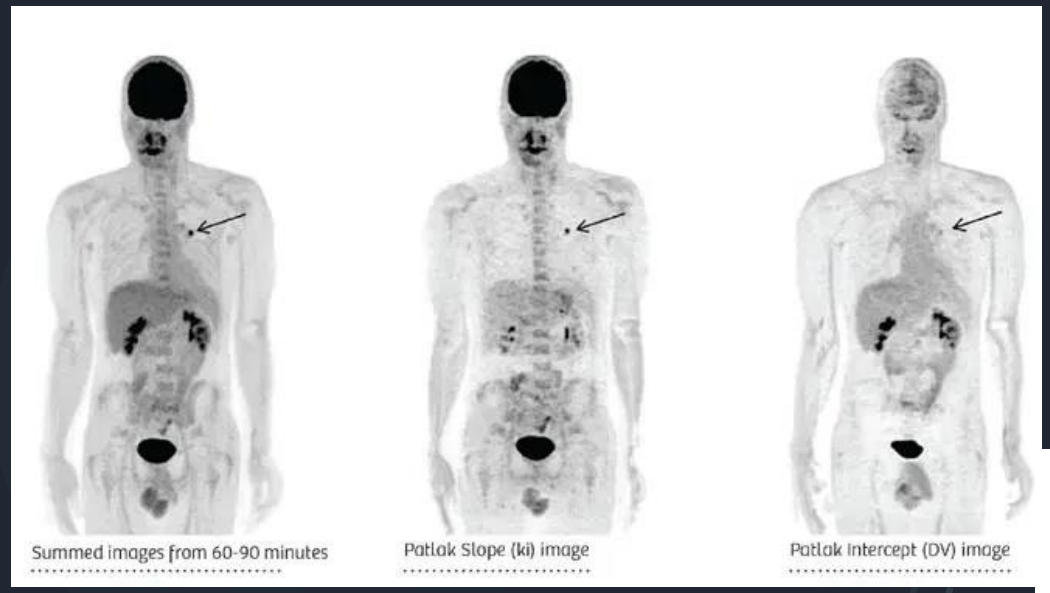


R. Shopa and K. Dulski, Bio-Algorithms and Med-Systems 2022; 18(1): 135-143



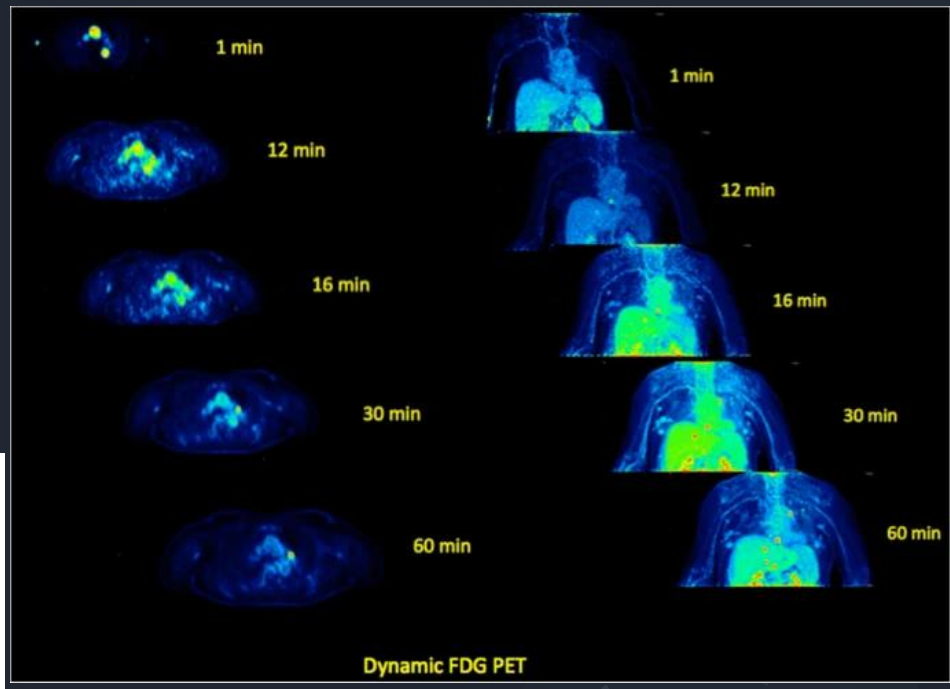


Advanced refinements – future advancements in imaging



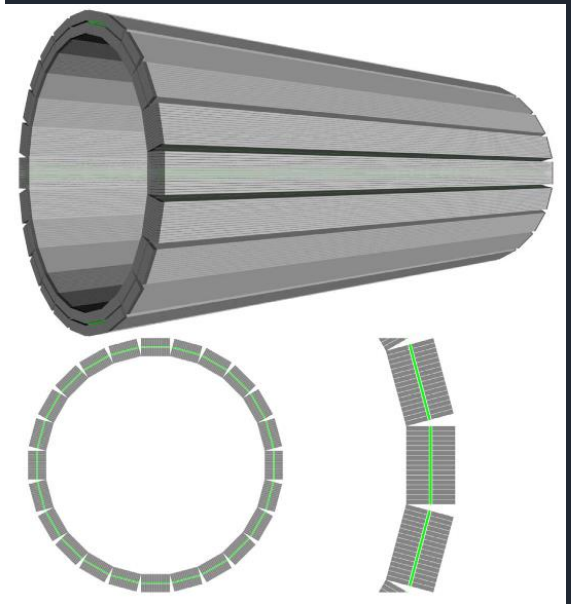
Siemens Healthineers

Parametric and dynamic imaging



A. Strauss et al., Eur. J. Nucl. Med. Mol. Imaging 48 (2021) 21

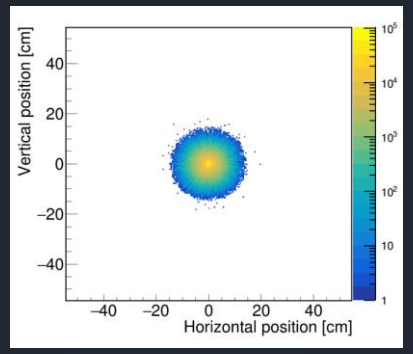
Total body J-PET

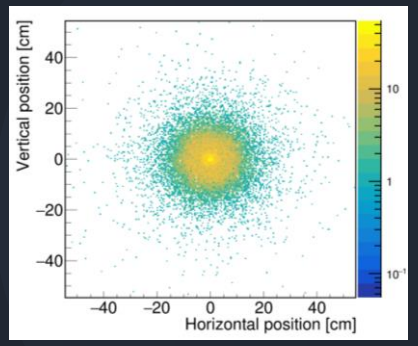


P. Moskal, E.Ł. Stępień, Front. Phys. 10 (2022) 969806
P. Moskal et al., Phys. Med. Biol. 66 (2021) 175015
P. Moskal, E.Ł. Stępień, PET Clin. 15 (2020) 439-452

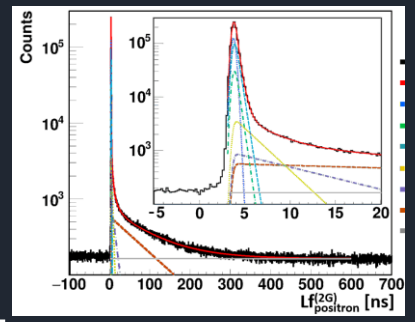
Advanced refinements – positronium physics

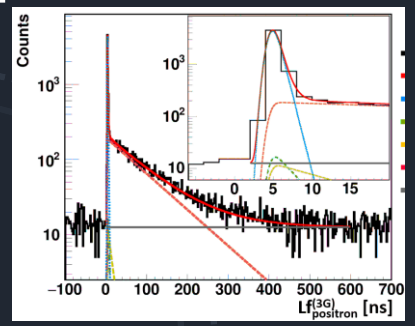
K. Dulski, PhD thesis

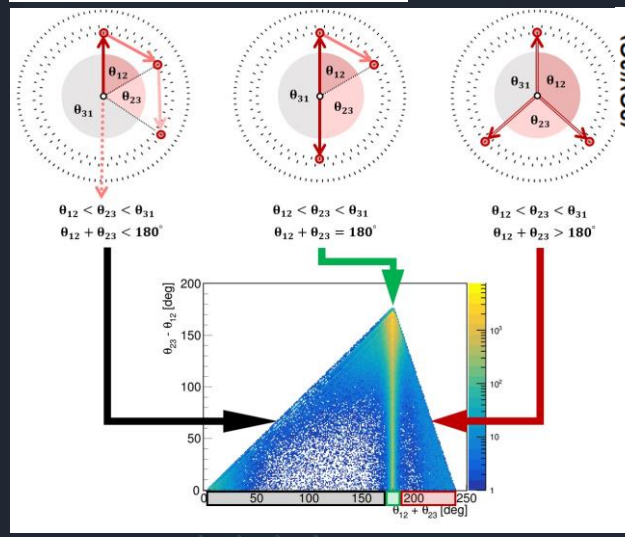


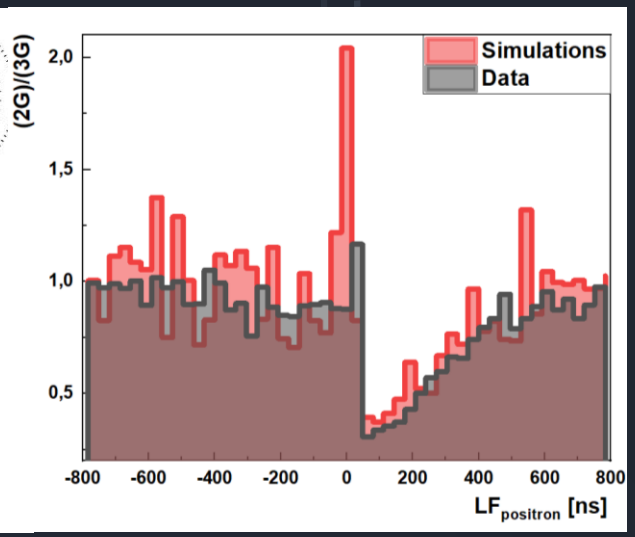


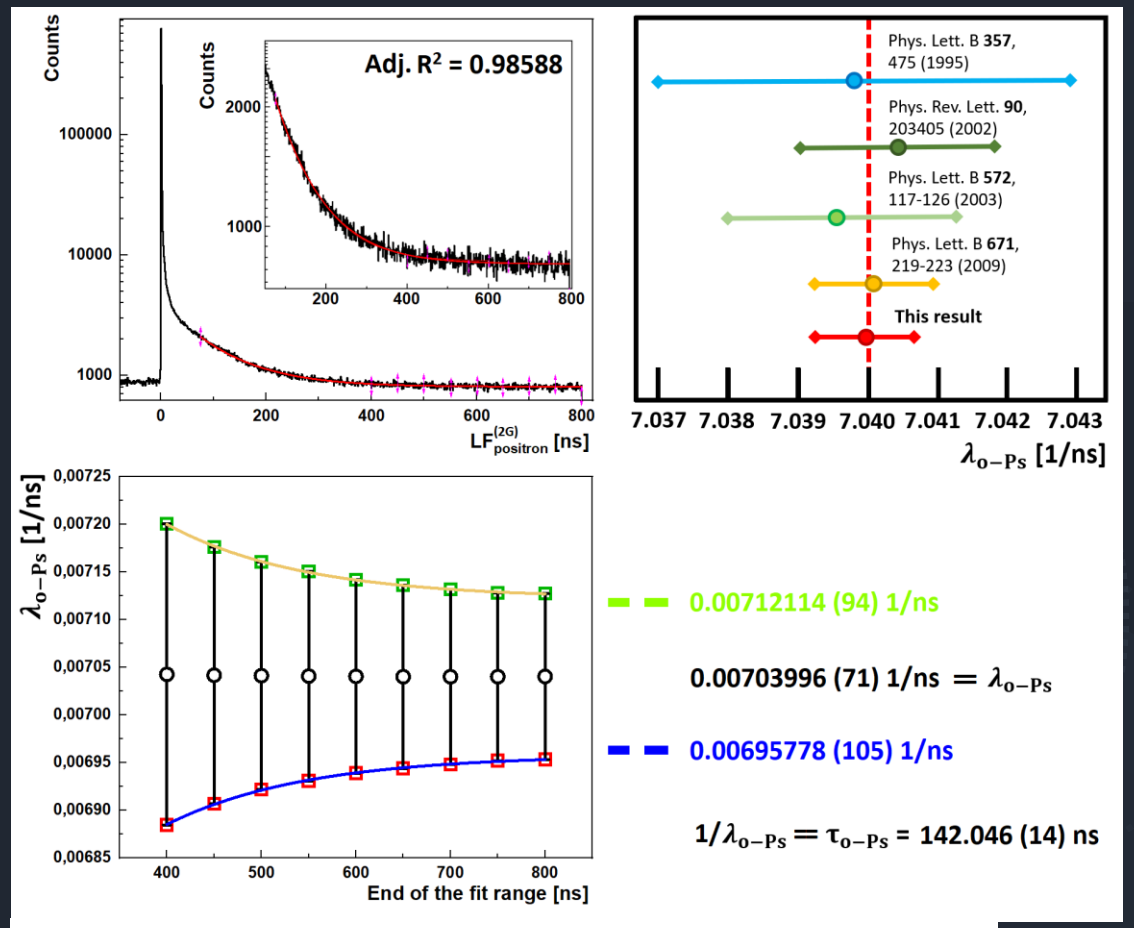
$$\frac{(2G)}{(3G)} =$$









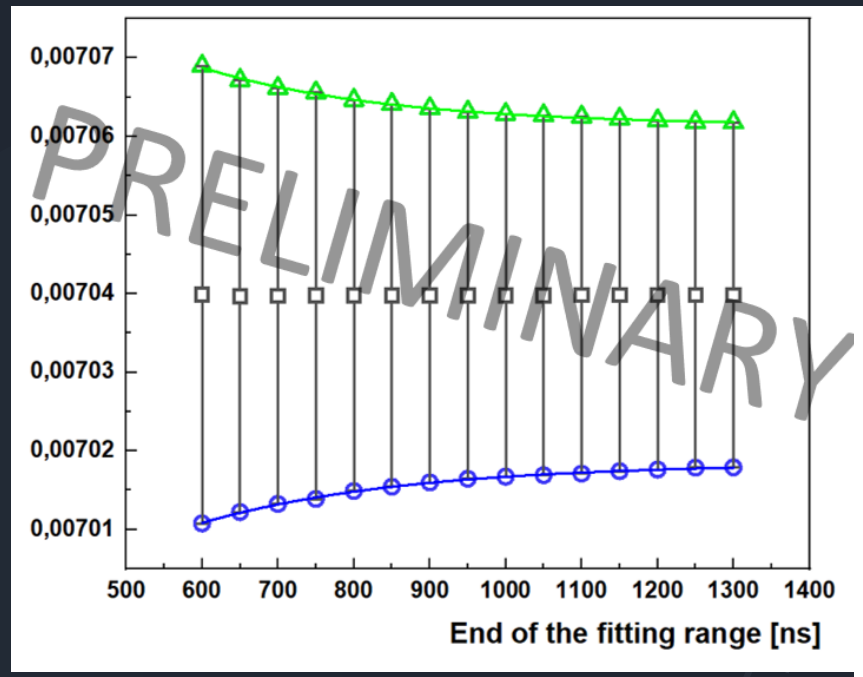


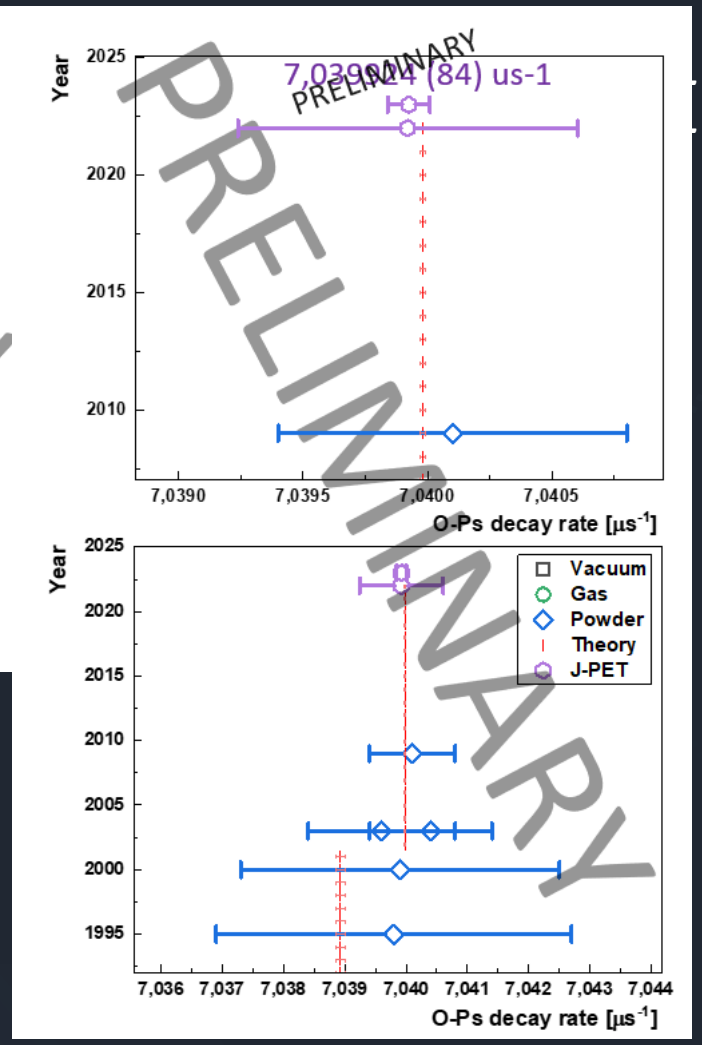
$$f\left(\mathrm{LF}_{\mathrm{positron}}\right) = f(0)\cdot\exp\left(-\lambda_{\text{o-Ps}}\left(1+\frac{\lambda_{\text{pick-off}}\left(\mathrm{LF}_{\mathrm{positron}}\right)}{\lambda_{\text{o-Ps}}}\right)\cdot\mathrm{LF}_{\mathrm{positron}}\right)$$

$$= f(0)\cdot\exp\left(-\lambda_{\text{o-Ps}}\left(1+\mathrm{C_b}+\mathrm{F}_{\frac{(2G)}{(3G)}}\left(\mathrm{LF}_{\mathrm{positron}}\right)\right)\cdot\mathrm{LF}_{\mathrm{positron}}\right).$$

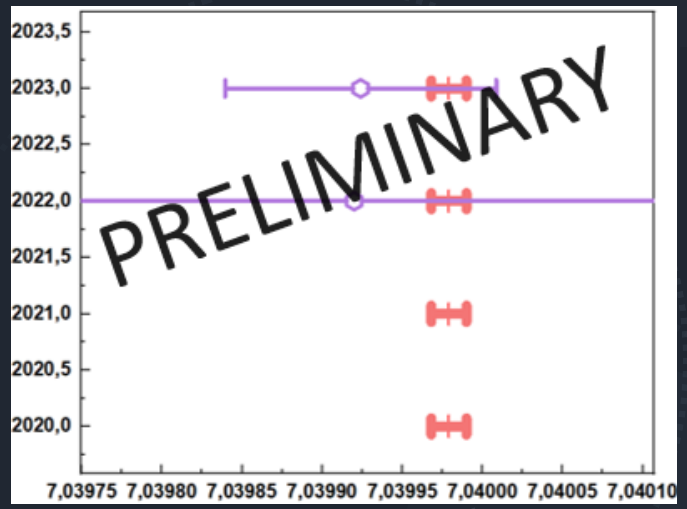
Advanced refinements – positronium physics

Theoretical prediction
7.039979(11) μs^{-1}





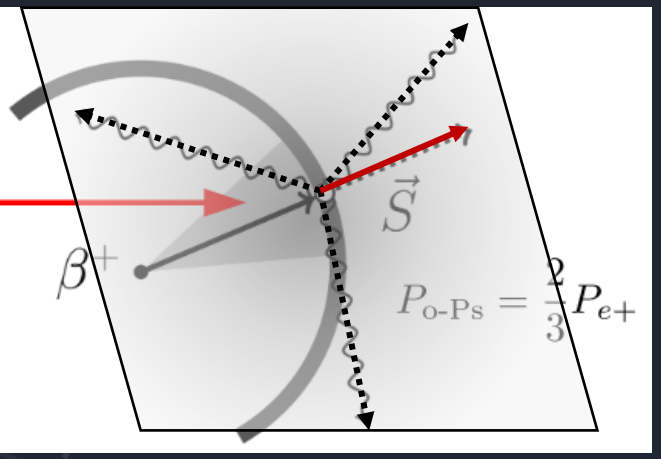
- *Part of Run11*
- *Run4*



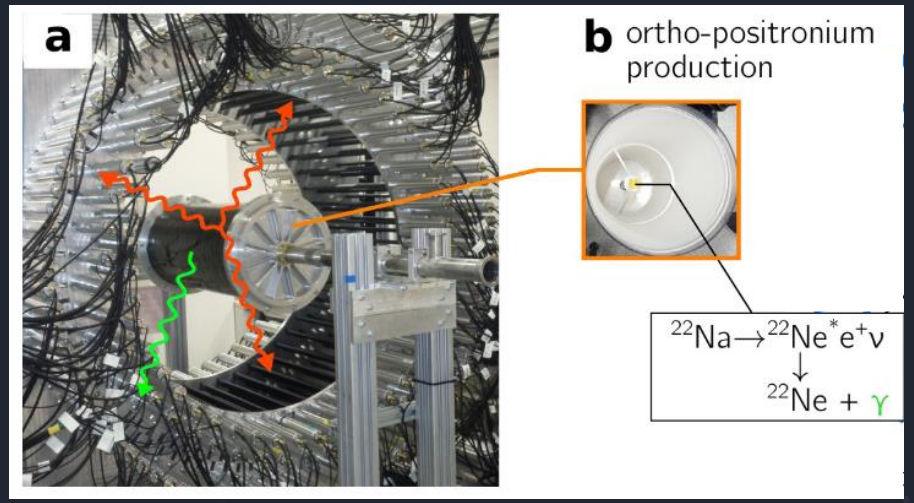
Advanced refinements – positronium physics

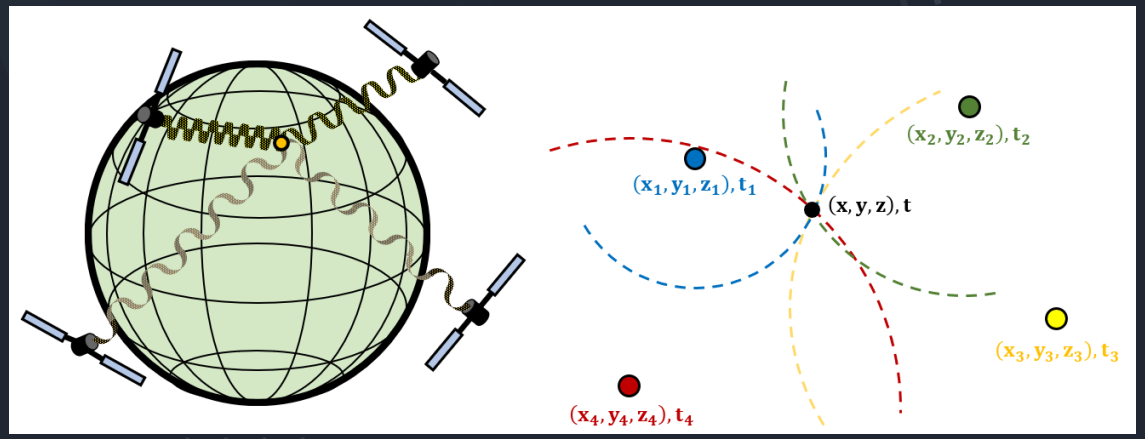
$$P_{e+} \approx \frac{v}{c} \cdot \frac{1}{2}(\cos\alpha + 1)$$

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



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





trilateration method (like in GPS)
A. Gajos et al., NIM A 819 (2016) 54-59

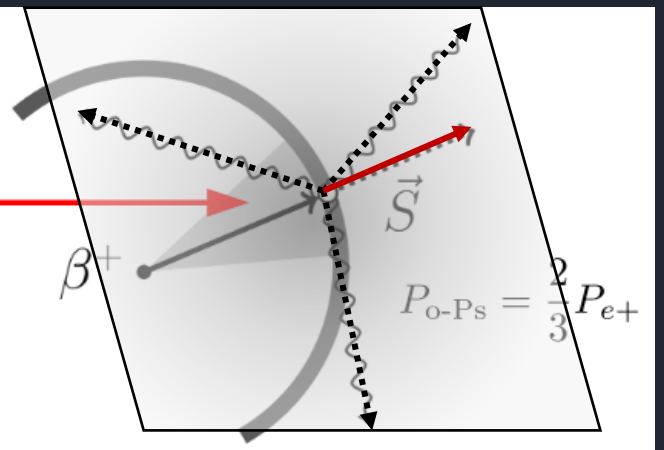
Operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	-	+	-	-
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	-	+	-
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))$	+	-	-	-	+
$\vec{k}_2 \cdot \vec{\epsilon}_1$	+	-	-	-	+
$\vec{S} \cdot \vec{\epsilon}_1$	+	+	-	+	-
$\vec{S} \cdot (\vec{k}_2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

Using photon polarization

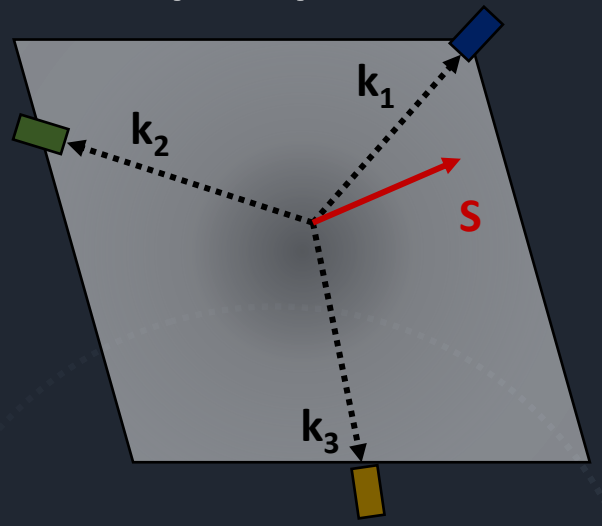
Advanced refinements – positronium physics

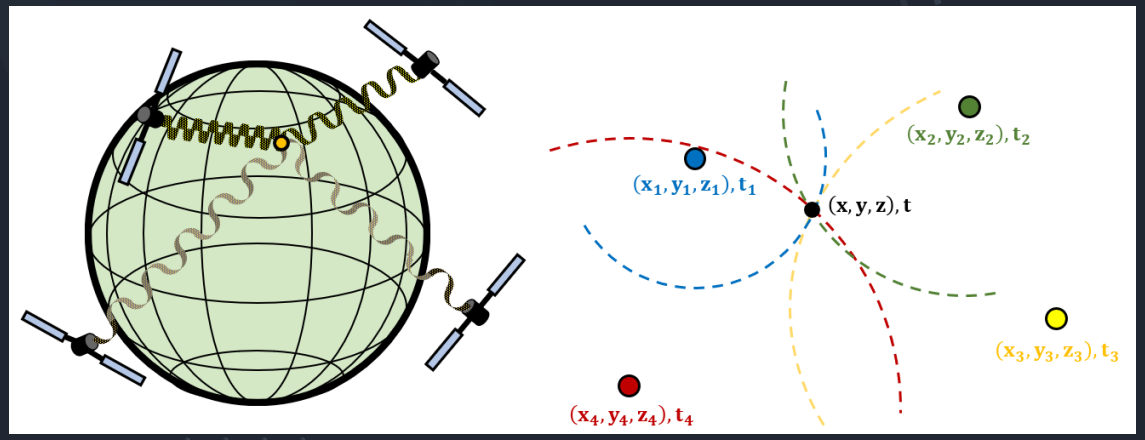
$$P_{e+} \approx \frac{v}{c} \cdot \frac{1}{2}(\cos\alpha + 1)$$

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



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





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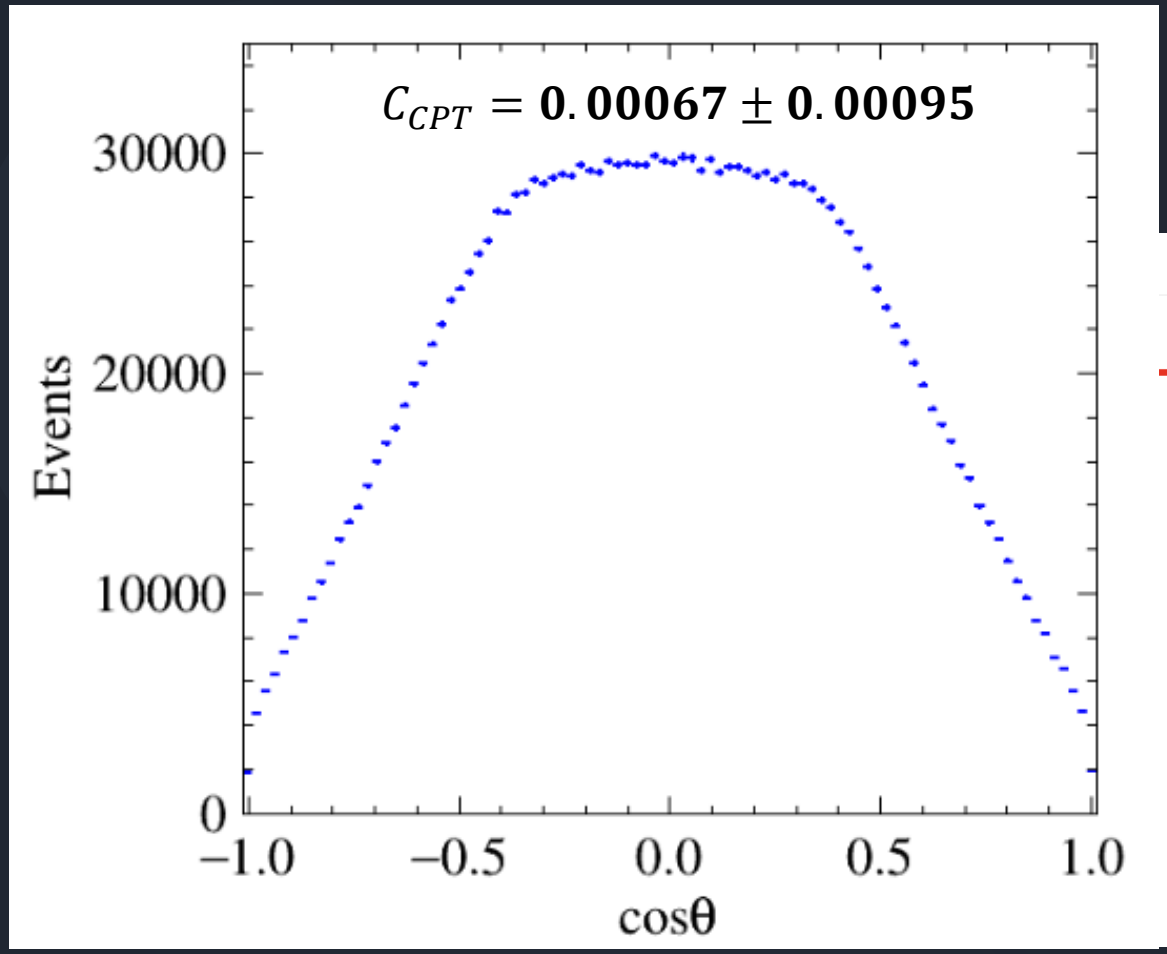
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	-	+	-
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))$	+	-	-	-	+
$\vec{k}_2 \cdot \vec{\epsilon}_1$	+	-	-	-	+
$\vec{S} \cdot \vec{\epsilon}_1$	+	+	-	+	-
$\vec{S} \cdot (\vec{k}_2 \times \vec{\epsilon}_1)$	+	-	+	-	-

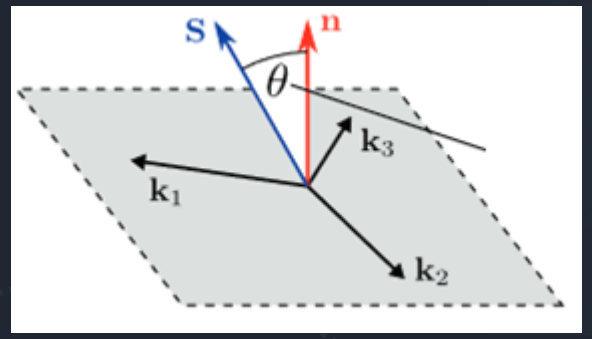
Using photon polarization

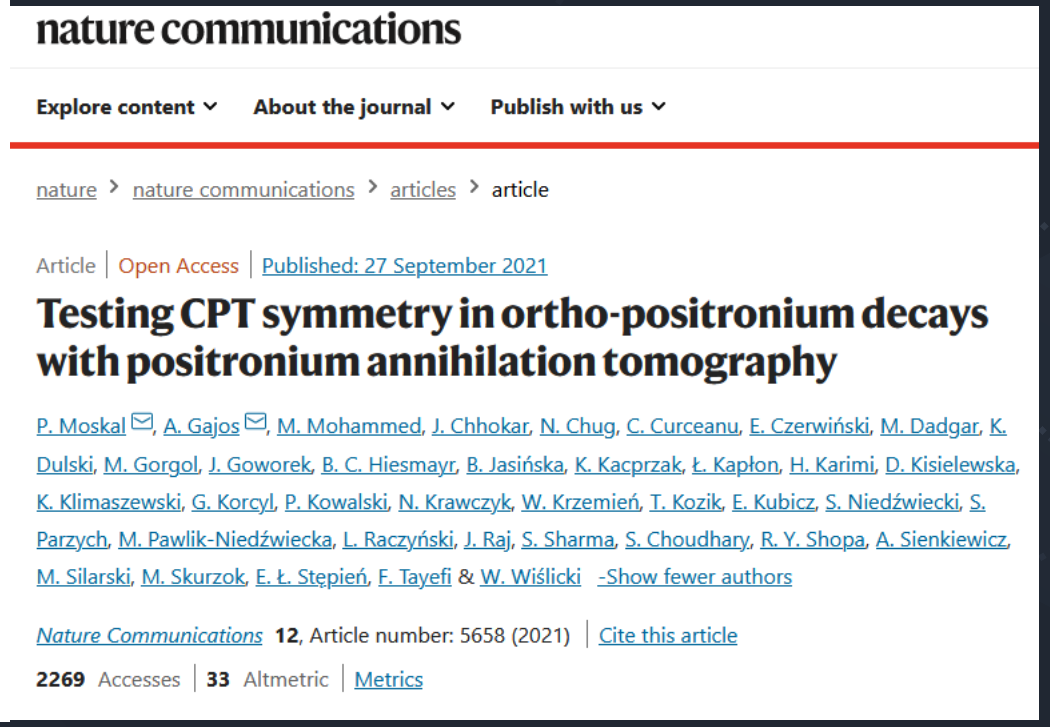
Advanced refinements – positronium physics

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

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Advanced refinements – positronium physics

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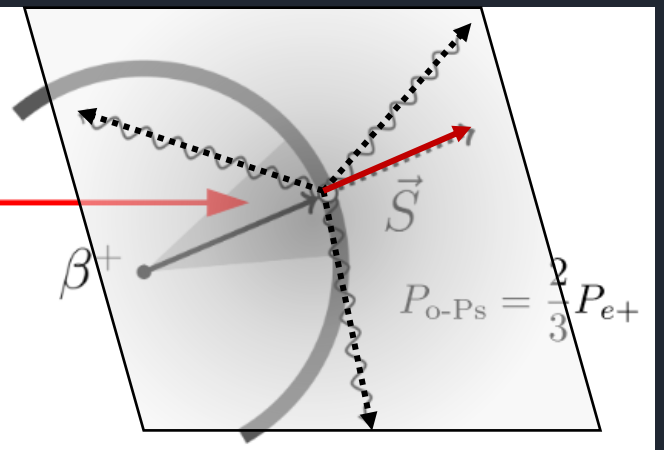
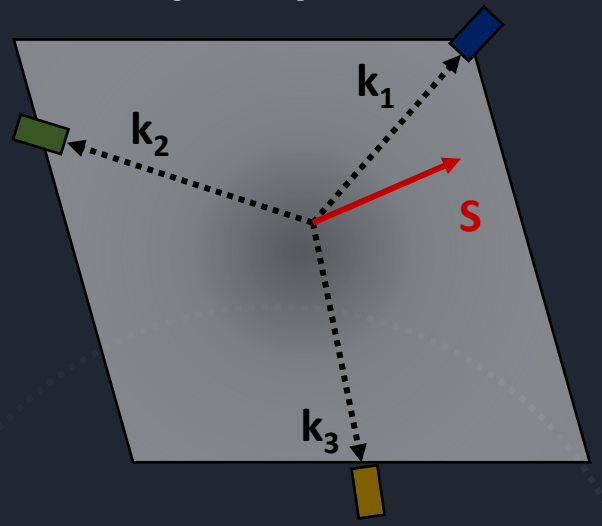
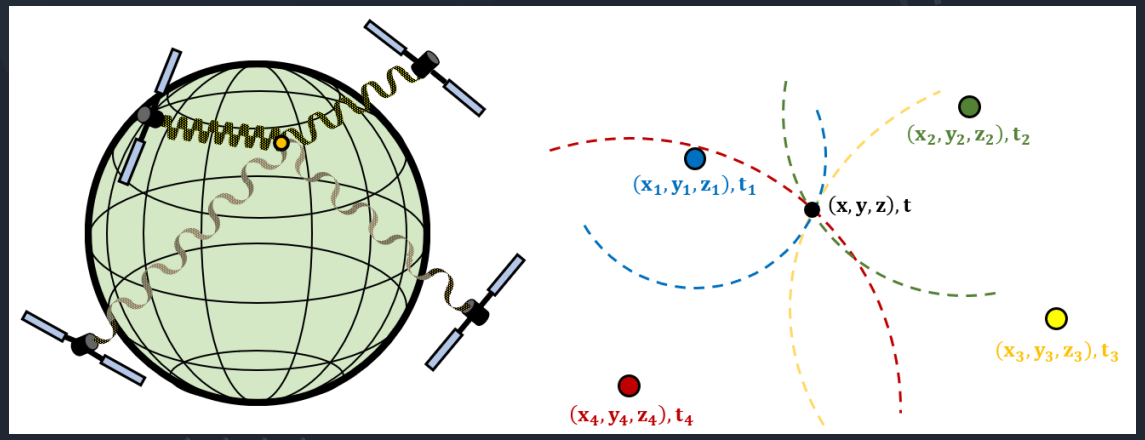
Effective polarization depends on o-Ps→3γ vertex resolution



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





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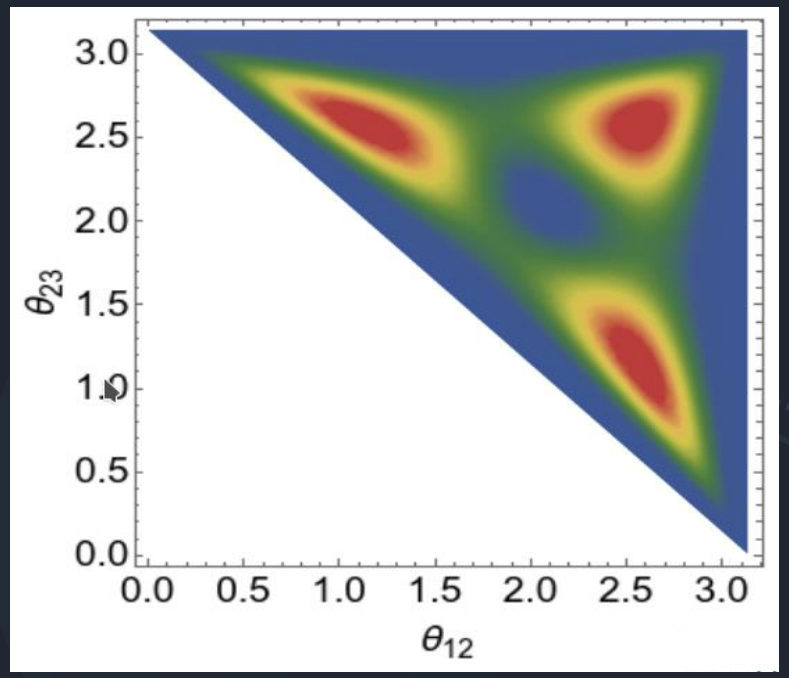
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$				+	-
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times$				-	+
$\vec{k}_2 \cdot \vec{\epsilon}_1$				-	+
$\vec{S} \cdot \vec{\epsilon}_1$				+	-
$\vec{S} \cdot (\vec{k}_2 \times \vec{\epsilon}_1)$	+	-	+	-	-

Using photon polarization

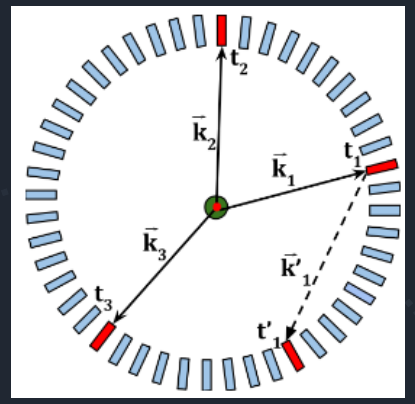
Test of the CP symmetry by J-PET -> see talk by K. Eliyan (next talk)

Advanced refinements – forbidden and raredecays



Study of the forbidden decays (p-Ps -> 3 photons)
- conjugation symmetry
Work by M. Skurzok
Acta. Phys. Polon. A 137 (2020) 134

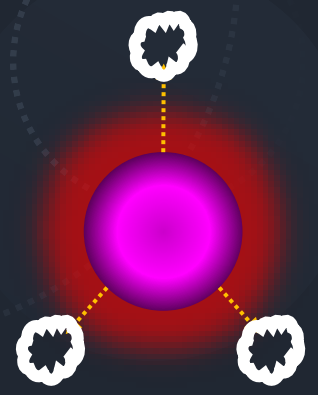
J. Raj, PhD thesis



Study of the T symmetry
J. Raj, D. Kisielewska and E. Czerwiński, Acta. Phys. Polon. A 137 (2020) 137
P. Moskal, E. Czerwiński, et al., under revision in Nature Communication

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

Study of the invisible decays (Ps -> no photons)
(Possible application of machine learning)
Work by E. Perez del Rio
Acta Phys. Polon. A 142(3) (2022) 386-390



Conclusions

- Analysis by the J-PET detector consists of various algorithms in order to reconstruct the data, select proper events, reduce the background and finally to apply dedicated refinement
- Presented analysis procedures were conducted for medical and fundamental physics fields. Obtained results show potential of the J-PET detector
- Further advancements, and in particular application of machine learning, could improve obtained results even further

Thank you for your attention