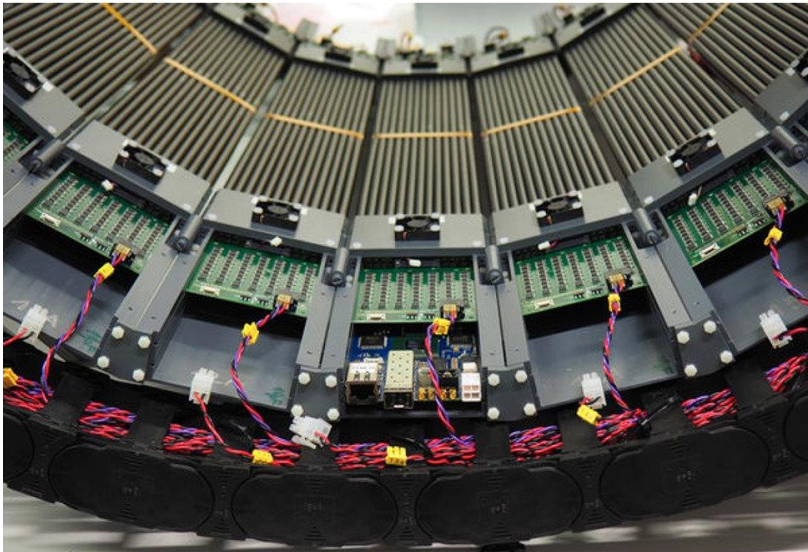




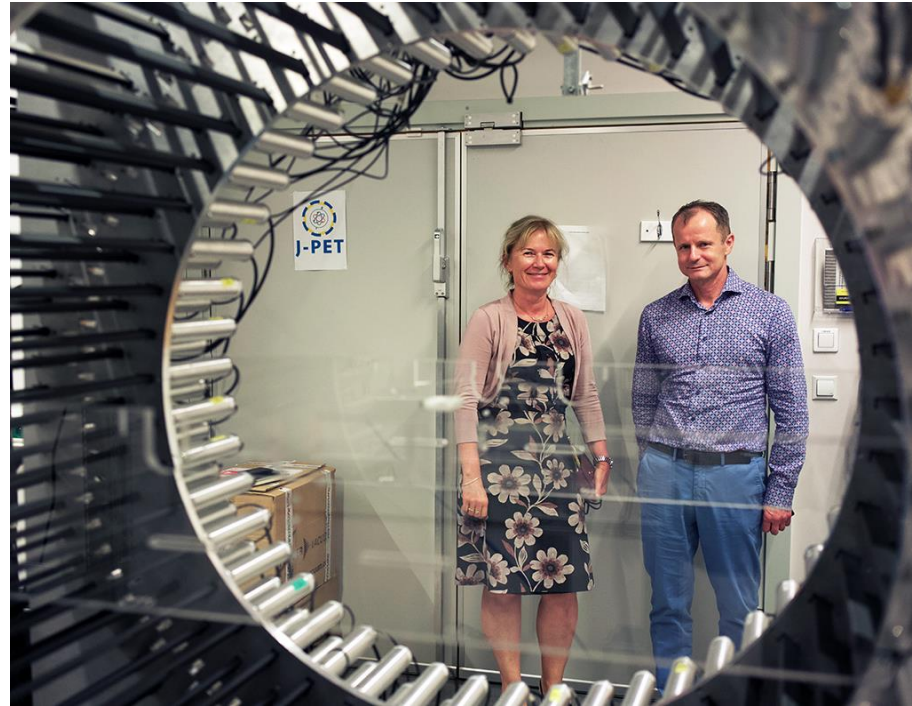
Pooja Tanty
Supervisor: Pawel Moskal
Jagiellonian University, Krakow, Poland



Testing Charge Conjugation Invariance: From pion to positronium



New twist on PET scans unlocks hidden signals for diagnosing disease

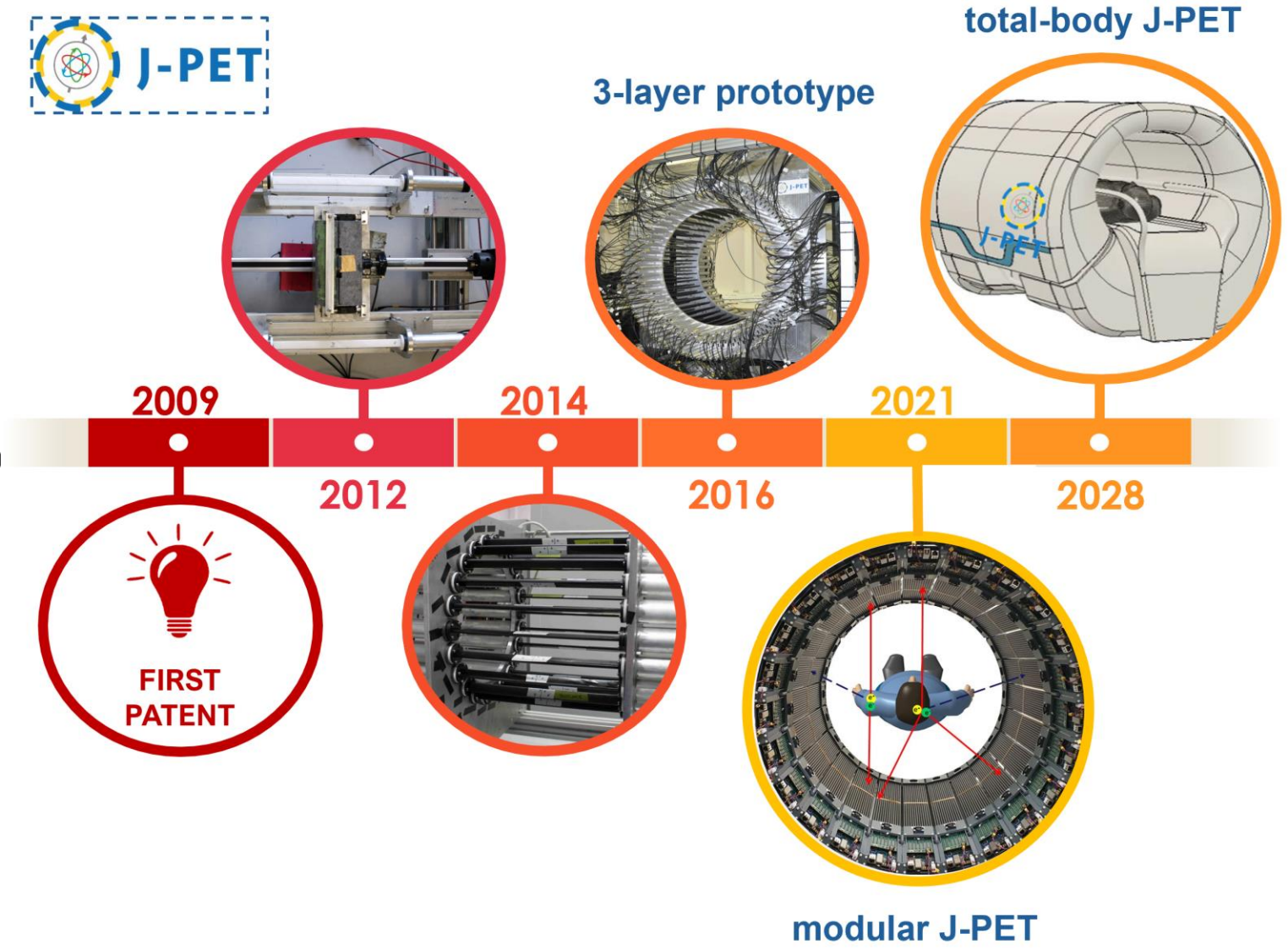


JPET: Science 389 (2025) 6761

The family portrait



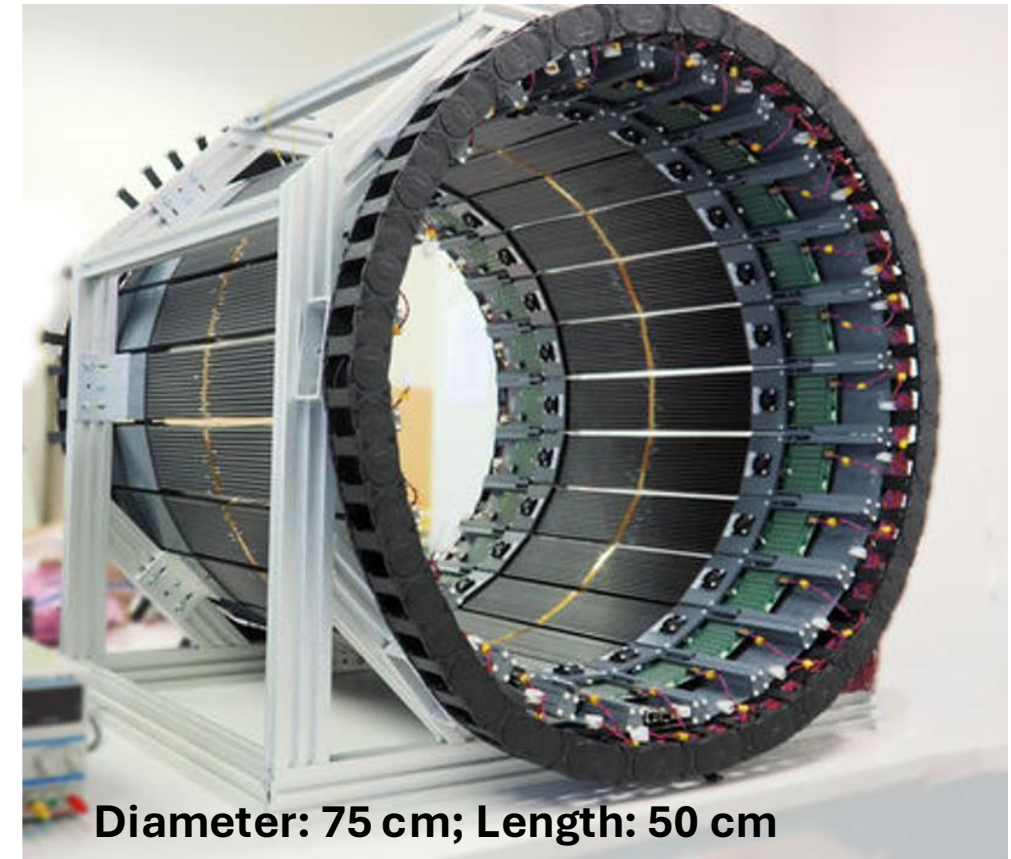
Unfolding the history.....



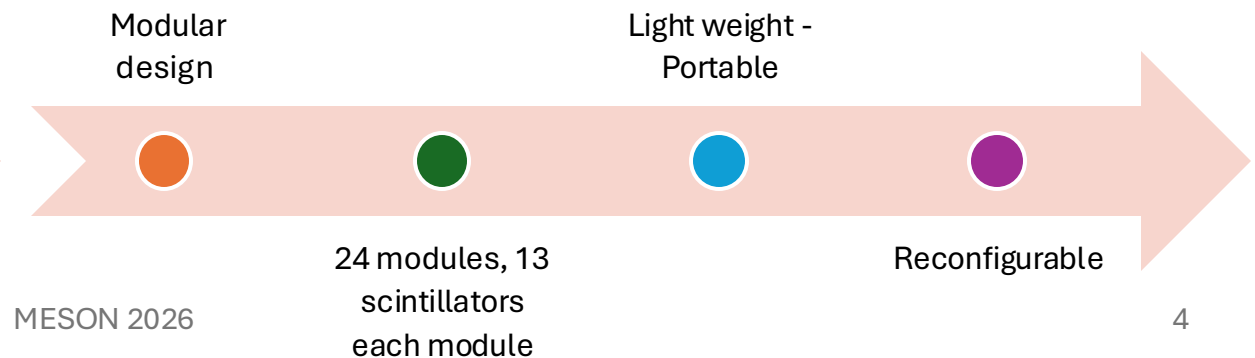
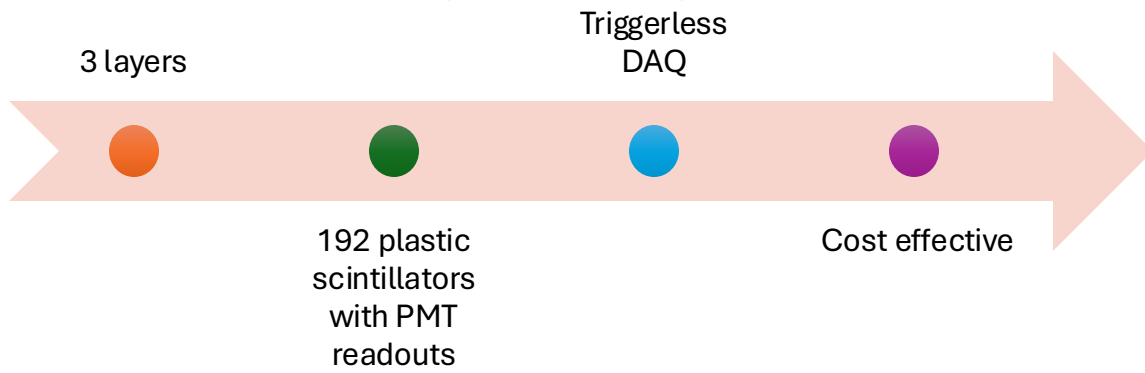
<https://koza.if.uj.edu.pl/pet/>

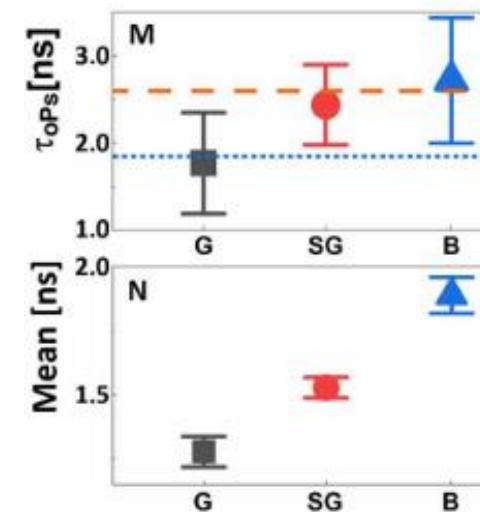
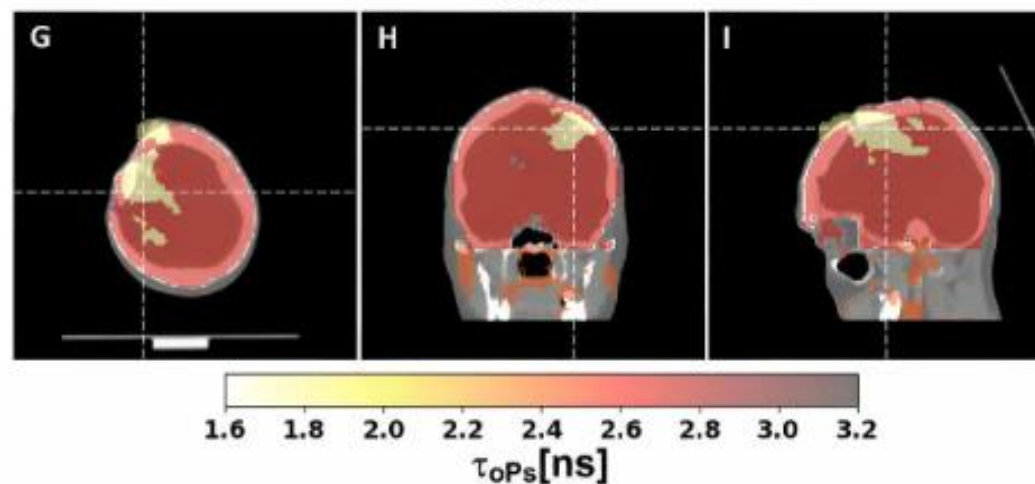
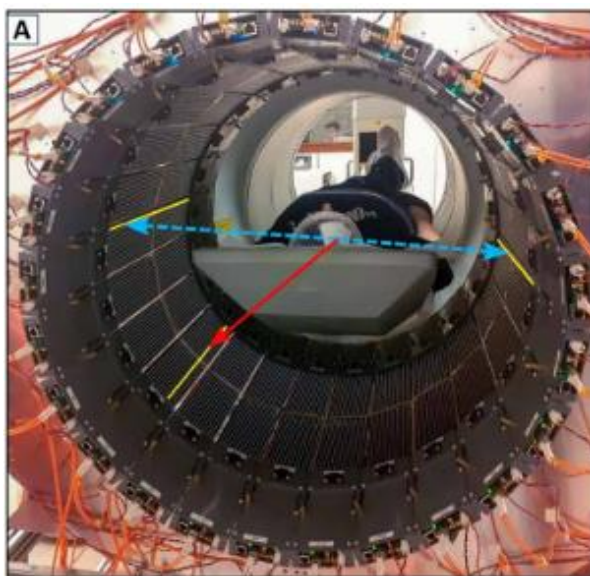


Diameter: 85 cm; Length: 50 cm



Diameter: 75 cm; Length: 50 cm





In-vivo positronium image of human brain using J-PET

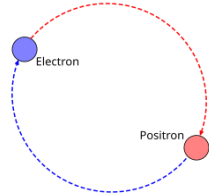
<https://koza.if.uj.edu.pl/pet/>

[J-PET: P. Moskal et. al., Science Advances 10 \(2024\) eadp2840](#)

Positronium

S. D. Bass et al., Rev. Mod. Phys. 95, 021002 (2023)

- Bound state of electron & positron
- Cleanest system for testing QED
- Can be used to test CPT, CP and C

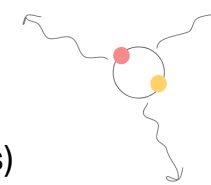


Para-Positronium (pPs)

Spin state: Singlet ($S = 0$) — spin antiparallel
C quantum number: $C = +1$
Lifetime: ~ 125 picoseconds
Dominant decay: $p\text{-Ps} \rightarrow 2\gamma$ (97.8%),

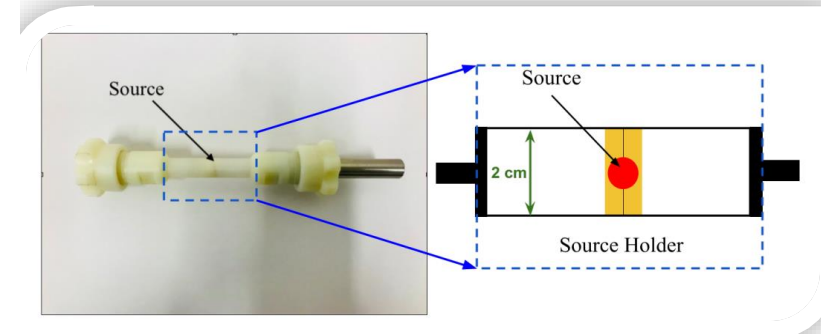
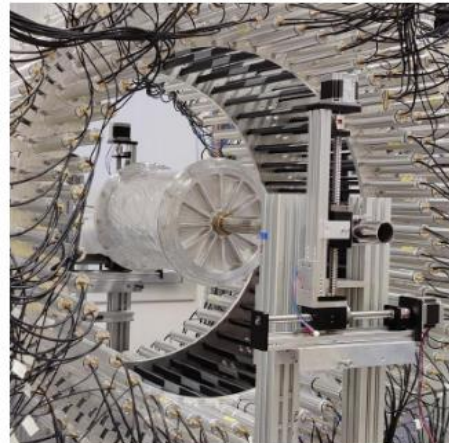
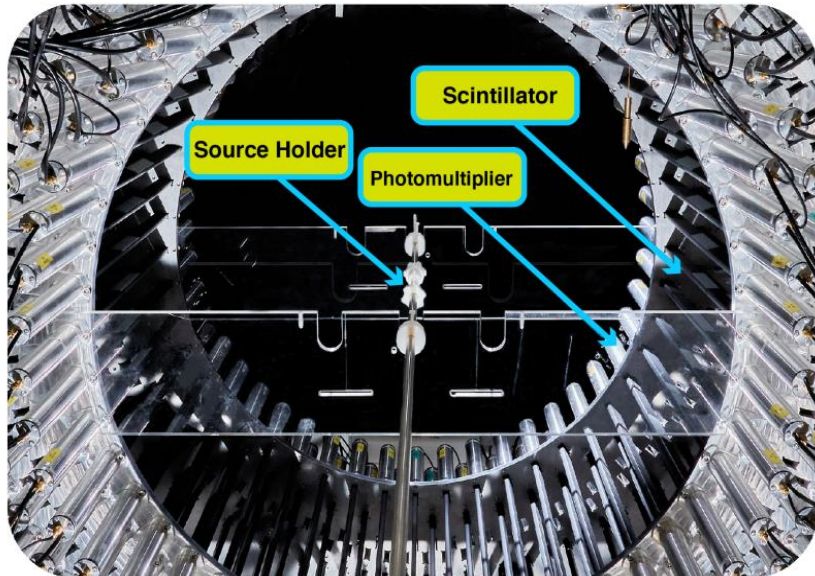
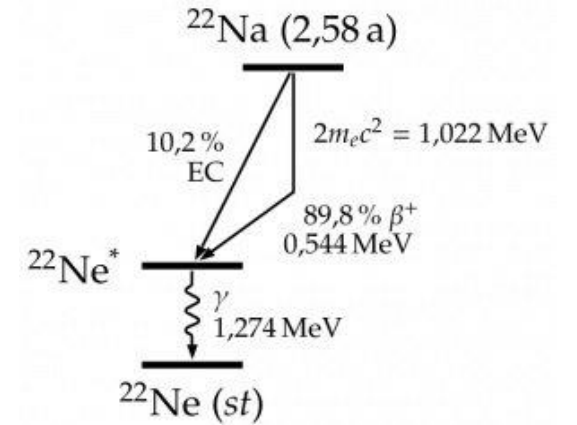


Spin state: Triplet ($S = 1$) — spins parallel
C quantum number: $C = -1$
Lifetime: ~ 142 nanoseconds
Dominant decay: $o\text{-Ps} \rightarrow 3\gamma$ (via QED)

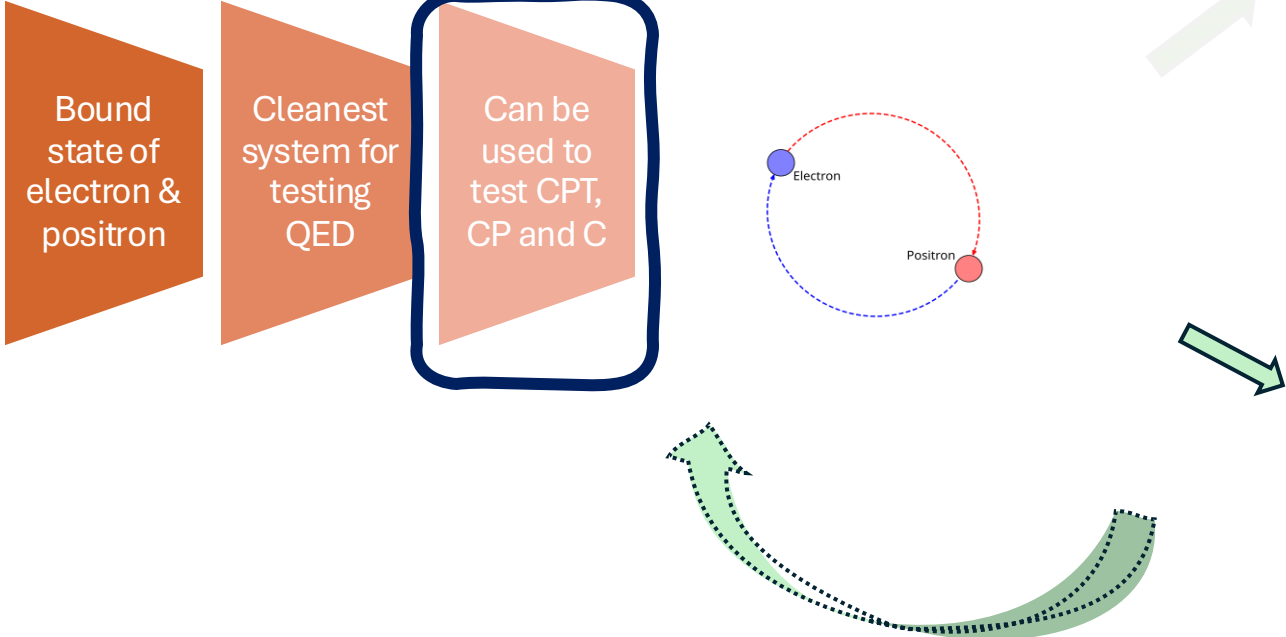


Ortho-Positronium (oPs)

Positron Source – Sodium 22



Importance of oPs



Para-Positronium (pPs)

Spin state: Singlet ($S = 0$) — spins antiparallel

C quantum number: $C = +1$

Lifetime: ~ 125 picoseconds

Dominant decay: $p\text{-Ps} \rightarrow 2\gamma$ (97.8%)

Ortho-Positronium (oPs)

Spin state: Triplet ($S = 1$) — spins parallel

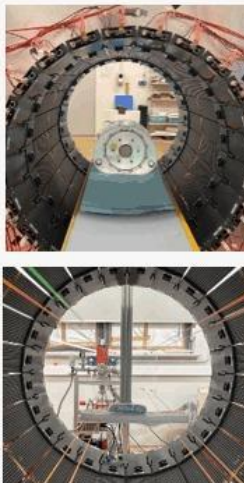
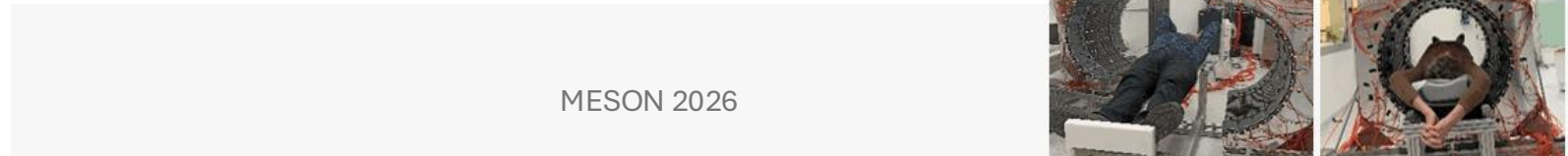
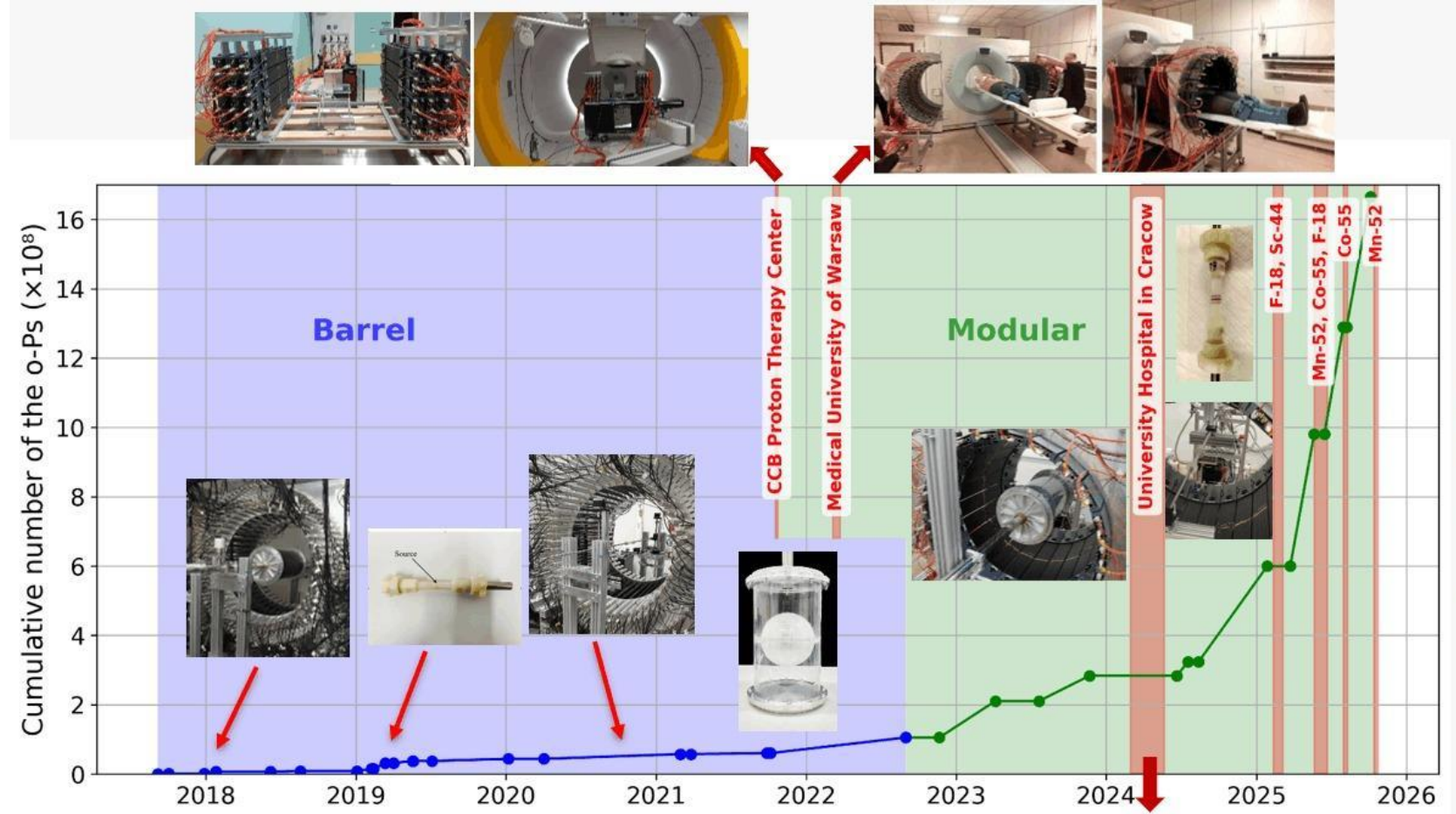
C quantum number: $C = -1$

Lifetime: ~ 142 nanoseconds

Dominant decay: $o\text{-Ps} \rightarrow 3\gamma$ (via QED)



Total o-Ps gathered so far.....



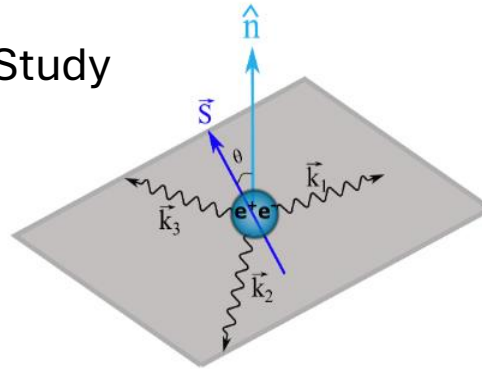
Discrete symmetries in leptonic system with J-PET

Measurement the expectation value of the symmetry odd-operators

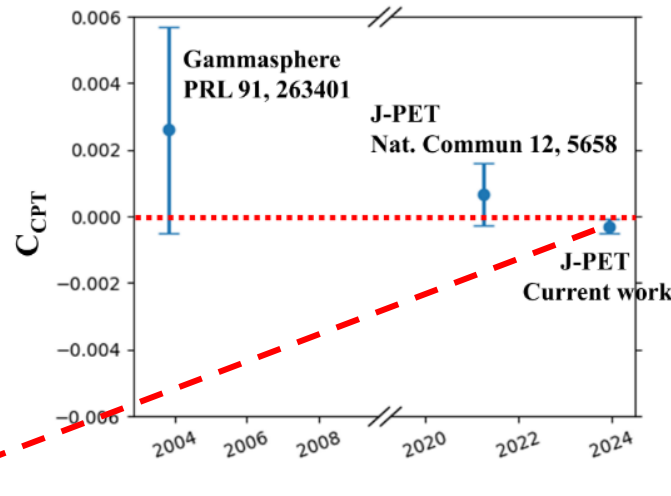


Operators are constructed out of the angular correlation of the out-going photons w.r.t the spin (oPs) and polarization vector

CPT Study



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

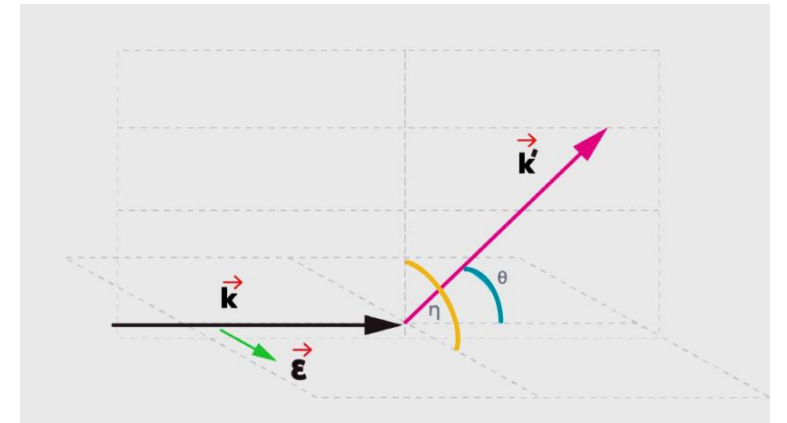


J-PET: N. Chug et al., Phys. Rev. D 113 (2026) 032003

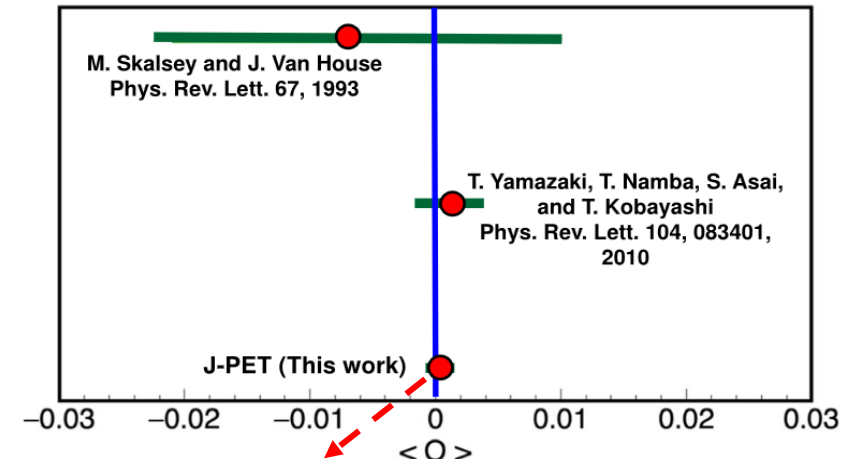
JPET: P. Moskal et al. Nature Communications 12 (2021) 5658

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CP Study



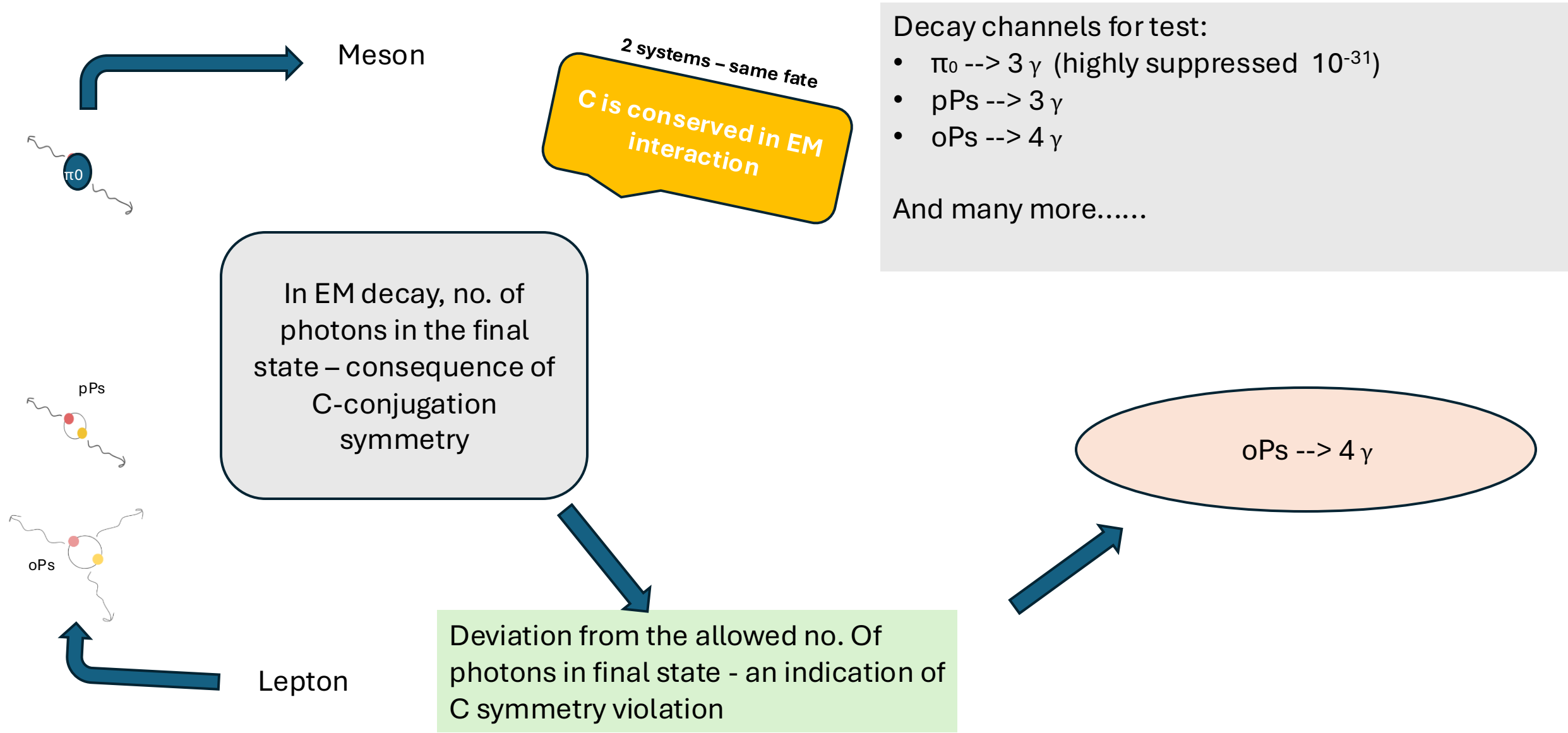
Operator	C	P	T	CP	CPT
$\vec{\epsilon}_1 \cdot \vec{k}_2$	+	-	-	-	+



JPET: P. Moskal et al. Nature Communications 15 (2024) 78

CP & CPT tested to a level of 10⁻⁴ precision

Motivation: Charge conjugation invariance test



Additional aid from Bose statistics

Direct Consequence of C-symmetry in pPs

- Can decay in even number of photons
- PPs --> 4γ possible

BUT

Not in a symmetric configuration of regular tetrahedron

The final state photons have inconsistent polarization state w.r.t pPs.

Mani and Rich. Phys. Rev. D, 4:122, 1971

Configuration (photon polarization states)	Symmetry operation	Effect	Result
RRRR	Rotate 120 deg. About axis through a vertex	Gains phase $e^{2i\pi/3}$	Forbidden (violates rotational invariance)
LRRR/RLRR/RLRR/RRL	Same 120 deg. rotation	Gains phase $e^{-2i\pi/3}$	Forbidden
RRL	Rotate 90 deg. + reflection	Returns to itself (w/ phase +1)	Forbidden (odd parity initial state)

Additional aid from Bose statistics

Mani and Rich. Phys. Rev. D, 4:122, 1971

Direct Consequence of C-symmetry in pPs

- Can decay in even number of photons
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BUT

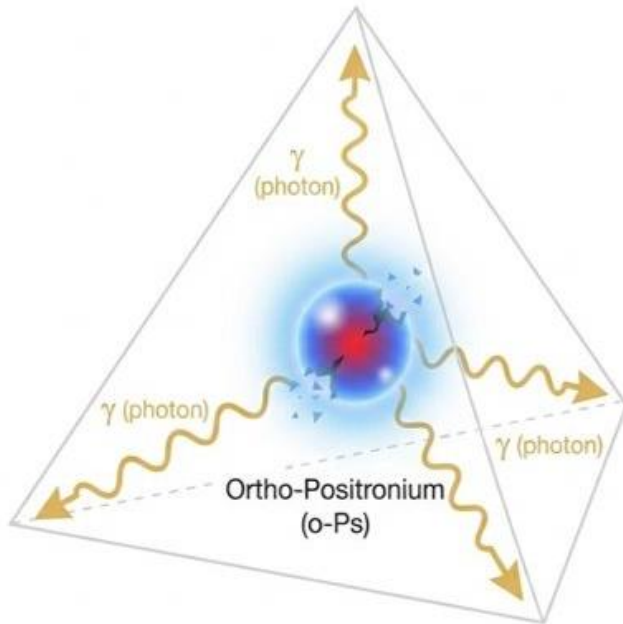
Not in a symmetric configuration tetrahedron



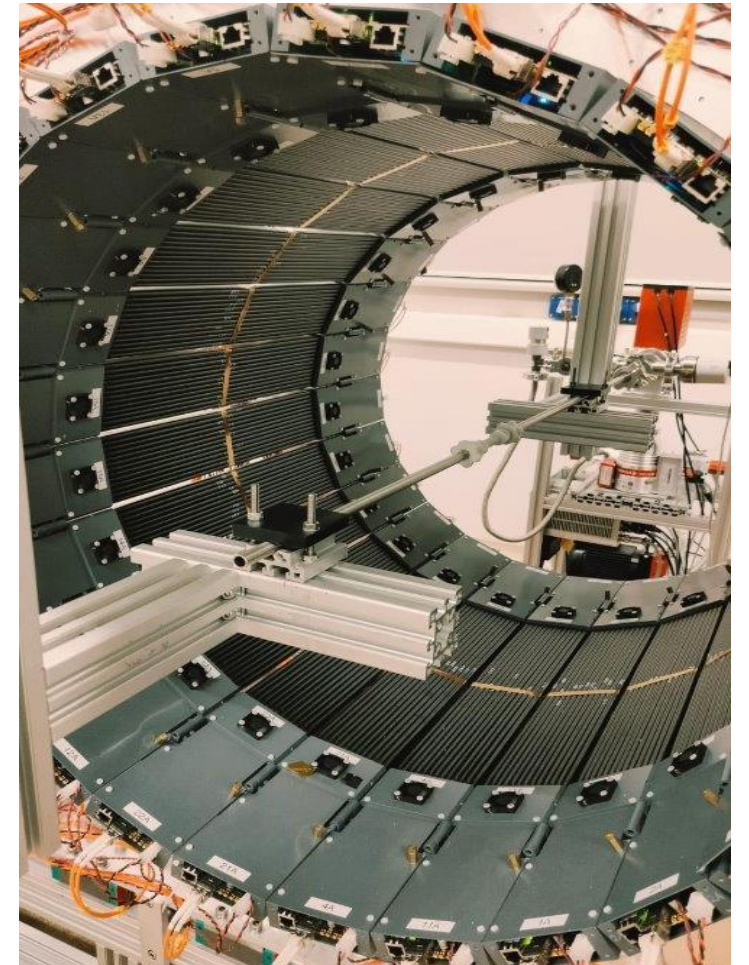
The final state photons have inconsistent polarization state w.r.t pPs.

Configuration (photon polarization states)	Symmetry operation	Effect	Result
		Gains phase $e^{2i\pi/3}$	Forbidden (violates rotational invariance)
		Gains phase $e^{-2i\pi/3}$	Forbidden
RRL	Rotate 90 deg. + reflection	Returns to itself (w/ phase +1)	Forbidden (odd parity initial state)

Forbidden search with J-PET – Main goal

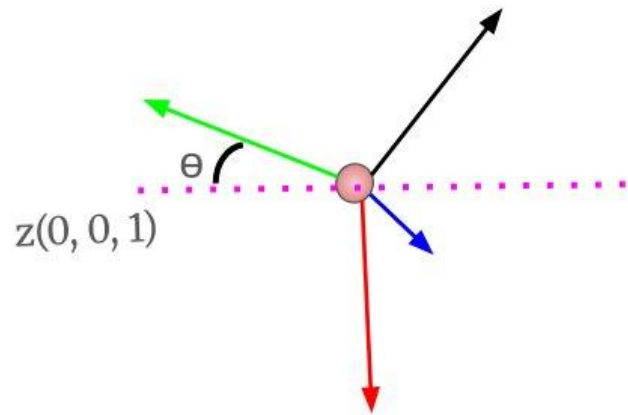
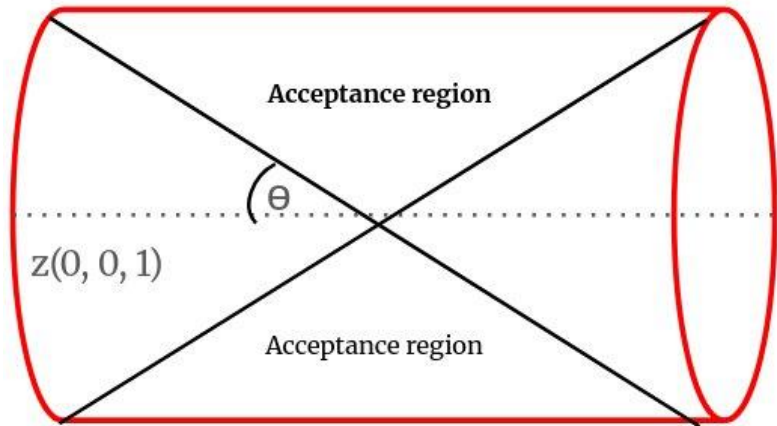


- 4 photons
- Photon energy: 255.5 keV
- Interangle: 109.5 deg.

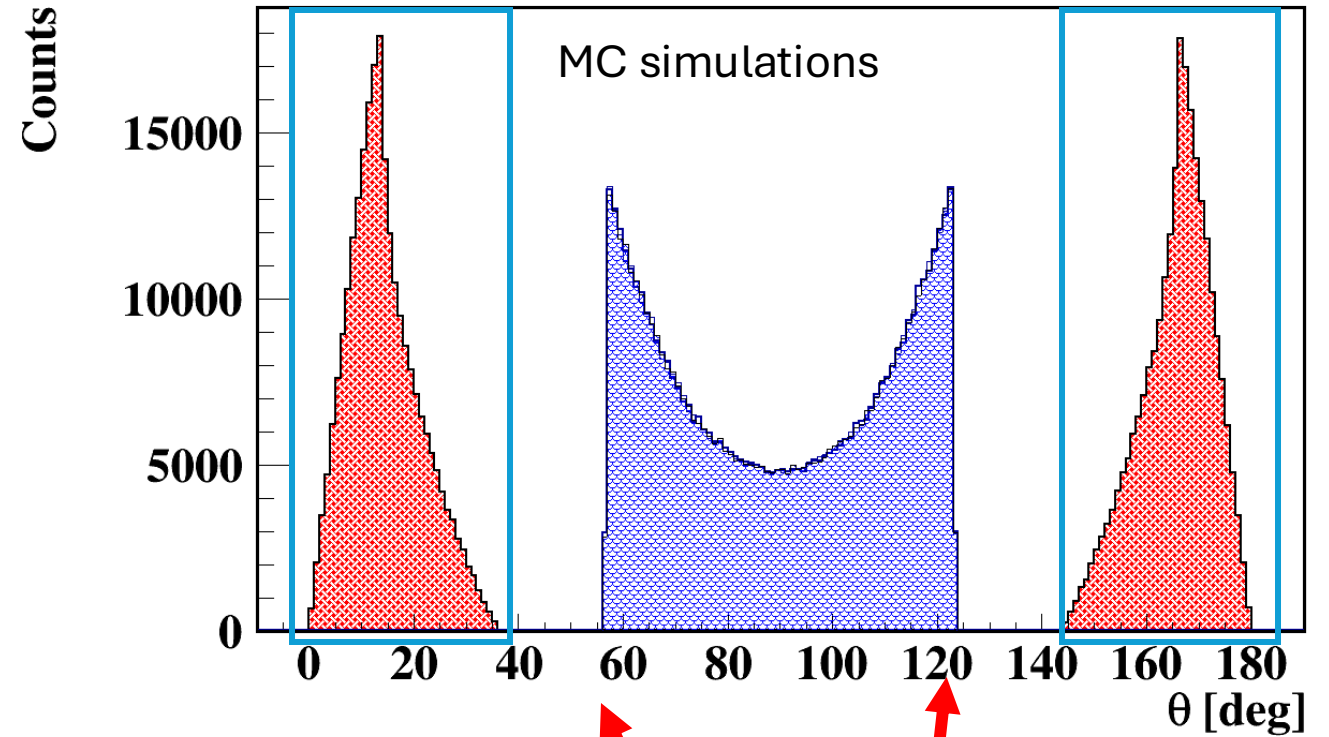


Geometrical Constraint

Length = 50 cm, Radius = 37.5 cm



Direction of 4th photon w.r.t the $z(0,0,1)$ axis



Acceptance region for a cylindrical detector $[\theta, 180 - \theta] \sim [56.6, 123.4]$

Alternatives!!

Reconfigure the detector (Reduce the detector radius)

- Simulation study ongoing

User a longer Detector

- Total Body J-PET on the way

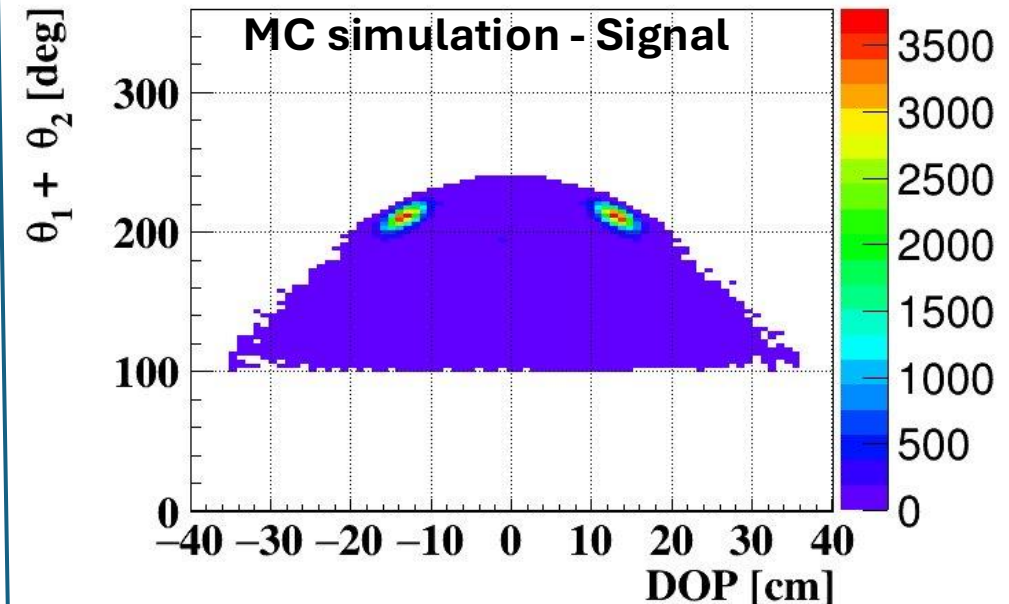
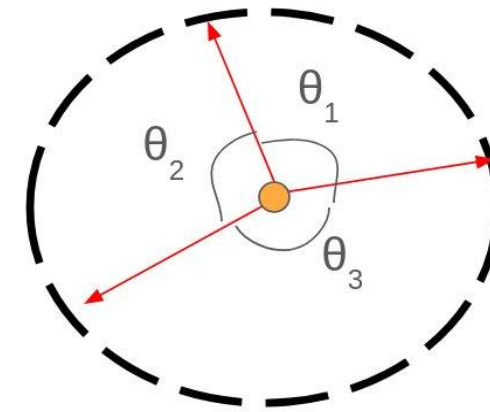
Use an extra detector at the endcaps with the existing detector

- Plan under consideration

Future Plans

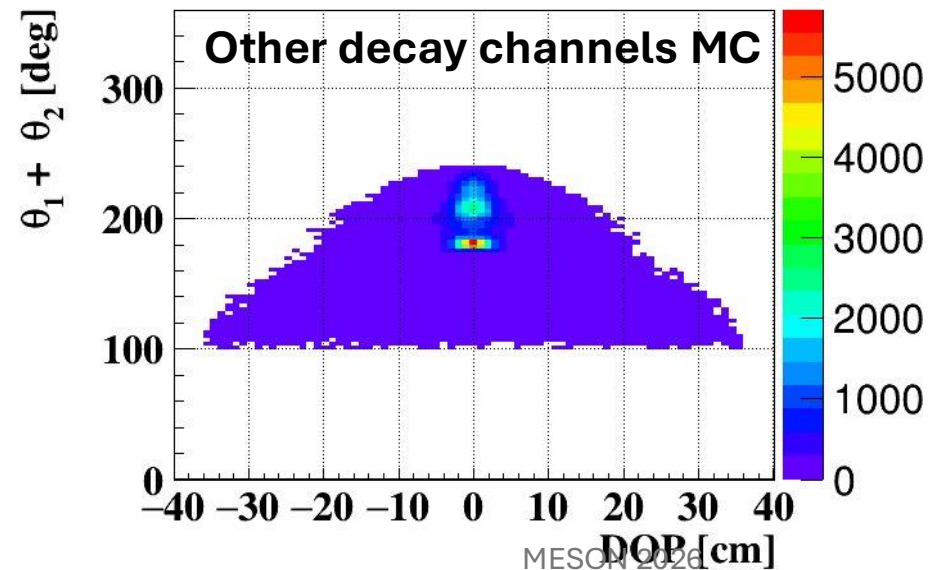
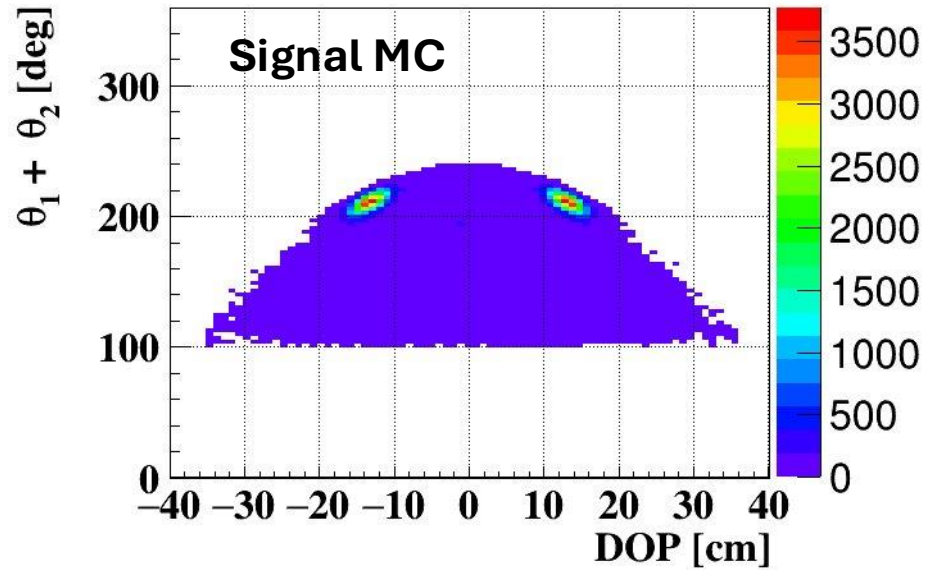
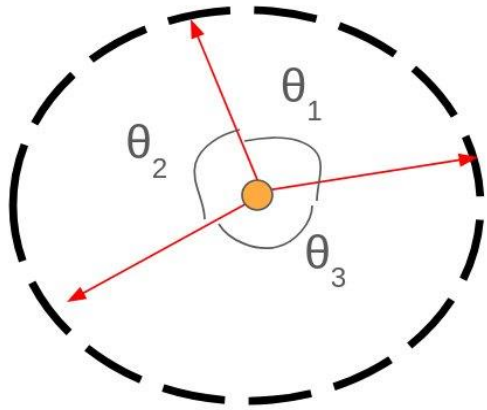
At present doable

Working with 3 photons instead of 4



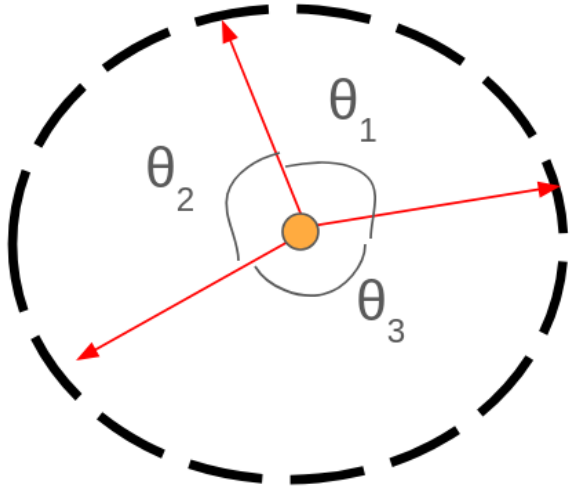
Distance of plane formed by 3 photons w.r.t annihilation point

Signal vs other dominant decay channels



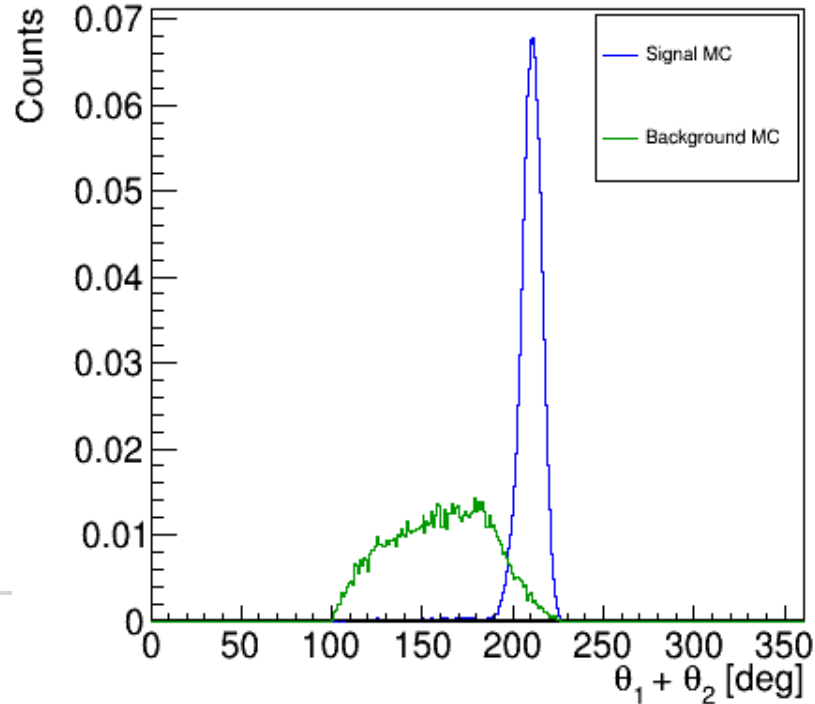
- 109.5 deg. - not the only characteristic of the signal
- Distance of plane from the annihilation point is also a distinct feature for signal selection

Simulation studies

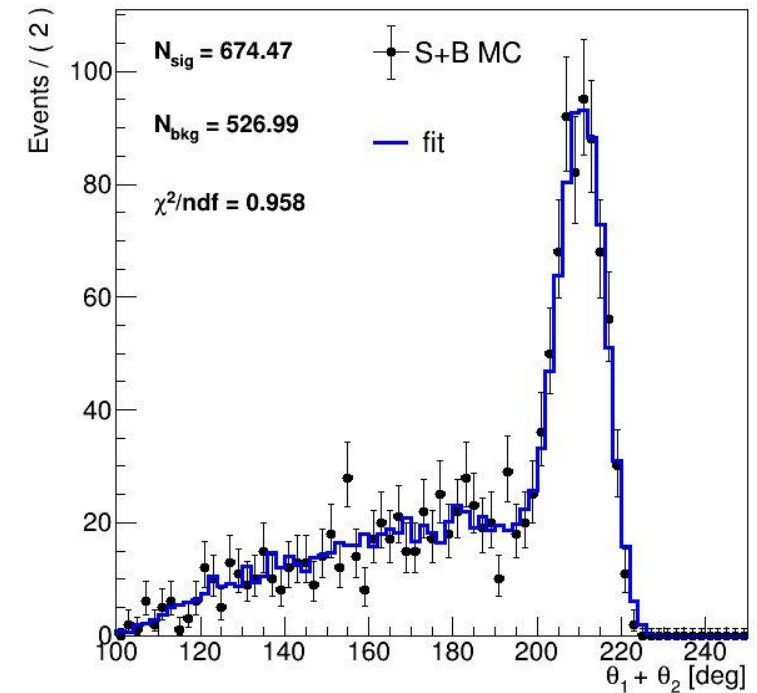


After reduction of major background sources

- oPs -> 3 gamma
- pPs -> 2 gamma



Test on pseudo-data



- Sample composition: signal (1%) & background (99%)
- Fit looks reasonable **BUT**
- Overestimation in signal and underestimation in background
- Improvements in background estimation ongoing

Summary

- J-PET is a **multi-Purpose detector** which can be used in medical imaging as well as discrete symmetries.
- We have tested **CP & CPT** in pure leptonic system to the precision of 10^{-4} level.
- The detector can also be used to test the Charge conjugation invariance.
- Results from recent simulation studies are presented.
- Further development in background reduction is ongoing!!

Thank you for your attention!!



CENTER FOR THERANOSTICS



J-PET

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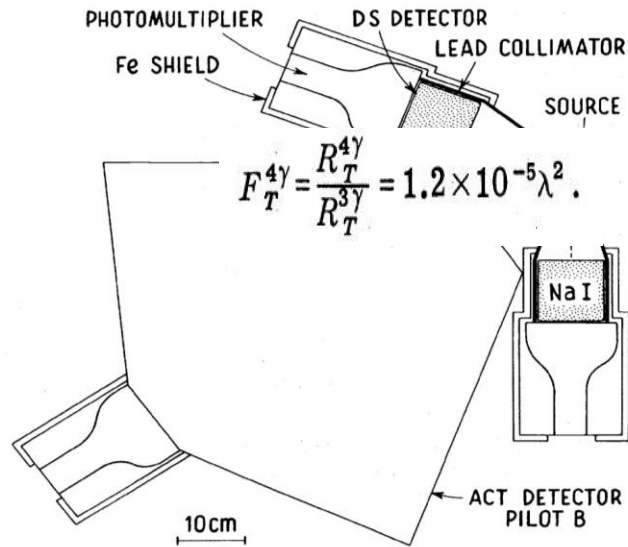
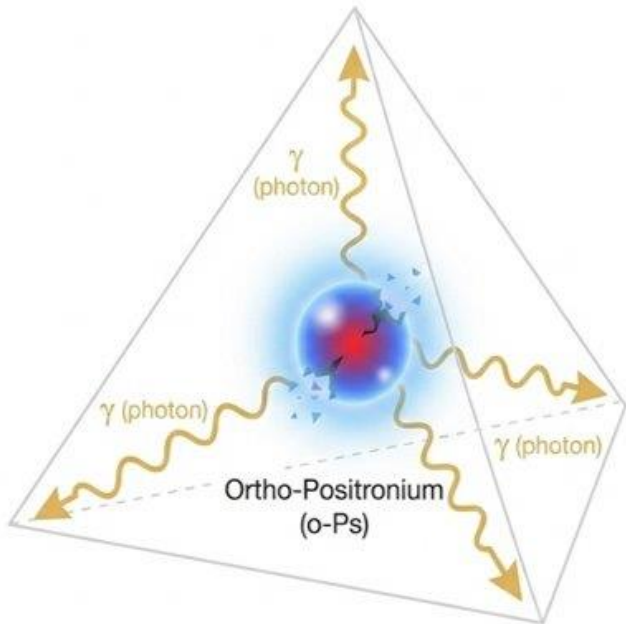
We acknowledge support from the National Science Centre (NCN), grant nos. 2021/42/A/ST2/00423, 2021/43/B/ST2/02150, 2022/47/I/NZ7/03112, 2025/57/N/ST2/04785, the Polish Ministry of Science and Higher Education (MNiSW), grants no. IAL/SP/596235/2023 and SPUB/SP/627733/2025; the SciMat and qLife Priority Research Areas; and the ERC Advanced Grant POSITRONIUM (no. 101199807). We also thank the PLGrid (HPC Center: ACK Cyfronet AGH) for computational resources under grant no. PLG/2024/017688 and PLG/2025/018762.



C symmetry test with J-PET

Mani and Rich. Phys. Rev. D, 4:122, 1971

Decay into 4 Photons



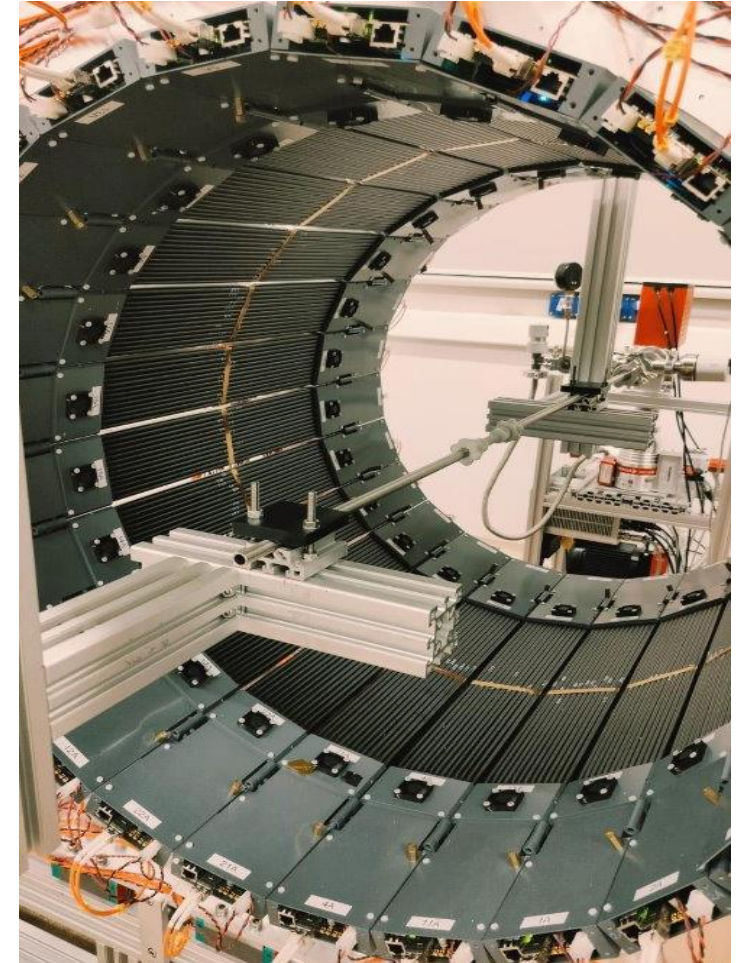
$$F_T^{4\gamma} = \frac{R_T^{4\gamma}}{R_T^{3\gamma}} = 1.2 \times 10^{-5} \lambda^2.$$

$$F_T^{4\gamma} = \frac{R_T^{4\gamma}}{R_T^{3\gamma}} = 1.2 \times 10^{-5} \lambda^2. \quad F_T^{4\gamma} < 8 \times 10^{-6}, \quad \lambda < 0.8.$$

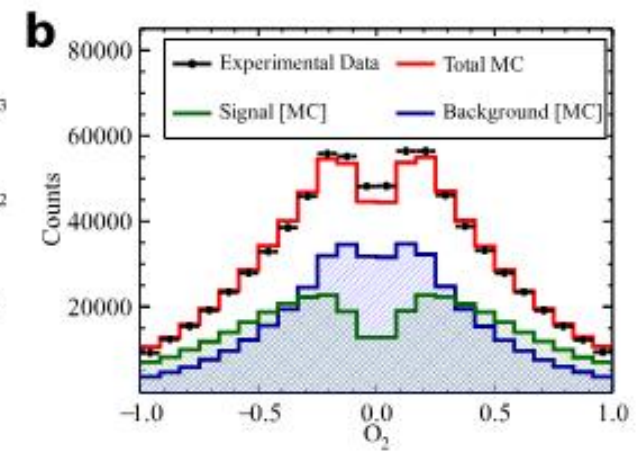
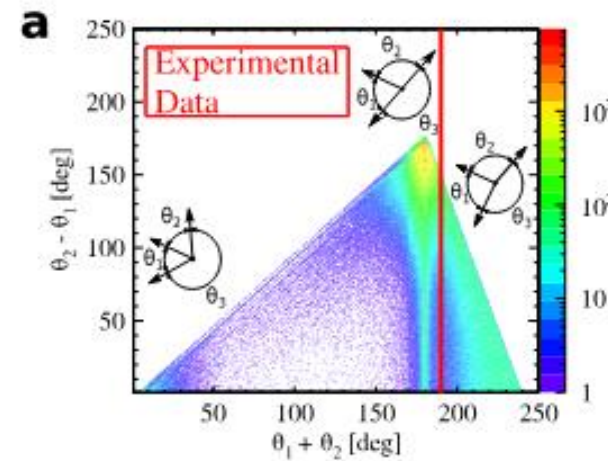
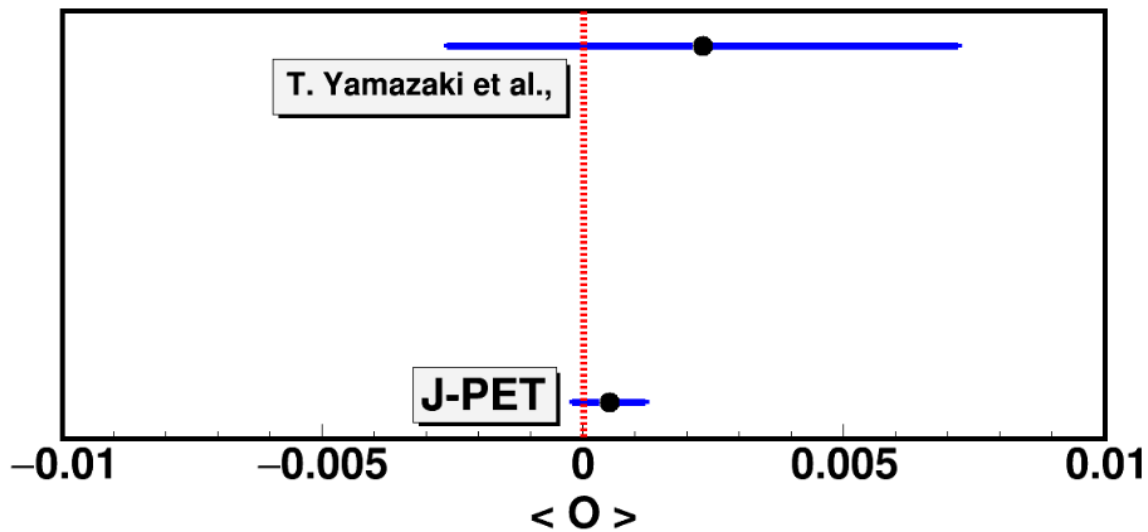
- 4 photons
- Photon energy: 255.5 keV
- Interangle: 109.5 deg.

- No. of measurement days: **24**
- No. of candidates found: **4**

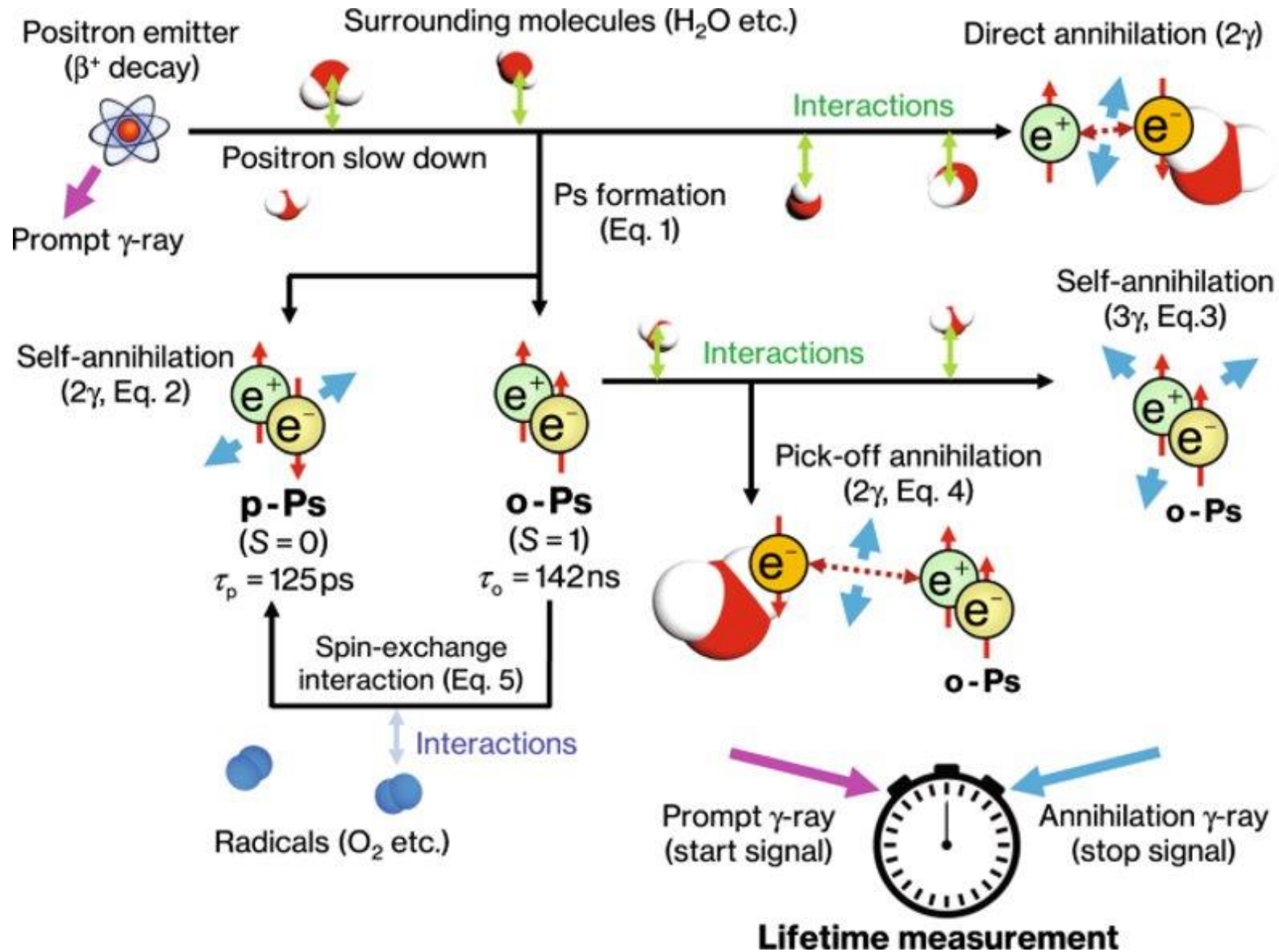
MESON 2026

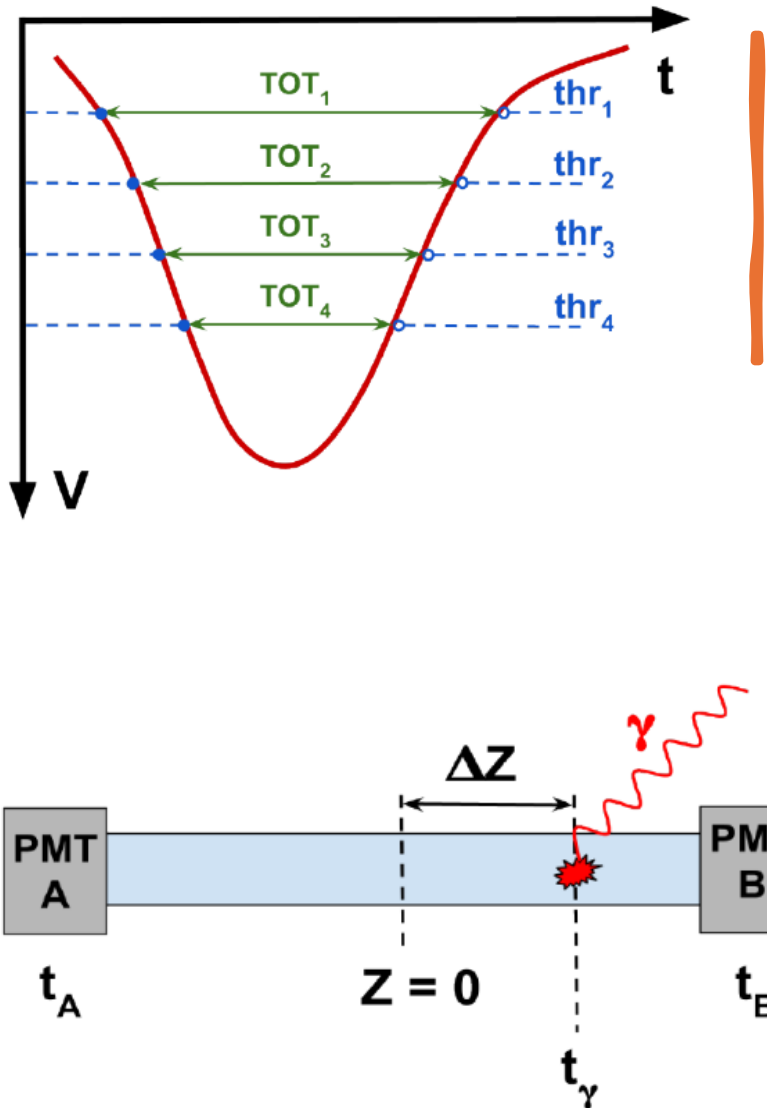


Results from CP tests

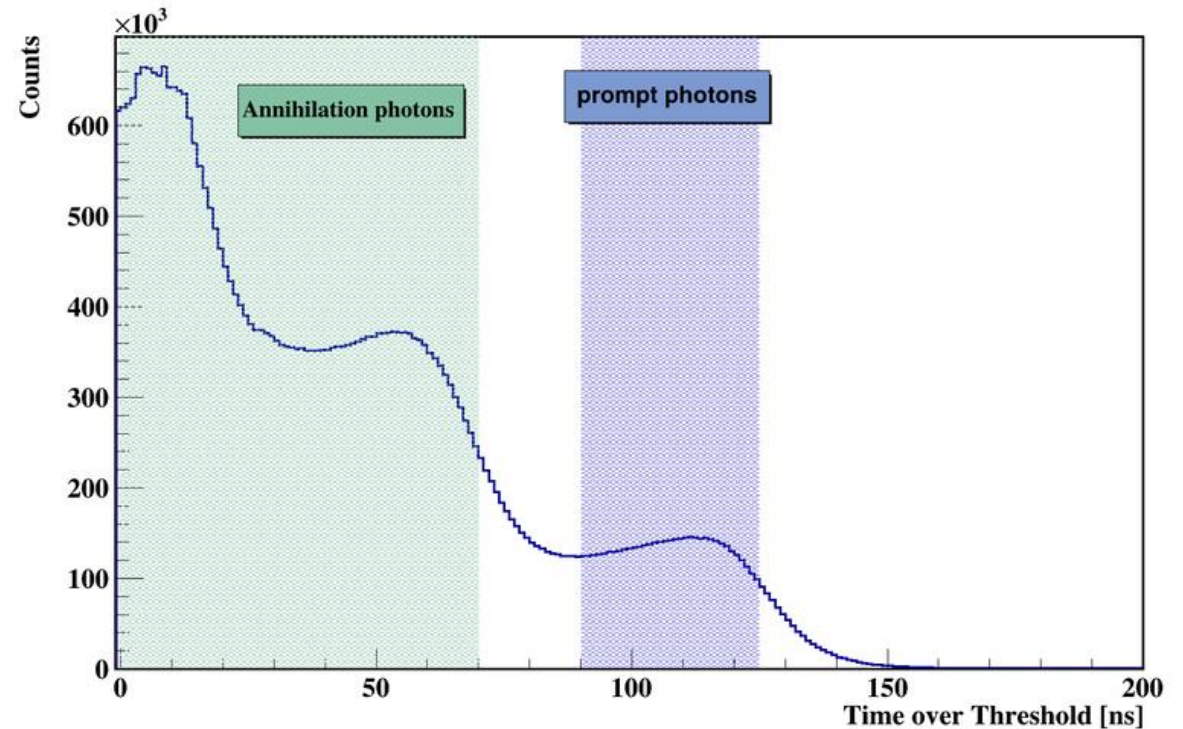


Evolution of Positronium





Time over threshold – The energy proxy



This opens up plethora of physics programs!!

Precision study of oPs decays with J-PET
– Talk by J. M. Sowa