Tests of discrete symmetries in positronium decays with the J-PET detector

Eryk Czerwiński
on behalf of the J-PET Collaboration

DISCRETE 2018

Outline

- Discrete symmetries tests with positronium
- The J-PET detector and reconstruction techniques
- Commissioning and upgrades
- Conclusions

Positronium (Ps)

para-positronium (p-Ps)	↑↓	$2n\gamma$	CP=+1	$\tau \approx 0.125$ns
ortho-positronium (o-Ps)	↑↑	$(2n+1)\gamma$	CP=-1	$\tau \approx 142$ns

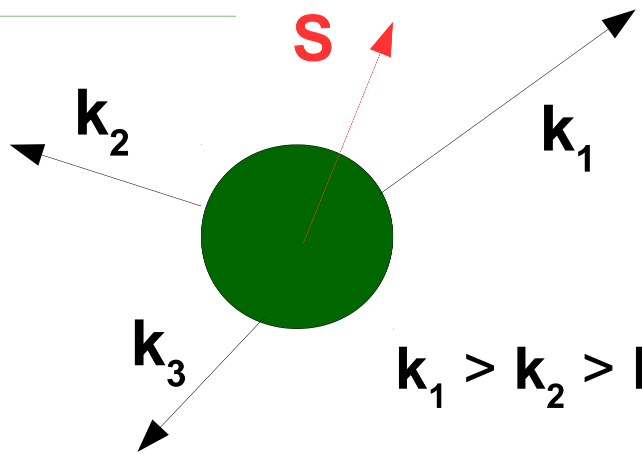
- Purely leptonic (e+e-) bound state
- C, P, CP operators and $\mathcal{H}$ eigenstate
- The lightest atom
- Undergoes self-annihilation
- e+ and e- do not decay into lighter particles via weak interaction, 10^{-14} violation level due to the weak interaction

  [M. Sozzi, Discrete Symmetries and CP Violation, Oxford University Press (2008)]
- No charged particles in the final state ($2*10^{-10}$ radiative corrections)
- No discrete symmetry violation observed in non-quark system, for e+e- system: Standard Model 10^{-9} – upper limits 10^{-3} for T, CP, CPT

$$^{22}Na \rightarrow {}^{22}Ne^{*} + e^{+} + \nu_e$$

$$^{22}Ne^{*} \rightarrow {}^{22}Ne + \gamma(1.247\ \mathrm{MeV}, \tau \approx 3.7\ \mathrm{ps})$$

o-Ps



$k_1 > k_2 > k_3$

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

Unique @J-PET

$C_{CP} = \langle\, (\mathbf{S}\cdot\mathbf{k}_1)\,(\mathbf{S}\cdot(\mathbf{k}_1\times\mathbf{k}_2))\,\rangle = 0.0013 \pm 0.0022$

[T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401]

$C_{CPT} = \langle\, \mathbf{S}\cdot(\mathbf{k}_1\times\mathbf{k}_2)\,\rangle = 0.0026 \pm 0.0031$

[P.A. Vetter, S.J. Freedman, Phys. Rev. Lett. 91 (2003) 263401]

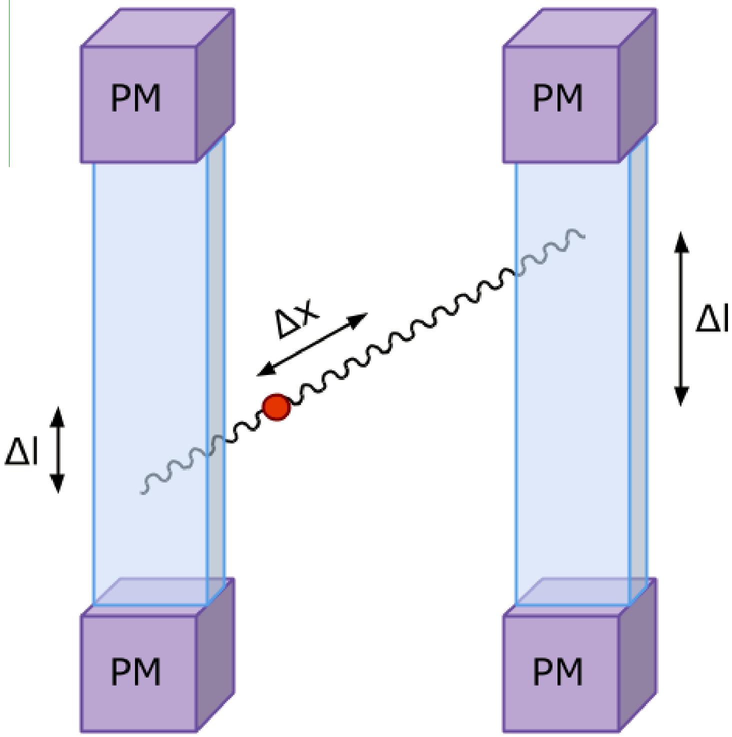
SM: 10^{-9} - 10^{-10} effects of final state interaction

[W. Bernreuther et al., Z. Phys. C 41 (1988) 143]

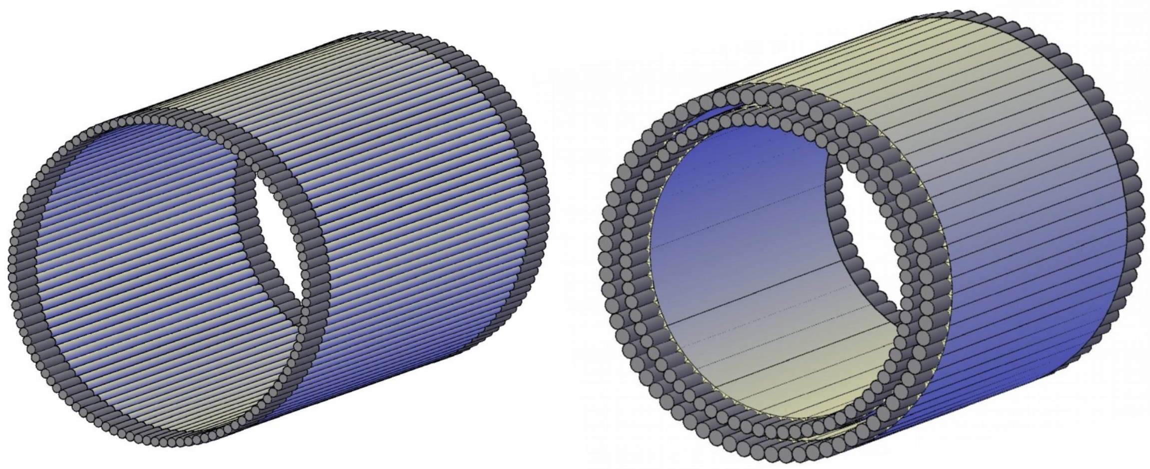
For preliminary result for T symmetry test see talk by J. Raj after lunch break

With the J-PET detector we are sensitive to the CP violating effects at the level of 10^{-5}. [J-PET: P. Moskal et al., Acta Phys. Polon. B47 (2016) 509]

J-PET (Jagiellonian PET)



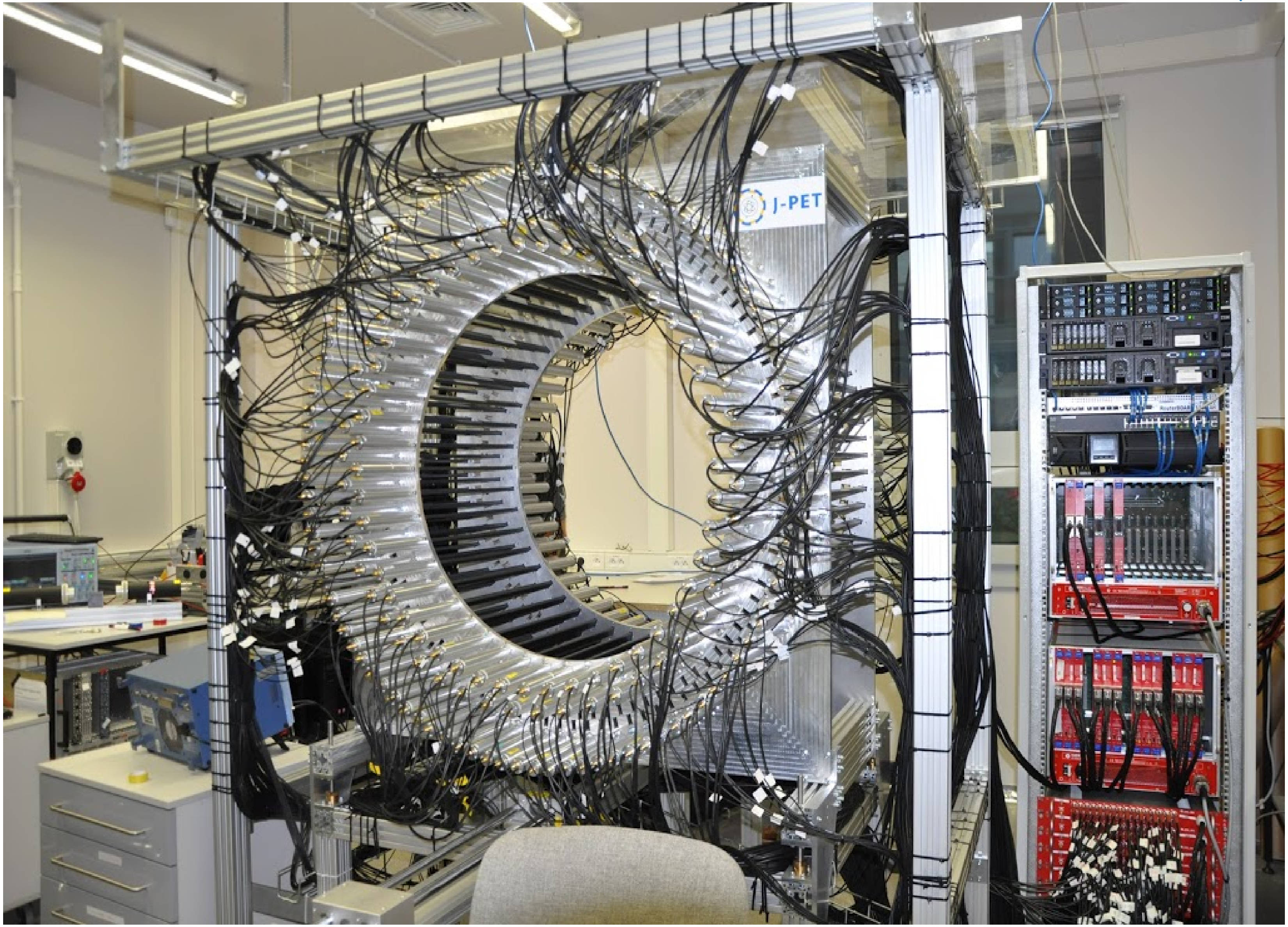
$$\Delta x = (t_l - t_r)\, c / 2$$
$$\Delta l = (t_2 - t_1)\, v / 2$$



P. Moskal, P 388 555 [WIPO ST 10/C PL388555] (2009), PCT/PL2010/00062 (2010), WO2011008119, US2012112079, JP2012533734, EP2454612.

J-PET: P. Moskal et al., Nucl. Inst. and Meth. A 764 (2014) 317-321
J-PET: P. Moskal et al., Nucl. Inst. and Meth. A 775 (2015) 54-62
J-PET: P. Moskal et al., Phys. Med. Biol. 61 (2016) 2025-2047

J-PET

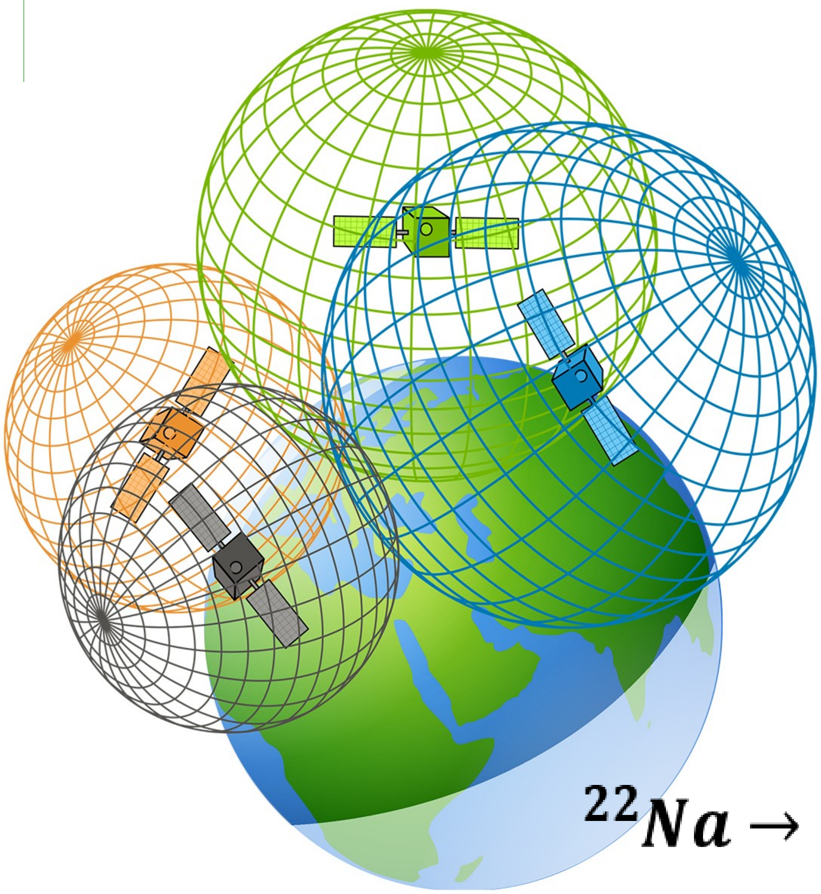


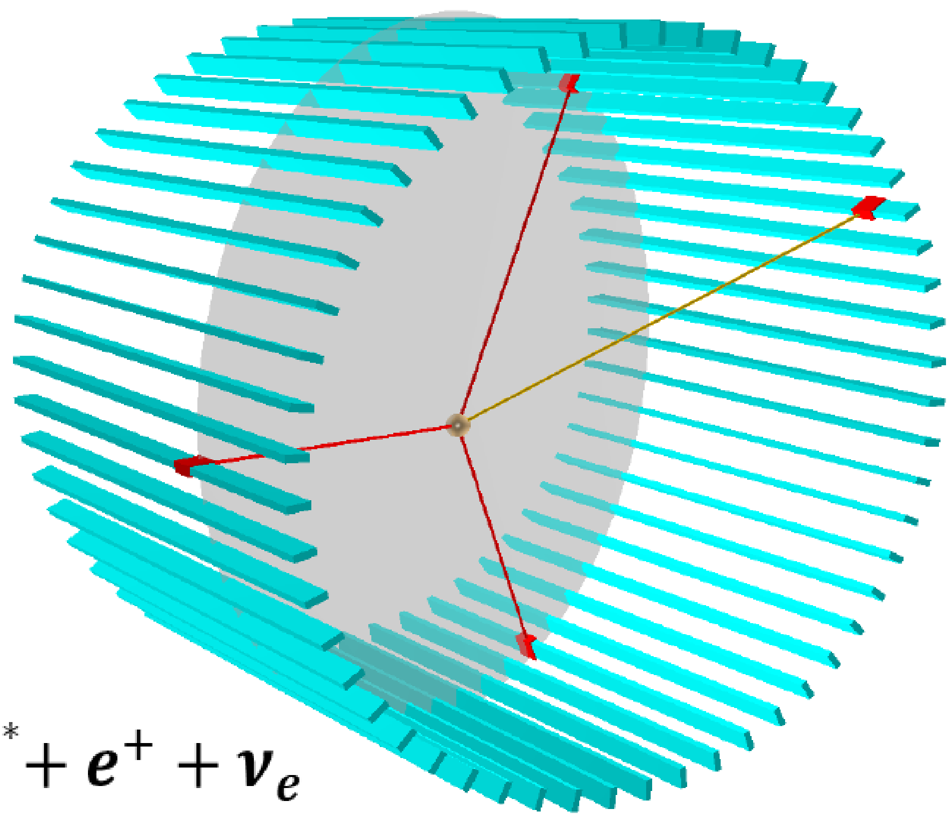
J-PET

J-PET

- 192 detection modules arranged in 3 layers
  - 19x5x500 mm^3 EJ-230 scintillator strips + Hamamatsu R9800 photomultipliers.
- Novel digital front-end electronics probing signals at multiple thresholds.
  [M. Pałka et al. JINST 12 (2017) no.08, P08001]
- Trigger-less and reconfigurable DAQ system.
  [G. Korcyl et al. Acta Phys.Polon. B47 (2016) 491]
- Annihilation gamma quanta hit time measurement:
  $\sigma_t(0.511 \text{ MeV}) \sim 125$ ps. [P. Moskal et al., Nucl.Instrum.Meth. A775 (2015) 54-62]
- Gamma quanta energy resolution:
  $\sigma_E/E = 0.044/\sqrt{E(\text{MeV})}$ [P. Moskal et al. Nucl.Instrum.Meth. A764 (2014) 317]
- Resolution of photons relative angles measurement ~ 1^o.
- o-ps spin and photon polarization measurement.

GPS @ J-PET



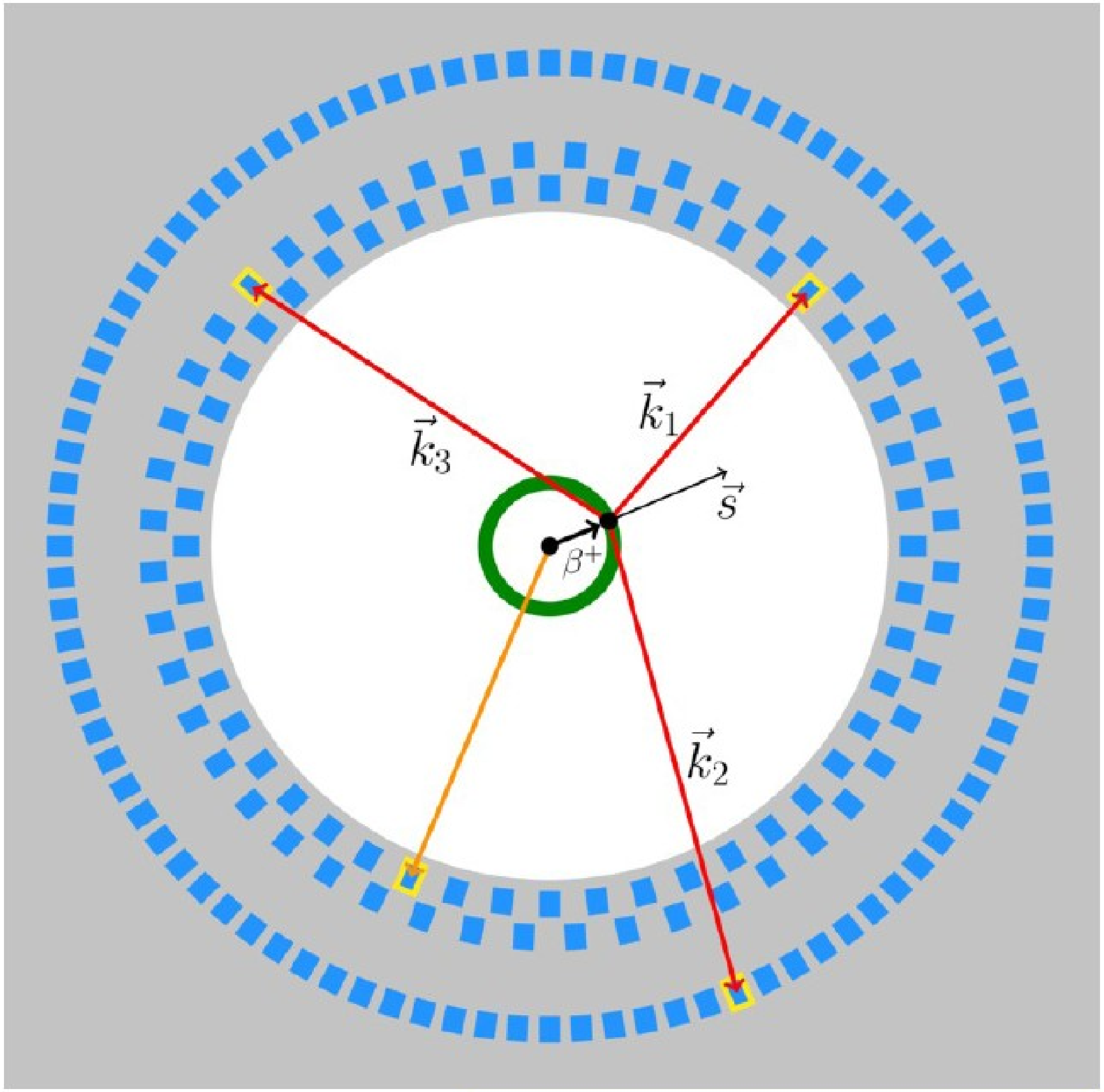


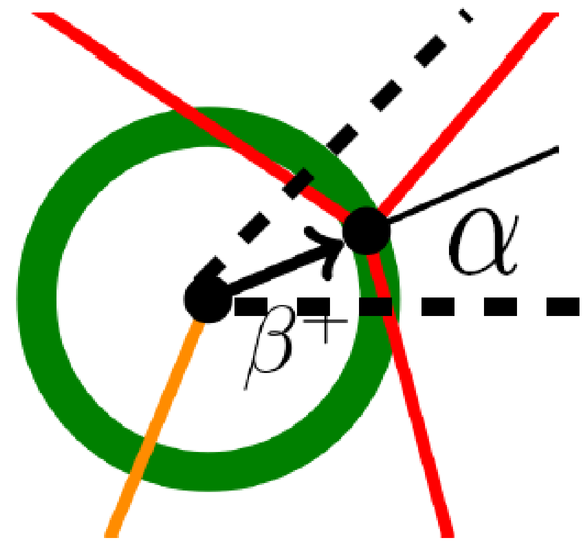
$$^{22}Na \rightarrow {}^{22}Ne^{*} + e^{+} + \nu_e$$

$$^{22}Ne^{*} \rightarrow {}^{22}Ne + \gamma(1.247\ \text{MeV}, \tau \approx 3.7\ \text{ps})$$

J-PET: A. Gajos, E.C. et al., Nucl. Inst. and Meth. A819 (2016) 54-59

Determination of o-Ps polarization



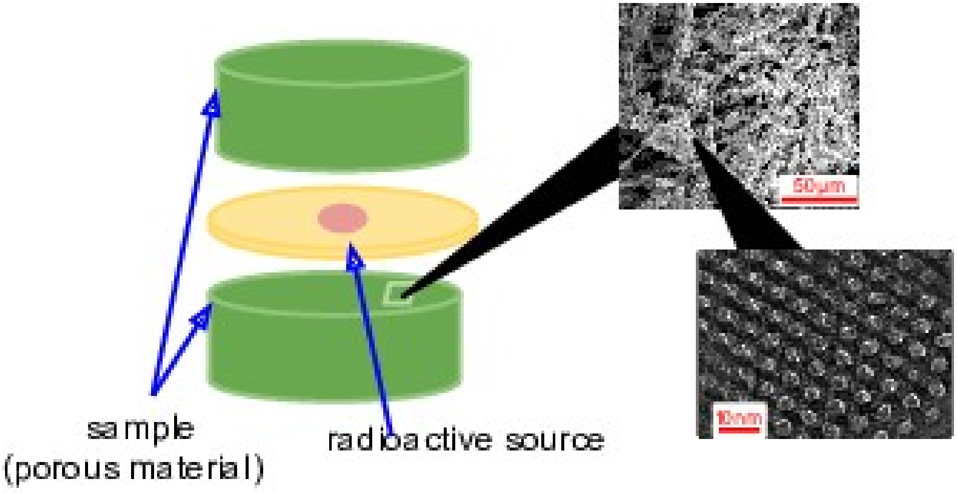


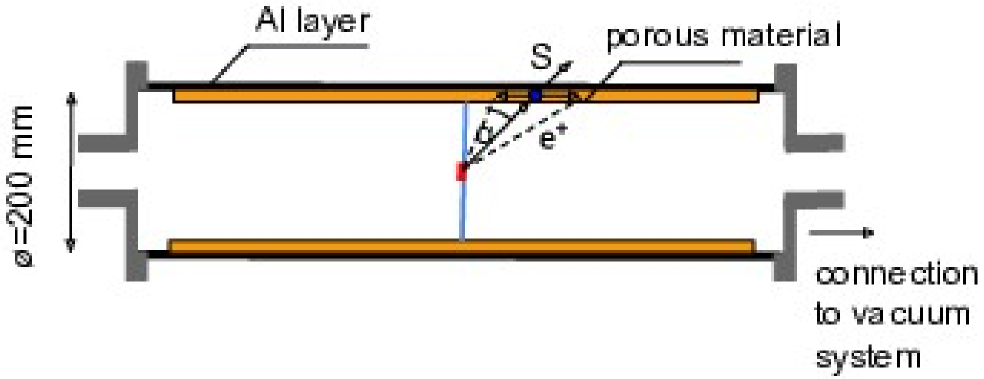
$$P = \frac{v}{c}(1 + \cos\alpha)/2$$

$$\approx 98\%$$

J.PET: A. Gajos, E.C. al., Nucl. Inst. and Meth. A819 (2016) 54-59
J-PET: P. Moskal et al., Acta Phys. Polon. B 47 (2016) 509

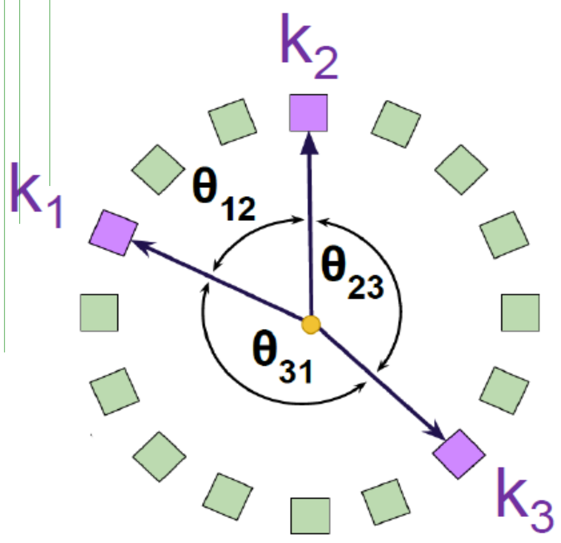
Determination of o-Ps polarization





J.PET: A. Gajos, E.C. al., Nucl. Inst. and Meth. A819 (2016) 54-59
J-PET: P. Moskal et al., Acta Phys. Polon. B 47 (2016) 509

Determination of energy of annihilation γ



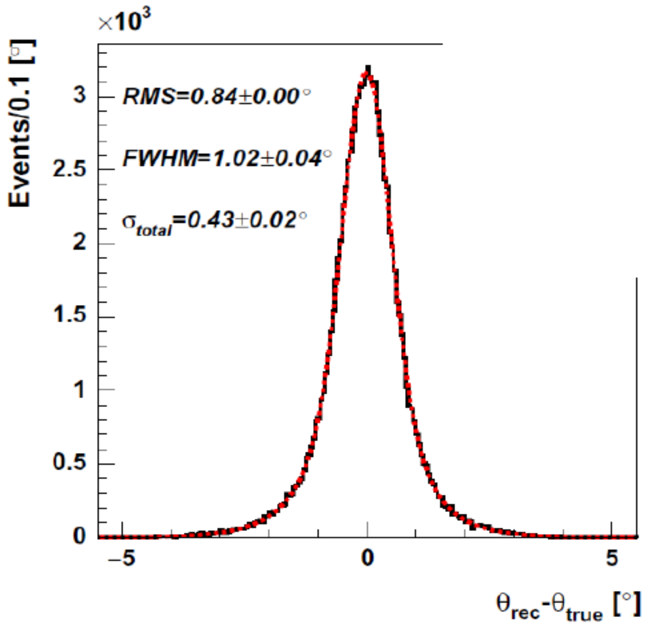
o-Ps → 3γ

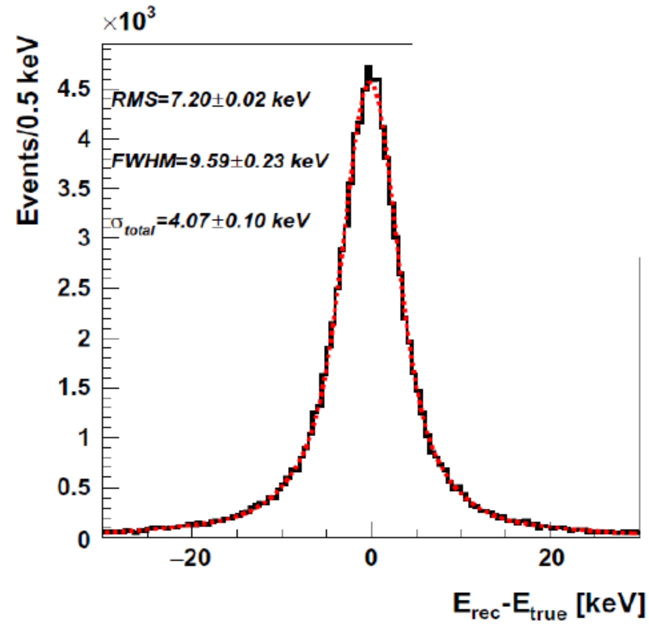
$$E_1 = -2m_e \frac{-\cos\theta_{13} + \cos\theta_{12}\cos\theta_{23}}{(-1+\cos\theta_{12})(1+\cos\theta_{12}-\cos\theta_{13}-\cos\theta_{23})},$$

$$E_2 = -2m_e \frac{\cos\theta_{12}\cos\theta_{13} - \cos\theta_{23}}{(-1+\cos\theta_{12})(1+\cos\theta_{12}-\cos\theta_{13}-\cos\theta_{23})},$$

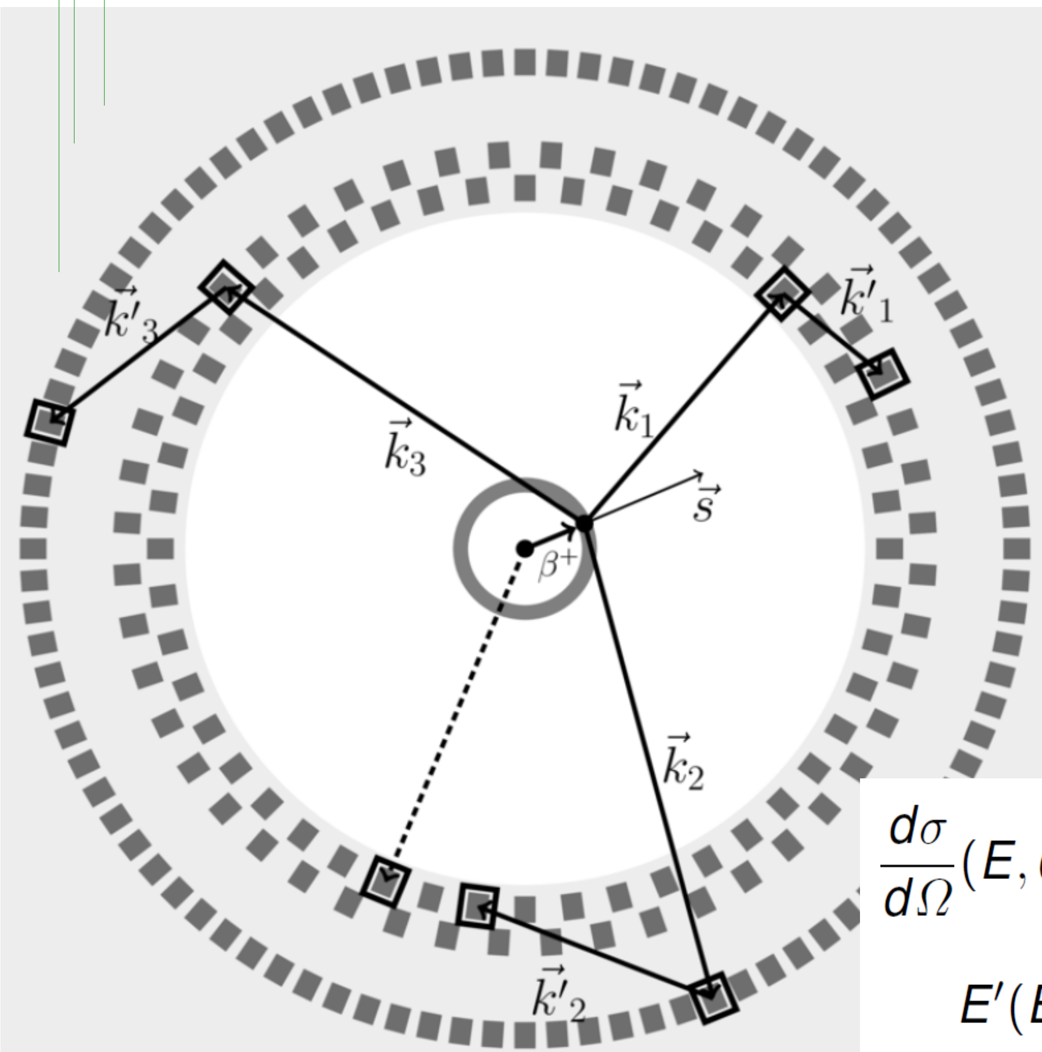
$$E_3 = 2m_e \frac{1+\cos\theta_{12}}{1+\cos\theta_{12}-\cos\theta_{13}-\cos\theta_{23}}.$$

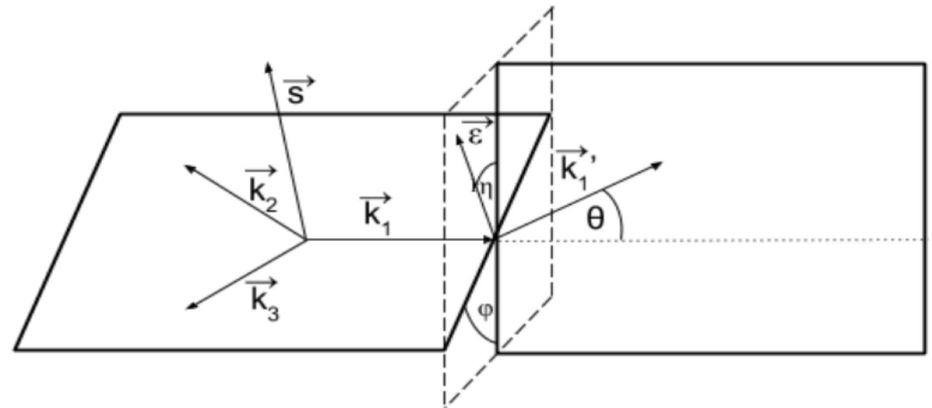
J-PET: D. Kamińska et al., Eur. Phys. J. C76 (2016) 445





Determination of polarization of anihilation γ

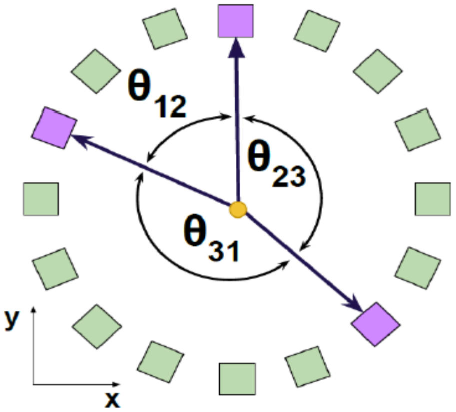




$$\frac{d\sigma}{d\Omega}(E,\theta,\eta) = \frac{r_0^2}{2}\left(\frac{E'}{E}\right)^2\left(\frac{E}{E'}+\frac{E'}{E}-2\sin^2\theta\cos^2\eta\right)$$

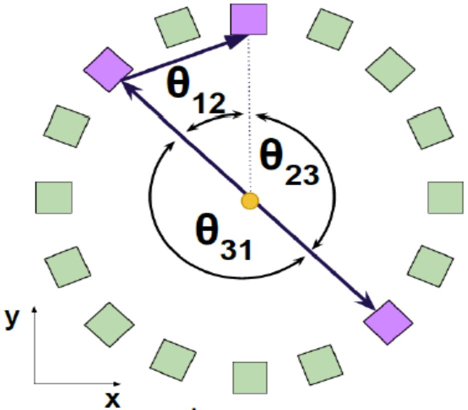
$$E'(E,\theta) = \frac{E}{1+\frac{E}{m_e c^2}(1-cos\theta)}$$

J-PET: P. Moskal et al., Acta Phys. Polon. B 47 (2016) 509



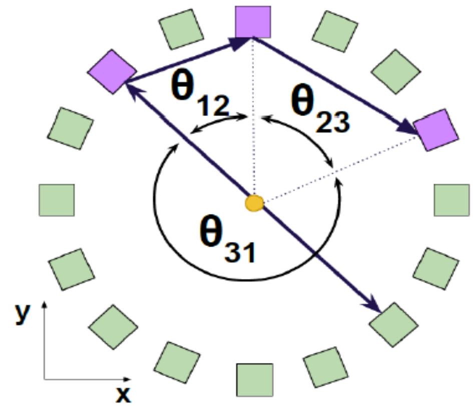
o-Ps → 3γ

$\theta_{23} > 180 - \theta_{12}$



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

$\theta_{23} = 180 - \theta_{12}$



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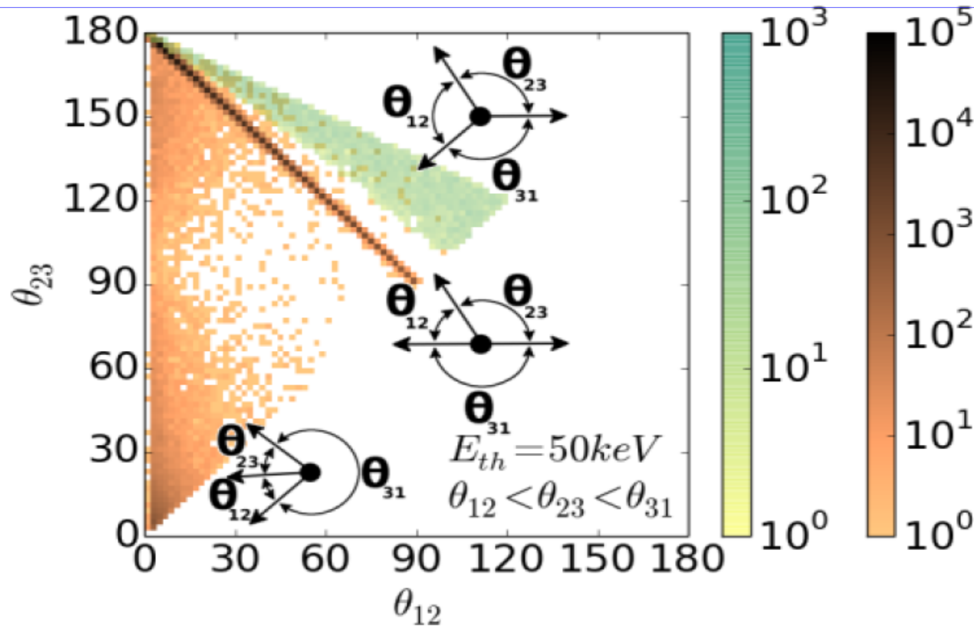
$\theta_{23} < 180 - \theta_{12}$

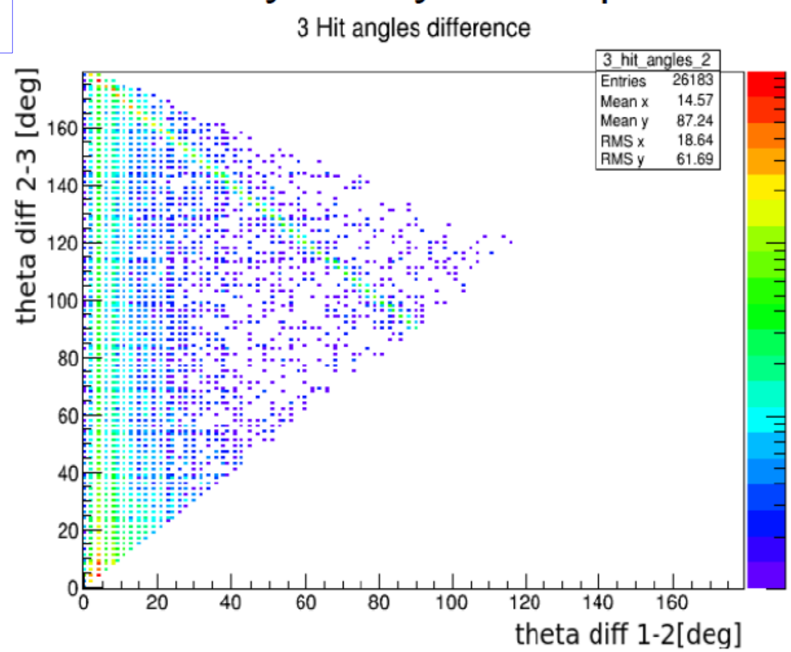
Simulations

J-PET: D. Kamińska et al., Eur. Phys. J. C76 (2016) 445



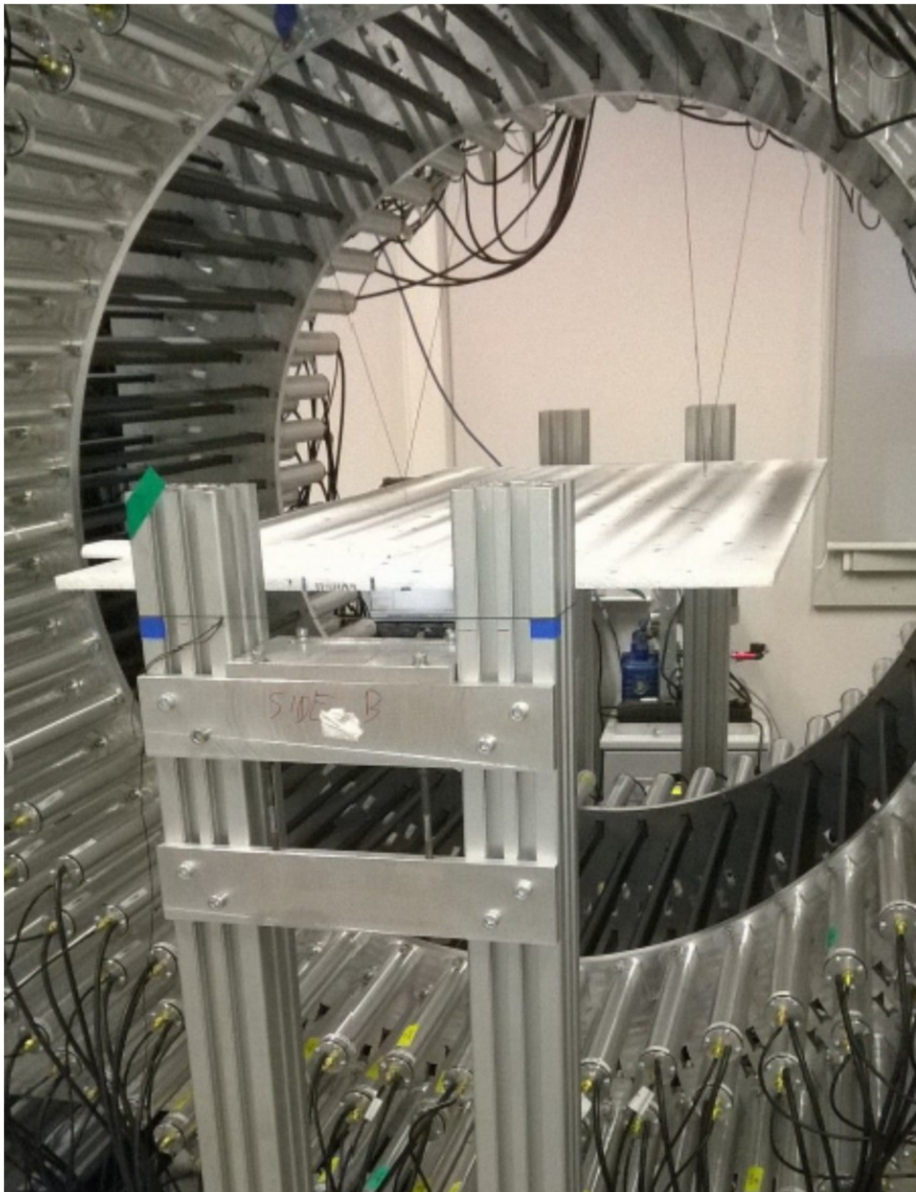
EXPERIMENT Run-1

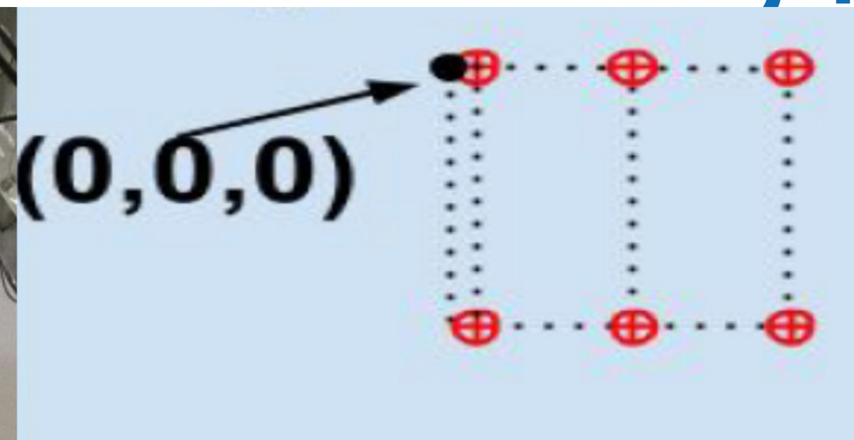
analysed by K. Kacprzak

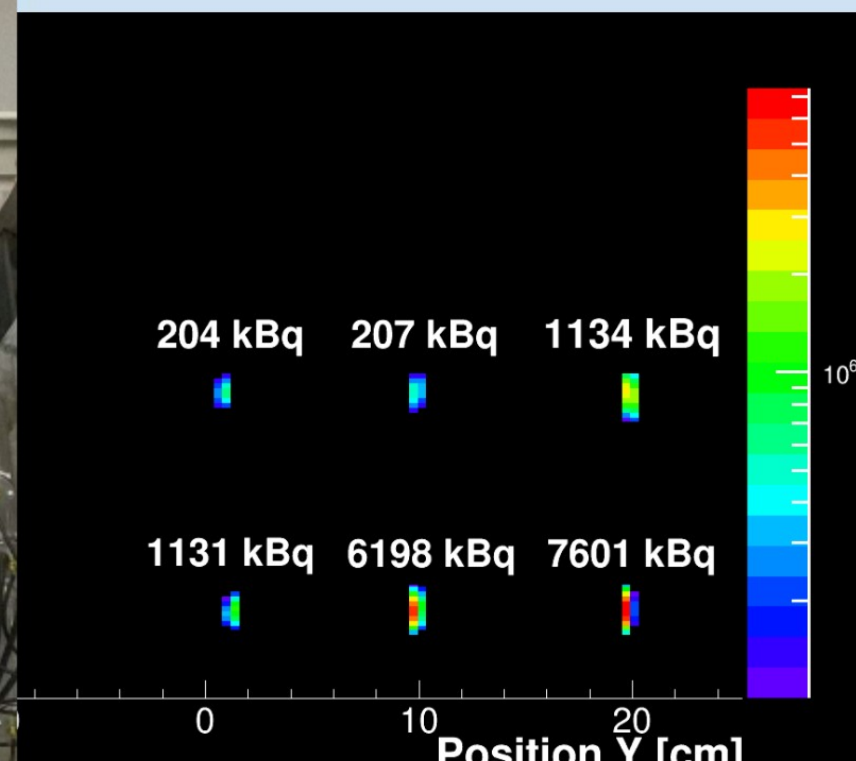


$$\theta_{12} < \theta_{23} < \theta_{31}$$

Commissioning



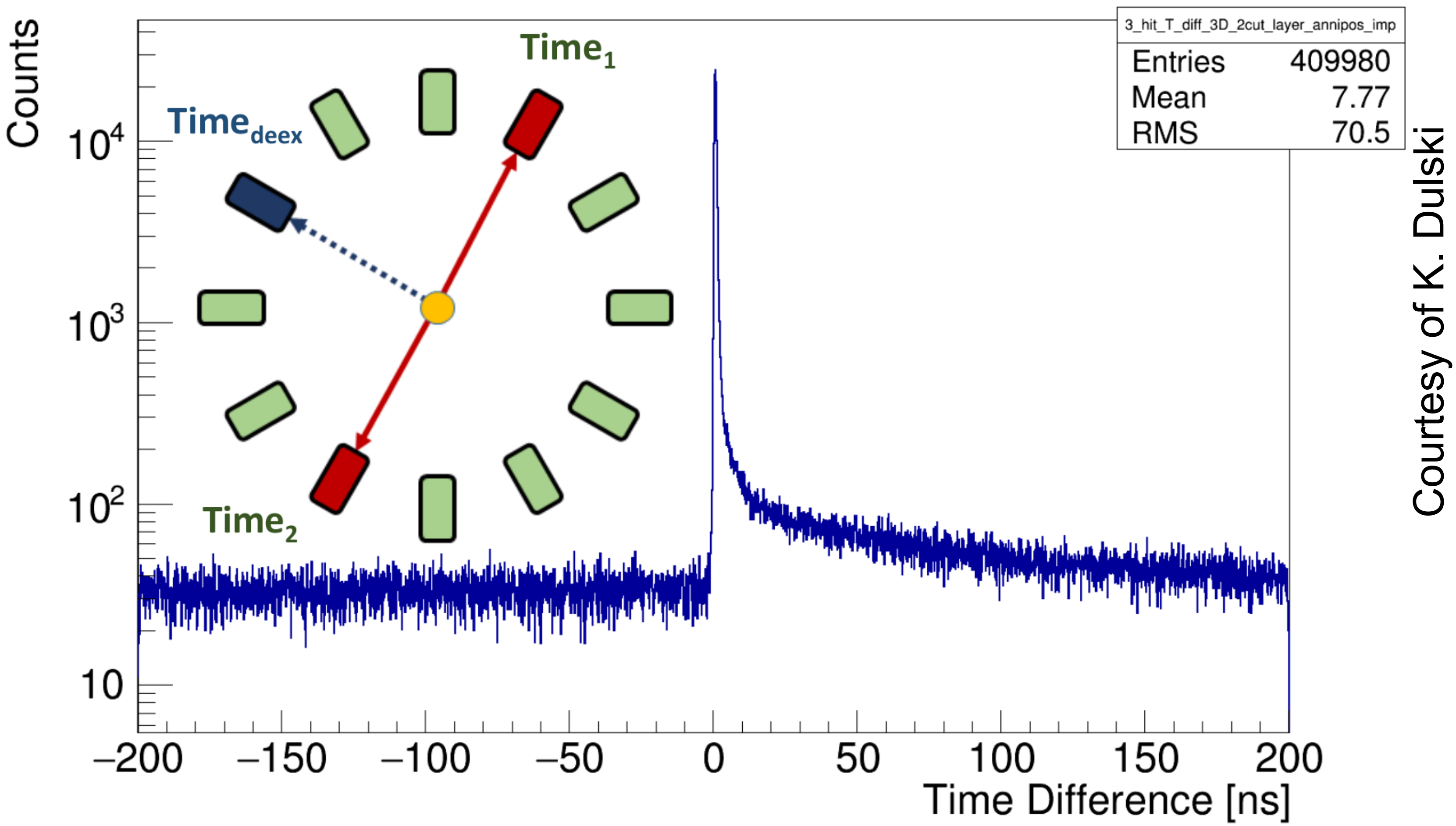




Courtesy of M.Pawlik-Niedźwiecka

Ps detection

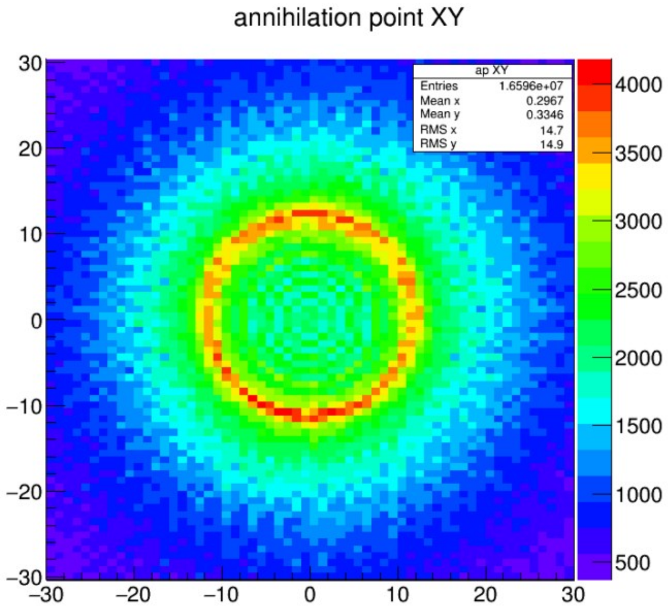
RUN2 with annihilation chamber wich XAD4 material (longest mean lifetime around 90 ns), 40% of all data



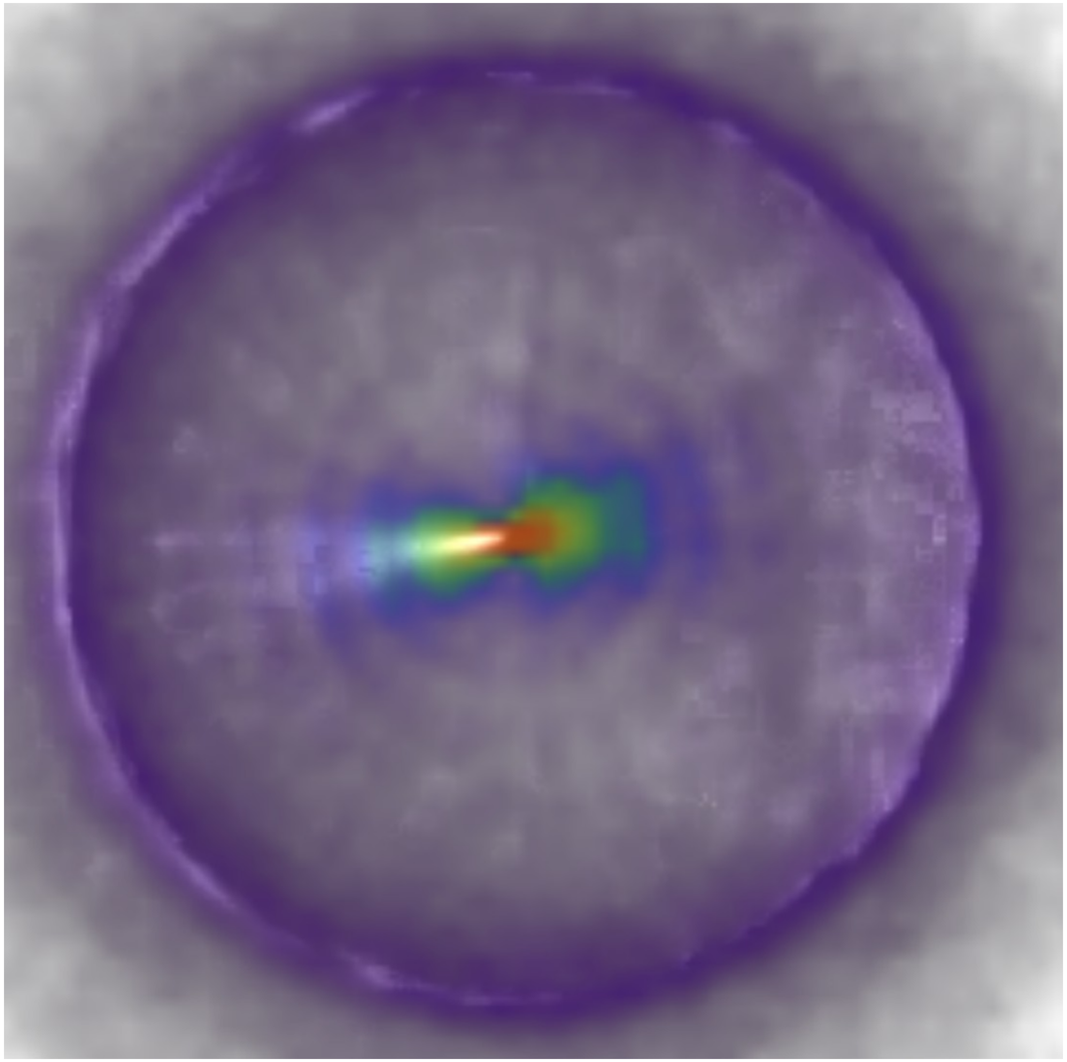
Time difference = $(\mathrm{Time}_1 + \mathrm{Time}_2)/2 - \mathrm{Time}_{deex}$

Ps detection

Result for ~20s data-taking

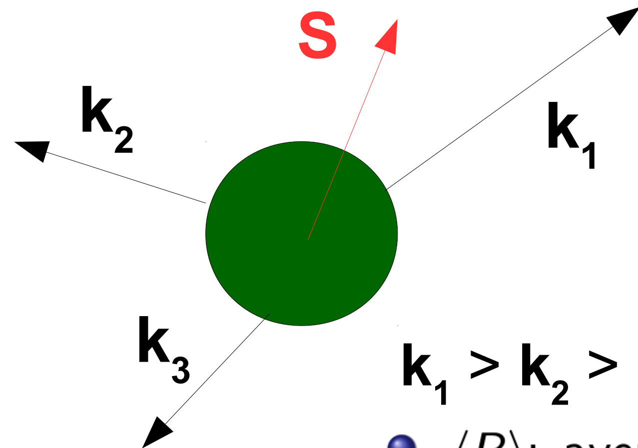


Central region in Z excluded



Central region in Z included

CPT test



$k_1 > k_2 > k_3$

$$A = \frac{N_+ - N_-}{N_+ + N_-}$$

$$C_{CPT} = A / \langle P \rangle$$

$$C_{CPT} = 0.0026 \pm 0.0031 \quad (\text{for } \vec{S} \cdot \vec{k}_1 \times \vec{k}_2)$$

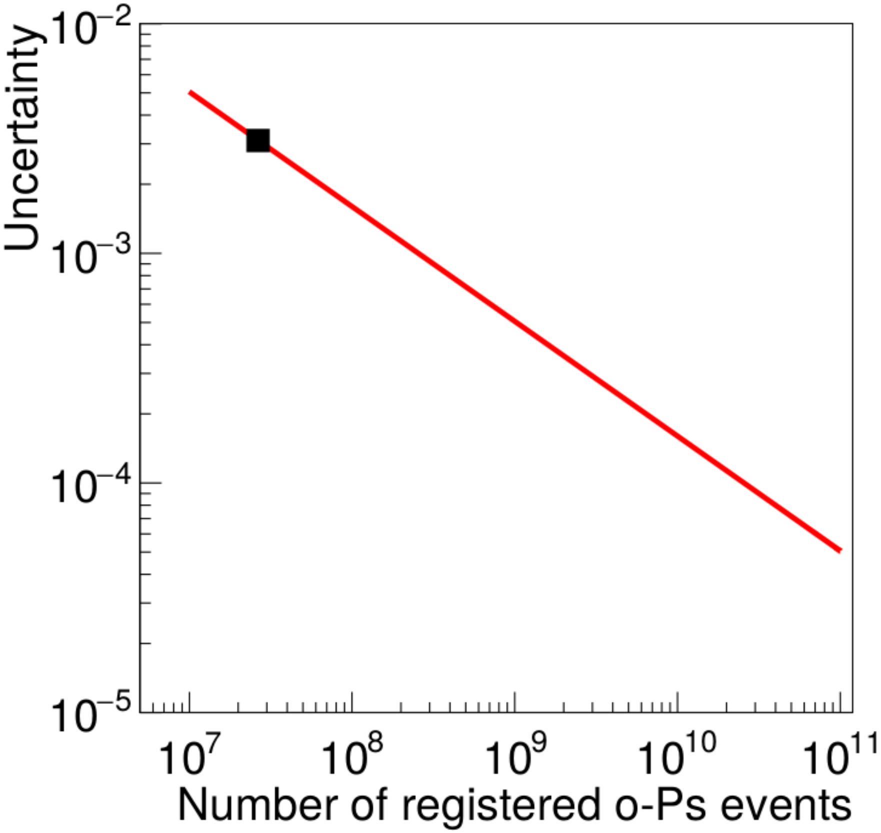
(P.A. Vetter et al., Phys. Rev. Lett. 91 (2003) 263401)

- $\langle P \rangle$: average polarization
- Gammasphere: 43% for ^{22}Na and 61% for ^{68}Ge. Determined on hemisphere
- J-PET: the uncertainty of determination of positron direction will amount to about 15°

	J-PET	**Gammasphere**
Detector material	BC-420	HPGe and BGO
Time resolution	80 ps	4.6 ns
Angular resolution (polar/azimuthal)	1.4°/0.5°	4°/4°
Source activity	10 MBq	1 MBq (limited by pile-ups)

Courtesy of D. Kisielewska

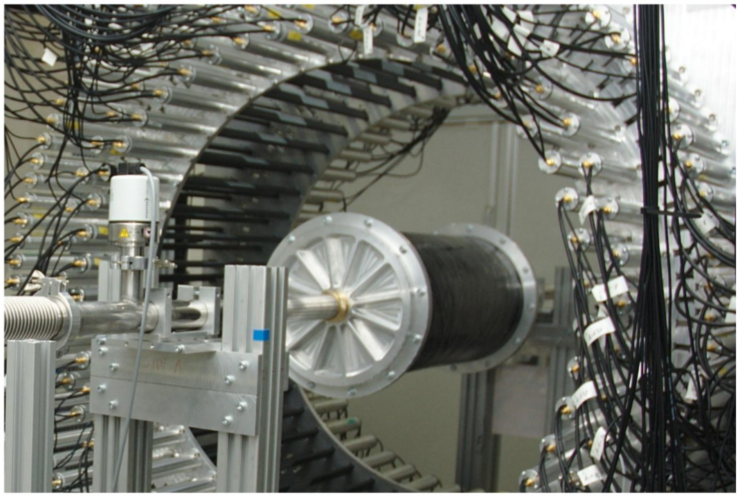
CPT test



Courtesy of D. Kisielewska

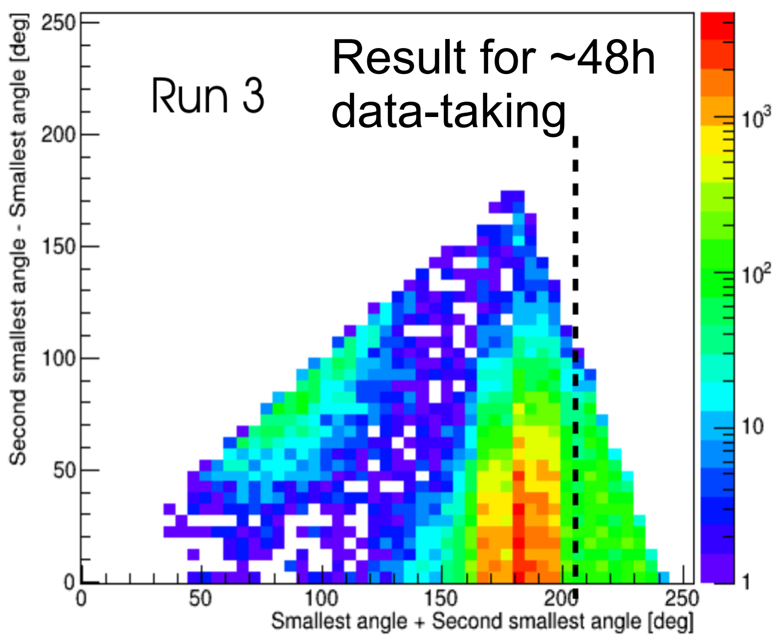
- $C_{CPT} = 0.0026 \pm 0.0031$ (for $\vec{S} \cdot \vec{k}_1 \times \vec{k}_2$)
  (P.A. Vetter et al., Phys. Rev. Lett. 91 (2003) 263401)
- $\Leftarrow$ Dependency between number of reconstructed o-Ps$\rightarrow$ 3γ events and the amplitude of $\mathcal{CPT}$ violating asymmetry uncertainty (red line). Plot is made assuming detection parameters as in Gammashpere detector. Result obtained by Vetter and Freedman is denoted by black square.
- $R_{o-Ps\rightarrow3\gamma} = \mathcal{A} \cdot f_{o-Ps\rightarrow3\gamma} \cdot \epsilon_{det}(th) \cdot \epsilon_{ana}$,
  - $\mathcal{A}$ - source activity
  - $f_{o-Ps\rightarrow3\gamma}$ - fraction of o-Ps$\rightarrow$ 3γ annihilation
  - $\epsilon_{det}(th)$ - detection efficiency
  - ϵ_{ana} - analysis efficiency
- XAD-4 (10MBq, th=50keV):
  $R_{o-Ps\rightarrow3\gamma} = 25$ events/s
  $\approx 1.5 \times 10^{7}$ events/week
- around 1.5 year of measurement is required to improve the previous result by an order of magnitude

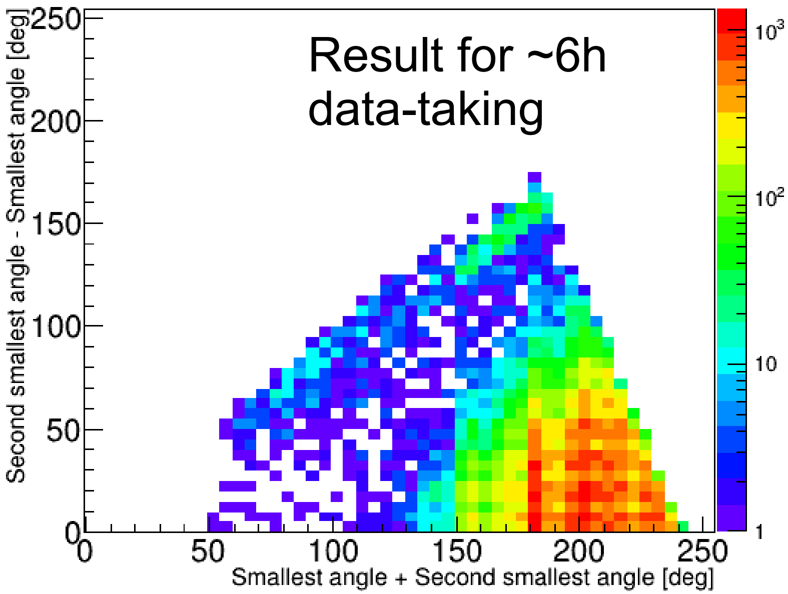
Ps detection



Run 3 chamber, R ≈ 7 cm
No o-Ps production medium
2 days of measurement

Run 6 chamber, R ≈ 12 cm
Walls coated with a porous polymer
180 days of measurement

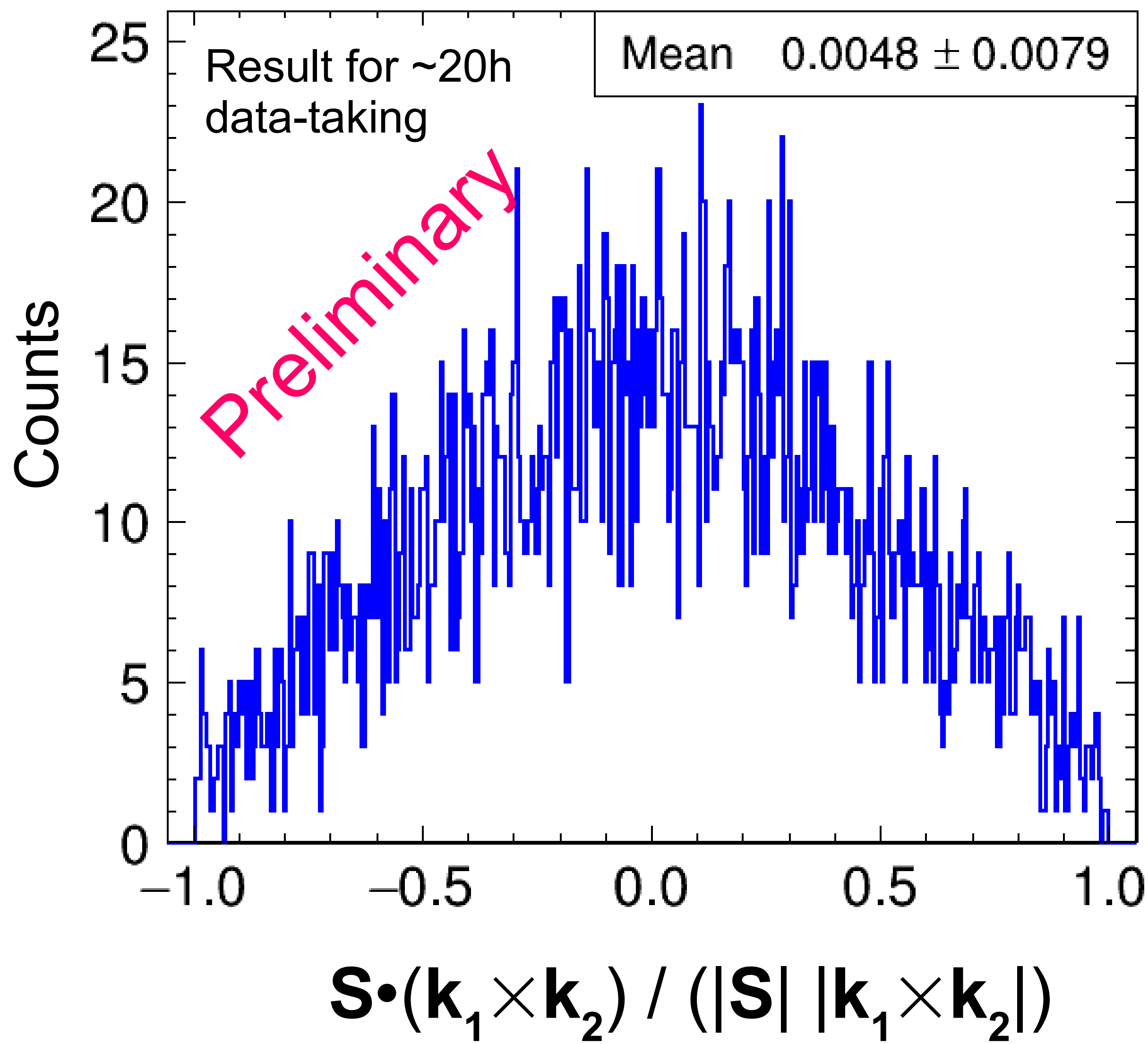




Courtesy of A. Gajos

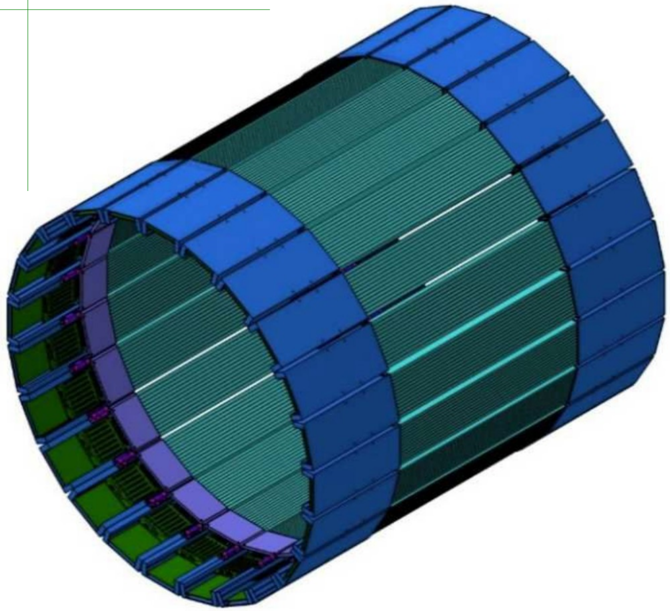
CPT test

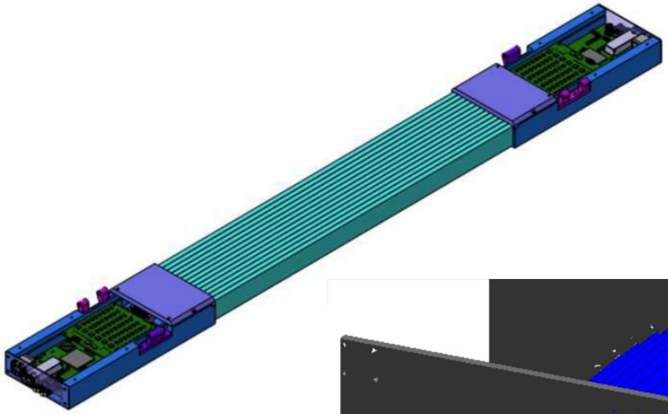
180 days of measurement

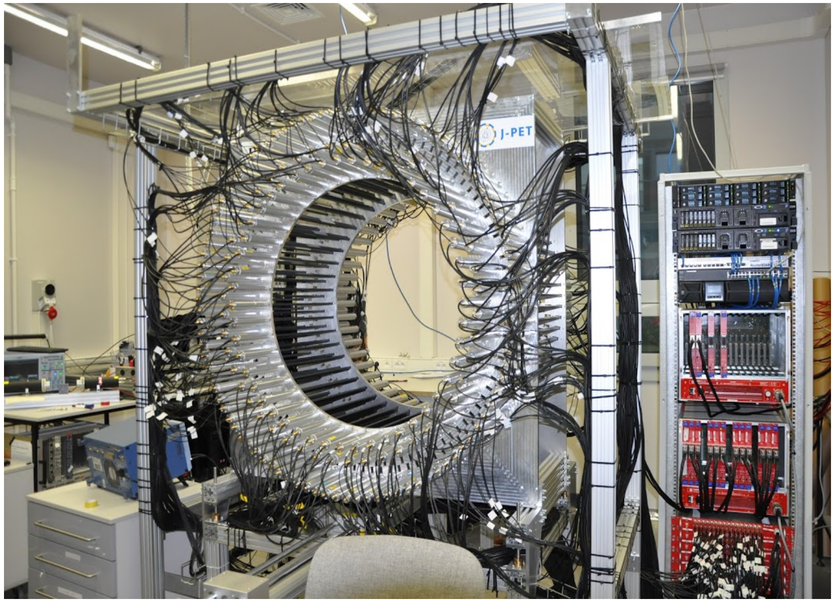


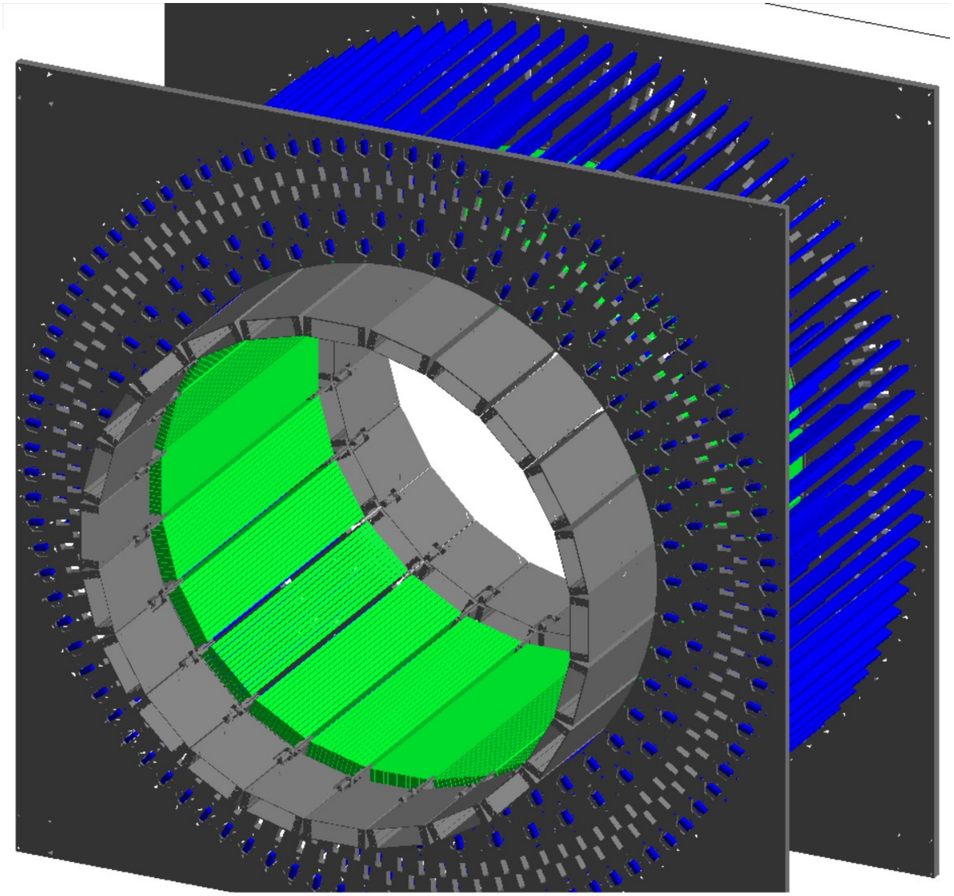
Courtesy of A. Gajos

Upgrades

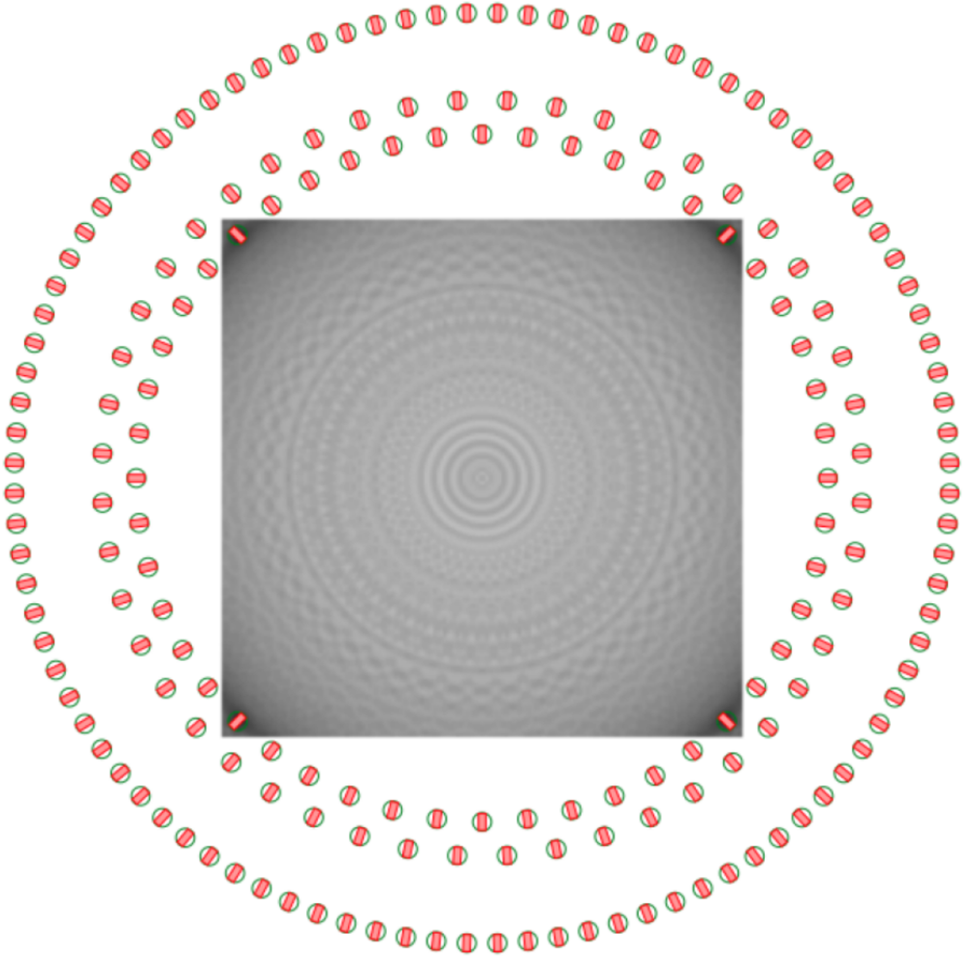




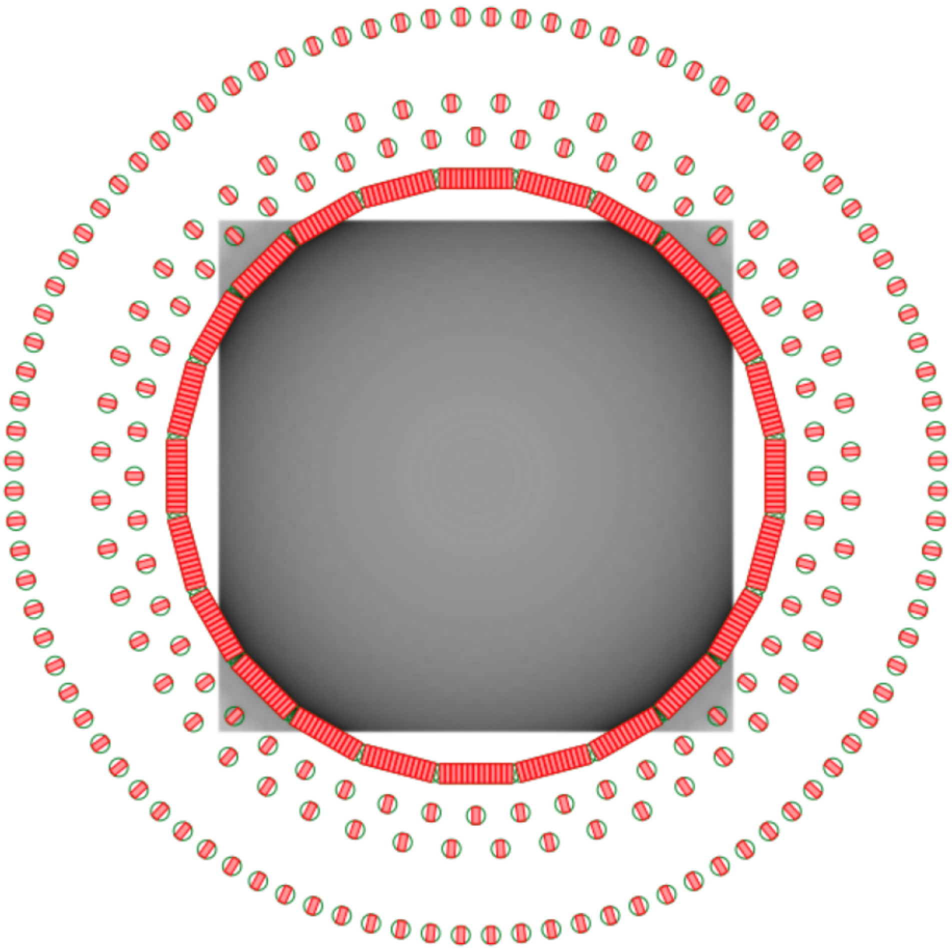




Upgrades – efficiency map

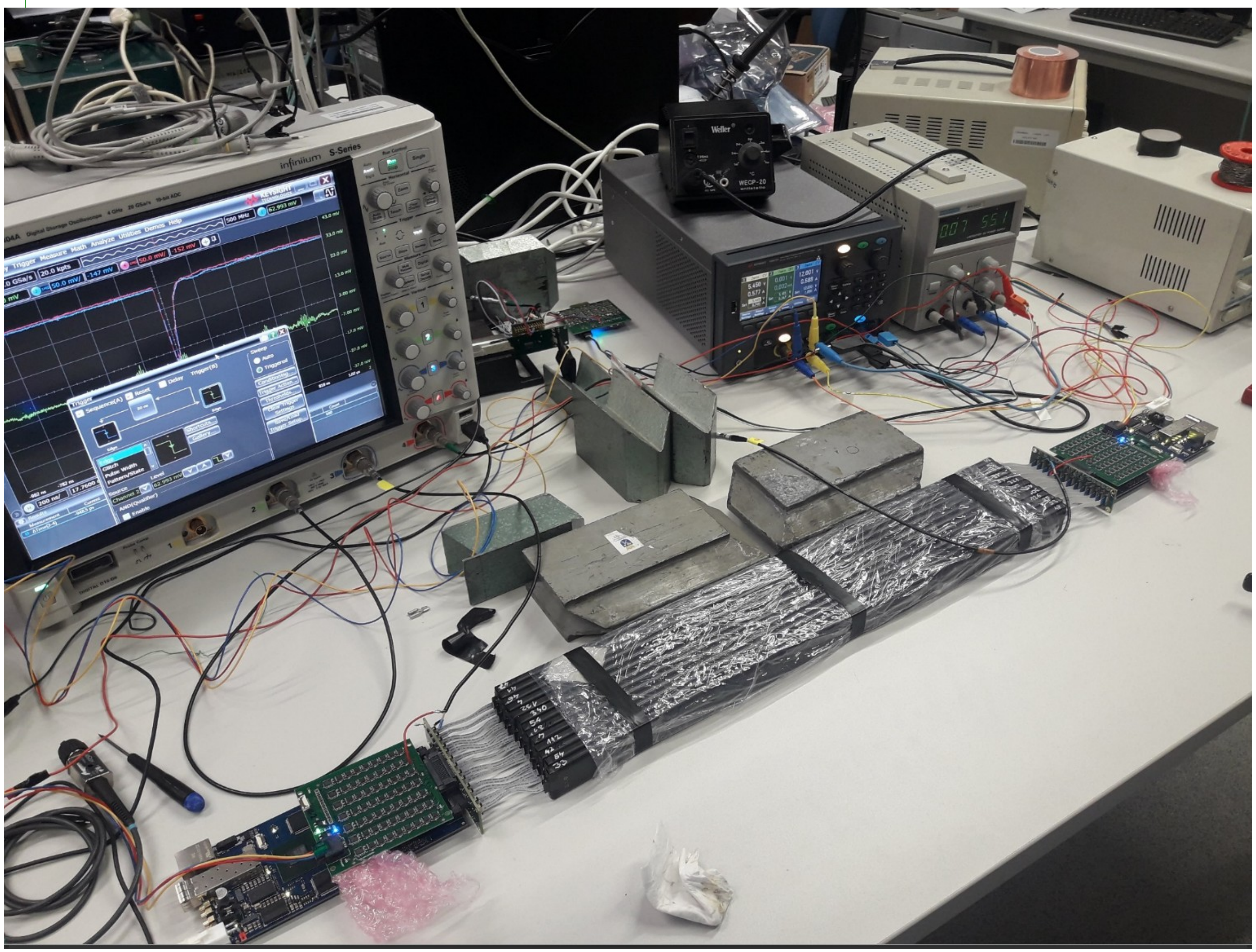


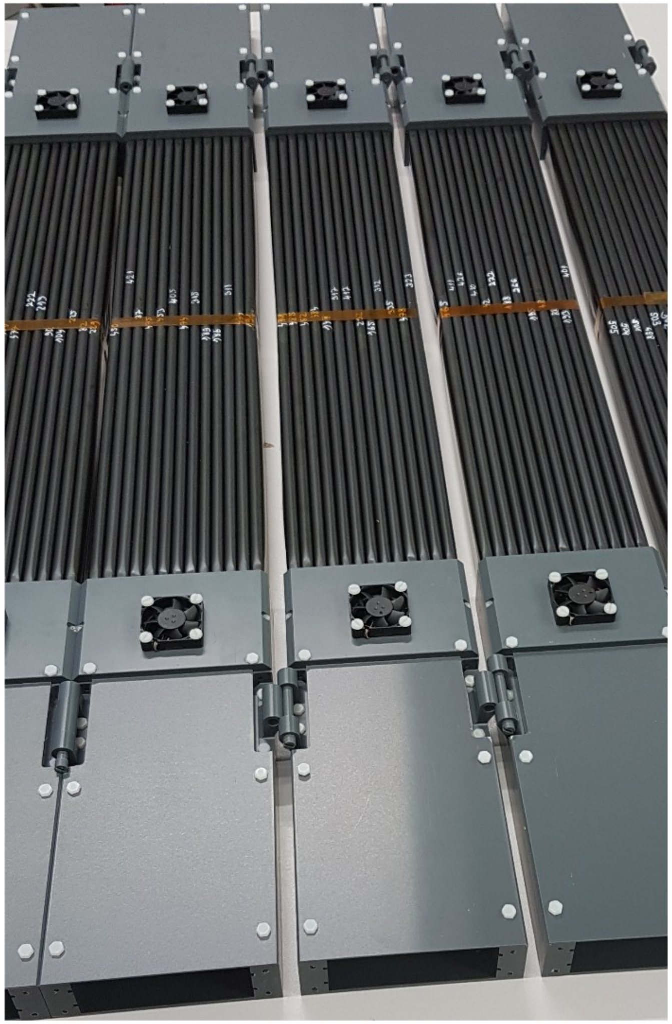
2016



2018

Upgrades





Conclusions

► lack of experimental data on discrete symmetries studies in the leptonic sector;

► C, T, CP and CPT tests in the o-Ps decays at the level of 10^{-5} possible with the J-PET detector;

► the J-PET detector during commissioning phase with first measurements' results.

Thank you for attention