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

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1. Positronium as a probe for fundamental symmetries tests
2. The J-PET detector
3. Potential of the discrete symmetries studies with J-PET
4. Conclusions and outlook

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Positronium as a probe for discrete symmetries tests

- The lightest purely leptonic object

- Eigenstate of the **CP** operator: e^+e^- state (**C** eigenstate) bound by a central potential (**P** eigenstate)

Ps state	τ [ns]	L	S	J	J_z	P	C	CP
$^1S_0$ (para-Ps)	0.125	0	0	0	0	-	+	-
$^3S_1$(ortho-Ps)	142	0	1	1	-1,0,1	-	-	+

$$\mathrm{P}|Ps> = (-1)^L|Ps>$$
$$\mathrm{C}|Ps> = (-1)^{L+S}|Ps>$$

- Effects due the weak interaction can lead to the violation at the order of 10^{-14}.
  [M. Sozzi, Discrete Symmetries and CP Violation, Oxford University Press (2008)]

- No charged particles in the final state (radiative corrections very small $2\cdot 10^{-10}$)
  [B. K. Arbic et al., Phys. Rev. A 37, 3189 (1988); W. Bernreuther et al., Z. Phys. C 41, 143 (1988)]

❖ **C tests**: search for decays to forbidden photons final state:
[A. Pokraka, A. Czarnecki, Phys. Rev. D 96, 093002 (2017)]

$$\mathrm{BR}(\mathrm{oPs} \to 4\gamma/\mathrm{oPs} \to 3\gamma) < 2.6 \cdot 10^{-6} \text{ at } 90\% \text{ C.L.}$$
$$\mathrm{BR}(\mathrm{pPs} \to 3\gamma/\mathrm{pPs} \to 2\gamma) < 2.8 \cdot 10^{-6} \text{ at } 68\% \text{ C.L.}$$
$$\mathrm{BR}(\mathrm{pPs} \to 5\gamma/\mathrm{pPs} \to 2\gamma) < 2.7 \cdot 10^{-7} \text{ at } 90\% \text{ C.L.}$$

[J. Yang et al., Phys. Rev. A54, 1952 (1996), A.P. Mills, S. Berko, Phys. Rev. Lett. 18, 420 (1967), P.A. Vetter, S.J. Freedman, Phys. Rev. A66, 052505 (2002)]

Positronium as a probe for symmetries tests

- Measurement of the expectation value of the symmetry-odd operators
- They are constructed using o-Ps spin ($\vec{S}$) and the decay photons momentum ($\vec{k_i}$) or polarization ($\vec{\varepsilon}_i$)
- There is no experimental data for most of the operators

$$\left\langle \vec{S}\cdot\left(\vec{k}_1\times\vec{k}_2\right) \right\rangle = 0.0026 \pm 0.0031$$ (CPTV)

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

$$\left\langle (\vec{S}\cdot k_1)\left[\vec{S}\left(\vec{k}_1\times\vec{k}_2\right)\right] \right\rangle = 0.0013 \pm 0.0022$$ (CPV)

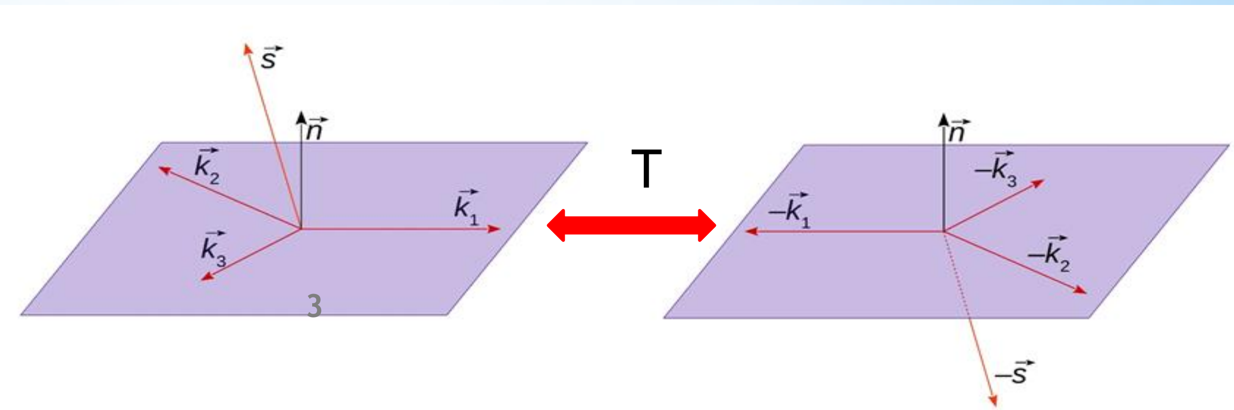
[T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401]

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

$$|k_1| > |k_2| > |k_3|$$

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

- SM prediction: 10^{-10} - 10^{-9} (photon-photon interactions)

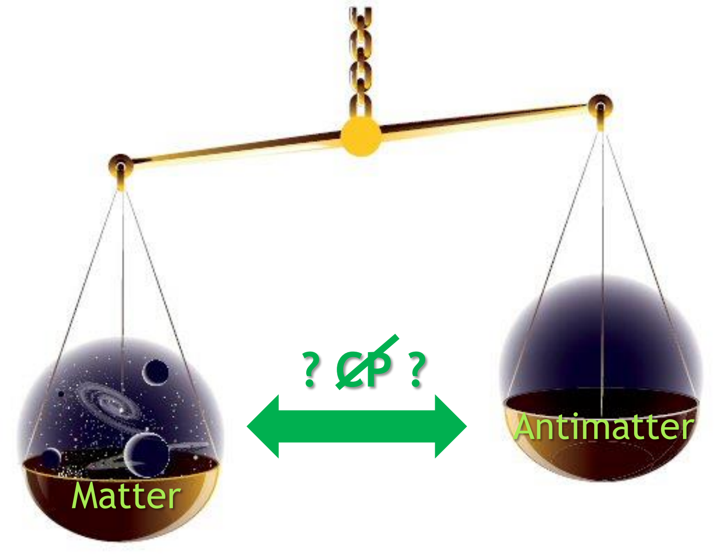


* Tests of the CP symmetry with positronium

- New sources of **CP** violation needed to explain the matter-antimatter asymmetry

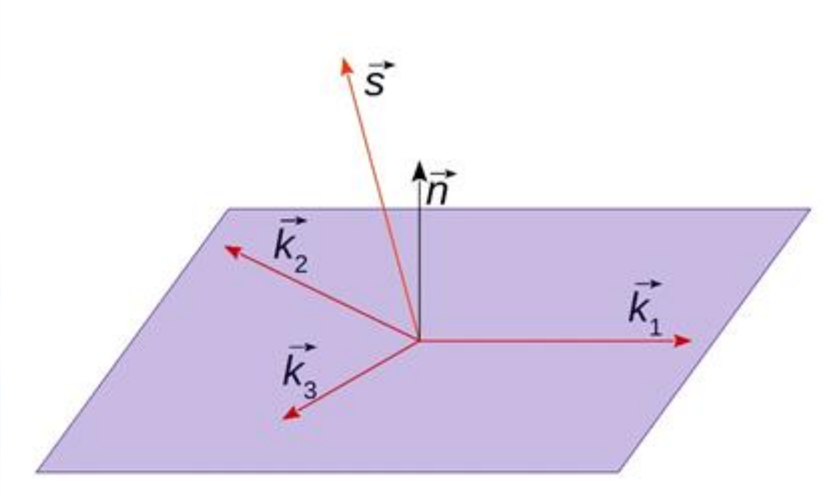
- CPV discovered experimentally so far only for hadrons

- Massive neutrinos suggest **CP** violation in the leptonic sector **(so far not observed)**
  - Neutrino oscillations studies (e.g. T2K experiment)
  - Positronium decay studies



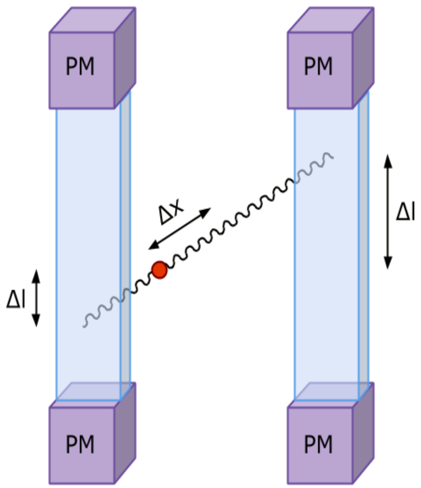
CP-odd operators:

- $\vec{S} \cdot \vec{k}_1$
- $\vec{S} \cdot \left(\vec{k}_1 \times \vec{k}_2\right)$ [M. Mohammed, A Gajos poster]
- $\left(\vec{S} \cdot \vec{k}_1\right)\left(\vec{S} \cdot \left(\vec{k}_1 \times \vec{k}_2\right)\right)$
- $\vec{k}_2 \cdot \vec{\varepsilon}_1$ [J. Raj poster]
- $\vec{S} \cdot \vec{\varepsilon}_1$
- $\vec{S} \cdot \left(\vec{k}_2 \times \vec{\varepsilon}_1\right)$

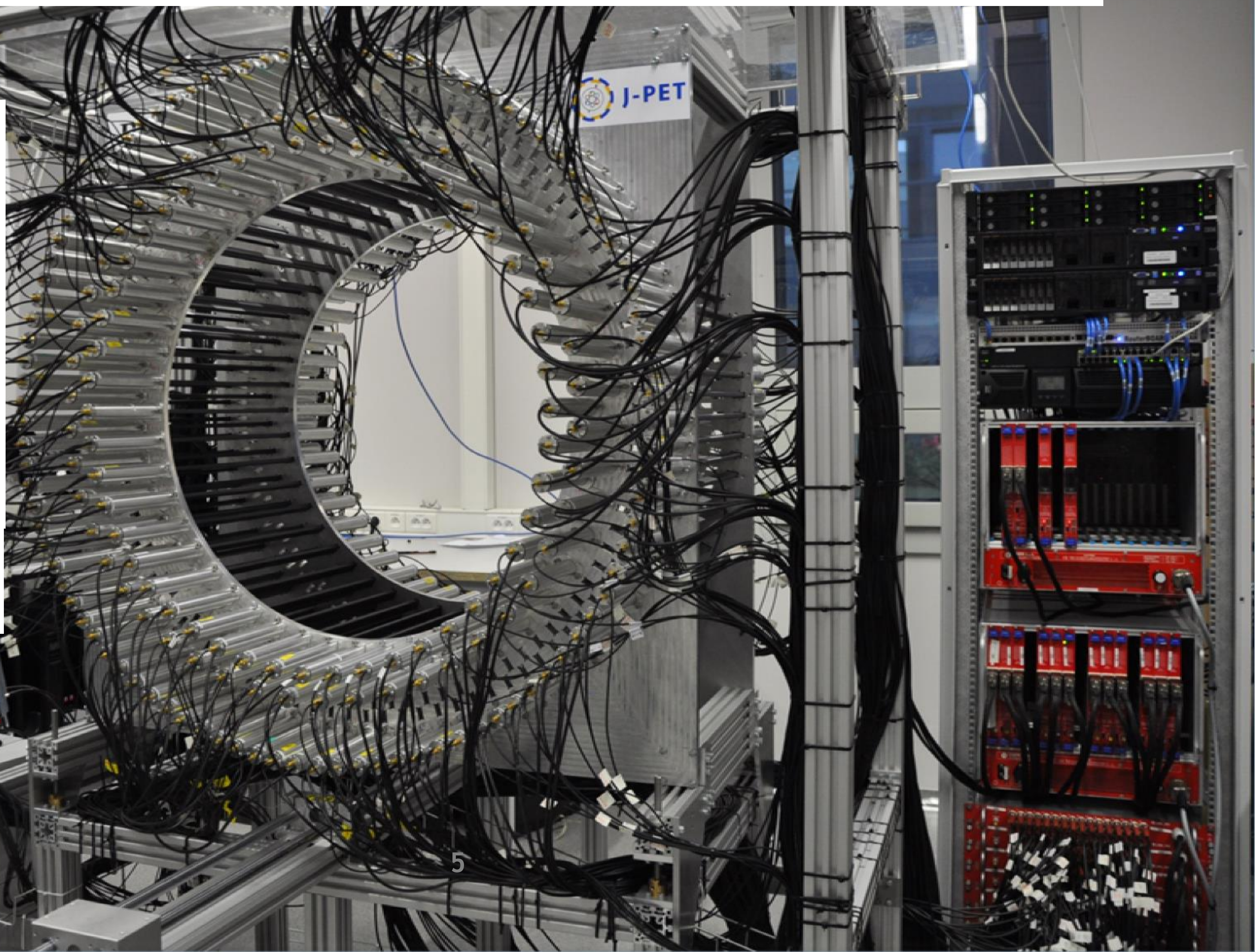


Jagiellonian PET

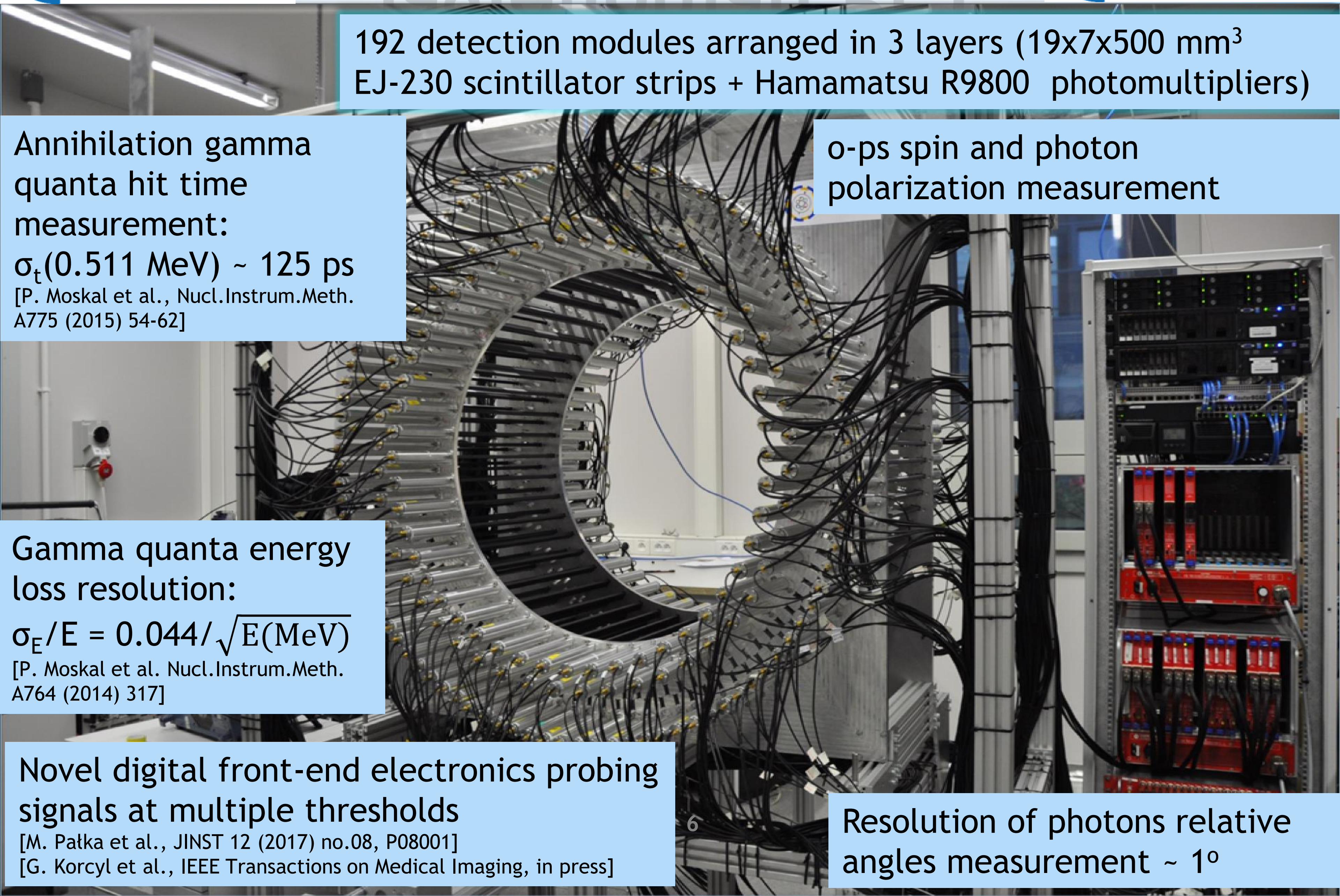
- ❖ First PET tomgraph based on plastic scintillators
- ❖ Multipurpose detector for fundamental particle physics



$$\Delta x = (t_2 - t_1) \cdot c/2$$
$$\Delta l = (t_L - t_R) \cdot v/2$$



Jagiellonian PET



192 detection modules arranged in 3 layers (19x7x500 mm^3 EJ-230 scintillator strips + Hamamatsu R9800 photomultipliers)

Annihilation gamma quanta hit time measurement:
$\sigma_t(0.511\ \mathrm{MeV}) \sim 125$ ps
[P. Moskal et al., Nucl.Instrum.Meth. A775 (2015) 54-62]

o-ps spin and photon polarization measurement

Gamma quanta energy loss resolution:
$\sigma_E/E = 0.044/\sqrt{E(\mathrm{MeV})}$
[P. Moskal et al. Nucl.Instrum.Meth. A764 (2014) 317]

Novel digital front-end electronics probing signals at multiple thresholds
[M. Pałka et al., JINST 12 (2017) no.08, P08001]
[G. Korcyl et al., IEEE Transactions on Medical Imaging, in press]

Resolution of photons relative angles measurement ~ 1°

* Discrete symmetries tests with the J-PET detector

- **Positrons source:**
  ^{22}Na β^+ decay (parity violation)

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

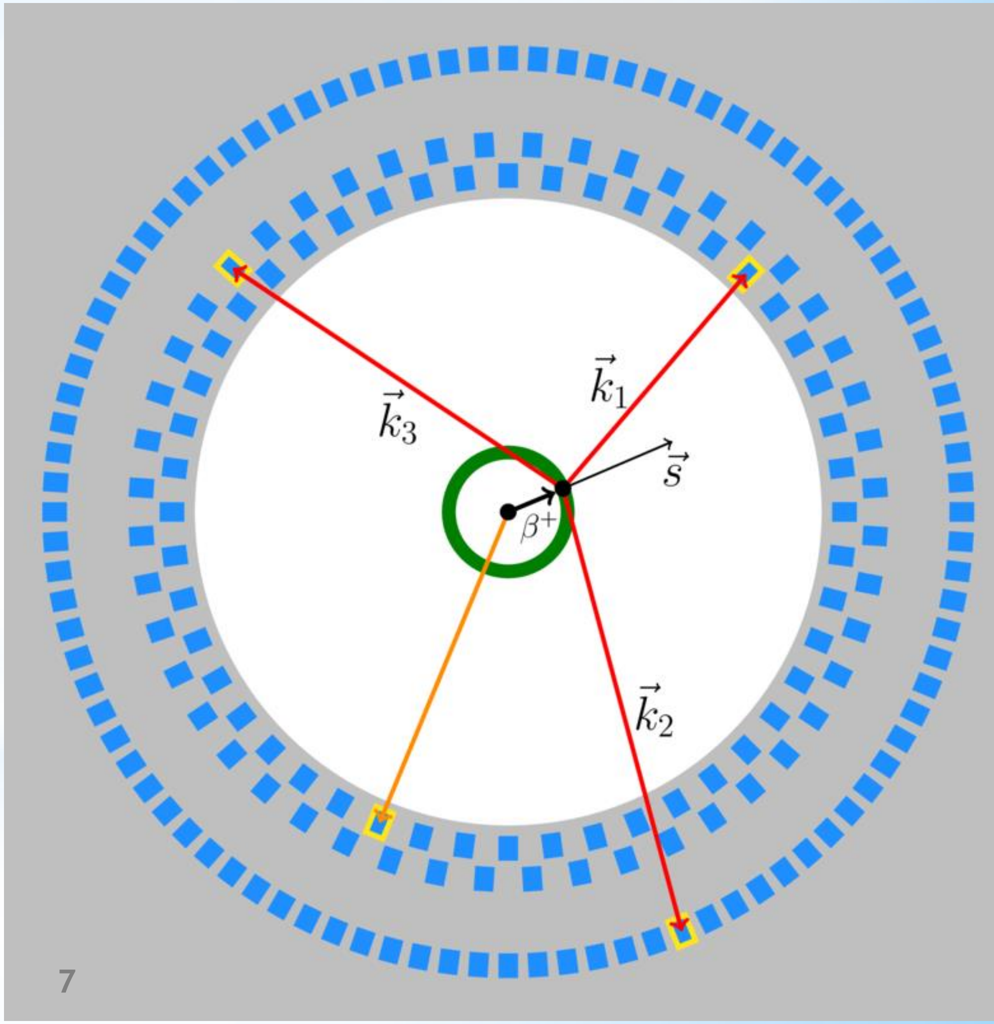
- **Target around the source**
  - e^+ thermalization + o-Ps formation

- Positron longitudinal polarization

⬇

o-Ps spin determination

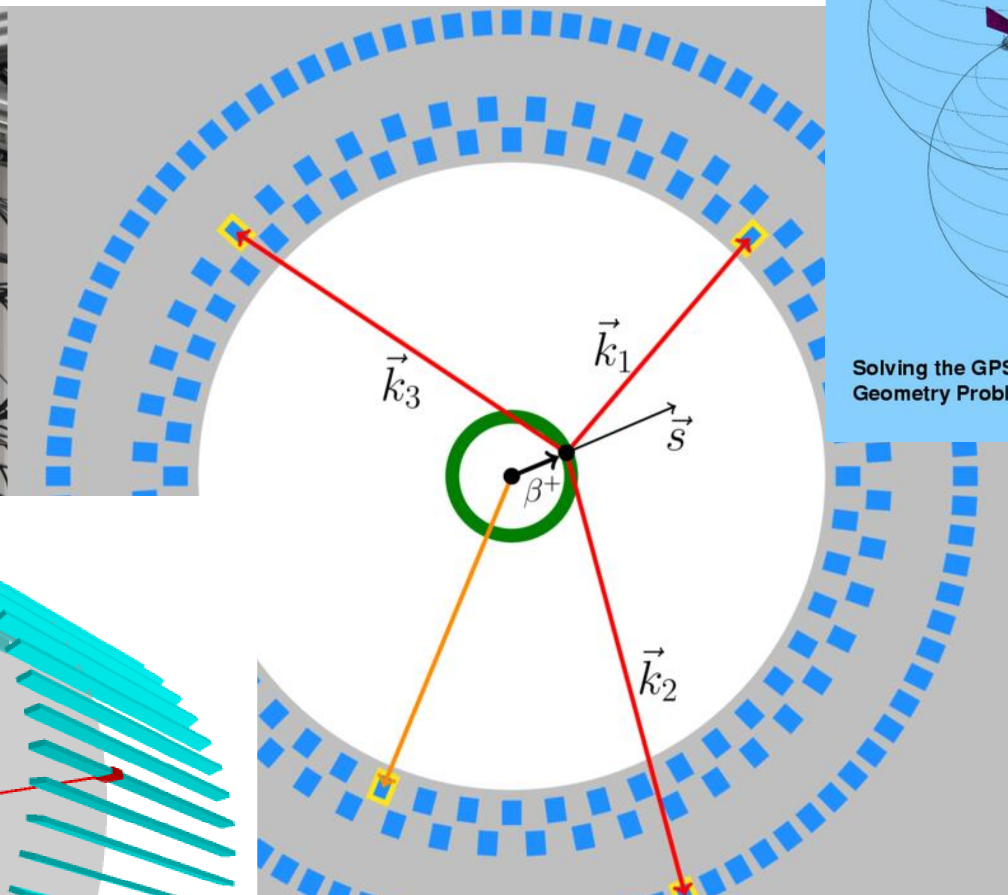
- **Signal signature:**
  - 3γ quanta with common vertex reconstructed in the target
  - Late decay with respect to the registration of the de-excitation photon
- Photon polarization determination using Compton scattering

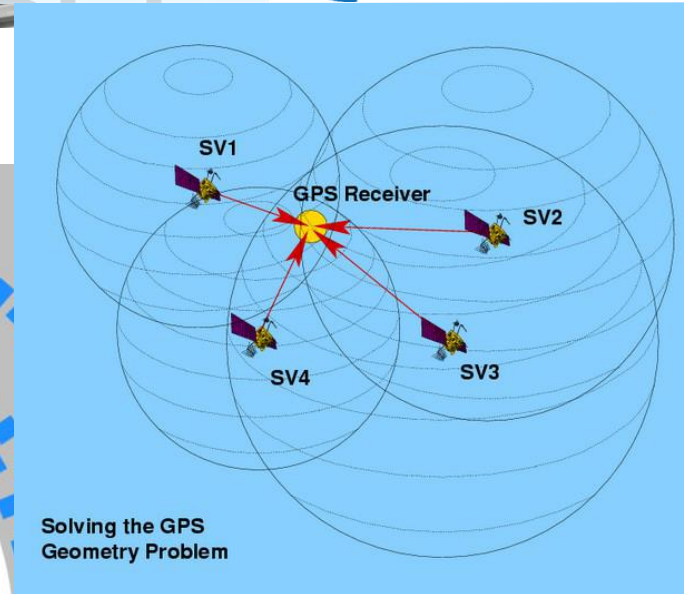


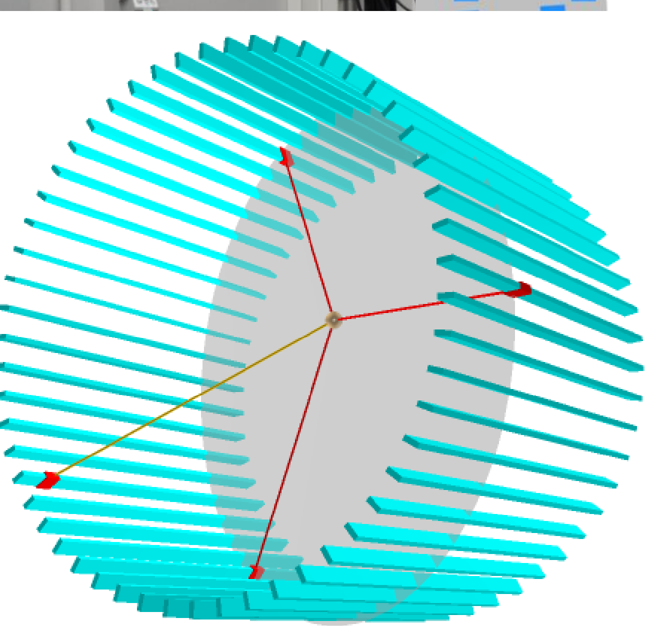
[P. Moskal et. al., Acta Phys.Polon. B47 (2016) 509]

Jagiellonian PET

- Positron direction can be determined using trilateration method (angular resolution $\sigma_\theta \approx 15^o$)







- Average polarization with ^{22}Na source ~ 40%.

P. Moskal et. al., Acta Phys. Polon. B47 (2016) 509
A. Gajos et al. Nucl. Instrum. Meth. A819 (2016) 54-59
D. Kamińska et al., Eur. Phys. J. C76 (2016) no.8, 445

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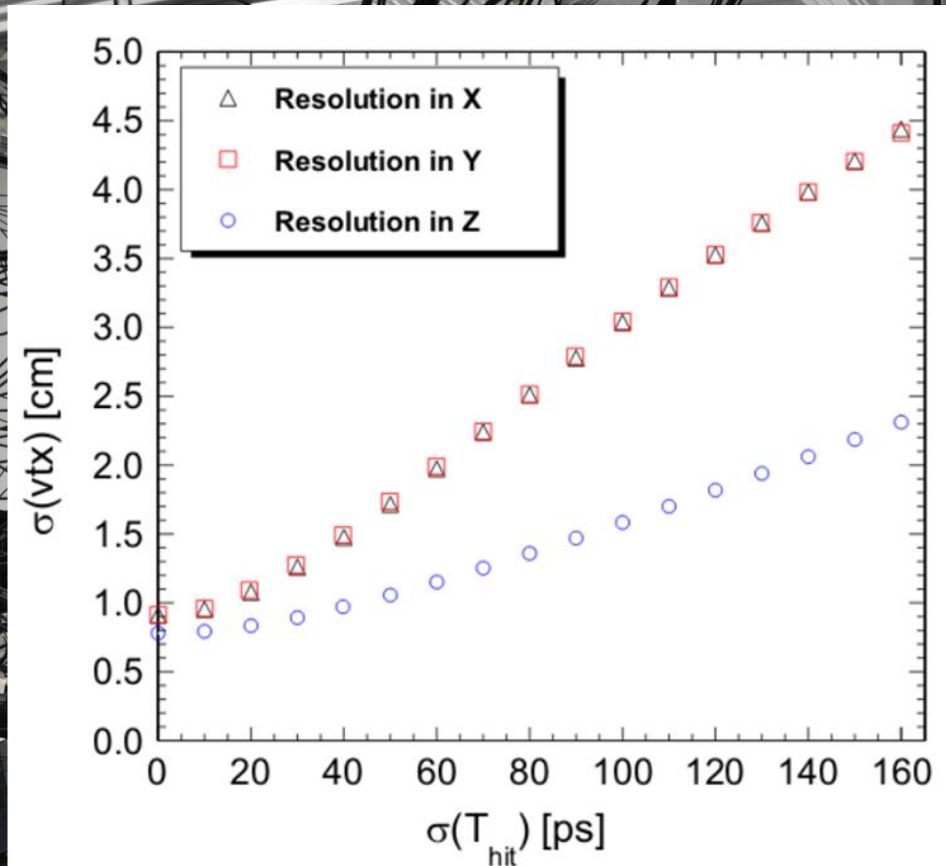

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* Discrete symmetries tests with the J-PET detector

- De-excitation photon reconstruction based on the energy deposition.

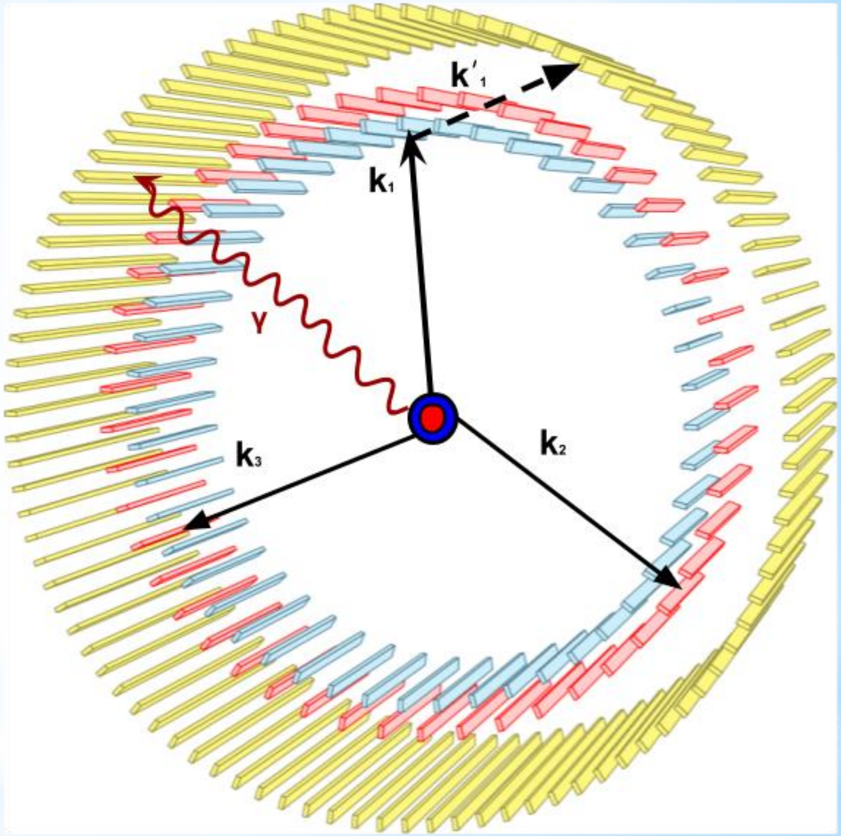
- Photon momentum reconstruction based on hit position and common vertex (with 4-momentum conservation).

- Photons polarisation (ansatz):

$$\vec{\varepsilon}_i = \vec{k}_i \times \vec{k}'_i$$

- Most probable angle between Compton scattering plane and the photon $\vec{E}$ vector $\eta \sim 90^o$

$$\frac{d\sigma}{d\Omega} \backsim \left(\frac{k_i'}{k_i}\right)^2 \left(\frac{k_i}{k_i'} + \frac{k_i'}{k_i} - 2\sin^2\theta\cos^2\eta\right)$$



- Background sources for the o-Ps $\rightarrow 3\gamma$ measurement:
  - $e^+e^- \rightarrow 2\gamma$ + scattering
  - void borders effects: pick-off annihilations or ortho-para conversion (7-36%)

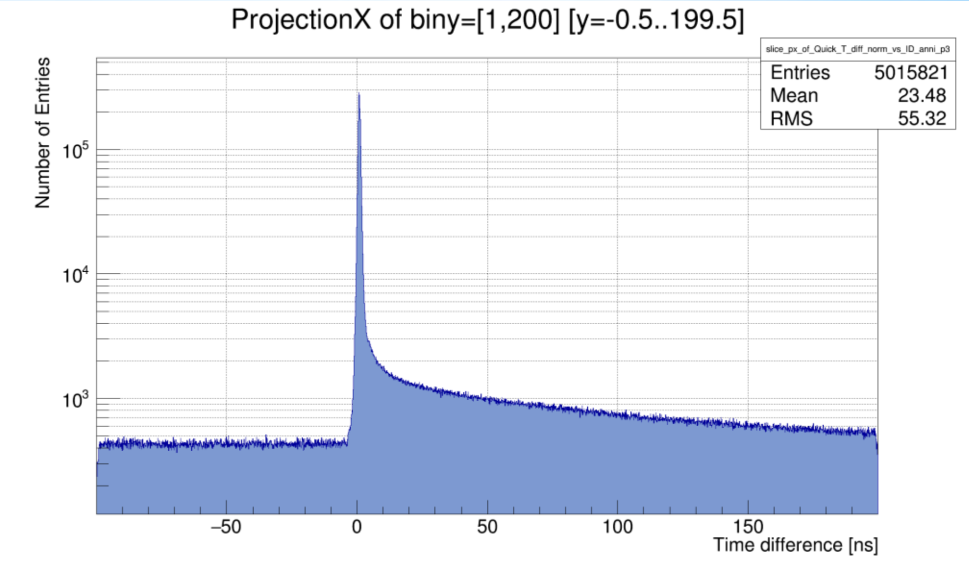
[P. Moskal et. al.,Acta Phys.Polon. B47 (2016) 509]

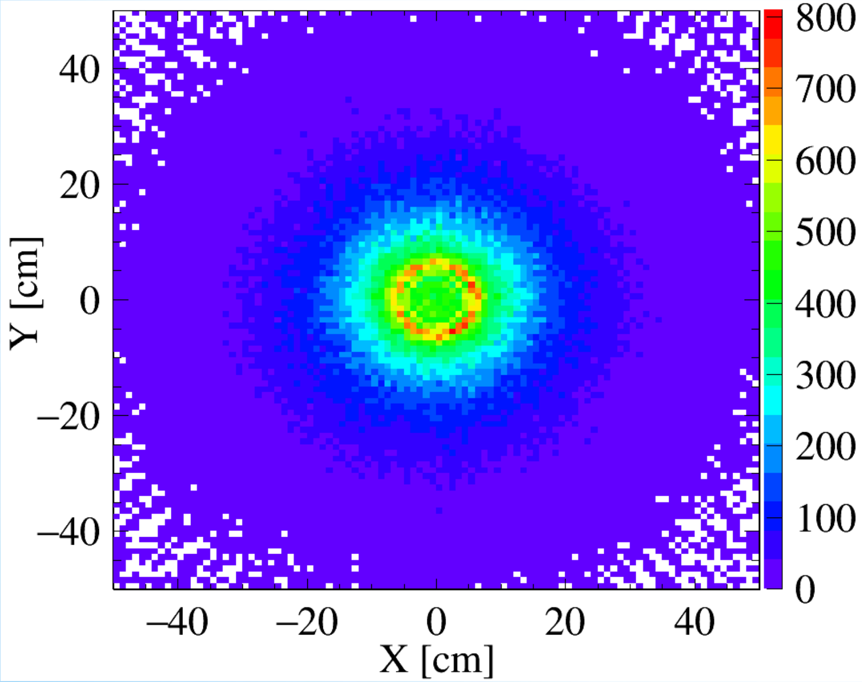

B
SIDE B
WARNING
KEEP HANDS OUT OF MACHINERY

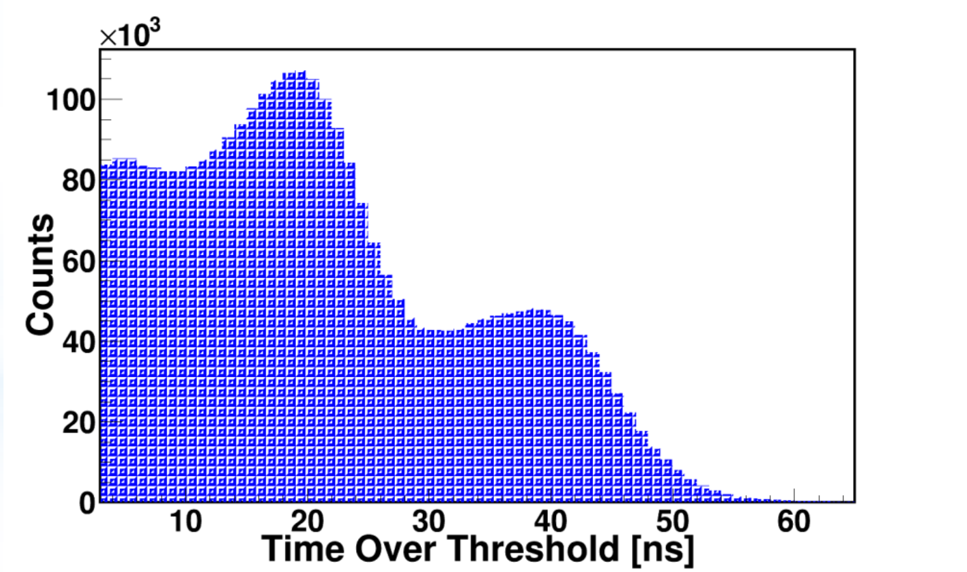
* Discrete symmetries tests with the J-PET detector

- ❖ FEE sampling signals at 4 thresholds on leading and trailing edge

- ❖ De-excitation gamma identification based on Time Over Threshold (TOT) measurement
  [S. Sharma poster]







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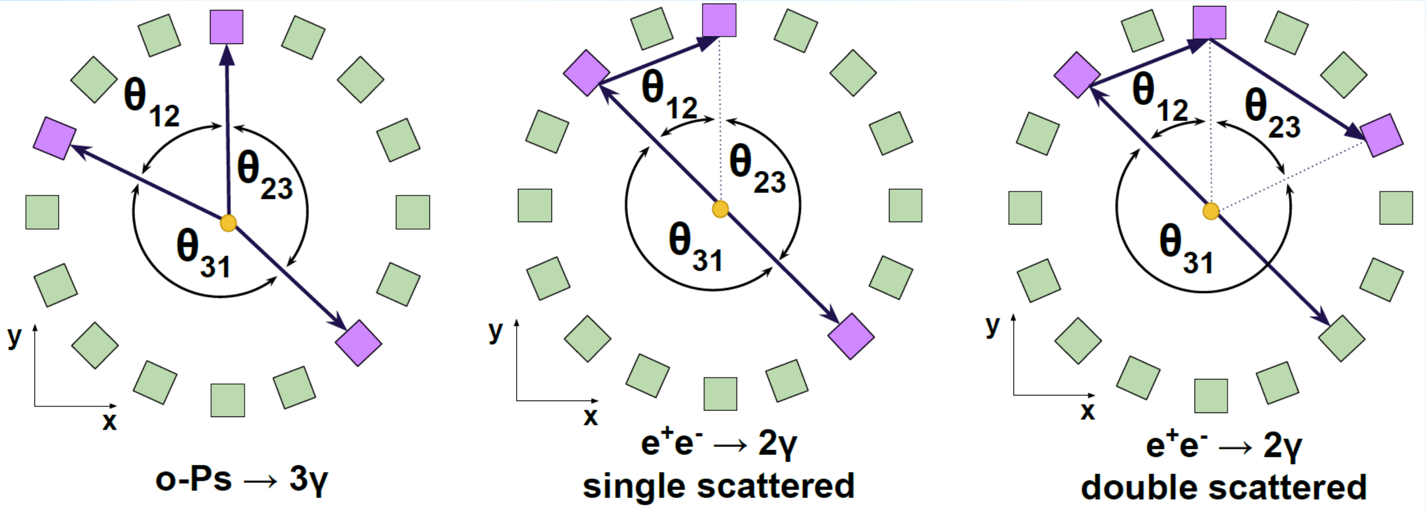
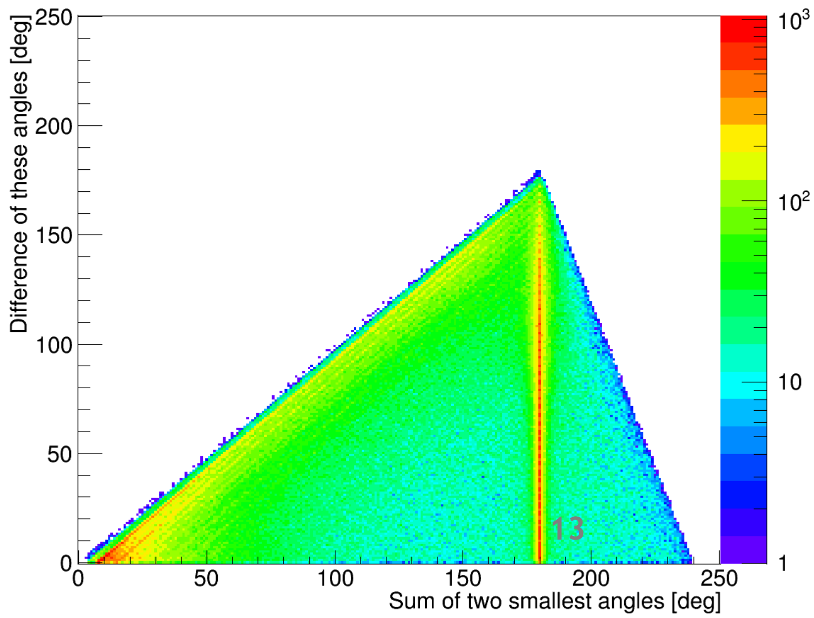
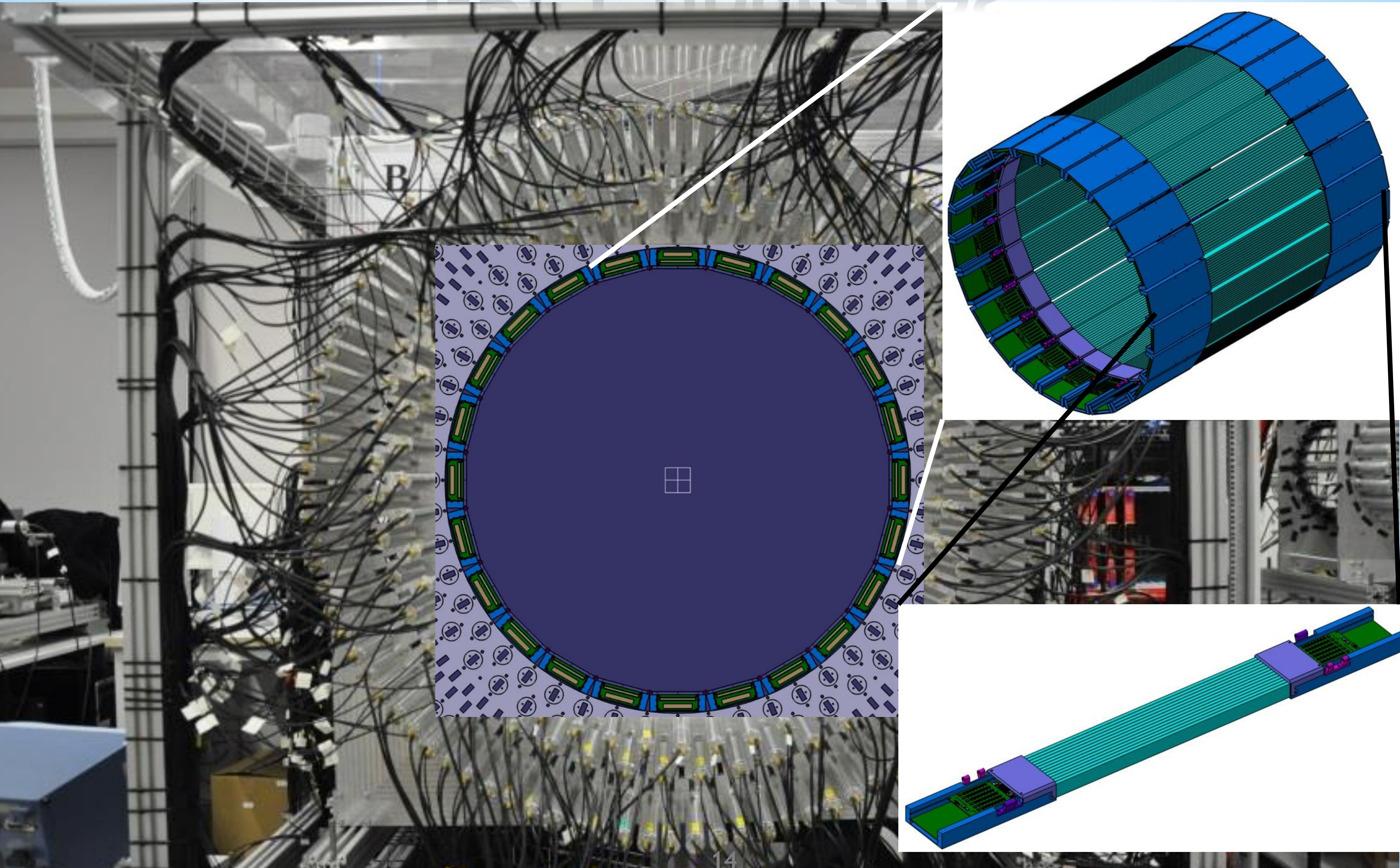


$\theta_{23} + \theta_{12} > 180$ $\theta_{23} + \theta_{12} = 180$ $\theta_{23} + \theta_{12} < 180$



J-PET upgrades



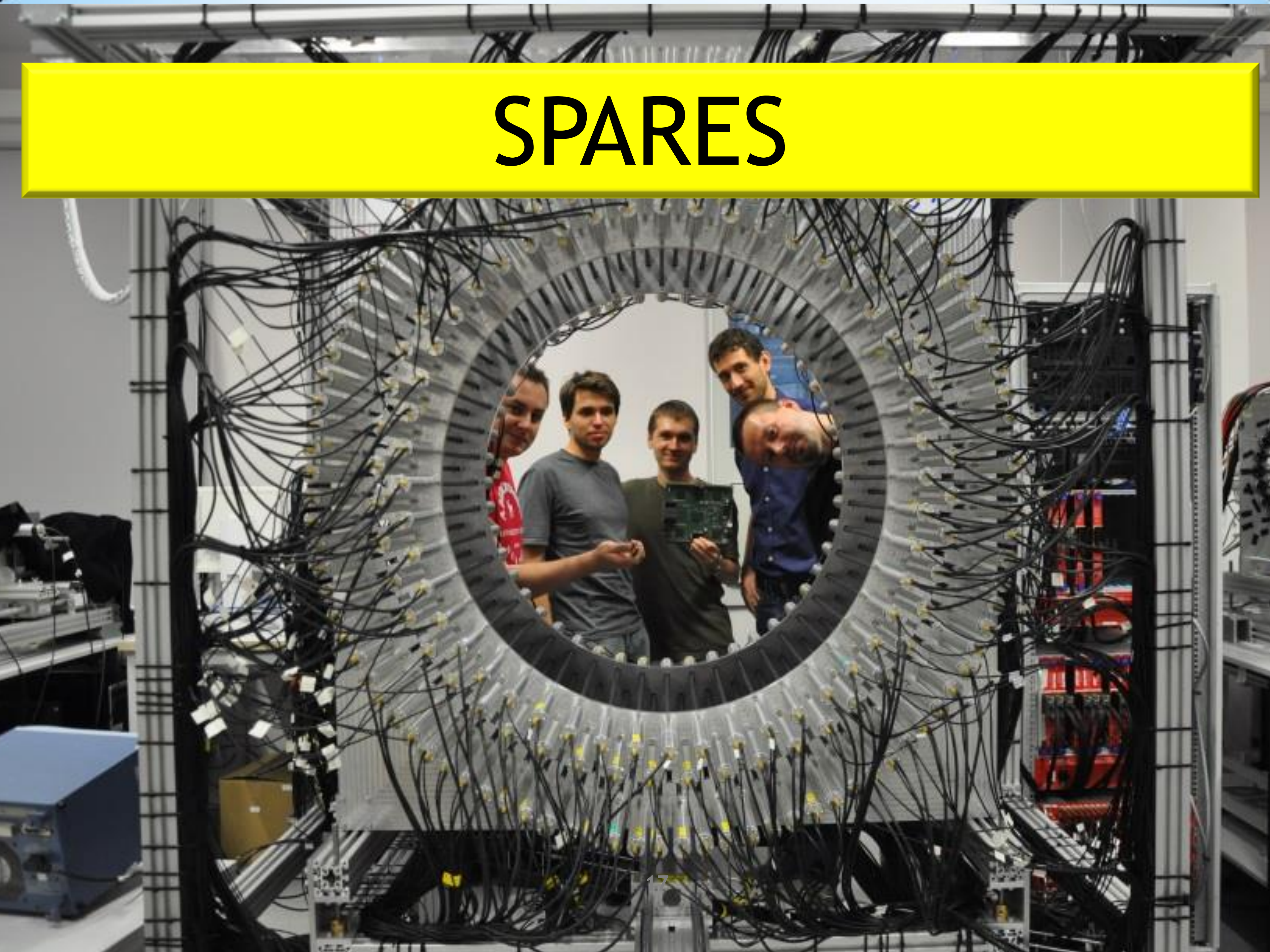
AFOV: 17 cm → 50 cm ; TOF < 500 ps

* Summary and outlook

- ❖ Discrete symmetries play a fundamental role in particle and nuclear physics.
- ❖ There is still substantial lack of experimental data on fundamental symmetries tests in the leptonic sector.
- ❖ The J-PET detector has a big potential to contribute in C, T, CP and CPT tests in the o-Ps decays at the level of 10^{-5}.
- ❖ The detector is under the commissioning and first tests measurements were done.
- ❖ Further detector upgrades are already under development
- ❖ With the J-PET detector we are sensitive to the CP violating effects at the level of 10^{-5}.

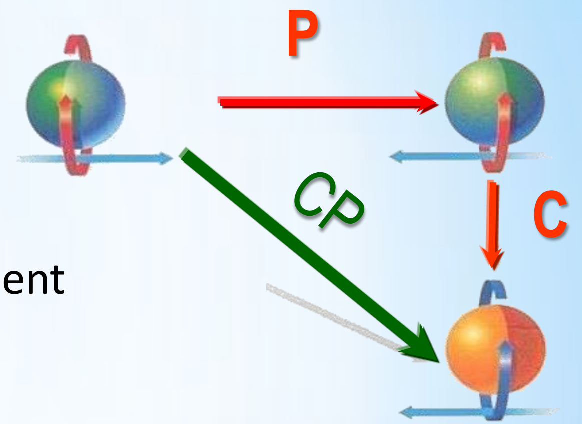
THANK YOU FOR ATTENTION

SPARES

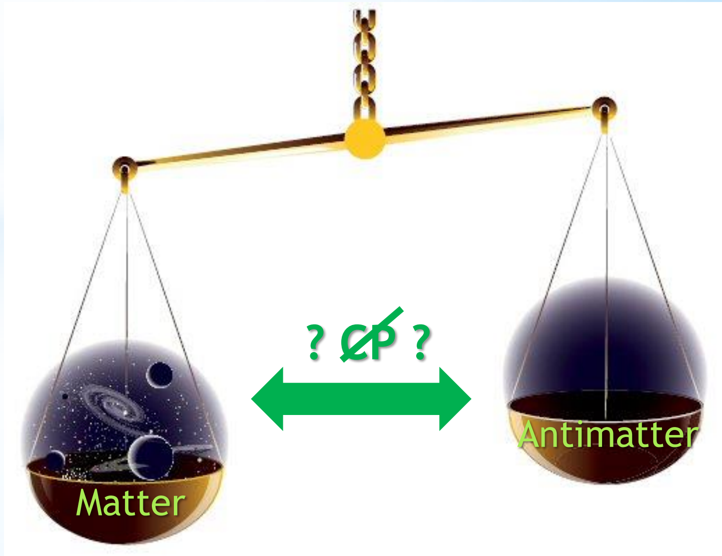


* Discrete symmetries in physics

- Parity transformation: P($\vec{x}$) = $-\vec{x}$
  - Not conserved by weak interactions (discovered in the $^{60}Co \rightarrow {}^{60}Ni\ e^{-}\bar{\nu}$ decay)



- Time reversal T: t→ -t
  - Violated by weak interactions (recent BaBar measurement in the B^0 meson system)
- Charge conjugation C: particle ↔ antiparticle
  - $C|\gamma> = -1|\gamma>$
  - Symmetry broken by weak interaction (discovered in the neutral kaon system)
- CP symmetry
  - Relevant in view of matter-antimater asymmetry
  - Broken in weak proesses
  - Strong **CP** problem



- CPT theorem: The combination CPT is always conserved in any local quantum field theory

TABLE 2.		JPET + START + NEW LAYER	Gammasphere [47]	CP-Tokyo [35]
Detector material		EJ-230 / BaF2	HPGe and BGO	LYSO
Time resolution (sigma)		**80 ps / 80 ps**	**4.6 ns**	**0.9 ns**
Reconstruction efficiency including registration of deexcitation γ(start)	p-Ps→2γ	$1.5 \cdot 10^{-3}$	$4 \cdot 10^{-2}$	—
	o-Ps→$\gamma\gamma\gamma_n$	$3 \cdot 10^{-4}$	$4 \cdot 10^{-2}$	$4 \cdot 10^{-4}$
	o-Ps→3γ	$6 \cdot 10^{-6}$	$5.7 \cdot 10^{-3}$	—
Reconstruction efficiency	p-Ps→γγ	10^{-2}	$\sim 4 \cdot 10^{-2}$	—
	o-Ps→3γ	$4 \cdot 10^{-5}$	$\sim 5.7 \cdot 10^{-3}$	—
Statistics of events (days of run)	p-Ps→2γ	$1.2 \cdot 10^{12}$ (~1000)*	—	—
	o-Ps→$\gamma\gamma\gamma_n$	2.4 10^{11} (~1000)*	—	~10^{7} (~180)
	o-Ps→3γ	5.0 10^{9} (~1000)*	$2.65 \cdot 10^{7}$ (~36)	—
Angular resolution (sigma)	polar	**~1°**	**~4°**	**~3.5°**
	azimuthal	**0.5°**	**~4°**	**~3.5°**
Polarization degree	tensor	~87%	—	~87%
	linear	~40%	less than 40%	—
Source activity		**10 MBq**	**0.04 MBq ^{22}Na or ^{68}Ge (limited by pile-ups)**	**1 MBq / ^{22}Na (limited by pile-ups)**
Available angular range		full range	full range	few fixed angles