Discrete symmetries tests in the 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

Workshop Quantum Foundations: New frontiers in testing quantum mechanics from underground to the space, Frascati, 01.12.2017

* Positronium as a probe for symmetries tests

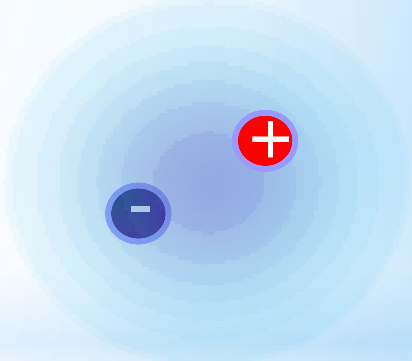
❖ Positronium:

- Eigenstate of the **CP** operator: e^+e^- state (**C** eigenstate) bound by a central potential (**P** eigenstate)
- The lightest purely leptonic object
- Effects due the weak interaction can lead to the violation at the order of 10^{-14}.
  M. Sozzi, Discrete Symmetries and CP Violation, Oxford Uviversity Press (2008)
- No charged particles in the final state (radiative corrections very small $2 * 10^{-10}$)

B. K. Arbic et al., Phys. Rev. A 37, 3189 (1988); W. Bernreuther et al., Z. Phys. C 41, 143 (1988).

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

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	-	-	+



❖ **C tests: search for decays to forbidden photons systems** (e.g. o-Ps → 4γ, p-Ps → 3γ):

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

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 ($\overrightarrow{k_i}$) or polarization ($\vec{\varepsilon}_i$)
- There is no experimental data for most of the operators

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

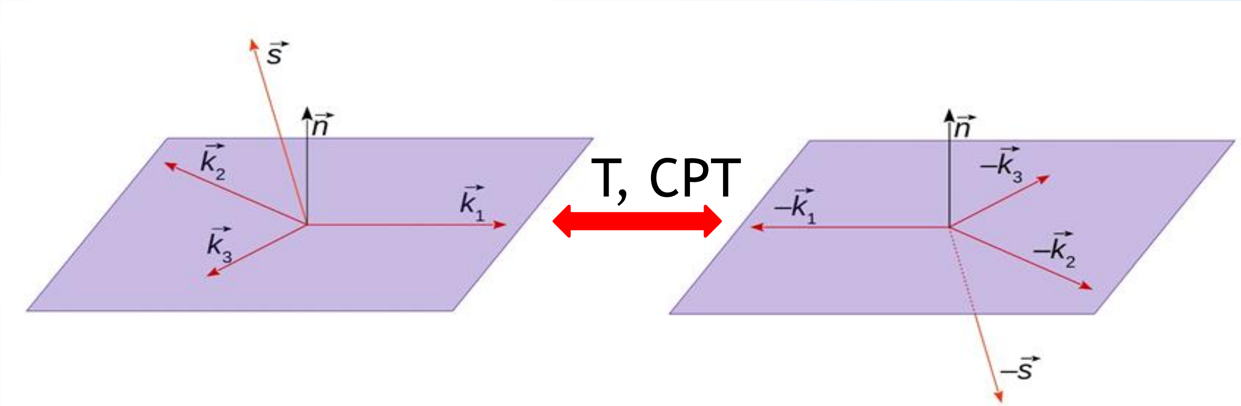
P.A. Vetter, S.J. Freedman, Phys. Rev. Lett. 91, 263401 (2003).

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

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

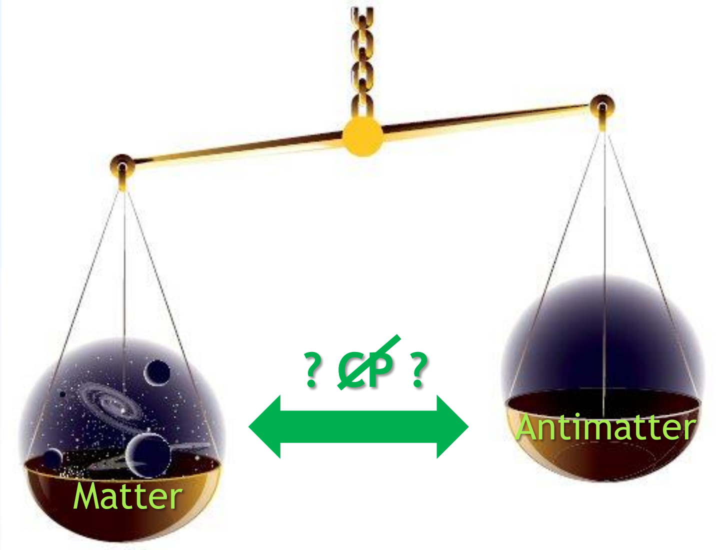
P. Moskal et. al.,Acta Phys.Polon. B47 (2016) 509

- CP/CPTV SM predicion~ 10^{-10} – 10^{-9} (photon-photon interactions)



* Tests of the CP symmetry with positronium

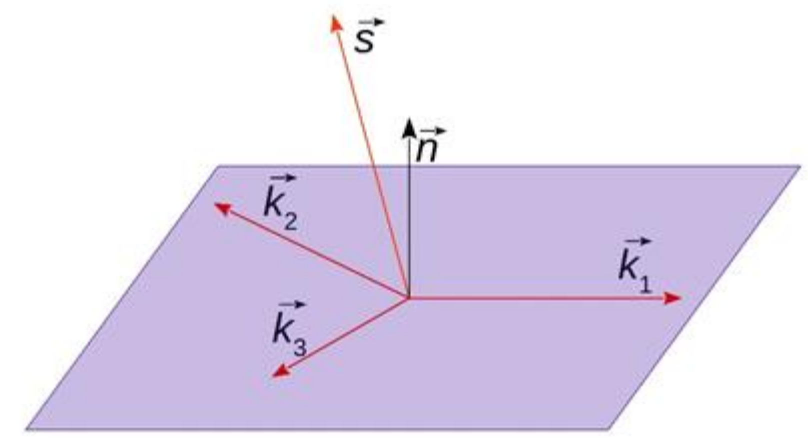
- New sources of **CP** violation needed to explain the matter-antimatter asymmetry



- 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:

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

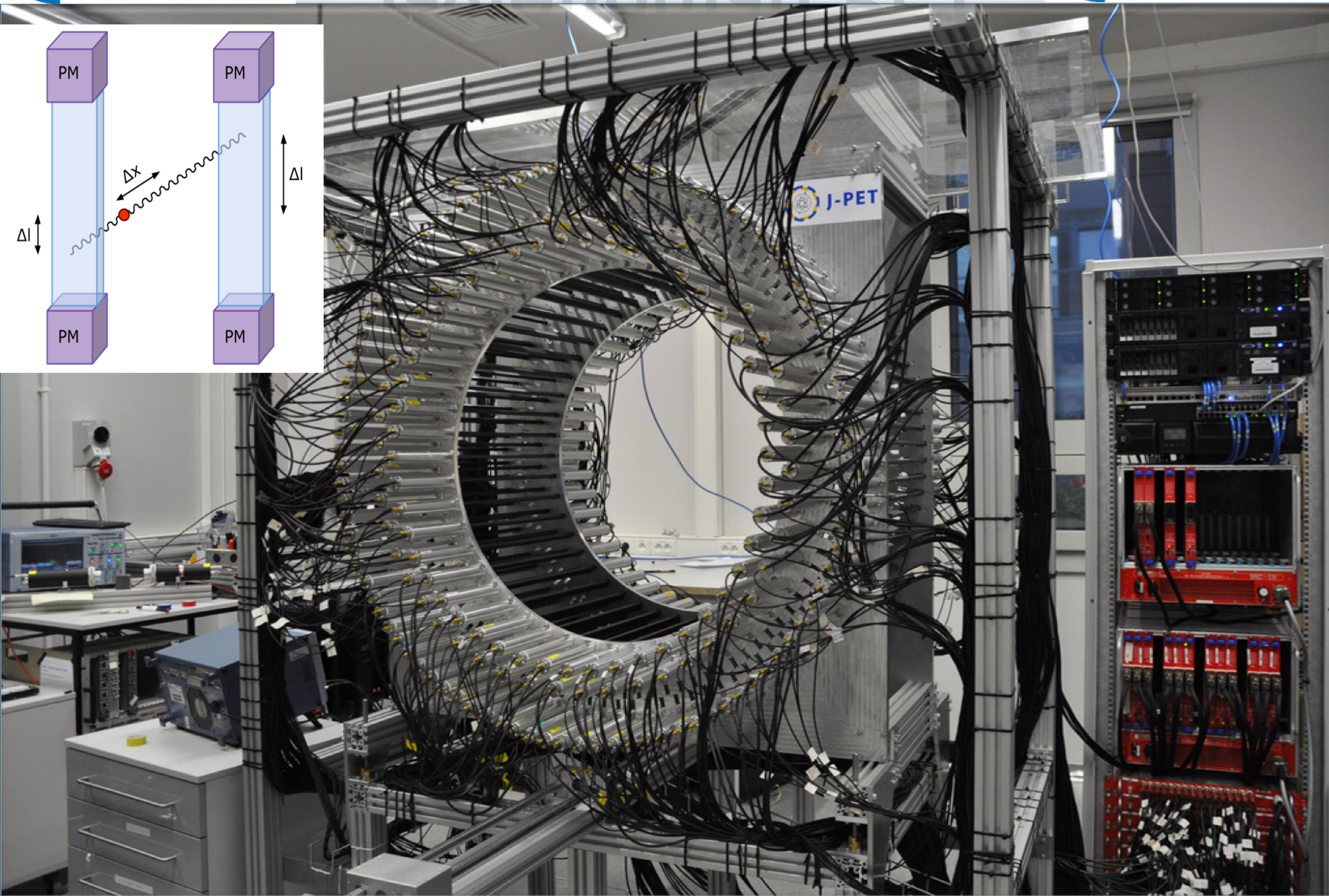


- The best limit of the CP non-invariance in the positronium decays:

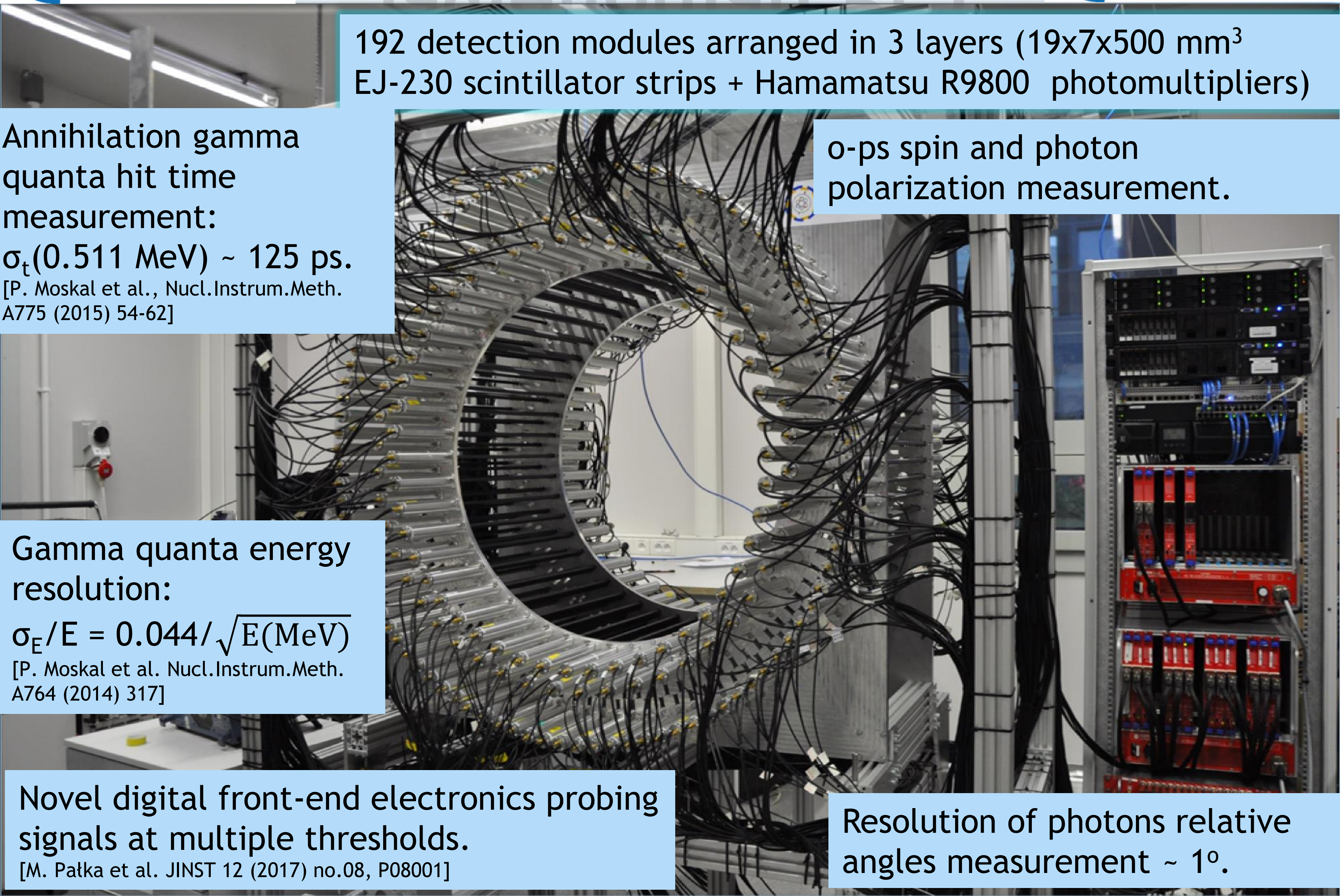
$$\left\langle \left(\vec{S} \cdot \vec{k}_1\right)\left(\vec{S} \cdot \left(\vec{k}_1 \times \vec{k}_2\right)\right) \right\rangle < 4.9 \cdot 10^{-3} \text{ at 90\% C.L.}$$

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

Jagiellonian PET



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 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]

Resolution of photons relative angles measurement ~ 1^o.

* CP symmetry tests with the J-PET detector

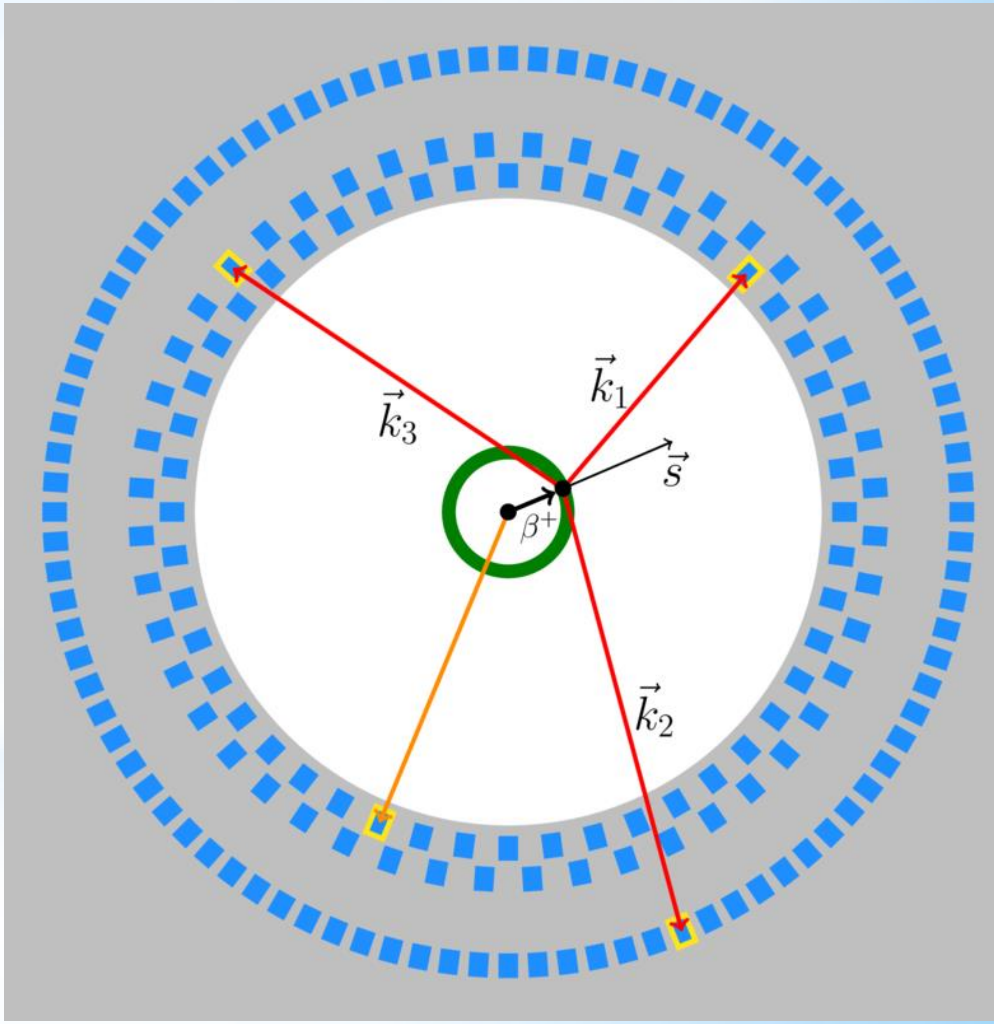
$$^{22}Na \rightarrow {}^{22}Ne^* + e^+ + \nu_e$$

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

- **Positrons source:**
  ^{22}Na β^+ decay (parity violation)
- **Target around the source**
  - e^+ thermalization + o-Ps formation
  - made of a porous material (aerogel IC3100/XAD-4 polymer)
- 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



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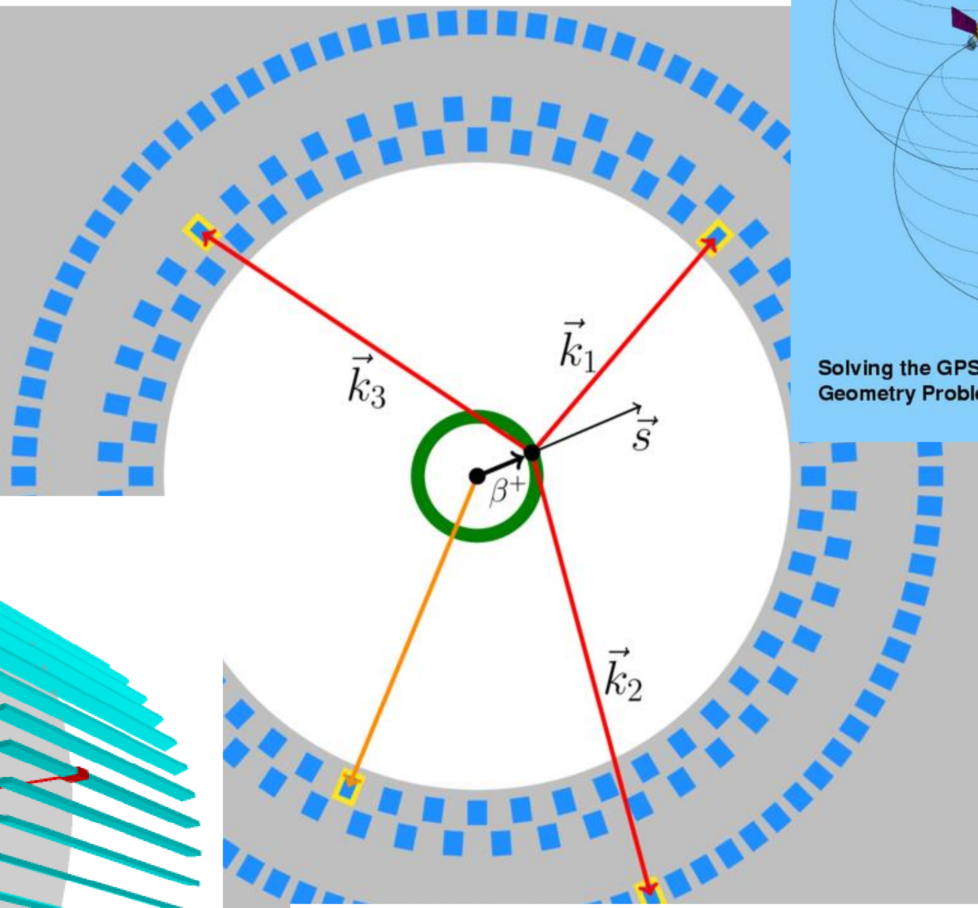
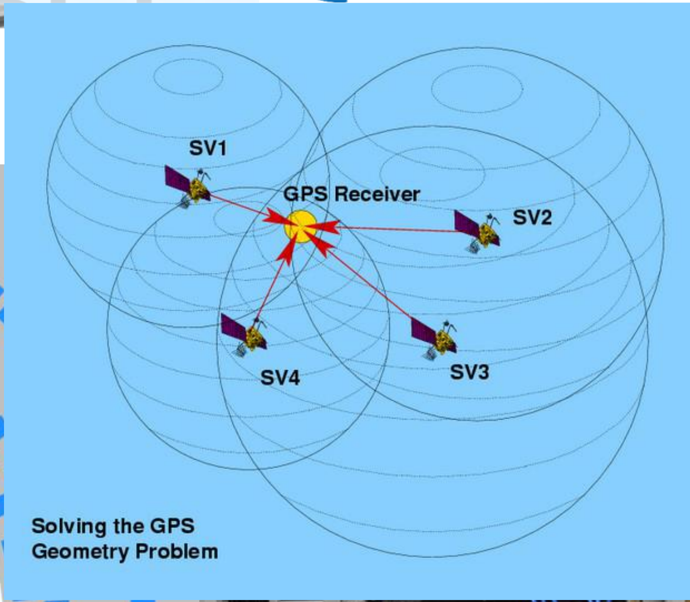
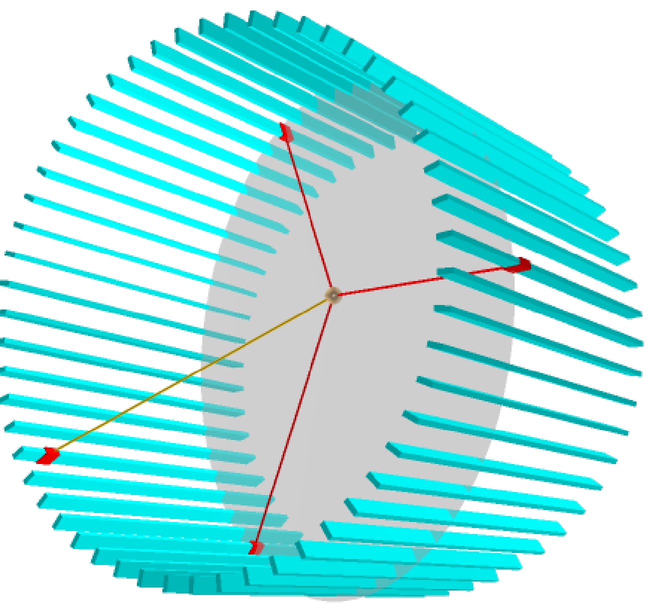
Jagiellonian PET

❖ 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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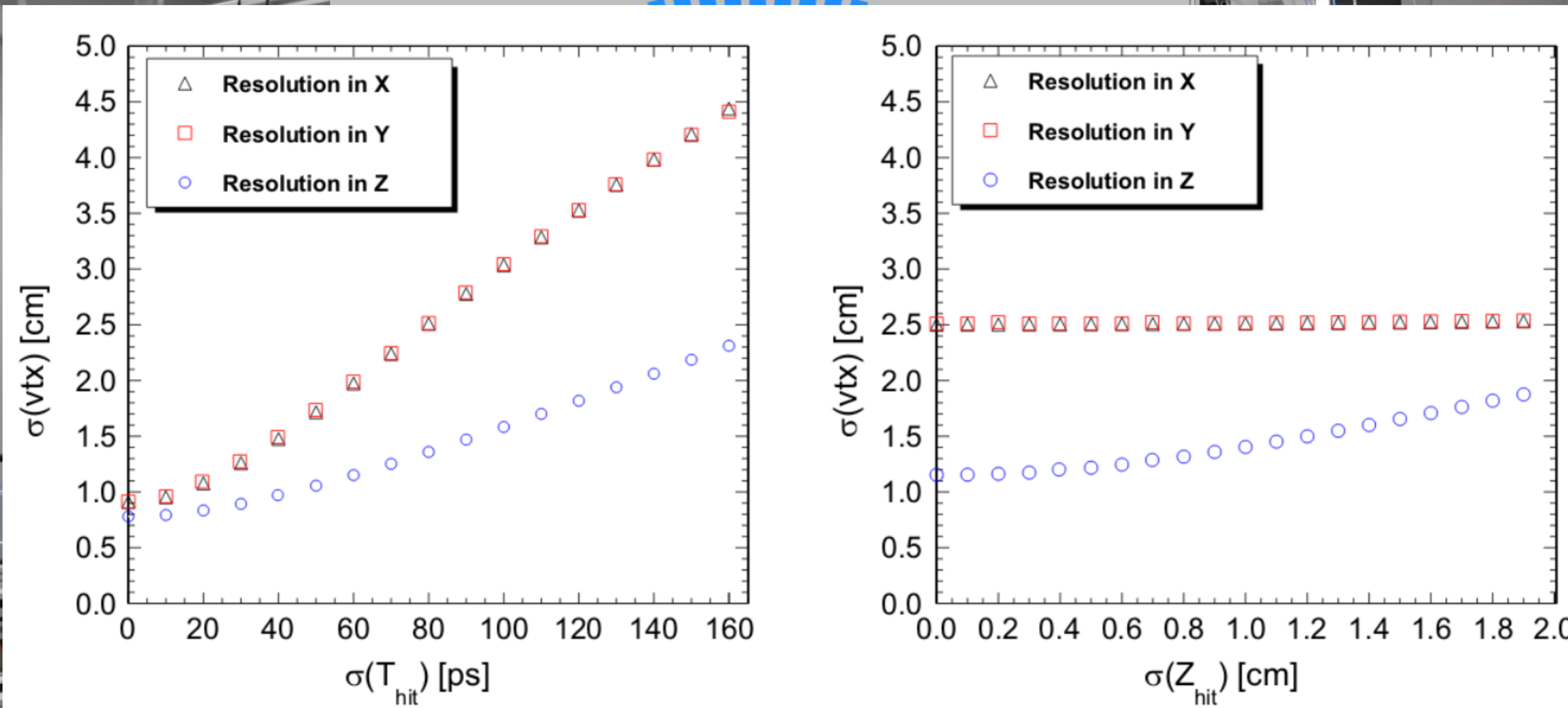

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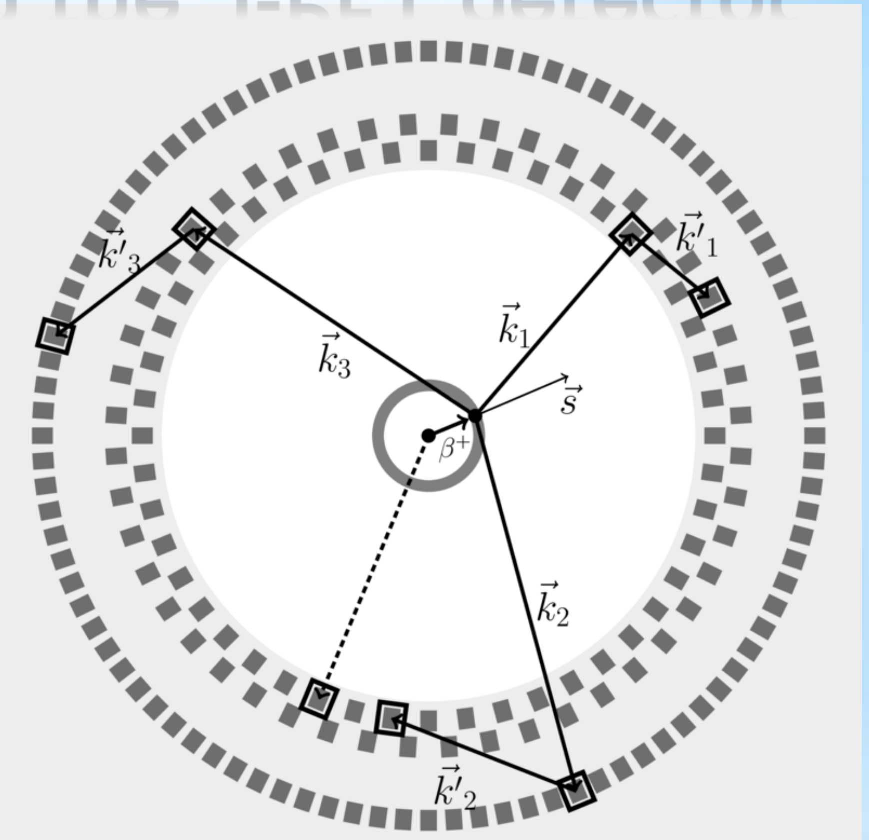
* CP symmetry tests with the J-PET detector

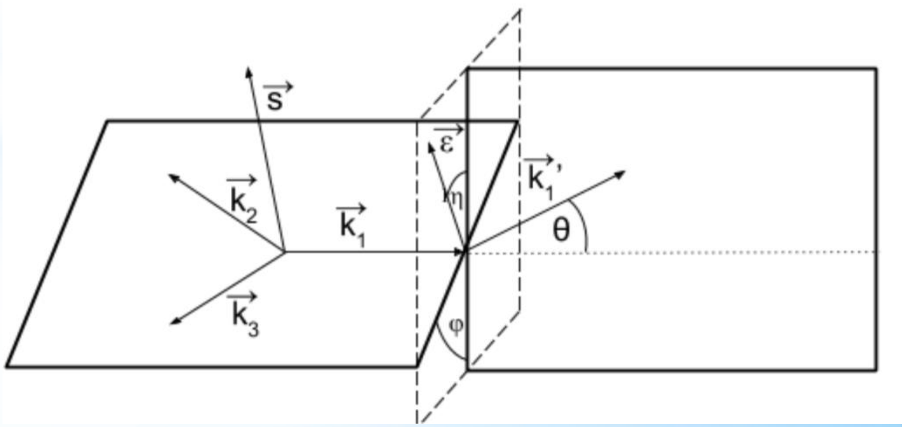
- De-excitation photon reconstruction based on the energy deposition.
- Photon momentum reconstruction based on hit position and common vertex (with 4-momentum conservation).
- Photons polarisation (ansatz):

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

- Most probable angle between Compton scattering plane and the photon $\vec{E}$ vector η ~ 90°

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





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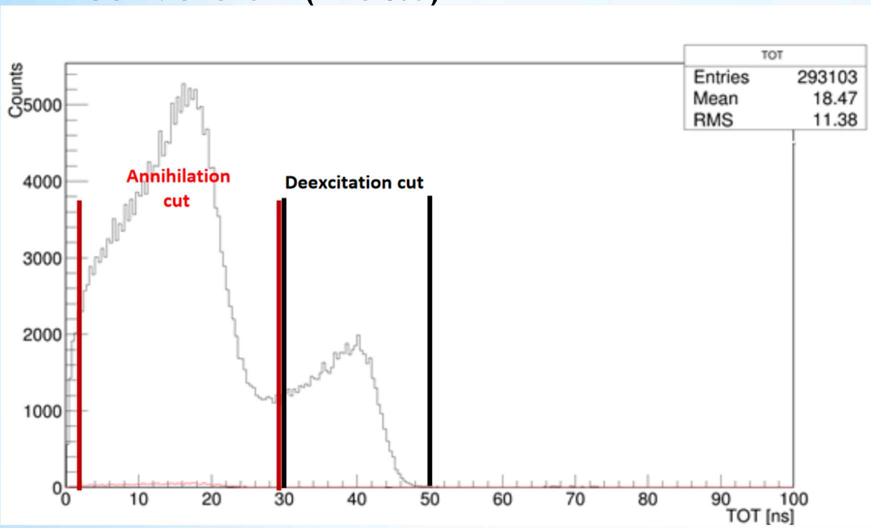
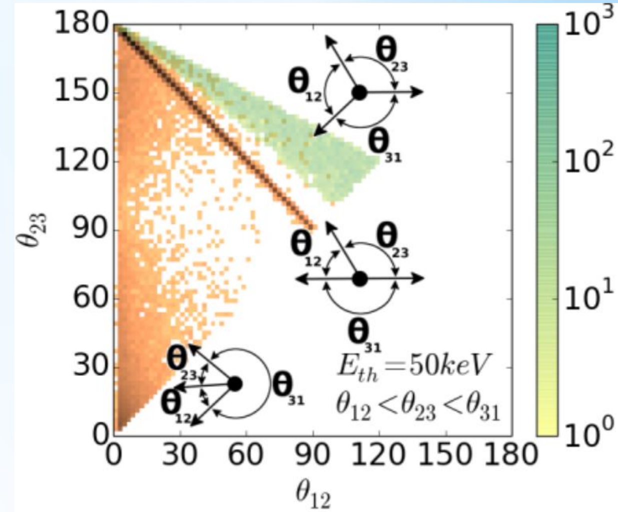
* CP symmetry tests with the J-PET detector

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





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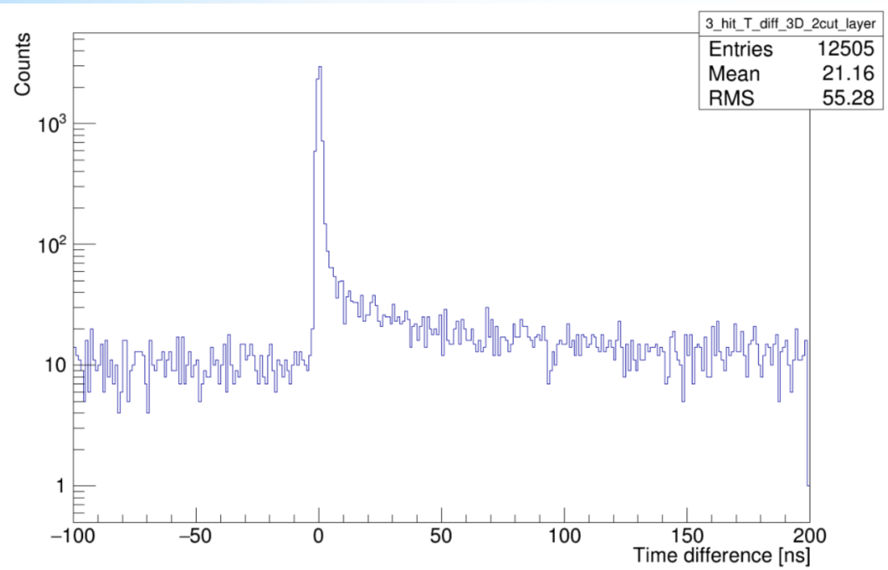
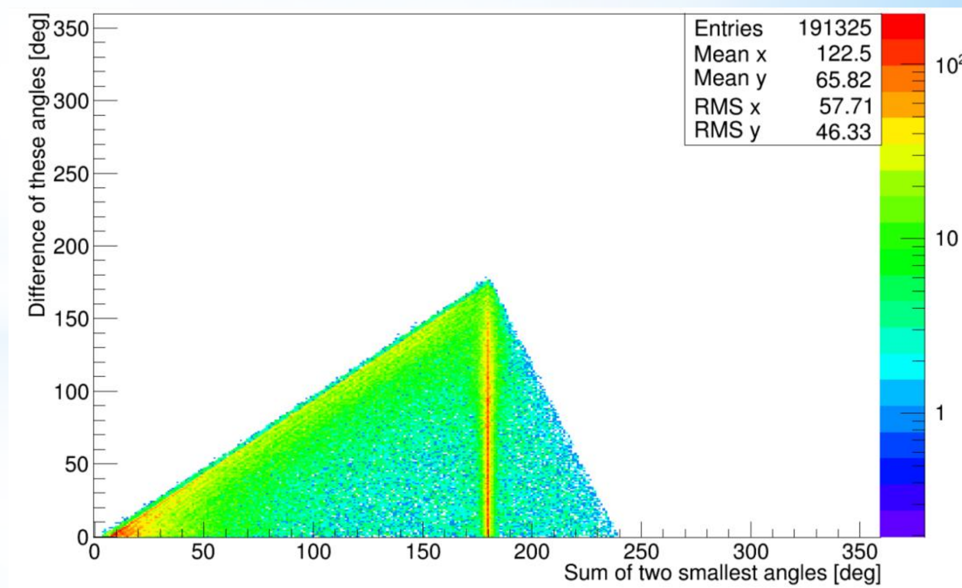
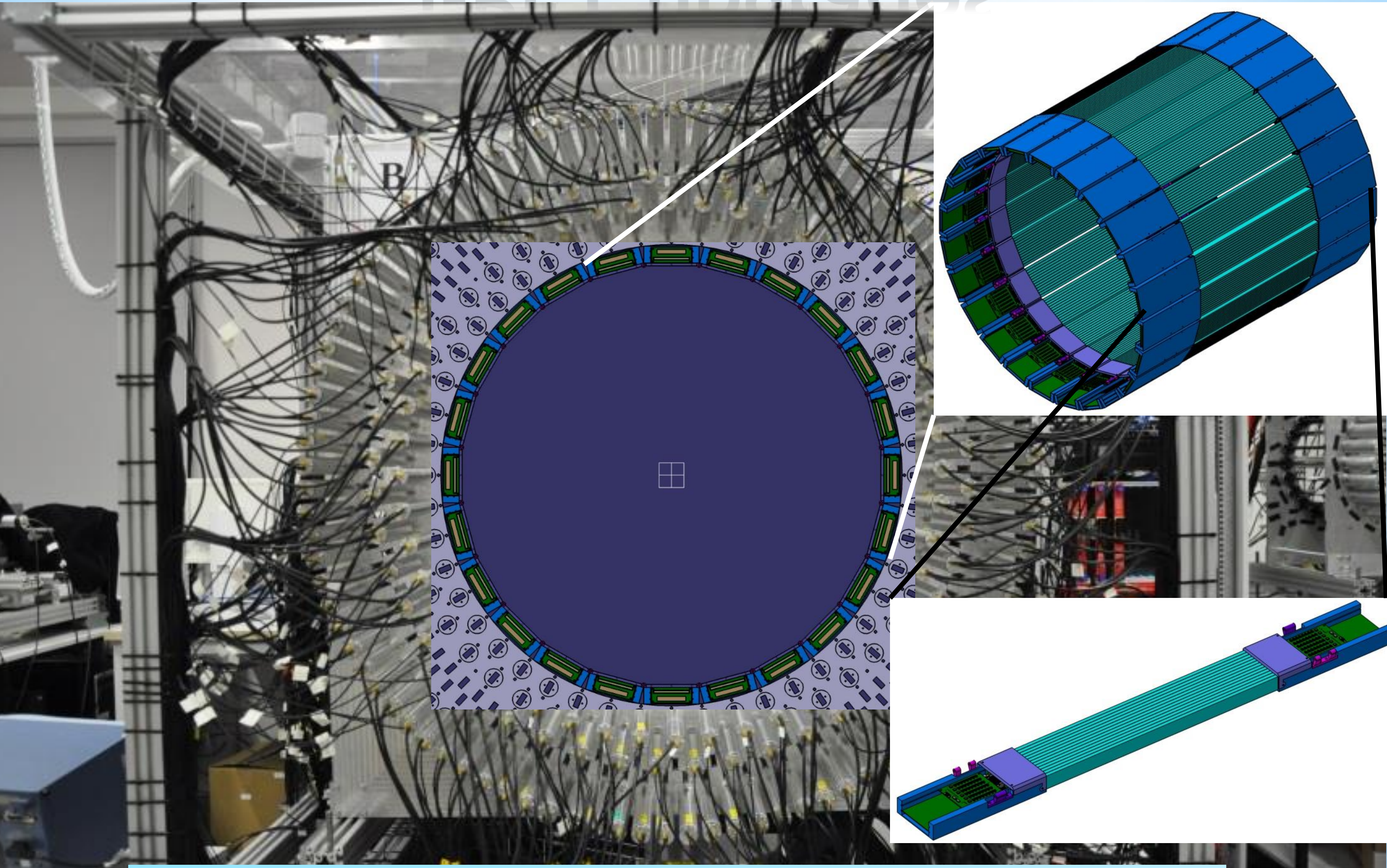




J-PET upgrades



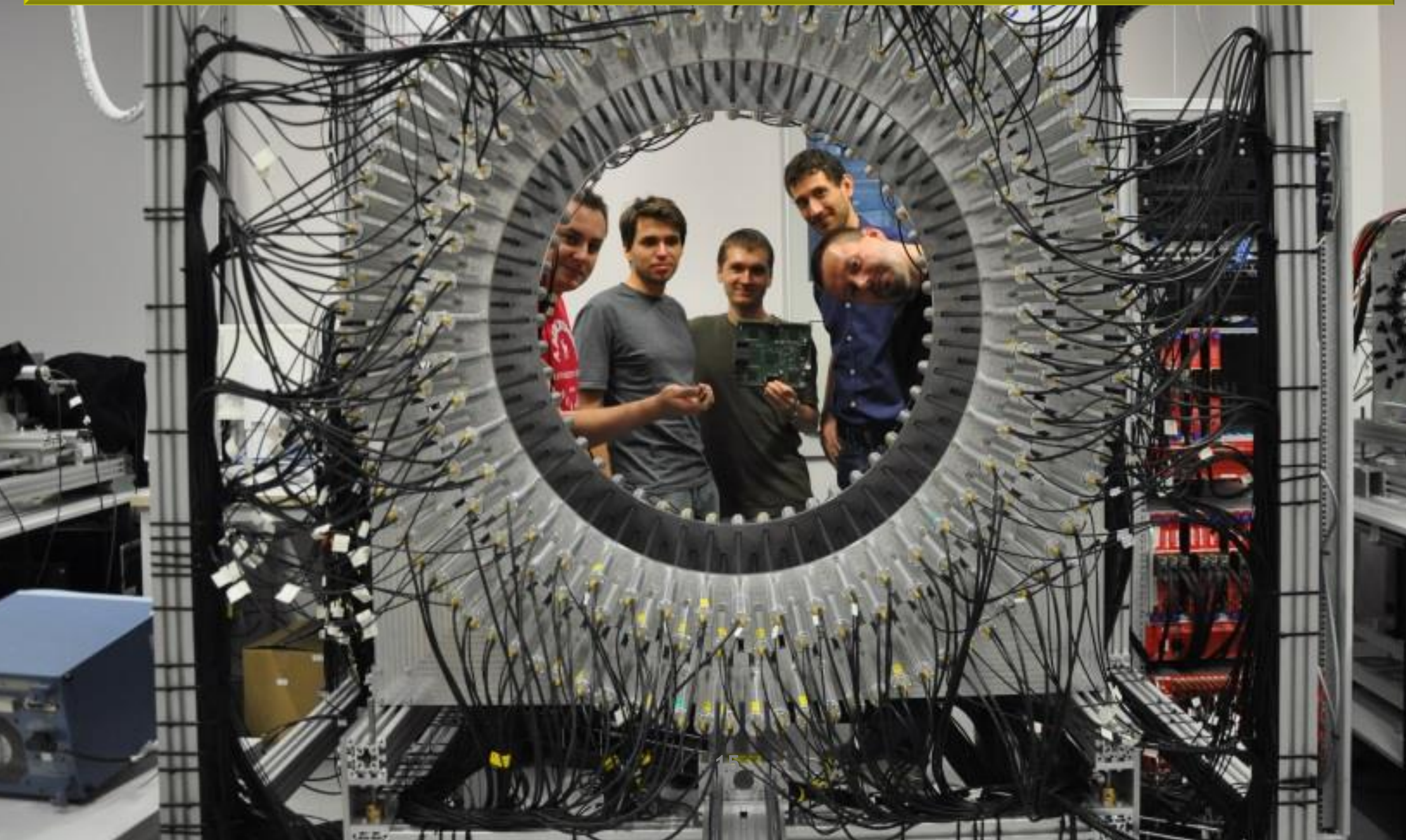
AFOV: 17 cm → 50 cm ;   TOF < 500 ps

* 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}.**

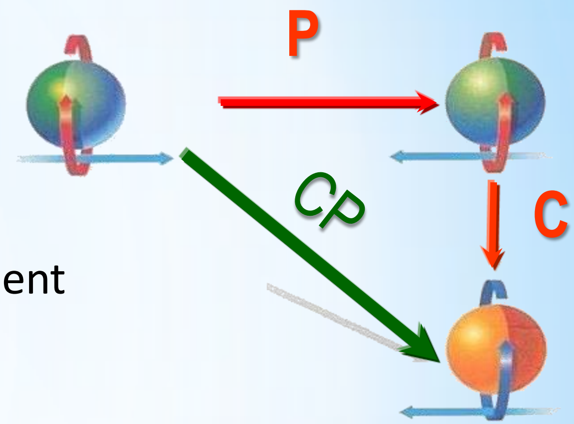
THANK YOU FOR ATTENTION

SPARES



* Discrete symmetries in physics

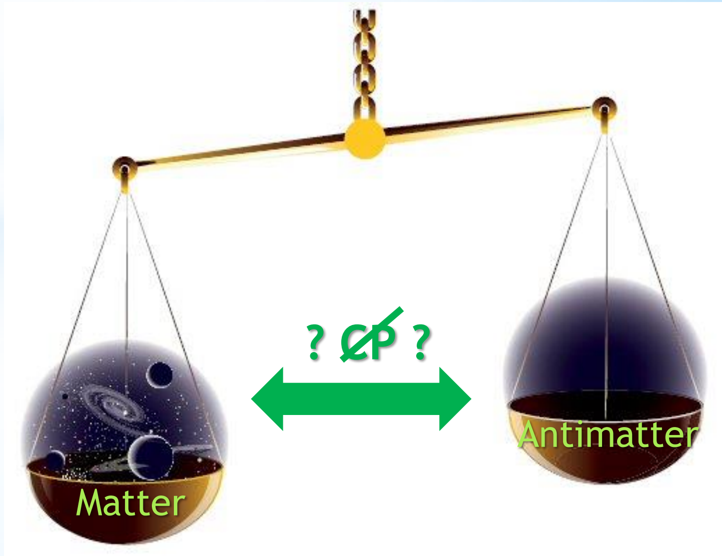
- Parity transformation: $P(\vec{x}) = -\vec{x}$
  - Not conserved by weak interactions (discovered in the $^{60}Co \rightarrow {}^{60}Ni\ e^{-}\bar{\nu}$ decay)



- 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→γγγ$_n$	$3 \cdot 10^{-4}$	$4 \cdot 10^{-2}$	$4 \cdot 10^{-4}$
	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→γγγ$_n$	2.4 10^{11} (~1000)*	—	$\sim 10^{7}$ (~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