# Testing the CPT symmetry in ortho-positronium annihilations with J-PET

Workshop: Investigating the Universe
with exotic atomic and nuclear matter

Frascati, 29.09.2020

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Jagiellonian University

J-PET

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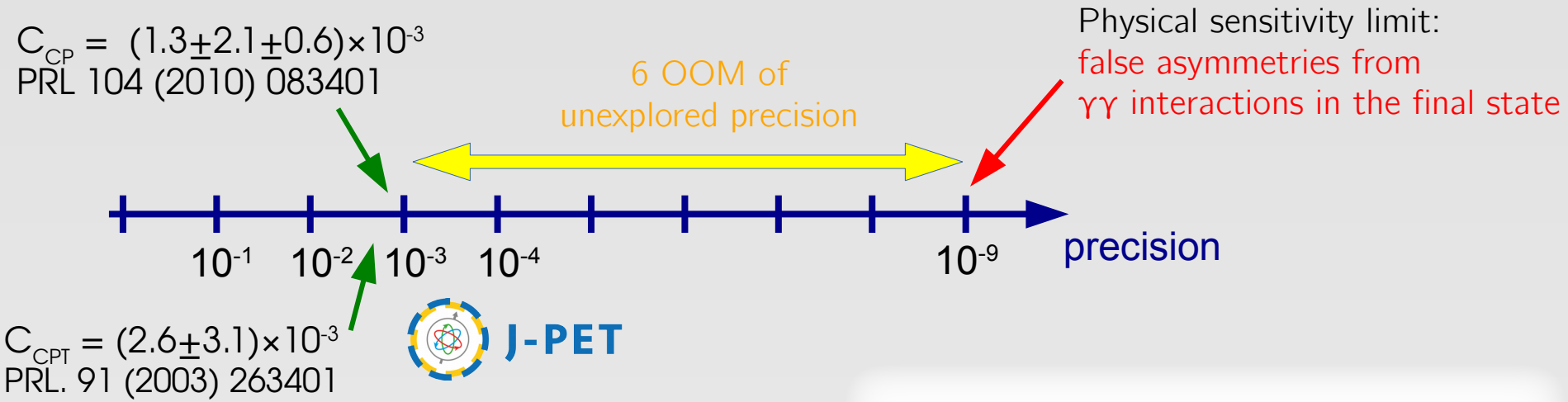
European Union European Regional Development Fund

# Motivation: discrete symetry tests with o-Ps → 3γ decays

**Discrete symmetries are scarcely tested in the leptonic sector!**

- Positronium – the only system consisting of charged leptons used for tests of CP and CPT to date




- The prominent alternative in the leptonic sector to date is **neutrinos**
- CP-violation results (Dirac phase, $\delta_{CP}$) approaching 5σ level (NovA, T2K II, JUNO)
- Can we test discrete symmetries in leptonic systems with smaller-scale experiments?

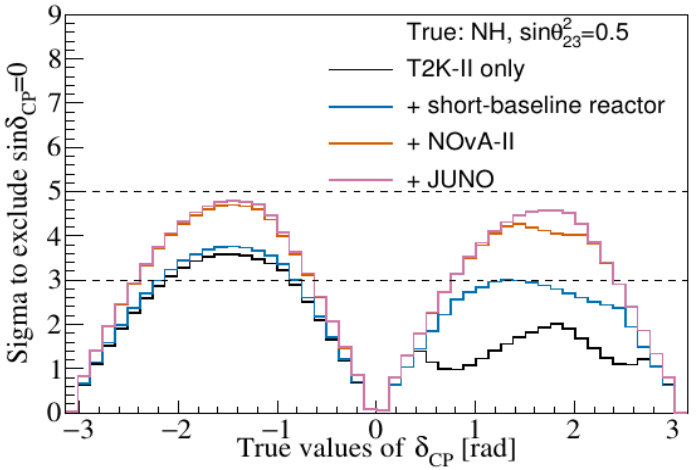
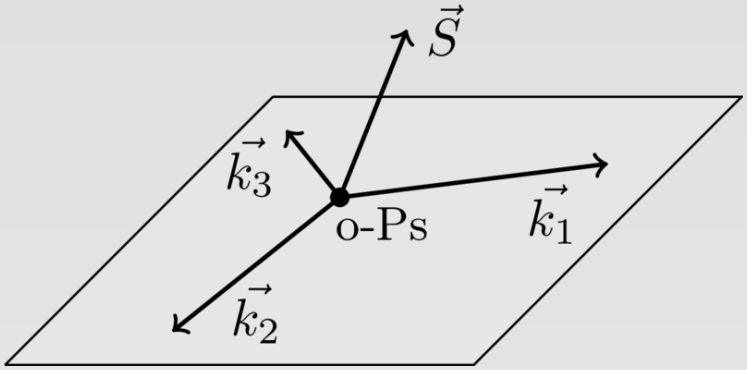



Figure from: arXiv:2009.08585]

# Testing discrete symmetries with angular correlations in o-Ps $\rightarrow 3\gamma$ decays

$$e^+e^- \rightarrow \text{o-Ps} \rightarrow 3\gamma$$

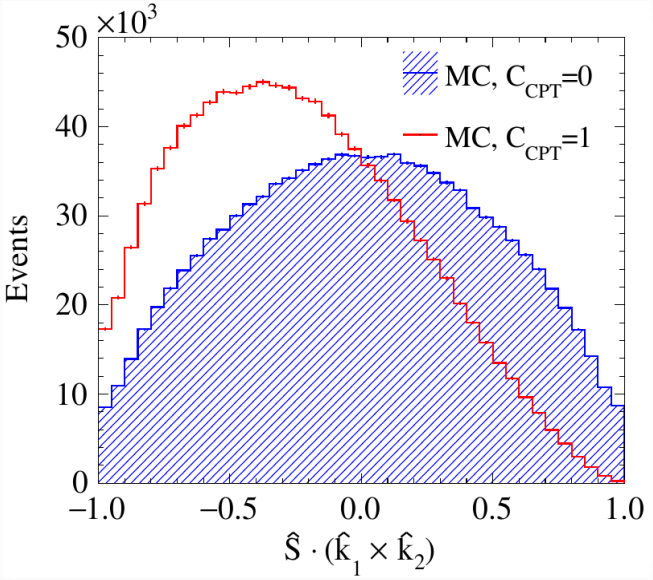



$$|\vec{k_1}| > |\vec{k_2}| > |\vec{k_3}|$$

**The method:**

$$\left\langle \hat{O} \right\rangle \stackrel{?}{=} 0$$

for an odd operator




Using ortho-positronium spin
Requires either:

- polarization
- spin control
- spin estimation

Using photon polarization
(covered in a talk of J. Raj)

| operator | C | P | T | CP | CPT |
|---|---|---|---|---|---|
| $\vec{S} \cdot \vec{k_1}$ | + | − | + | − | − |
| $\vec{S} \cdot (\vec{k_1} \times \vec{k_2})$ | + | + | − | + | − |
| $(\vec{S} \cdot \vec{k_1})(\vec{S} \cdot (\vec{k_1} \times \vec{k_2}))$ | + | − | − | − | + |
| $\vec{k_2} \cdot \vec{\epsilon}_1$ | + | − | − | − | + |
| $\vec{S} \cdot \vec{\epsilon}_1$ | + | + | − | + | − |
| $\vec{S} \cdot (\vec{k_2} \times \vec{\epsilon}_1)$ | + | − | + | − | − |

[ W. Bernreuther *et al., Z. Phys. C41 (1988) 143* ]

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

# o-Ps $\longrightarrow$ 3$\gamma$ operators involving spin

**Presently studied with J-PET:**

$\vec{S} \cdot (\vec{k_1} \times \vec{k_2})$ T & CPT-violation sensitive

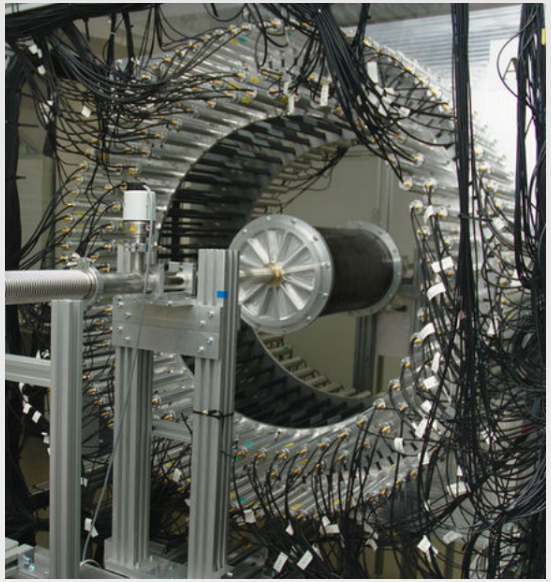
$\vec{S} \cdot \vec{k_1}$ CP-violation sensitive

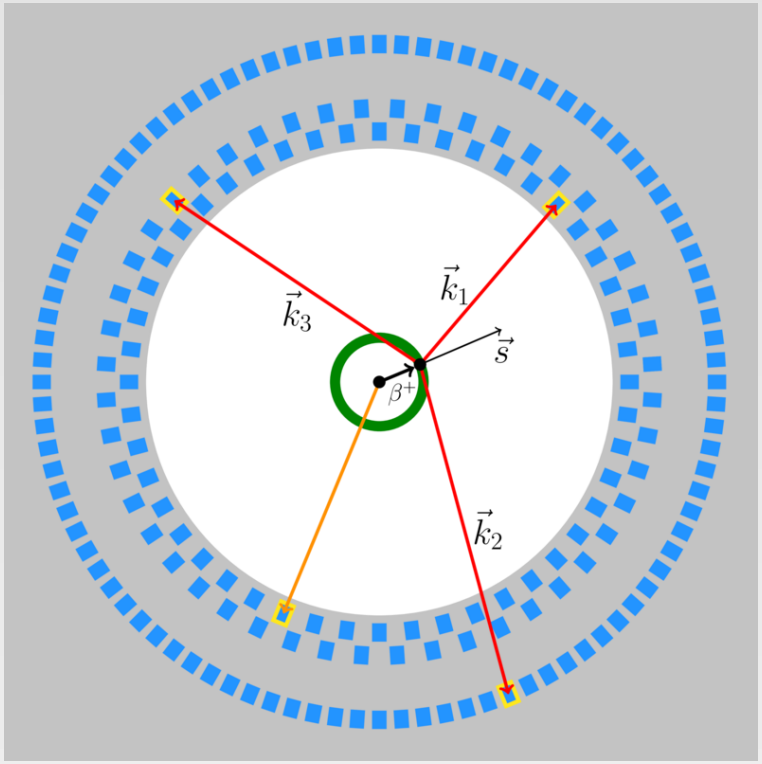
$(\vec{S} \cdot \vec{k_1})(\vec{S} \cdot (\vec{k_1} \times \vec{k_2}))$

T & CP-violation sensitive but requires o-Ps tensor polarization $\rightarrow$ not available with the current J-PET approach

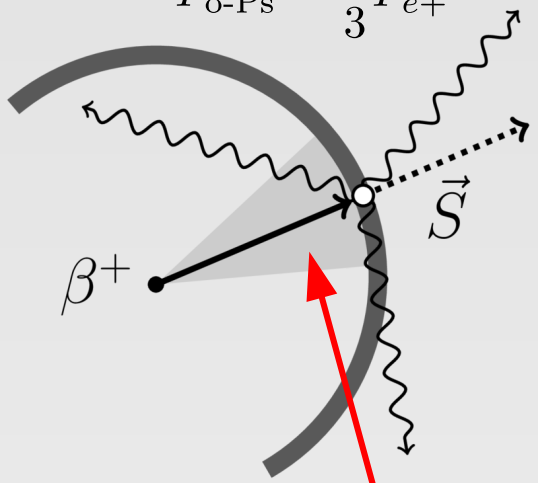
**Event-by-event spin estimation**

Using an extensive-size o-Ps production and annihilation medium





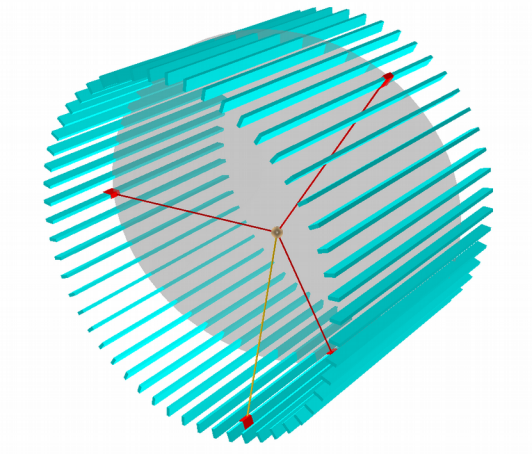

$$P_{\text{o-Ps}} = \frac{2}{3} P_{e+}$$



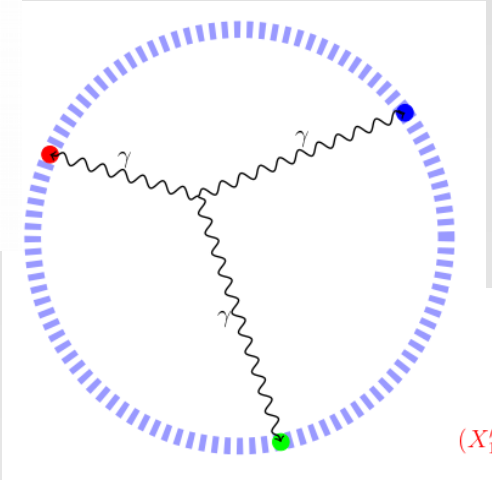

$$P_{e+} \approx \frac{v}{c} \cdot \frac{1}{2}(\cos\alpha + 1)$$

Effective polarization depends on o-Ps$\rightarrow$3$\gamma$ vertex resolution

# Reconstruction of o-Ps→3γ decays in J-PET

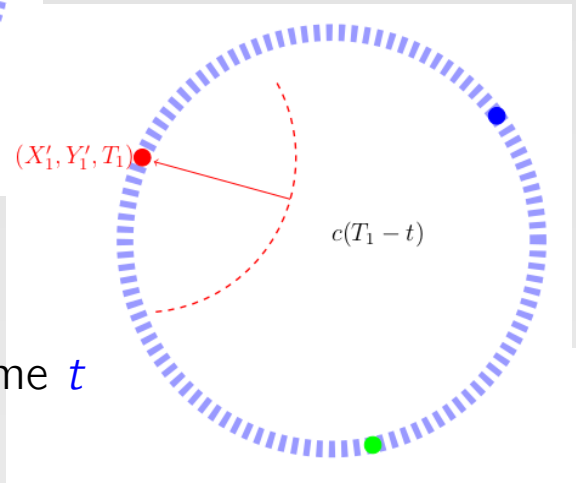


1. Find the decay plane containing the 3 hits in the J-PET barrel

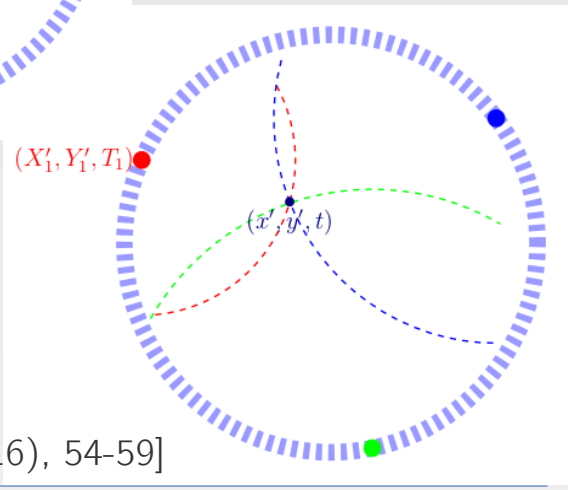



2. Transform the hit coordinates to a 2D coordinate system in the decay plane

$$(X_i, Y_i, Z_i, T_i) \rightarrow (X'_i, Y'_i, 0, T_i)$$




3. For each of the recorded γ hits, define a circle of possible origin points of the incident γ assuming o-Ps decay at time $t$




4. The decay point (x',y') in the decay plane and time t is an intersection of 3 such circles:

$$(T_i - t)^2 c^2 = (X'_i - x')^2 + (Y'_i - y')^2, \quad i = 1, 2, 3$$

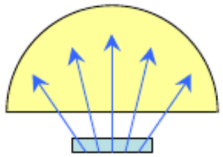
[A. Gajos et al., NIM A 819 (2016), 54-59]

# J-PET vs previous measurements

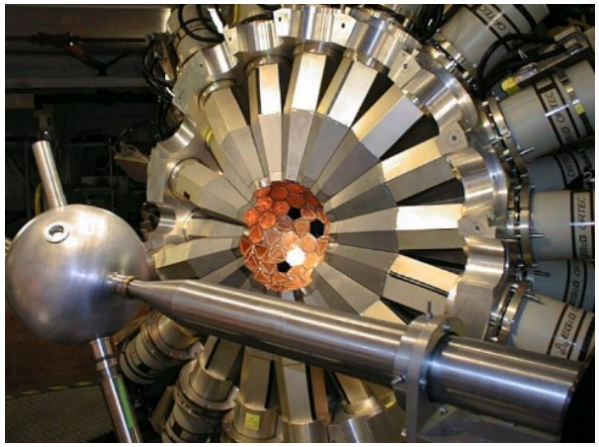
**Gammasphere**
PRL. 91 (2003) 263401

$C_{CPT} = (2.6 \pm 3.1) \times 10^{-3}$

$$\vec{S} \cdot (\vec{k_1} \times \vec{k_2})$$



$$P_{e+} = \frac{v}{c} \cdot 0.686$$

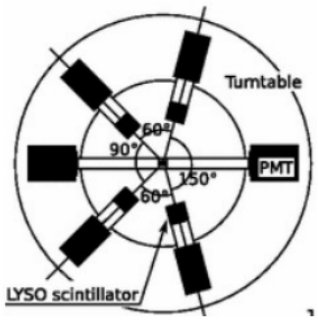


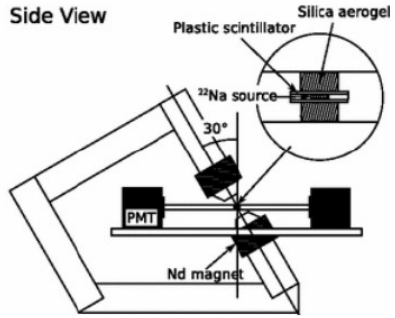
Limiting positron emission direction
1 Mbq $\beta^+$ emitter activity
4π detector but low angular resolution

**Yamazaki et al.**
PRL 104 (2010) 083401

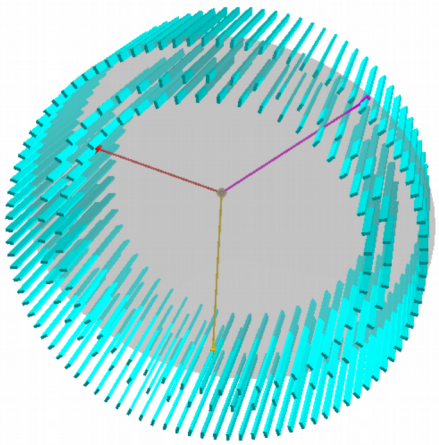
$$(\vec{S} \cdot \vec{k_1})(\vec{S} \cdot (\vec{k_1} \times \vec{k_2}))$$

$C_{CP} = (1.3 \pm 2.1 \pm 0.6) \times 10^{-3}$




Polarized o-Ps using external B field
Inclusive measurement
Only certain angular configurations



J-PET

Recording multiple geometrical configurations

e+ spin estimated event-by-event

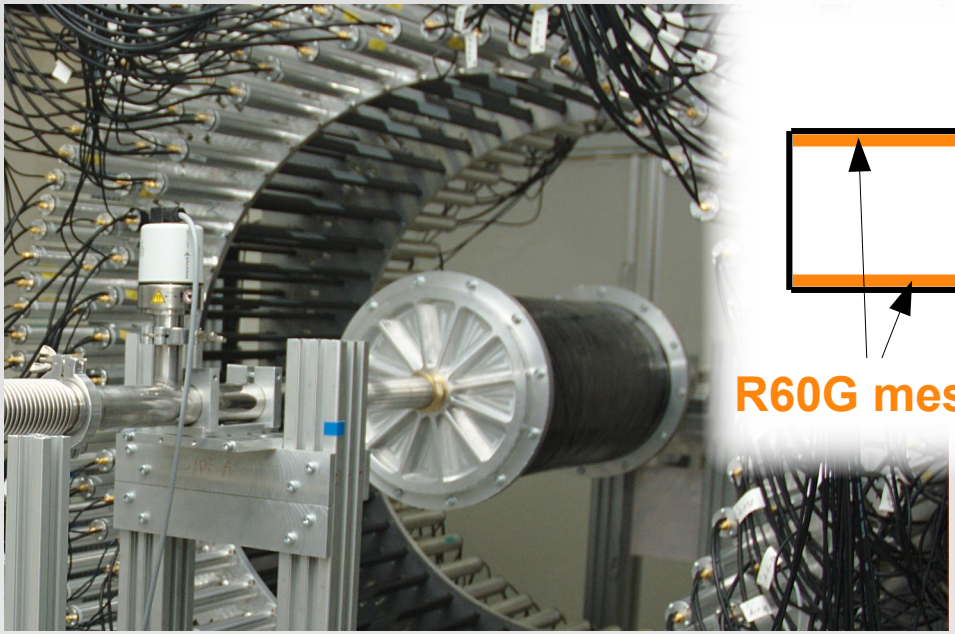
$$P_{e+} \approx \frac{v}{c} \cdot 0.98$$

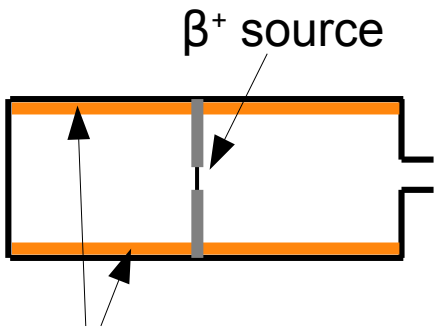
[NIM A 819 (2016), 54]

Plastic scintillators = fast timing
→ using high $\beta^+$ emitter activity (tested up to 10 Mbq)

Recording all 3 annihilation photons

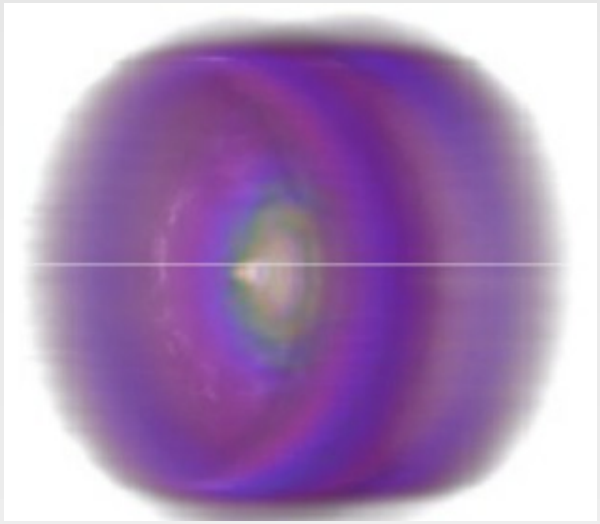
# o-Ps production in J-PET with an extensive size annihilation chamber

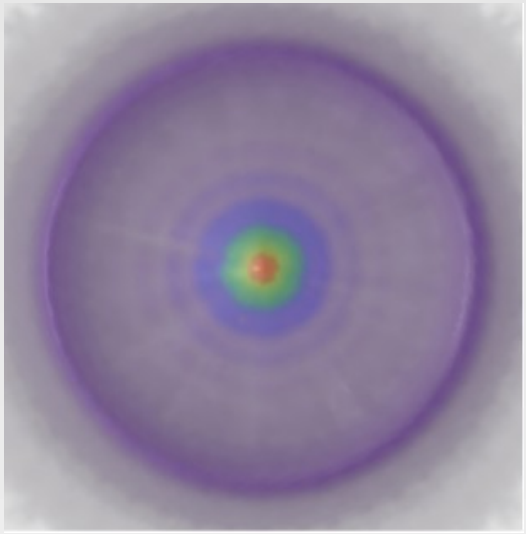





- Extensive-size chamber, R=12 cm
- Walls coated with XAD-4 porous material enhancing o-Ps formation
- $\beta^+$ emitter ($^{22}$Na) placed in the center of the chamber
- 2 different $^{22}$Na activities used:
  - 10 MBq – 3 months meas..
  - 0.8 Mbq – 14 days meas.

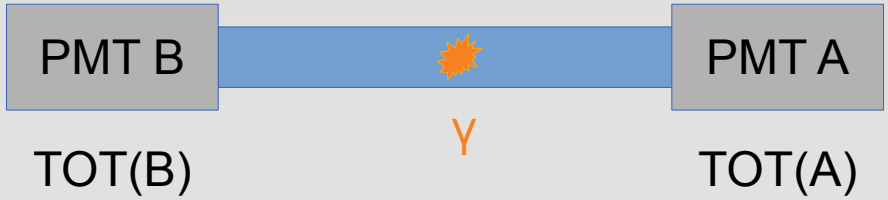
Tomographic images of the chamber obtained using $\gamma\gamma$ annihilations:

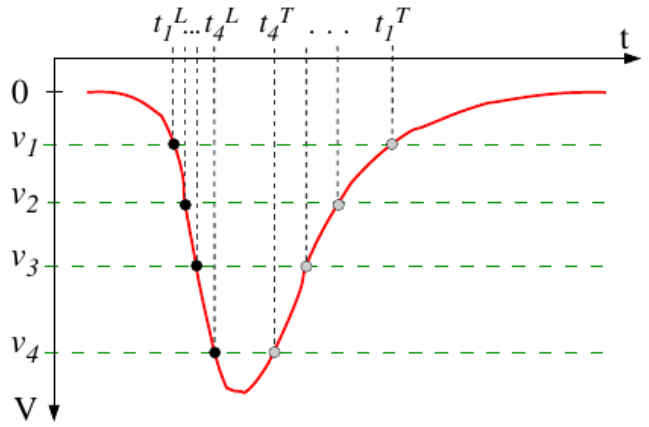




# Identification of prompt and annihilation γ

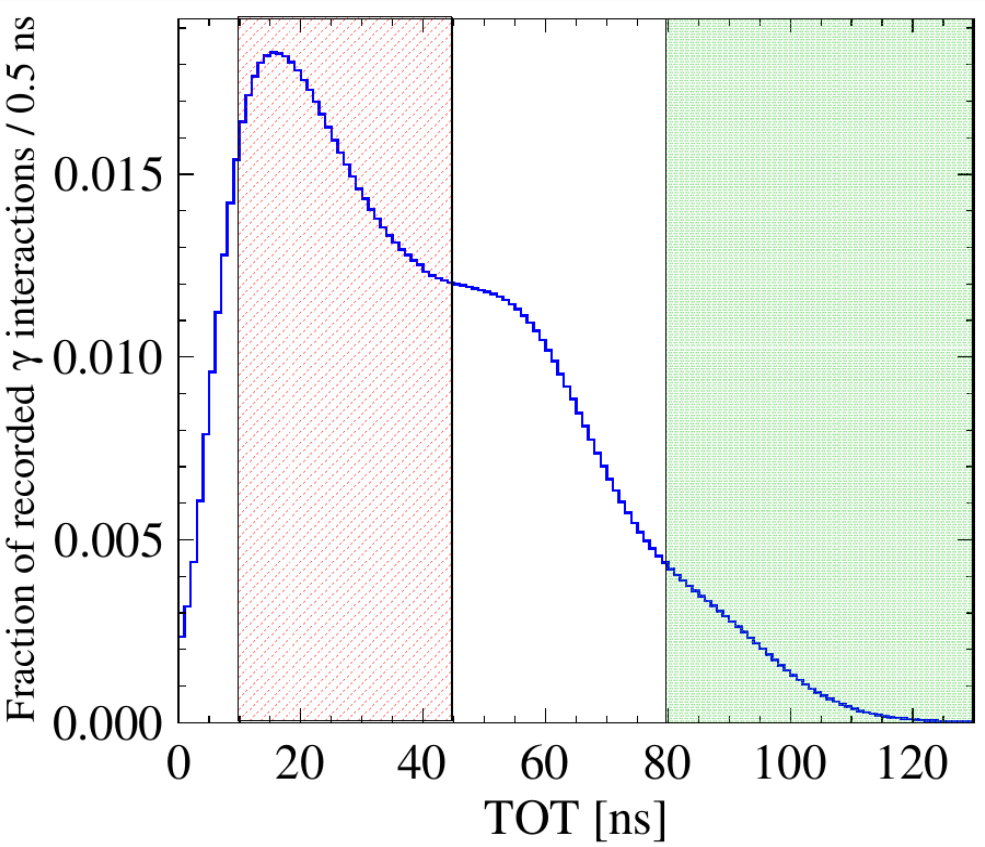
Using total Time Over Threshold (TOT) of PMT signals from a scintillator strip




o-Ps →3γ annihilation (E<511 keV)

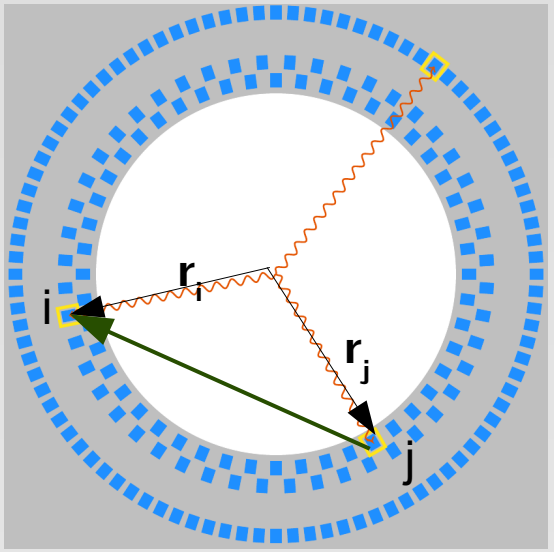
$^{22}$Ne* de-excitation (E=1274 keV)



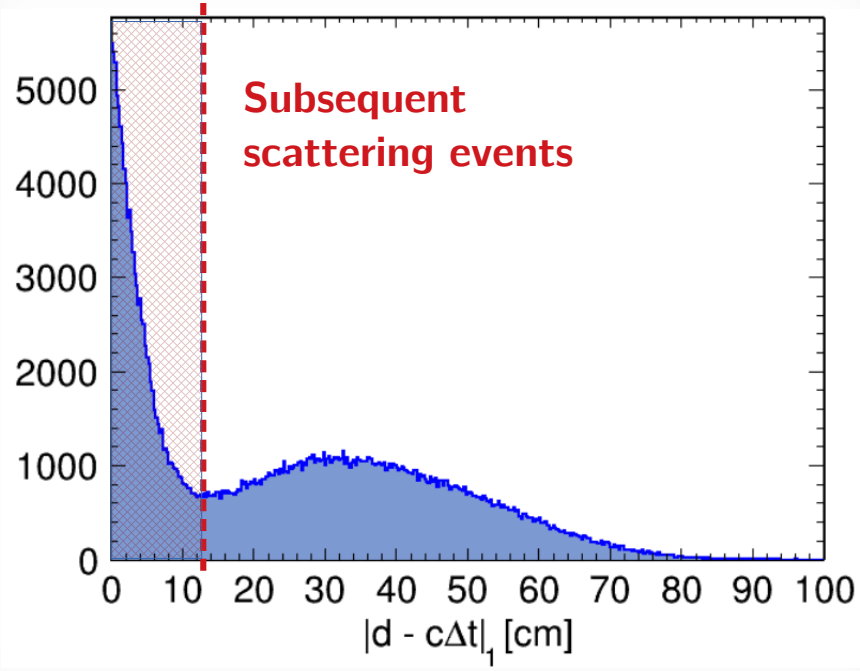
# Rejection of subsequent scatterings in the detector

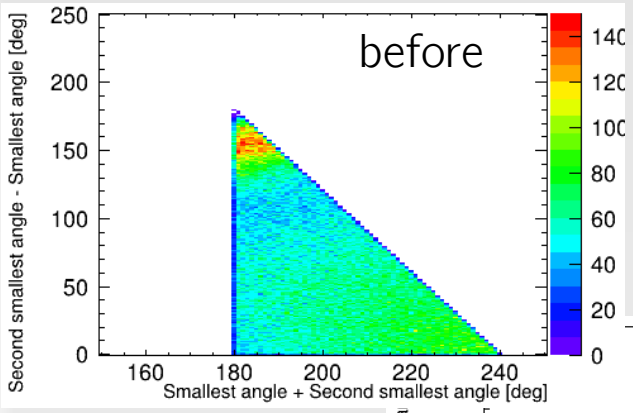
- See talks by J. Raj and N. Krawczyk for the cases when we **do not** want to reject these scatterings
- For each pair of annihilation photon candidates *i* and *j* (*i*,*j*=1,2,3) the following figure is computed:

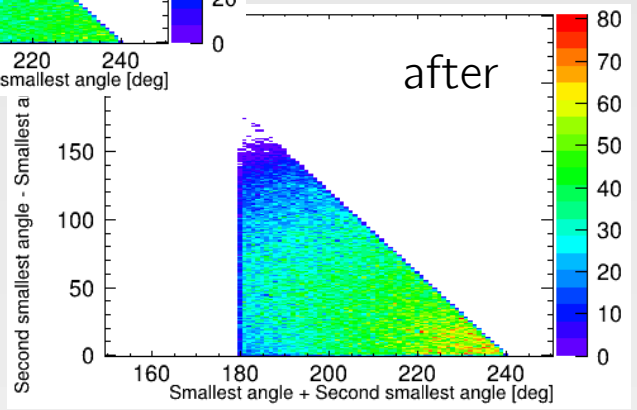
$$\delta t_{ij} = |d_{ij} - c\Delta t_{ij}| = ||\vec{r}_i - \vec{r}_j| - c(t_i - t_j)|$$




Distribution of the minimum $\delta t_{ij}$ over all photon pair choices in a events:



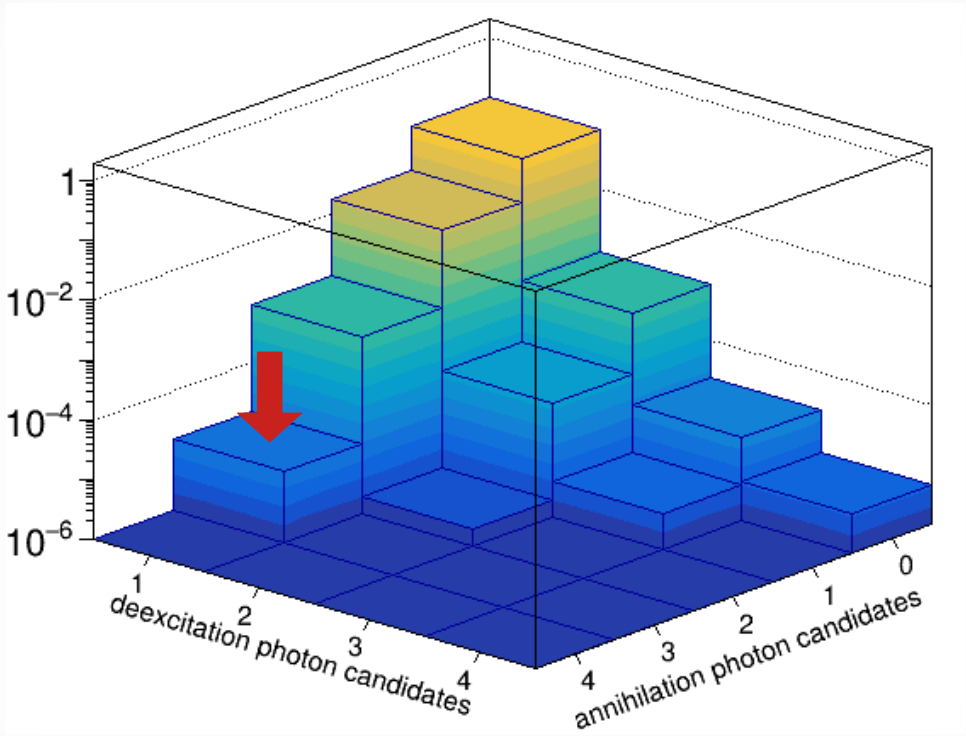



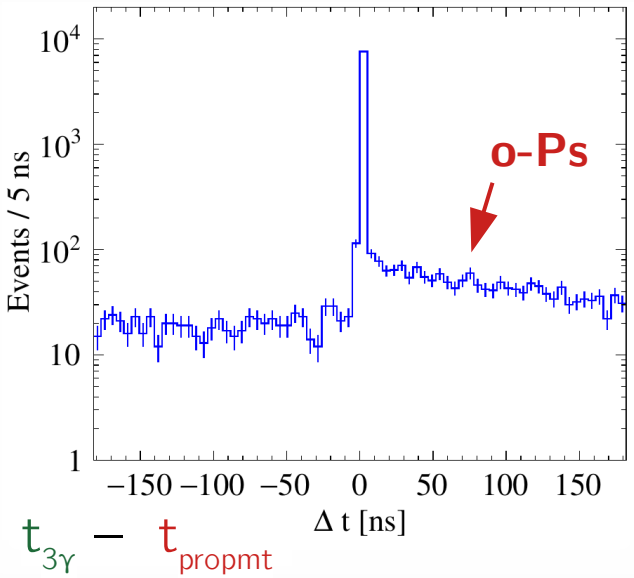



# o-Ps → 3γ in J-PET

**Selecting events with:**

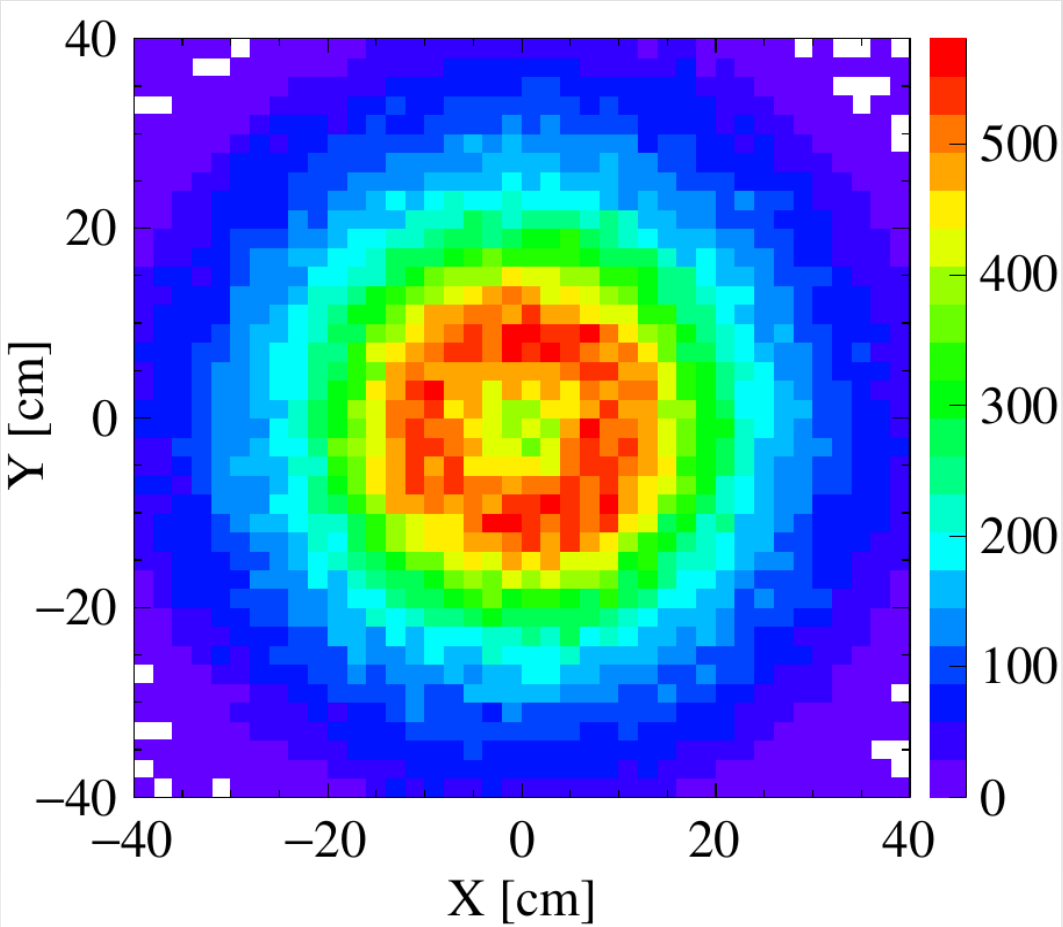
- 3 annihilation photon candidates within 2.5 ns
- A single prompt photon candidate within 250 ns from the 3 ahhinilation photons



# 3γ image of the o-Ps production chamber

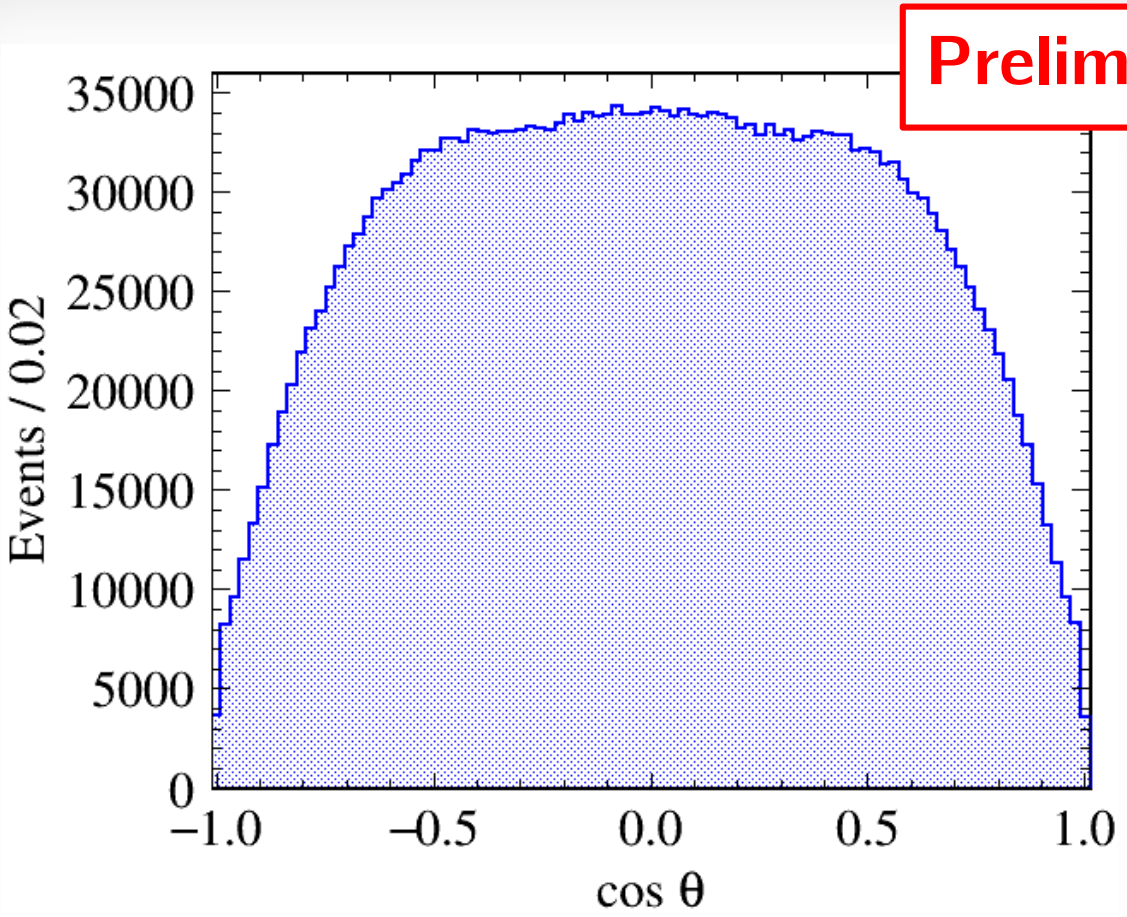
Image of the chamber in the tranverse view of the detector




**The first "image" of an extensive-size object obtained with o-Ps→3γ annihilations**

# CPT-violation sensitive operator

$$\hat{S} \cdot (\vec{k}_1 \times \vec{k}_2)/|\vec{k}_1 \times \vec{k}_2)| = cos\theta$$




$$\langle cos\theta \rangle = 0.00015 \pm 0.00032_{stat}$$

$$\Rightarrow \sigma(C_{CPT}) \approx 8 \times 10^{-4}$$

- **over 2.5M of exclusively recorded o-Ps → 3γ annihilations with spin estimation**
- **no signal of CPT-violating effects**
- result using 84% of available data

# Summary and perspectives

- The J-PET detector is capable of exclusive registration of o-Ps$\rightarrow 3\gamma$ annihilations
  - Full event recontruction including determination of the annihilaiton point in an extensive-size medium => first image from o-Ps$\rightarrow 3\gamma$ events
  - Estimation of o-Ps spin can be done on an event-by-event basis

- With the first measurements, J-PET reached a sensitivity of the CPT test at the level of $10^{-4}$
  - improvement over the best published result to date ($3 \times 10^{-3}$)
  - results to be published soon

- Further improvements are already under way – **stay tuned for the next talk!**

*Thank you for your attention!*

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