Studies of ortho-positronium decays into three photons using the J-PET detector

15th International Workshop on Slow Positron Beam Techniques & Applications
Prague, 2.09.2019

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on behalf of the J-PET Collaboration
Jagiellonian University

European Funds Smart Growth
Republic of Poland
FNP Foundation for Polish Science
European Union European Regional Development Fund

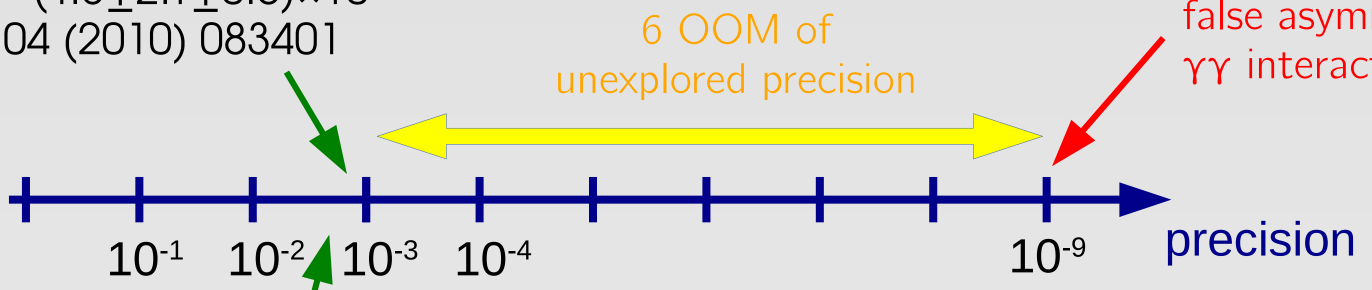
Motivation: discrete symetry tests with o-Ps $\rightarrow 3\gamma$ decays

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

$C_{CP} = (1.3 \pm 2.1 \pm 0.6) \times 10^{-3}$
PRL 104 (2010) 083401

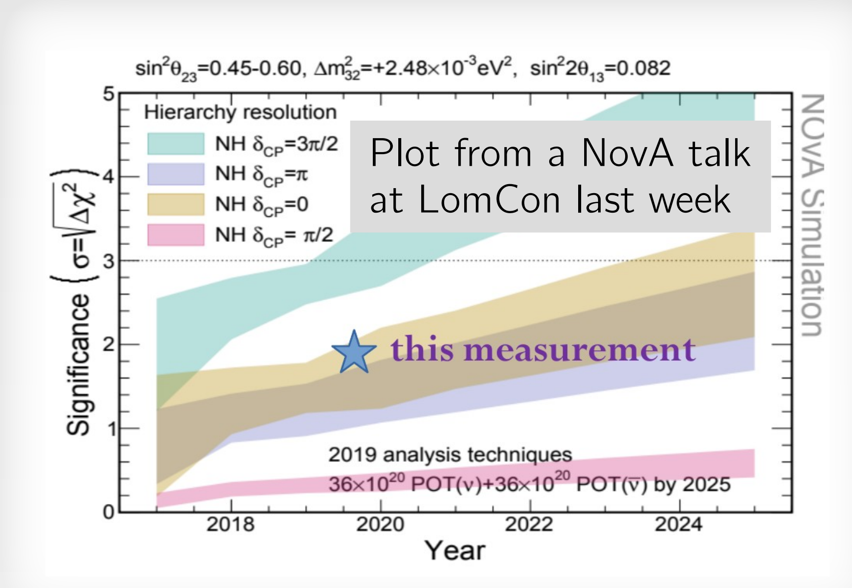
Physical sensitivity limit:
false asymmetries from $\gamma\gamma$ interactions in the final state



$C_{CPT} = (2.6 \pm 3.1) \times 10^{-3}$
PRL. 91 (2003) 263401

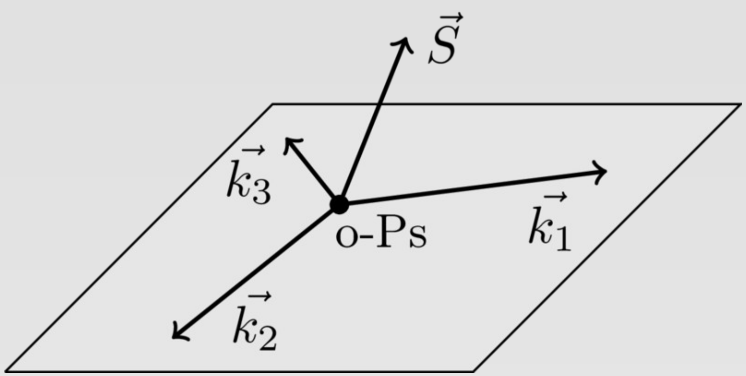
J-PET

- The only alternative in the leptonic sector to date: **neutrinos**
- CP-violation results (Dirac phase, δ_{CP}) at the 2σ level (NovA, T2K II)
- Can we probe CP violation in leptonic systems in smaller-scale experiments?



Testing discrete symmetries with angular correlations in o-Ps → 3γ decays

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



$$\left\langle \hat{O} \right\rangle \stackrel{?}{=} 0 \quad \text{for an odd operator}$$

$$\Leftrightarrow \mathcal{CPT}(\hat{O}) = -1$$

$$\Leftrightarrow \mathcal{T}(\hat{O}) = -1$$

$$|\vec{k}_1| > |\vec{k}_2| > |\vec{k}_3|$$

Using ortho-positronium spin
Requires either:

- polarization
- spin control
- spin estimation

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

Using photon polarization
Covered in a talk of J. Raj
In the same session.

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

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

o-Ps → 3γ operators involving spin

Presently studied with J-PET:

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

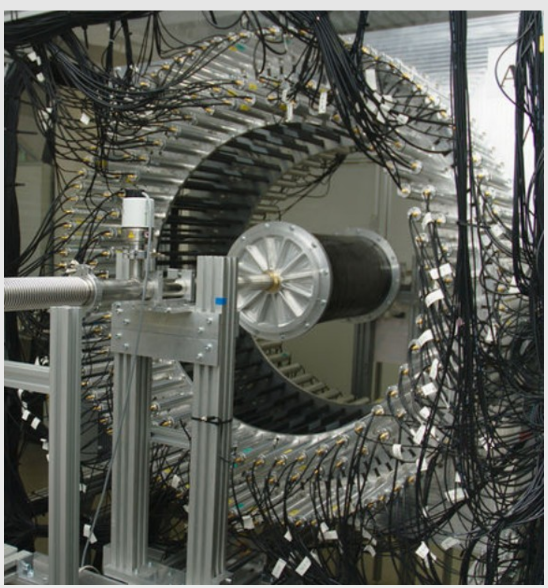
$\vec{S} \cdot \vec{k_1}$ CP-violation sensitive

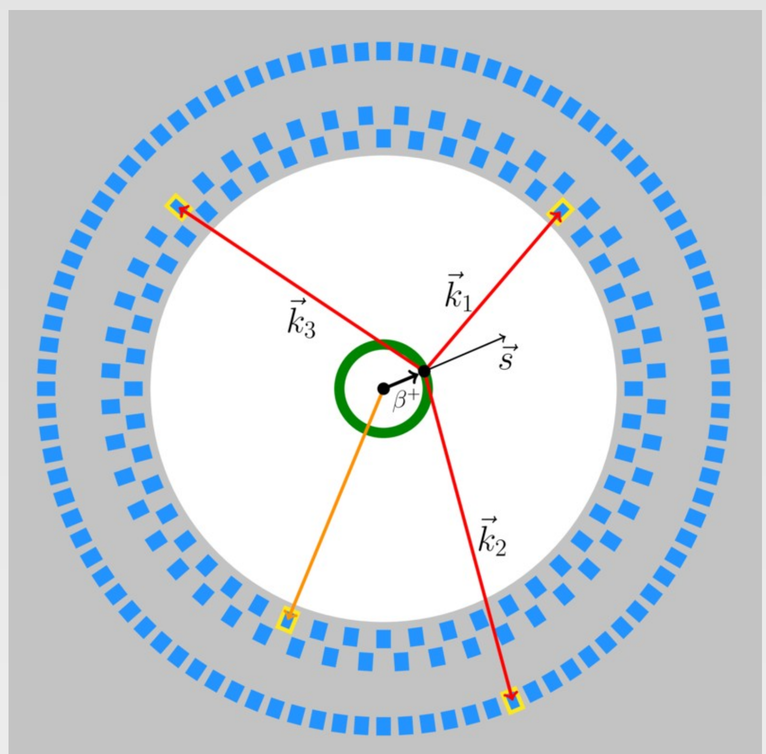
$(\vec{S} \cdot \vec{k_1})(\vec{S} \cdot (\vec{k_1} \times \vec{k_2}))$

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

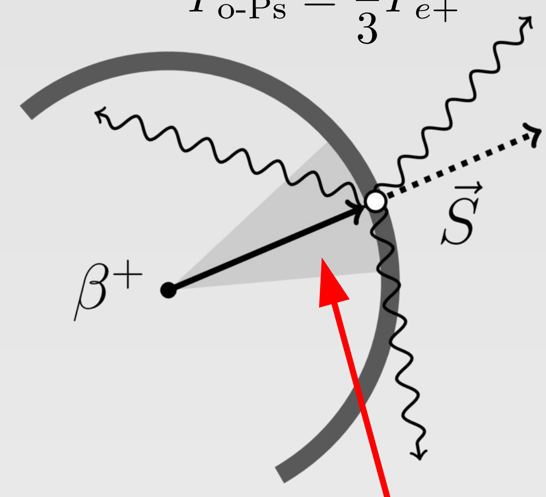
Event-by-event spin estimation

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





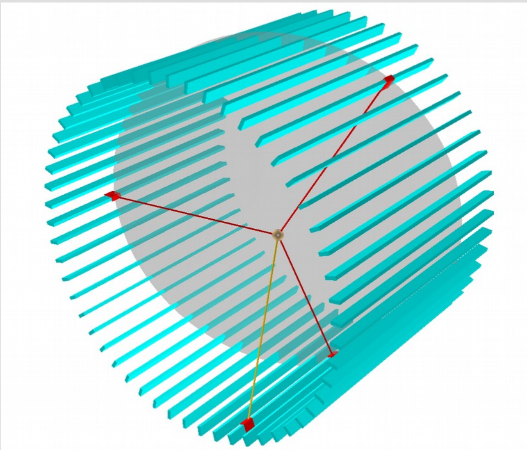
$$P_{\text{o-Ps}} = \frac{2}{3} P_{e+}$$



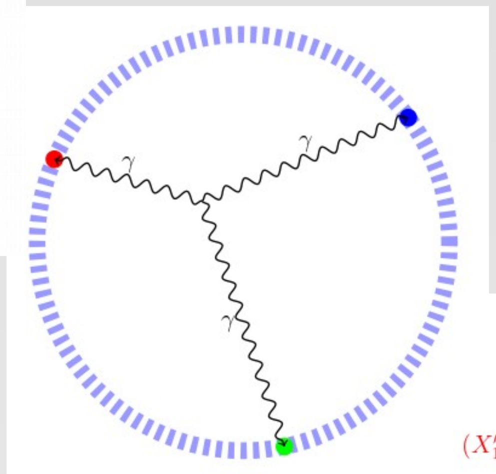
$$P_{e+} \approx \frac{v}{c} \cdot \frac{1}{2}(\cos\alpha + 1)$$

Effective polarization depends on o-Ps→3γ vertex resolution

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

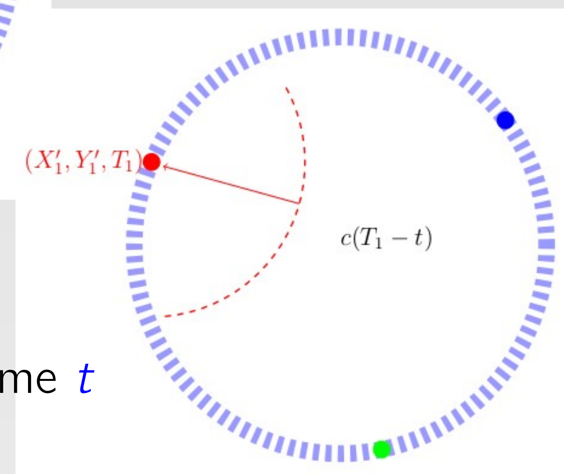


1. Find the decay plane containing the 3 hits in the J-PET barrel



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

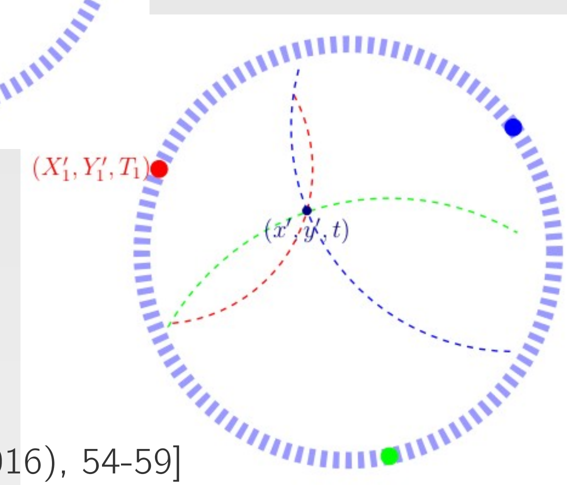
$$(X_i, Y_i, Z_i, T_i) \rightarrow (X_i', Y_i', 0, T_i)$$



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:

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



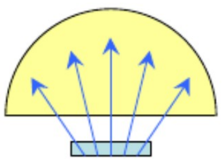
[A. Gajos et al., NIM A 819 (2016), 54-59]

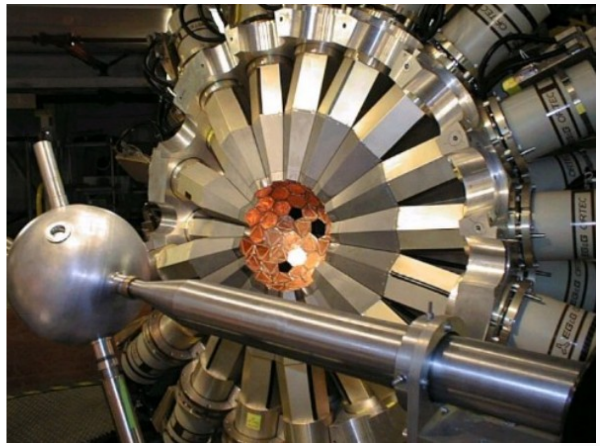
J-PET vs previous measurements

Gammasphere
PRL. 91 (2003) 263401

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

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





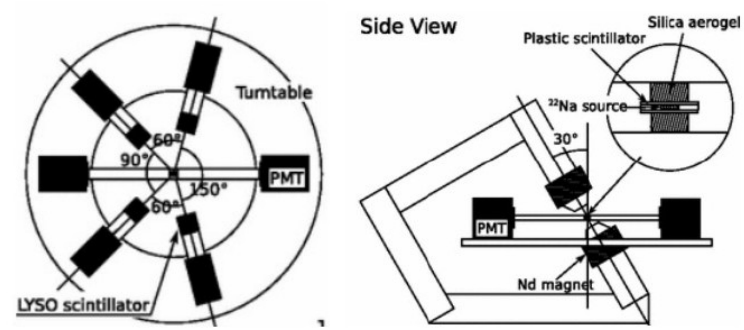
$$P_{e+} = \frac{v}{c}\cdot 0.5$$

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

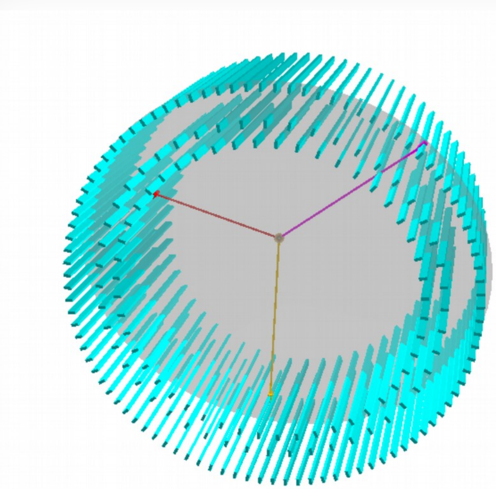
Yamazaki et al.
PRL 104 (2010) 083401

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

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



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

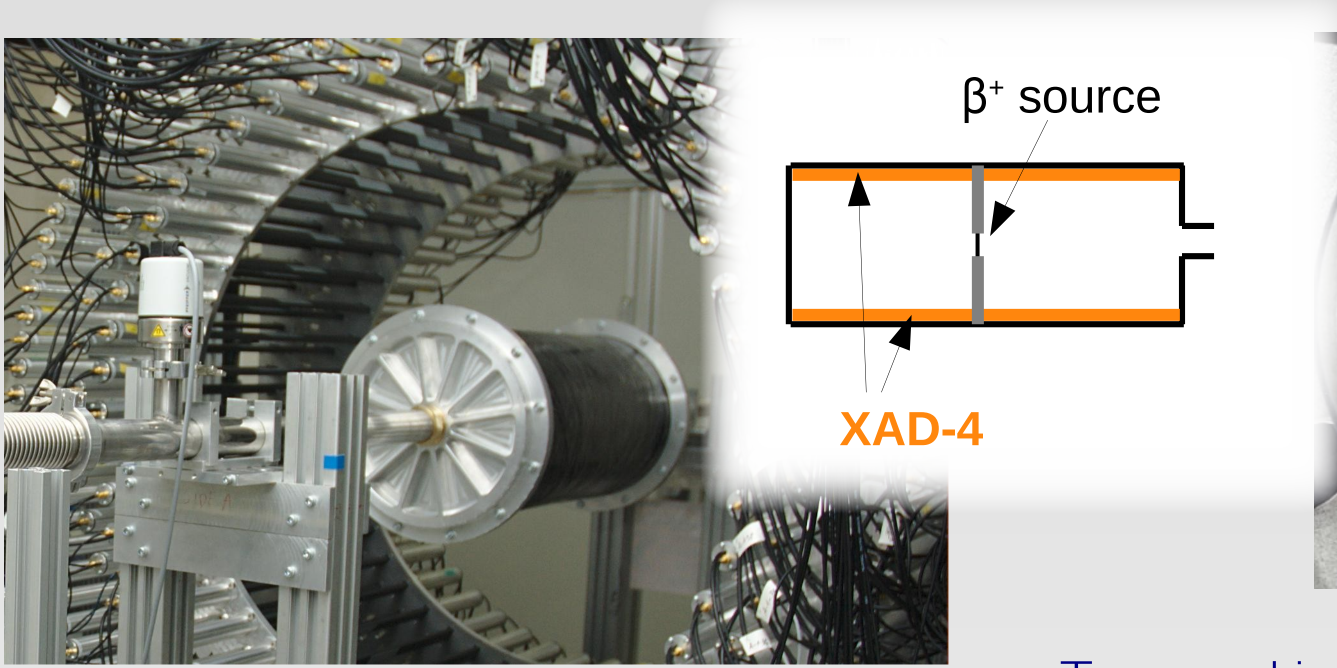
$$P_{e+} \approx \frac{v}{c}\cdot 0.98$$

[NIM A 819 (2016), 54]

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

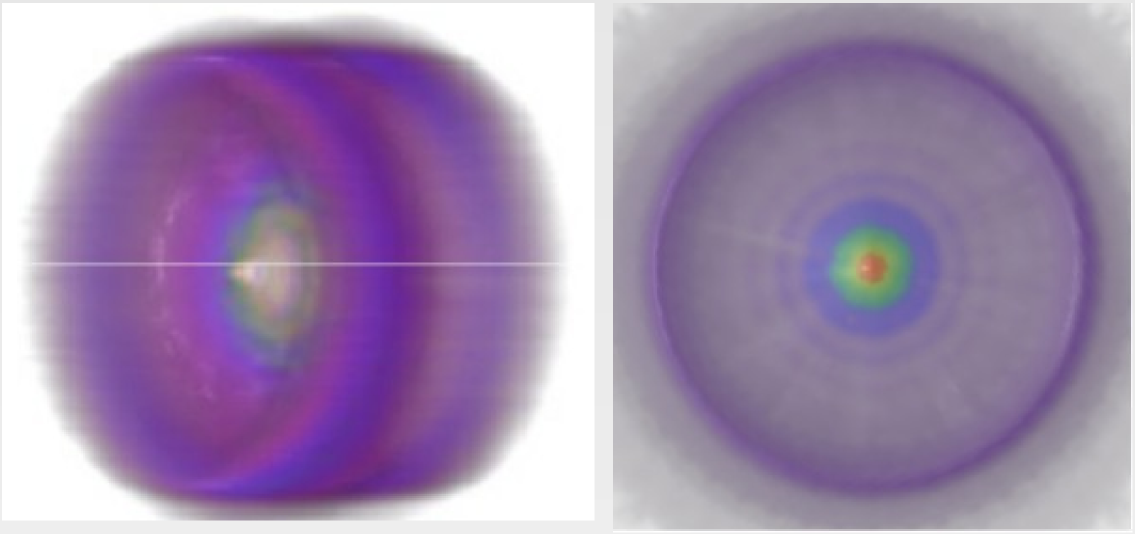
Recording all 3 annihilation photons

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



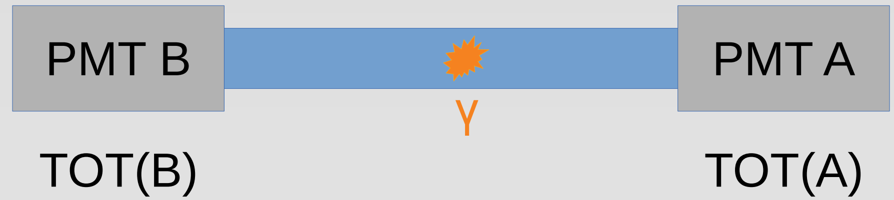
- Extensive-size chamber, R=12 cm
- Walls coated with XAD-4 porous material enhancing o-Ps formation
- β^+ emitter (^{22}Na) placed in the center of the chamber
- 2 different ^{22}Na activities used:
  - 10 MBq – 180 days meas.
  - 0.8 Mbq – 14 days meas.

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

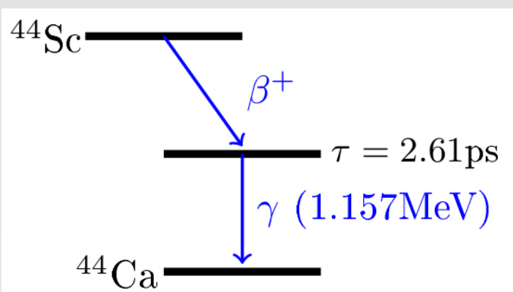


Identification of prompt and annihilation γ

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

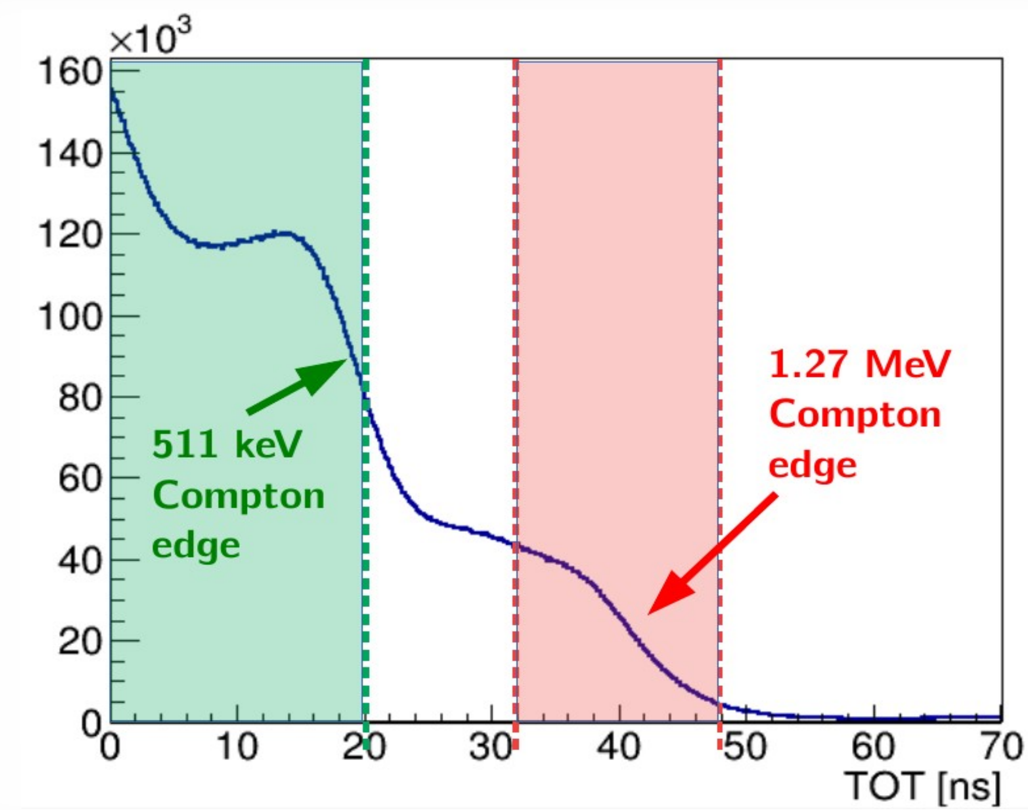


Details on estimation of the deposited energy using TOT were presented by S. Sharma in the same session



o-Ps → 3γ annihilation (E<511 keV)

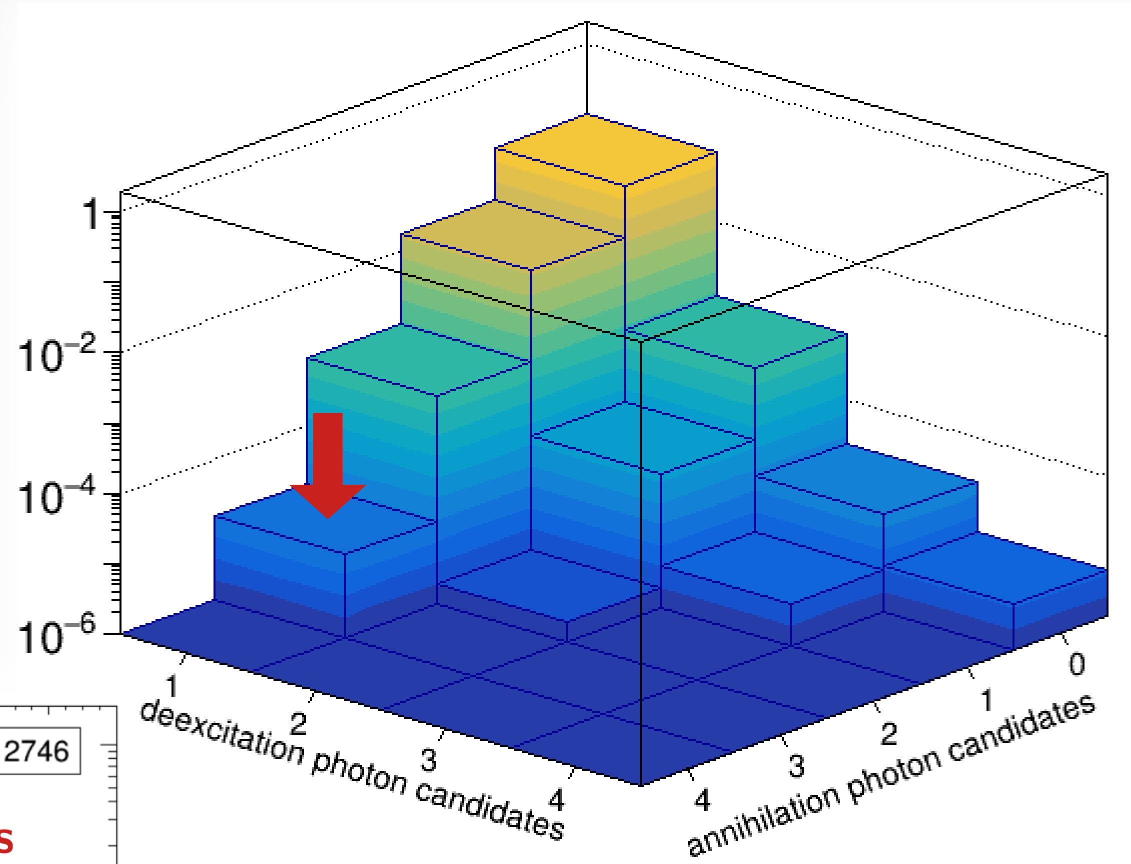
^{22}Ne* de-excitation (E=1274 keV)

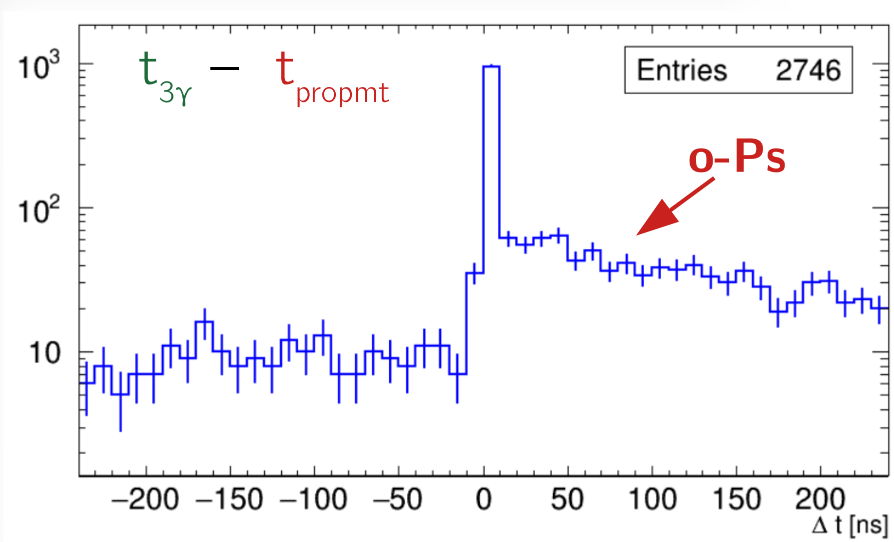


o-Ps → 3γ in J-PET

Selecting events with:

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

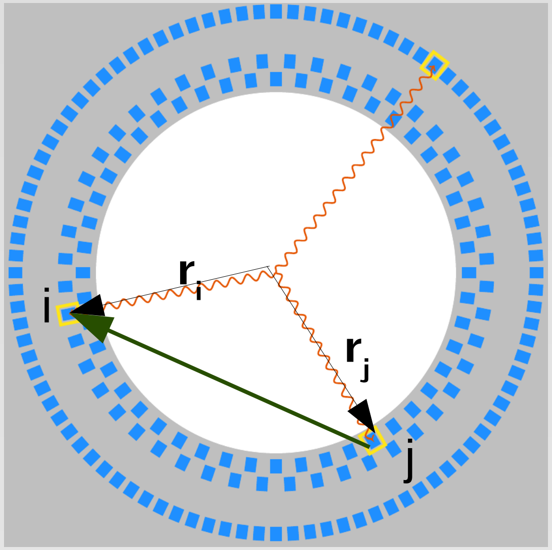




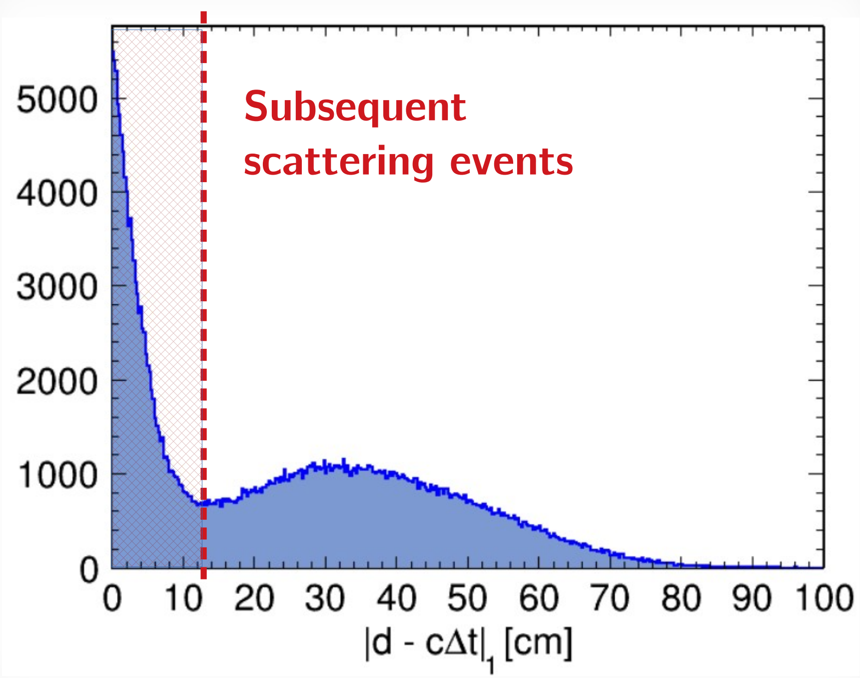
Rejection of subsequent scatterings in the detector

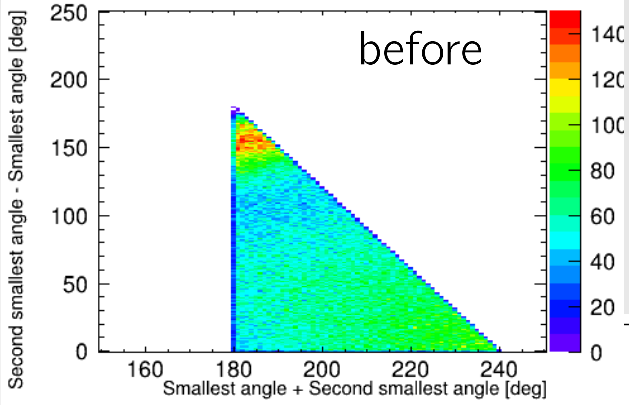
- See talks by J. Raj and N. Krawczyk for the cases when we **do not** want to reject these scatterings
- For each pair of annihilation photon candidates *i* and *j* (*i*,*j*=1,2,3) the following figure is computed:

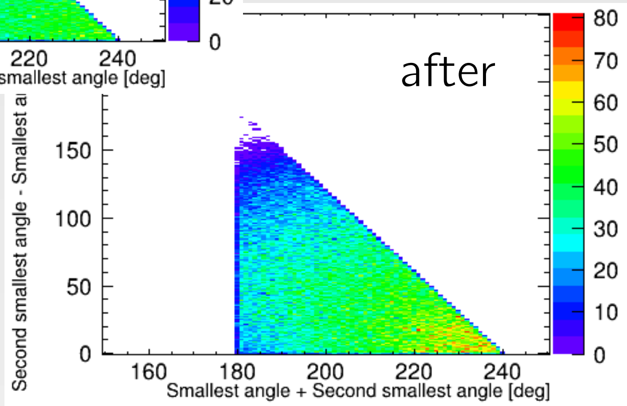
$$\delta t_{ij} = |d_{ij} - c\Delta t_{ij}| = \left| \frac{1}{c}|\vec{r}_i - \vec{r}_j| - (t_i - t_j) \right|$$



Distribution of the minimum δt_{ij} over all photon pair choices in a events:



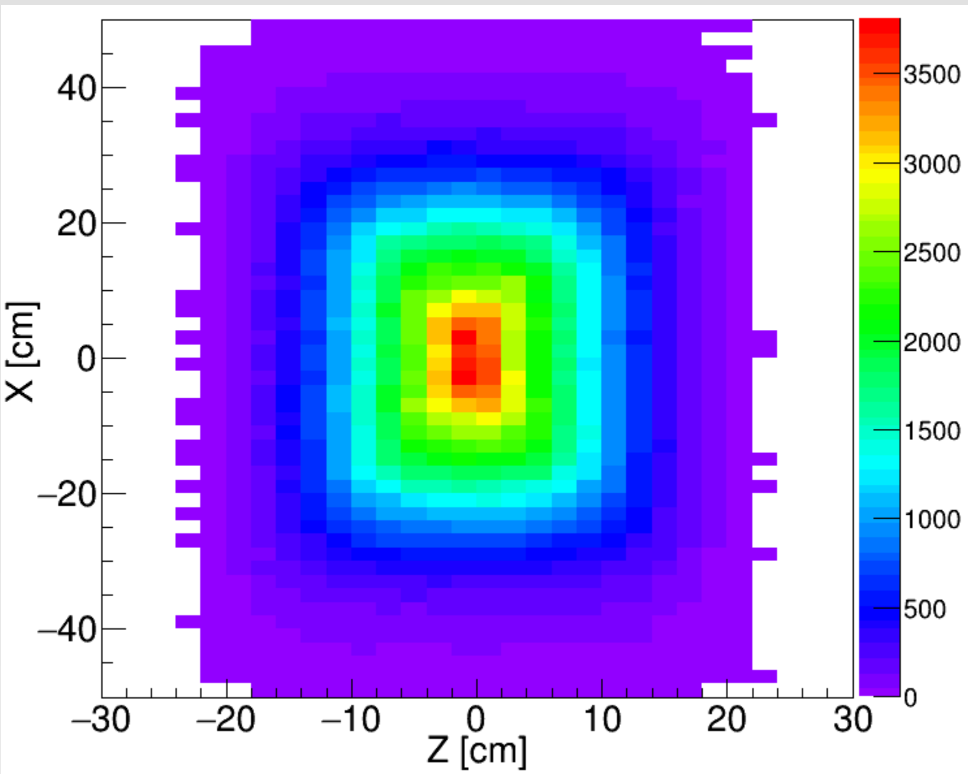


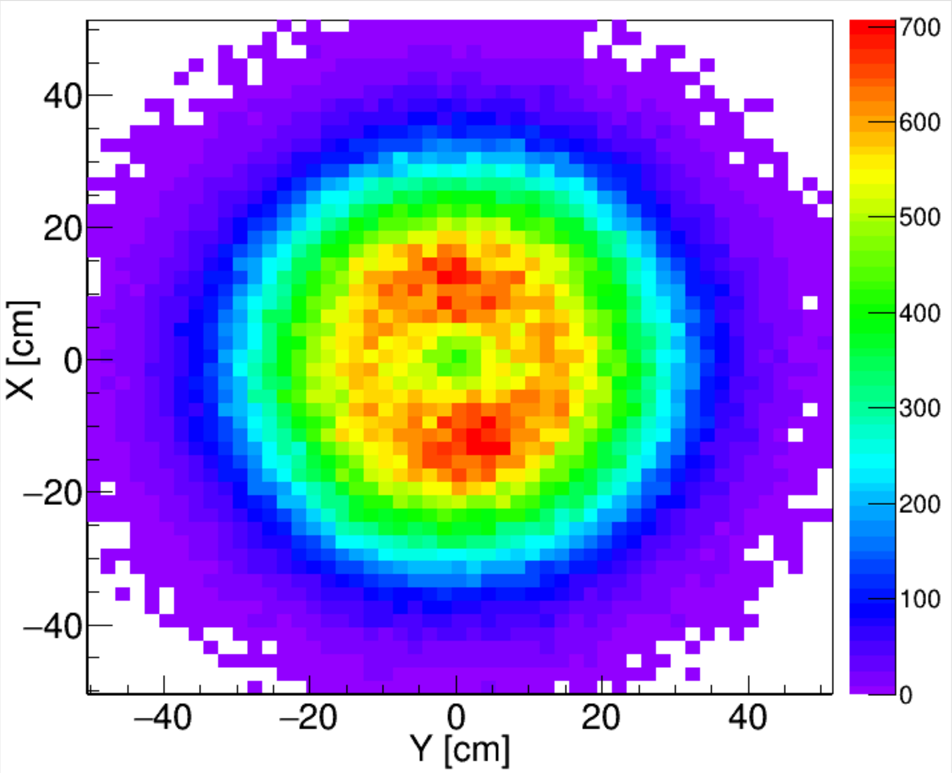


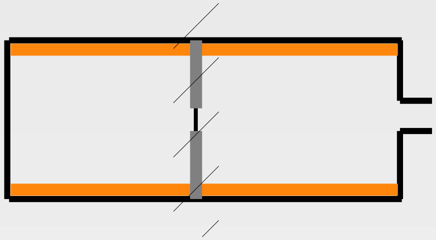
3γ image of the o-Ps production chamber

Side view of the detector

Tranverse view of the detector excluding the source setup region ($|z| > 2$ cm)



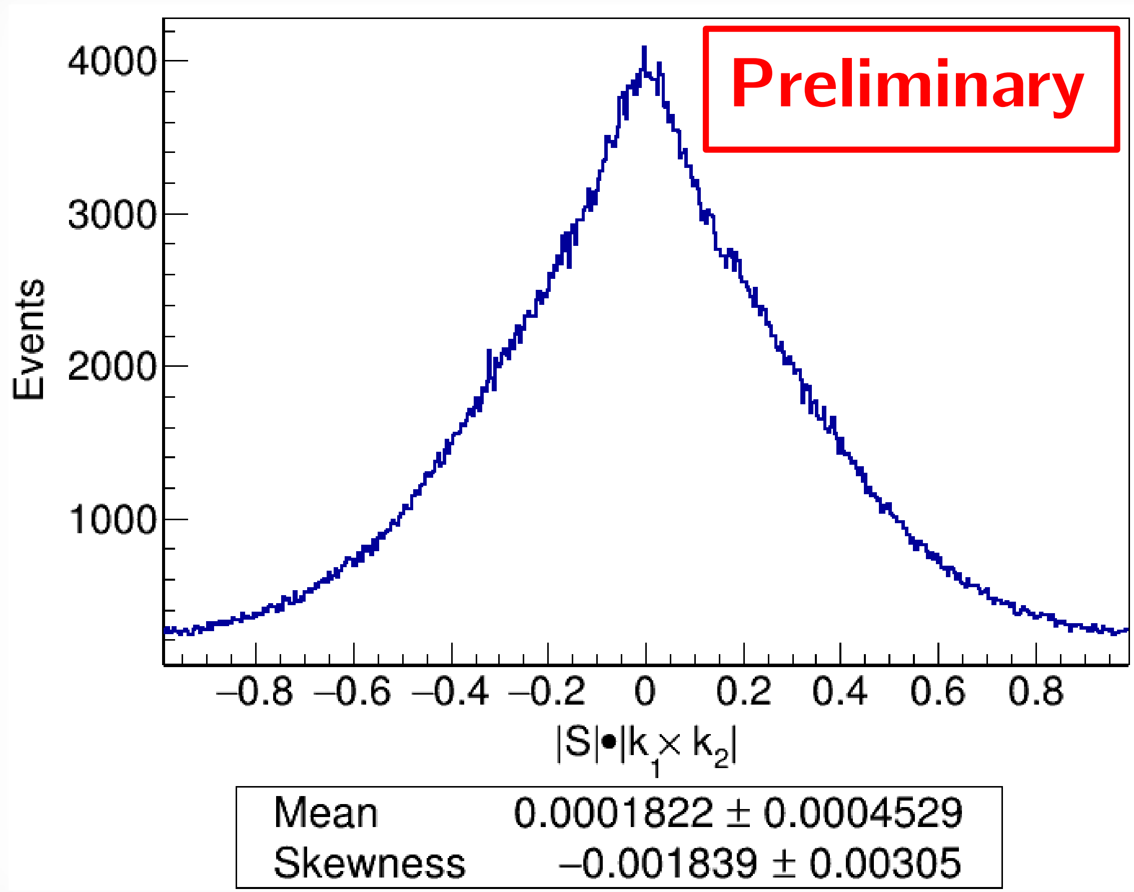




The first "image" of an extensive-size object obtained with o-Ps→3γ annihilations

CPT-violation sensitive operator

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



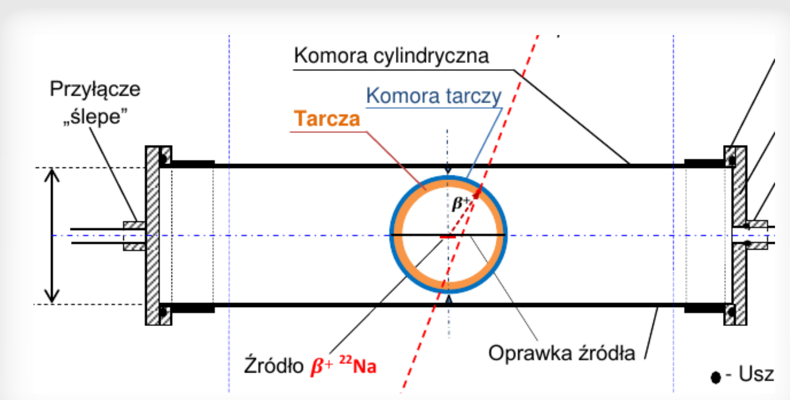
- Uncertainty: 4.5×10^{-4} (statistical only)
- Using ~ 1/4 of available data (~300 TB in total)
- Not corrected for detector acceptance
  (currently under study using MC simulations)

Summary and perspectives

- The J-PET detector is capable of exclusive registration of o-Ps→3γ annihilations
    - Full event recontruction including determination of the annihilaiton point in an extensive-size medium
    - Estimation of o-Ps spin on an event-by-event basis

- J-PET aims at improving sensitivity of the CP and CPT symmetry tests by at least an order of magnitude
    - Target sensitivity: 10^{-4} available with the already collected data

- Prospects for further improvement:



Thank you for your attention!

This work is supported in the framework of the TEAM/2017-4/39 programme of the Foundation for Polish Science

European Funds Smart Growth
Republic of Poland
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Backup Slides

Testing discrete symmetries with ortho-positronium

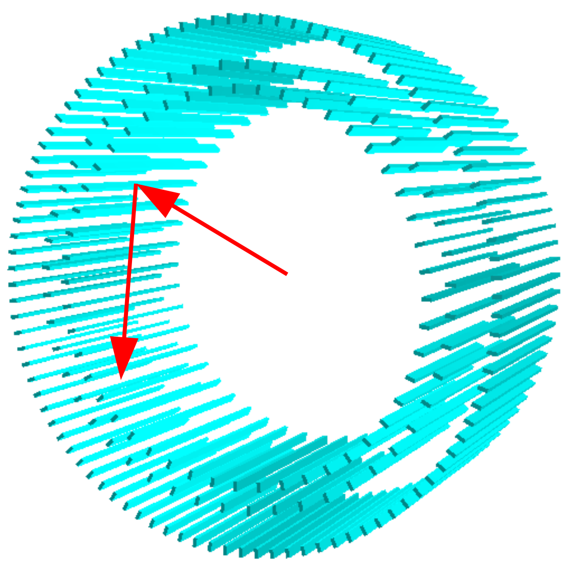
operator	C	P	T	CP	CPT
$\vec{S}\cdot\vec{k_1}$	+	−	+	−	−
$\vec{S}\cdot(\vec{k_1}\times\vec{k_2})$	+	+	−	+	−
$(\vec{S}\cdot\vec{k_1})(\vec{S}\cdot(\vec{k_1}\times\vec{k_2}))$	+	−	−	−	+
$\vec{k}_2\cdot\vec{\epsilon}_1$	+	−	−	−	+
$\vec{S}\cdot\vec{\epsilon}_1$	+	+	−	+	−
$\vec{S}\cdot(\vec{k}_2\times\vec{\epsilon}_1)$	+	−	+	−	−

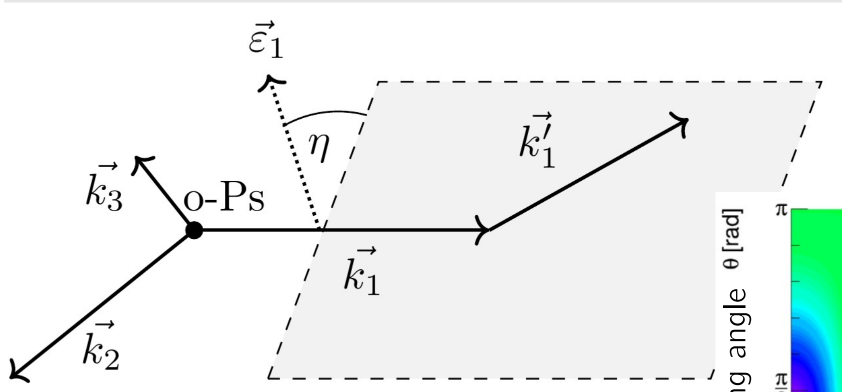
If polarization direction of the photons (ϵ) can be estimated, a new class of operators becomes available for measurement!

For details of the study of this operator at J-PET see the talk of J. Raj in the same session

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

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

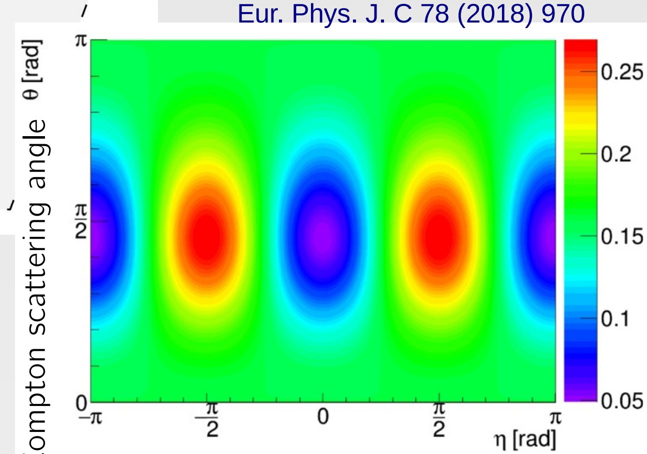




$$|\vec{k}_1| > |\vec{k}_2| > |\vec{k}_3|$$

J-PET can determine the scattering plane in events with secondary Compton scatterings!

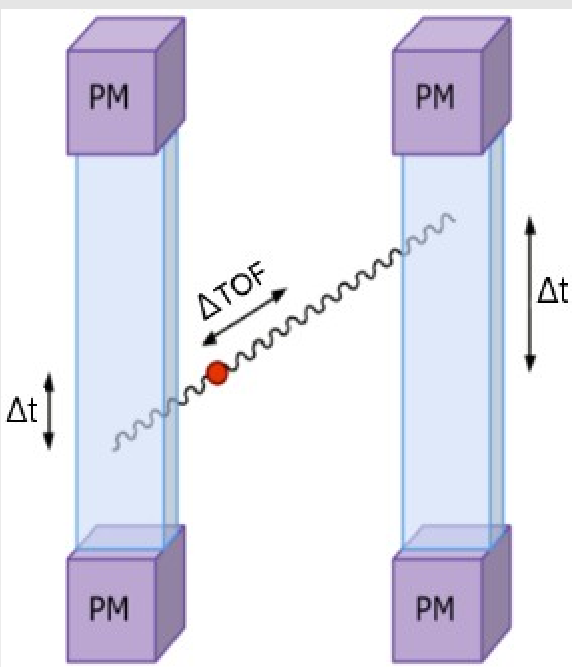
Eur. Phys. J. C 78 (2018) 970

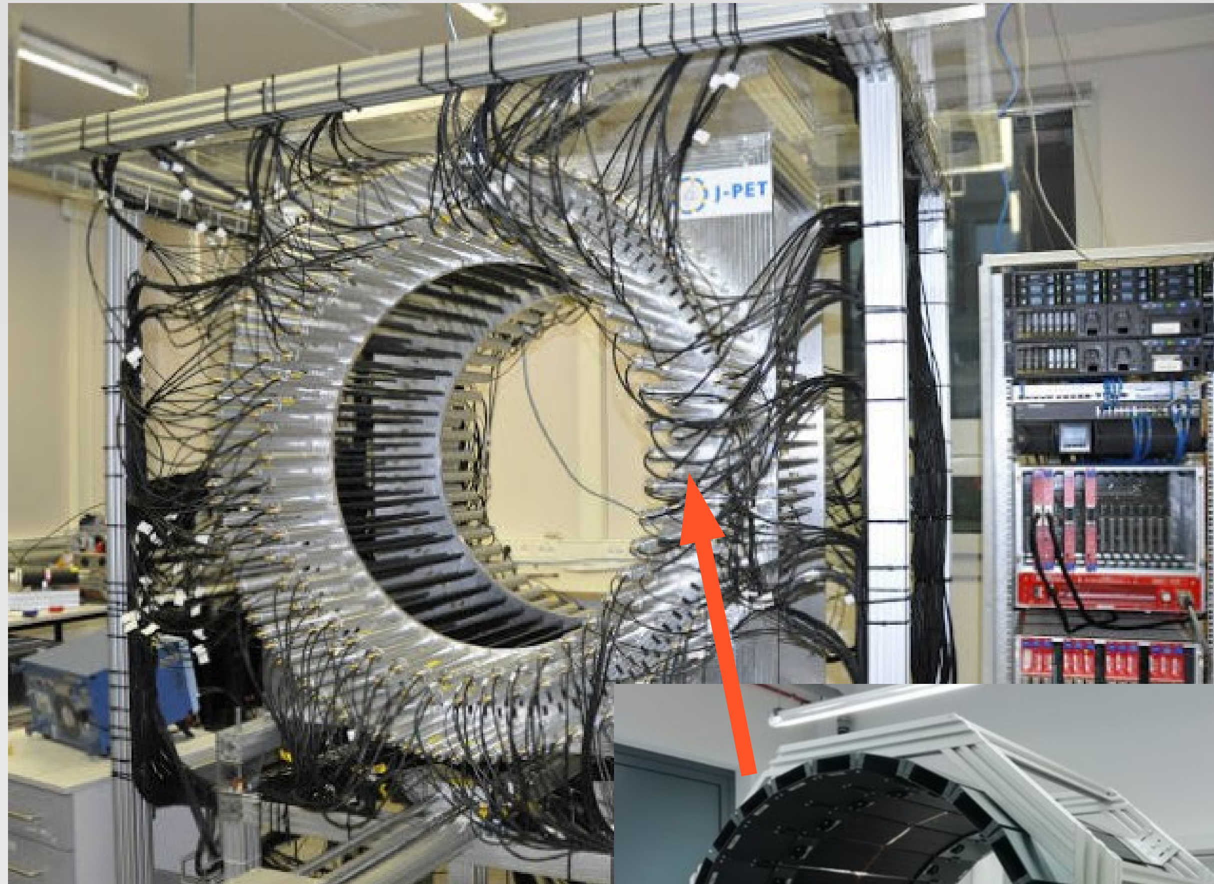


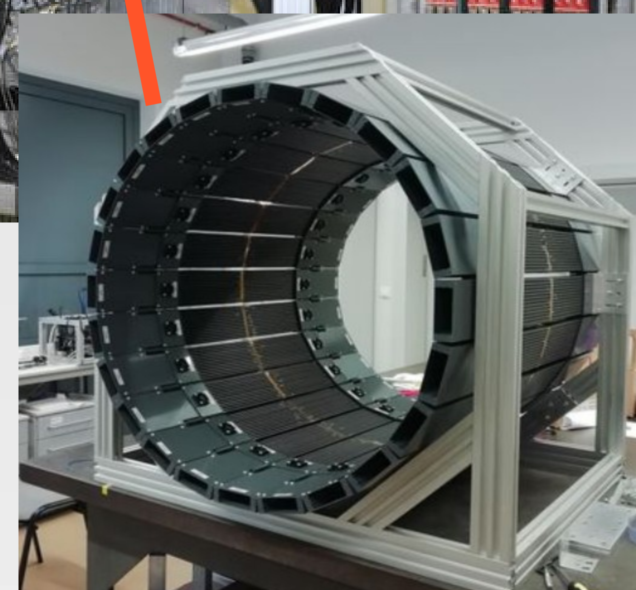
Angle between ϵ and the scattering plane

The J-PET Detector

- Constructed at the Jagiellonian University
- Fist PET device using strips of plastic scintillators
- At the same time: a robust photon detector for fundamental research!

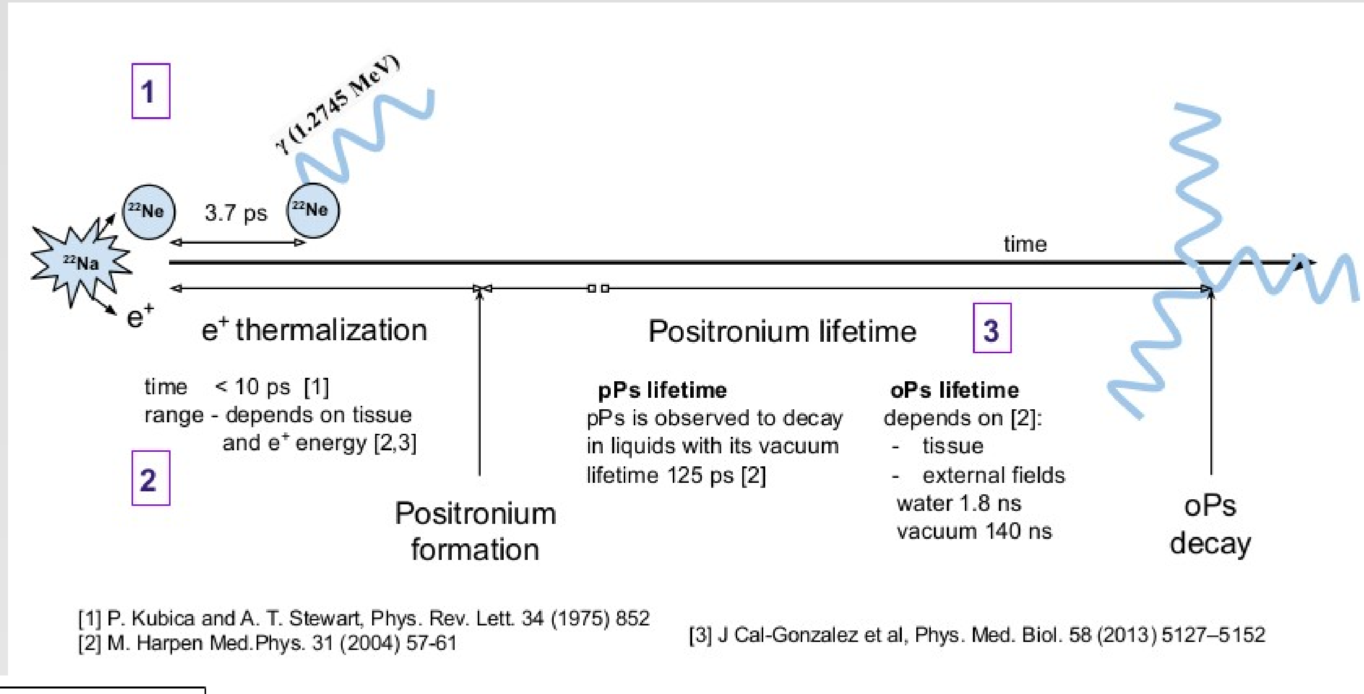


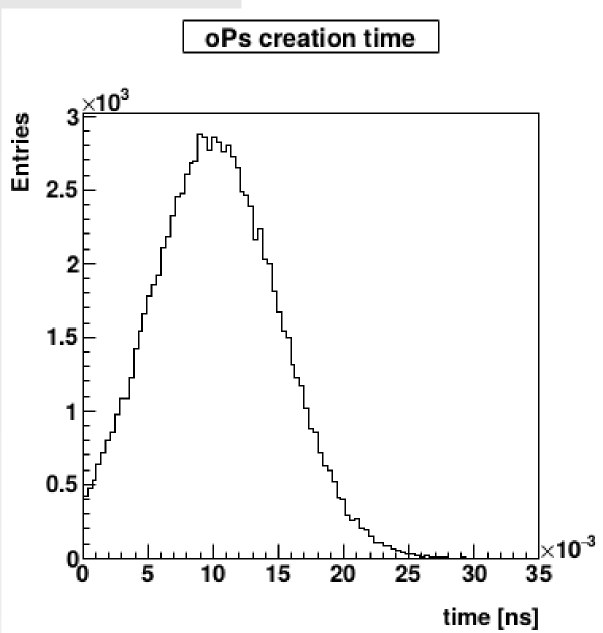


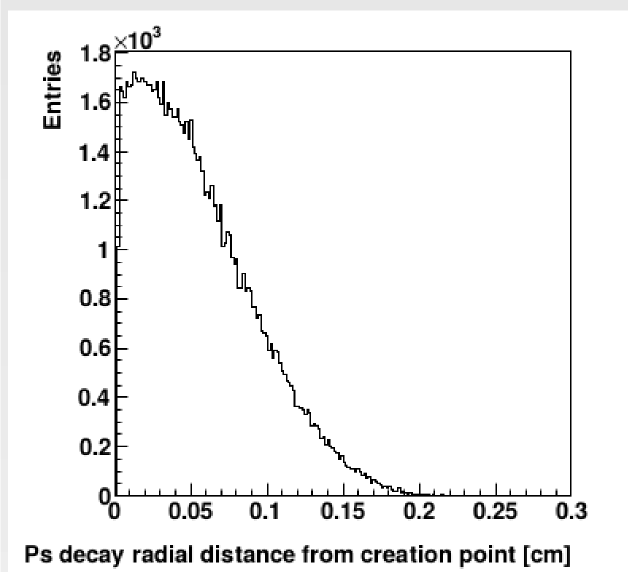


A new inner layer with digital readout
→ See talks by:
G. Korcyl
Sz. Niedźwiecki
On Thursday

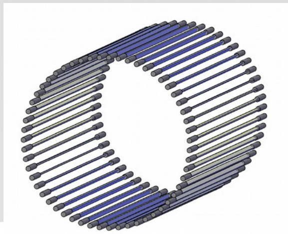
O-Ps creation and decay







Distinguishing o-Ps→3γ and e^+e^-→2γ



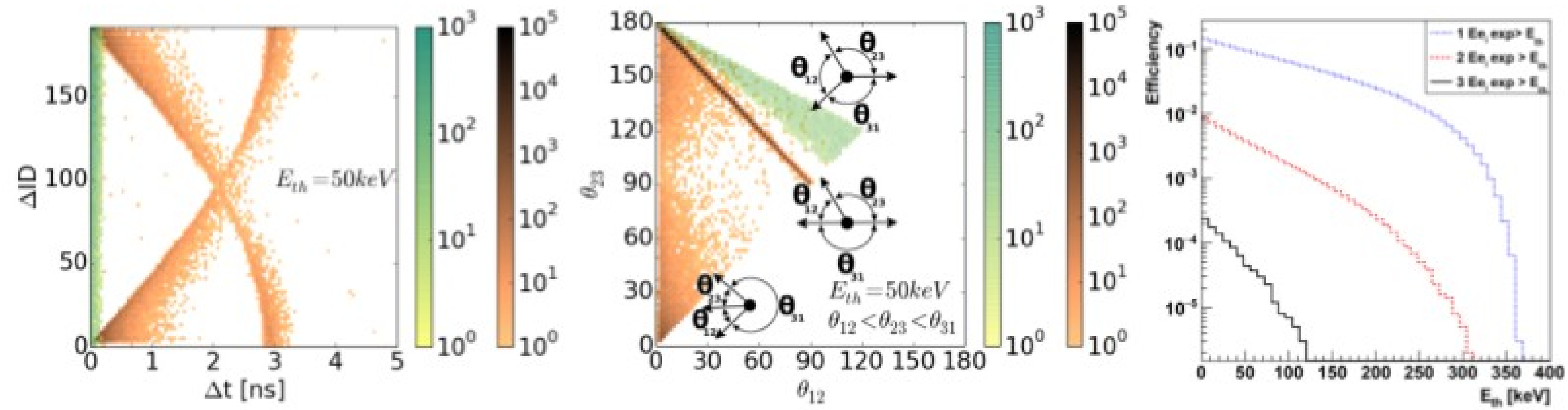


Figure 9. (Left) Simulated distributions of differences between detectors ID (ΔID) and differences of hit-times (Δt) for events with three hits registered from the annihilation e+e- → 2γ (gold colours) and o-Ps → 3γ (green colours). **(Middle)** Disribution of relative angles between reconstructed directions of gamma quanta. The numbering of quanta was assinged such that $\theta_{12} < \theta_{23} < \theta_{31}$. Shown distributions were obtained requiring three hits each with energy deposition larger than Eth = 50 keV. Gold colour scale shows results for simulations of e+e- → 2γ and green scale corresponds to o-Ps → 3γ. Typical topology of o-Ps → 3γ and two kinds of background events is indicated. **(Right)** Detection efficiency of the J-PET detector for registration of one, two and three gamma quanta from o-Ps → 3γ decay. The efficiency is shown as a function of threshold energy applied in the analysis to each gamma quantum.

[J-PET: P.Kowalski, P.Moskal, in preparation]

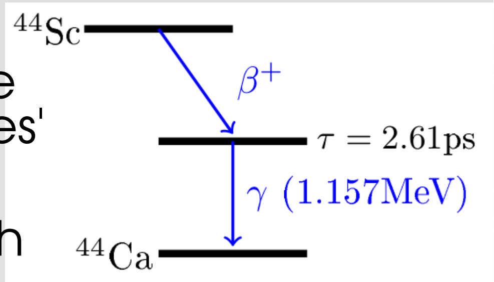
Ortho-positronium decay tomography

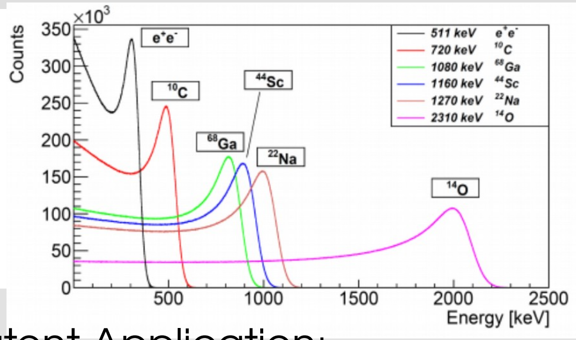
Motivation:

- Ortho-positronium (o-Ps) lifetime in tissue strongly depends on inter-cellular spaces' size
- Morphological imaging possible through determination of o-Ps lifetime
- 4-th photon coming from β+ emitter deexcitation is used to estimate o-Ps creation time
- o-Ps→3γ decay location and time must be reconstructed using 3 recorded photons

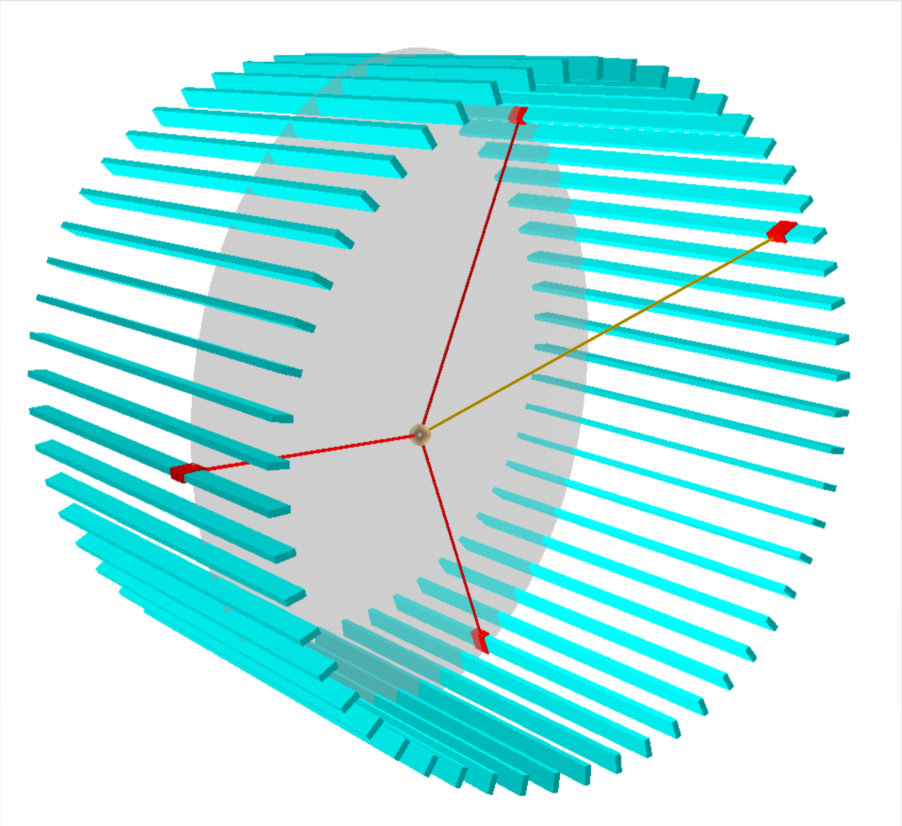
Properties of the process:

- Momenta of the 3 photons from o-Ps decay lie in one plane (in the o-Ps ref. frame)
- 4-th (deexcitaion) photon momentum is not correlated with the other three
- o-Ps→3γ decay and deexcitation photon emission differ by distance and time related to free e+ path and positronium life

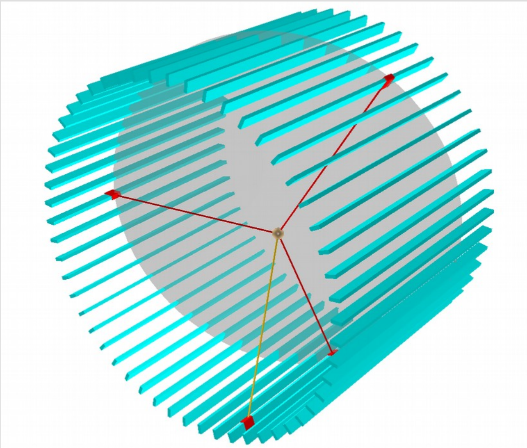




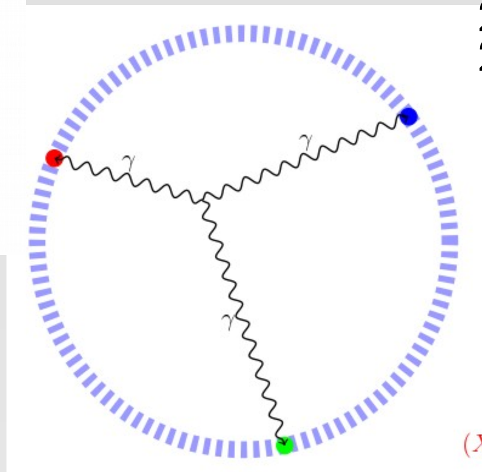
[P.M. et al., Patent Application: PCT/EP2014/068374; WO2015028604]



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

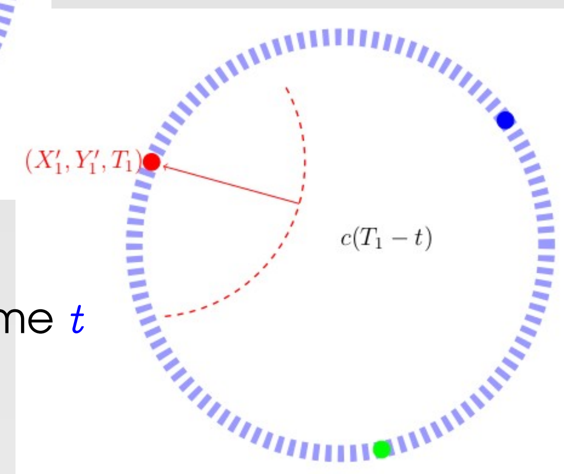


1. Find the decay plane containing the 3 hits in the J-PET barrel

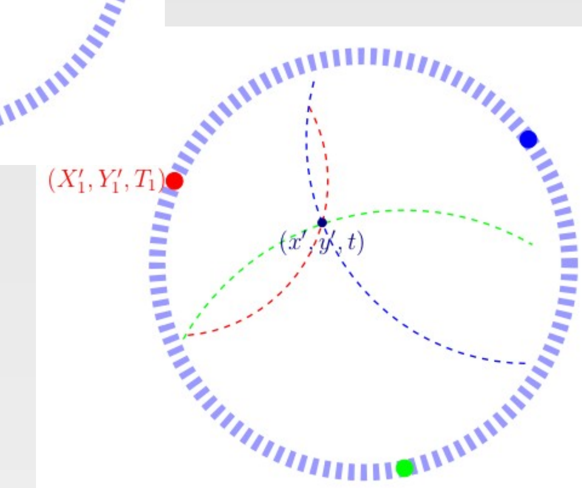


2. Transform the hit coordinates to a 2D coordinate system in the decay plane

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



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



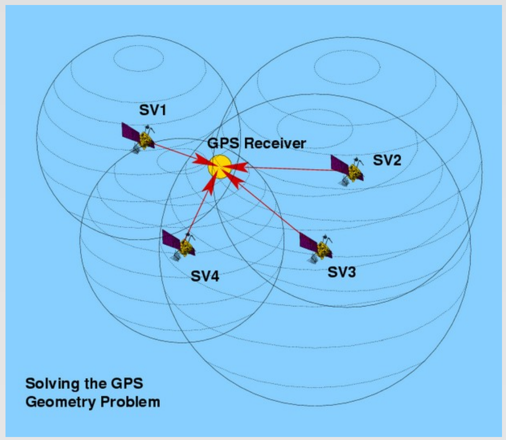
4. The decay point (x', y') in the decay plane and time t is an intersection of 3 such circles:

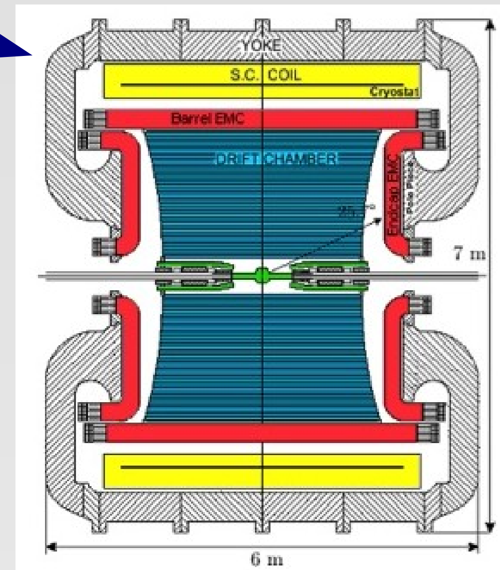
$$(T_i - t)^2 c^2 = (X_i' - x')^2 + (Y_i' - y')^2, \quad i = 1, 2, 3$$

Origin of the reconstruction method

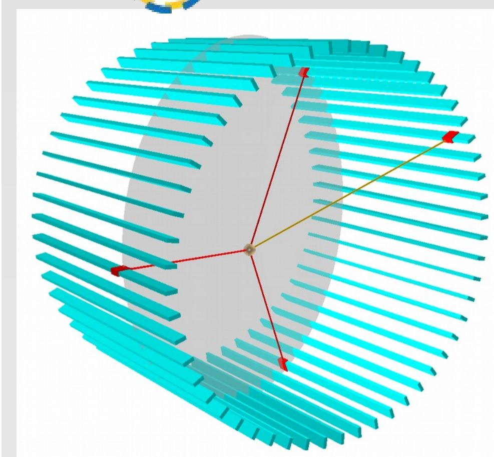
- The reconstruction method applied to o-Ps decays in J-PET was originally created for kaon decays at the KLOE detector [A. Gajos Dipl.Thesis (2013) Jagiellonian University] [Acta Phys. Pol. B 46 (2015) 13]

- Mathematical principle of the reconstruction is similar to GPS positioning





J-PET

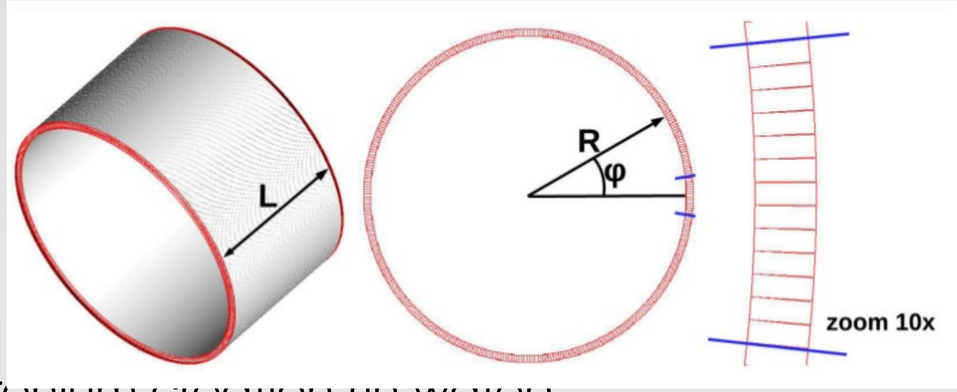


	GPS	$K_L \to 3\pi^0 \to 6\gamma$ at KLOE	o-Ps$\to 3\gamma$ at J-PET
Shere centers	Satellite locations	γ hits in KLOE calorimeter	γ hits in J-PET barrel
Whose travel time is measured?	Radio signals from satellites	Photons from π^0 decays	Photons from o-Ps decay
Reconstructing position of	GPS receiver	$K_L \to 3\pi^0 \to 6\gamma$ decay	o-Ps$\to 3\gamma$ decay
Reconstructed time	Current GPS time	Time of K_L decay	Time of positronium decay
Using information on	At least 4 satellites	4-6 recorded photons	3 recorded photons and coplanarity

MC simulation of o-Ps decays in J-PET

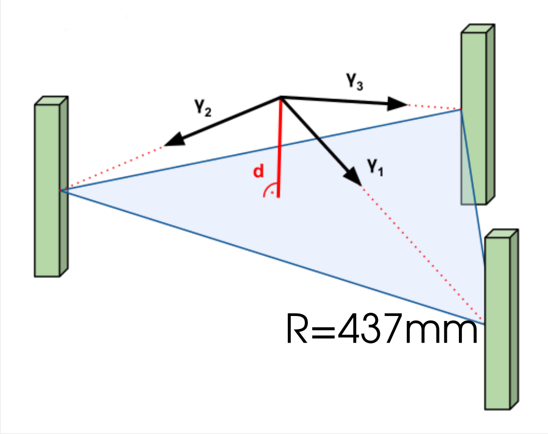
- Monte Carlo simulations of o-Ps decays recorded by the J-PET detector were prepared
- J-PET detector with 384 scintillator strips was assumed in simulations
    - Single strip size: 7x19x500mm^3
    - Barrel dimensions:

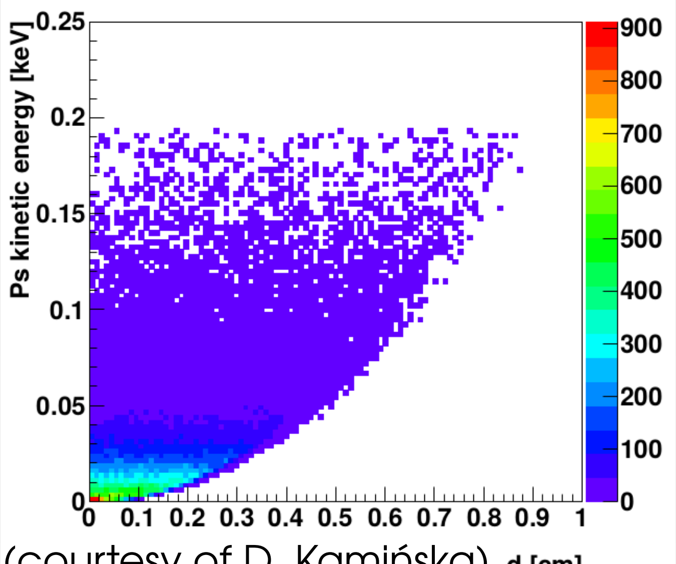
      R = 43cm, L = 50cm
    - Resolution in XY plane: $\Delta\varphi \approx 0.5$deg
- Simulation includes:
    - β^+ emitter deexcitation and prompt
    - Positron thermalization before positronium creation (in water)
    - Ortho-positronium lifetime (for water)
    - Momentum of the decaying positronium – deviation from 3 photons' coplanarity in LAB frame



Effects included in the simulation

Non-coplanarity of photons' momenta

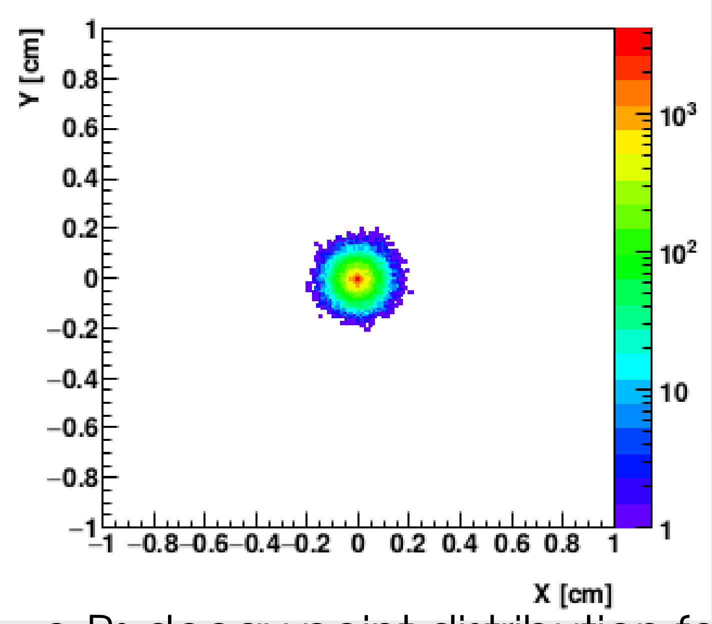




(courtesy of D. Kamińska)

Positron thermalization and oPs flight before decay

result in a difference between the o-Ps decay point and the deexcitation photon emission point



o-Ps decay point distribution for a point β^+ source placed at (0,0)
(courtesy of D. Kamińska)

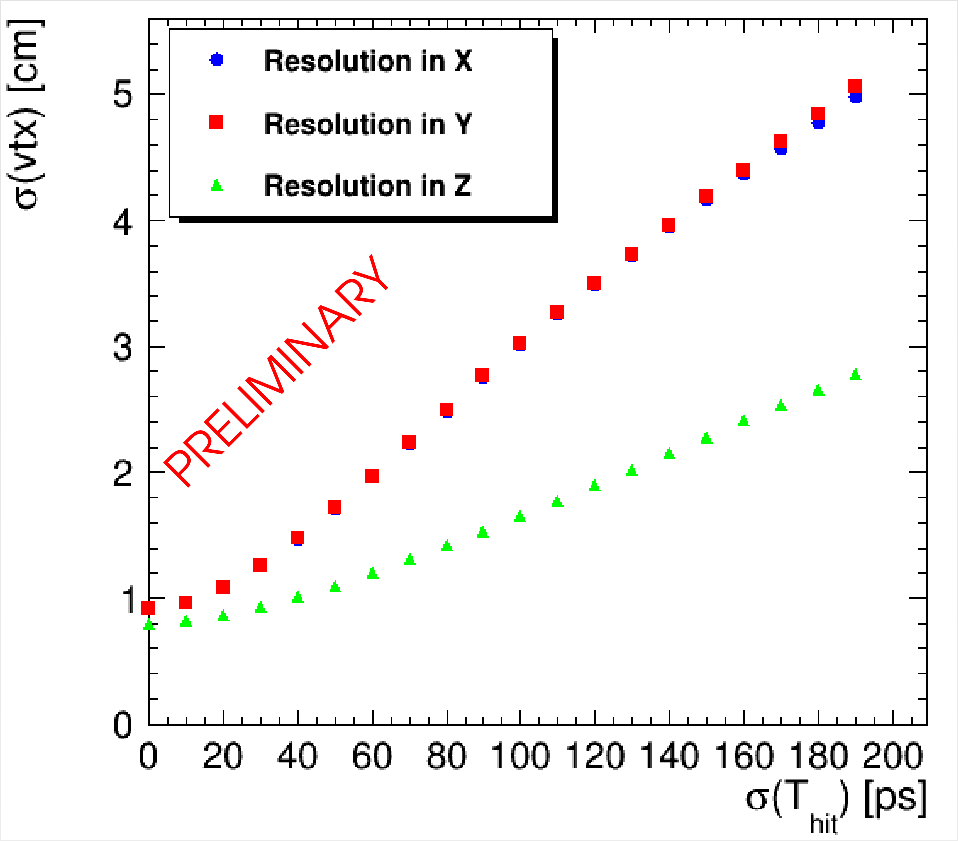
Both effects are negligible within reconstruction resolution (presented on next slides).

Resolution dependence on γ hit time resolution

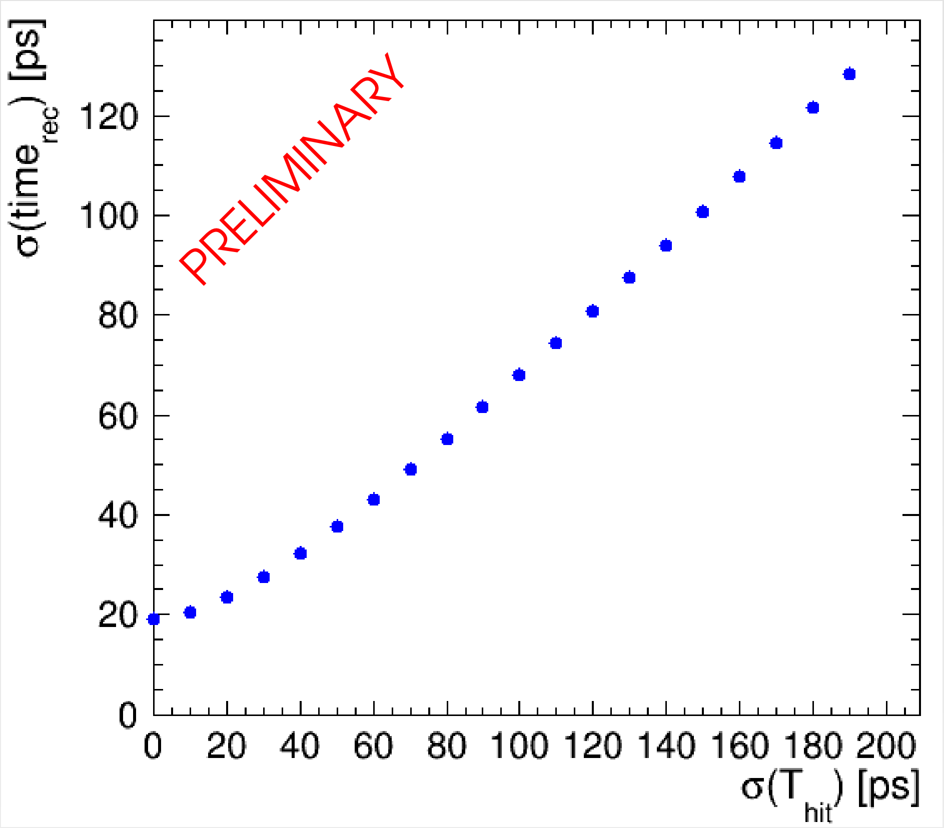
The resolution of o-Ps decay obtained with the presented reconstruction method depends predominantly on the timing resolution of γ hits in scintillator strips.

O-Ps decay resolution

spatial



time

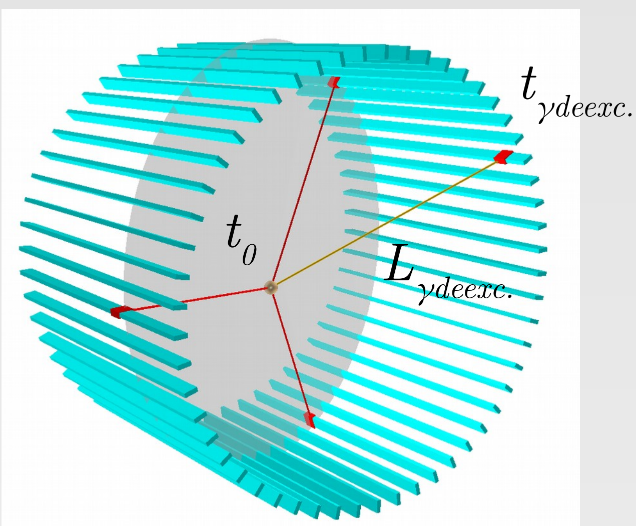


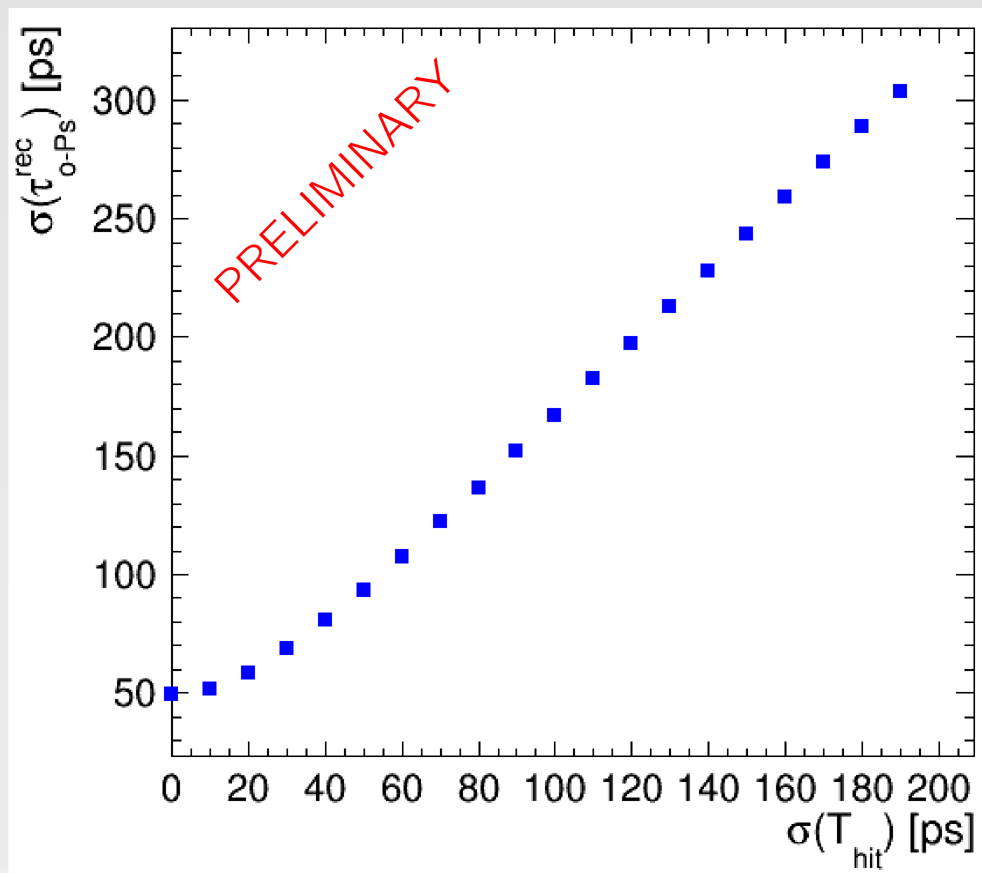
Ortho-positronium life time resolution

For each event of o-Ps decay, the positronium decay time can be estimated as:

$$\tau^{rec}_{o-Ps} = t_0 - \left(t_{\gamma deexc.} - \frac{L_{\gamma deexc.}}{c} \right)$$

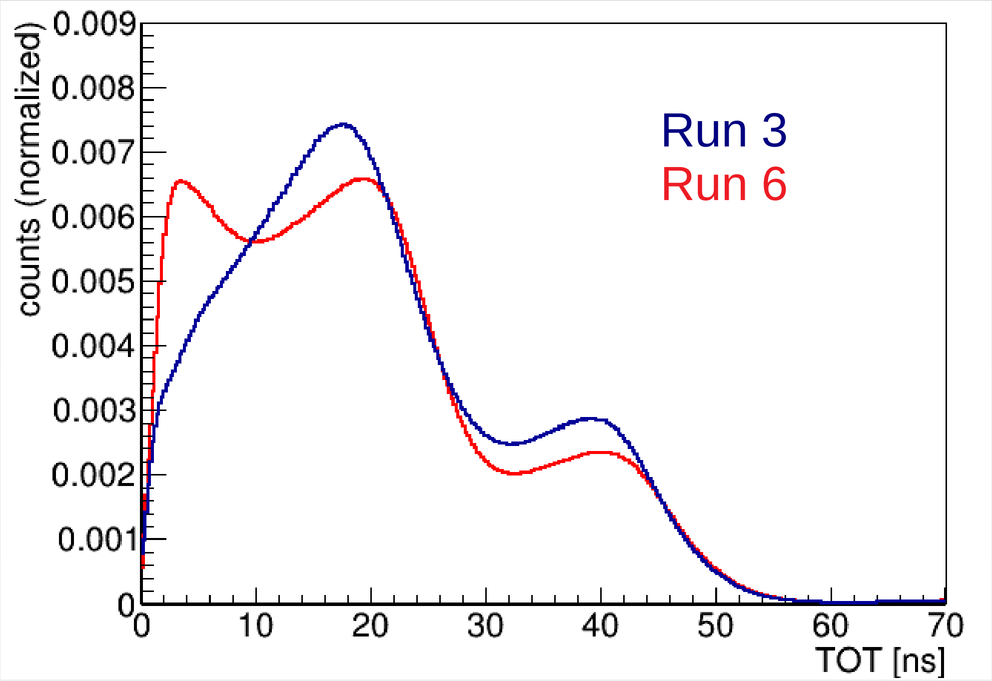
where t_0 is the o-Ps decay time reconstructed with the presented method and $L_{\gamma deexc.}$ is calculated using reconstructed o-Ps decay point.



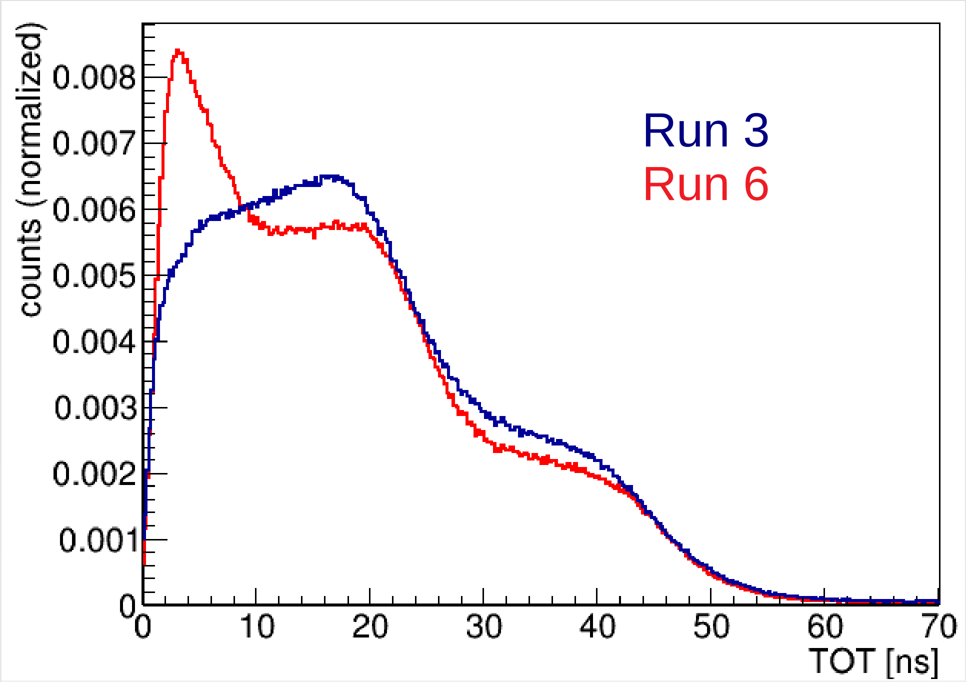


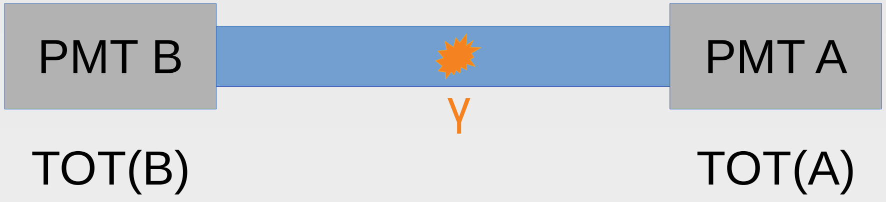
Time Over Threshold (TOT) distributions

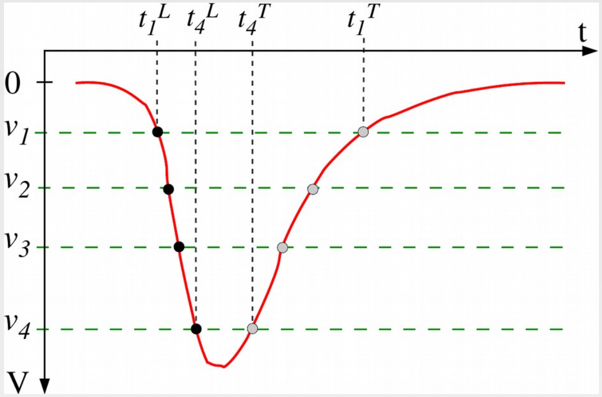
TOT for all recorded γ hits



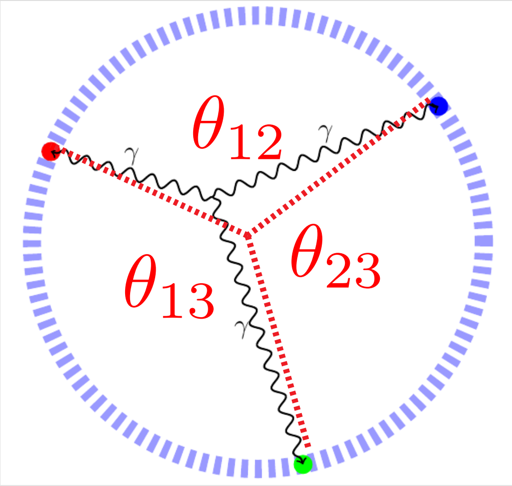
TOT for γ hits recorded in events with at least 3 hits within 20 ns





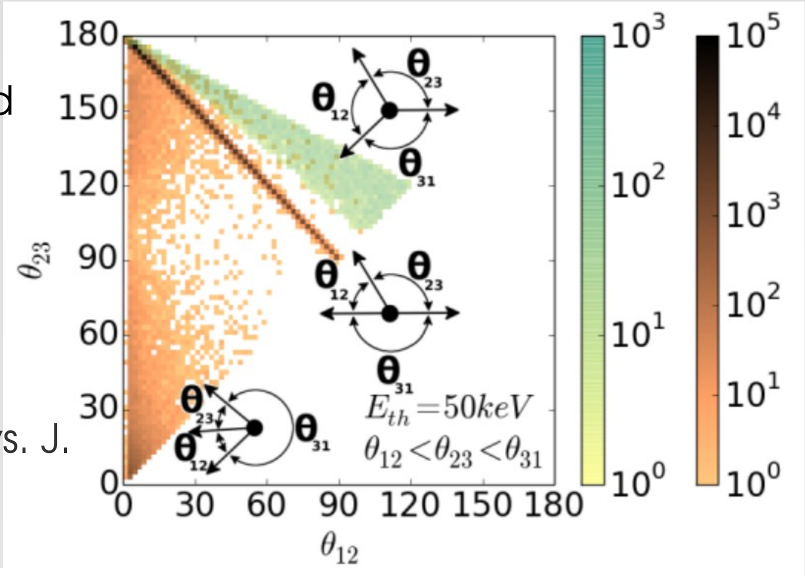


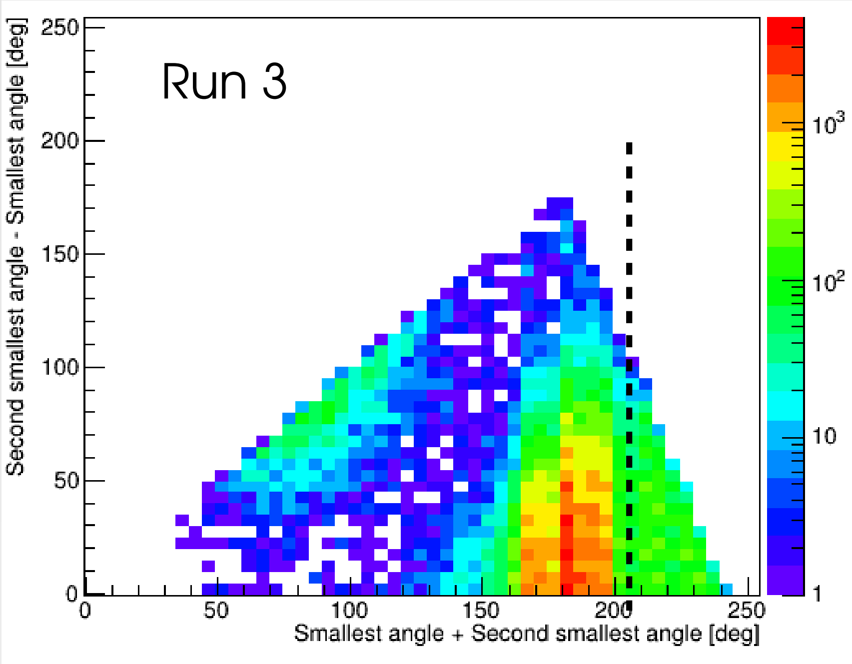
Angular topology of three-photon events

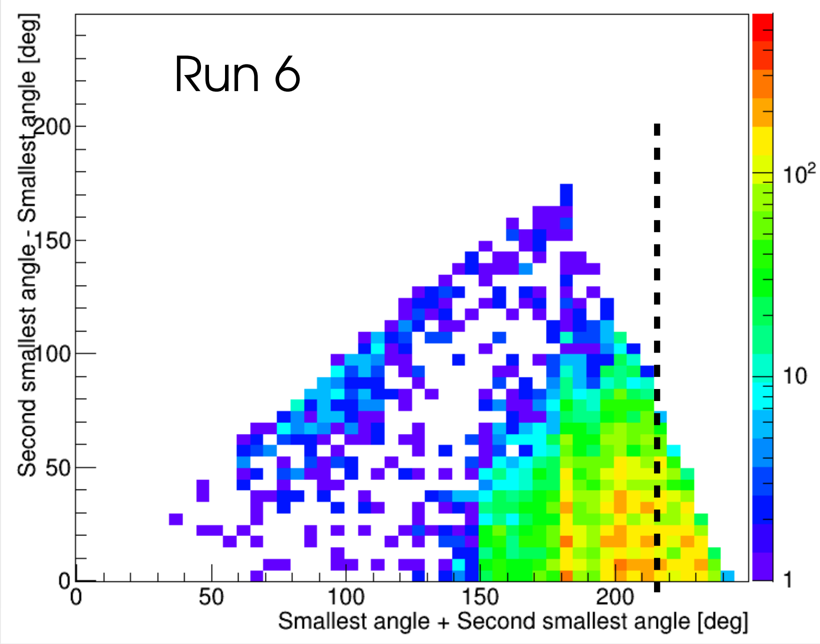


Reference:
Angles between three photons' momenta expected for different types of events (MC simulation results)

[D. Kamińska et al., Eur. Phys. J. C76 (2016) no.8, 445]







For details on the 2γ event properties, see the talk by M. Mohammed, Session 8, Wed 15:50

Detector efficiency for $S^{*}k_1 x k_2$