Searches for discrete symmetry violation signals in decays of positronium atoms at J-PET

3rd Jagiellonian Symposium

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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

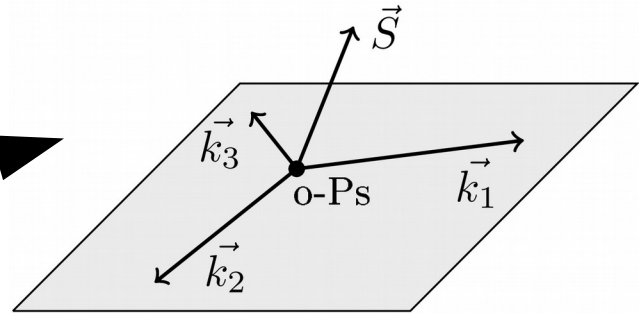
Testing discrete symmetries with ortho-positronium: motivation

- Purely leptonic systems, scarcely tested
  - Only alternative to date: neutrinos, still no conclusive results
  - Compared to neutrinos, can be tested with smaller setups → J-PET!

- Results at precision 10^{-3}, limiting effects at 10^{-9}

Testing discrete symmetries with ortho-positronium: methods

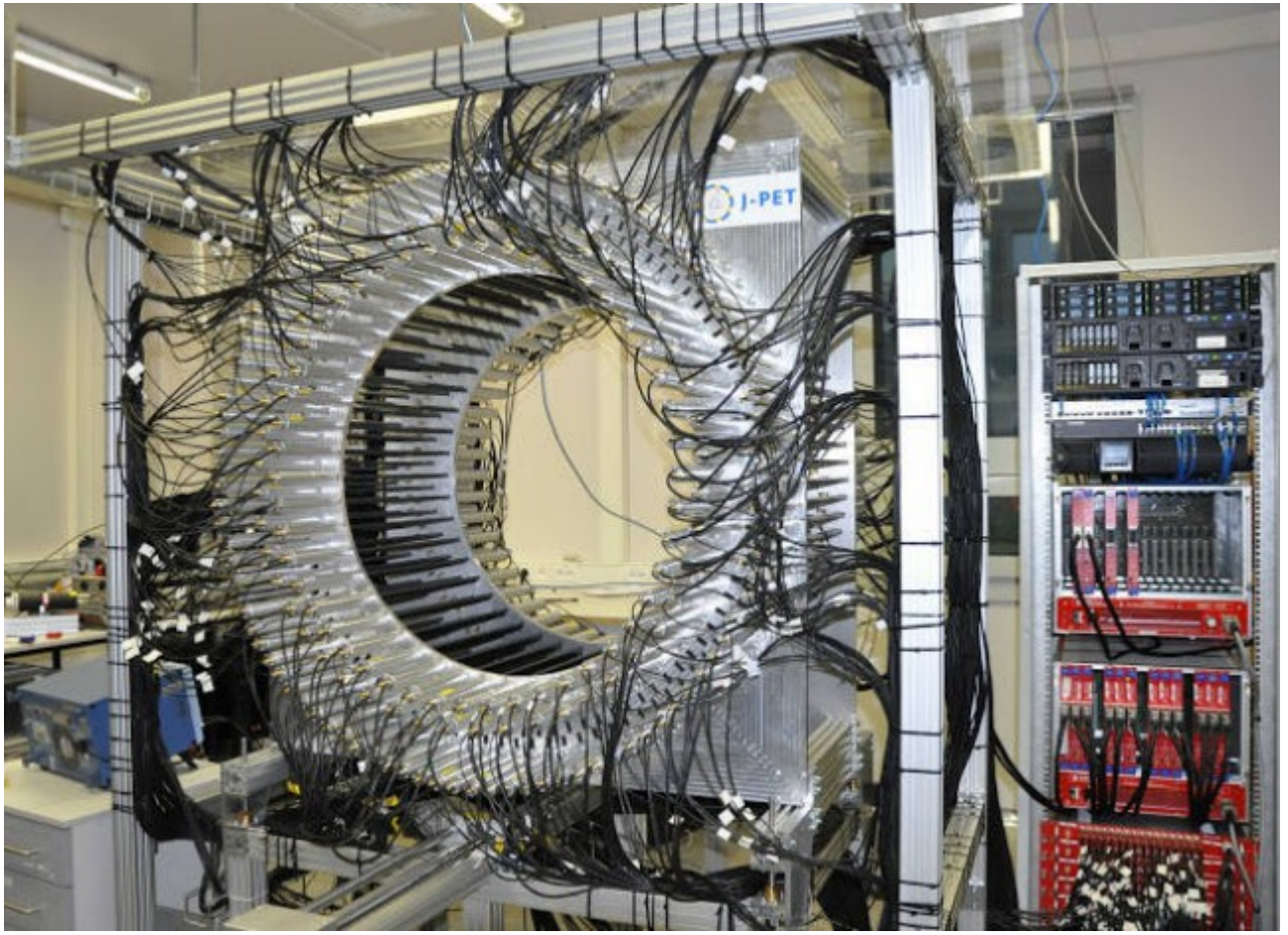
Operator	C	P	T	CP	CPT
$\vec{S}\cdot\vec{k_1}$	+	−	+	−	−
$\vec{S}\cdot\left(\vec{k_1}\times\vec{k_2}\right)$	+	+	−	+	−
$\left(\vec{S}\cdot\vec{k_1}\right)\left(\vec{S}\cdot\left(\vec{k_1}\times\vec{k_2}\right)\right)$	+	−	−	−	+
$\vec{k_2}\times\vec{\epsilon_1}$	+	−	−	−	+
$\vec{S}\cdot\vec{\epsilon_1}$	+	+	−	+	−
$\vec{S}\cdot\left(\vec{k_2}\times\vec{\epsilon_1}\right)$	+	−	+	−	−

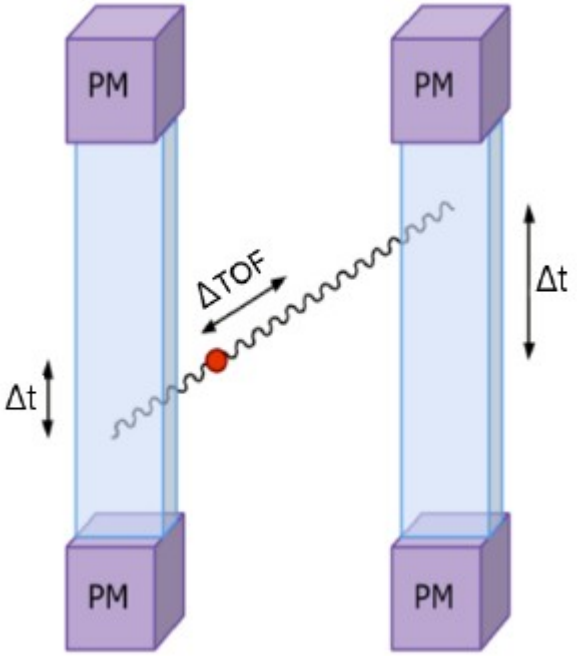


Similar image depicting operators with photon polarization

Anticipate the talk of Juhi

The J-PET Detector

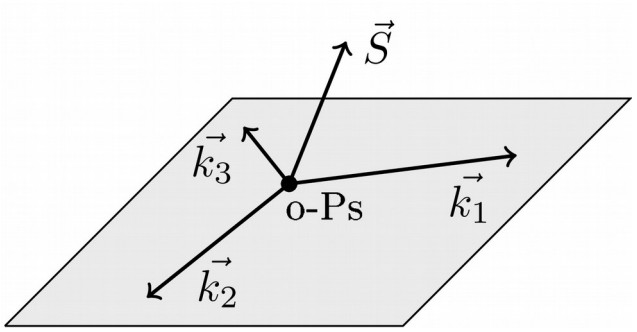




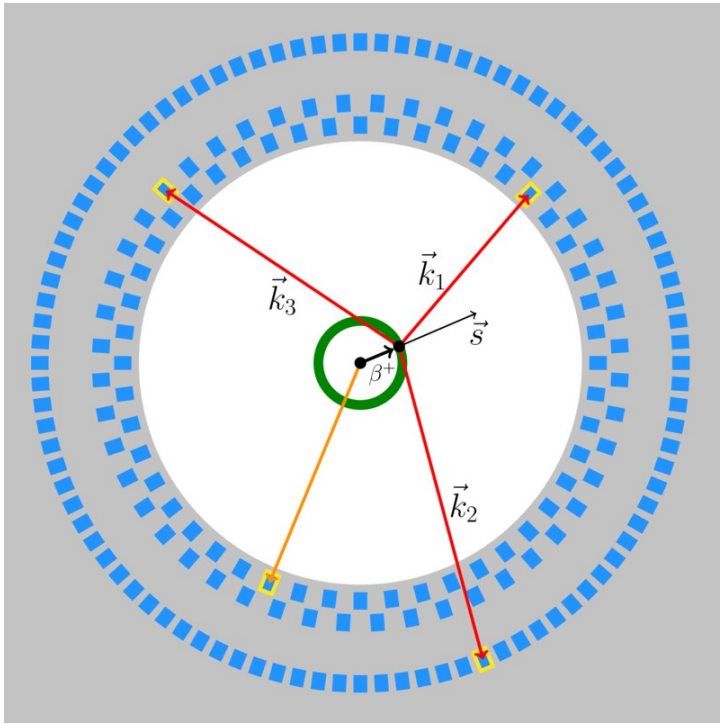
Anticipate the talks about 4th layer on Thursday

Symmetry-sensitive operators involving o-Ps spin

- Measurement of expectation values of angular corelation operators odd under a given discrete symmetry transformation

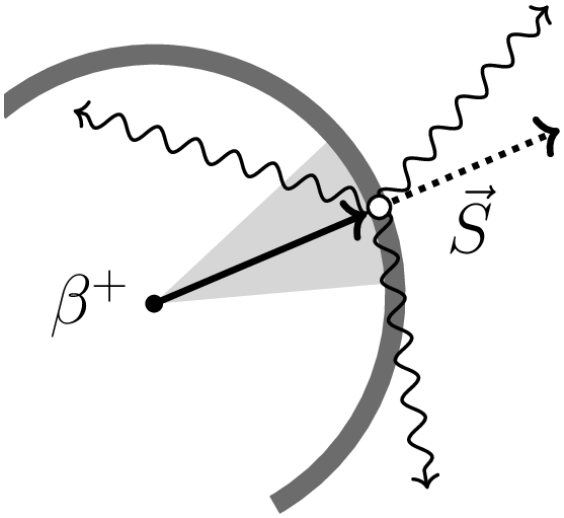


operator	C	P	T	CP	CPT
$\vec{S}\cdot\vec{k_1}$	+	−	+	−	−
$\vec{S}\cdot(\vec{k_1}\times\vec{k_2})$	+	+	−	+	−
$(\vec{S}\cdot\vec{k_1})(\vec{S}\cdot(\vec{k_1}\times\vec{k_2}))$	+	−	−	−	+



- Knowledge of the spin of ortho-positronium is required
- An alternative to using external magnetic field:

  Estimating the original positron spin event-by-event

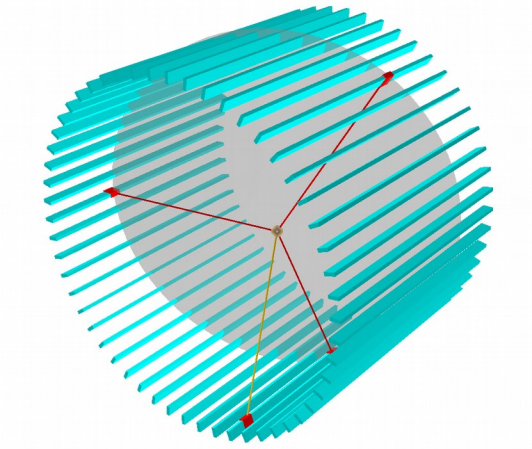


[A. Gajos et al., NIM A 819 (2016), 54-59]

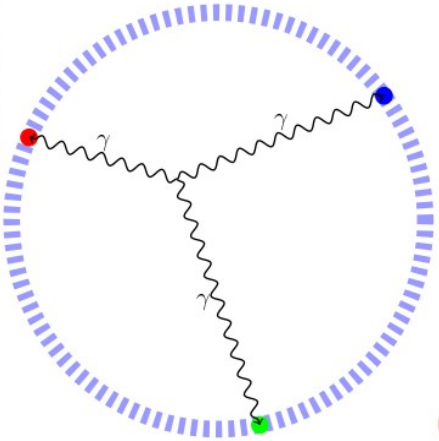
J-PET vs previous measurements

- Compare to Gammasphere and Tokyo

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

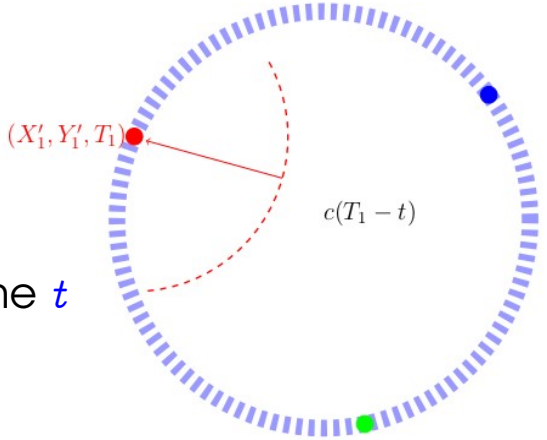


1. Find the decay plane containing the 3 hits in the J-PET barrel

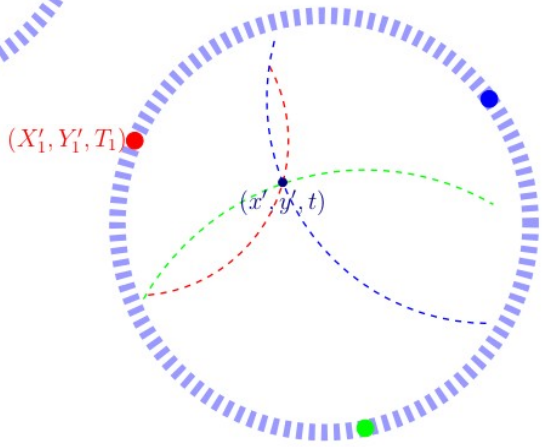


2. Transform the hit coordinates to a 2D coordinate system in the decay plane

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



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:

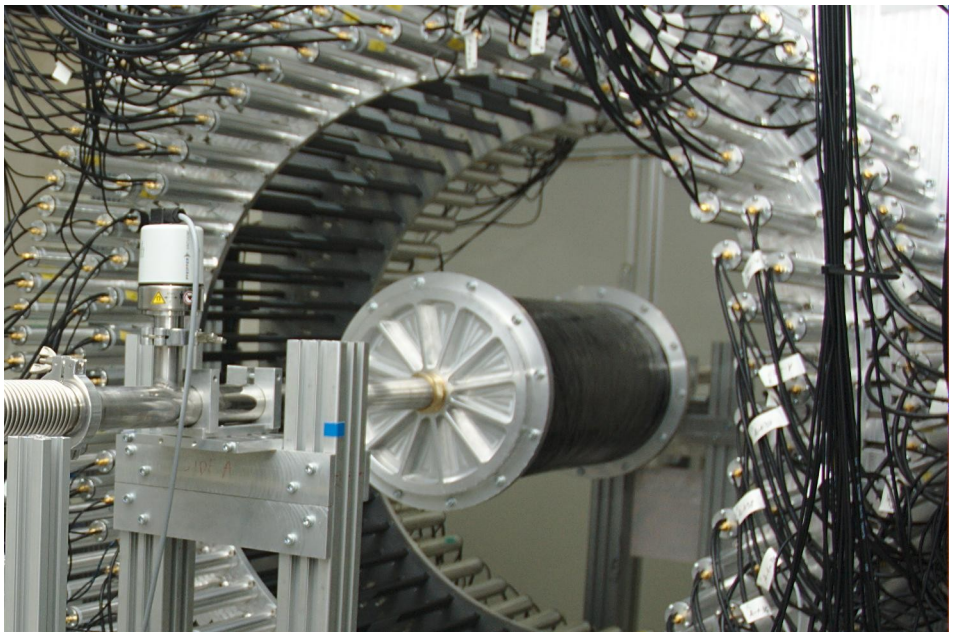
$$(T_i - t)^2 c^2 = (X'_i - x')^2 + (Y'_i - y')^2, \quad i = 1, 2, 3$$

Reconstructing o-Ps→3γ in the J-PET data

- For studies of o-Ps decays without reconstruction of the decay position,

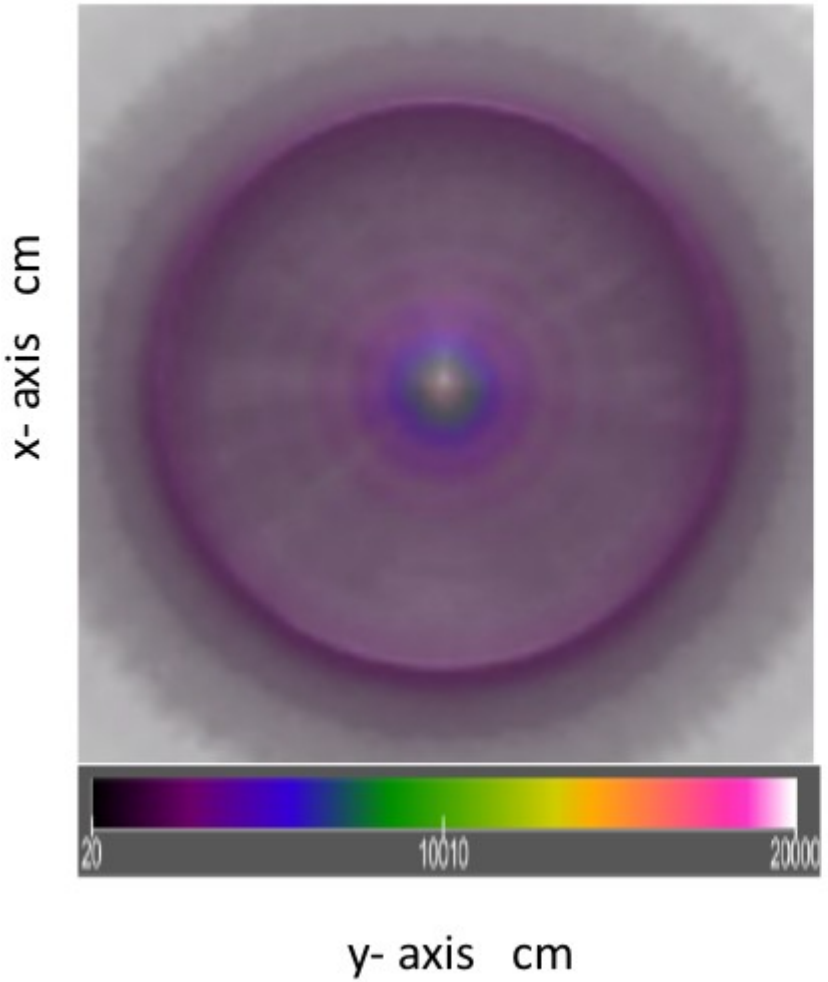
- Three measurements were done with extensive-size annihilation chambers inside J-PET

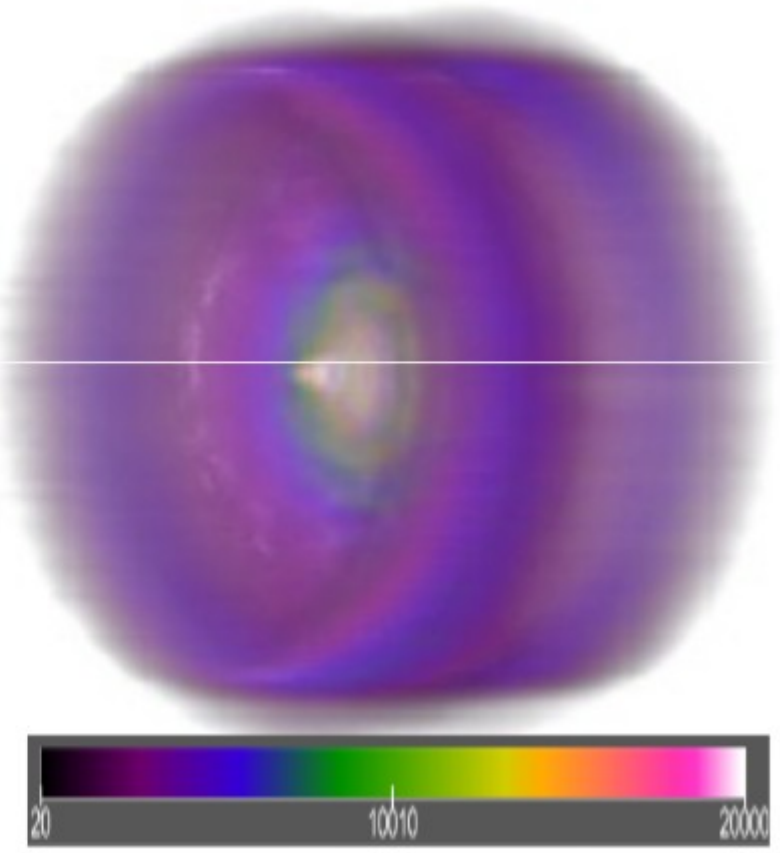
First tests with extensive chamber,
R ≈ 7 cm
No o-Ps production medium
2 days of measurement



New extensive chamber, R ≈ 12 cm
Walls coated with a porous polymer
2 different 22Na source activities used
10 Mbq - 180 days of measurement
0.8 Mbq - ??? days of measurement

2gamma images





(with scale included)

Data analysis flow for o-Ps→3γ identification

- Assembling of PMT signals and photon hits in the scintillator strips using the standard J-PET procedures

- Identification of candidates for:
  - annihilation photons
  - prompt photons

  based on the Time-Over-Threshold (TOT) values

- Requirement of 3 annihilation photon candidates in a 2.5 ns event

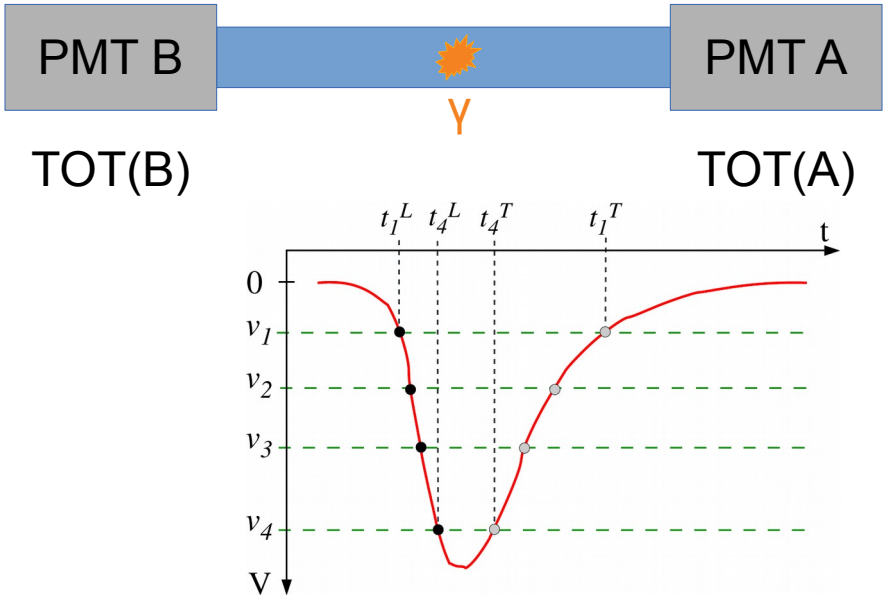
- Rejection of multiple subsequent γ scatterings in the detector

- Study of the angular topology of the events

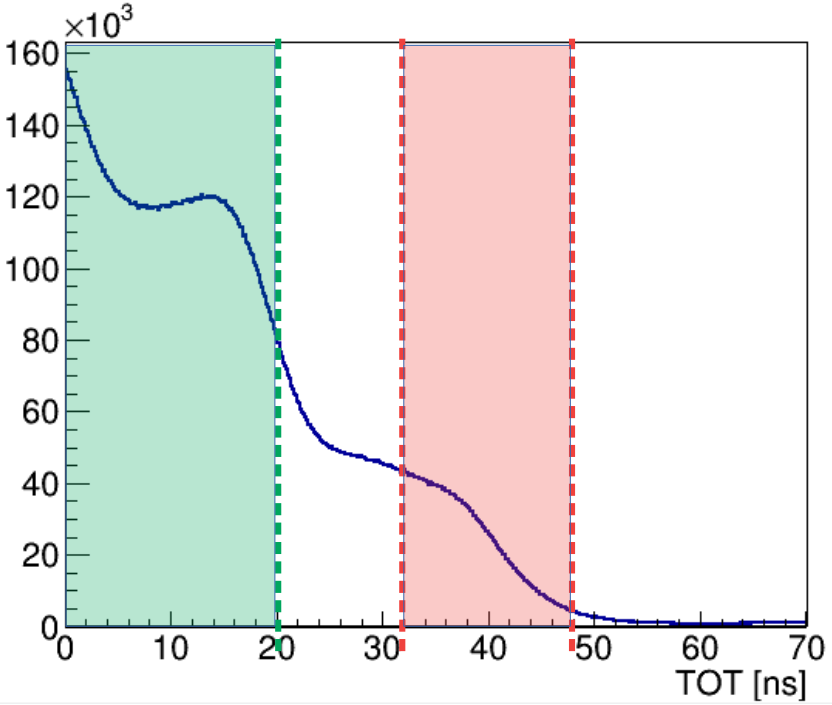
- Trilateration-based reconstruction of o-Ps → 3γ decay point and time

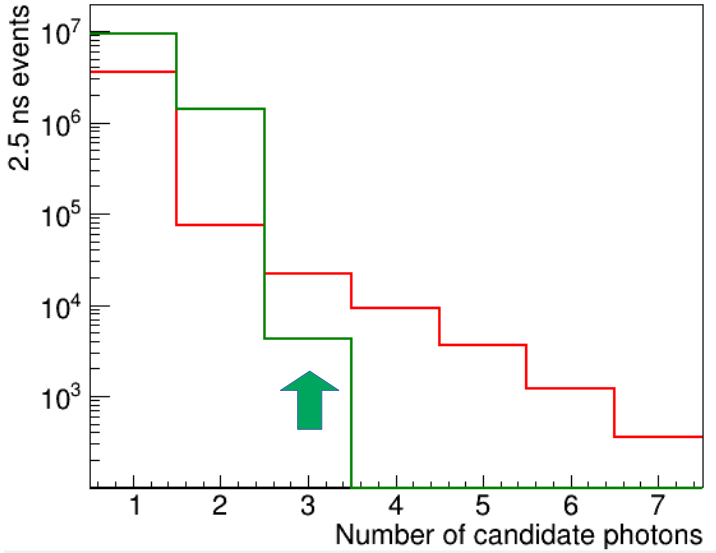
Using TOT to identify prompt and annihilation γ

- Normalized TOT spectrum including a simple correction for uneven charge response of particluar detection modules



o-Ps →3γ annihilation (E<511 keV)
^{22}Ne* de-excitation (E=1274 keV)

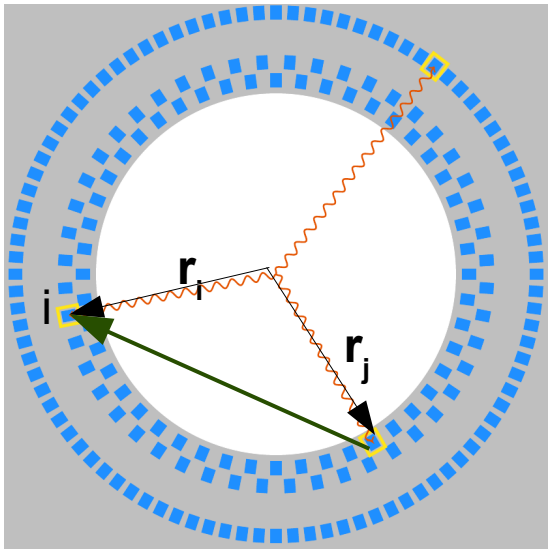




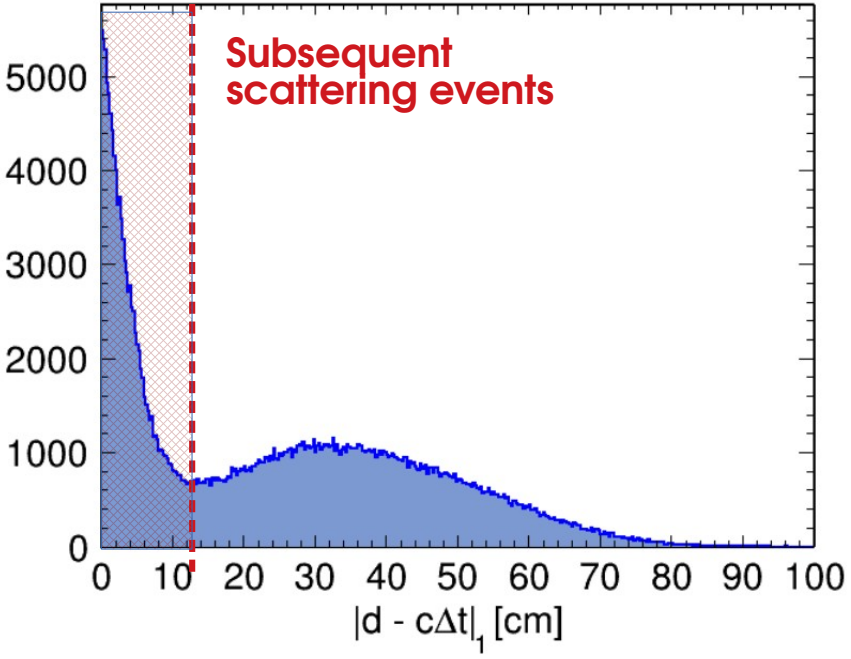
Rejection of subsequent scatterings in the detector

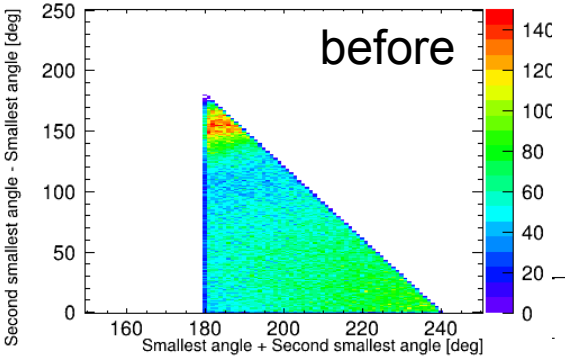
- See talk by J. Raj for the case when we **do not** want to reject these scatterings
- For each pair of annihilation photon candidates *i* and *j* (*i*,*j*=1,2,3) the following figure is computed:

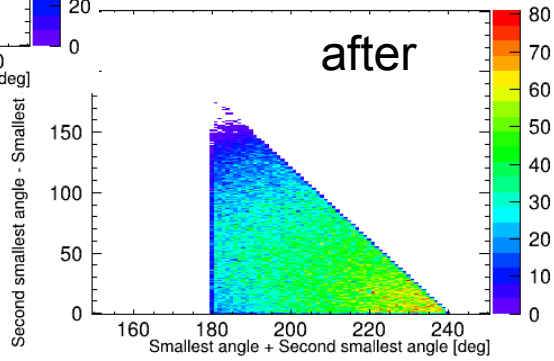
$$\delta t_{ij} = |t_i - t_j| - \frac{1}{c}|\vec{r}_i - \vec{r}_j|$$



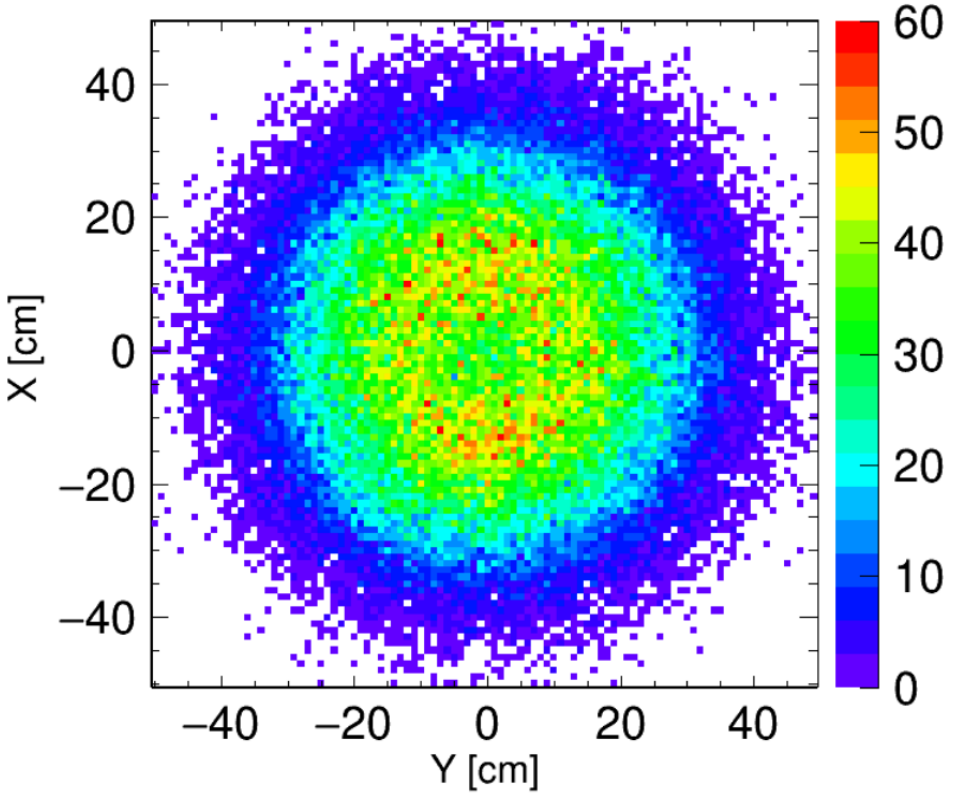
Distribution of the minimum δt_{ij} over all photon pair choices in a events:





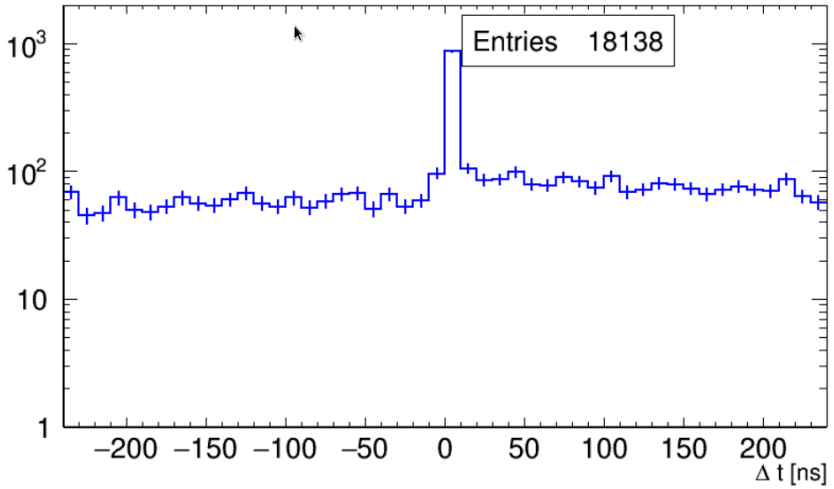


Images of the large chamber

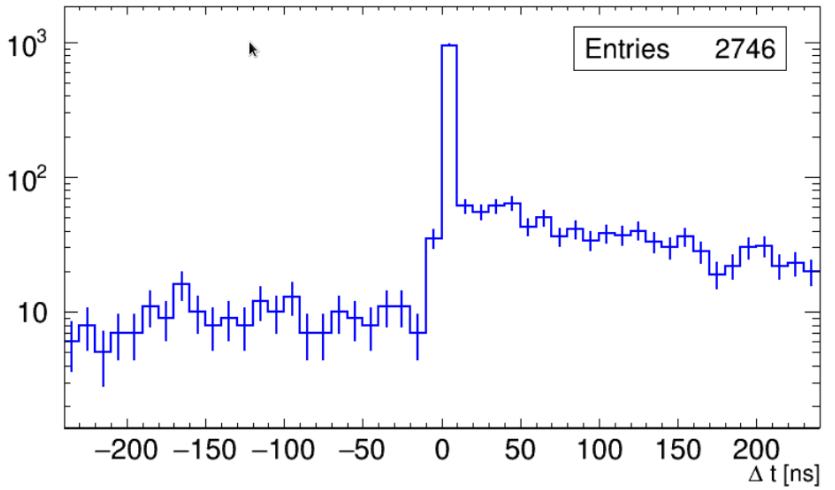


O-Ps lifetime spectra and accidental conicidences

Scheme with a propmt photon followed by an o-Ps → 3g annihilations

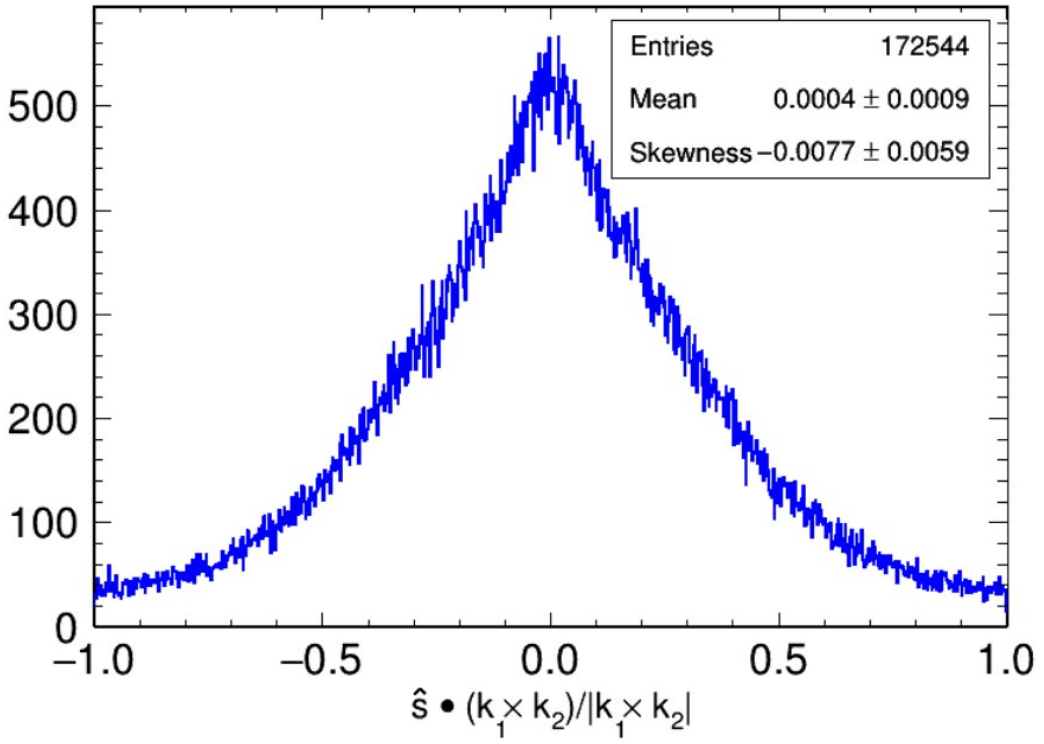


Soure activity 10 MBq



Soure activity 0.8 MBq

CPT-violation sensitive operator



Using: [fraction] of available data

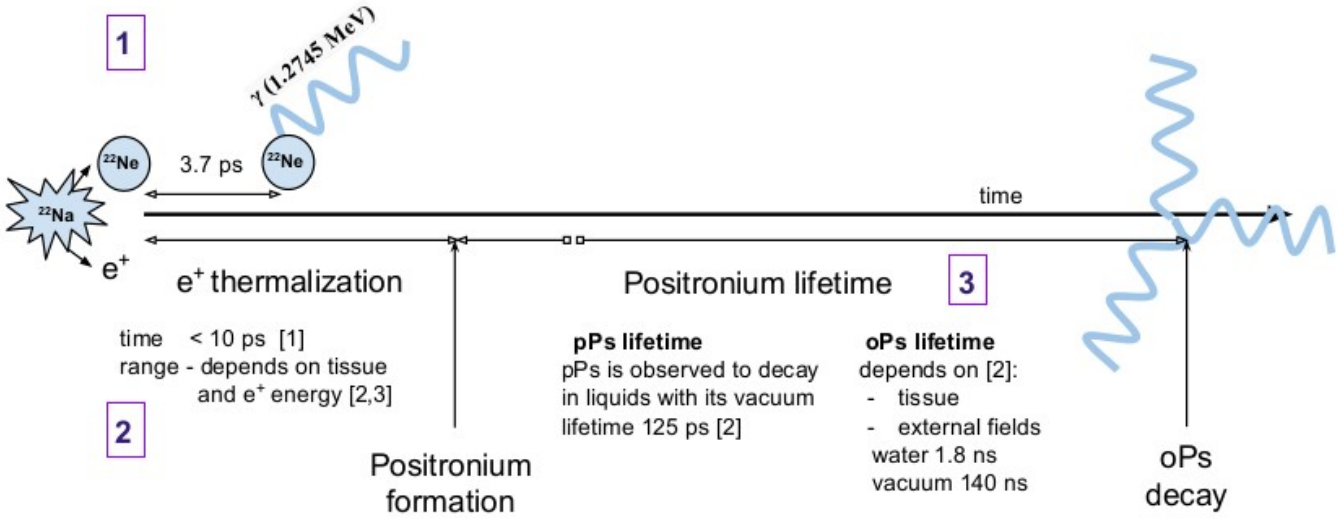
Summary and perspectives

- Estimate the expected statistical uncertainty with full analysed dataset
- Show the spherical chamber?

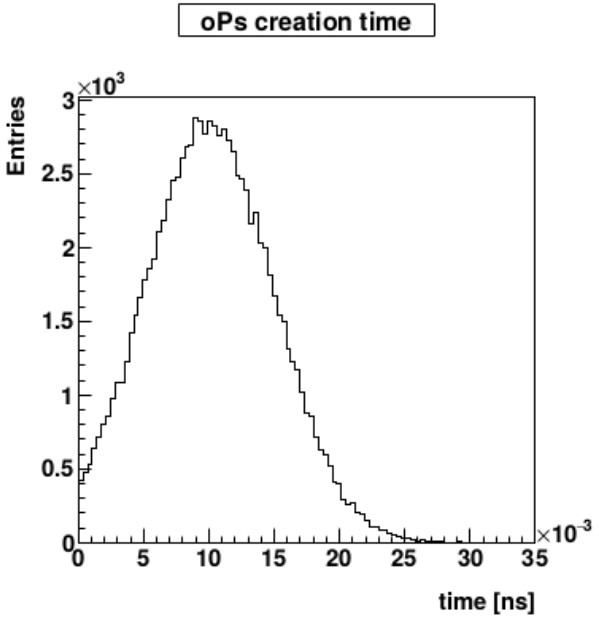
Thank you for your attention!

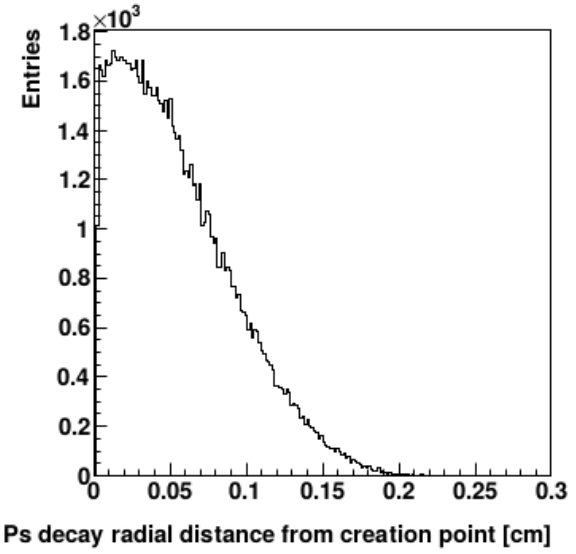
Backup Slides

O-Ps creation and decay



[1] P. Kubica and A. T. Stewart, Phys. Rev. Lett. 34 (1975) 852
[2] M. Harpen Med.Phys. 31 (2004) 57-61
[3] J Cal-Gonzalez et al, Phys. Med. Biol. 58 (2013) 5127–5152





Distinguishing o-Ps→3γ and e^+e^-→2γ

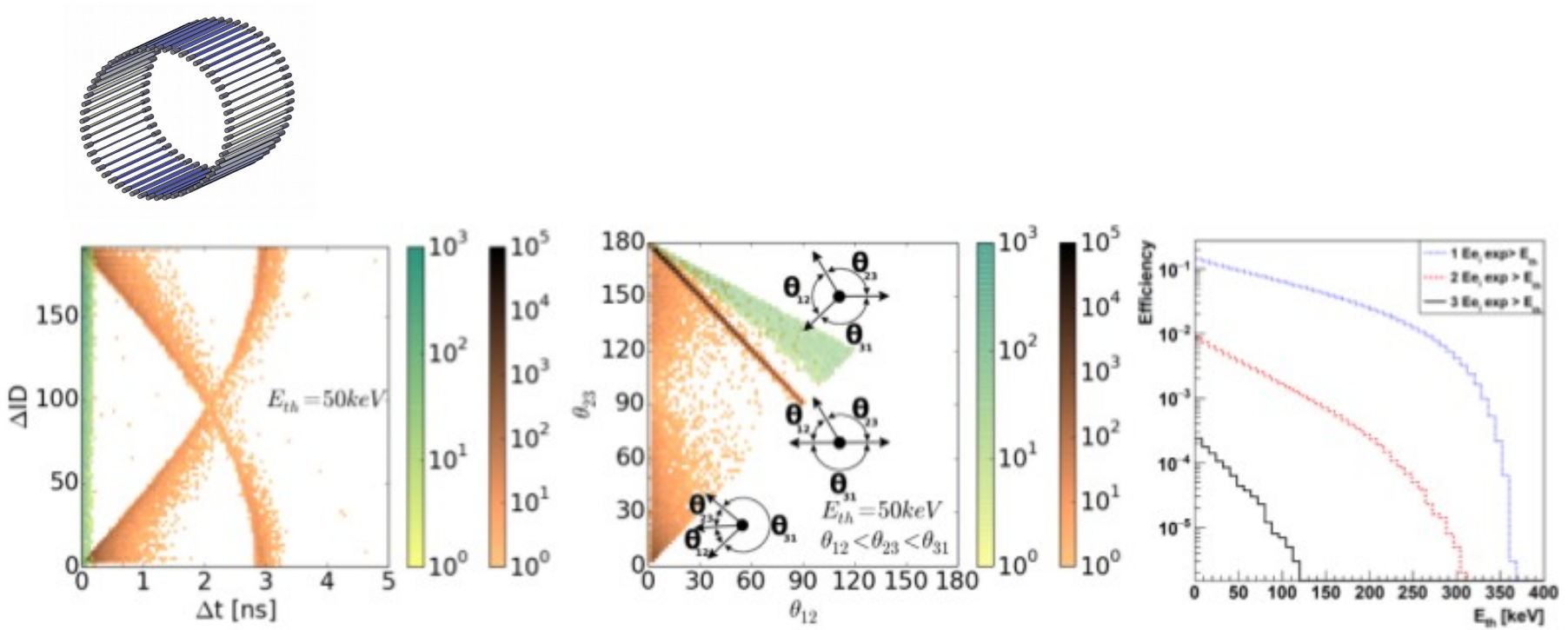


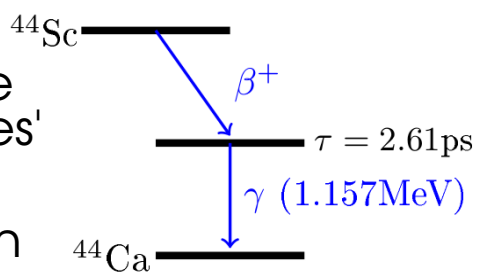
Figure 9. (Left) Simulated distributions of differences between detectors ID (ΔID) and differences of hit-times (Δt) for events with three hits registered from the annihilation e+e- → 2γ (gold colours) and o-Ps → 3γ (green colours). **(Middle)** Disribution of relative angles between reconstructed directions 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.

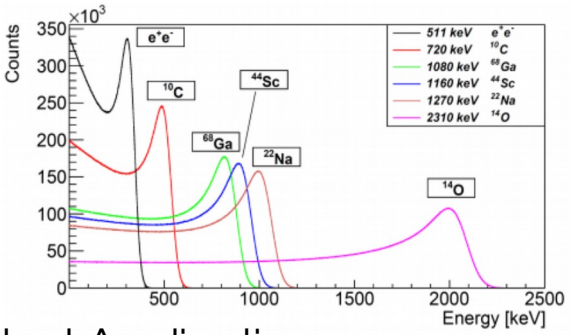
[J-PET: P.Kowalski, P.Moskal, in preparation]

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

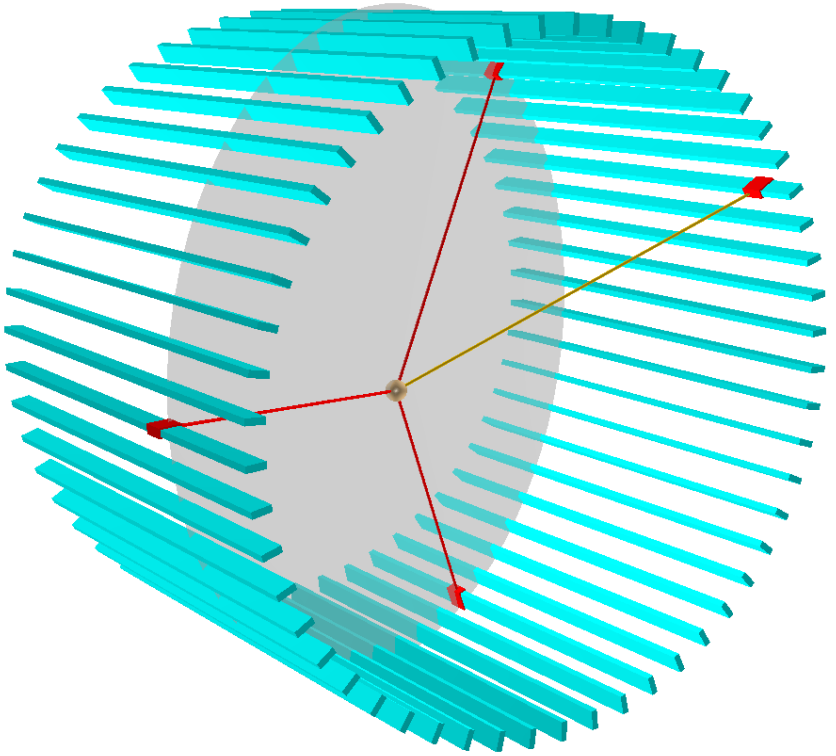




[P.M. et al., Patent Application: PCT/EP2014/068374; WO2015028604]

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

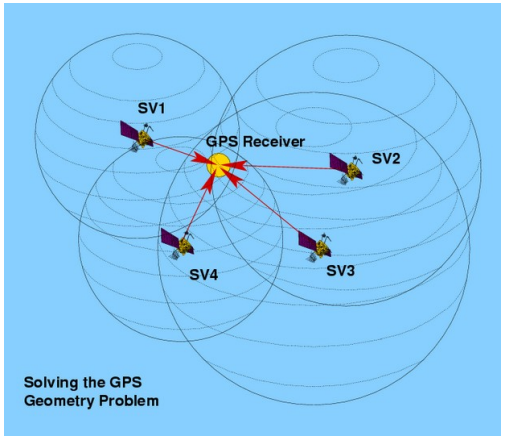


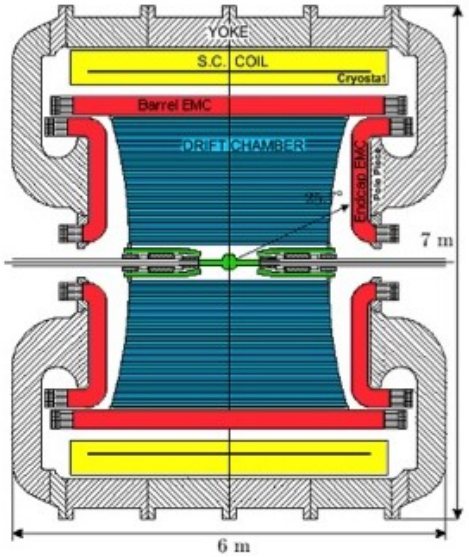
Origin of the reconstruction method

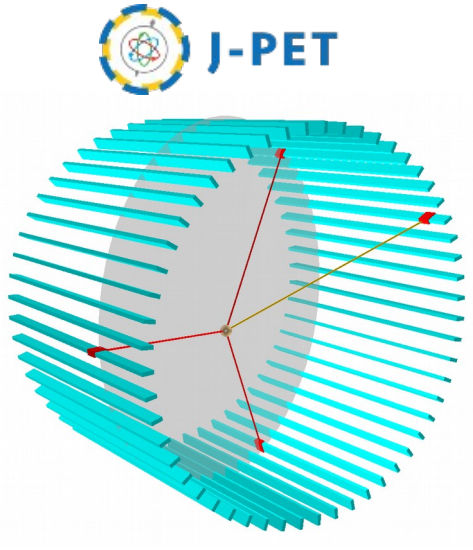
- The reconstruction method applied to o-Ps decays in J-PET was originally created for kaon decays at the KLOE detector

[A. Gajos Dipl.Thesis (2013) Jagiellonian University]
[Acta Phys. Pol. B 46 (2015) 13]

- Mathematical principle of the reconstruction is similar to GPS positioning





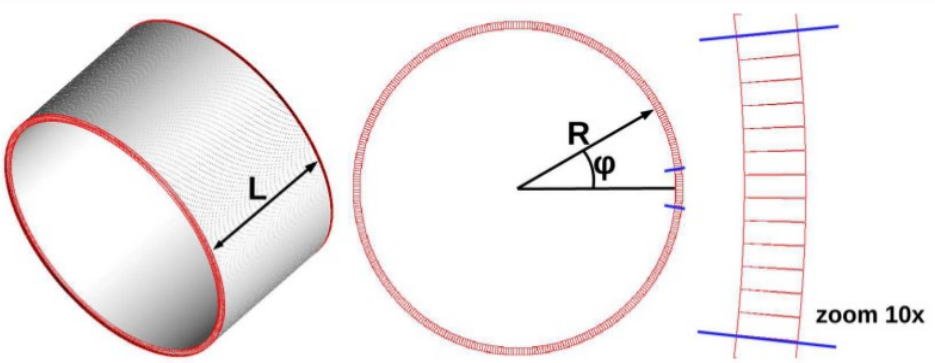


	GPS	$K_L \rightarrow 3\pi^0 \rightarrow 6\gamma$ at KLOE	o-Ps$\rightarrow 3\gamma$ at J-PET
Shere centers	Satellite locations	γ hits in KLOE calorimeter	γ hits in J-PET barrel
Whose travel time is measured?	Radio signals from satellites	Photons from π^0 decays	Photons from o-Ps decay
Reconstructing position of	GPS receiver	$K_L \rightarrow 3\pi^0 \rightarrow 6\gamma$ decay	o-Ps$\rightarrow 3\gamma$ 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

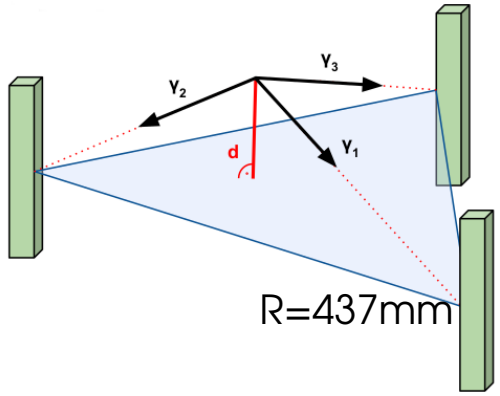
- Monte Carlo simulations of o-Ps decays recorded by the J-PET detector were prepared
- J-PET detector with 384 scintillator strips was assumed in simulations
  - Single strip size: 7x19x500mm^3
  - Barrel dimensions:

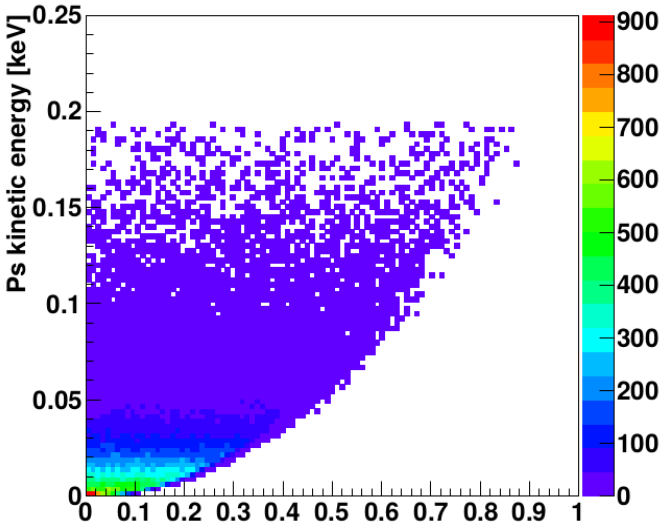
    R = 43cm, L = 50cm
  - Resolution in XY plane: $\Delta\varphi \approx 0.5$deg
- Simulation includes:
  - β^+ emitter deexcitation and prompt
  - Positron thermalization before positronium creation (in water)
  - Ortho-positronium lifetime (for water)
  - Momentum of the decaying positronium – deviation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



Effects included in the simulation

Non-coplanarity of photons' momenta

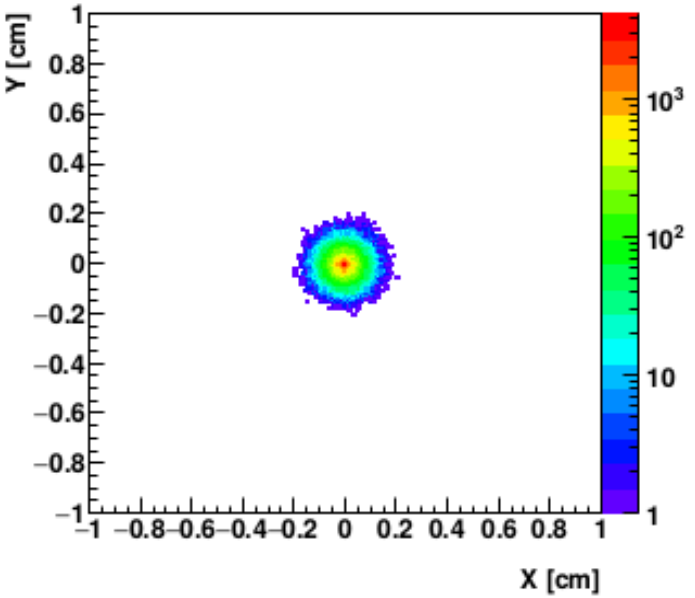




(courtesy of D. Kamińska)

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)

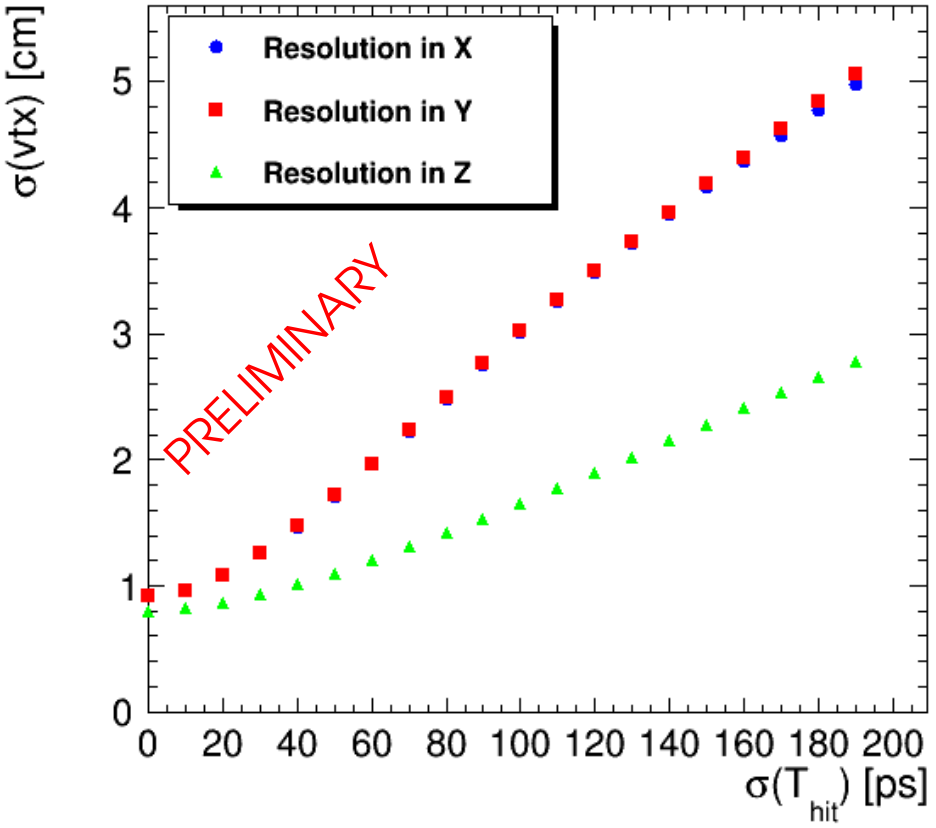
Both effects are negligible within reconstruction resolution (presented on next slides).

Resolution dependence on γ hit time resolution

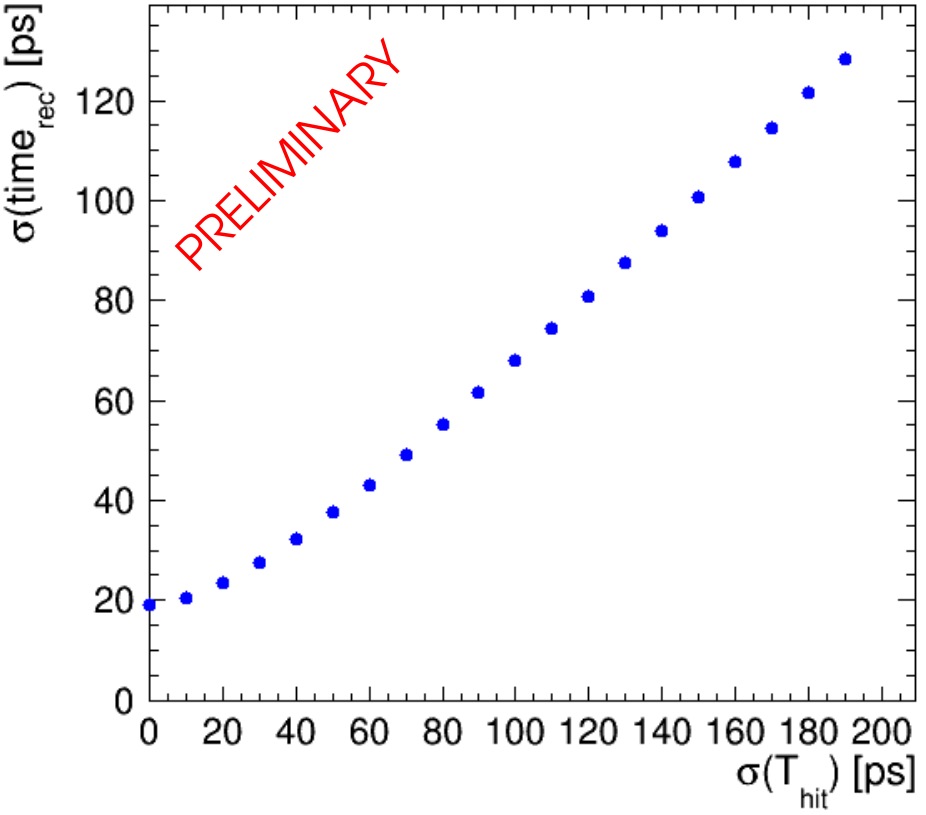
The resolution of o-Ps decay obtained with the presented reconstruction method depends predominantly on the timing resolution of γ hits in scintillator strips.

O-Ps decay resolution

spatial



time

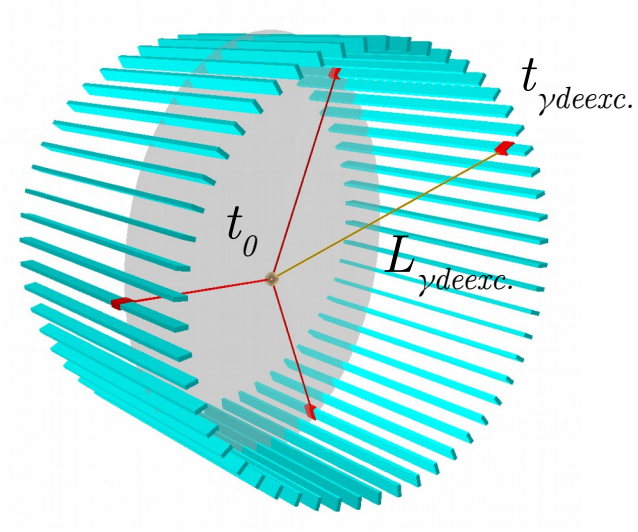


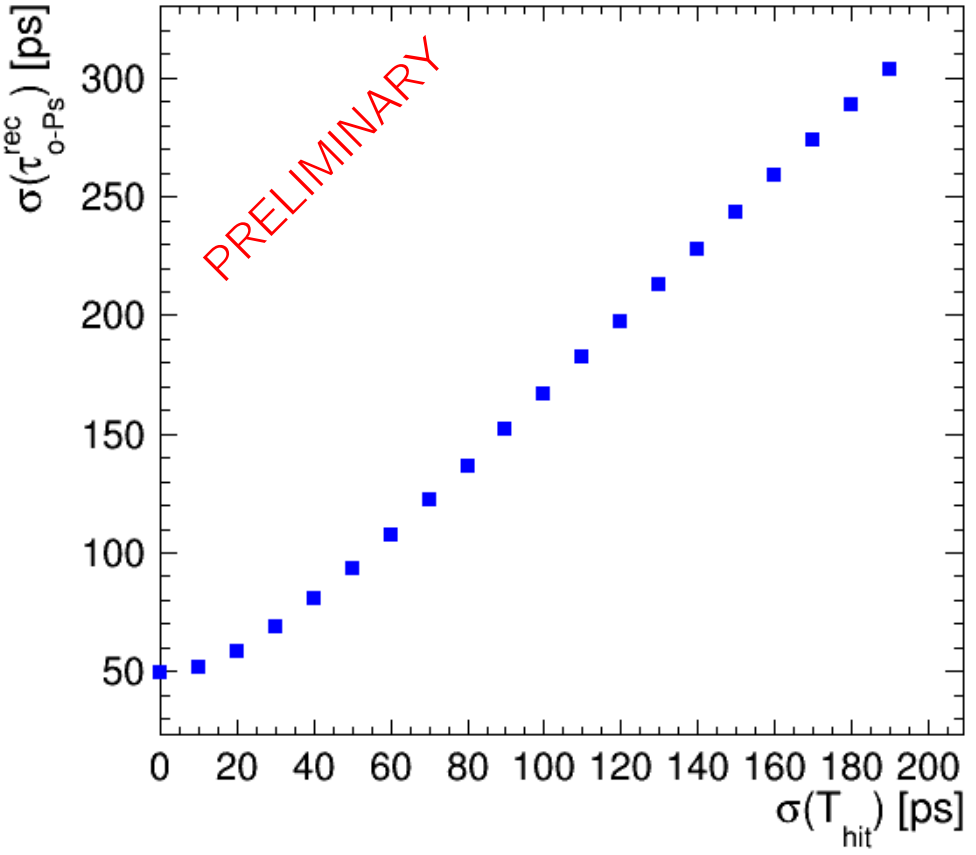
Ortho-positronium life time resolution

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

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

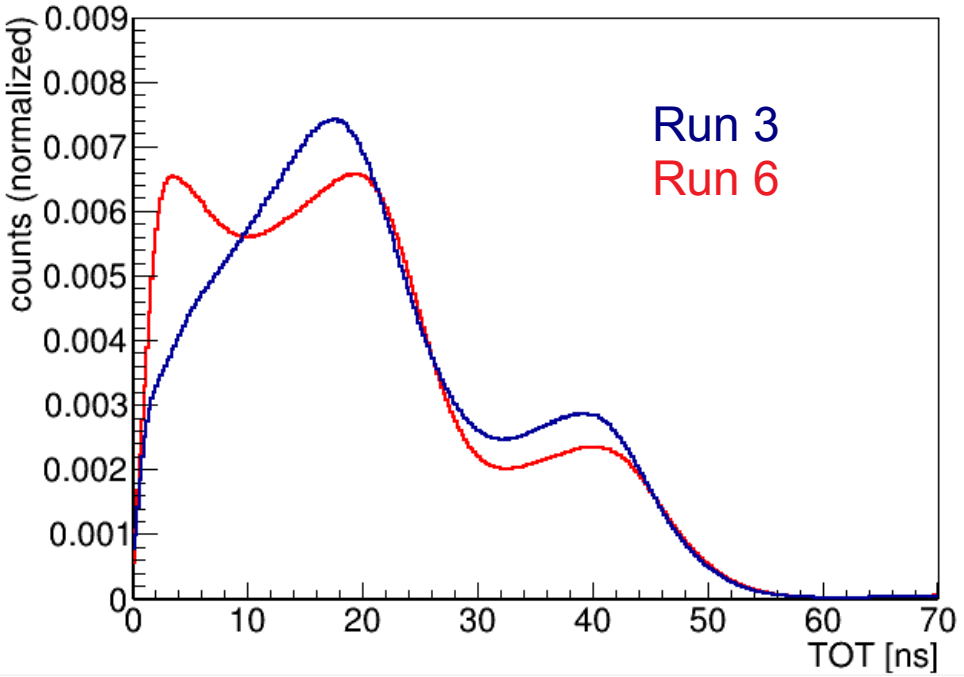
where t_0 is the o-Ps d[illegible] presented method and $L_{\gamma deexc.}$ is calculated using reconstructed o-Ps decay point.



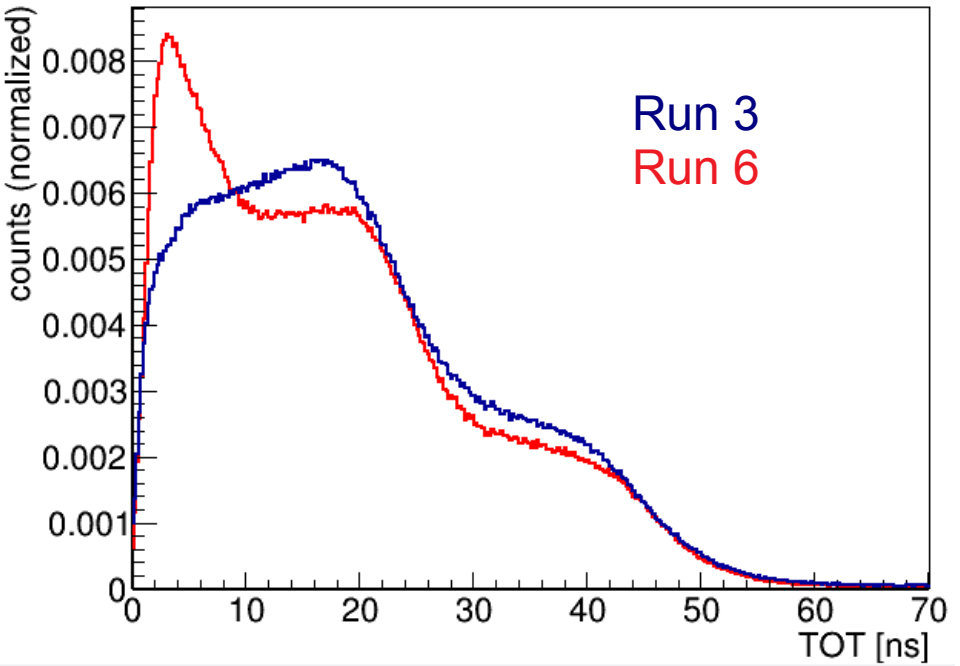


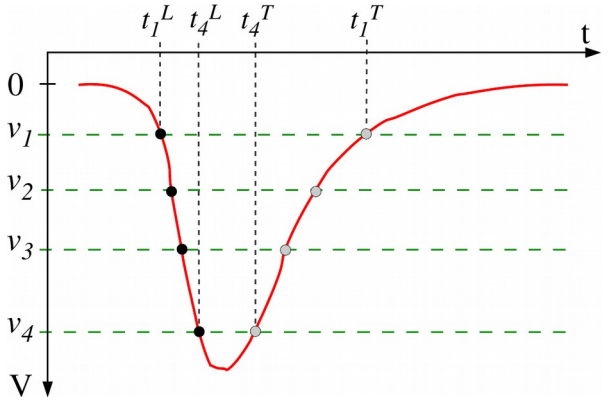
Time Over Threshold (TOT) distributions

TOT for all recorded γ hits

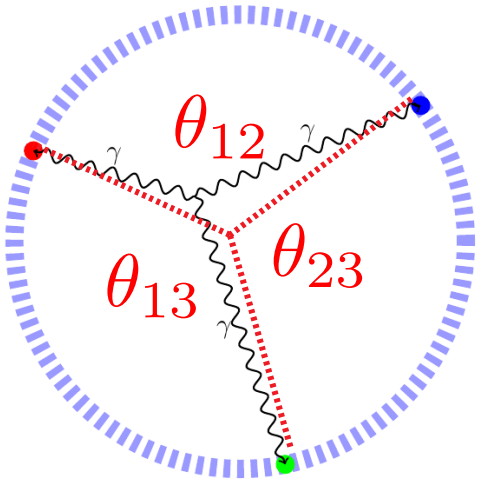


TOT for γ hits recorded in events with at least 3 hits within 20 ns



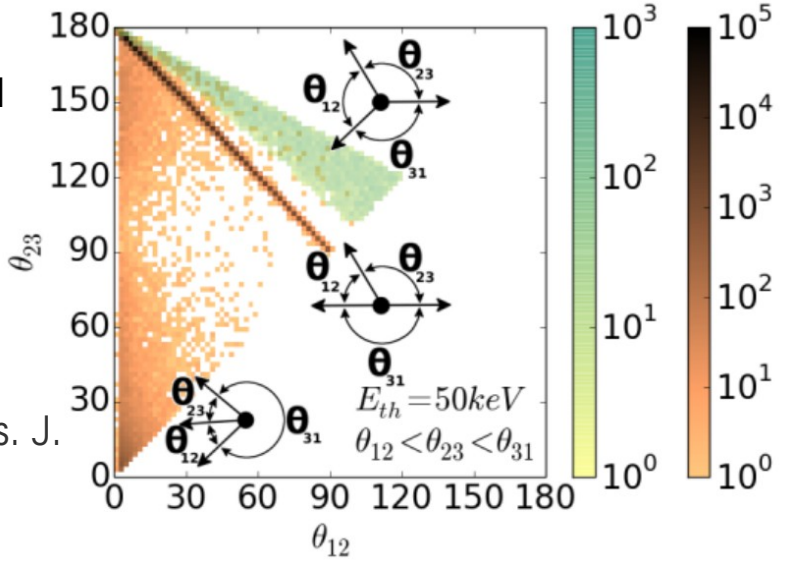


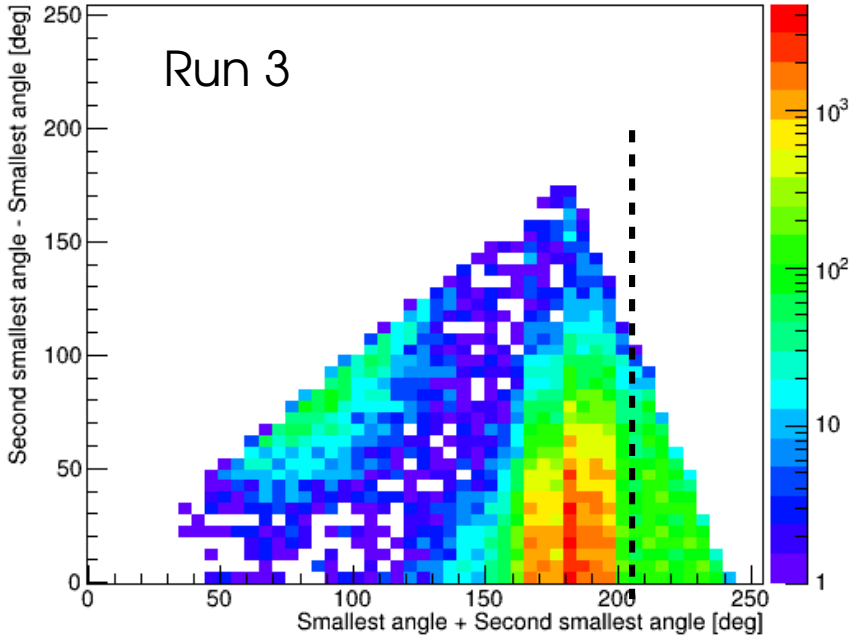
Angular topology of three-photon events

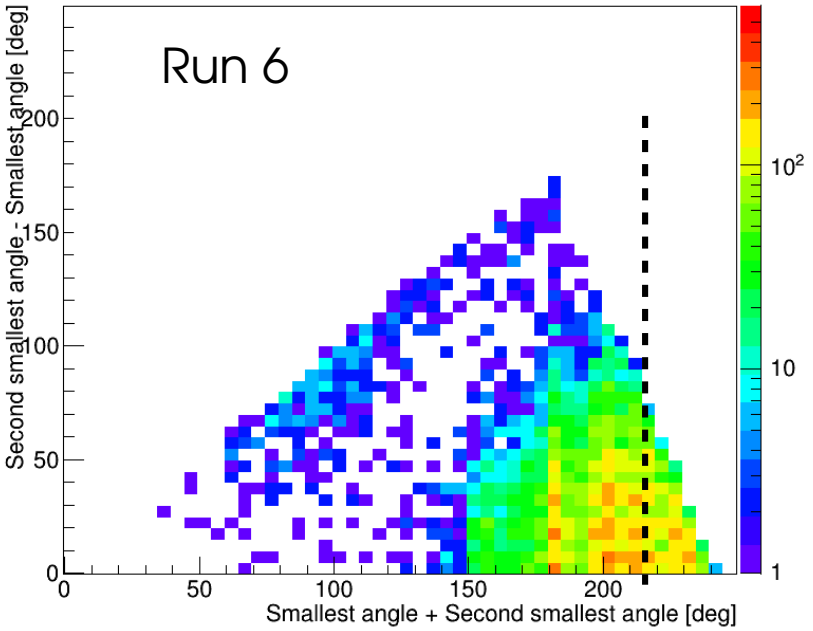


Reference:
Angles between three photons' momenta expected for different types of events (MC simulation results)

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



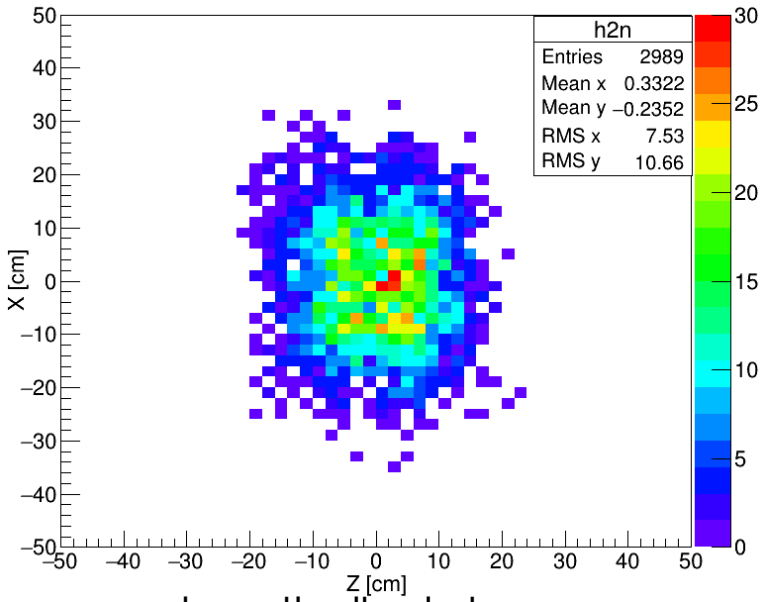




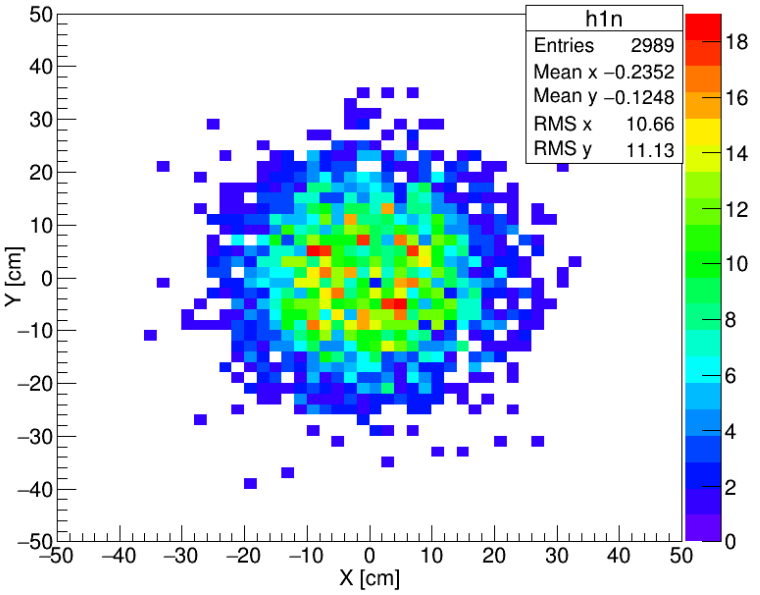
For details on the 2γ event properties, see the talk by M. Mohammed, Session 8, Wed 15:50

Reconstructed o-Ps → 3γ decay points

Results obtained with the trilaterative decay point reconstruction
Using about 3 % of the collected Run 6 data



Longitudinal view



Transverse view