XIV International conference on Beauty, Charm And Hyperon Hadrons, AGH-UST, Krakow

J-PET tomography as a *novel detector*

for discrete symmetries studies in charge leptonic system

S. Sharma on behalf of the J-PET collaboration

07.06.2022

Outline

Jagiellonian Positron Emission Tomography

first plastic scintillator based tomograph as novel detectors for testing symmetries

Positronium atom

Purely charged leptonic system, a potential laboratory for discrete symmetry test

Odd-symmetry operators accessible with J-PET

New list of operators considering the photon's polarization

Future upgrades

Towards modular based detectors

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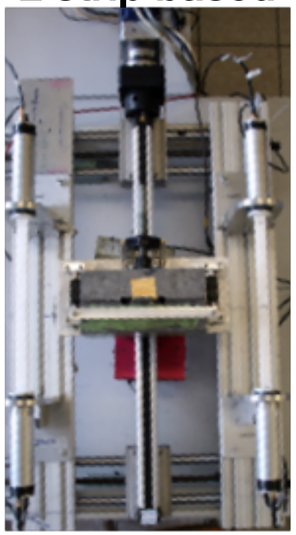
Evolution of plastic scintillator based multi-modules detector

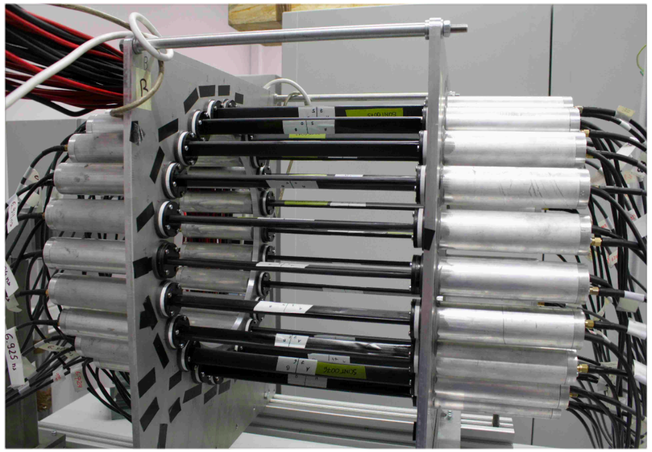
2 strip based



Characterize scintillator properties
Energy resolution, hit time, ..

NIM A 764 (2014) 317

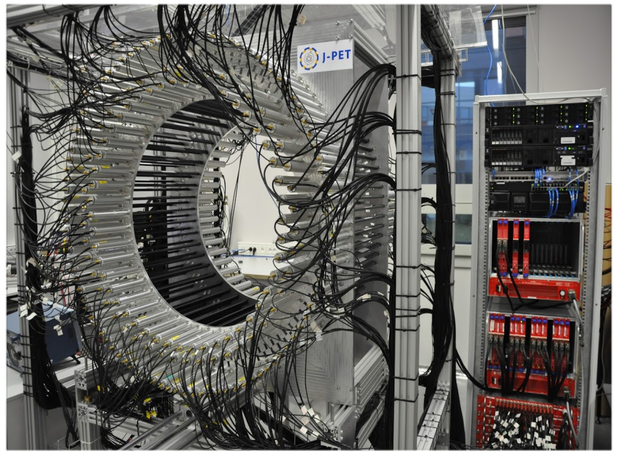
Prototype with 24 plastic strips



Data acquisition validation for multi-modules

IEEE TIM 70 (2021) 1-10

3-Layer prototype (192 strips)



Current version
Fundamental symmetries test and Positronium imaging

Acta Phys. Pol. B 47 (2016) 509
Nature comm. 12 (2021) 5658
Science advances 7 (2021) eabh4394

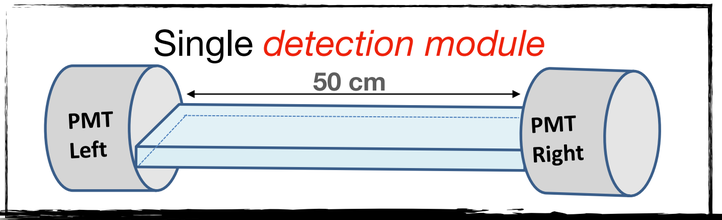
Modular J-PET (24 Modules)

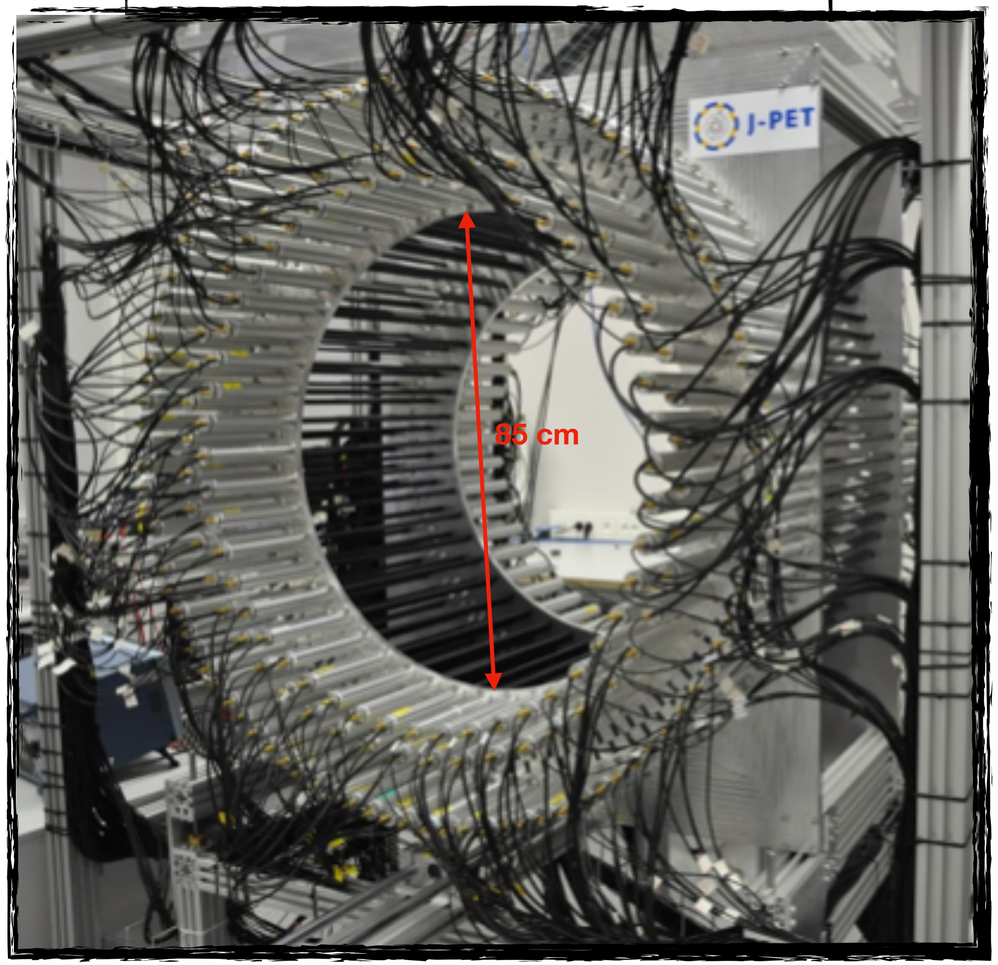
First data campaign (2022)
J-PET's Plastic Revolution - CERN COURIER
https://cerncourier.com/a/j-pets-plastic-revolution/

2012 → 2014 → 2016 → 2021

Key Features of 3 - layer prototype of J-PET

- **192** *detection modules* are arranged in 3 concentric cylinders (diameter of innermost is 85 cm).
- Each detection module consist of *one plastic scintillator* (50 x 1.9 x .7 cm3) read-out at each end by photomultipliers
- **Trigger less** and **reconfigurable** DAQ
- Time Over Threshold (TOT) is used, as a measure of energy deposition
- **A dedicated J-PET data analysis framework** : an open source software platform written in C++ , based on ROOT package
  - ➡ Signal reconstruction,
  - ➡ Calibrations,
  - ➡ filtering procedures,
  - ➡ **User-level data analysis** by **accessing** the in-built function
- Monte Carlo simulations based on Geant4-toolkit, adapted to Simulation Ps decays events





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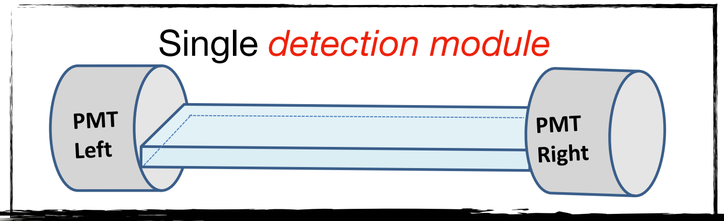

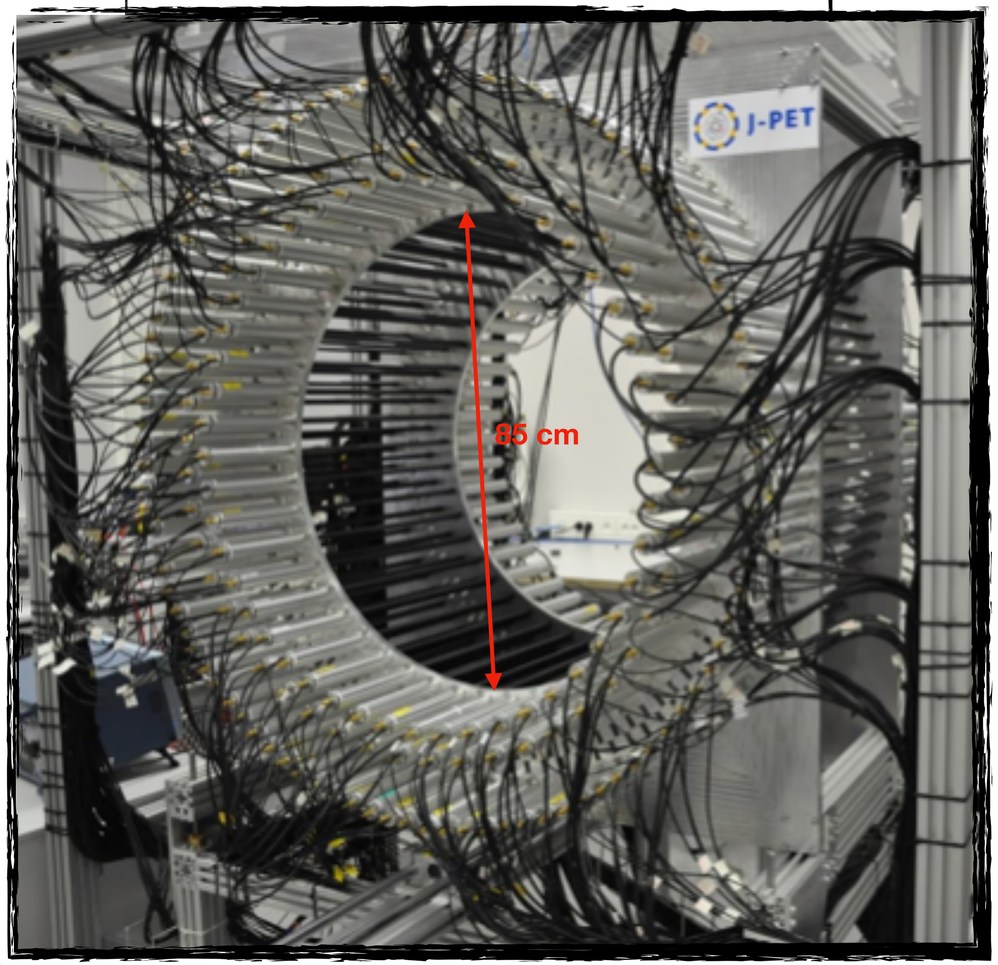

*IEEE Trans. on med. Imaging 37,11 (2018) 2526

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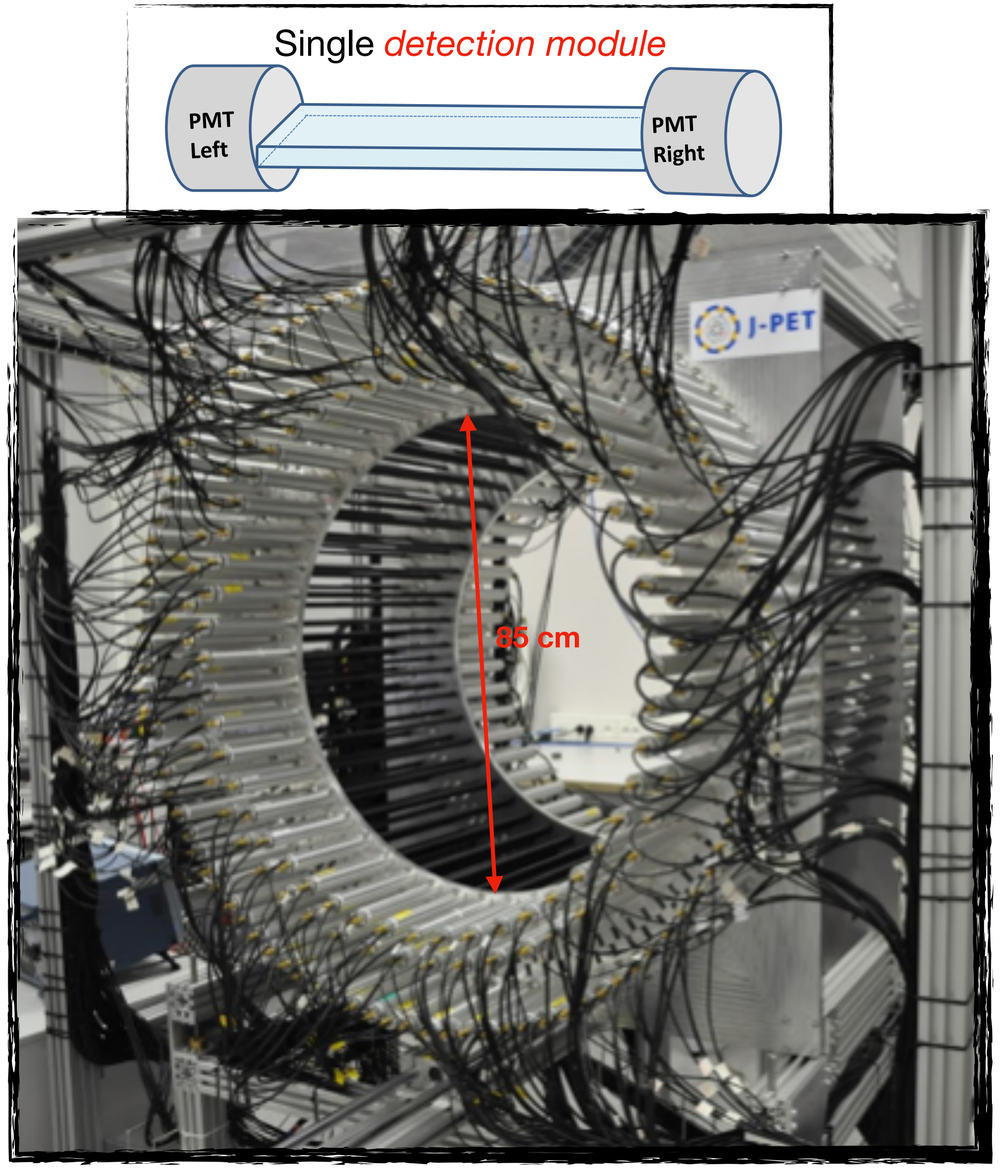

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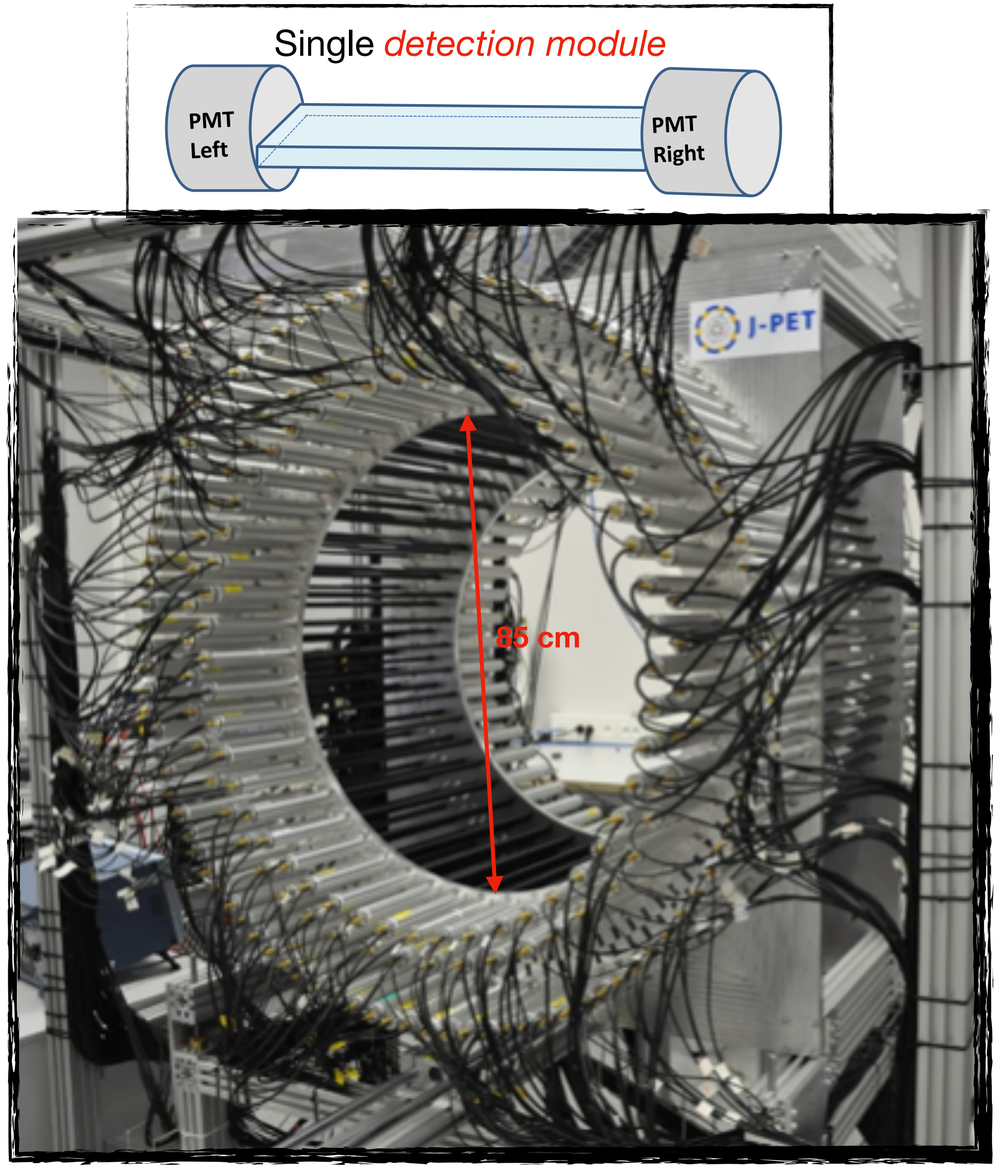

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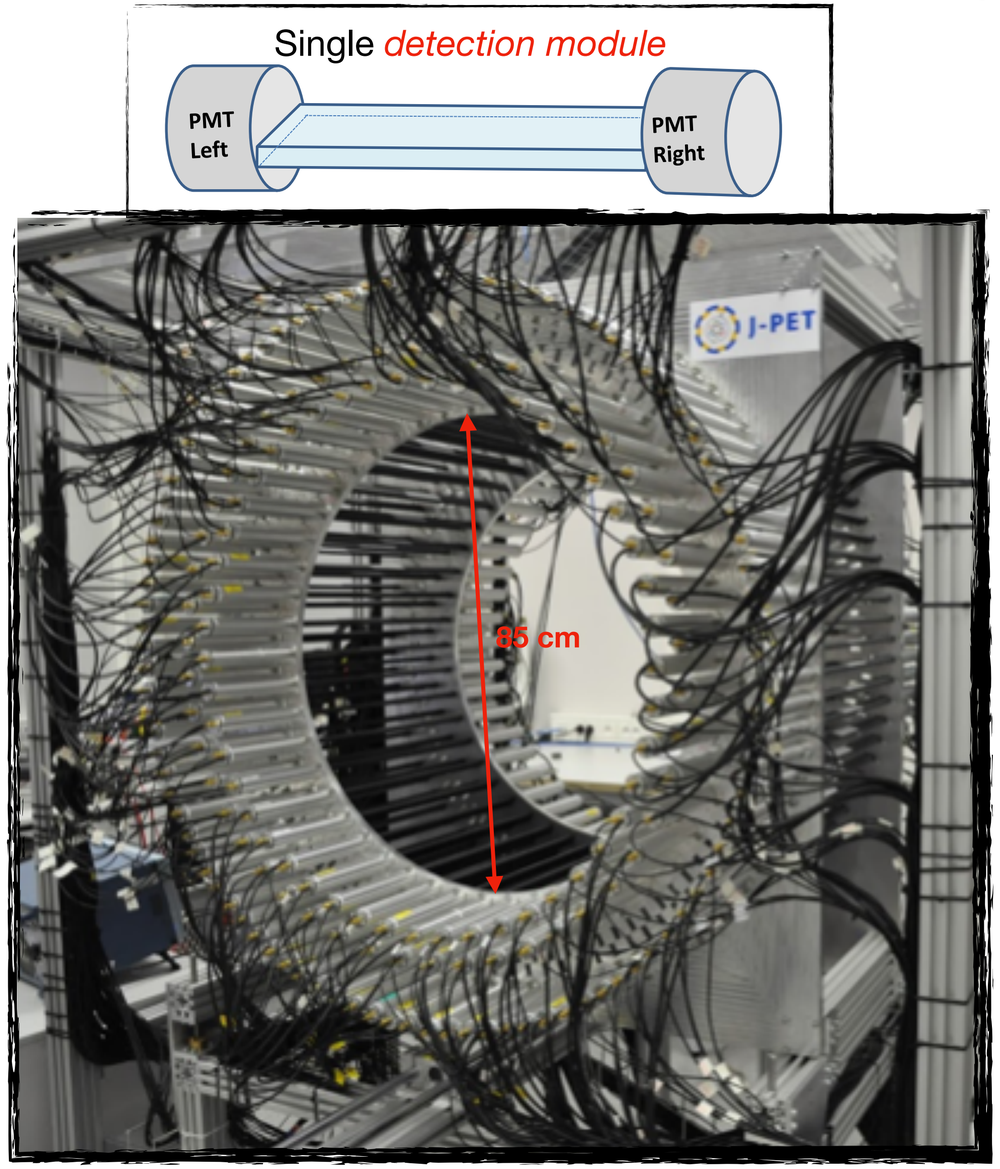
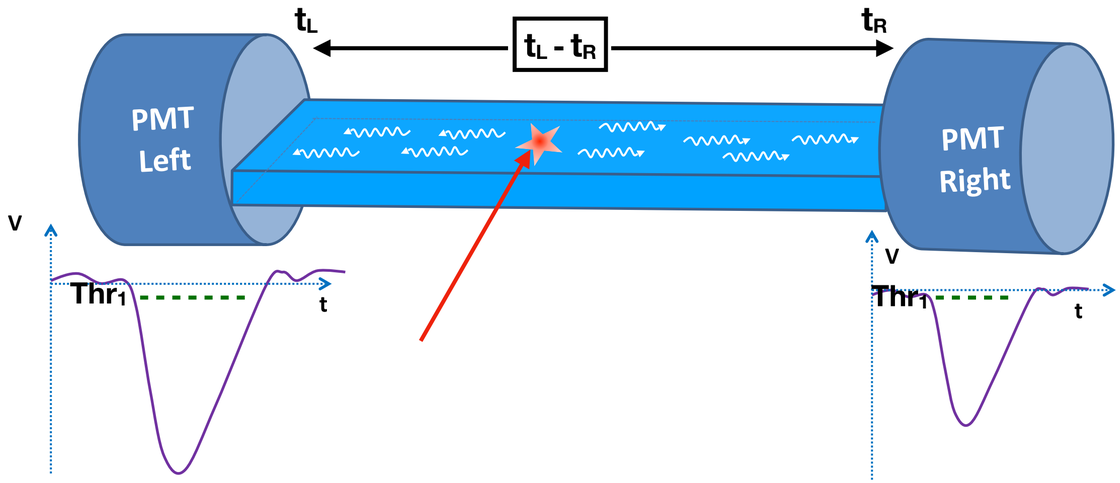


Working Principle

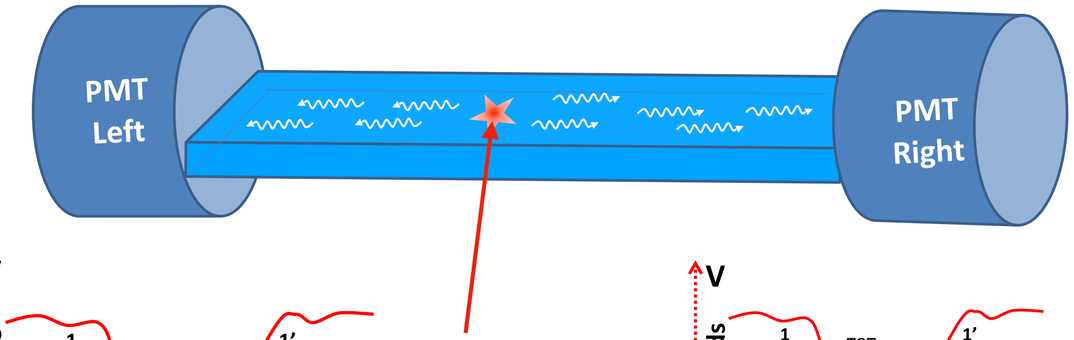


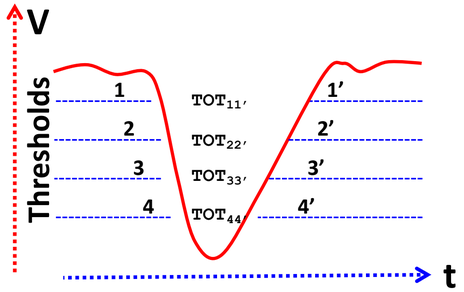
t_L and t_R refers the time of arrival of light signal at left and right PMT. respectively.

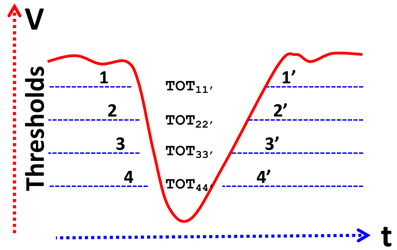
Hit position along the scintillator = $(t_L - t_R) * V_{eff}$
(from center of scintillator)

P. Moskal, patents no. P 388 555 [WIPO ST 10/C PL388555] (2009), PCT/PL2010/00062 (2010), WO2011008119, US2012112079, JP2012533734, EP2454612
Nucl. Inst. and Meth. A 764 (2014) 317-321 ; Nucl. Inst. and Meth. A 775 (2015) 54-62 ;

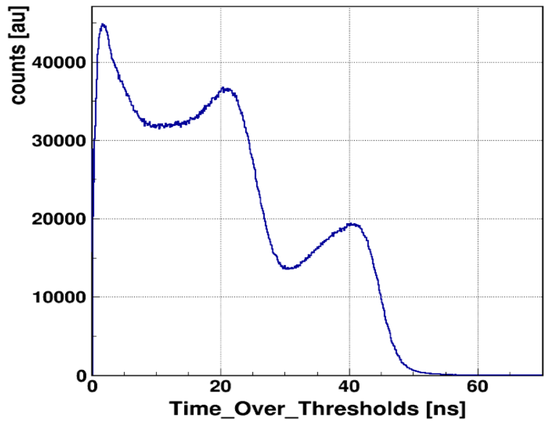
TOT as measure of Energy deposition : a relationship TOT vs Edep was established

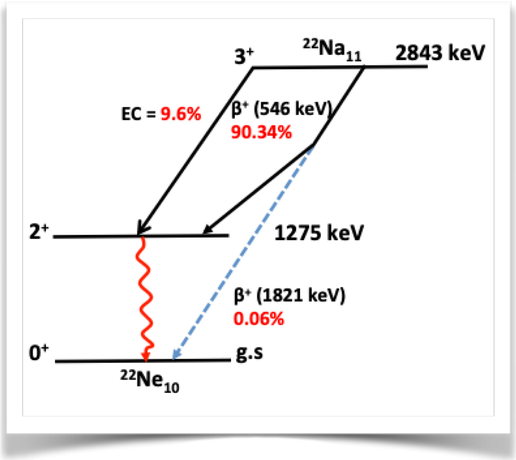




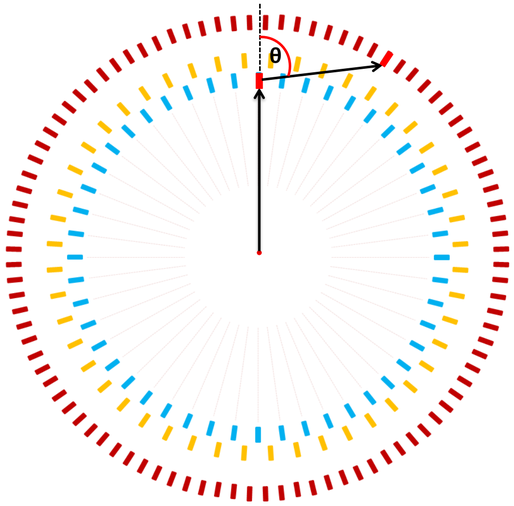


$$TOT = \sum_{PMT=A}^{B} \sum_{Thr=1}^{4} TOT_{PMT,Thr}$$

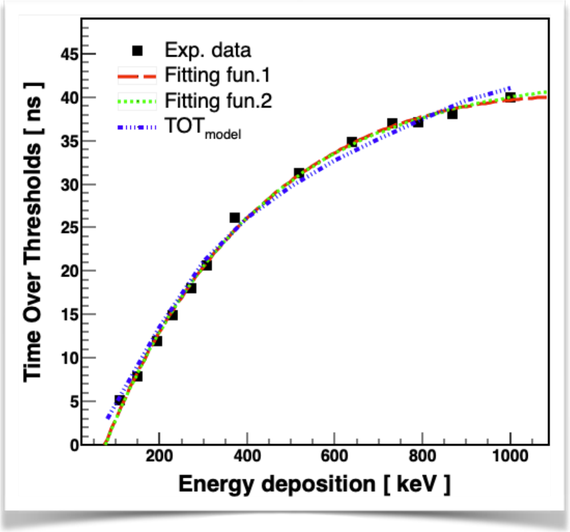




^{22}Na decay scheme



2D cross section of J-PET



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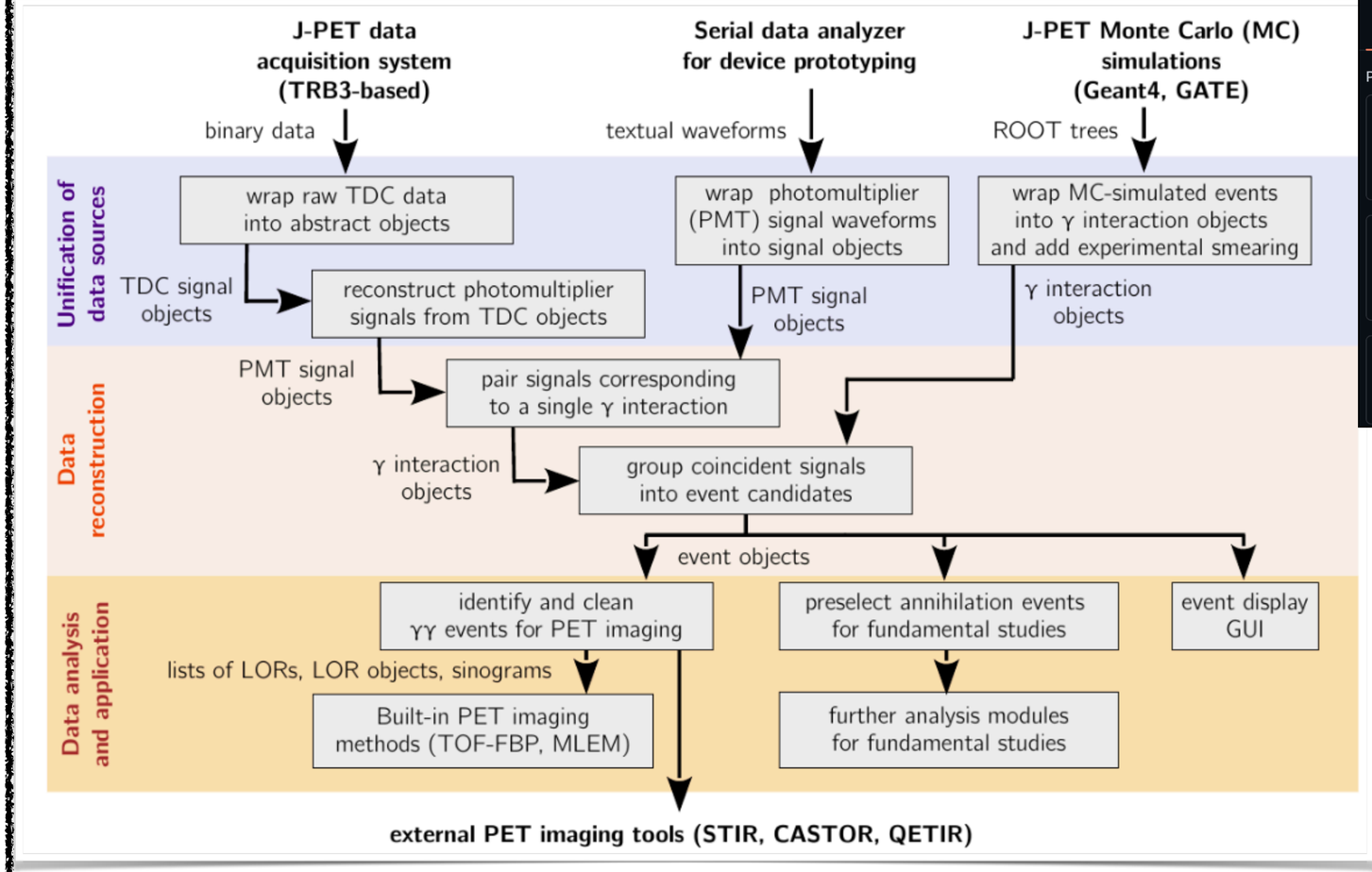
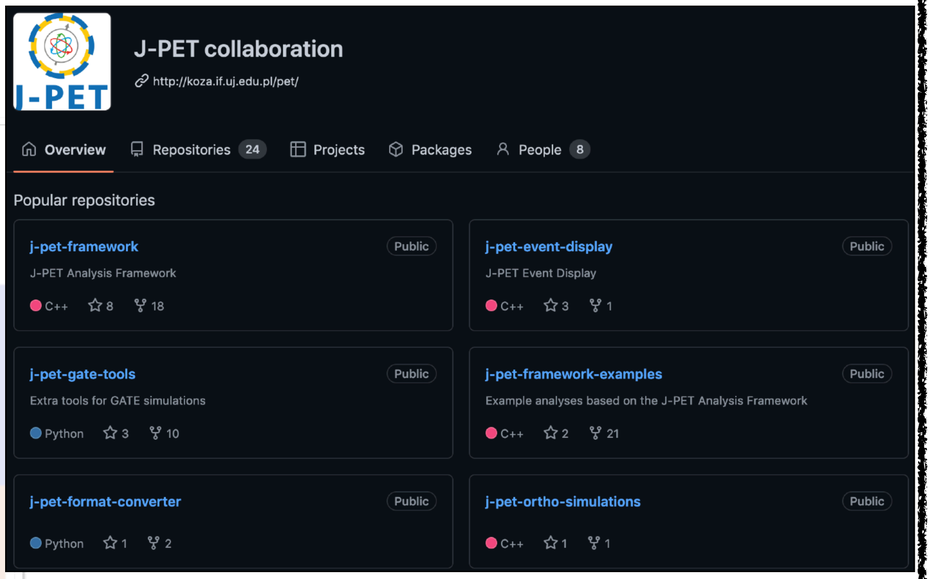
Data analysis scheme with J-PET Framework



W. Krzemien et al., SoftwareX 11 (2020) 100487



J-PET Geant4

https://github.com/JPETTomography/J-PET-geant4.git

Sources : photons beams,
Ps decays (energy and angular distributions of photons (primary) originating from **Ps**)

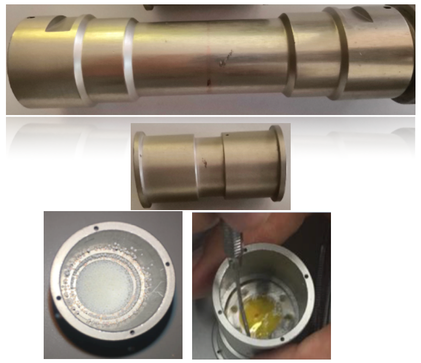
Compton interaction characteristics :
energy deposition, hit-position, hit time, scattering angles, multiple scattering

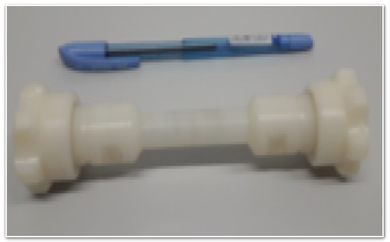
Source chambers

Physics list : G4LivermorePolarizedPhysics
(Livermore physics models with polarized photon model)

J-PET Geant4 simulation capabilities and annihilation chambers

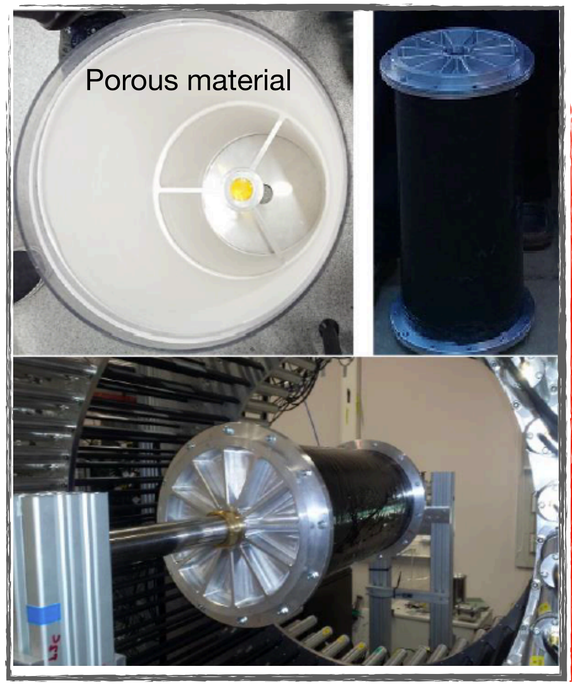
Small chambers



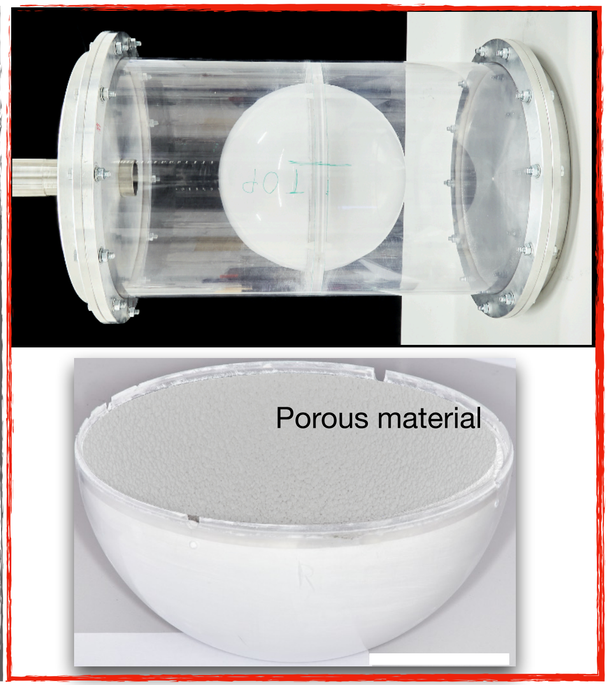


Large chambers

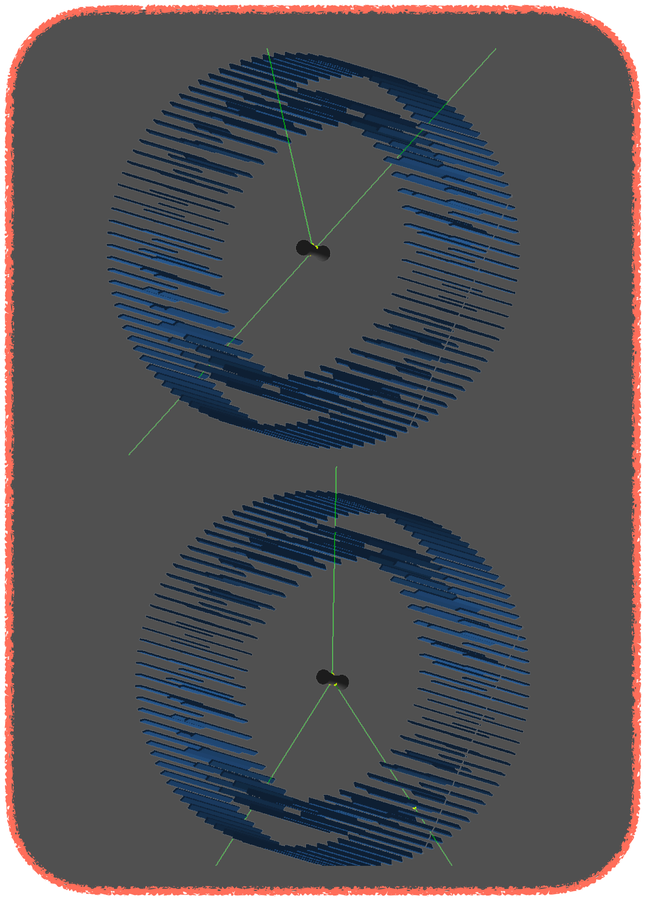
Cylindrical



Spherical



Exemplary 2 types events using small chamber



Positronium atom, a charge leptonic system for discrete symmetries test

- Hydrogen like atom without nuclei : purely leptonic object, a bound state of particle: e^- and anti-particle : e^+

- Eigenstate of C, P, CP operators

- Formed in two gnd. States

S=0 $\downarrow\uparrow - \uparrow\downarrow$ **Para** – positronium (**p - Ps**), **τ(vac)** = **0.125** ns, $^1S_0$

S=1 $\uparrow\uparrow + \downarrow\downarrow$ **ortho** – positronium (**o - Ps**), **τ(vac)** = **142** ns, $^3S_1$

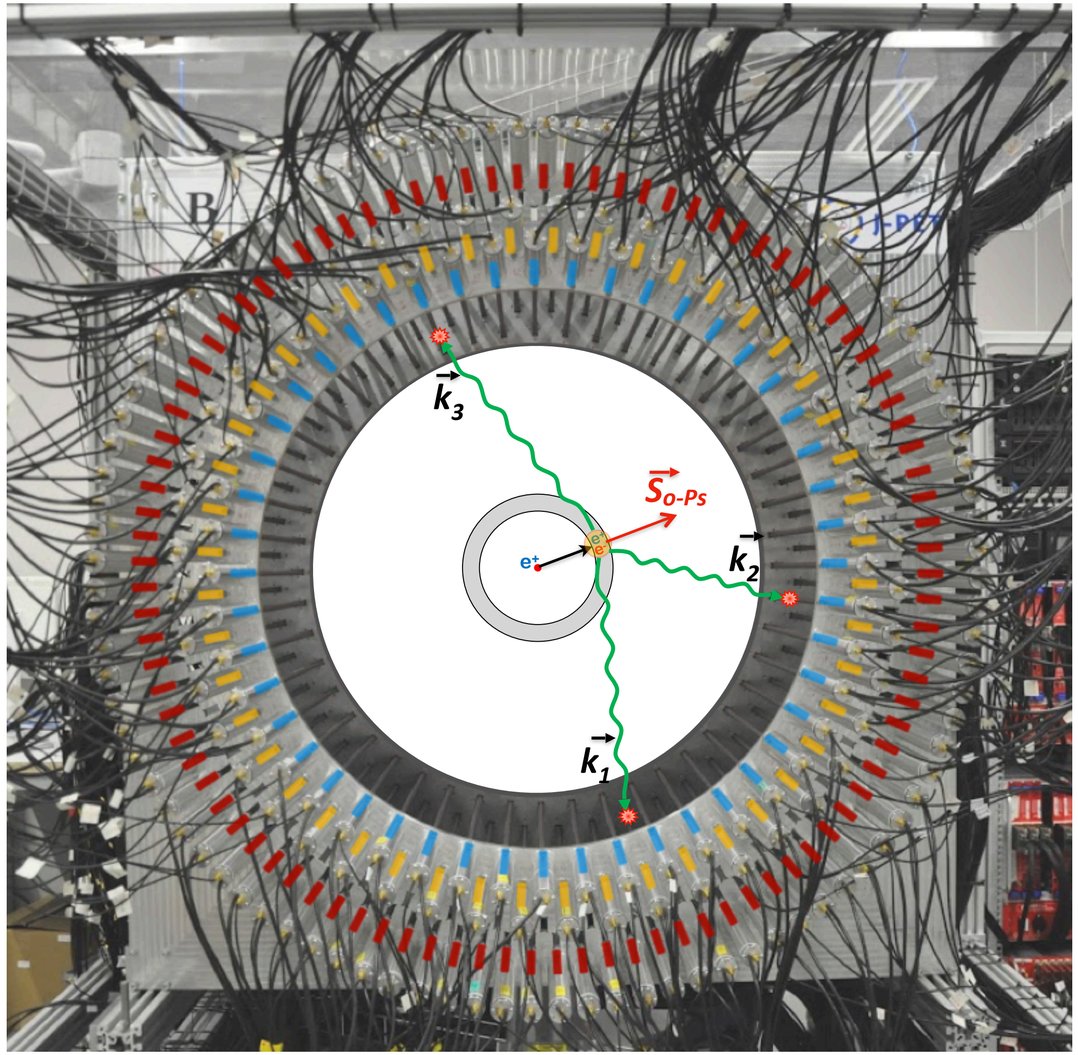
- Undergoes self-annihilation into gamma quanta. Requirement of invariance of charge conjugation, the decays of Ps atoms follow the selection rules:

$(-1)^{L+S} = (-1)^n \gamma$

- **p-Ps (S=0, L=0)** Decays into $2n\gamma$ where n = 1,2,4…. ;
- **o-Ps (S=1, L=0)** Decays into $(2n+1)\gamma$ where n = 1,2…. ;

- With ability, to *register multi photon simultaneously*, *J-PET qualifies* to perform ***test*** *on* ***discrete symmetries*** in the decays of ***o-Ps atoms***

Odd-symmetry operators in decays of o-Ps atoms



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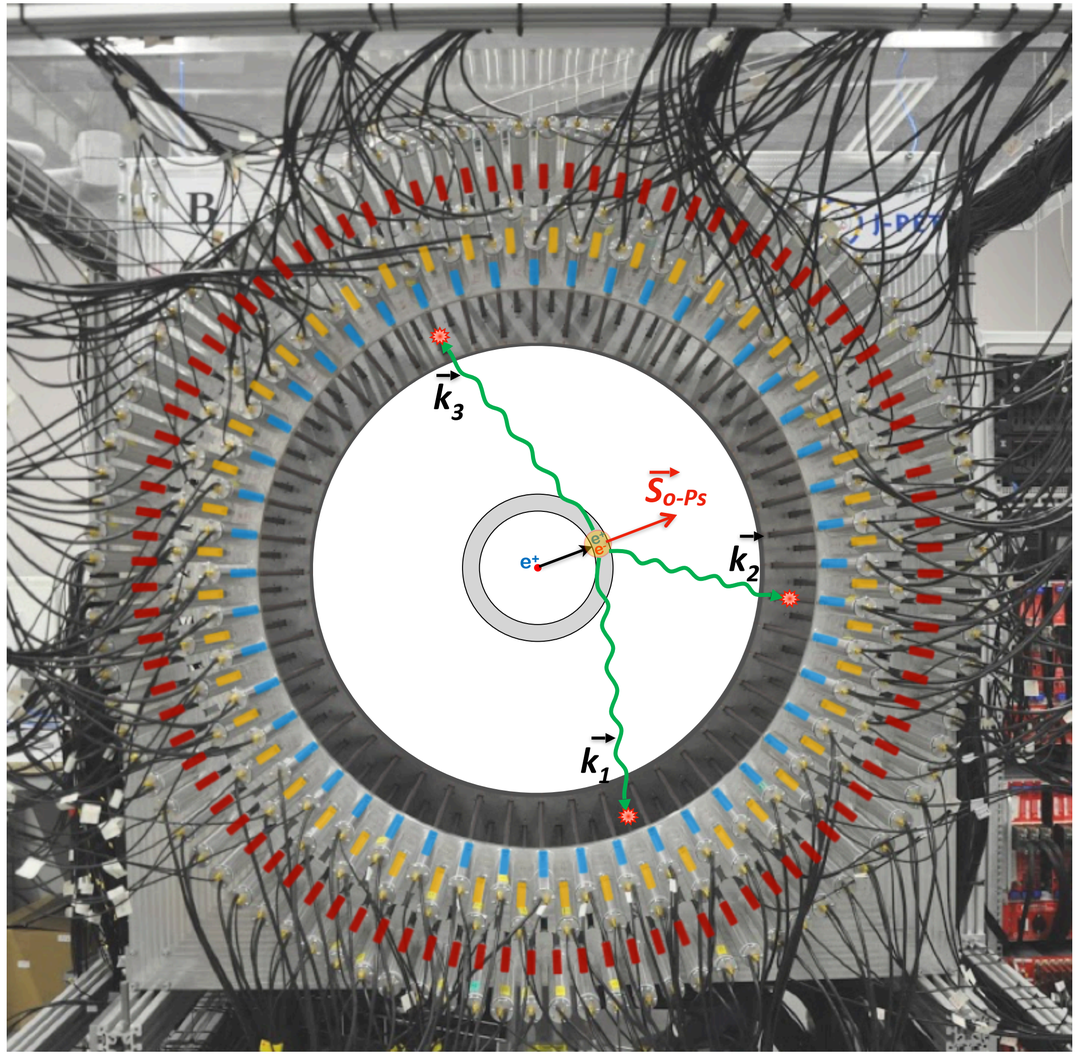
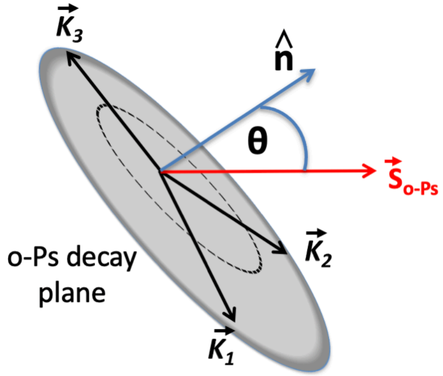


Operators

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

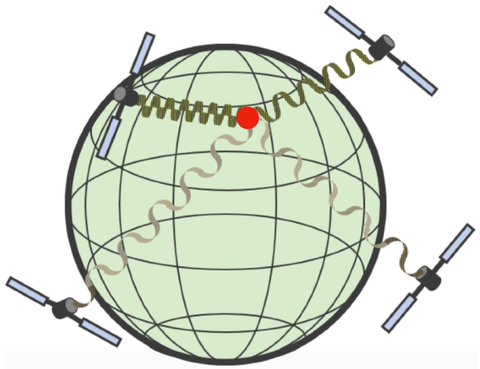
$|\vec{K}_1| > |\vec{K}_2| > |\vec{K}_3|$

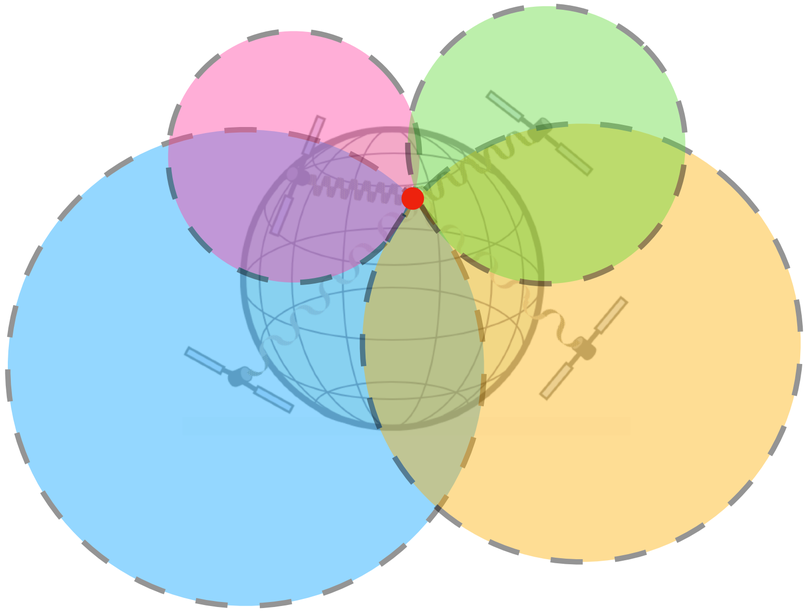


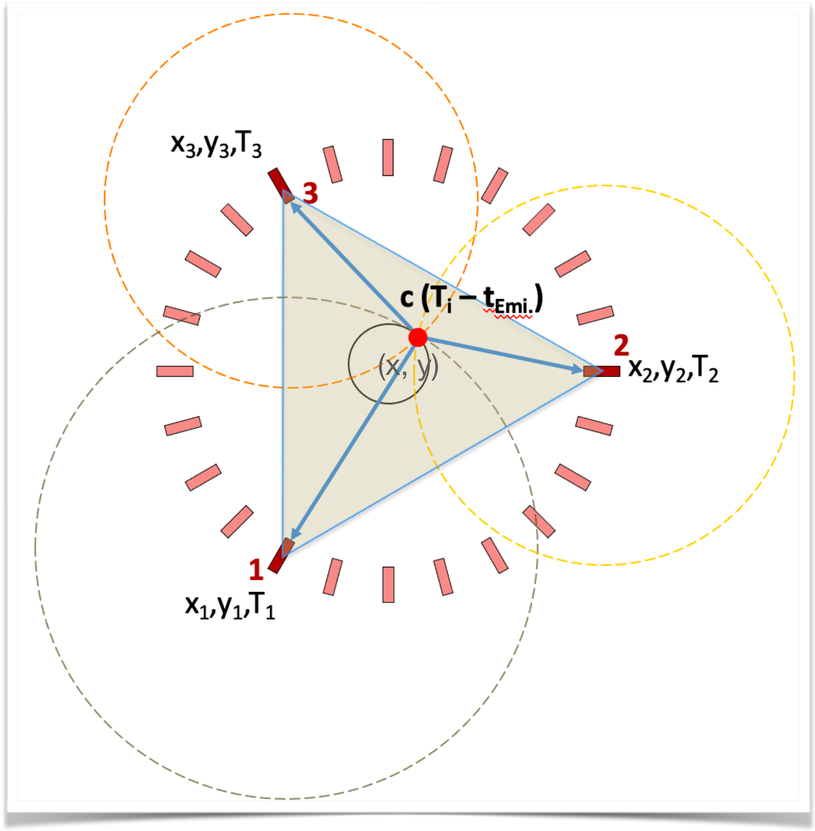
$$< \widehat{O} > = \hat{S} \cdot \frac{(\vec{k}_1 \times \vec{k}_2)}{|\vec{k}_1 \times \vec{k}_2|} = cos(\theta)$$

Determination of **o-Ps annihilation point**

Annihilation point can be estimated using the **<u>trilateration method</u>**, based on GPS







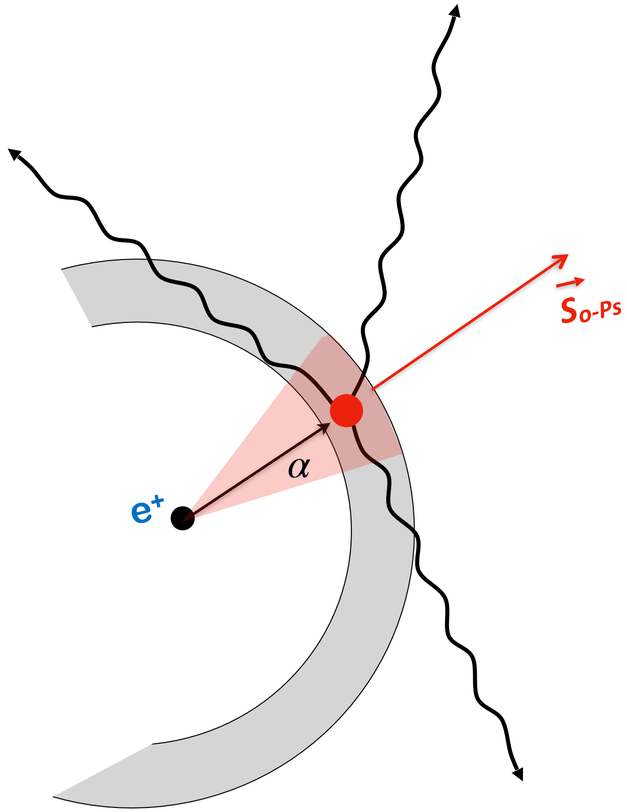
$$c^2(T_i - t)^2 = (x_i - x)^2 + (y_i - y)^2,$$

Where x,y is annihilation point on decay plane and t is decay time

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

Spin determination of o-Ps atom

- Spin is estimated event-by-event, based on the registration of o-Ps decay
- Estimation of effective polarization (spin) depends on the vertex resolution.



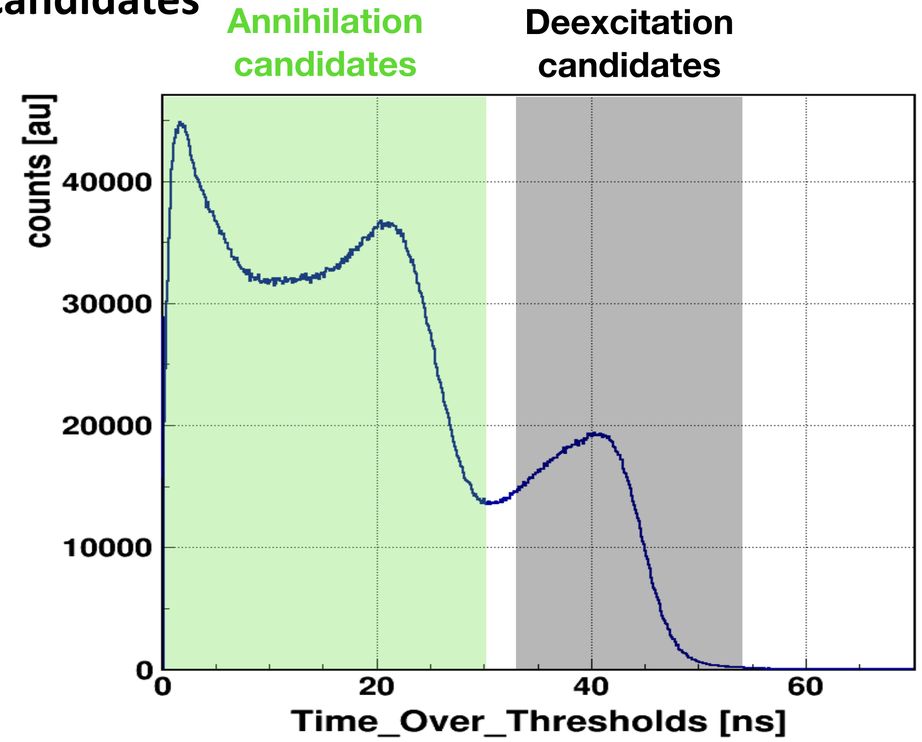
$$P_{o-Ps} = \frac{2}{3} P_{e^+}$$

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

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

Analysis scheme to select o-Ps events

TOT cut to select the annihilation and de-excitation candidates



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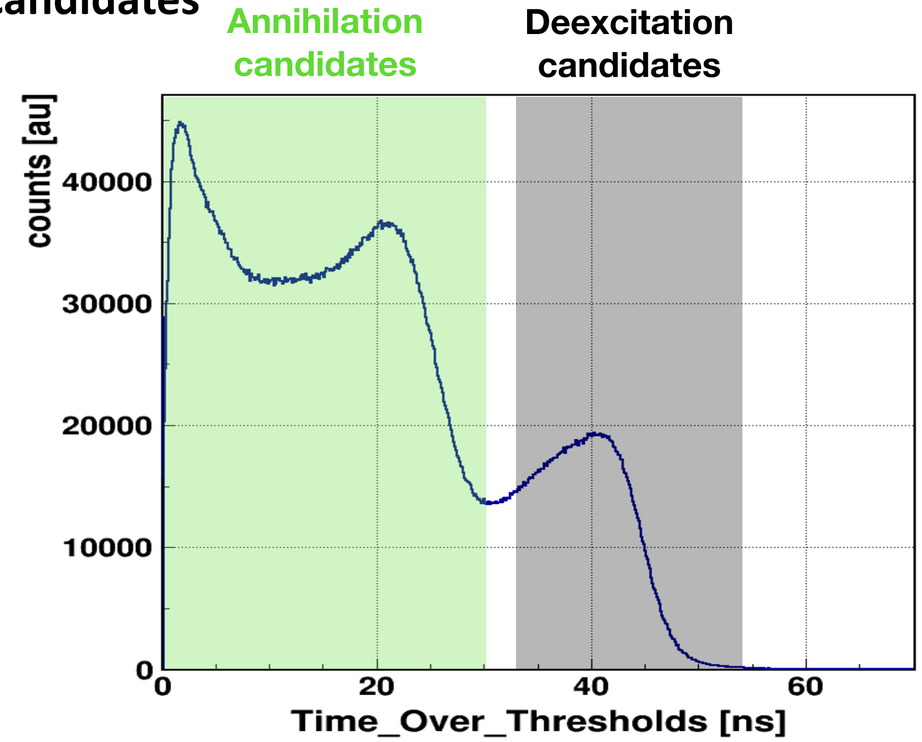
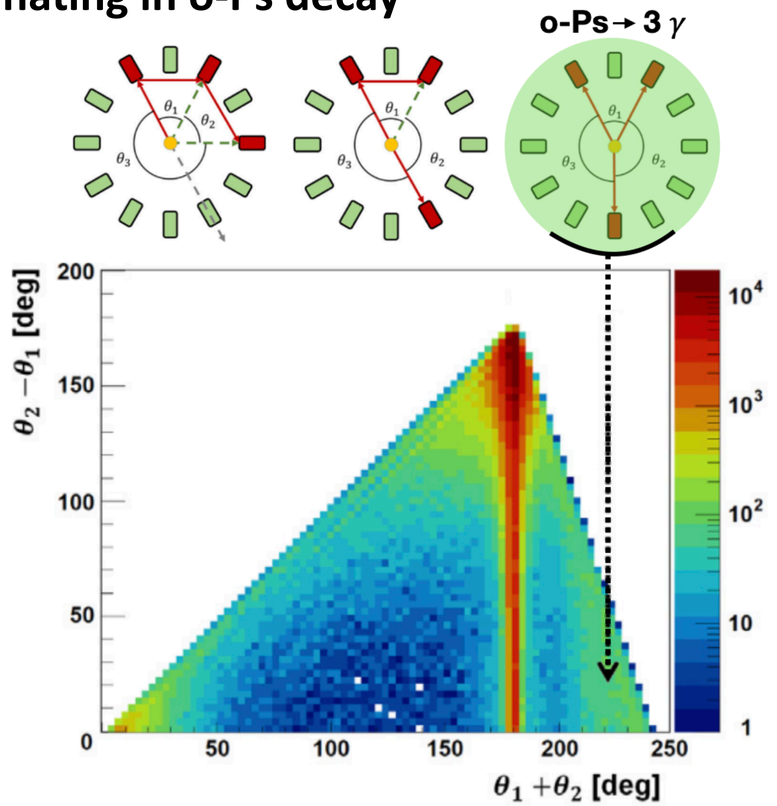


Angular correlations in the annihilation photons originating in o-Ps decay



K. Dulski et al., NIM A 1008 (2021) 165452

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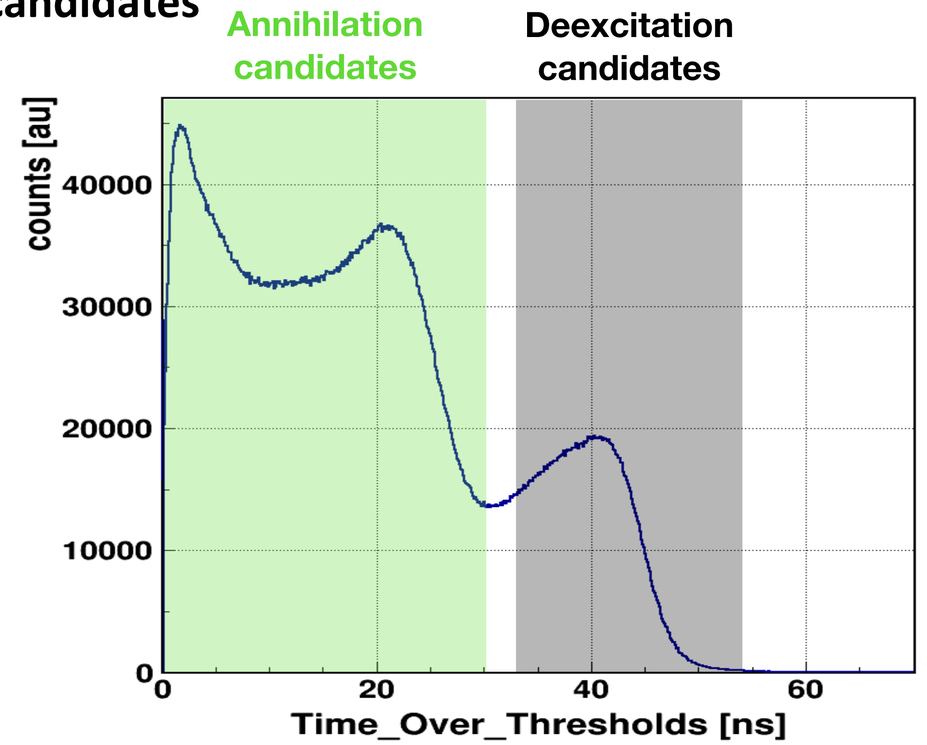

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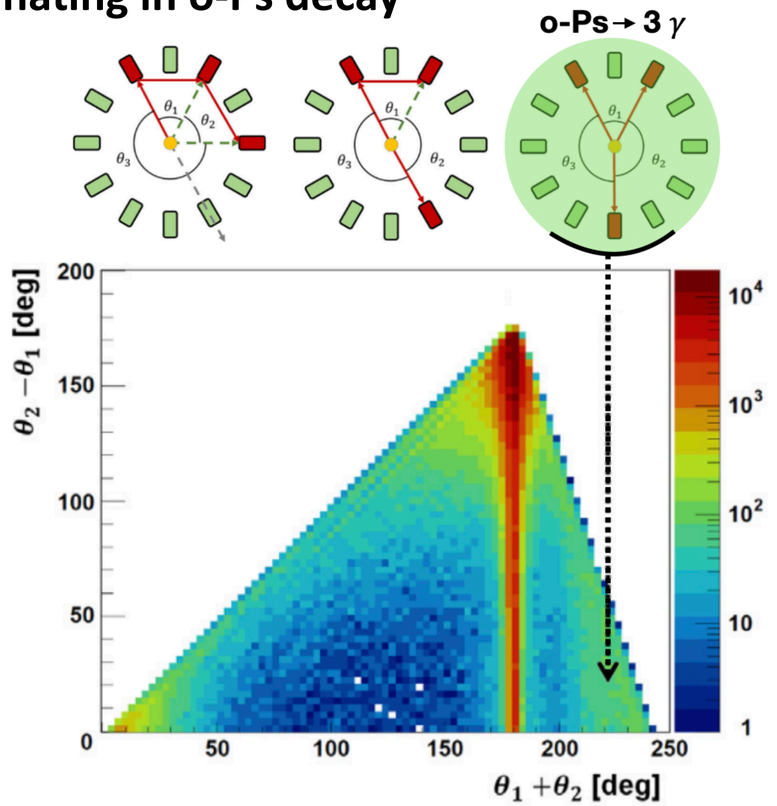


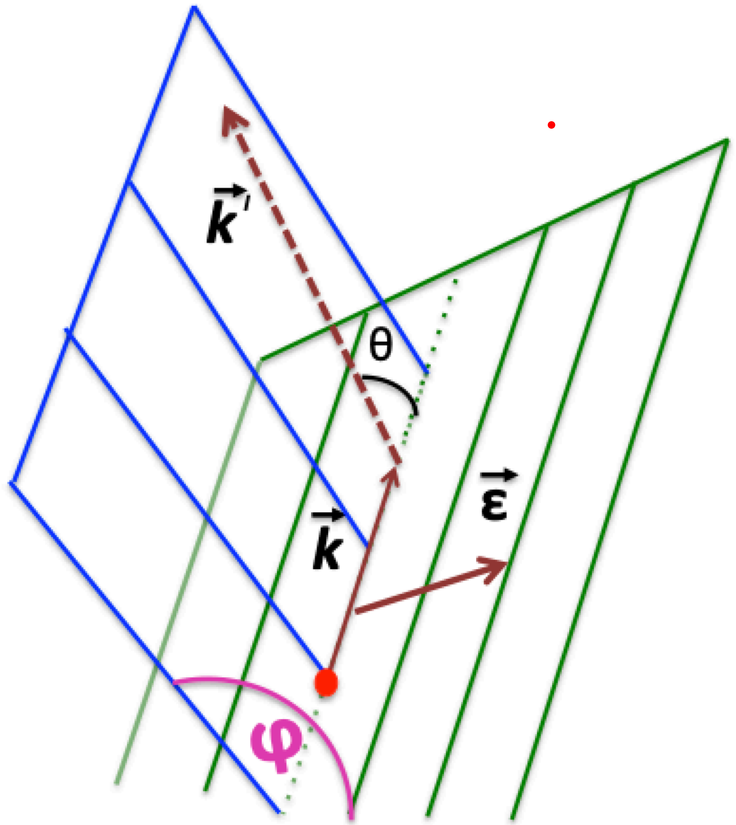
☑ **Additional cuts to suppress the background, such as:**

I. Emission time difference between registered annihilation photons

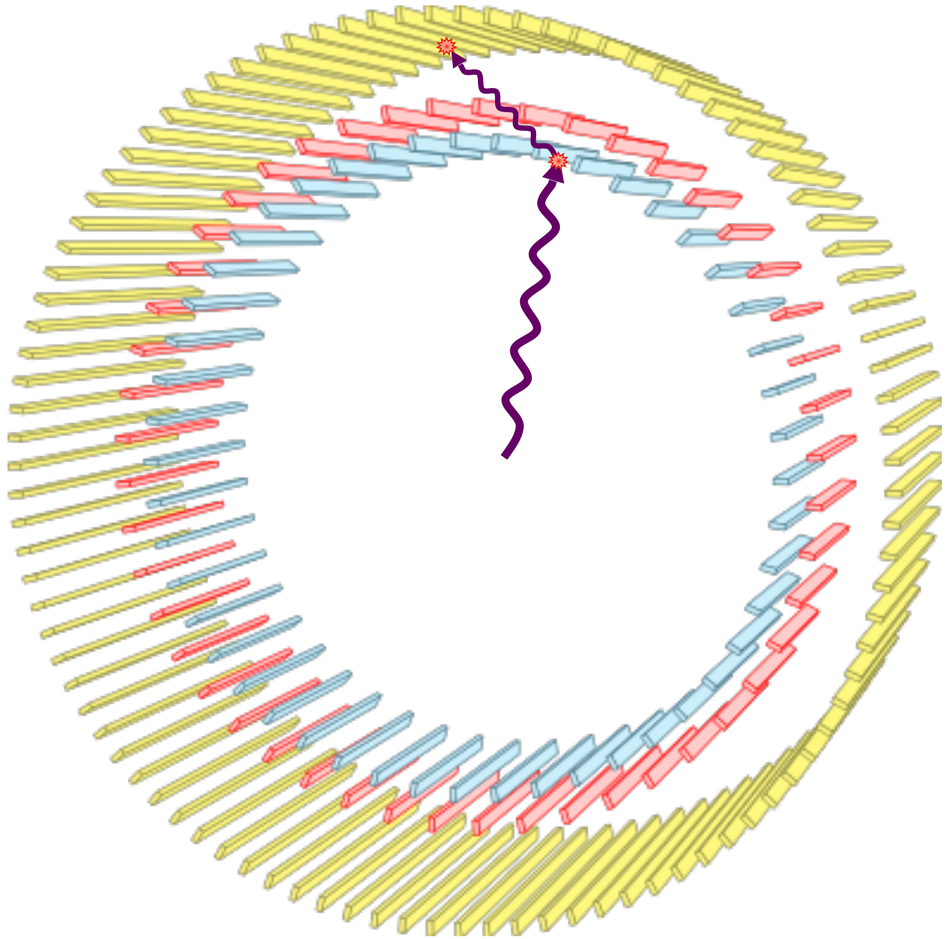
II. Distance of annihilation point/decay plane from the center of detector

III.....

New operators added utilizing the **photon's polarization**



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



New operators added utilizing the **photon's polarization**

Odd symmetric	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	−	+	−	−
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	−	+	−
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	−	−	−	+
New Operators unique with J-PET $= \vec{\epsilon}$					
$\vec{k}_2 \cdot \vec{\epsilon}_1$	+	−	−	−	+
$\vec{S} \cdot \vec{\epsilon}_1$	+	+	−	+	−
$\vec{S} \cdot (\vec{k}_2 \times \vec{\epsilon}_1)$	+	−	+	−	−

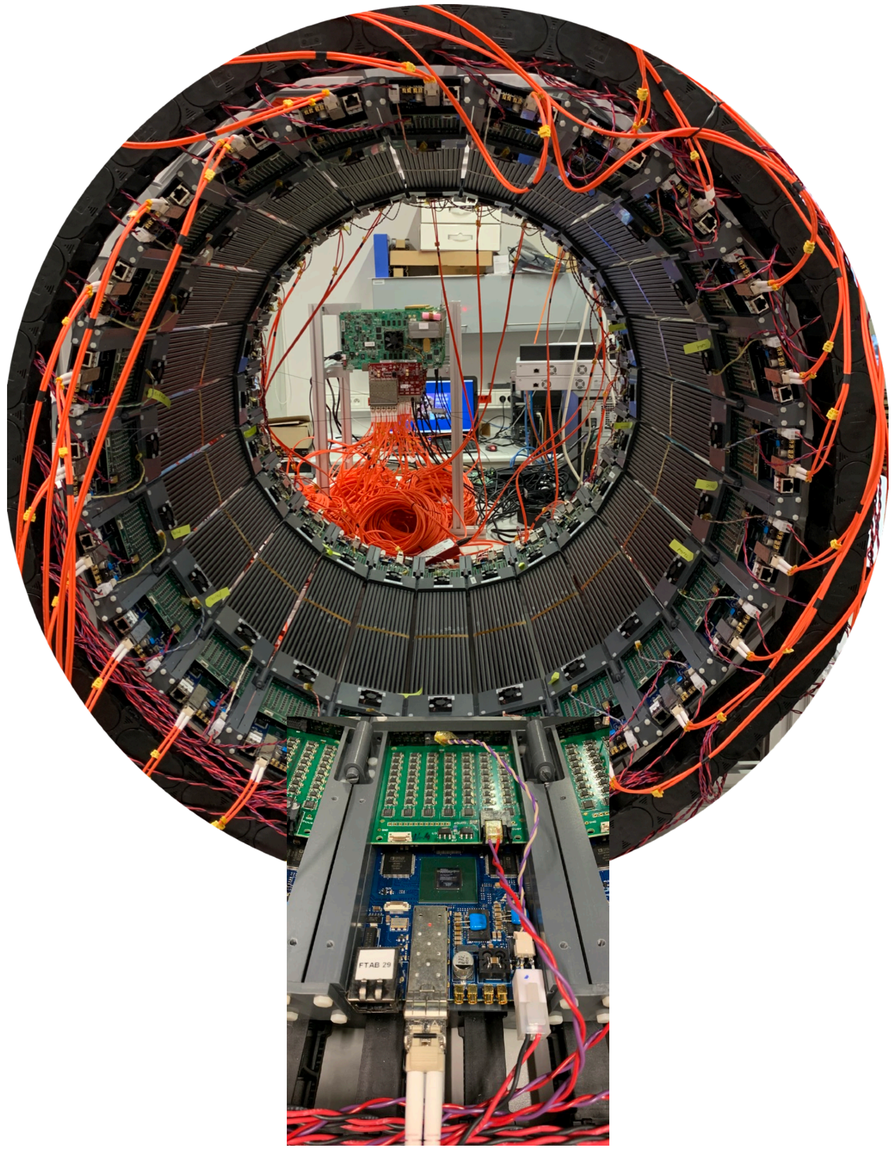
P. Moskal, A. Gajoss et al.
Nature communication 12, 5658 (2021)

$\langle O_{CPT} \rangle$ = 0.00025 ± 0.000036

*Final **value**, **to be reported soon***

$\langle O_{CP} \rangle$ = value ± 0.0007_{stat}

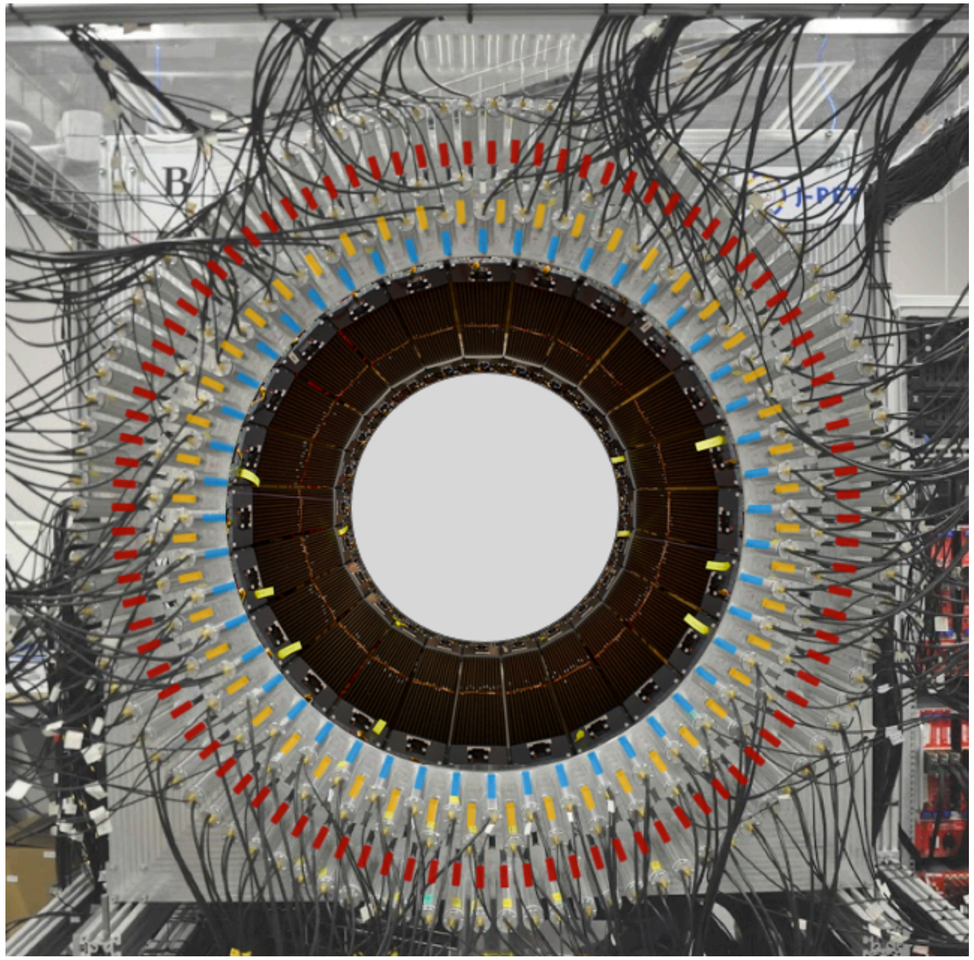
Future upgrades : towards modular based J-PET prototype



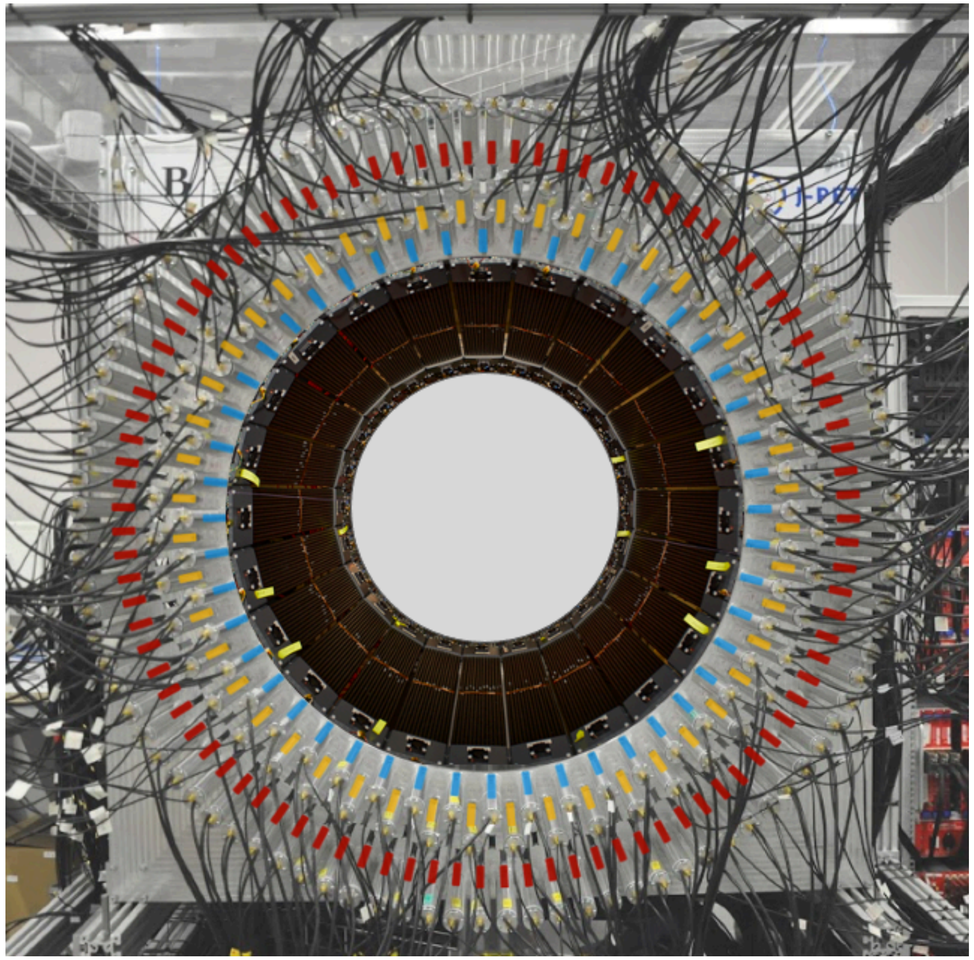
- Composed of **24 individual** (standalone) detection **modules**
- **Each module** is made of **13 plastic scintillators** (50x24x6 mm^3)
- **Scintillators** are read out by matrix of SiPM on each end
- Modules can be operated individually enabling to utilize as **multi-role detector**
- Easy to transport (full barrel around 60 kg), can be assembled in a time span of 2-3 hours.
- **Modular construction** (FEE* attached) allows to configure one layer (**24**) or multiple layer (e.g., **8+16** , requirement specific)

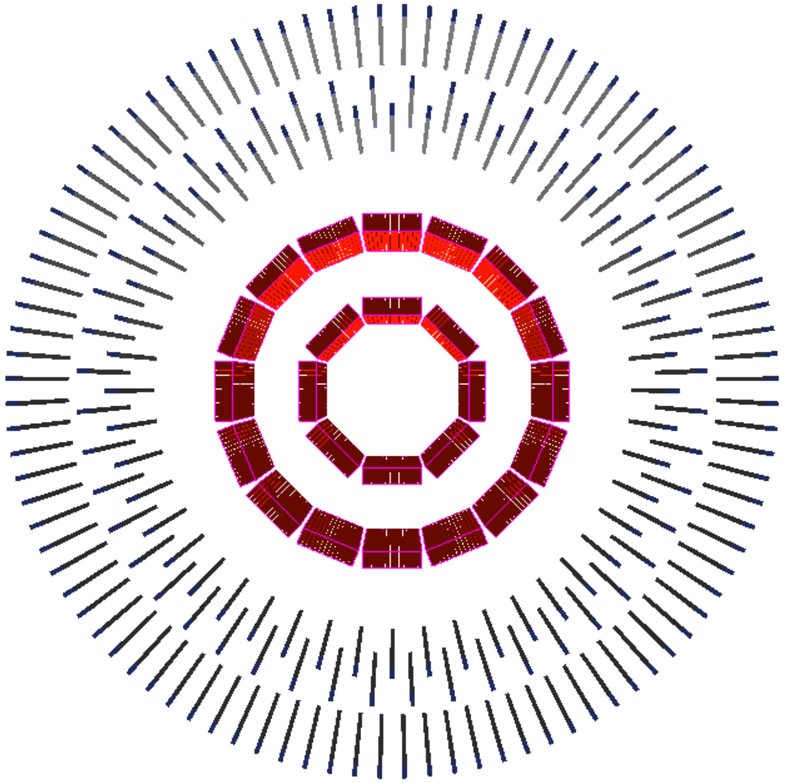
FEE* - **F**ront **E**nd **E**lectronics

Modular layer in different configuration



Modular layer in different configuration





Multi-layer configuration

Conclusions and summary

- J-PET detector has demonstrated its potentialities to perform the test on discrete symmetries in the Decays of o-Ps atoms. First results are already published.

  P. Moskal et al., Nature Communication 12 (2021) 5658

- Test with new odd-symmetry operators utilizing the **photon's polarization** are currently feasible with the J-PET detector.

  First Results from one of mentioned operator will be reported soon

- **Modular J-PET** will enable to achieve the **several time enhanced efficiency** in using along with present 3-layer prototype *as an additional layer* or as of *multiple layers*.

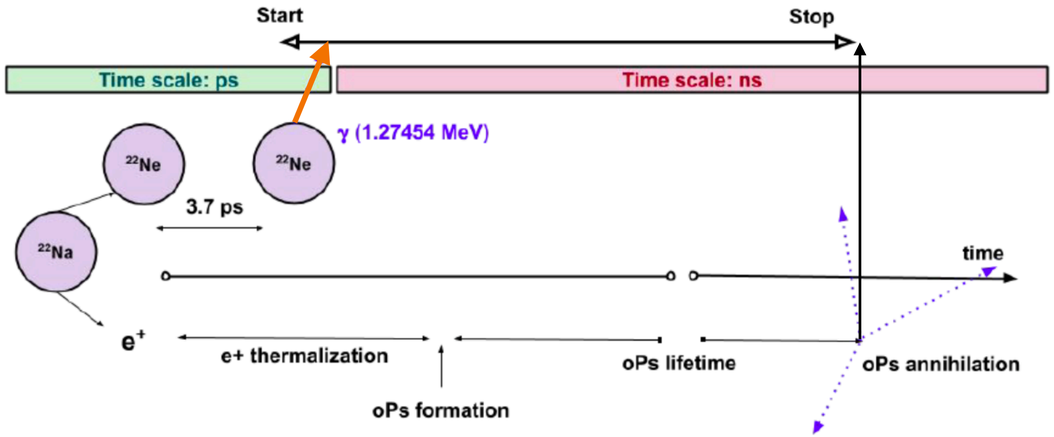
  Simulations for the optimized configuration is going on.

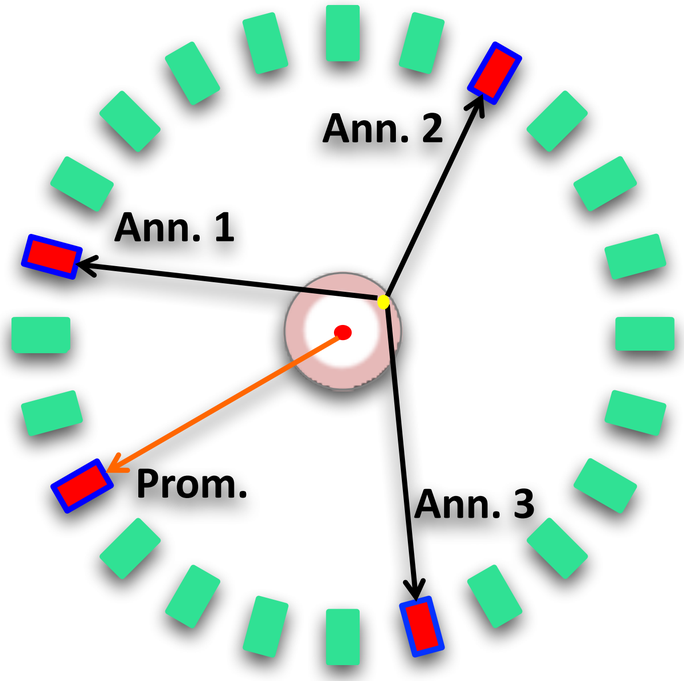
- Modular construction and ability to work as standalone detection modules, new prototype can be useful for performing tests in various labs aiming to study the decays of Ps atoms or other relevant studies.

THANK YOU

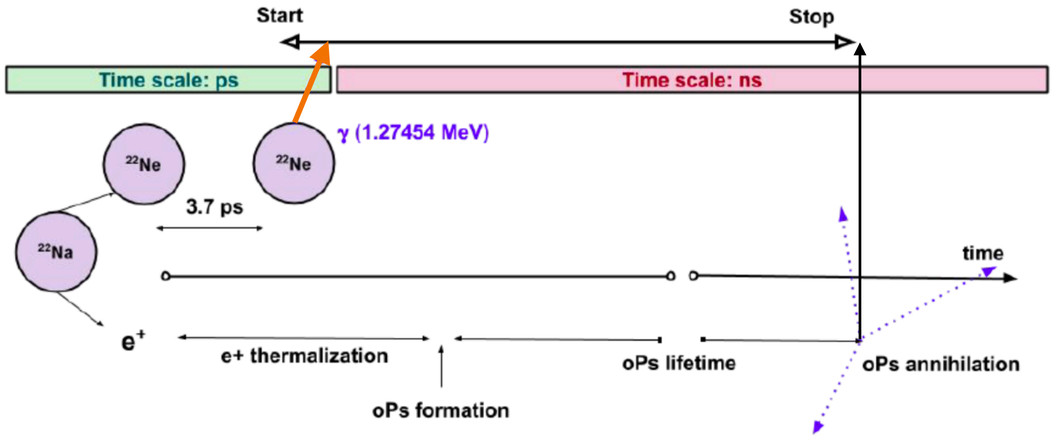
S. Sharma on behalf of the the J-PET collaboration

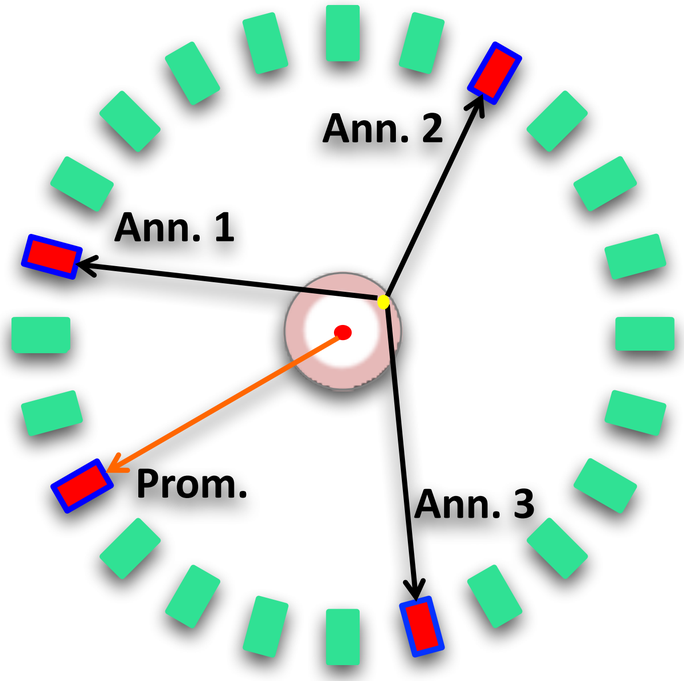
Lifetime of o-Ps atoms

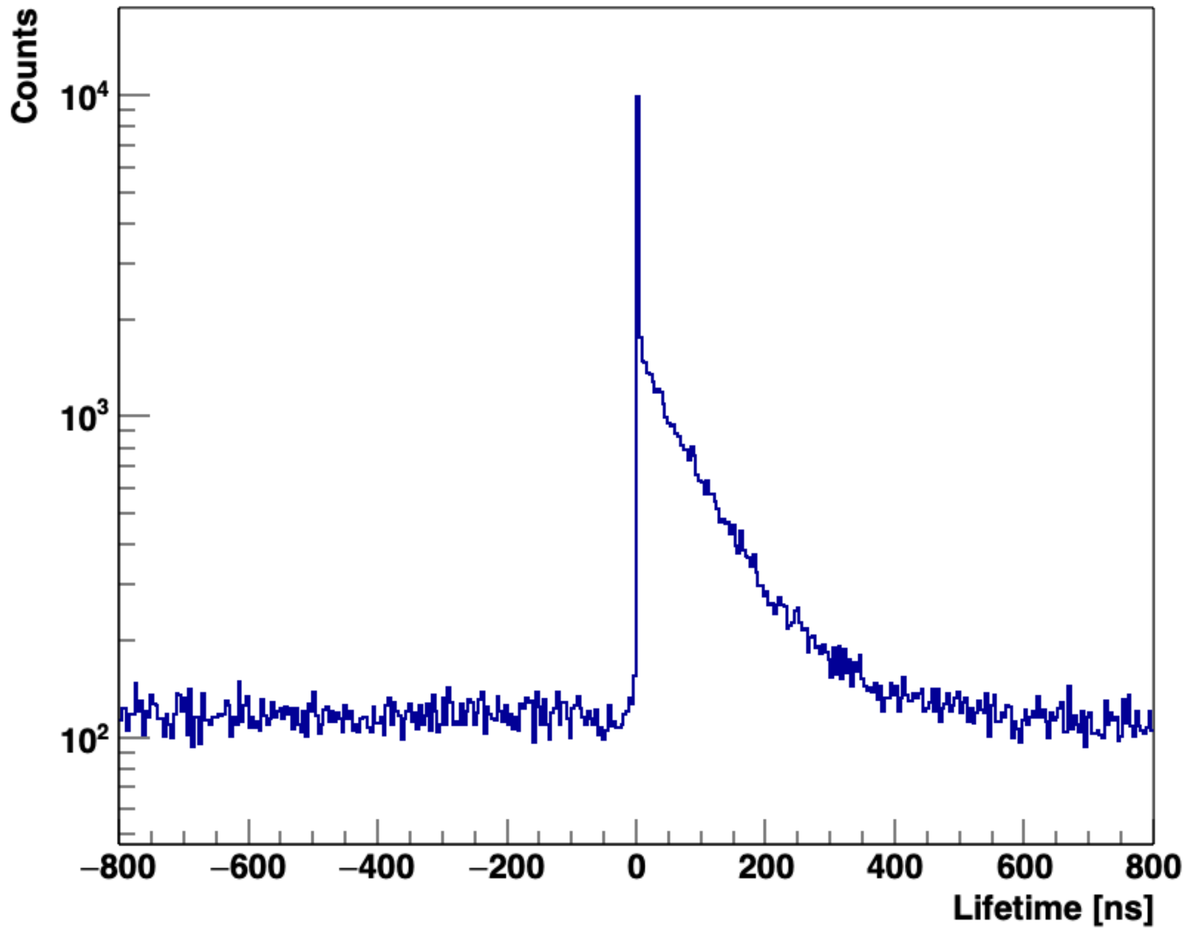




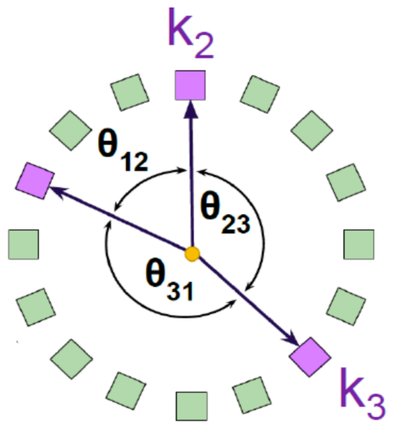
Lifetime of o-Ps atoms







Energy of annihilated gamma quanta from o-Ps decay



$$E_1 = -2m_e \frac{-\cos\theta_{13} + \cos\theta_{12}\cos\theta_{23}}{(-1+\cos\theta_{12})(1+\cos\theta_{12}-\cos\theta_{13}-\cos\theta_{23})},$$

$$E_2 = -2m_e \frac{\cos\theta_{12}\cos\theta_{13} - \cos\theta_{23}}{(-1+\cos\theta_{12})(1+\cos\theta_{12}-\cos\theta_{13}-\cos\theta_{23})},$$

$$E_3 = 2m_e \frac{1+\cos\theta_{12}}{1+\cos\theta_{12}-\cos\theta_{13}-\cos\theta_{23}}.$$

D. Kaminska et al., Eur. Phys. J. C 76 (2016) 445

Back-up slides