Studies of the decay of positronium atoms with the J-PET detector

S. Sharma on behalf of the J-PET collaboration

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

Outline

Jagiellonian PET - *built from plastic scintillators*

Positronium atom 

- *Hydrogen like atom without nucleus*

Discrete symmetries - C (*Charge conjugation*)

- $\mathcal{P}$ (*Reflection in space*)

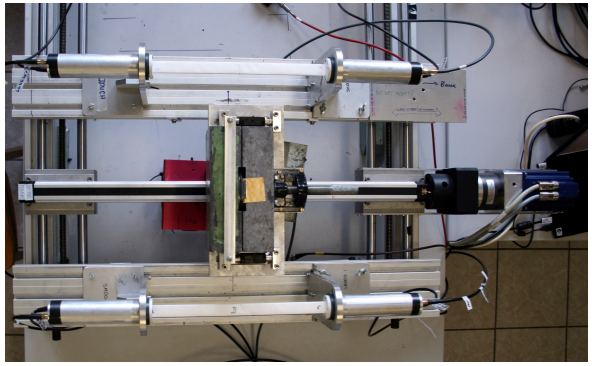
- $\mathcal{T}$ (*Time reversal*)

Photon's Polarization - *access to additional odd-symmetry operator*

Modular PET - *Standalone / portable PET*

Development cycles of J-PET

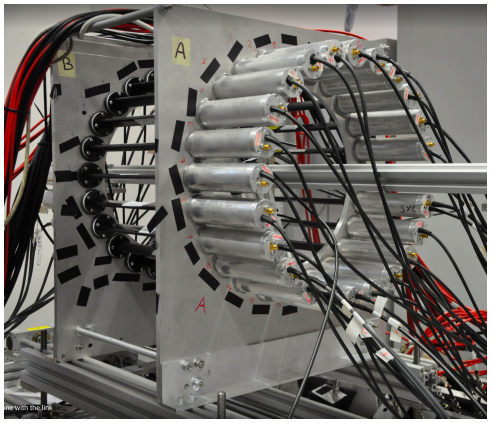
2012



Characterize scintillator properties

Energy, time resolution, hit time,..

2014

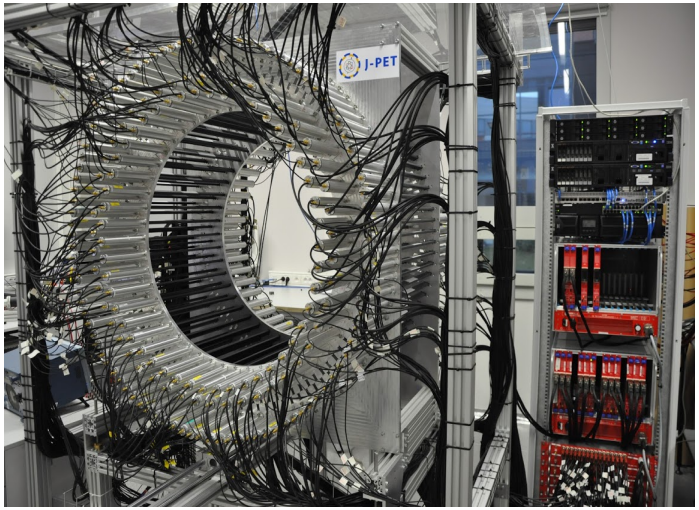


24 strips

Data acquisition for multi-modules

2016

192 strips



Current version

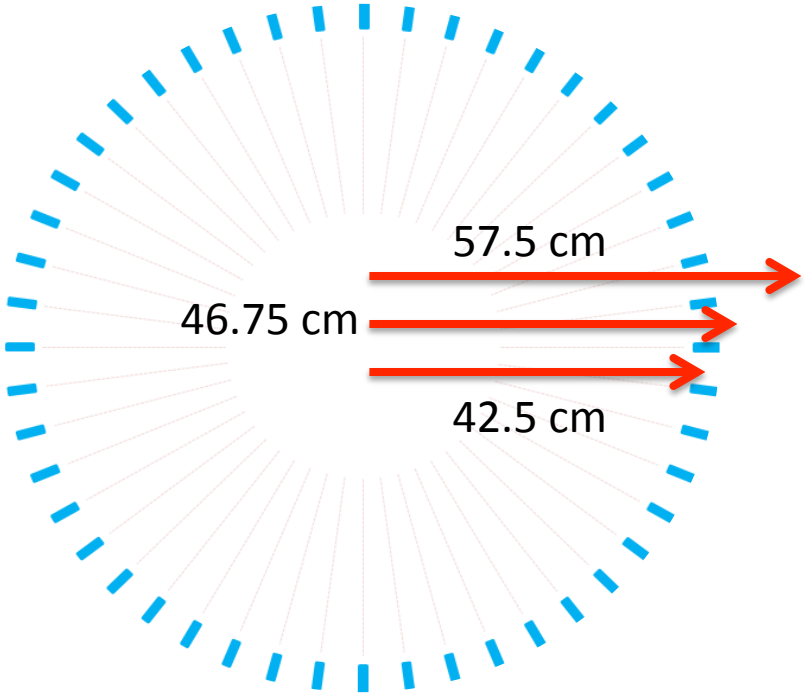
Tests on discrete symmetries

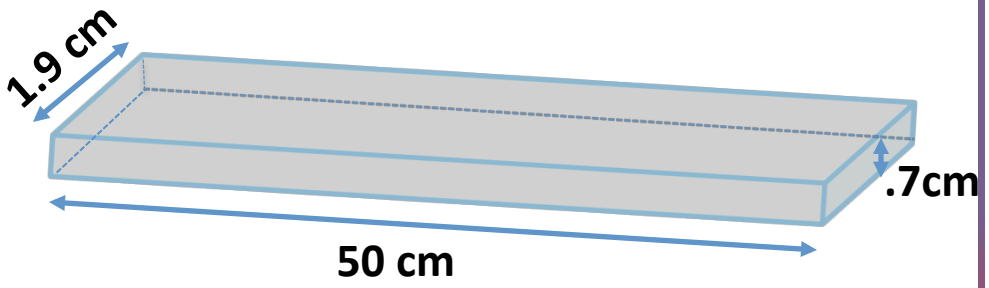
2018

24 modules, each with 13 scintillators

Modular PET – ready for first data campaign

2-D front view J-PET





192 plastic Scintillators

Arranged axially in 3 layers

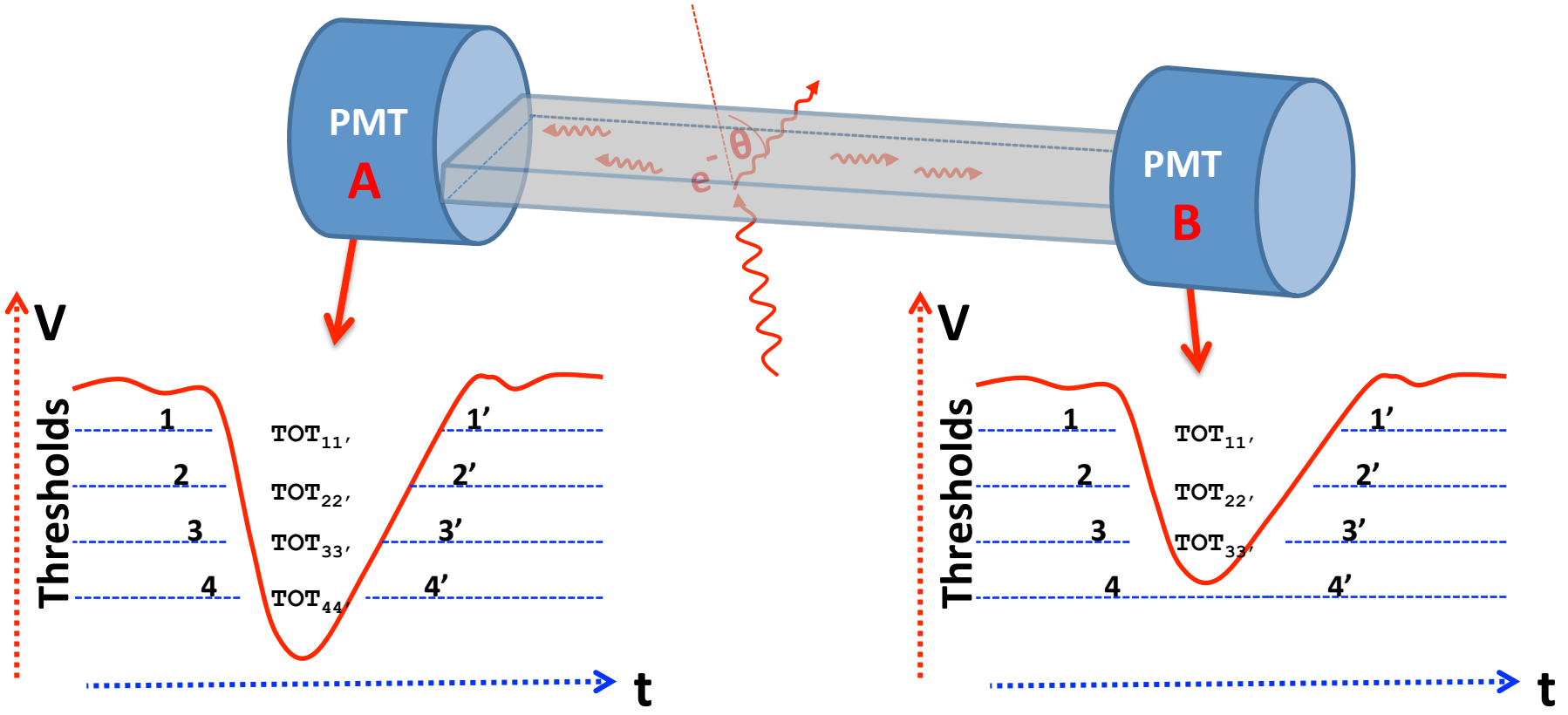
Key features :

☑ **Trigger less and reconfigurable DAQ**

☑ **TOT as measure of energy deposition**

- ✓ *Good angular resolution and small light attenuation*
- ✓ *Superior time properties and lower pile-ups*

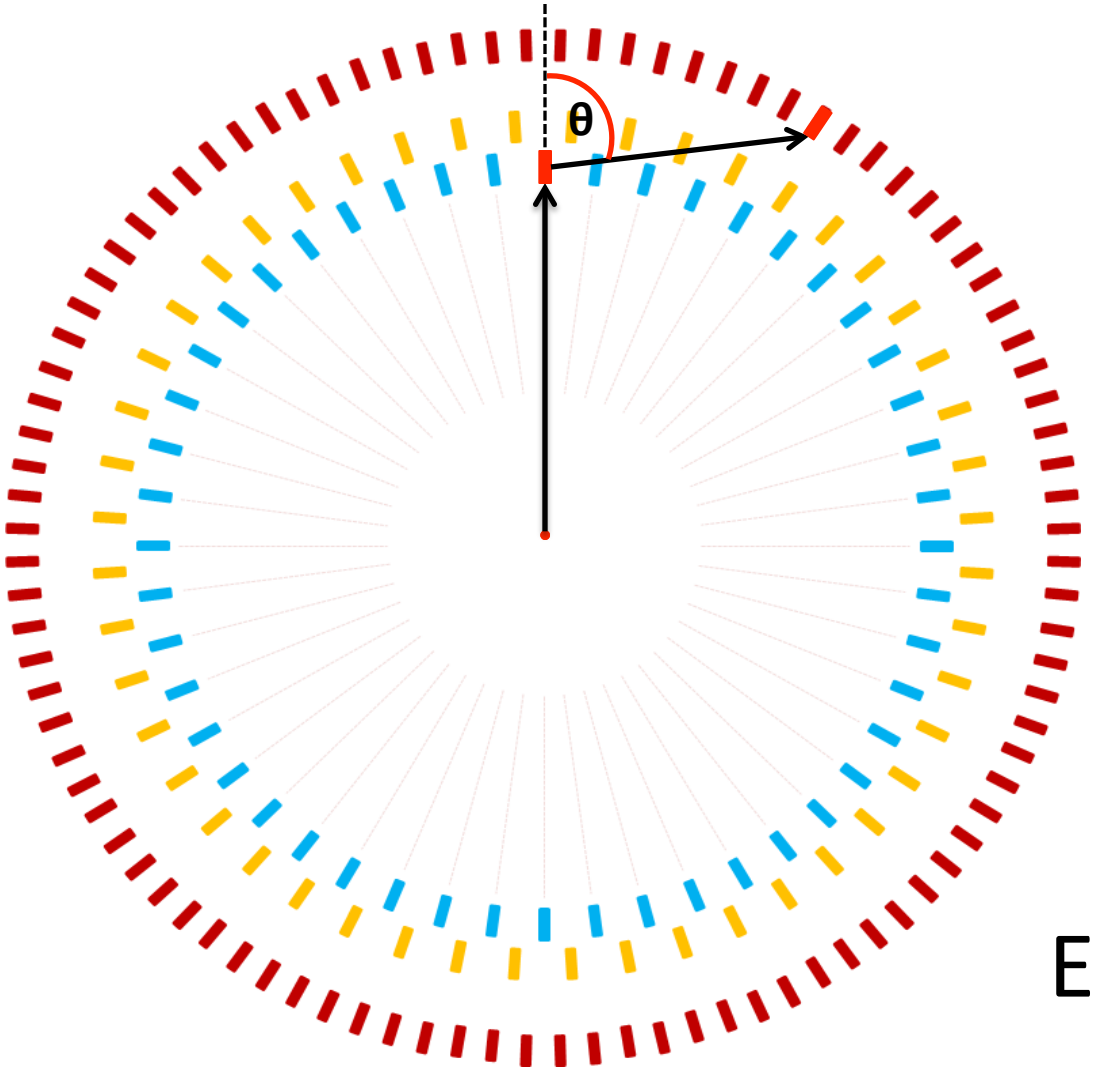
TOT as a response of energy deposition by incident photon



Signals from each photomultiplier are ***probed at four thresholds***.

$$TOT = TOT_{sum}A + TOT_{sum}B$$

Recipe to establish relationship between TOT and Energy dep(scat. Ang.)



What we have :

- ✓ Measured **TOT** values
- ✓ Hit positions and time of primary and scattered photon gives **access to the θ** values

What is required :

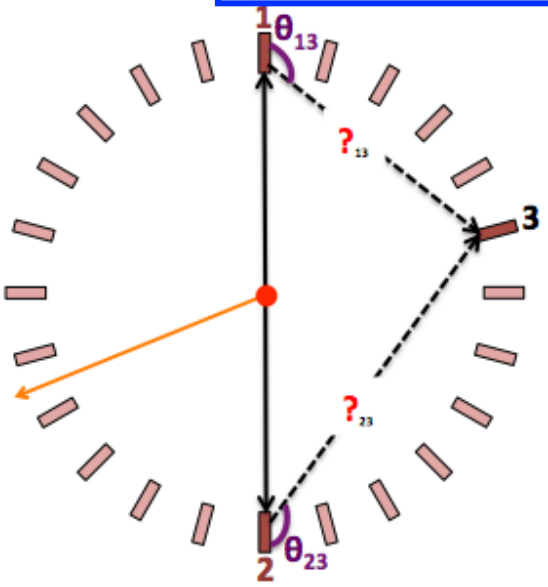
- ✧ **Identify** the origin of **incident photon**

$$E_{dep} = f(E_{inc}, \theta)$$

Analyzed : 3 Hit Events

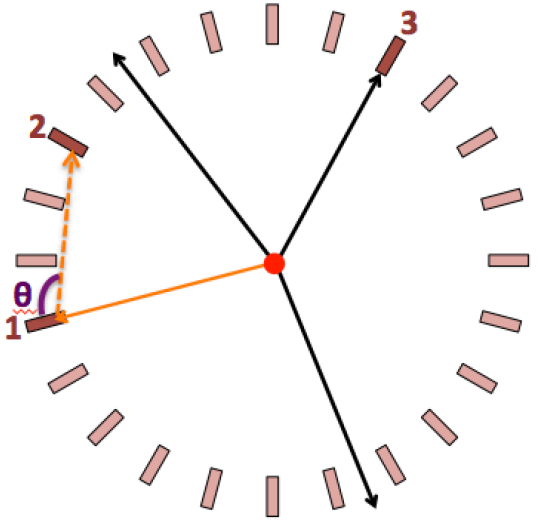
- In order to study *scattering of a photon*, two hits are sufficient.
- 3rd Hit allows to use additional constraints to conjecture and tag the photon of different energy/origin

Scatter test = time$_{measured}$ – time$_{calculated}$



Case 1

e^+ - e^- annihilation into two photons (511 keV)

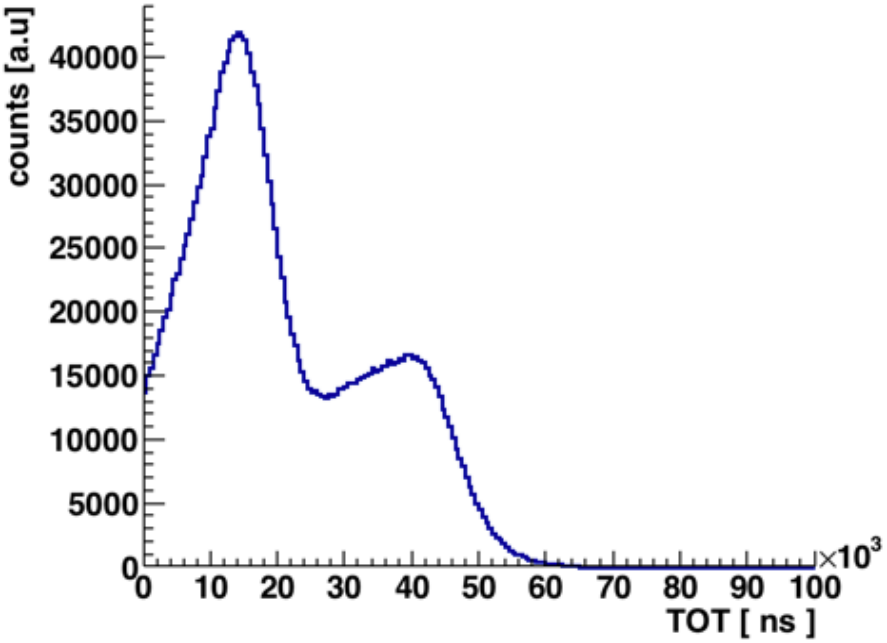


Case 2

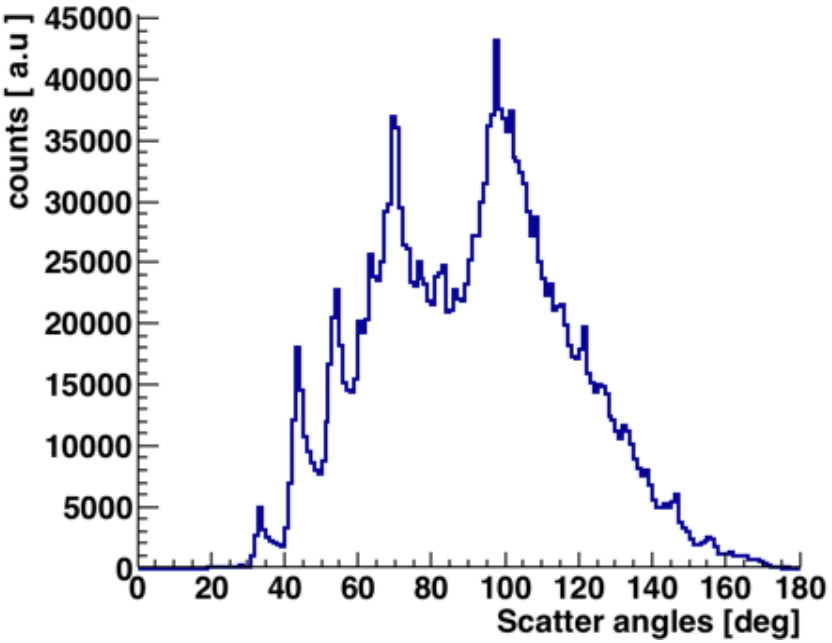
high energetic photons 1274.6keV (Prompt)

TOT spectra for 511 keV and 1274.6 keV and their scattering angles

TOT spectra

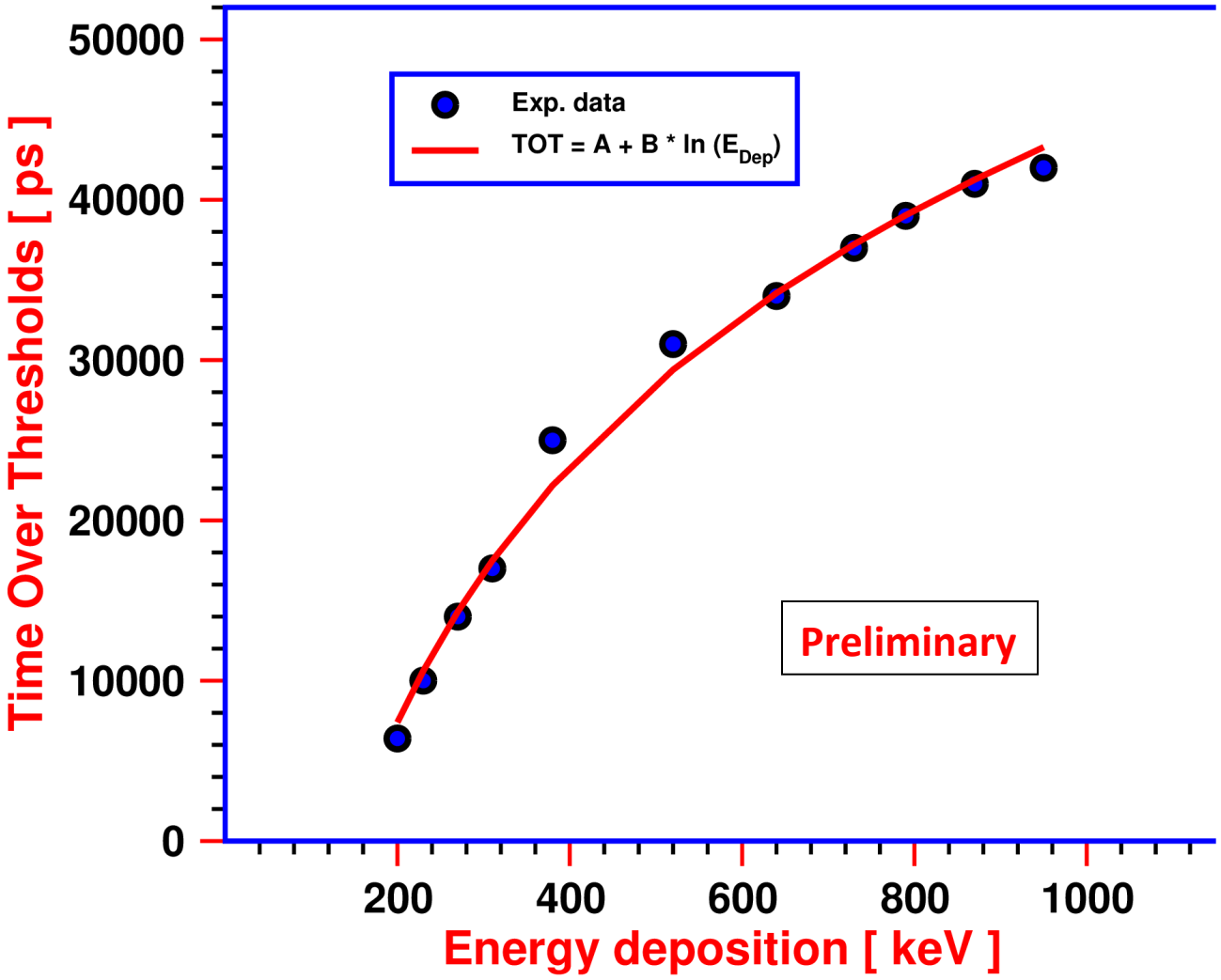


Scattered angles (θ)



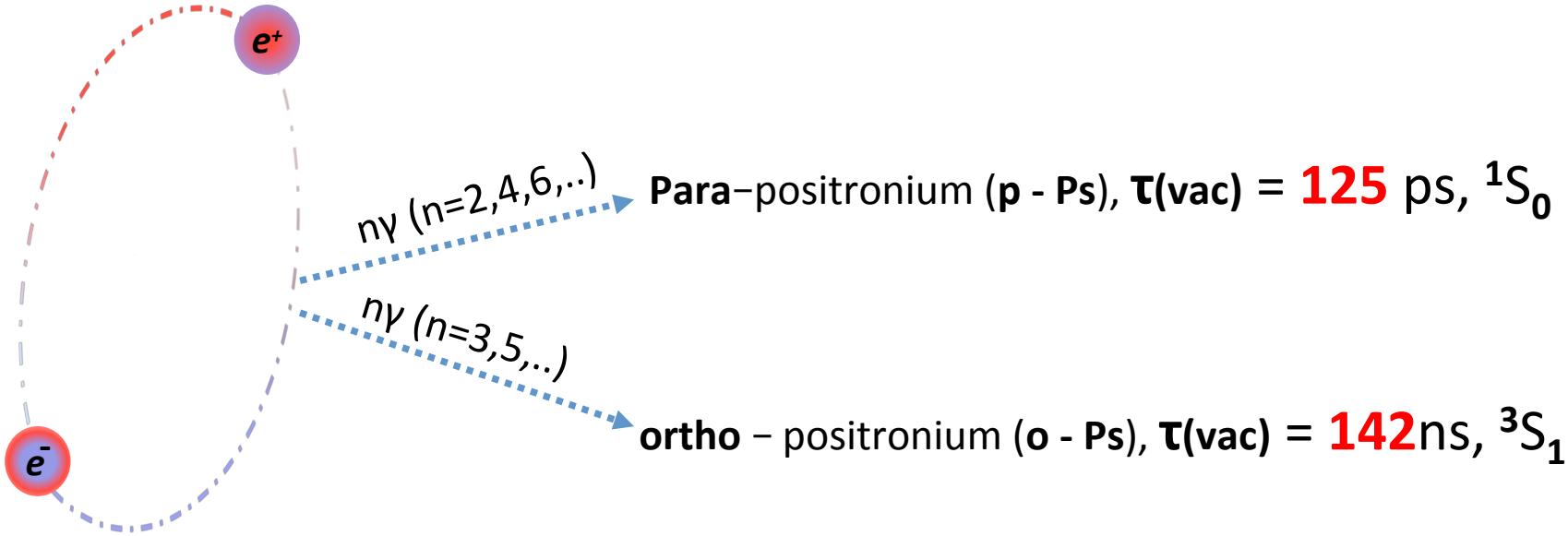
- From the ^{22}Na source, one can get 511 keV from the e^+ e^- annihilation and 1274.6 from prompt.
- TOT spectra resemble the Compton like structure, where *TOT is the estimation of energy deposition*.

TOT vs Energy deposition



Positronium atom – a unique laboratory

- First time detected positronium in Gas : Martin Deutsch
  Nobel prize in 1956 for discovering **Ps**
- Positronium is like hydrogen atom without nuclei consist of electron and positron.
- Eigenstate for C,P, CP operators
- Undergoes self-annihilation into gamma quanta



Tests of discrete symmetries with J-PET detector

Charge conjugation

C

Particle -> anti-particle

Reflection in space

P

x, y, z -> -x, -y, -z

Reversal in time

T

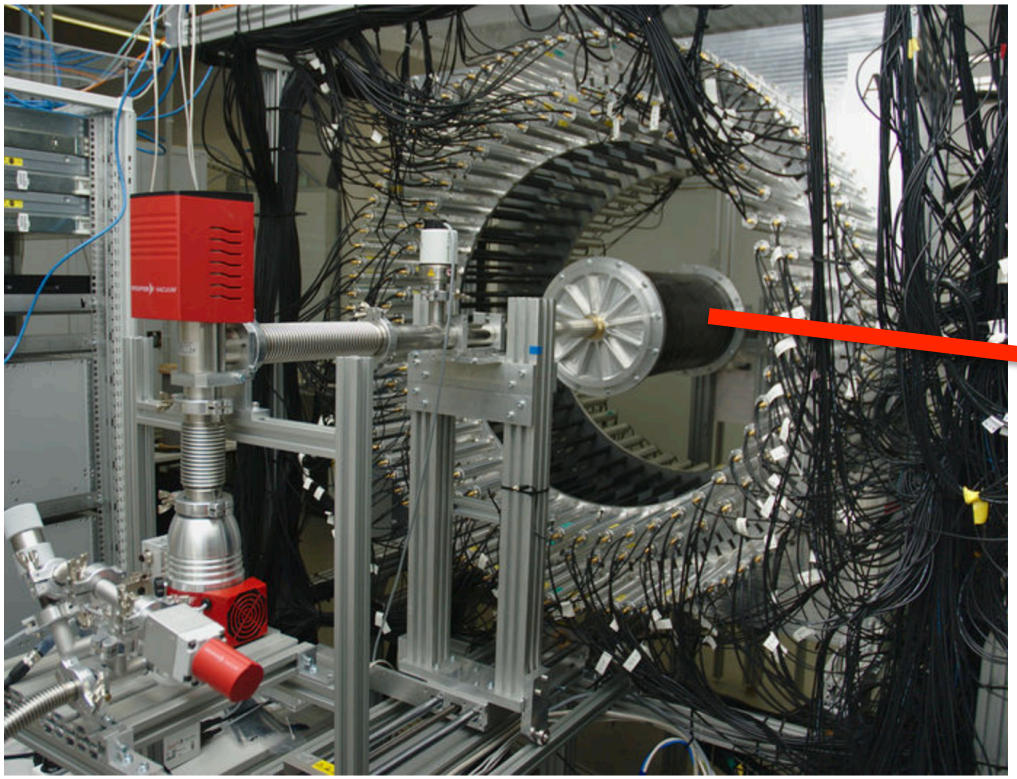
A->B ⇌ B->A

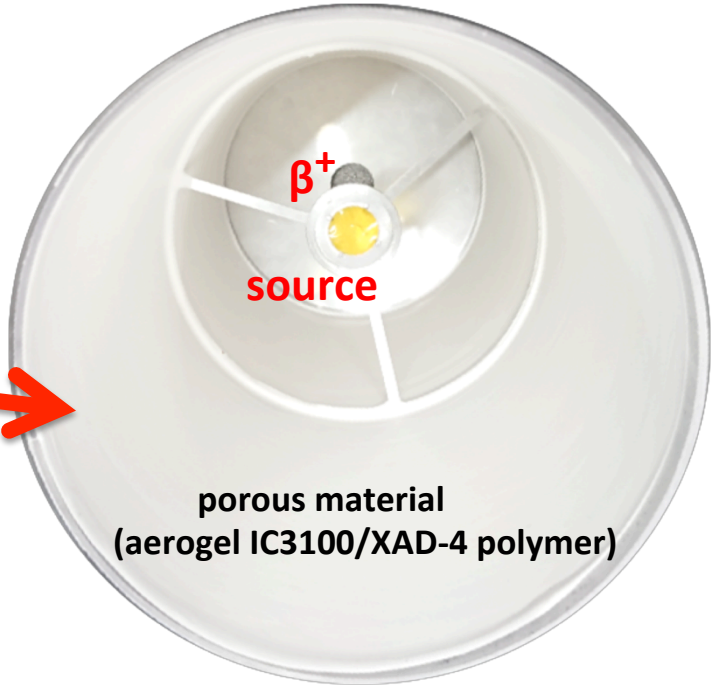
Combination :

CP

CPT

J-PET detector with the target chamber





Annihilation chamber

Selected recent publications -

P. Kowalski et al., **Phys. in Med. & Bio. 63** (2018)

L. *Raczyński et al.*, **Phys. Med. Bio. 62** (2017) 5076

P. Moskal et al., **Phys. in Med. & Bio. 61** (2016) 2025

A.Gajos et al., **Nucl. Inst. & Meth. In Phys. Res. A 819**(2016) 54

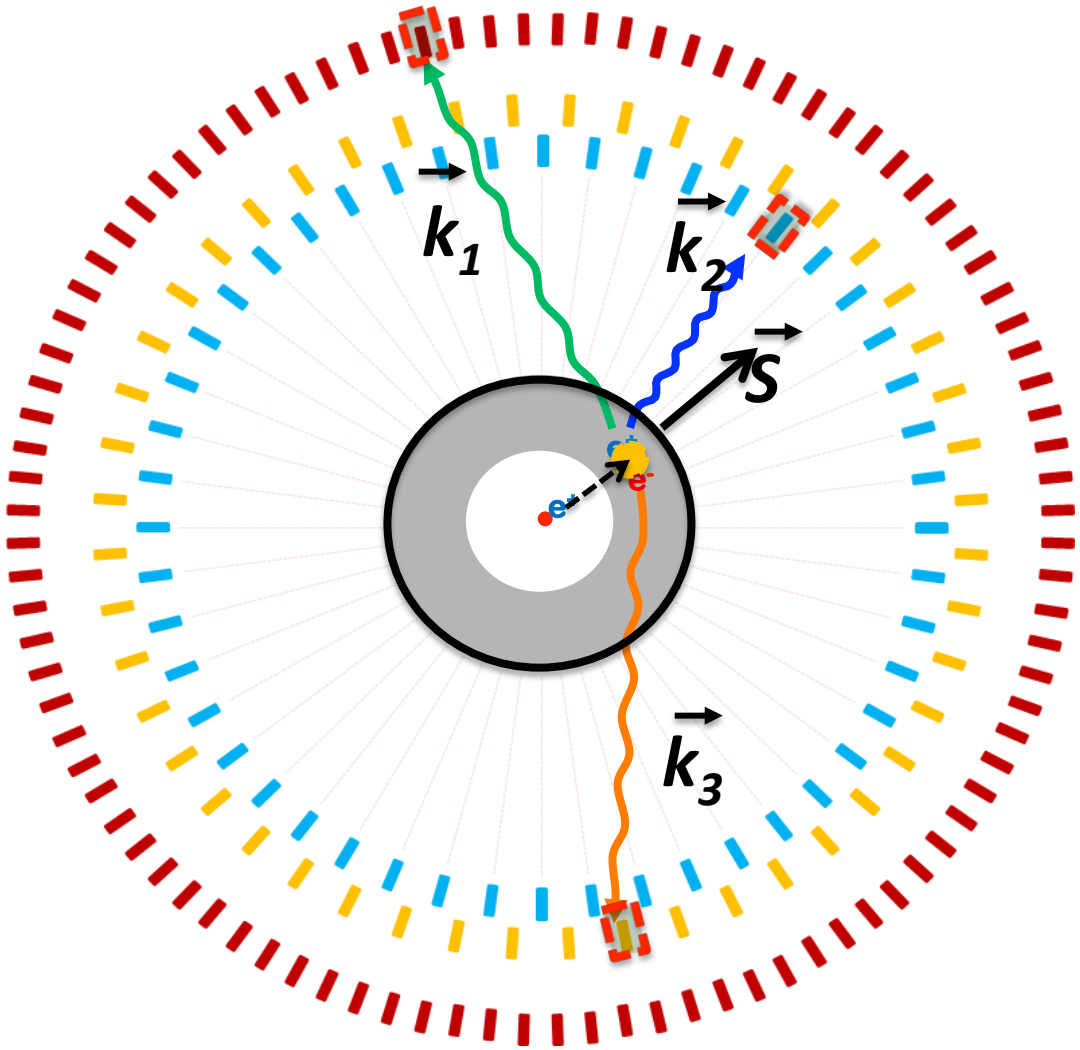
G. Korcyl et al., **IEEE Trans. on Med. Imag.** (2018)

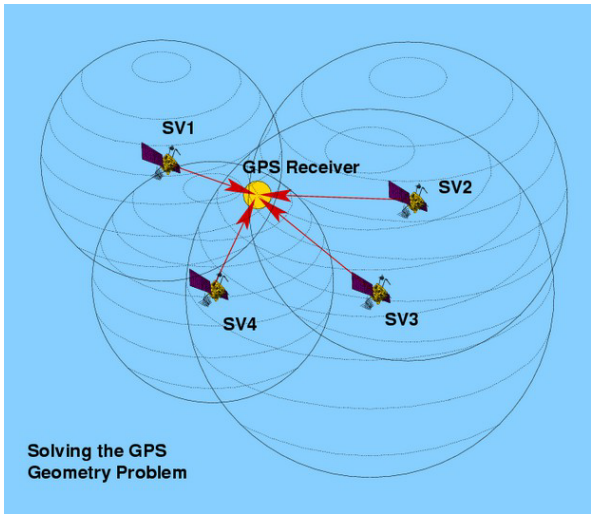
A. Wieczorek et al., **PLoS ONE 12 (11)**: E0186728 (2017)

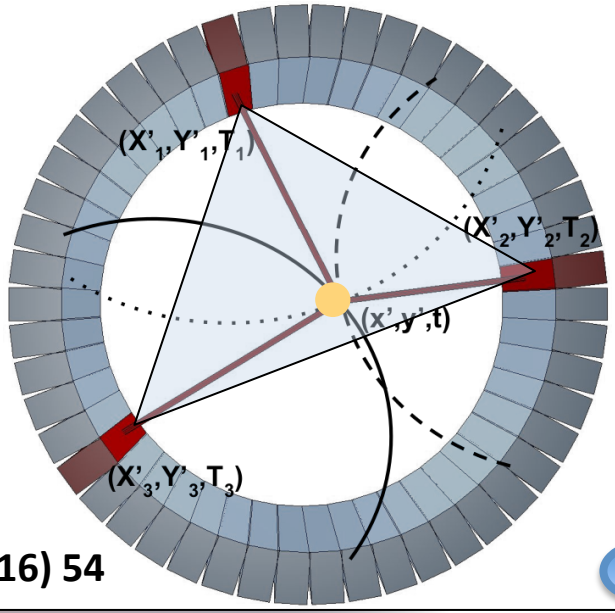
D. Kaminska et al., **Eup. Phys. J. C 76** (2016)

J-PET's plastic revolution, **Cern Courier, October 2018**

Trilateration methods







A. Gajos et al., Nucl. Inst. and Meth. A819 (2016) 54

Operators constructed using o-Ps spin

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

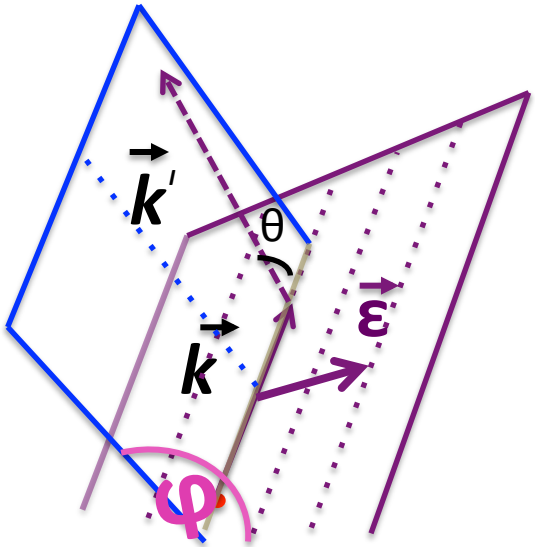
Additional operators with J-PET detector

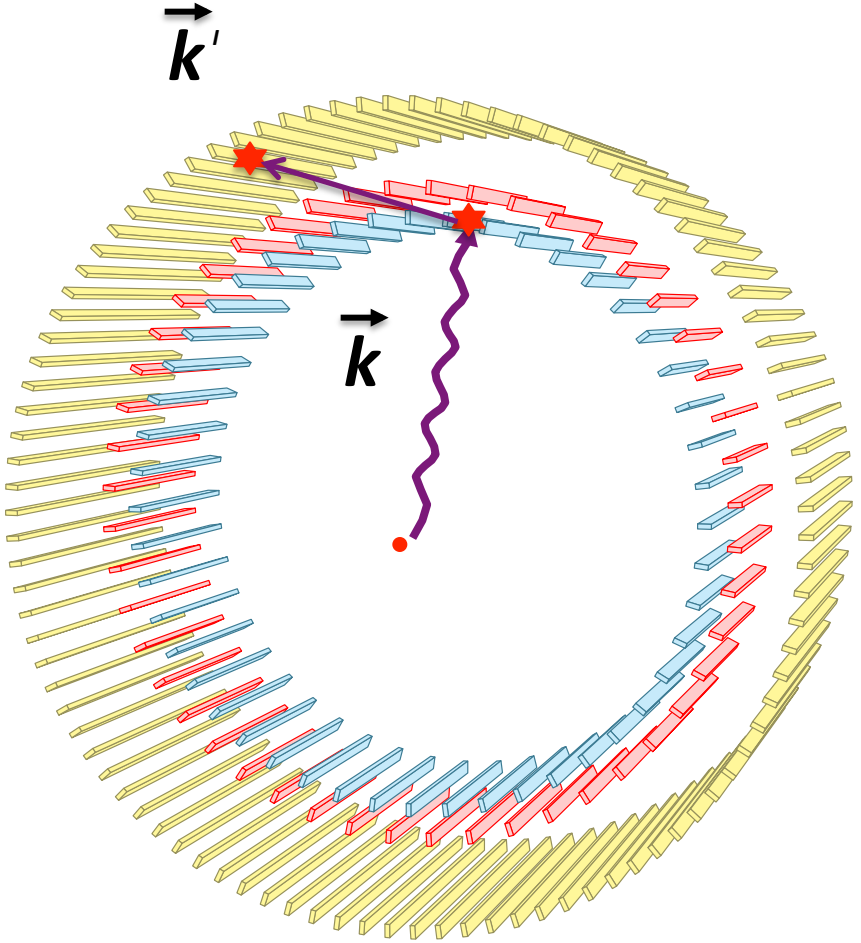
Operators	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	−	+	−	−
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	−	+	−
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))$	+	−	−	−	+

Studies of discrete symmetries using the photon's polarization

Unique feature of the J-PET

Photon's polarization





Photon's Polarization

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

P. Moskal et al., **Eur. PhyS. J C 78** (2018) 970

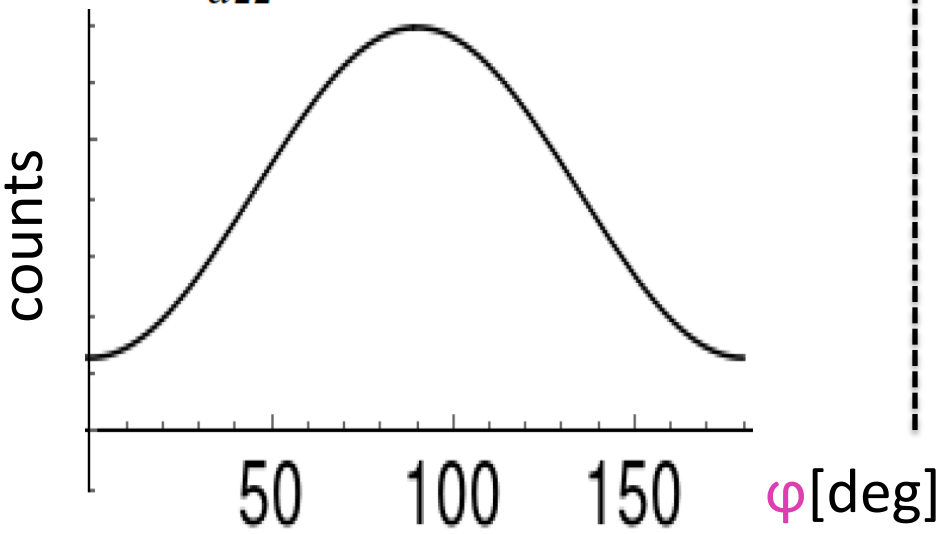
P. Moskal et al., **Acta. Phys. Polon. B 47** (2016) 509, P. Moskal et al., arXiv : 1809.10397v1

Determining the Single photon's polarization

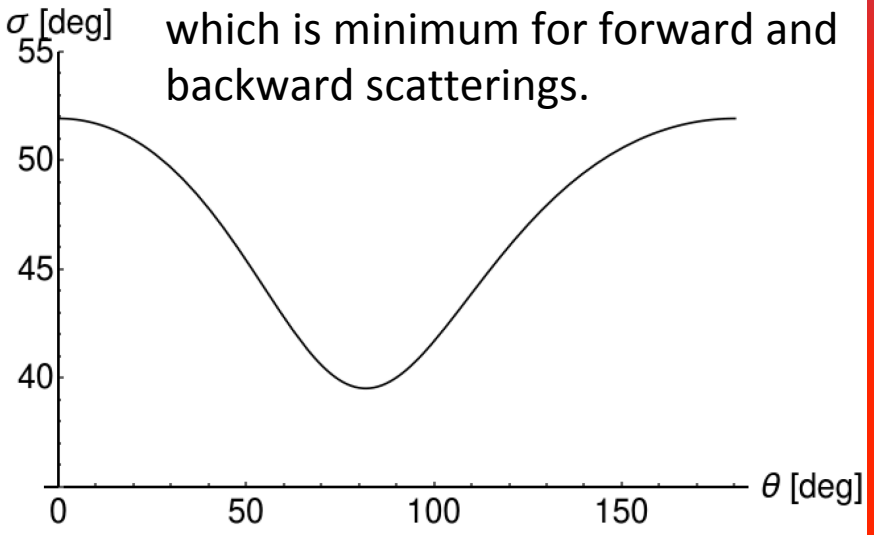
(Based on only the Compton scattering)

- ☑ The scattering distribution of photons can be described by Klein-Nishina diff. cross section.
- ☑ The visibility to observe the angular correlation between scattering and polarization plane(φ) is a function of **Photon's energy** and its **scattering angle (θ)**.
- ☑ For **511 keV photon** and scattering **θ = 81.66⁰** , the Klein-Nishina differential xn for φ:

$$\frac{d\sigma(E,\theta,\varphi)}{d\Omega}$$

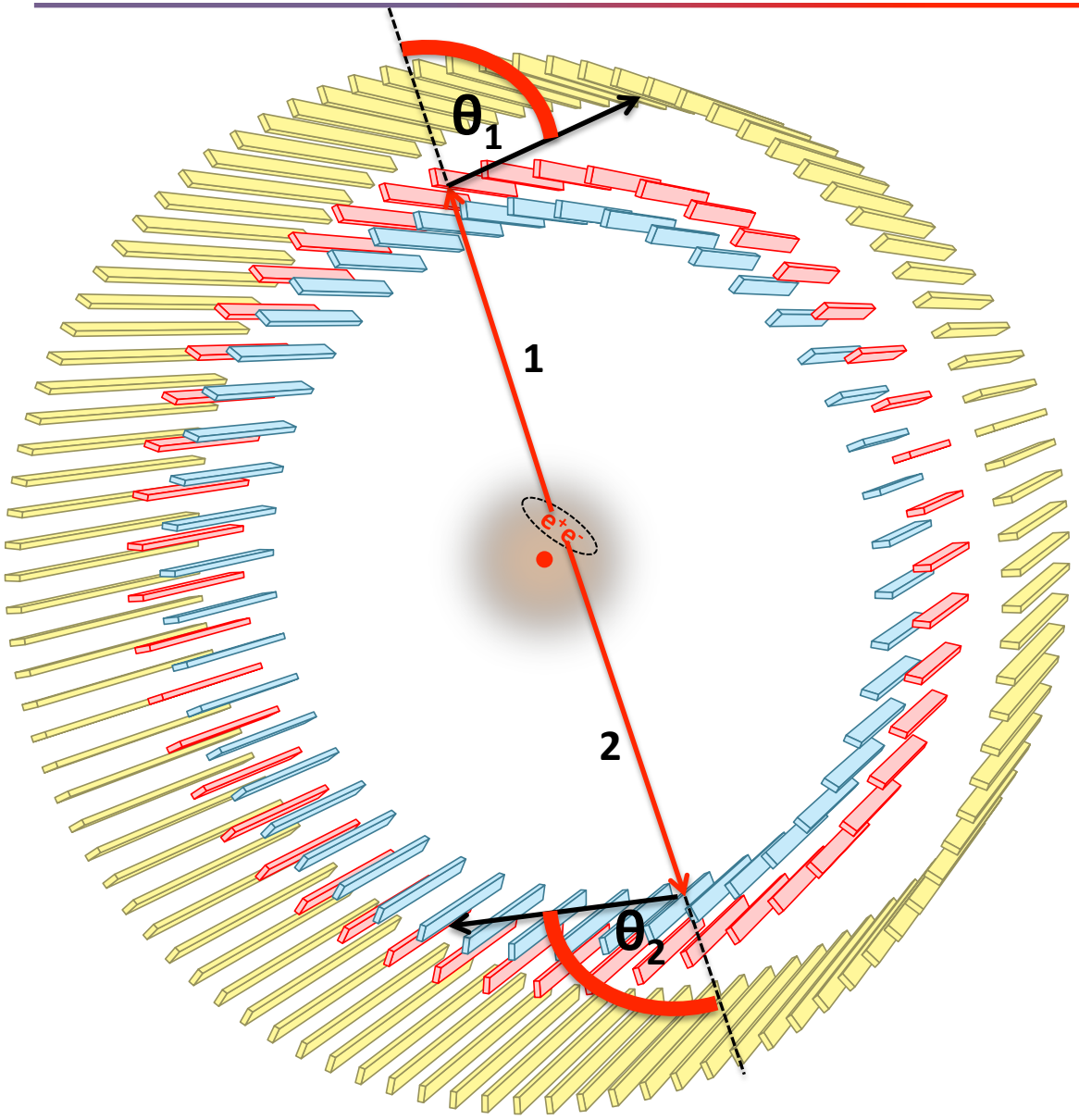


standard deviation around 40⁰, which is minimum for forward and backward scatterings.



P. Moskal et al., **Eur. Phys. J C 78** (2018) 970, P. Moskal et al., **Acta. Phys. Polon. B 47** (2016) 509

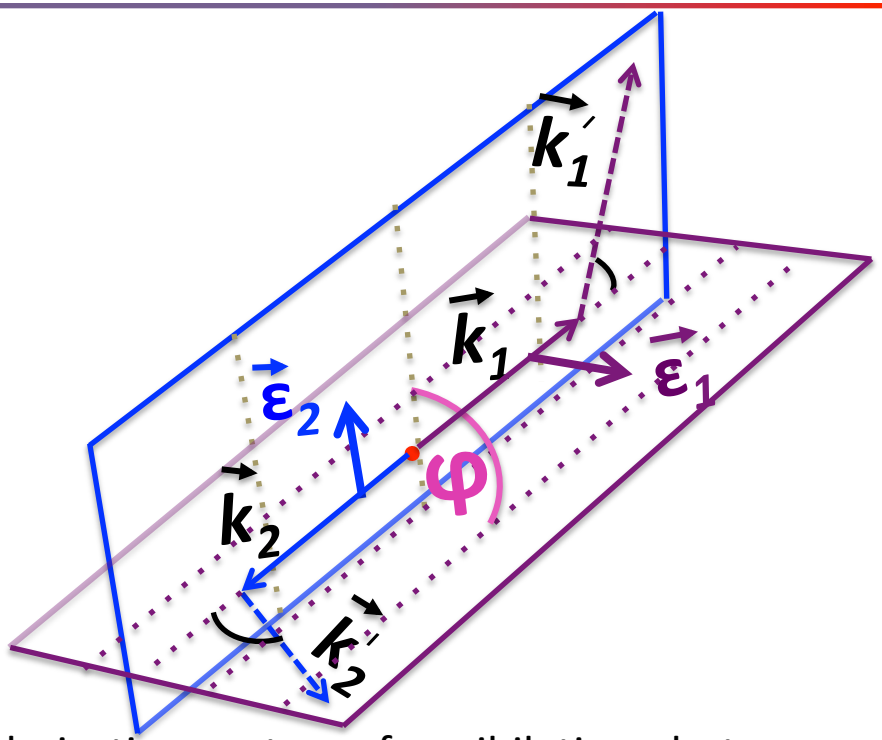
Eventwise observation of scattering angles of back -to- back photons

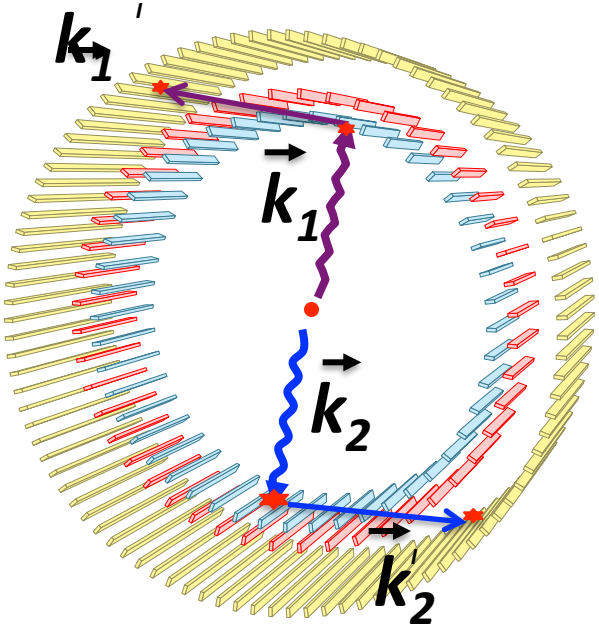


The positron emitting from the ^{22}Na source can annihilate into two photons, directly or through the formation of positronium atoms.

The interactions of the annihilated photons can be measured event-wise and allow to study the ***correlation between the scattering angles***.

Relative polarization of entangled annihilated photons in decay of p-Ps atom





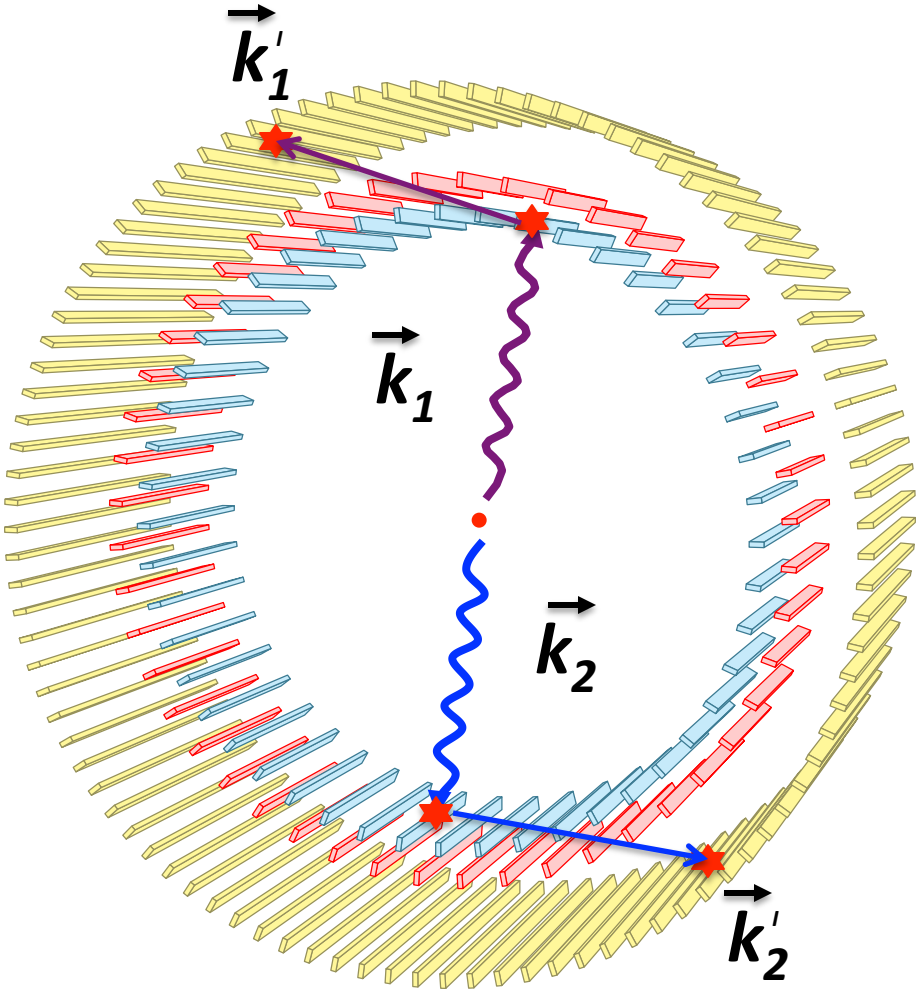
- Polarization vectors of annihilation photons are mutually orthogonal states.
- Photons mostly scatter at right angles to their electric field vector and this impose an **Expected angular correlation** between the scattering angles.
- With the J-PET detector we can measure scatterings of back-to-back photons and thus can study the angular correlation(φ) between the scattering angles.
- Thus the **angle between two scattering planes(φ)** can be an estimator of relative polarization of two photons.

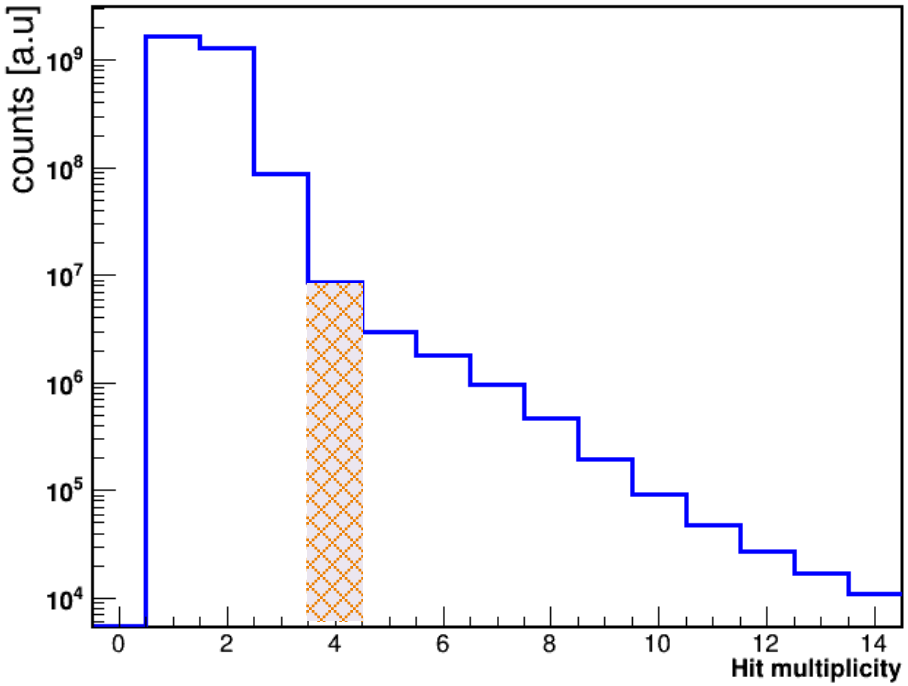
P. Moskal et al., **Eur. Phys. J C 78** (2018) 970, P. Moskal et al., **Acta. Phys. Polon. B 47** (2016) 509

Experimental evidence for the measurement of photon's polarization with the J-PET detector

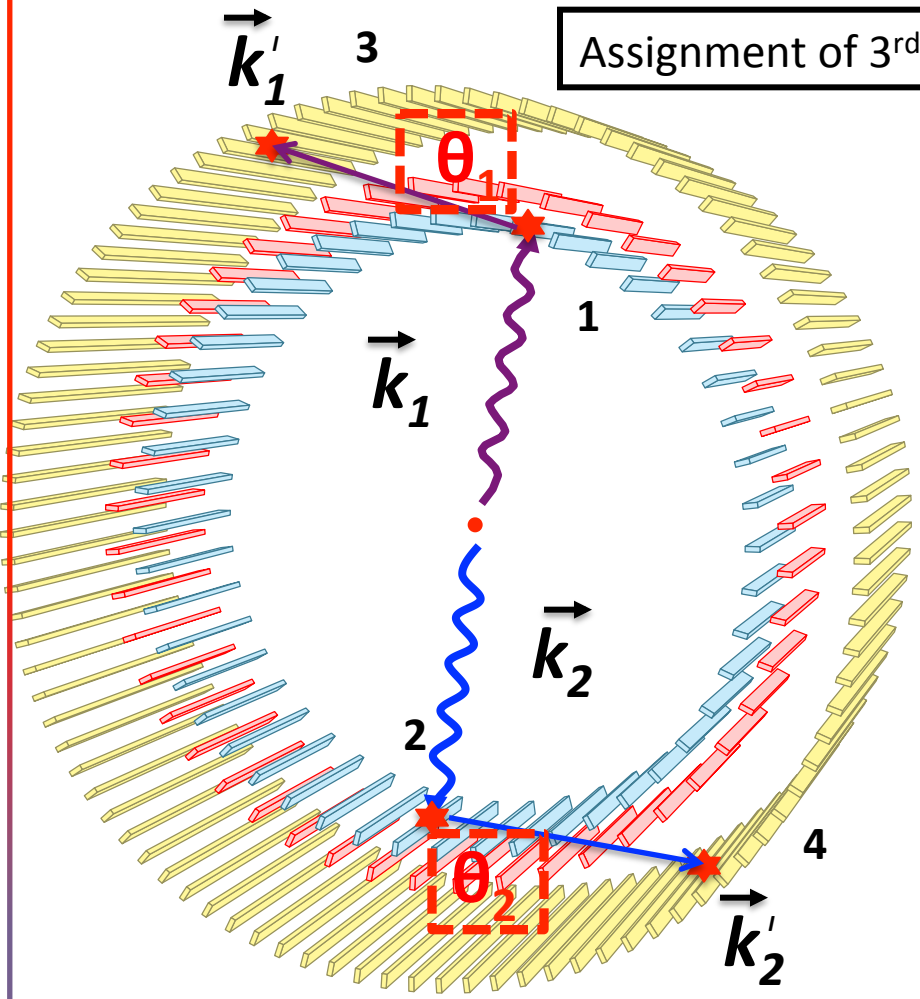
Small annihilation chamber was used

4 – hit events were studied





4 – hit events were studied

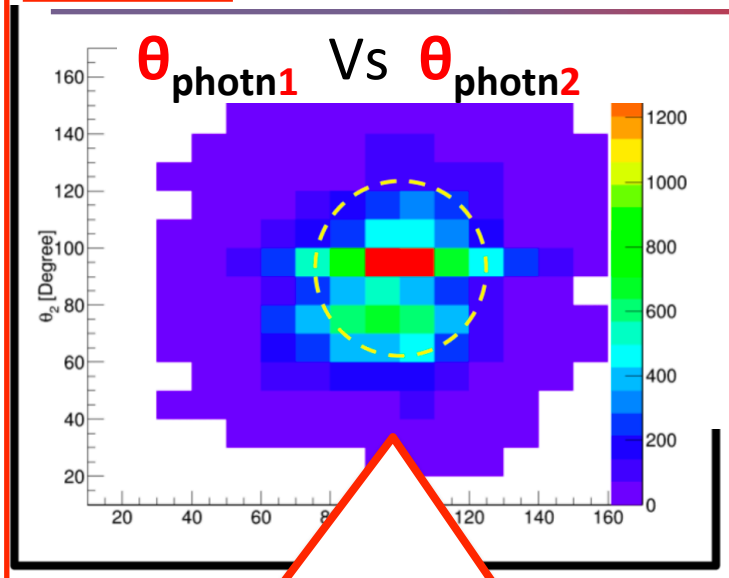


Assignment of 3rd HIT

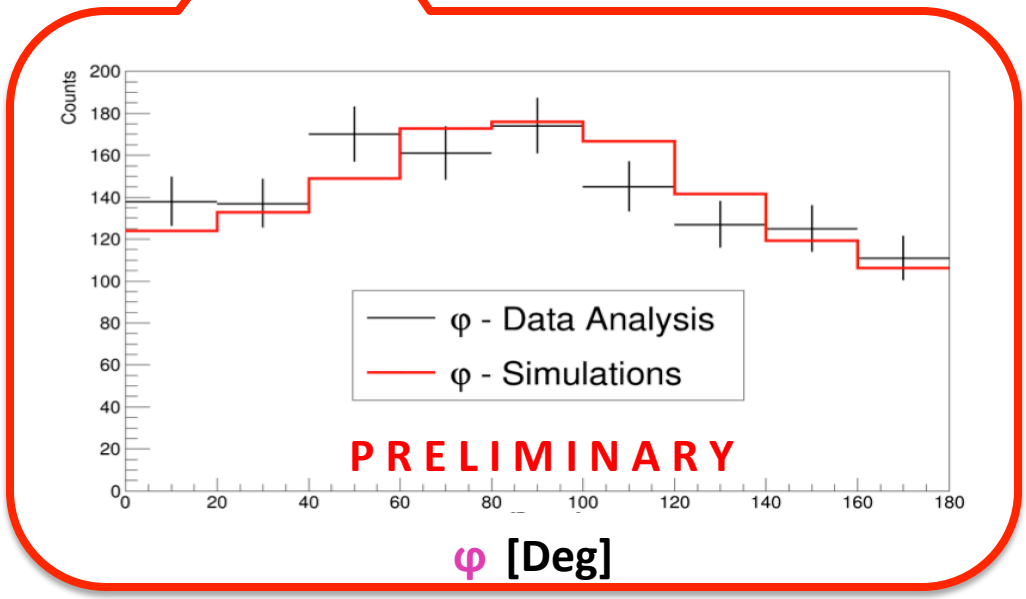
Assignment of 4th HIT

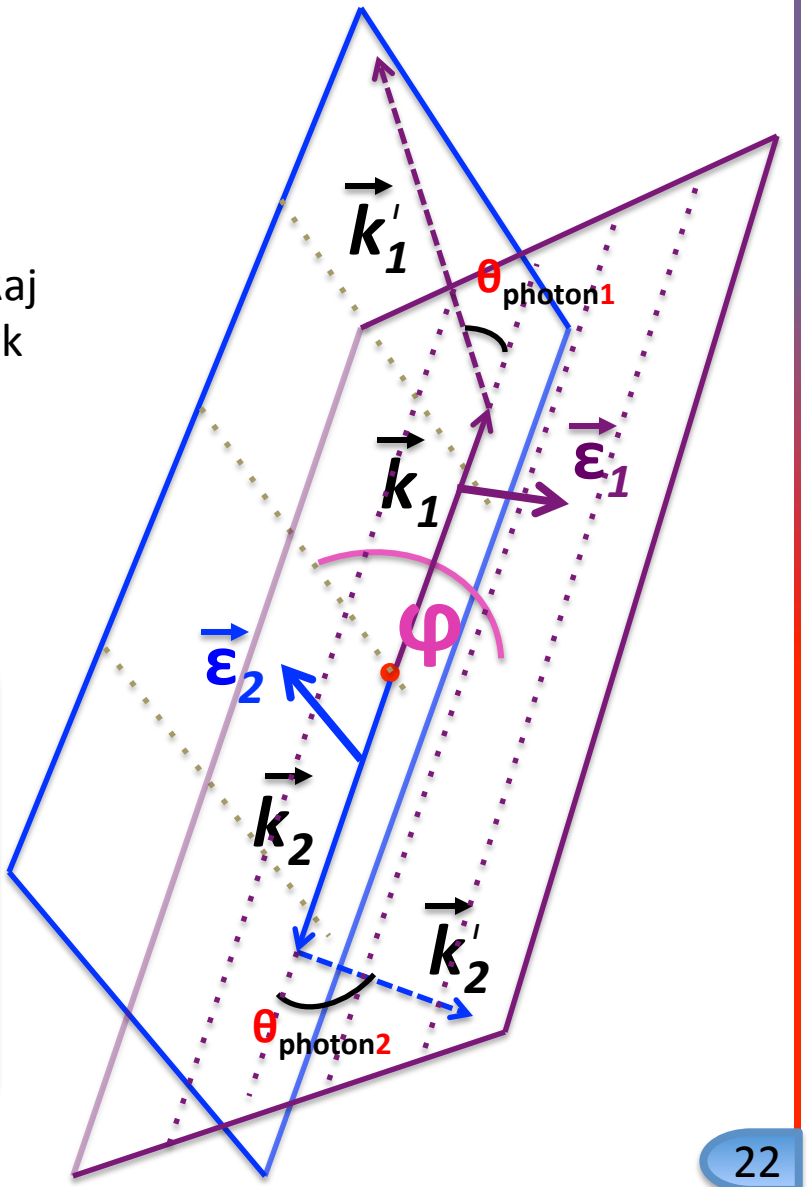
Scatter test = $\text{time}_{\text{measured}} - \text{time}_{\text{calculated}}$

Relative angles between scattered planes *as a measure of* Relative polarization of annihillation photons



Courtesy to J. Raj and N. Krawczyk





Eventwise observation of scattering angles of back -to- back photons

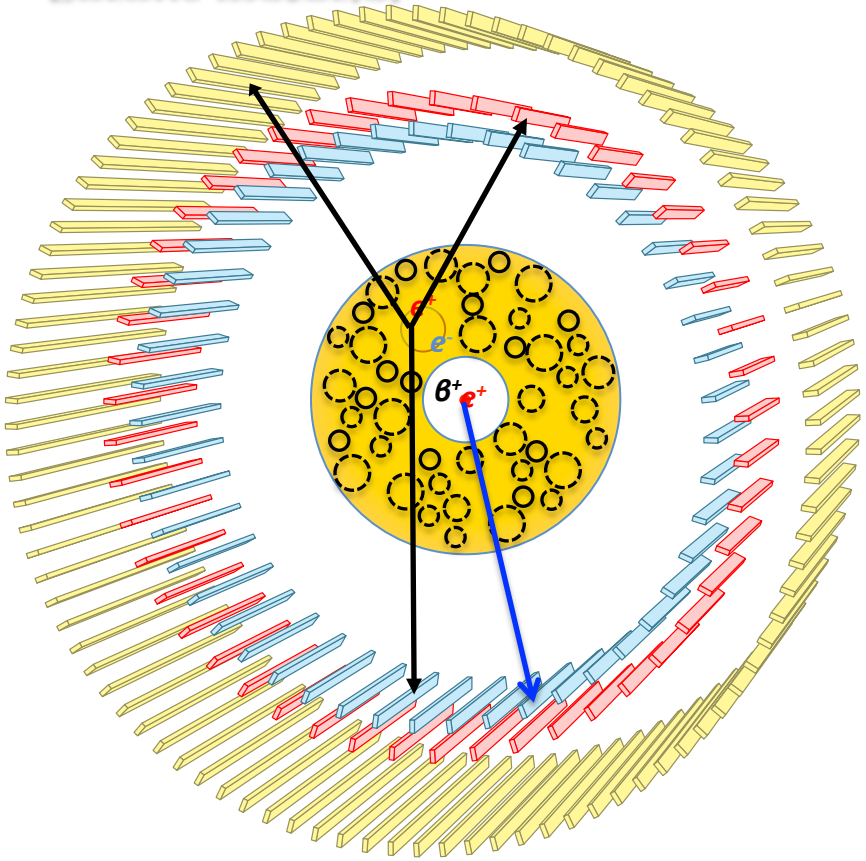
Operators	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	−	+	−	−
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	−	+	−
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))$	+	−	−	−	+

New operators available with J-PET With $\vec{\varepsilon}_i = \vec{k}_i \times \vec{k'}_i$

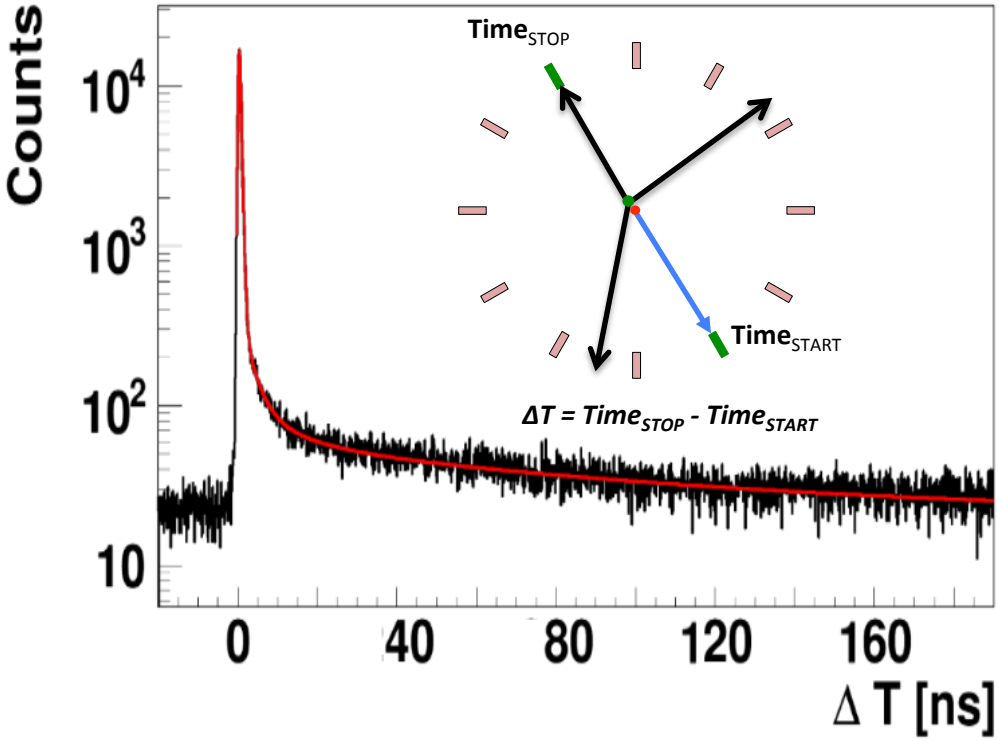
Poster [F3]

$\vec{k}_2 \cdot \vec{\varepsilon}_1$	+	−	−	−	+
$\vec{S} \cdot \vec{\varepsilon}_1$	+	+	−	+	−
$\vec{S} \cdot (\vec{k}_2 \times \vec{\varepsilon}_1)$	+	−	+	−	−

Porous material



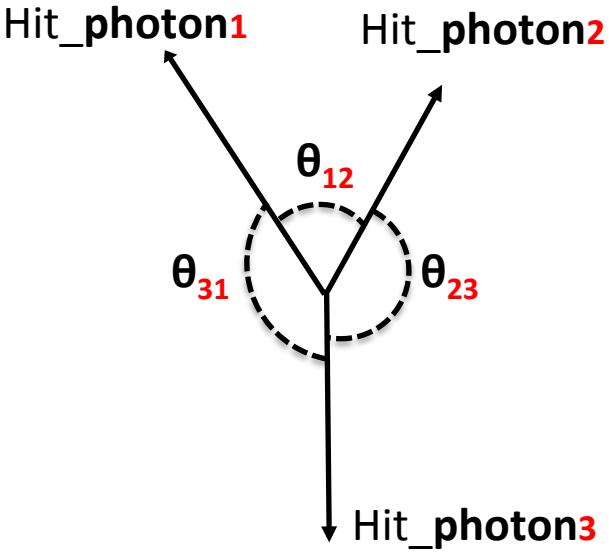
Positronium life time spectra*



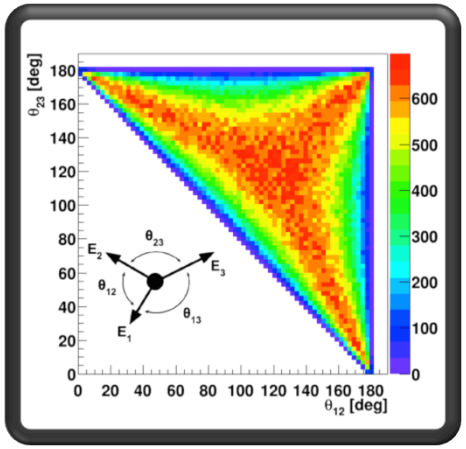
*K. Dulski et al., Hyperfine Interact 40 (2018) 239

Study of angular correlations among the photon originating from the decay of Positronium atom can provide an insight into the rare decays : e.g: p-Ps -> 3γ

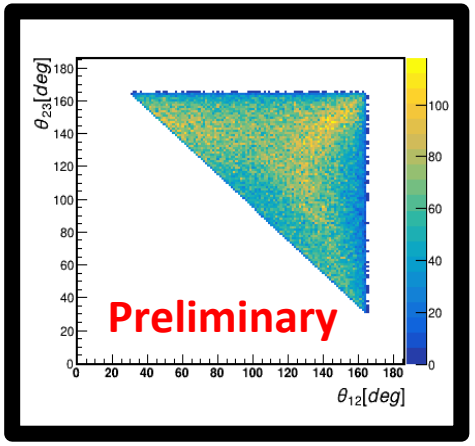
In o-Ps decay : angular correlation



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

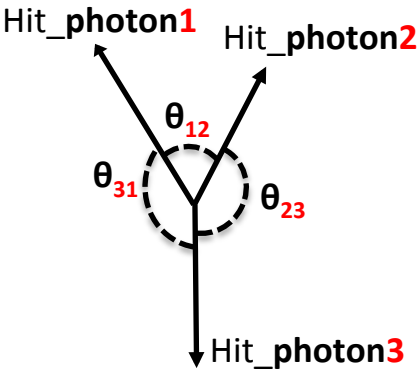


Experimental : Courtesy to **J. Chhokar**

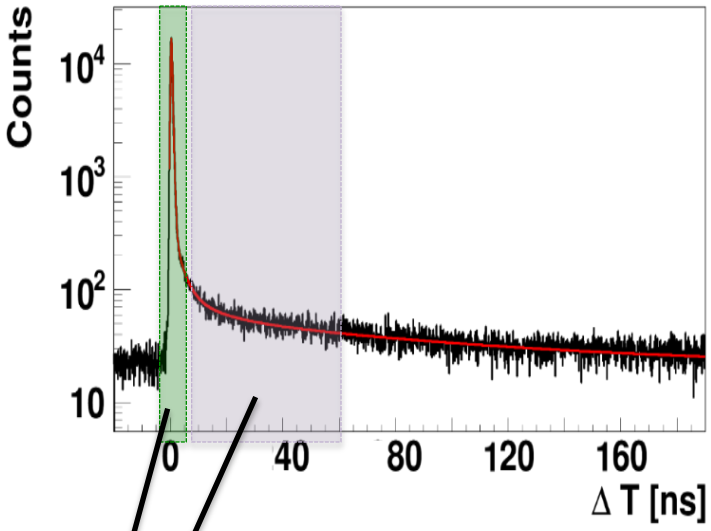


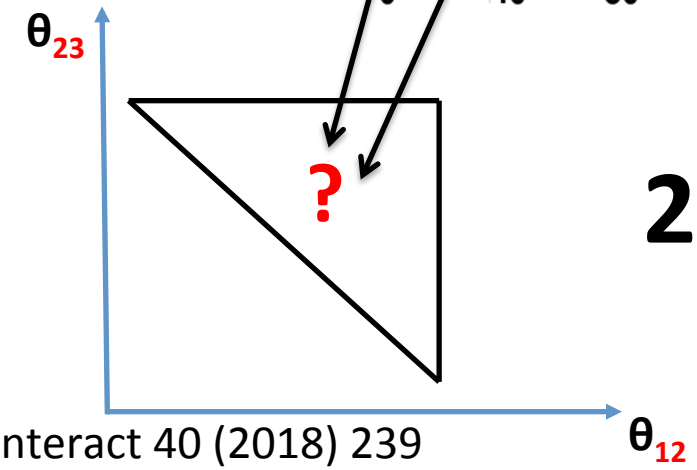
Poster [F5]

Study of angular correlations among the 3 photon originating from the decay of Positronium atom, distinguish based on the life time of positronium atom at various symmetrical configuration (p-ps-> 3γ decay mode is restricted by Bose-statistics)



Positronium life time*





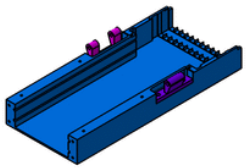
1

2 **Decay Rate ratio : ?**

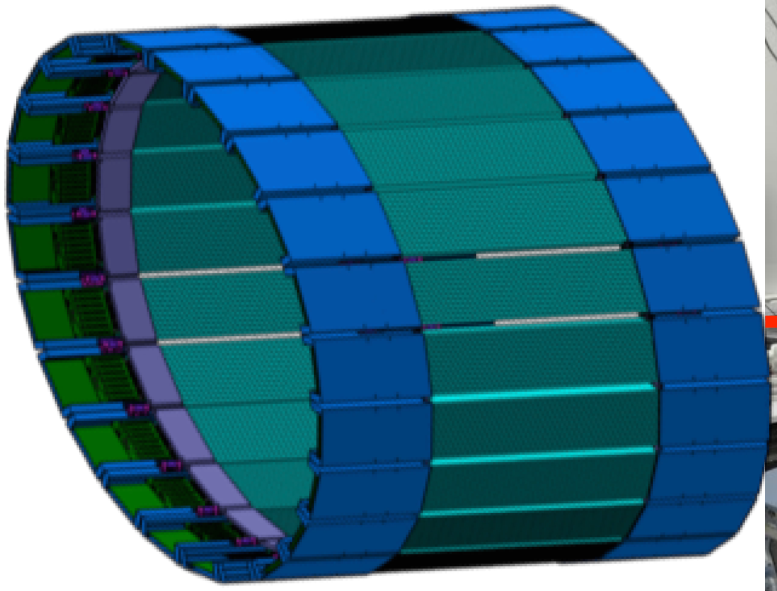
3γ / 2γ

* K. Dulski et al., Hyperfine Interact 40 (2018) 239

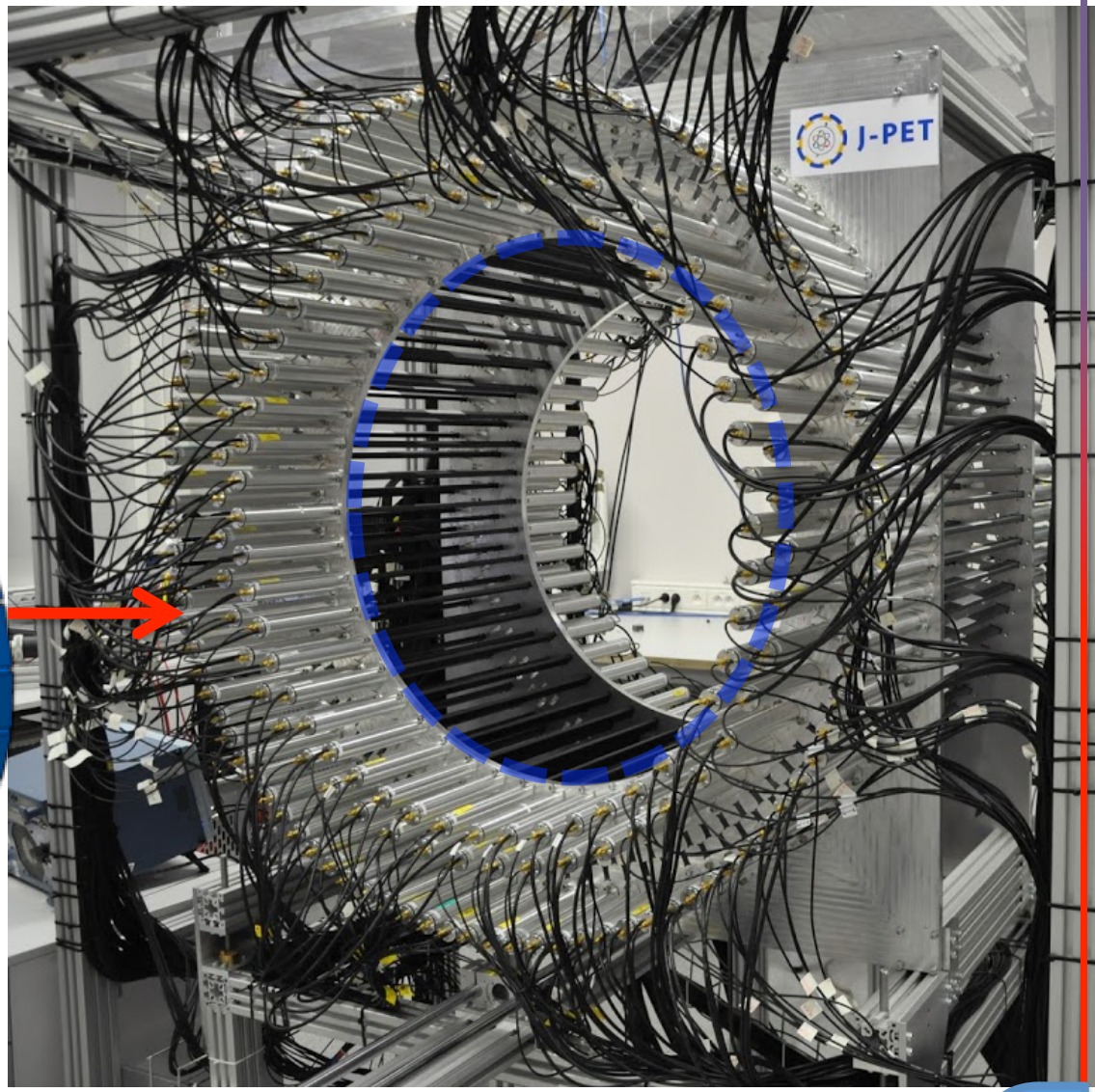
Modular J-PET – extention to 3 lyaer prototype



Fourth Layer along with current prototype



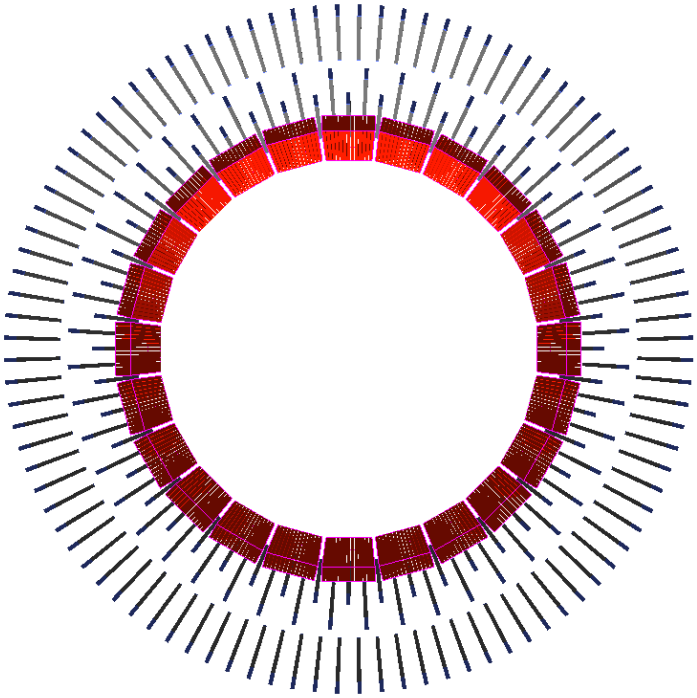
24 PORTABLE modules



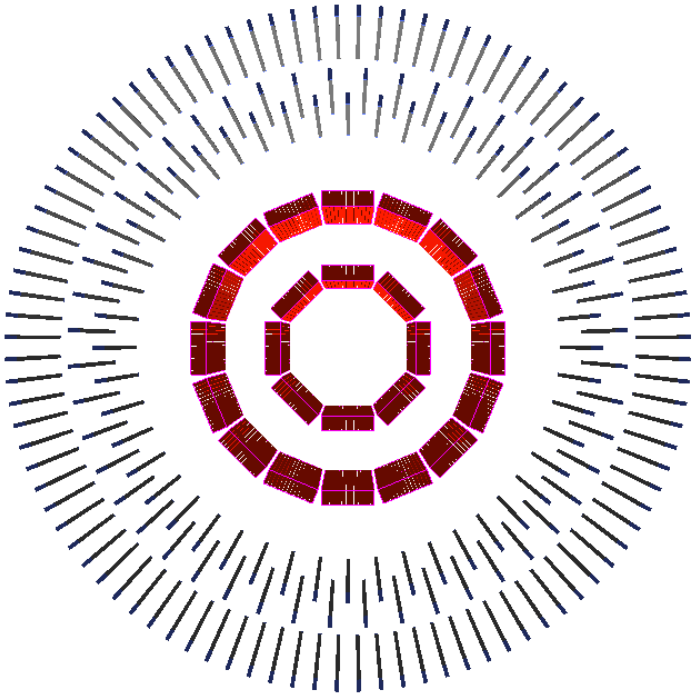
Advantages with Modular J-PET

Geometry configuration made with Geant4 package

24 Modules placed as the innermost layer



24 Modules rearranged and add 2 layers



Advantage

- ✓ **Several times better efficiency**
- ✓ **Standalone PET/detector**

Multi-configurational

Summary

- ☑ A Positron Emission Tomograph based on *plastic scintillators* **constructed and commissioned** .
- ☑ Discrete symmetries are very crucial in order to understand the inequality between matter and anti-matter.
- ☑ Such inequality should have contribution of symmetry violation not only in baryonic and mesonic sectors **but also from leptons**.
- ☑ The experimental data on fundamental symmetry tests in **leptonic sector is very scarce**.
- ☑ The J-PET detector is capable to study the **C, T, CP and CPT test in the decays of Ps atoms** with better precision.
- ☑ Possibility to measure polarization will add up new scope to study the additional odd symmetric operators and phenomena like **multi-particle entanglement**.

J–PET collaboration

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Thank you for your attention