Jagiellonian **P**ositron **E**mission **T**omograph

From tests on
fundamental symmetries
to the applications
in **medical imaging**

***Sushil K. 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

Indian Institute of Technology Bombay, India, 15.01.2020

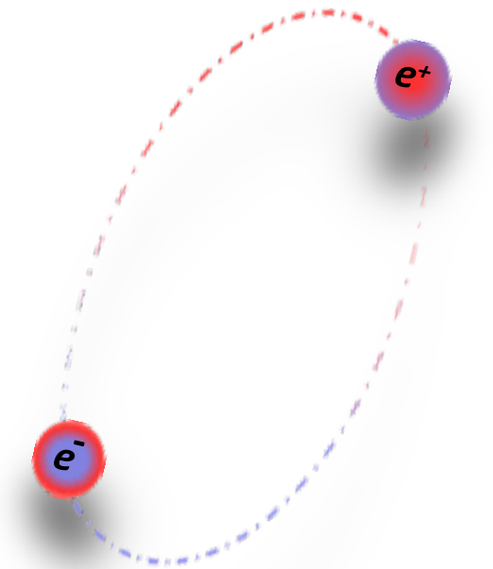
Outline

Historical review

Jagiellonian Positron Emission Tomograph

Positronium decays

- *Tests on discrete symmetries*
- *Photon's polarization*
- *Recent results*

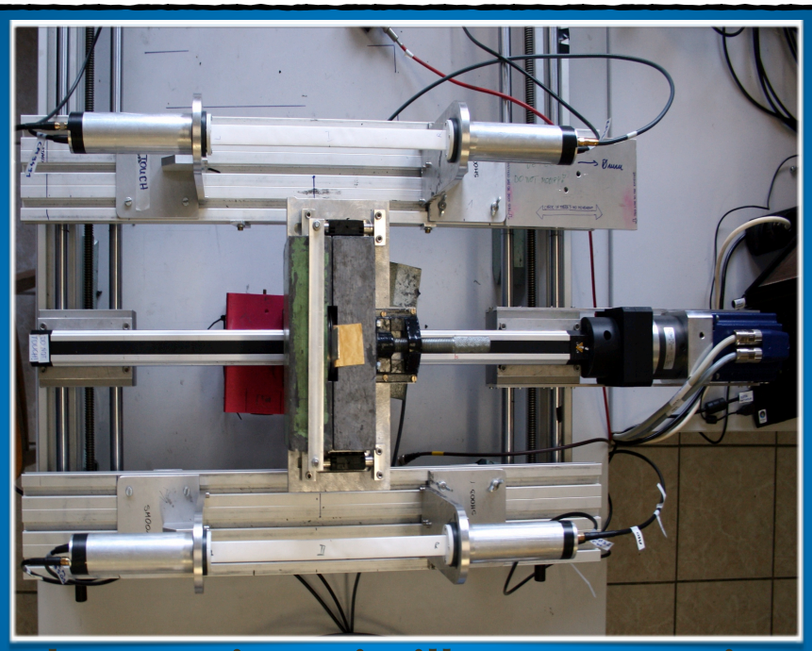


Future perspectives

Modular PET

Historical review of J-PET

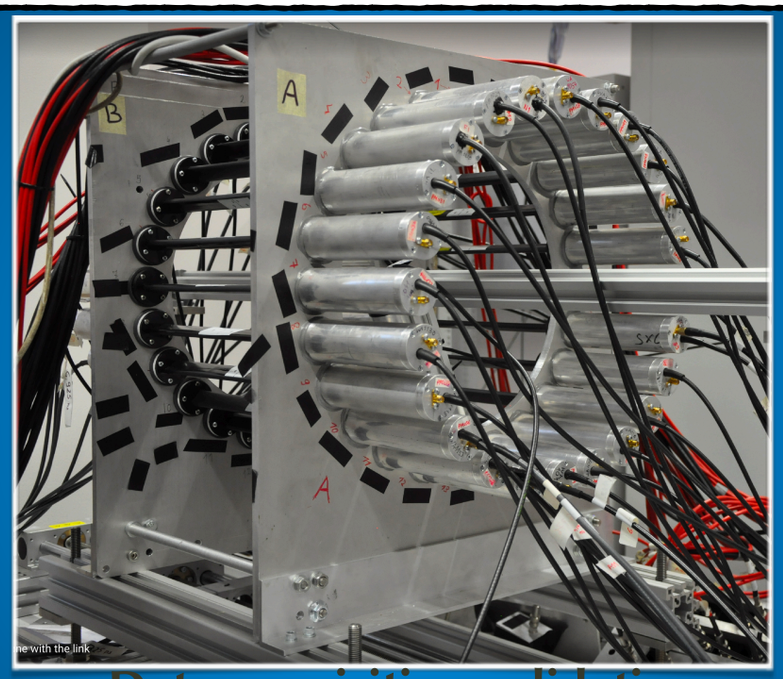
2012



Characterize scintillator properties

Energy resolution, hit time, ..

2014

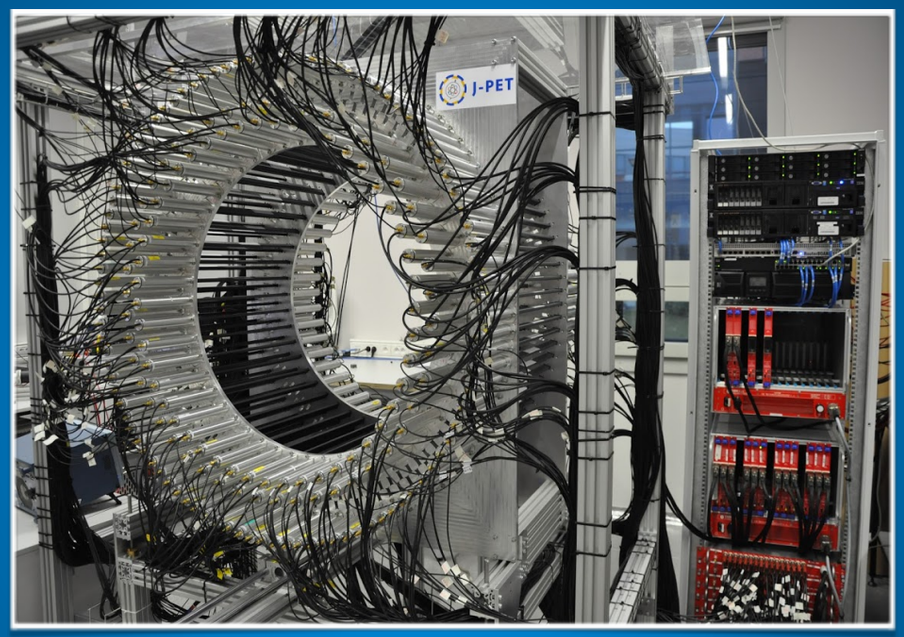


24 strips

Data acquisition validation

for multi-modules

2016



Current version

Fundamental symmetries test and Positronium imaging

2018

24 modules

Modular PET : Ready for first data campaign

J-PET's Plastic Revolution - CERN COURIER

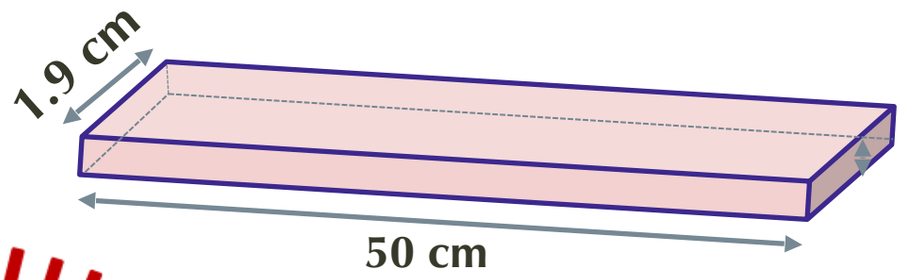
https://cerncourier.com/a/j-pets-plastic-revolution/

Selected Recent Publications

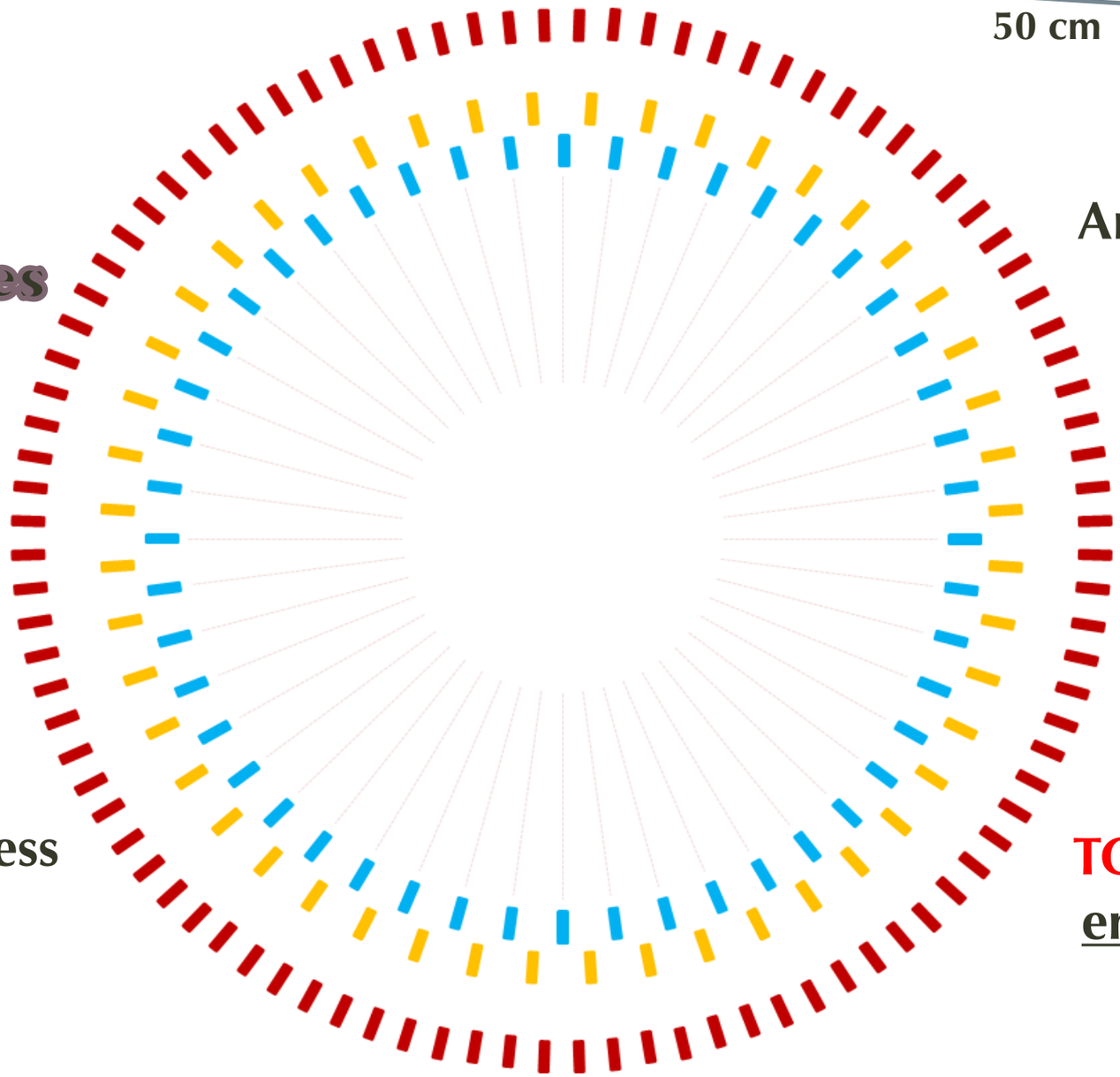
- P. Moskal et al., ***Nature Reviews Physics*** 1 (2019) 527
- Beatrix C. Hiesmayr, Pawel Moskal; ***Nature scientific reports 9*** (2019) 8166
- P. Moskal et al., **Phys. Med. Bio. 64** (2019) 055017
- P. Kowalski et al., **Phys. in Med. & Bio. 63** (2018)
- G. Korcyl et al., **IEEE Trans. on Med. Imag.** (2018)
- B.C. Hiesmayr, P. Moskal; ***Nature Scientific reports 7*** (2017) 15349
- L. *Raczyński et al.*, **Phys. Med. Bio. 62** (2017) 5076
- A. Wieczorek et al., **PLoS ONE 12 (11)**: E0186728 (2017)
- 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
- D. Kaminska et al., **Eup. Phys. J. C 76** (2016)
- …….

More than 70 articles and 18 patents applications
For more information : http://koza.if.u.edu.pl

Plastic Scintillator



192 Modules



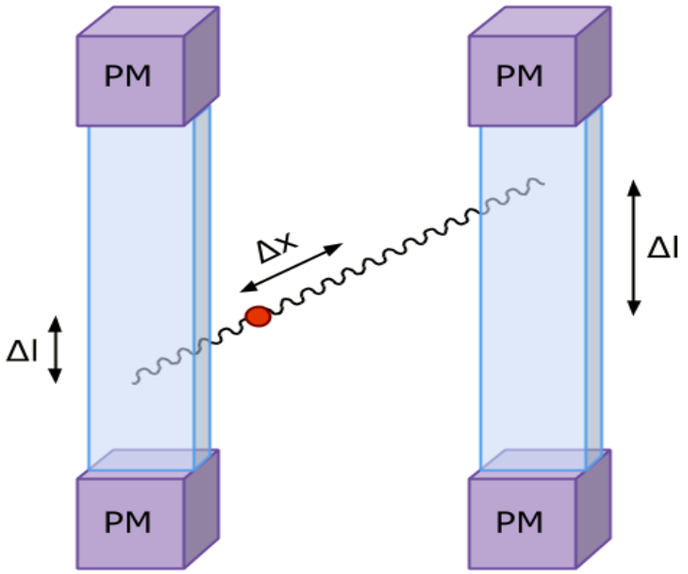
Arranged axially in 3 layers

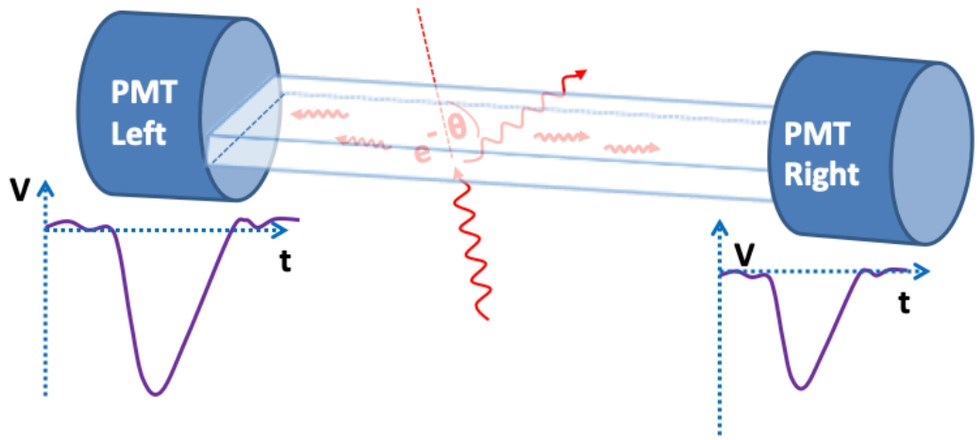
(48,48,96)

Trigger less DAQ

TOT as measure of energy deposition

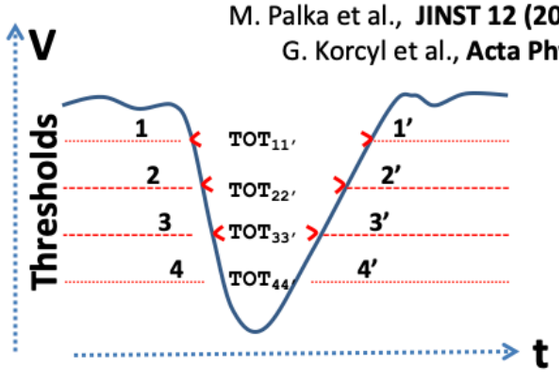
Positronium : Scintillation principal



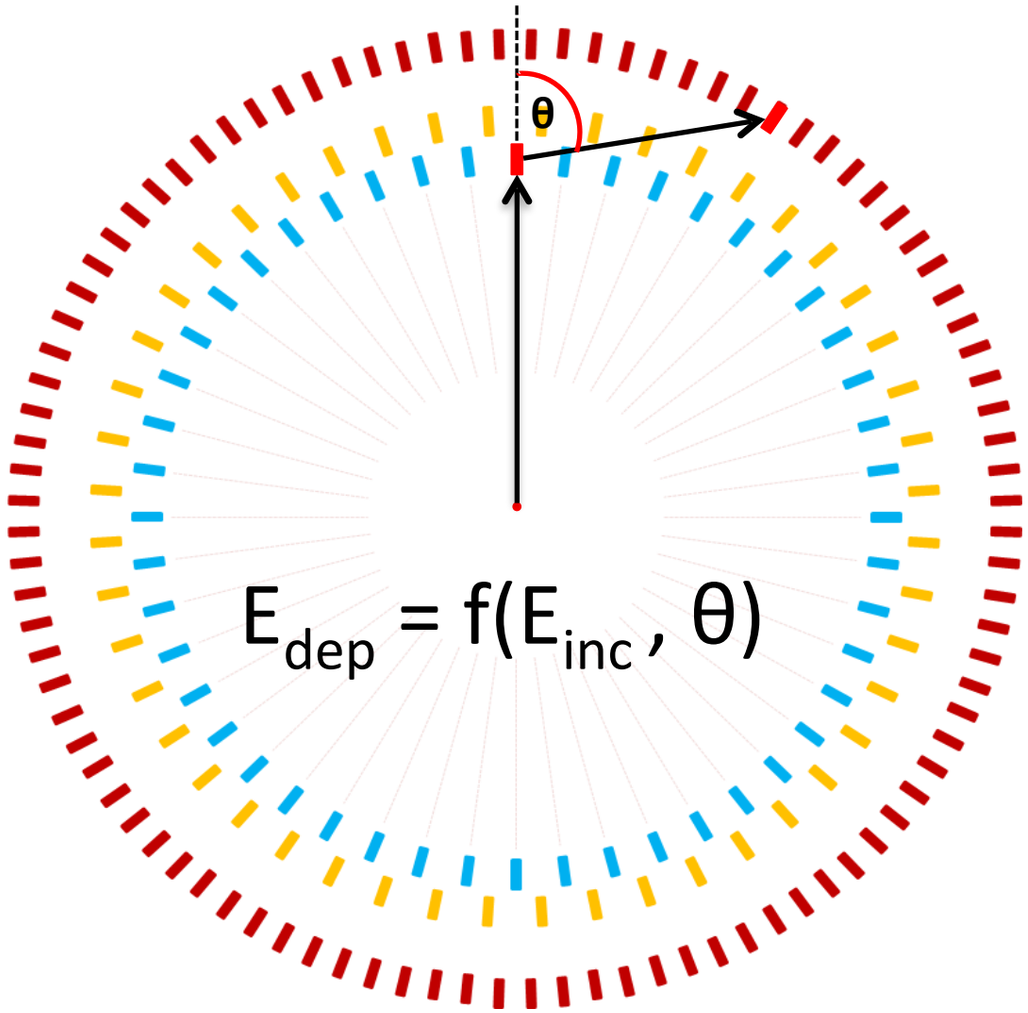


M. Palka et al., **JINST 12 (2017)** P08001
G. Korcyl et al., **Acta Phys. Polon. B 47, 491 (2016)**

Signals are probed at **four thresholds**.



Time Over Threshold (measure of energy deposition)



What we have :

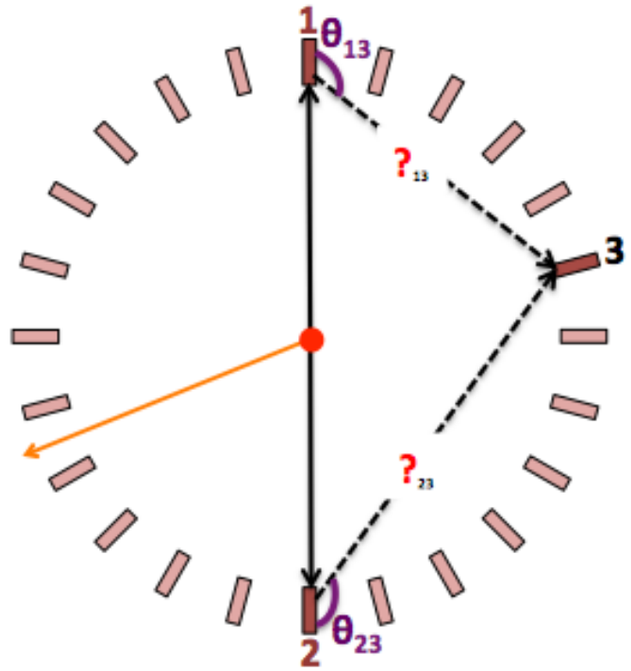
- ✓ Measured **TOT** values
- ✓ Hit positions and time of primary and scattered photon gives **access to the θ values**

What is required :

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

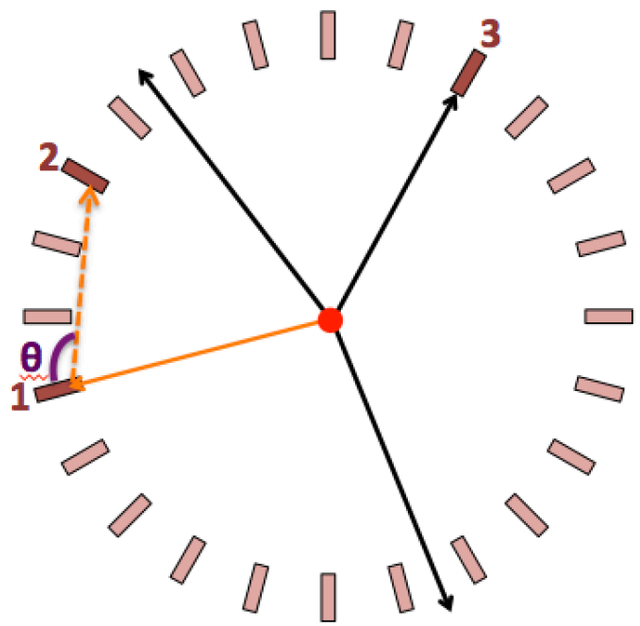
Analyzed : 3 Hit Events

Case 1 : (511 keV)

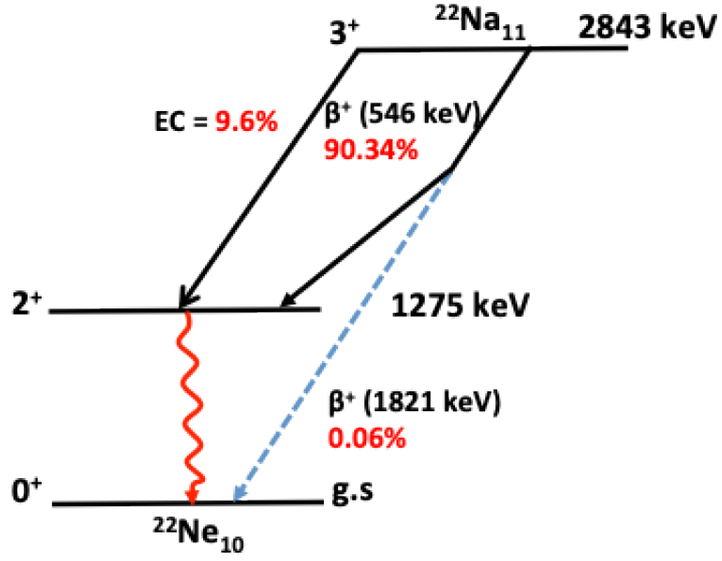


Scatter test = $time_{measured} - time_{calculated}$

Case 2 : (1275 keV)

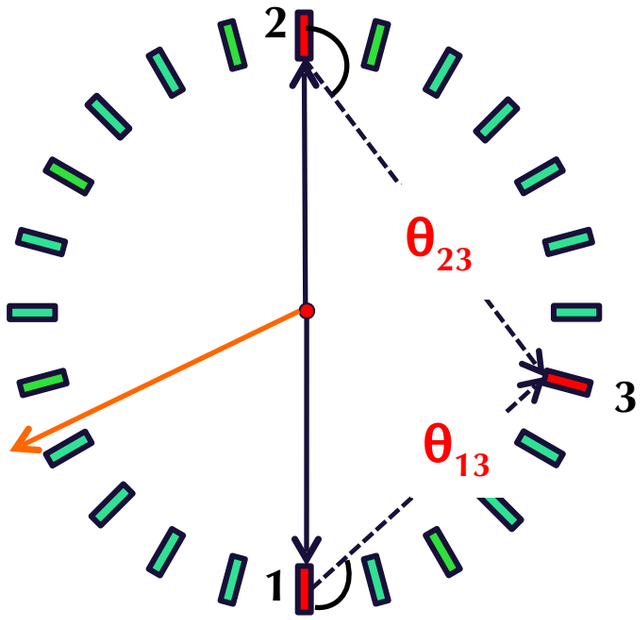


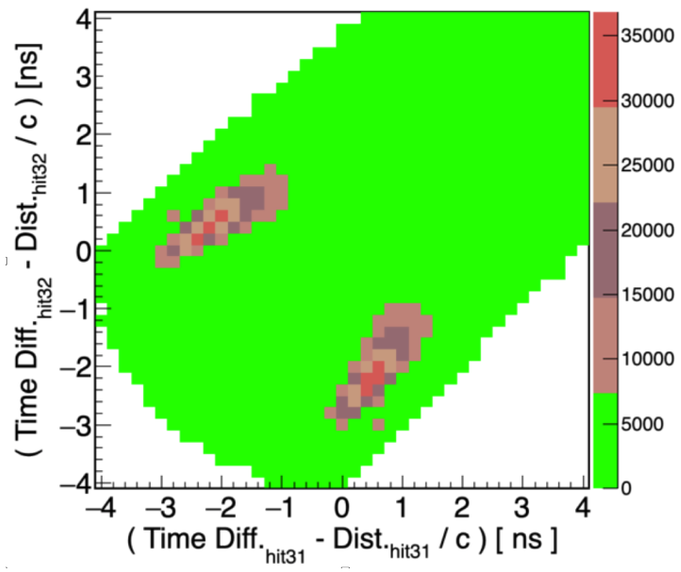
Time Over Threshold as measure of energy deposition



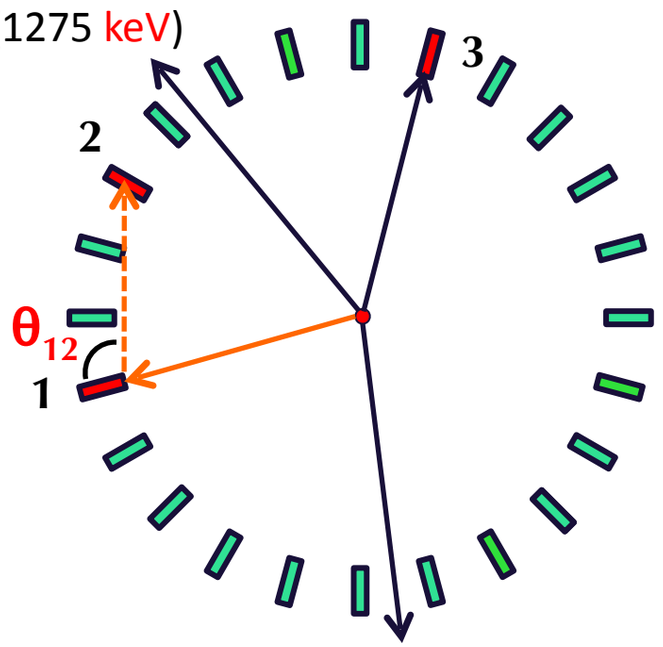
Time Over Threshold as measure of energy deposition

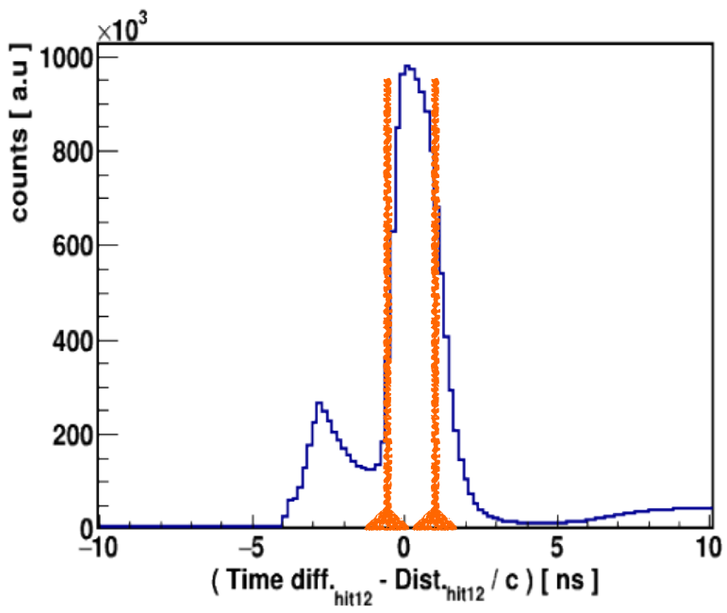
(511 keV)



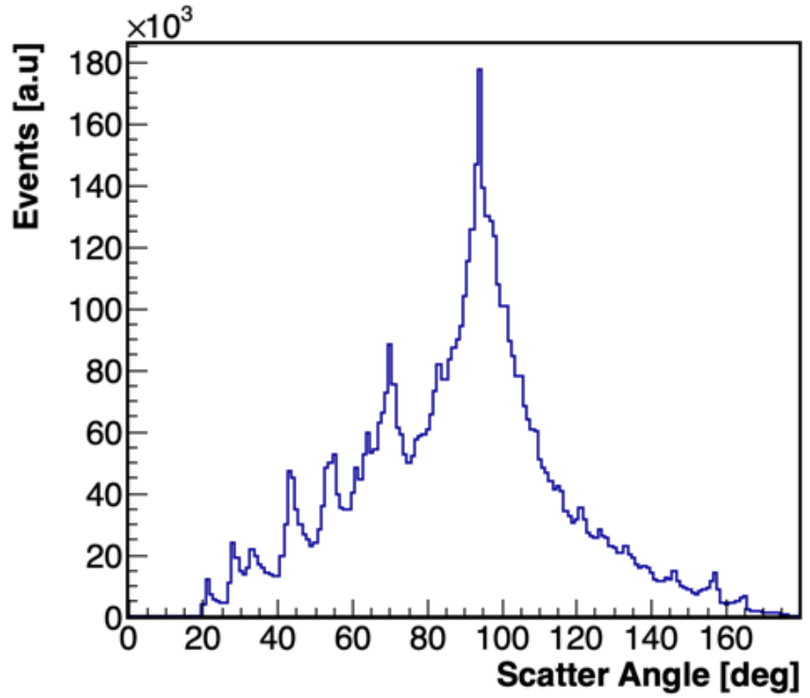


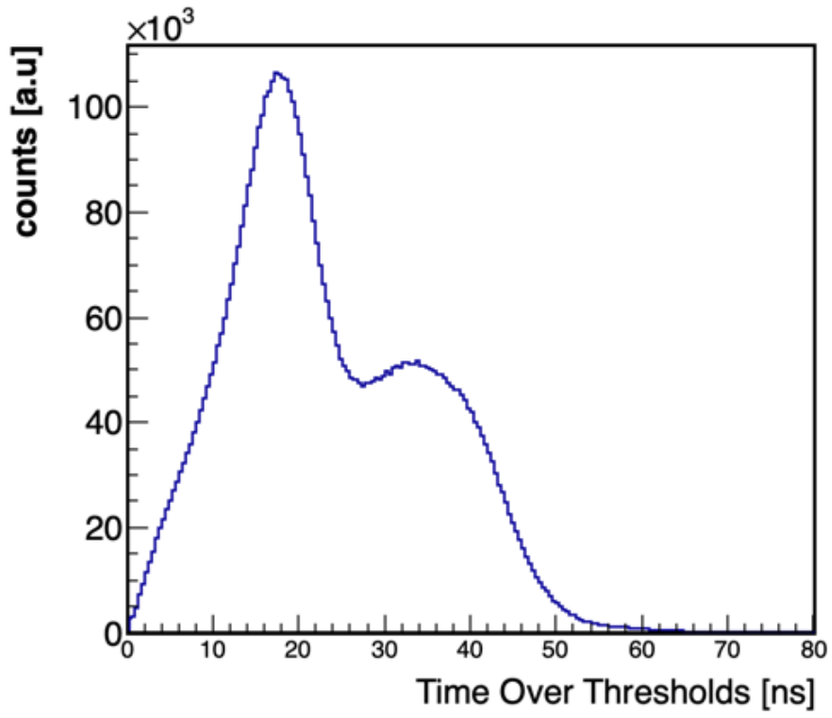
(1275 keV)



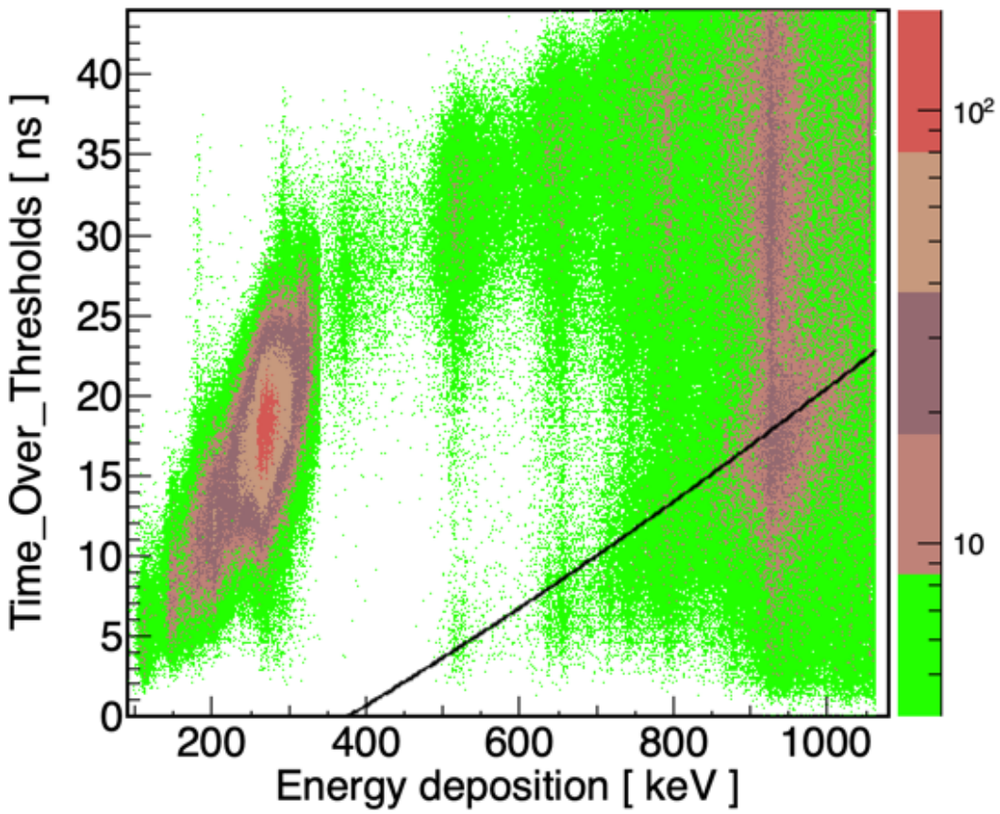


Results



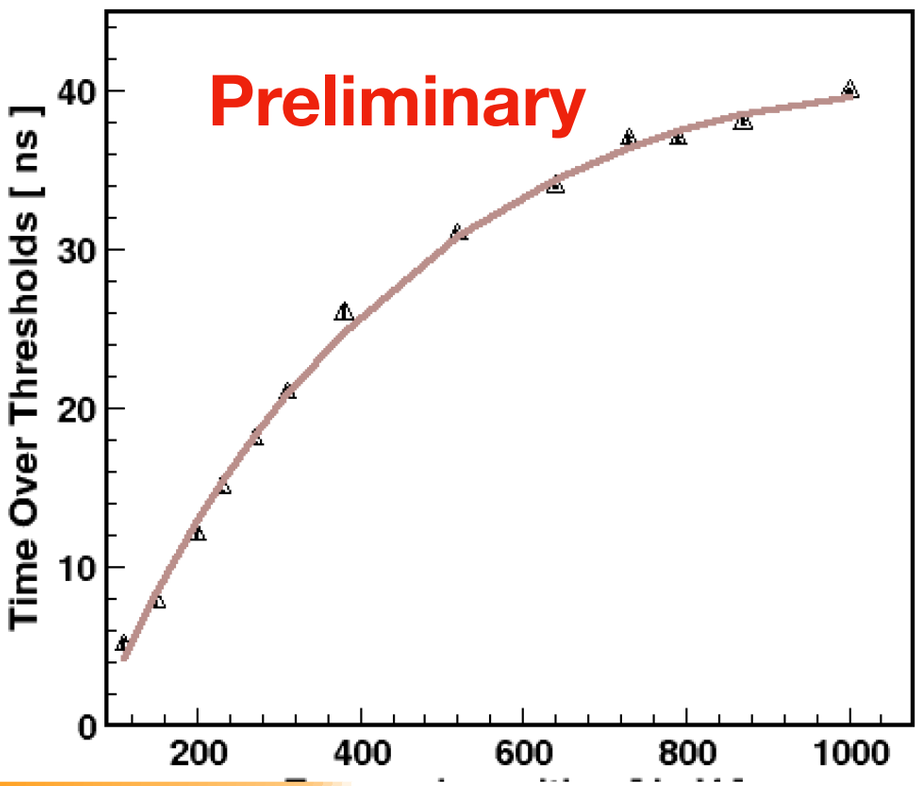


Time Over Threshold as measure of energy deposition



TOT vs Edep

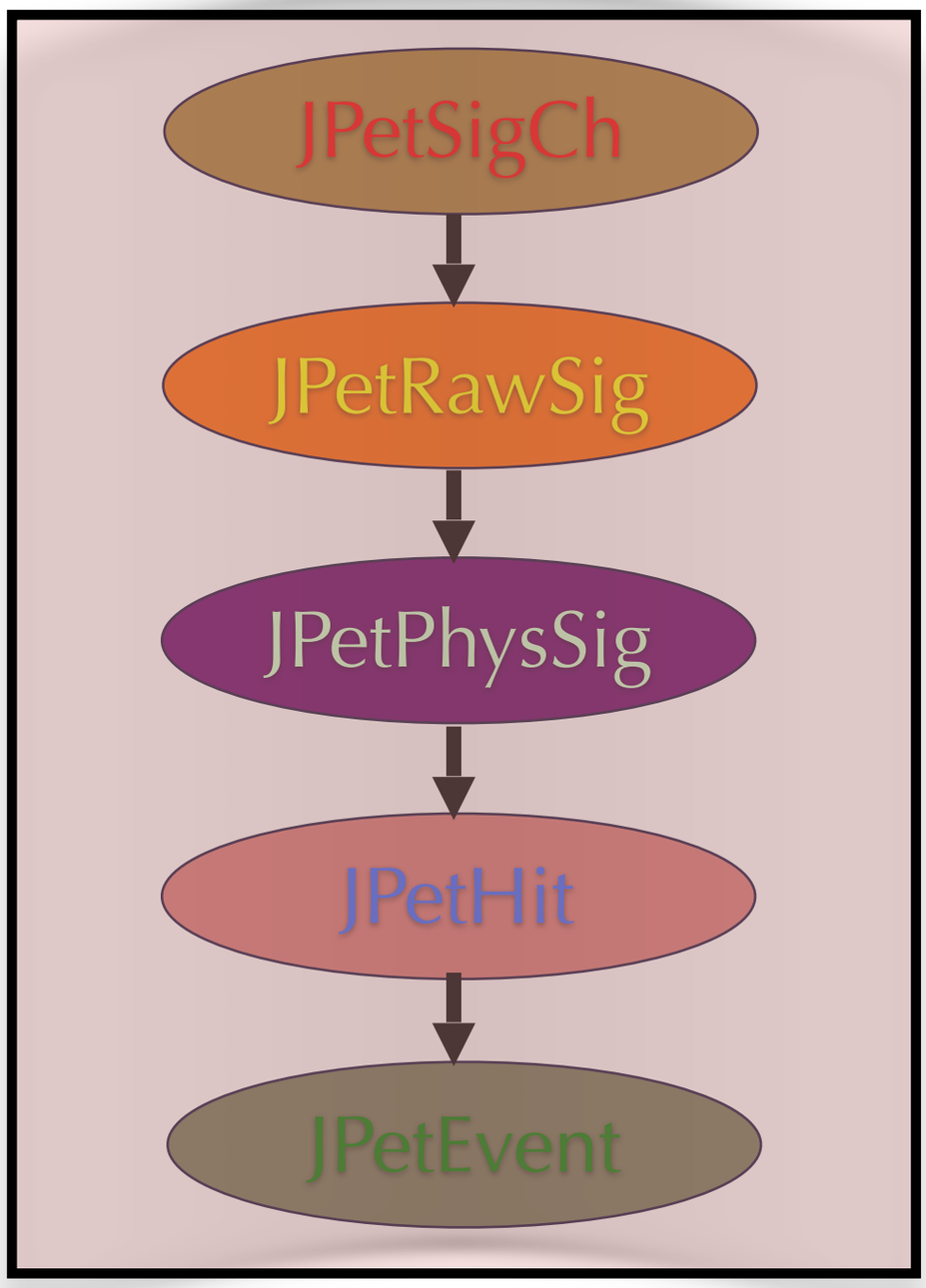
- ✓ 2-D spectrum of TOT versus energy deposition
- ✓ For the final relation the *profile histograms for the most populated energy bins* are selected and fitted.



- ✓ Mean value of TOT distribution as a function of the *center value of the energy interval* is plotted.
- ✓ The experimental data (black triangles) are nicely fit by the function of form:

$$TOT = A0 + A1 * \ln(Edep + A2) + A3 * (\ln(Edep + A2))^2$$

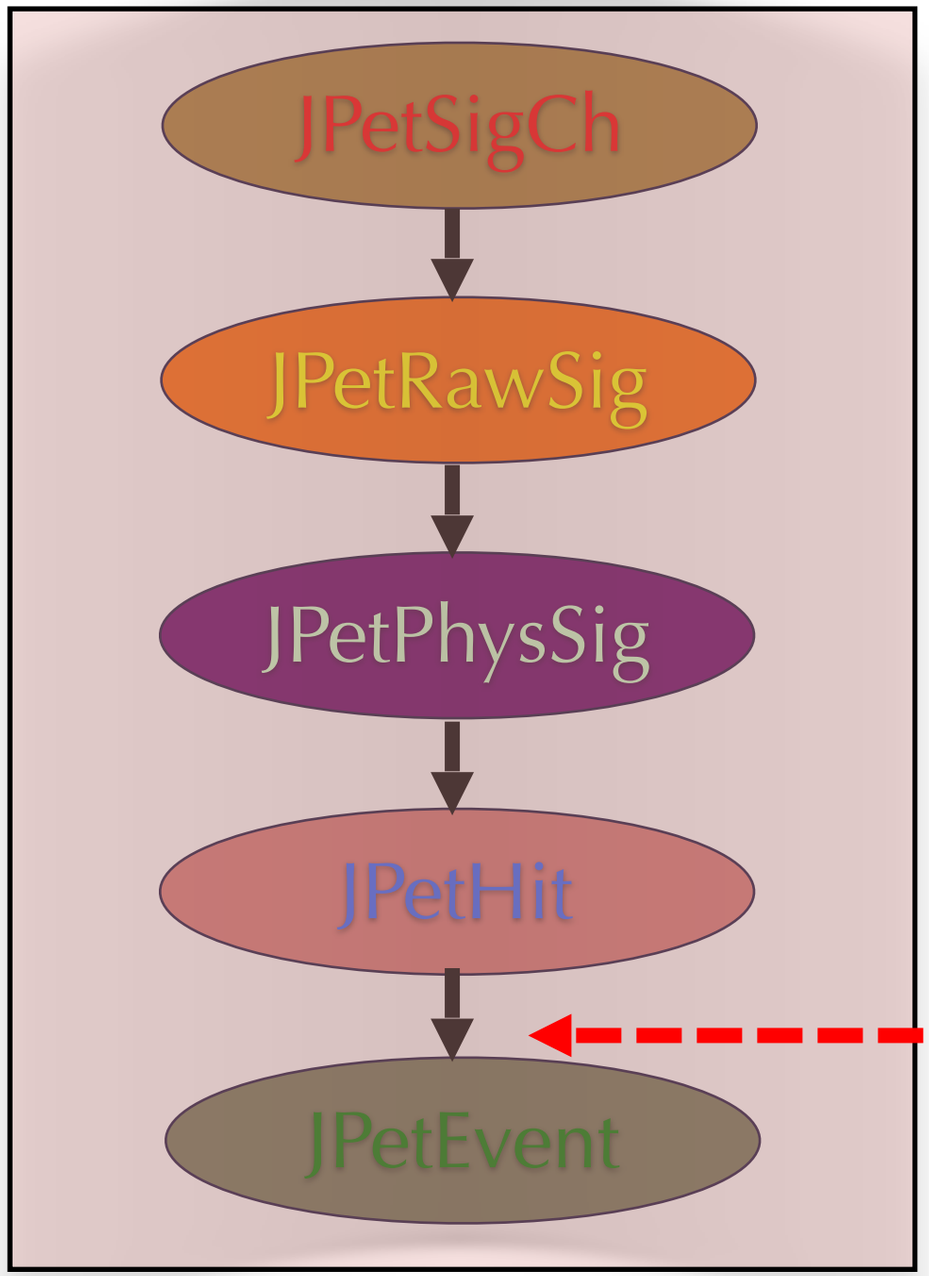
Data Analysis



JPetTimeWindow

J-PET Analysis Framework : Open-source platform

Data Analysis



JPetTimeWindow

MC simulation

Dedicated simulation package

Source :
Photons beam, Ps decays,..

Relative angles and energy distributions of primary photons
(e.g., decay of Ps into Multi-photons)

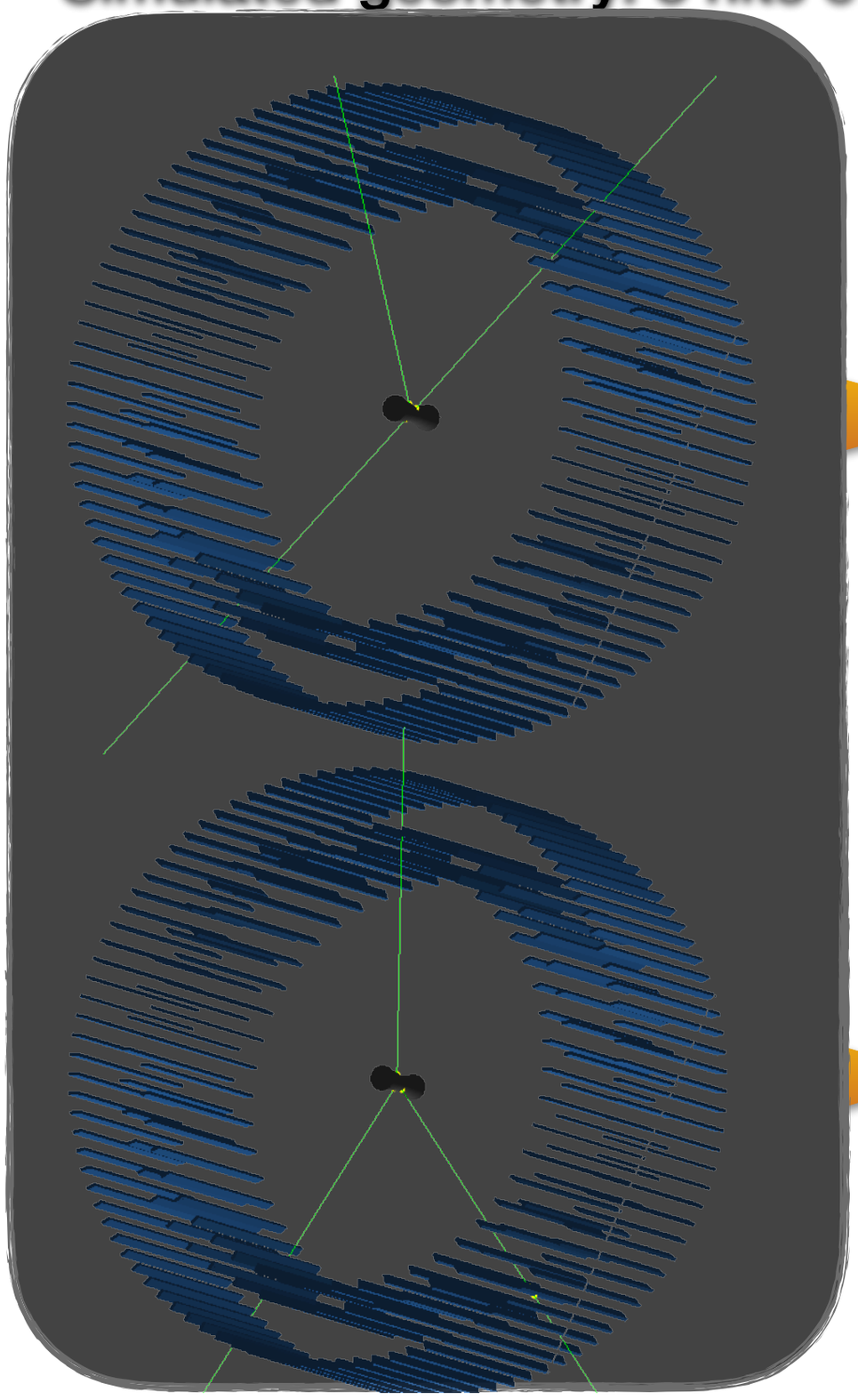
Interaction of Gamma quanta : (**Comp. Scatt**)
hit – position , hit time, Scattering angle
Multiple-scattering

Geant4 –Parsar (empowered to introduce experimental resolution

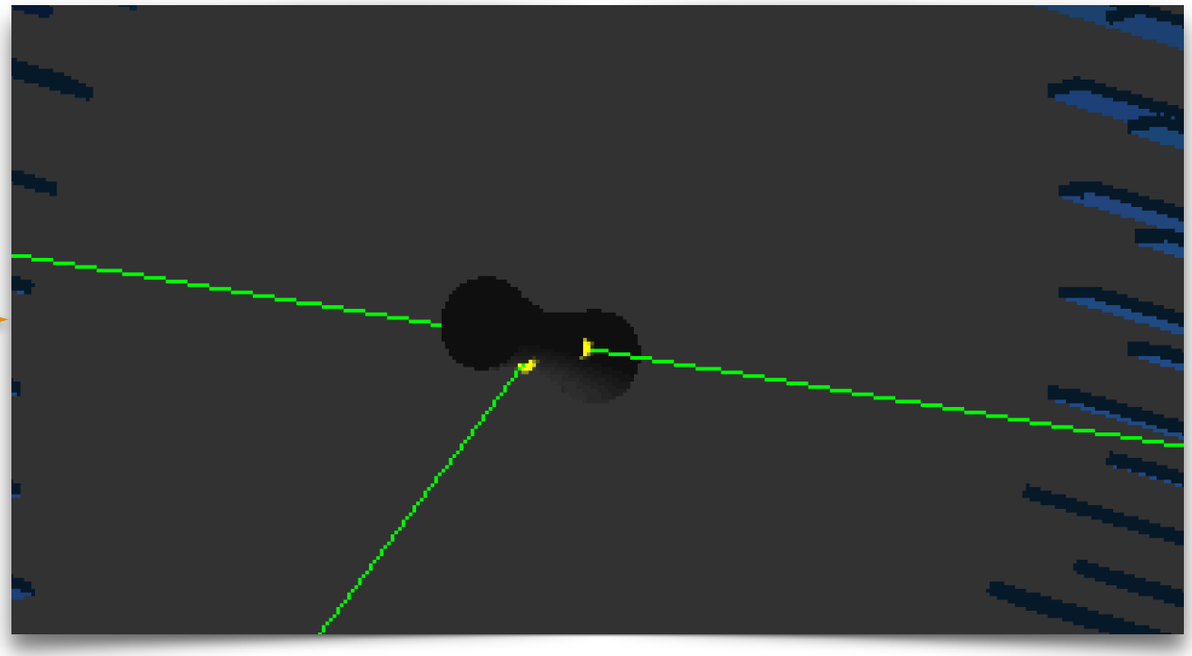
Bonus

Adjusted to utilize the multiple-threading feature

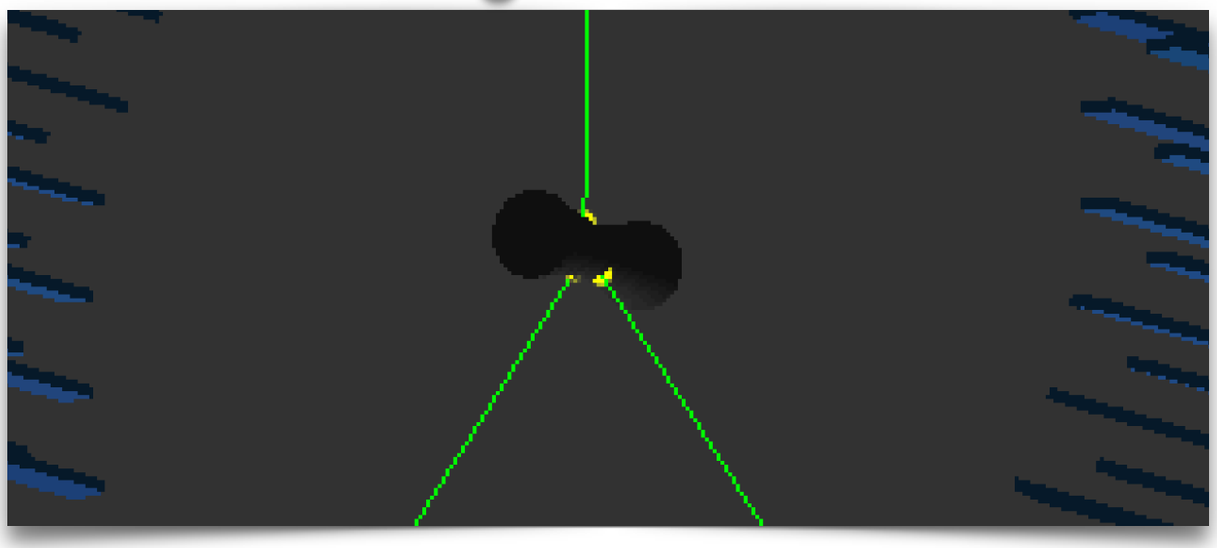
Simulated geometry: 3 hits event



(2 annihilation + 1 prompt)



Scattering within chamber



Positronium : 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

Purely Leptonic object !!!

- Eigenstate for C,P, CP operators
- Undergoes self-annihilation into gamma quanta

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- Eigenstate for C,P, CP operators
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S=0 ↓↑ - ↑↓ ***nγ (n=2,4,6,..)*** **Para**–positronium (**p - Ps**), **τ(vac)** = **0.125** ns, $^1S_0$

S=1 ↑↑ / ↑↑ + ↓↓ / ↓↓ ***(2n+1)γ (n=3,5,..)*** **ortho** – positronium (**o - Ps**), **τ(vac)** = **142**ns, $^3S_1$

Effects due the weak interaction can lead to the violation at the order of 10^{-14}.

M. Sozzi, Discrete Symmetries and CP Violation, Oxford University Press (2008)

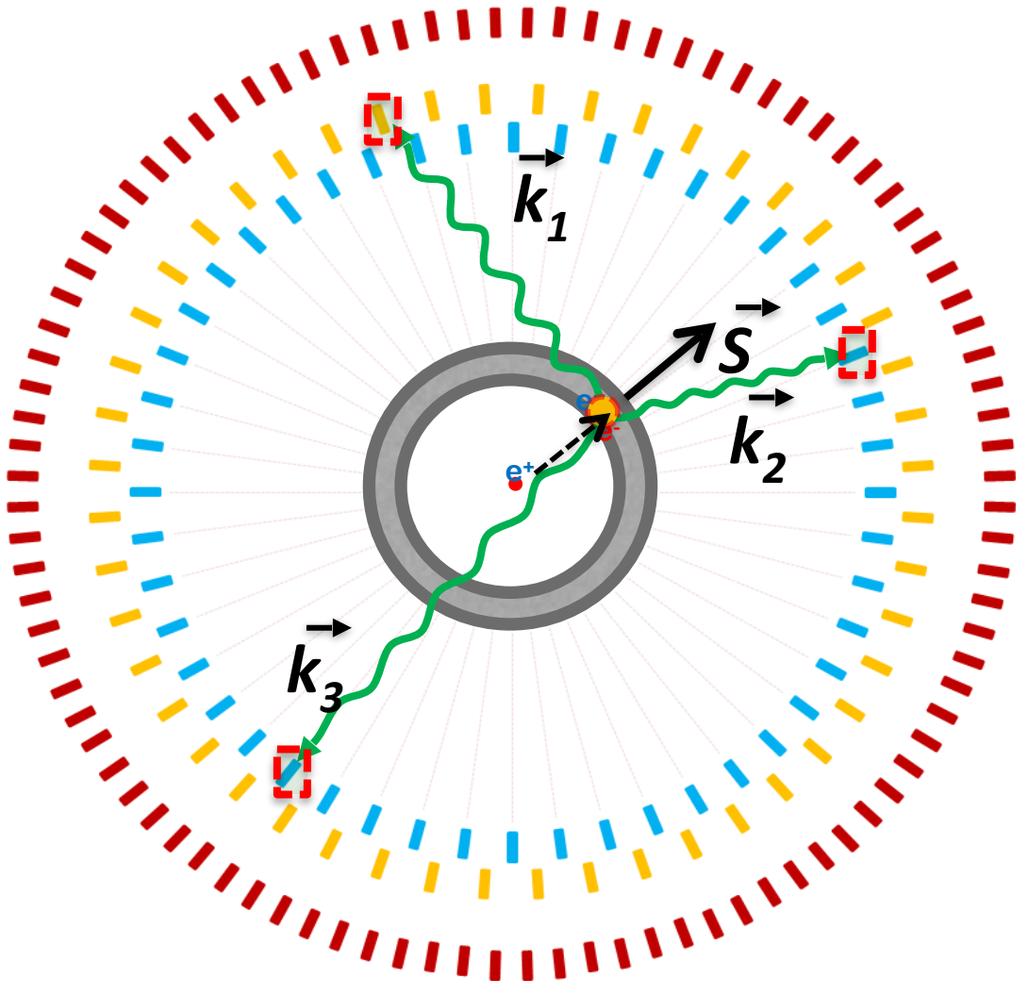
Odd - symmetry operators

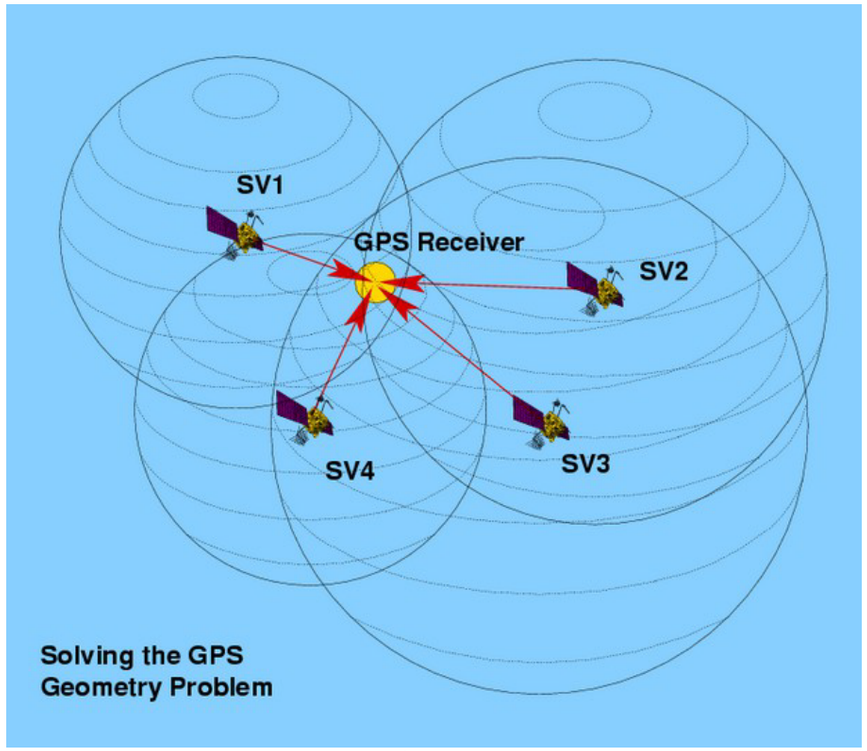
Operators	C	P	T	CP	CPT
$\vec{S} . \vec{k}_1$	+	−	+	−	−
$\vec{S} . (\vec{k}_1 \times \vec{k}_2)$	+	+	−	+	−
$(\vec{S} . \vec{k}_1)(\vec{S} . (\vec{k}_1 \times \vec{k}_2))$	+	−	−	−	+

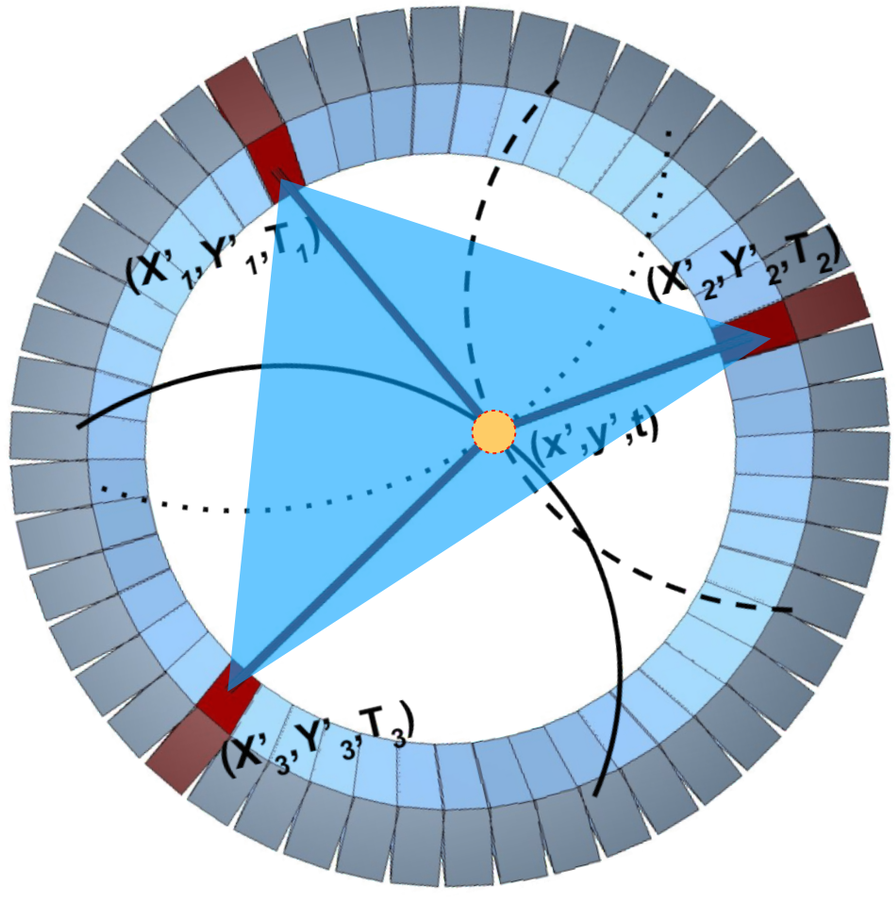
P. Moskal et al., Acta Phys. Pol. B 47, 509 (2016)

Ortho-Positronium spin

Trilateration methods*



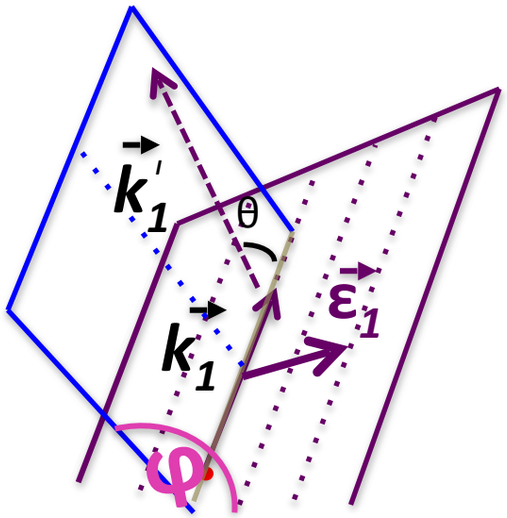




*P. M., PCT/EP2014/068374 (2013)
A. Gajos, E. Czerwiński, D. Kamińska, P. M., PCT/PL2015/050038 (2015)

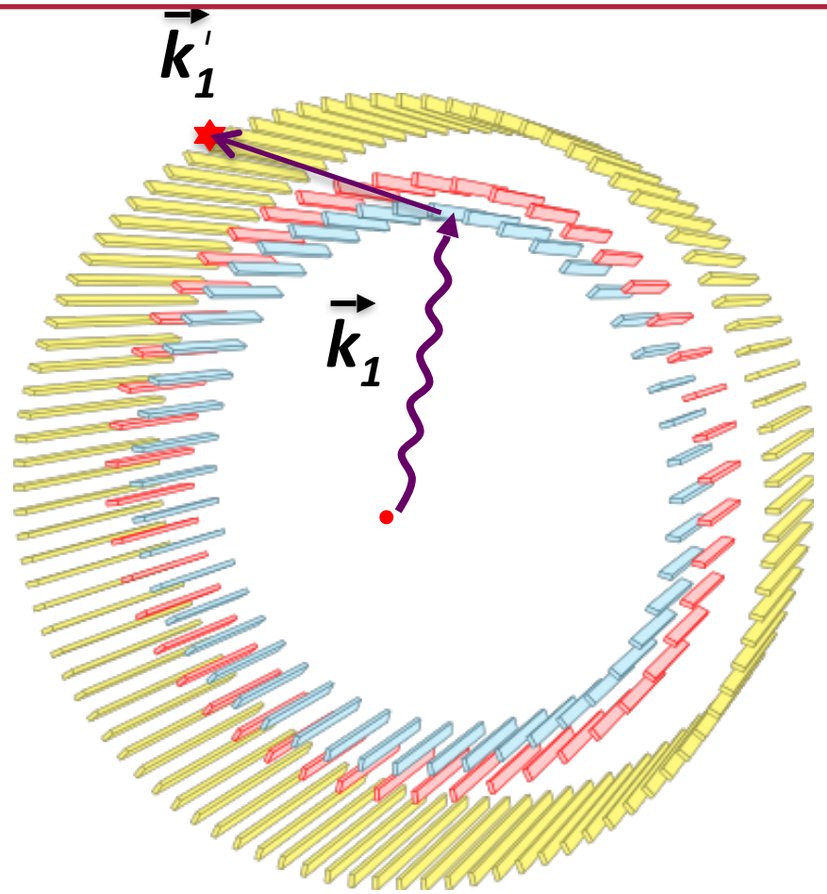
*A. Gajos et al., Nucl. Inst. and Meth. A819 (2016) 54

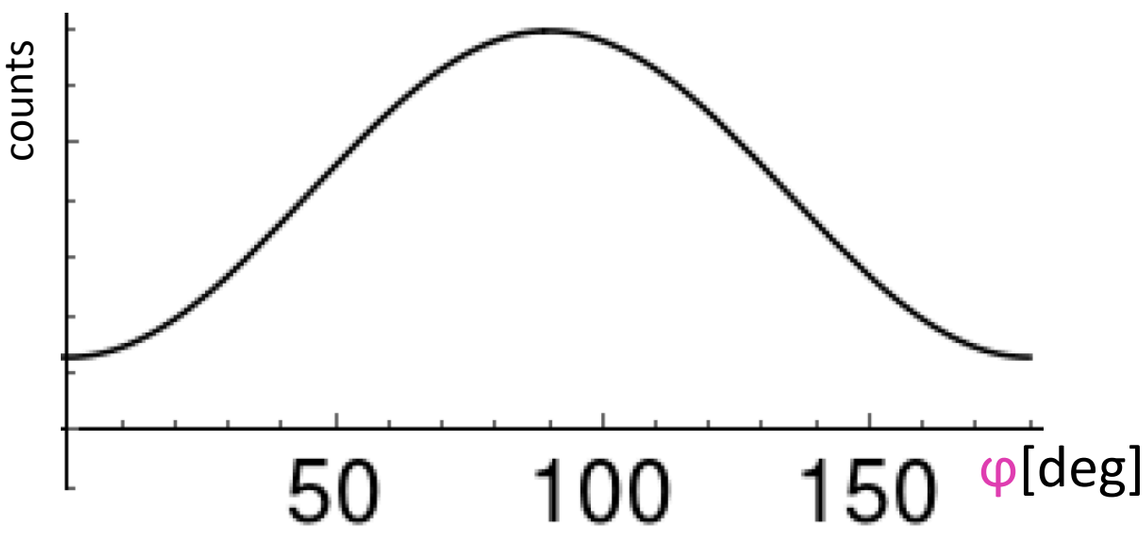
J-PET potentialities to measure photon's polarization



Photon's Polarization

$$\vec{\varepsilon}_1 = \vec{k}_1 \times \vec{k}_1'$$





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

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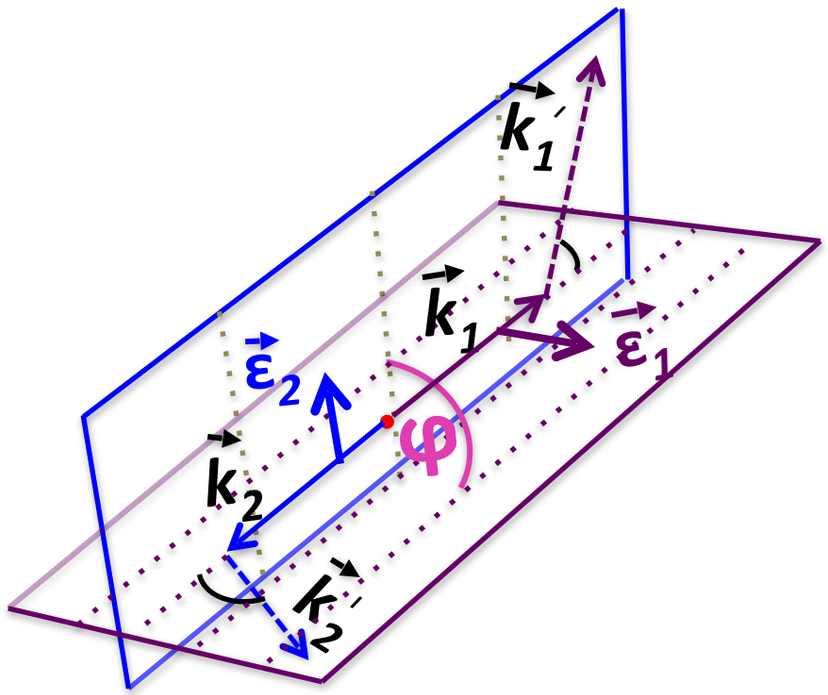
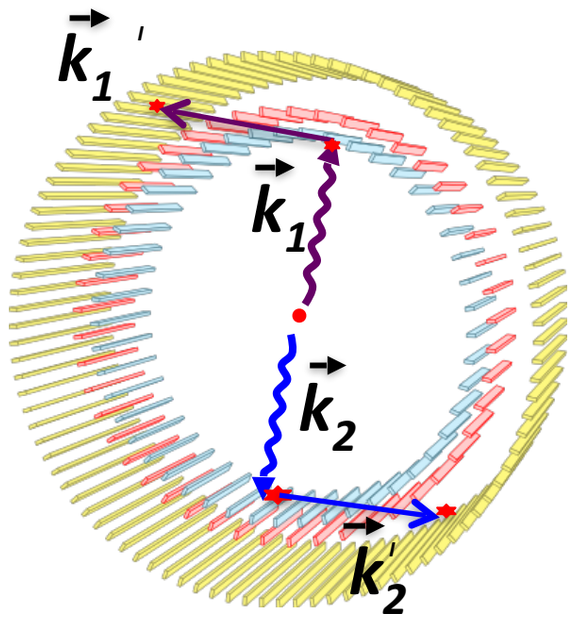




➢Angle between polarization vectors of annihilation photons is 90^0.

➢Photons *<u>mostly scatter</u>* at right angles to their electric field vector and this impose an **<u>Expected angular correlation</u>** between the scattering angles.

➢With the J-PET detector we can measure scatterings of back-to-back photons originating from the decay of positronium atoms and thus can study the angular correlation between the scattering angles.

B. Hiesmayr and P. Moskal, **Scientific Reports 7**: 15349 (2017)

Odd - symmetry operators

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

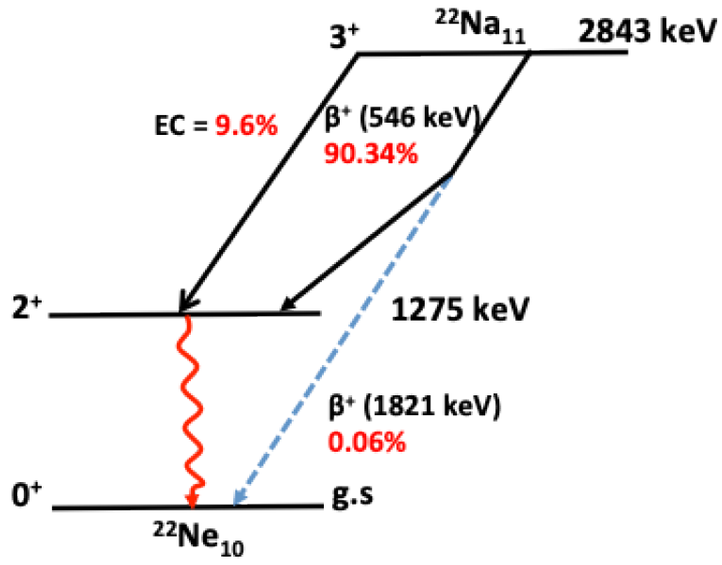
Studies of discrete symmetries using the photon's polarization

Unique feature of the J-PET

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

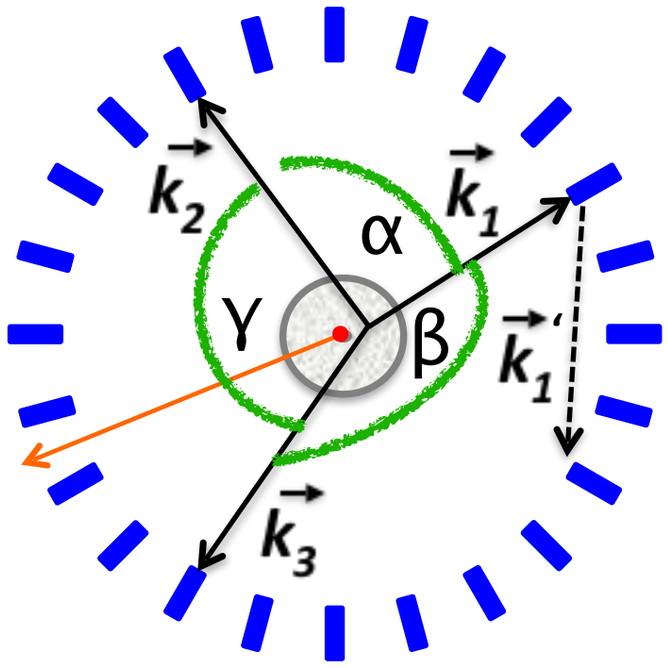
Operators	C	P	T	CP	CPT
$\vec{\varepsilon}_1 \cdot \vec{k}_2$	+	−	−	−	+
$\vec{S} \cdot \vec{\varepsilon}_1$	+	+	−	+	−
$\vec{S} \cdot (\vec{k}_2 \times \vec{\varepsilon}_1)$	+	−	+	−	−

Precision test in T-symmetry violation in Leptonic system

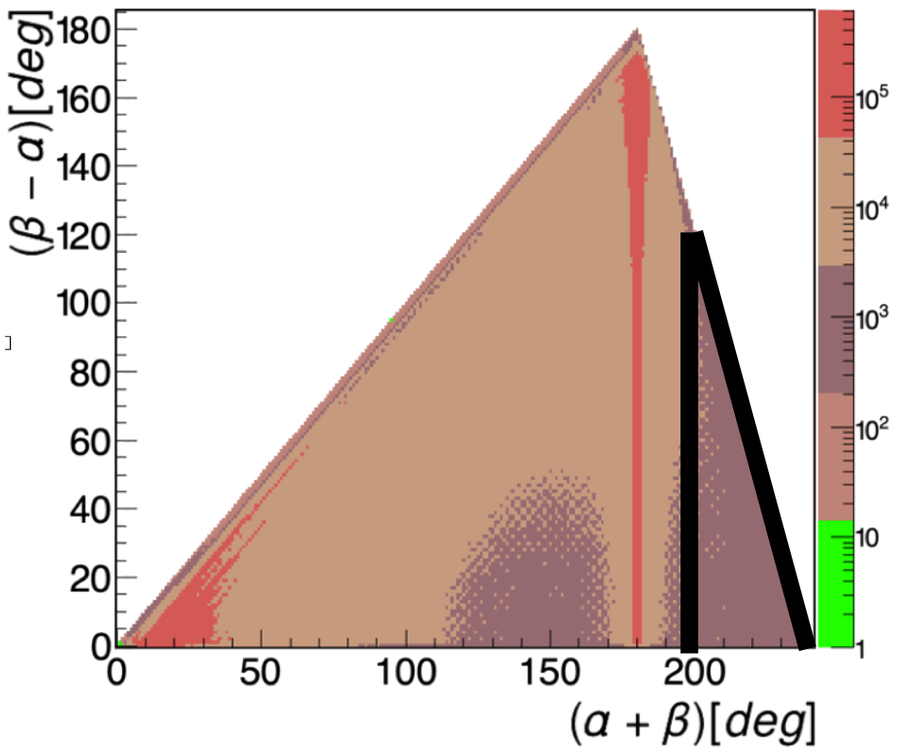


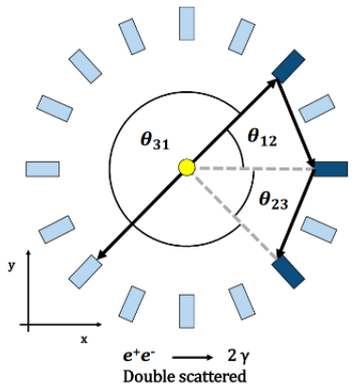
Schematic for the selection of signal

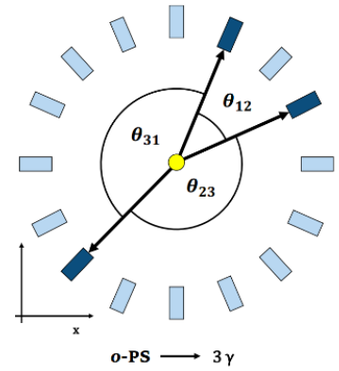
4-Hit events

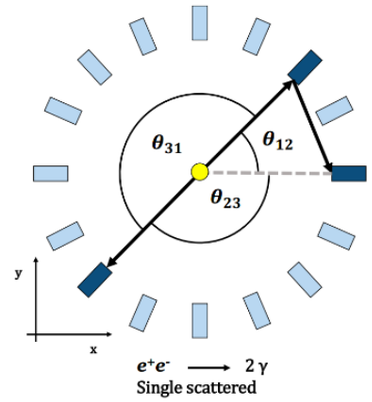


Angular correlations







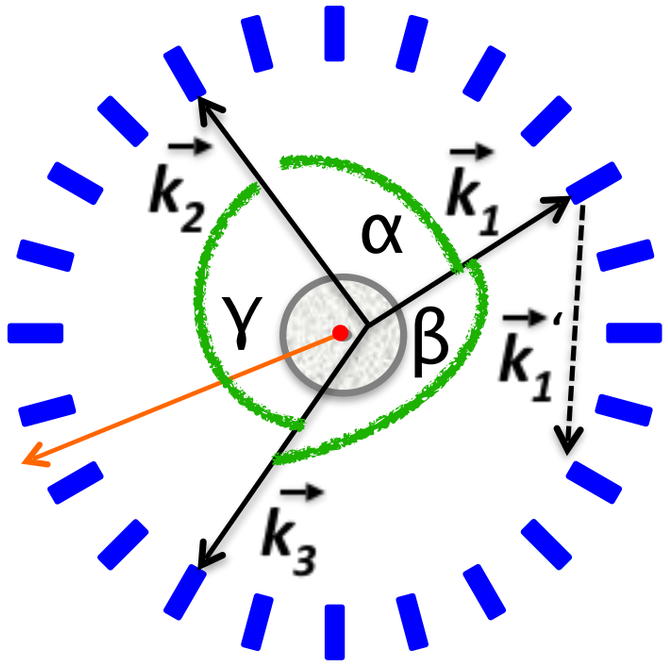


Selection of o-Ps -> 3γ

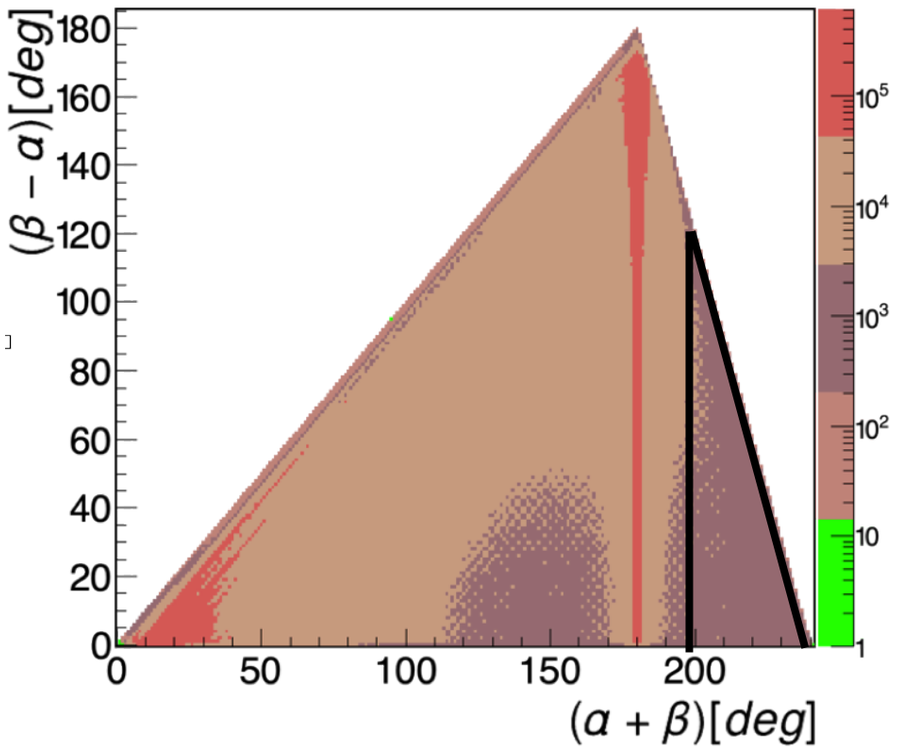
E. Czerwiński et al., Acta Phys. Polo. B 48 (2017) 1961

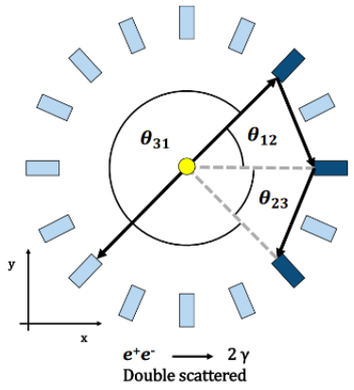
Schematic for the selection of signal

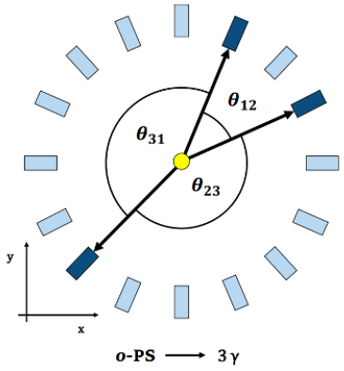
4-Hit events

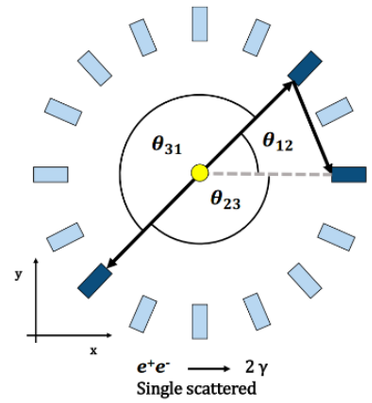


Angular correlations









Selection of o-Ps -> 3γ

E. Czerwiński et al., Acta Phys. Polo. B 48 (2017) 1961

Photon identification:

o-Ps $\rightarrow 3\gamma$ annihilation (E<511 keV) photon candidates

$^{22}Ne^*$ de-excitation (E=1.27 MeV) photon candidates

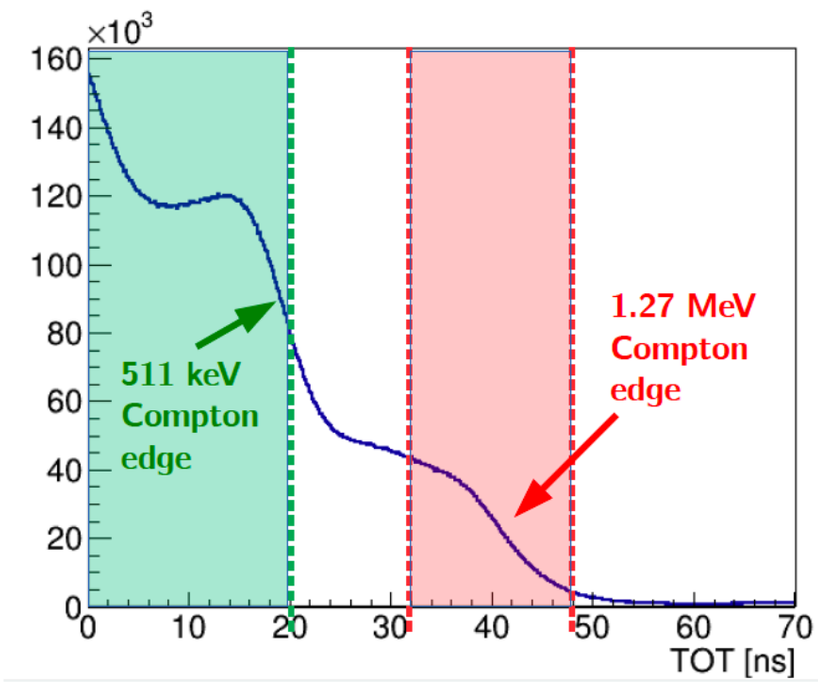
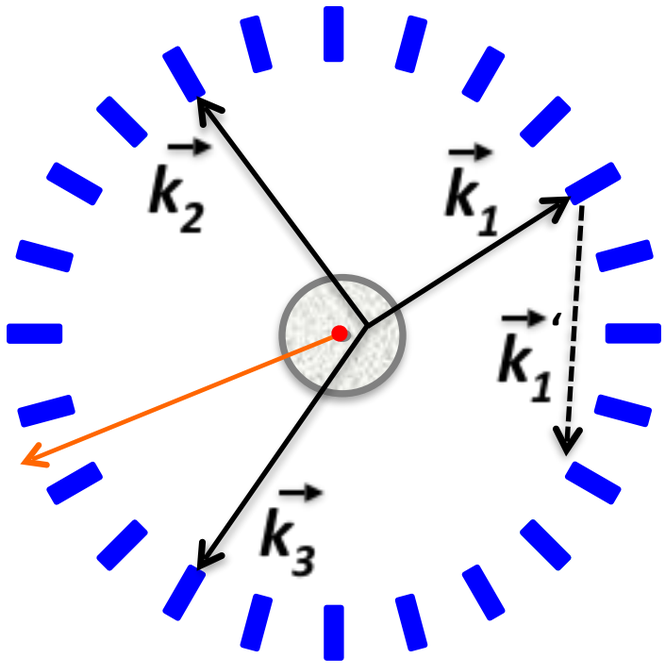


Figure is adopted from A. Gajos slides

Schematic for the selection of signal

4-Hit events



Selection of o-Ps -> 3γ

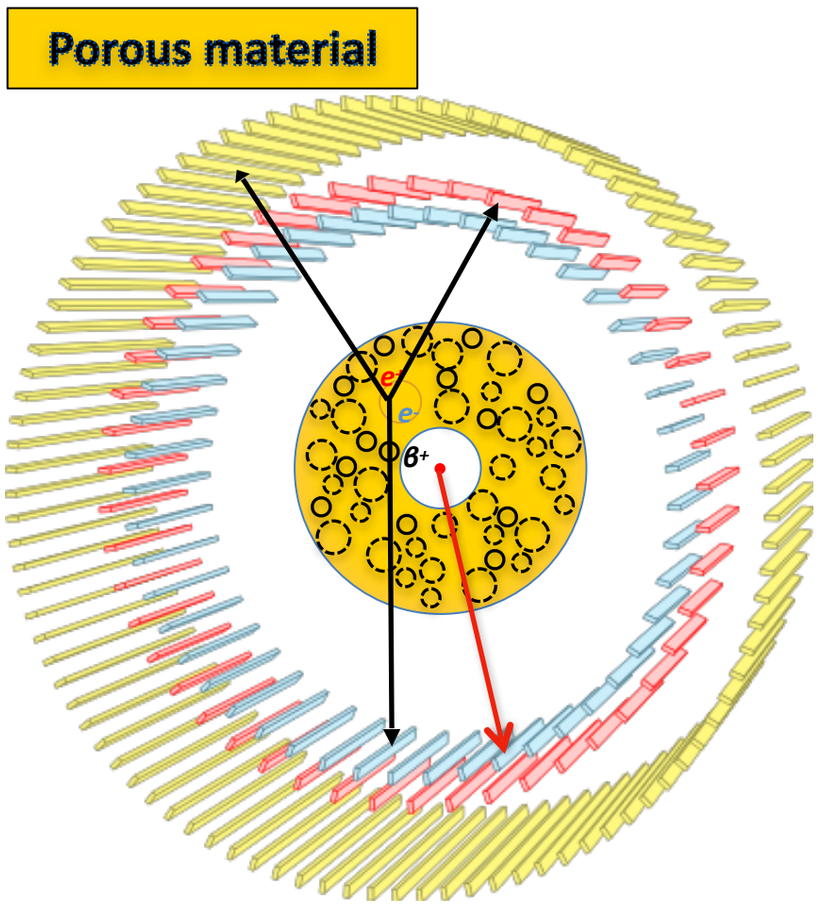
$$\vec{\varepsilon}_1 = \vec{k}_1 \times \vec{k}_1'$$

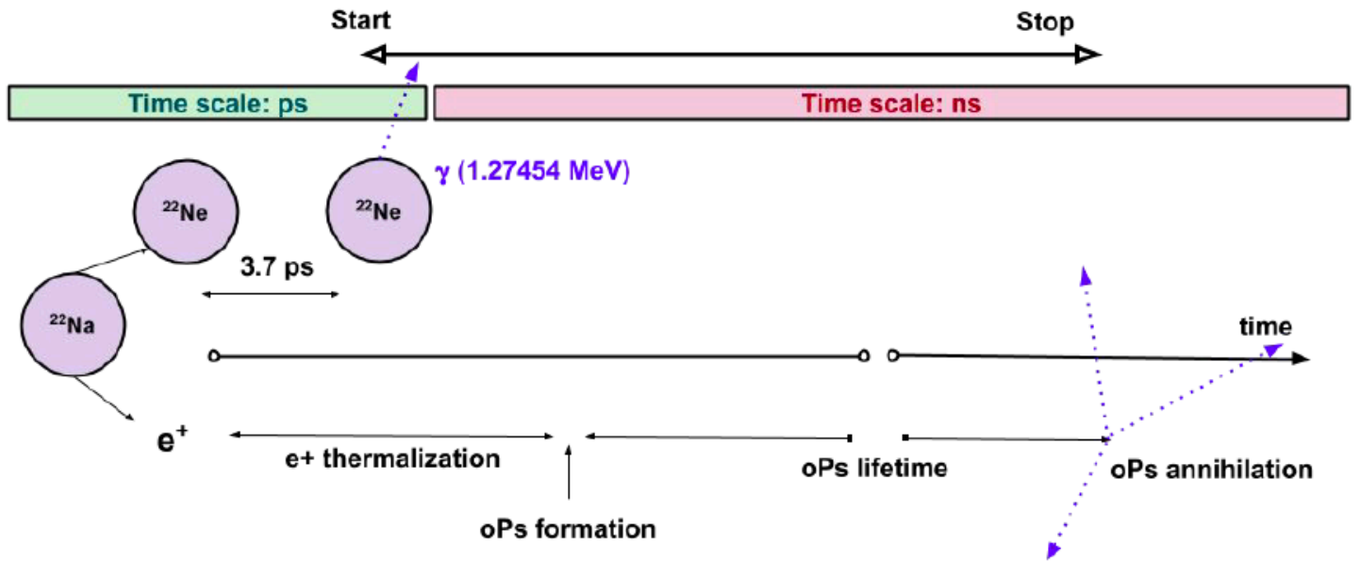
$$S = (time_{scatter} - time_{origin}) - Distance_{scatter\text{-}origin} / c$$

First experimental results will be reported soon !!!!!!!

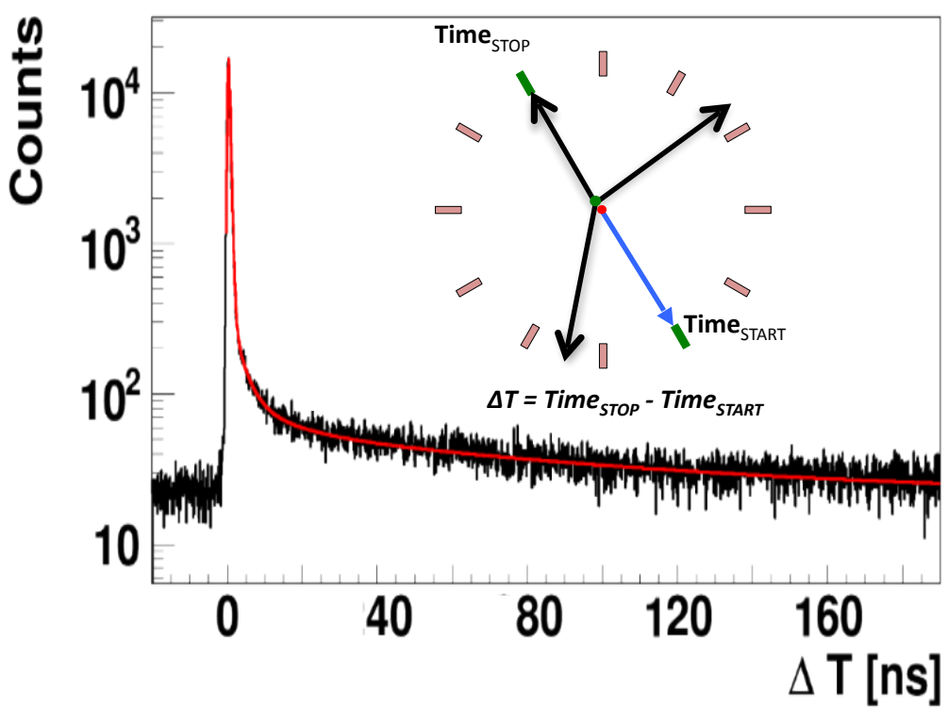
$$< \vec{\varepsilon}_i \cdot \vec{k}_j >$$

Positronium lifetime





Positronium life time spectra*

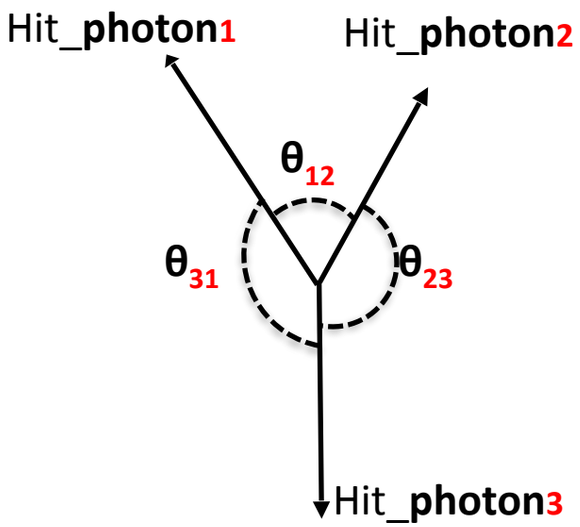


*K. Dulski et al., Hyperfine Interact 40 (2018) 239

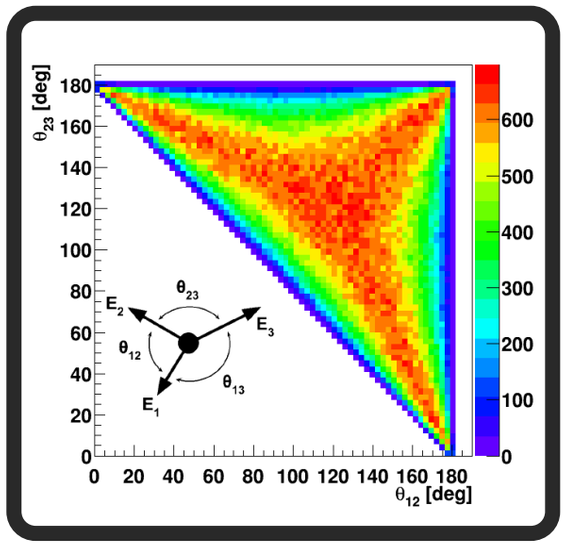
Charge conjugation symmetry based on angular correlations

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

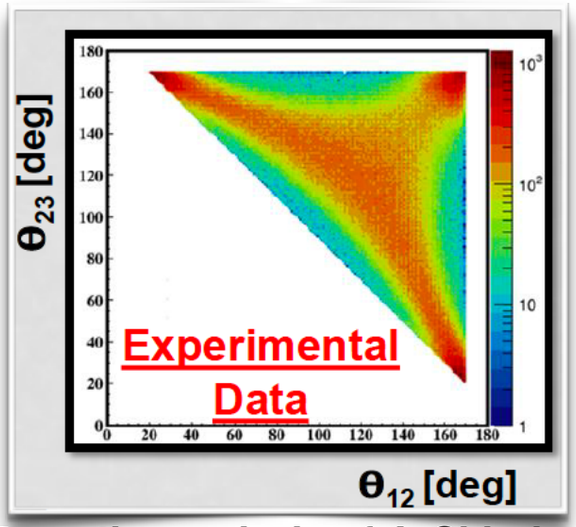
In o-Ps decay : angular correlation



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

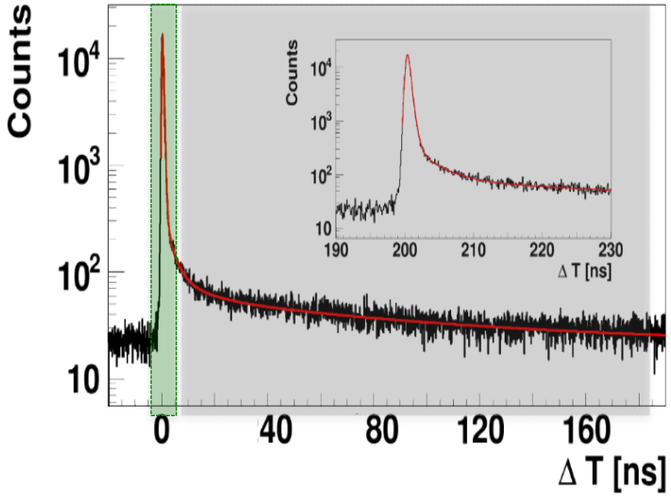


Preliminary



From the analysis of J. Chhokar

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 configuratioon (p-ps-> 3γ decay mode is restricted by Bose-statistics)

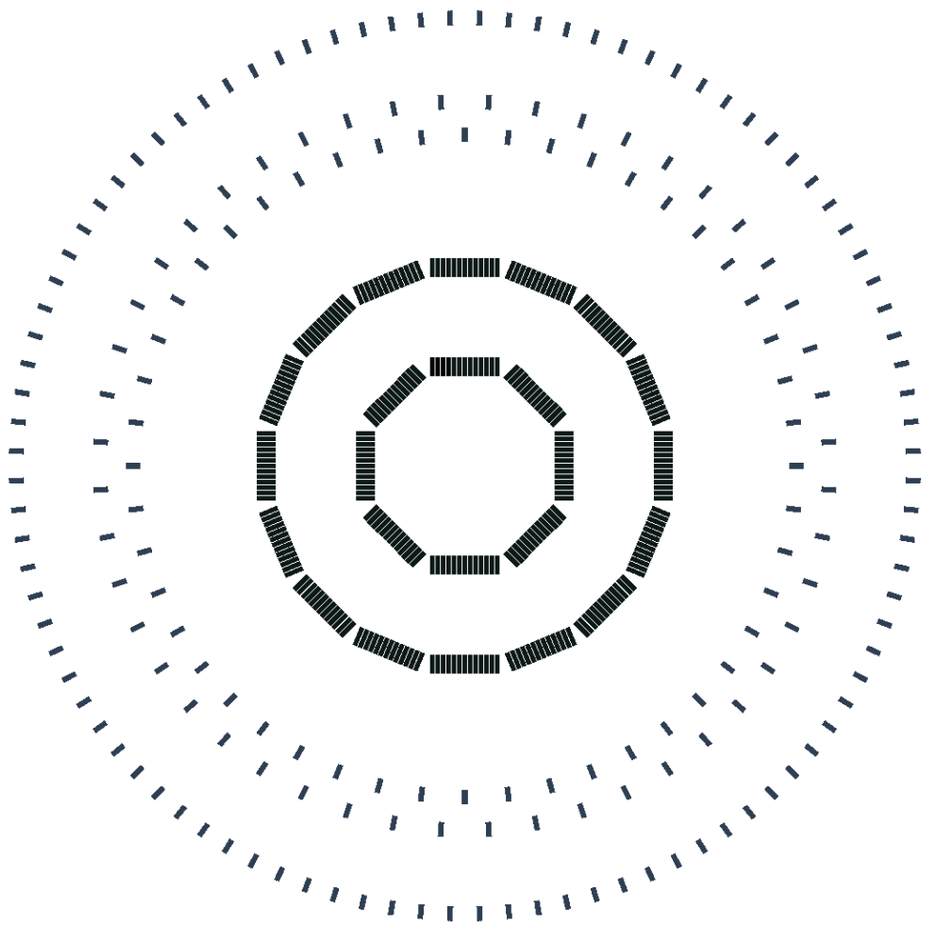


K. Dulski et al., Hyperfine Interact 40 (2018) 239

Charge Symmetry violation test using J-PET detector

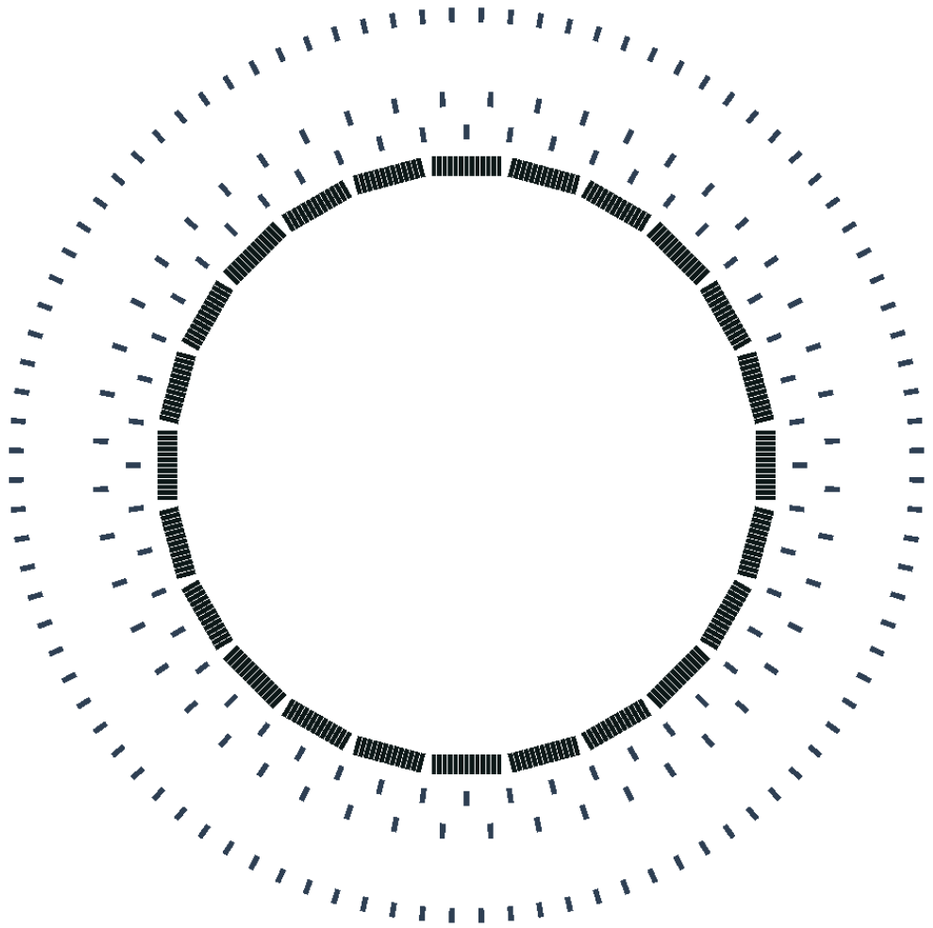
Advantages with Modular J-PET - Future Prospective

Stand – Alone



Multi-configurable

As inner layer of 3-Layer prototype



Several times better efficiency [Advantage]

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**.

Thank you for your attention