Study of time reversal symmetry in the decay of ortho-Positronium atoms using the J-PET detector

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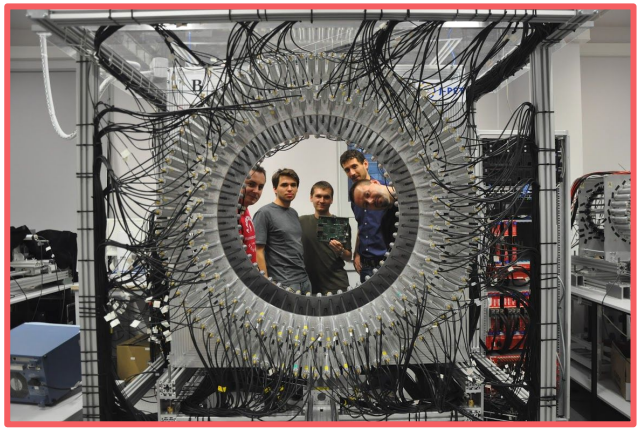


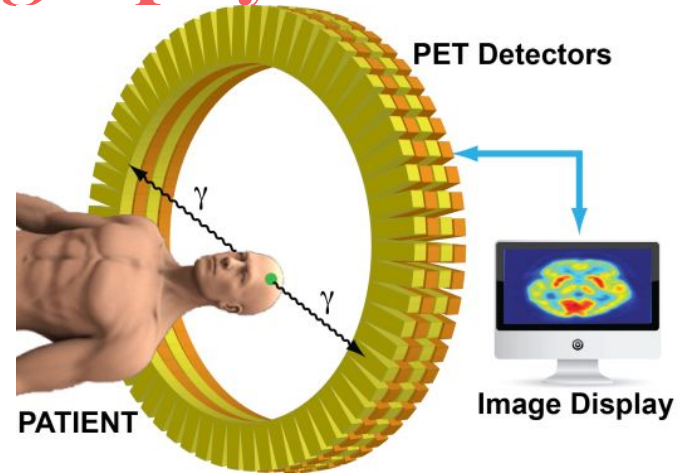
16th Conference on Flavor Physics and CP Violation (FPCP 2018), Hyderabad, India.

Overview:

- Introduction to the J-PET Detector
- Positronium as a probe to study discrete symmetries in the leptonic sector
- Experimental method and preliminary results

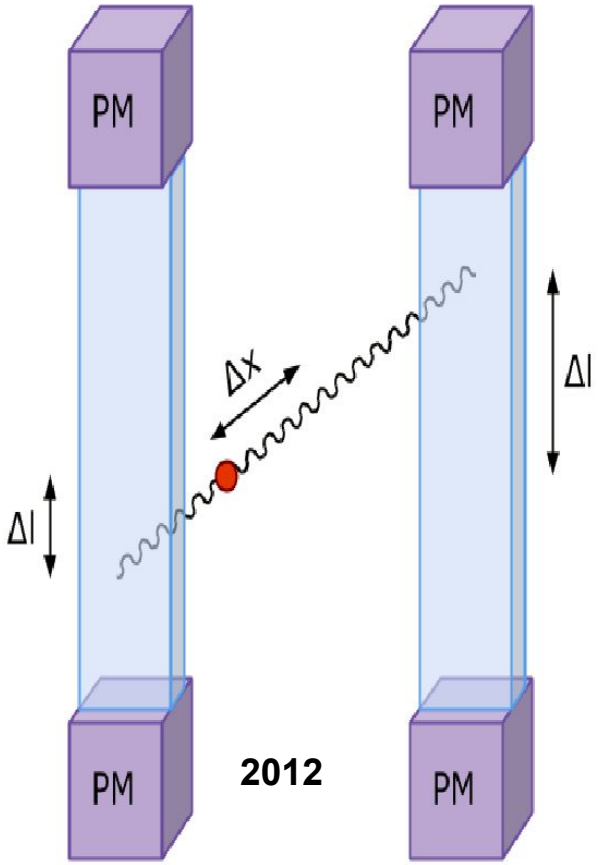
Positron Emission Tomography:

- Radioactive Sugar **Fluoro–deoxy-glucose (F-18 FDG)** is injected into the patient and it accumulates in highly metabolic areas of the body.
- The produced positrons interact with the tissue to produce metastable positronium atoms.
- Annihilated photons are detected to trace the tumour cells.
- **~200 000 000** gammas per second.



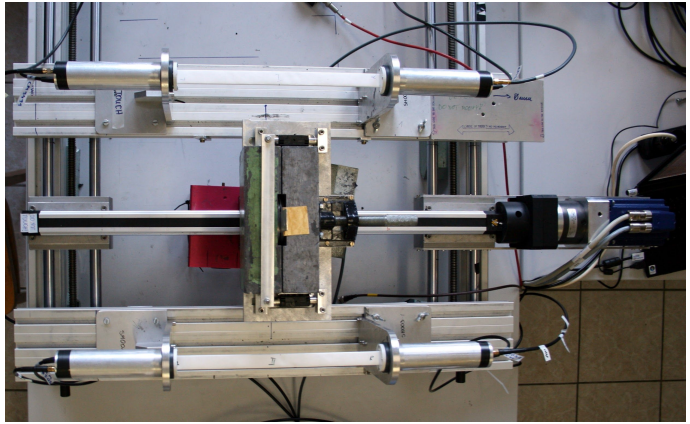
Birth of the J-PET detector:

- The J-PET predominantly uses time information instead of energy to acquire place of annihilation.
- Photons interact with plastic scintillators predominantly via compton effect.
- Figure shows the schematic of two plastic scintillator strips used in the J-PET detector. Each plastic strip is read out by photomultipliers at two ends (PM). Red dot in the point of annihilation.



Evolution of the J-PET detector

Two Strip Module

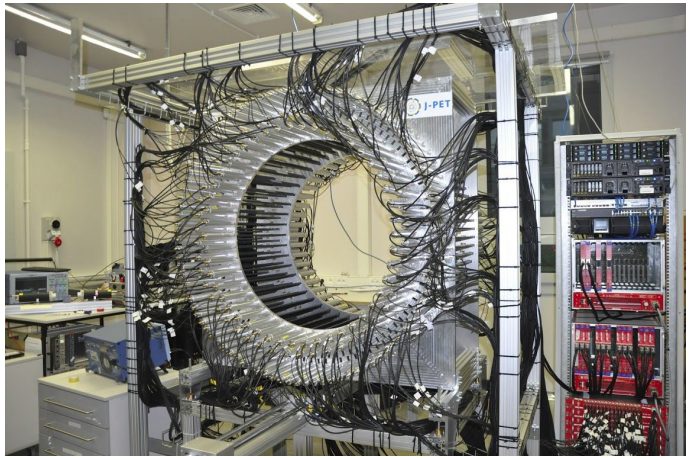


2012

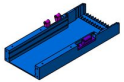
24 Strip Module

2014

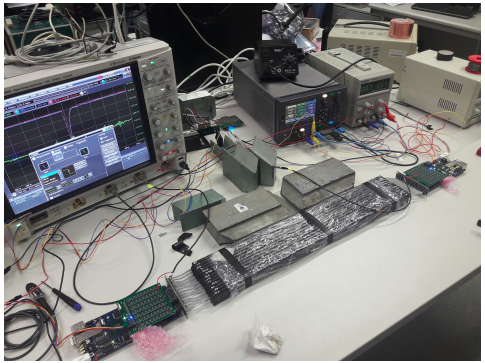
192 Strip Module



2016



~50cm FOV

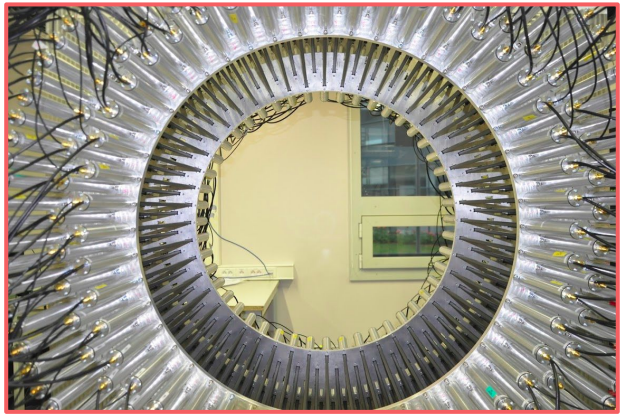


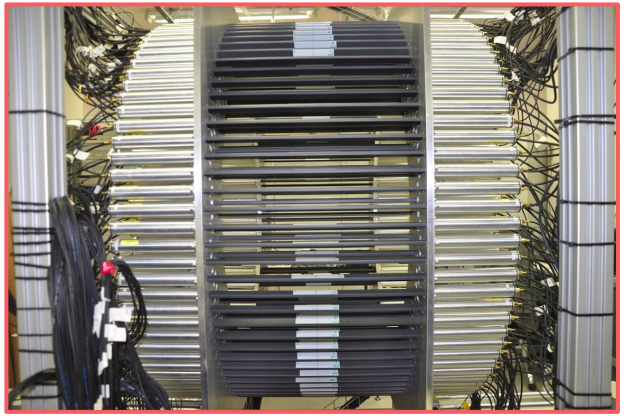
2018

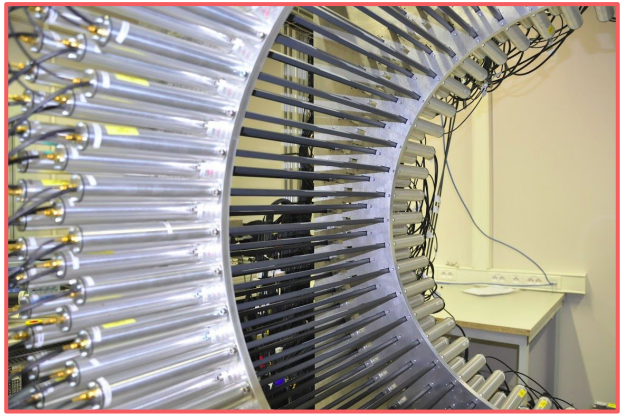
Each Module with 13 Scintillators - Total of 24 Modules

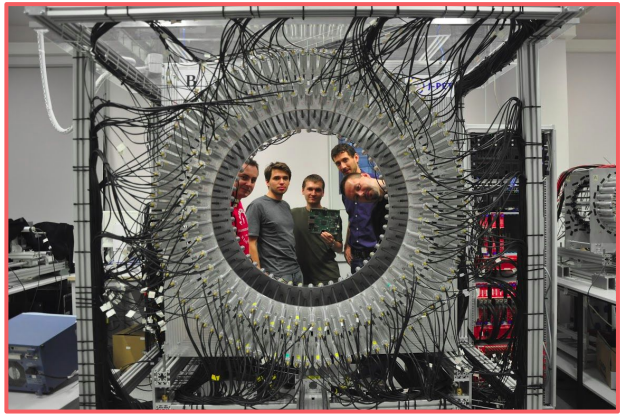
Jagiellonian - Positron Emission Tomograph

- 3 - Layers (192 Modules)
- Polymers
- Low granularity
- High acceptance
- Compton scattering
- Time domain
- Digital electronics
- Cost Effective
- Portable
- Whole body PET









~ 70 Articles
16 International Patents

J-PET: First PET based on plastic scintillators

Jagiellonian-PET Collaboration:

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[1]Jagiellonian University, Poland; [2]LNF INFN, Italy; [3]Maria Curie-Skłodowska University, Poland; [4]University of Vienna, Austria; [5]National Centre for Nuclear Research, Poland;

AIM:

1.) Cost Effective PET Scanner
2.) Portable & Compatible with MRI & CT
3.) Configurable
4.) Whole Body PET

Positronium systems for symmetry tests:

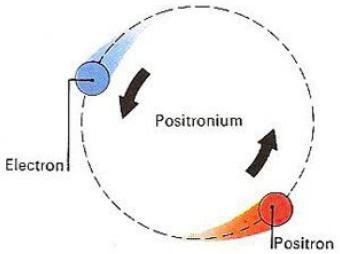
- Hamiltonian eigenstates of P, C, CP operators
- The lightest known atom and anti-atom
- The simplest atomic system with charge conjugation eigenstates.
- Electrons and positrons are the lightest leptons hence, they do not decay into lighter particles via weak interaction
- Weak interaction leads to the violation at the order of 10^{-14}.

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

- No charged particles in the final state (radiative corrections very small $2 * 10^{-10}$)
- Light by light contributions to various correlations are small

(B. K. Arbic et al., Phys. Rev. A 37, 3189 (1988))

(W. Bernreuther et al., Z. Phys. C 41, 143 (1988))



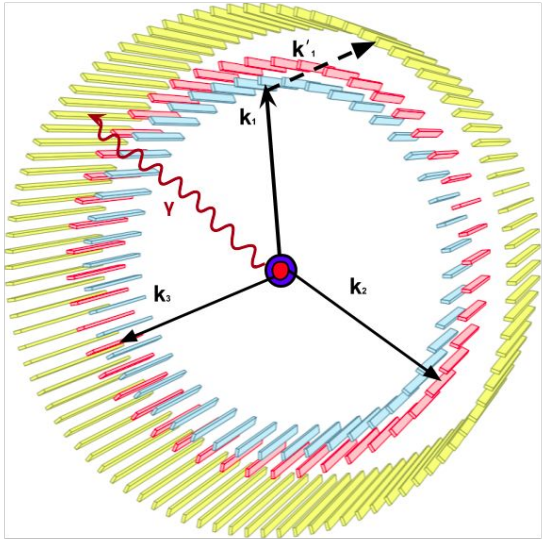
- Purely Leptonic state!
- Breaking of T and CP was observed but only for processes involving quarks.
- So far, breaking of these symmetries was not observed for purely leptonic systems.
- 10^{-9} vs upper limits of $3 * 10^{-3}$ for T, CP, CPT

(P.A. Vetter and S.J. Freedman, Phys. Rev. Lett. 91, 263401 (2003))

(T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 083401)

- 10^{-9} vs upper limits of $3*10^{-7}$ for C

Discrete Symmetries in ortho-Positronium:



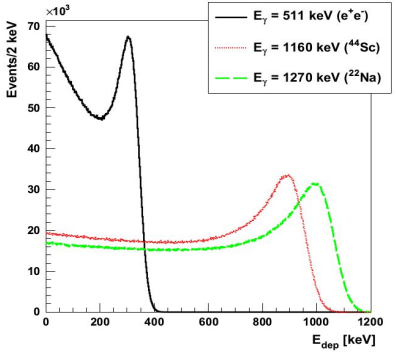


Figure 1: Schematic of the J-PET detector with a positron source (red) placed in the center, covered in XAD-4 porous polymer (blue).

$$^{22}Na \rightarrow {}^{22}Ne^{*} + e^{+} + \nu_e$$

$$^{22}Ne^{*} \rightarrow {}^{22}Ne + \gamma(1.247\ \text{MeV}, \tau \approx 3.7\ \text{ps})$$

Poster titled ***"Test of CP symmetry in positronium decay with the J-PET detector"*** by Shivani

Table 1: Symmetry Odd-Operators

Operator	C	P	T	CP	CPT
$\vec{S}.\vec{k_1}$	+	-	+	-	-
$S.(k_1 x k_2)$	+	+	-	+	-
$(\vec{S}.\vec{k_1})(\vec{S}.(\vec{k_1} x \vec{k_2}))$	+	-	-	-	+
$\vec{\epsilon_1}.\vec{k_2}$	+	-	-	-	+
$\vec{S}.\vec{\epsilon_1}$	+	+	-	+	-
$\vec{S}.(\vec{k_2} x \vec{\epsilon_2})$	+	-	+	-	-

Where,

$$|\vec{k_1}| > |\vec{k_2}| > |\vec{k_3}| \quad (1)$$

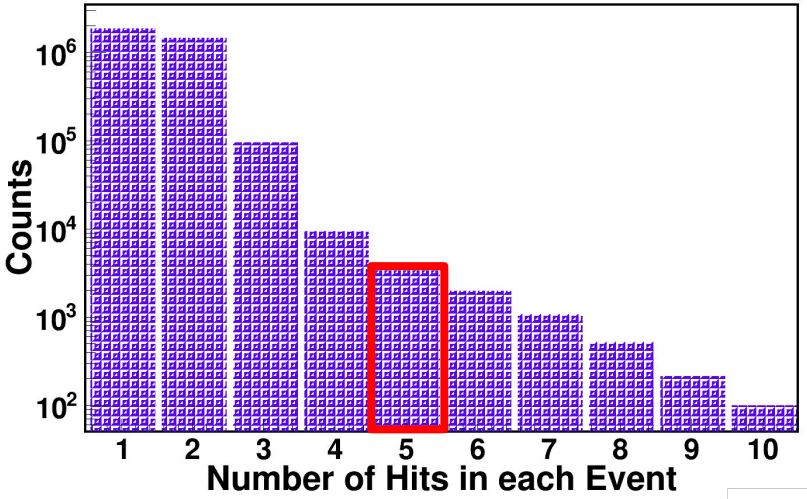
P.Moskal et. al., Acta Phys. Polon. B47 (2016) 509

Table 2: Time Reversal Symmetry Odd-Operator

Operator	C	P	T	CP	CPT
$\vec{\epsilon_1}.\vec{k_2}$	+	-	-	-	+

$$\vec{\epsilon_1} = (\vec{k_1} x \vec{k_1'}) \quad (2)$$

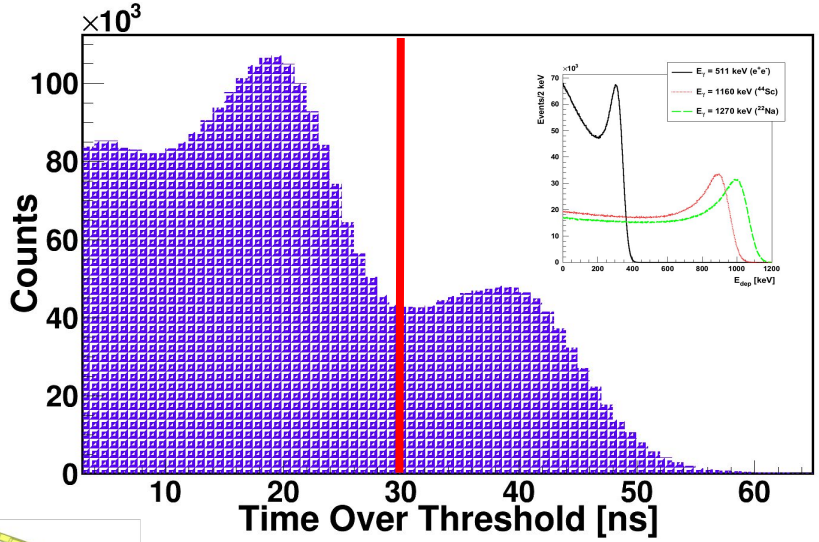
Hit Multiplicity:

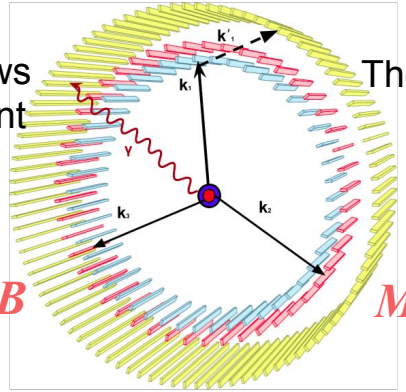


The signal (hit) multiplicity distribution shows that the requirement of five hits in one event reduces the measured data sample by a factor of about 10^3.

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

Energy Deposition:

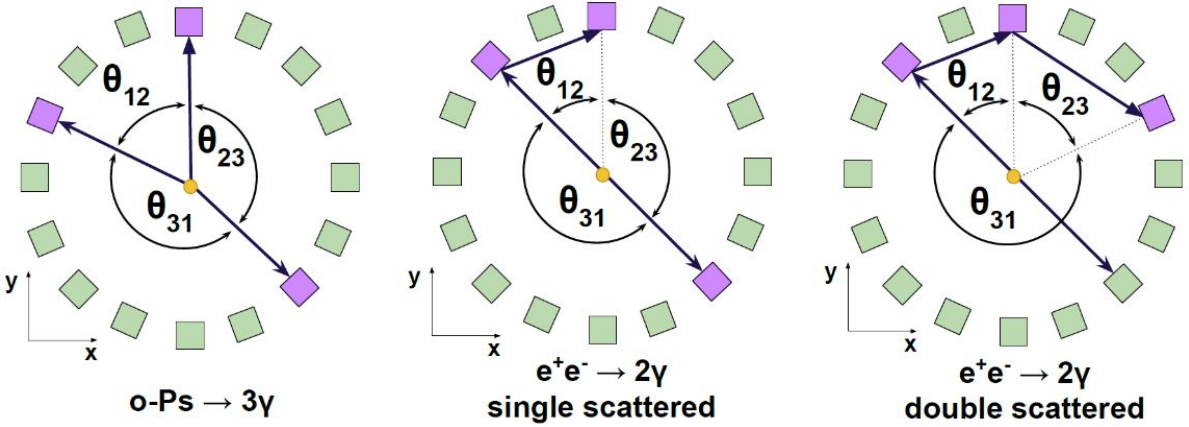




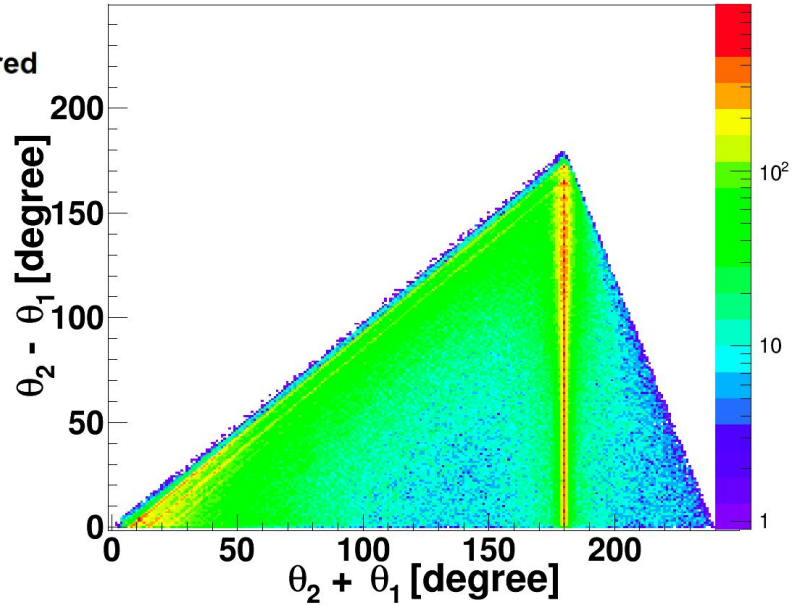
The de-excitation photon is identified using the time-over-threshold (TOT) measurement which is related to the energy deposited in the scintillator

M. Palka et al., JINST 12 P08001, (2017)

Relative azimuthal angles of the interacting photons in an event:



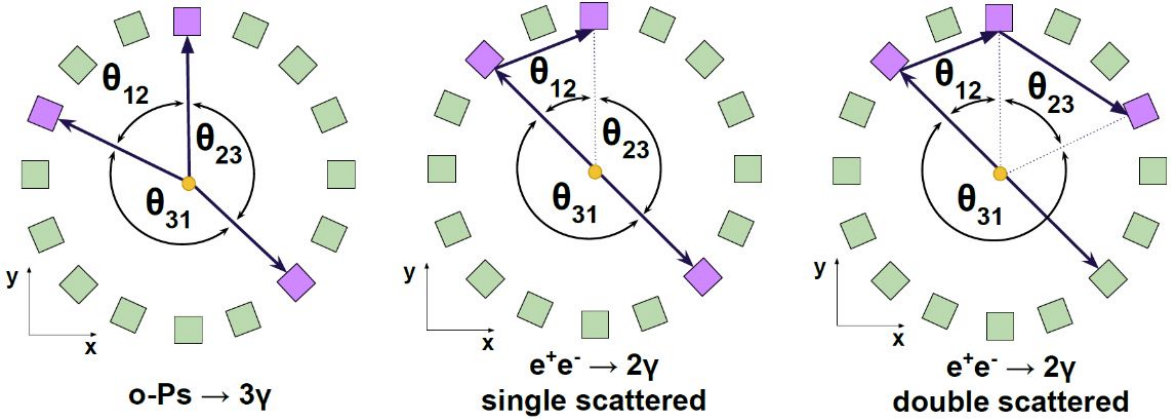
- Distribution of o-Ps → 3γ (greater than 180°) and scattered events (less than 180°) as a function of θ_{12} vs θ_{23} angle.
- Events, where two of the gamma from $e^+e^- \rightarrow 2\gamma$ annihilation is registered in the detector while the other is scattered and cause signals in two detectors, lies on the band at 180°



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

A. Gajos et al., Nucl. Instrum. Methods A 819, 54 (2016)

Correlating the primary & secondary photons using a time algorithm:

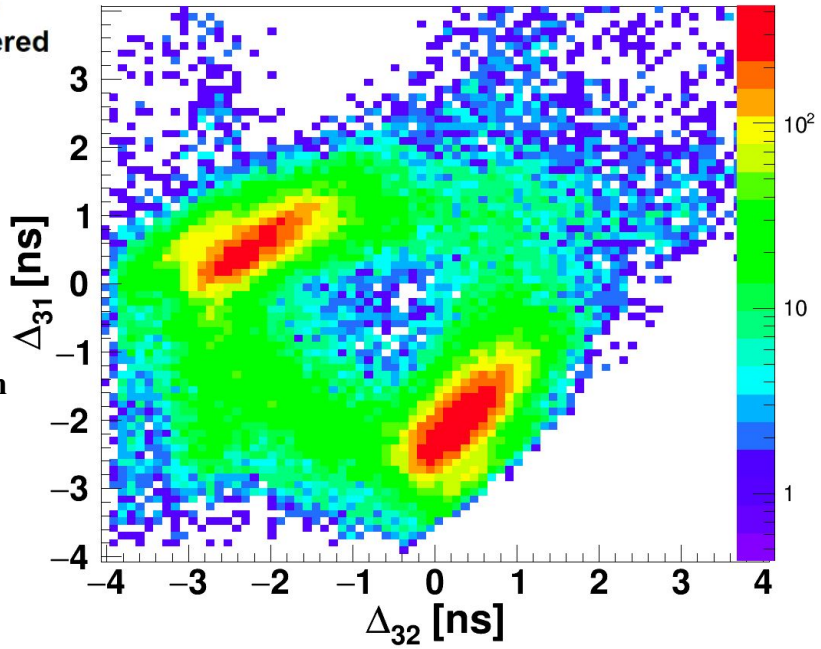


$$\Delta_{ij} = t_M - t_C$$

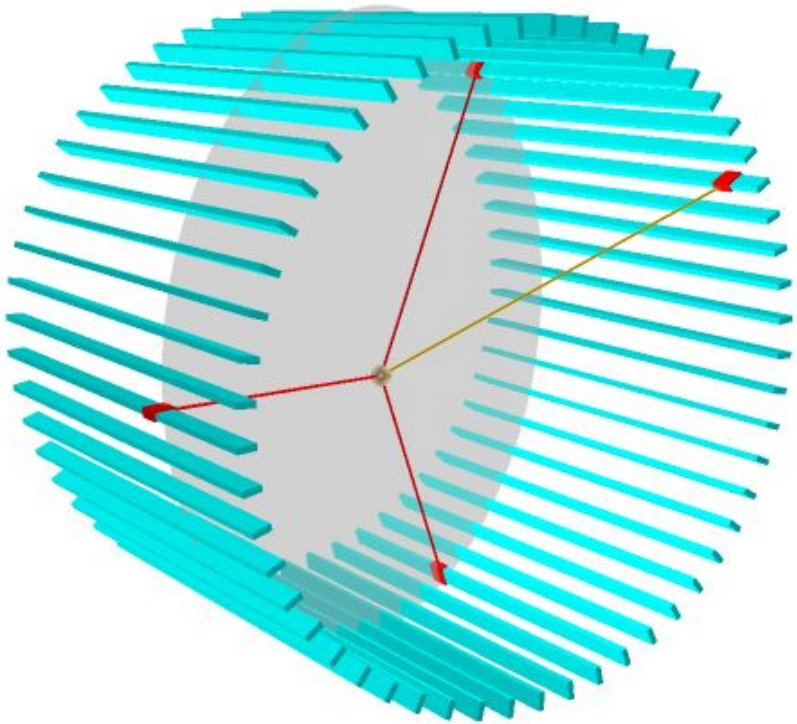
t_M = Measured Time Difference

t_C = Calculated Time Difference

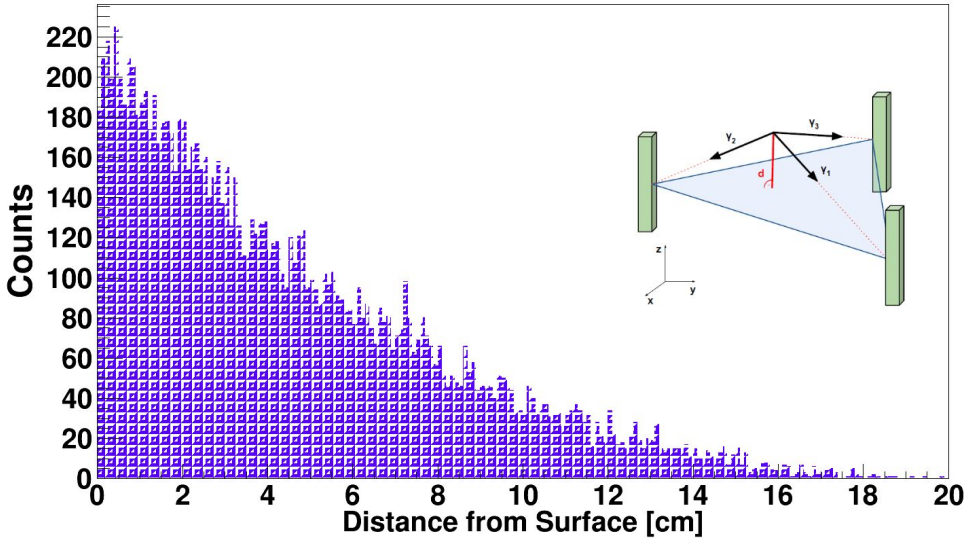
Therefore, Δ_{ij} should be equal to zero in case if the jth signal is due to the ith scattered photon.
The figure shows an exemplary spectrum allowing to relate the primary annihilation photon to its corresponding secondary photon.



Distance of the annihilation plane from the center:

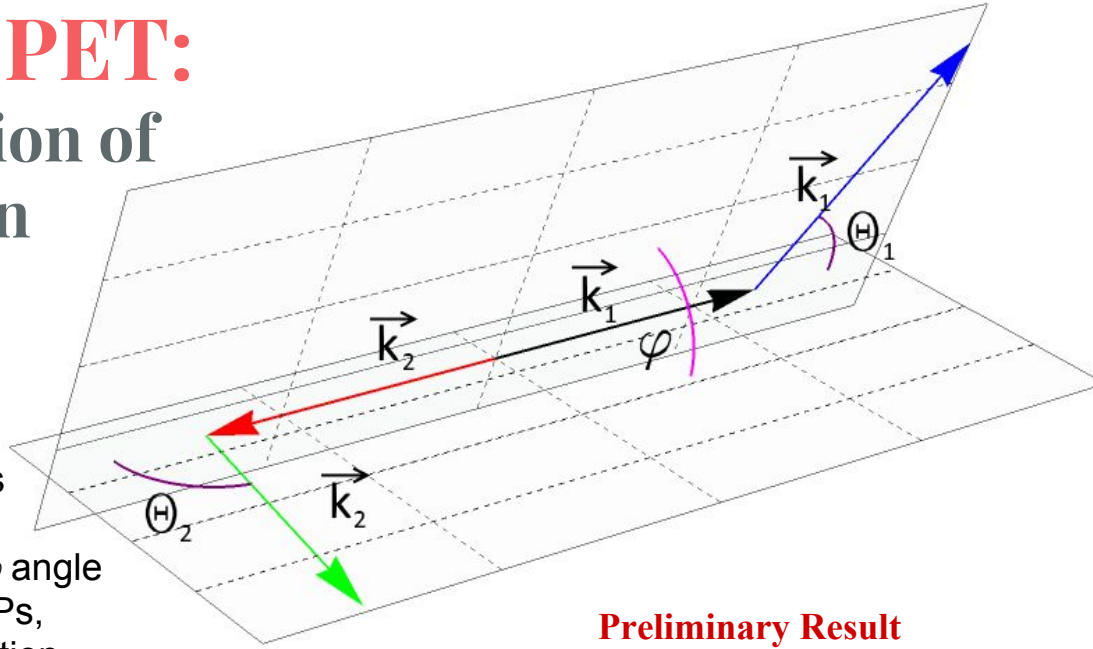


- Due to the conservation of momentum, the annihilation photons lie on a single plane of response.
- Annihilation plane of response can be determined from gamma quanta interaction position in the scintillators.
- The distance between the annihilation plane of response and geometrical center vertex gives information about annihilation position uncertainty.



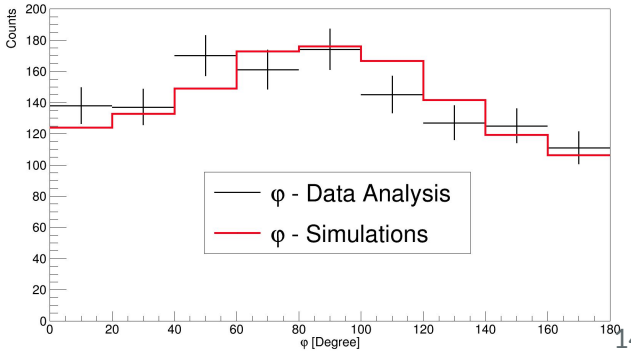
Unique Feature of J-PET:

Measurement of the direction of Polarization of Annihilation photons



- Photons interact in plastic scintillators predominantly via compton effect.
- The angle between the scattering planes is denoted by 'φ'.
- The orthogonality in the measurement of φ angle between the 2-γ annihilation photons of p-Ps, opens possibilities to measure the polarization operator for the decay of o-Ps into 3-γ.

Preliminary Result

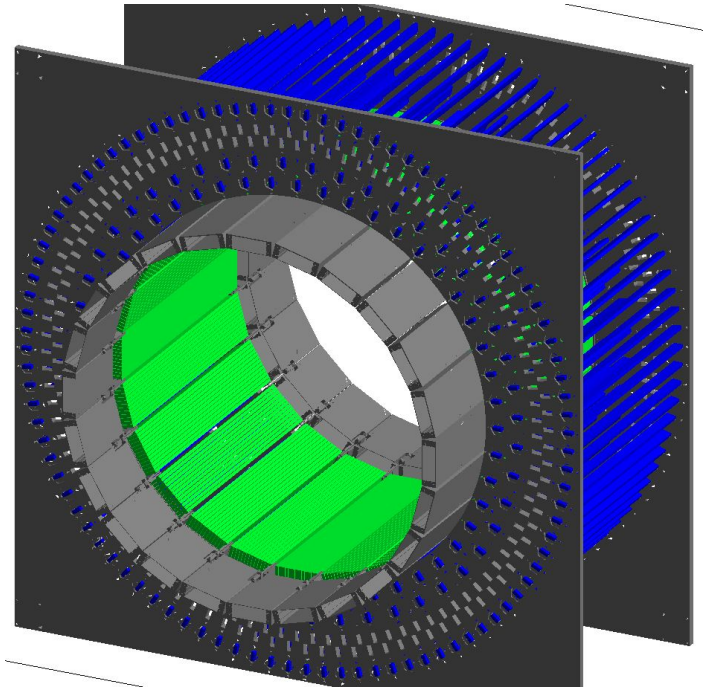


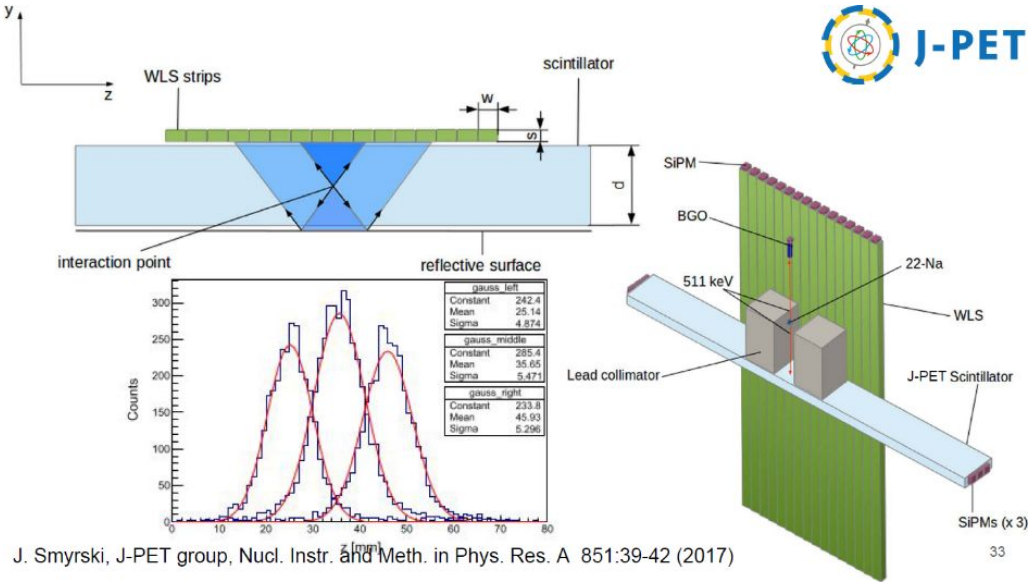
B.C. Hiesmayr, P. Moskal, Scientific Reports 7 (2017)

P. Moskal et al., Acta Phys. Polon. B 47, 537 (2016)

Future Endeavors:

First experimental 'Run' with upgraded J-PET (Digitized 4-Layer J-PET) shall start in winter 2018



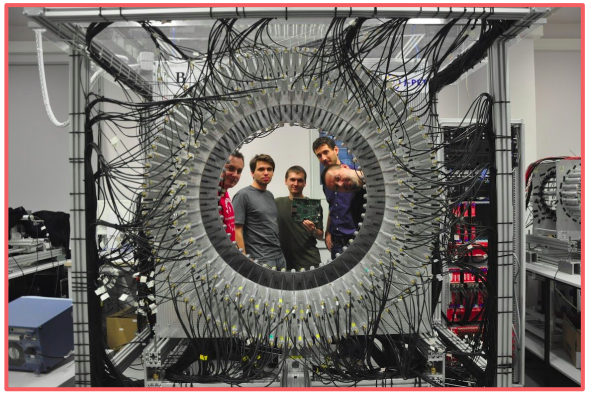


Usage of WLS strips in the J-PET geometry to substantially suppress the background of the reconstructed PET images.

J. Smyrski, et al., Nuclear Instruments and Methods in Physics Research A 851 (2017) 39-42

Summary:

- Discrete symmetries play a fundamental role in particle and nuclear physics.
- There is still a substantial lack of experimental data on fundamental symmetries tests in the leptonic sector.
- The J-PET detector has a potential to contribute in Time Reversal Symmetry and improve the limits by at least one order of magnitude.
- The detector is under the commissioning and first test measurements were done.



Thank you!