Testing time reversal symmetry with Compton scattered photons from positronium decays

Juhi Raj
On Behalf of the J-PET Collaboration
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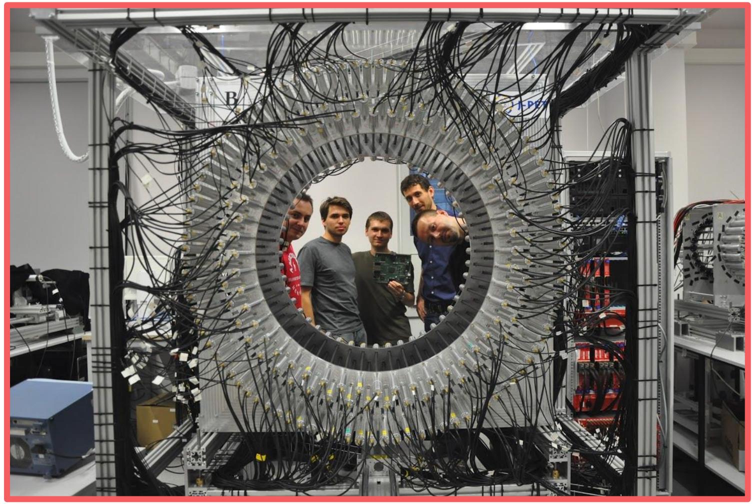
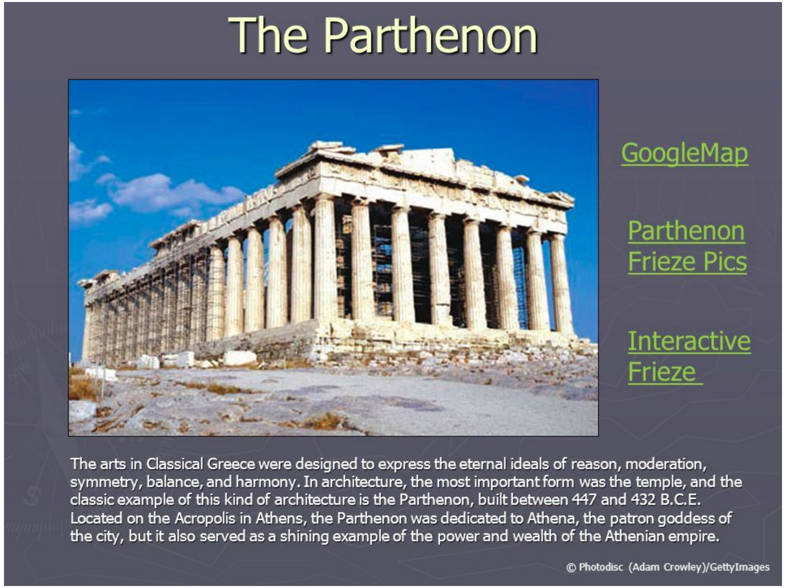


3rd Symposium on Positron Emission Tomography and 1st Symposium on Boron Neutron Capture Therapy
10th - 15th September 2018, Krakow, Poland

Symmetry

(from Greek συμμετρία ***symmetria*** "agreement in dimensions, due proportion, arrangement")

Greek Mosaic Carpets



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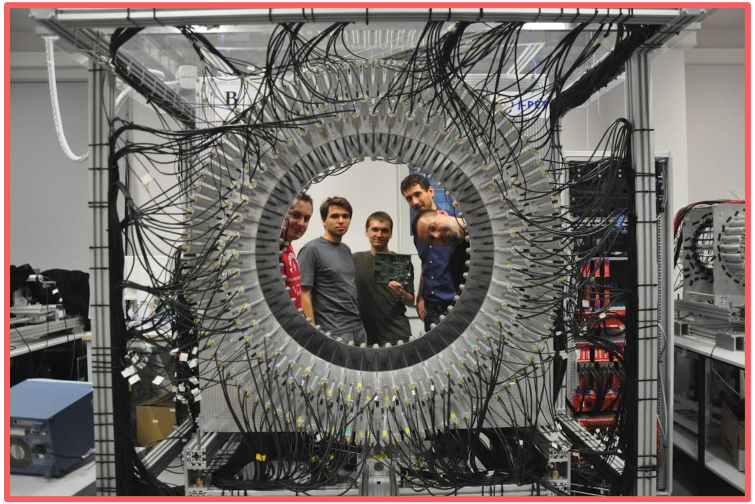

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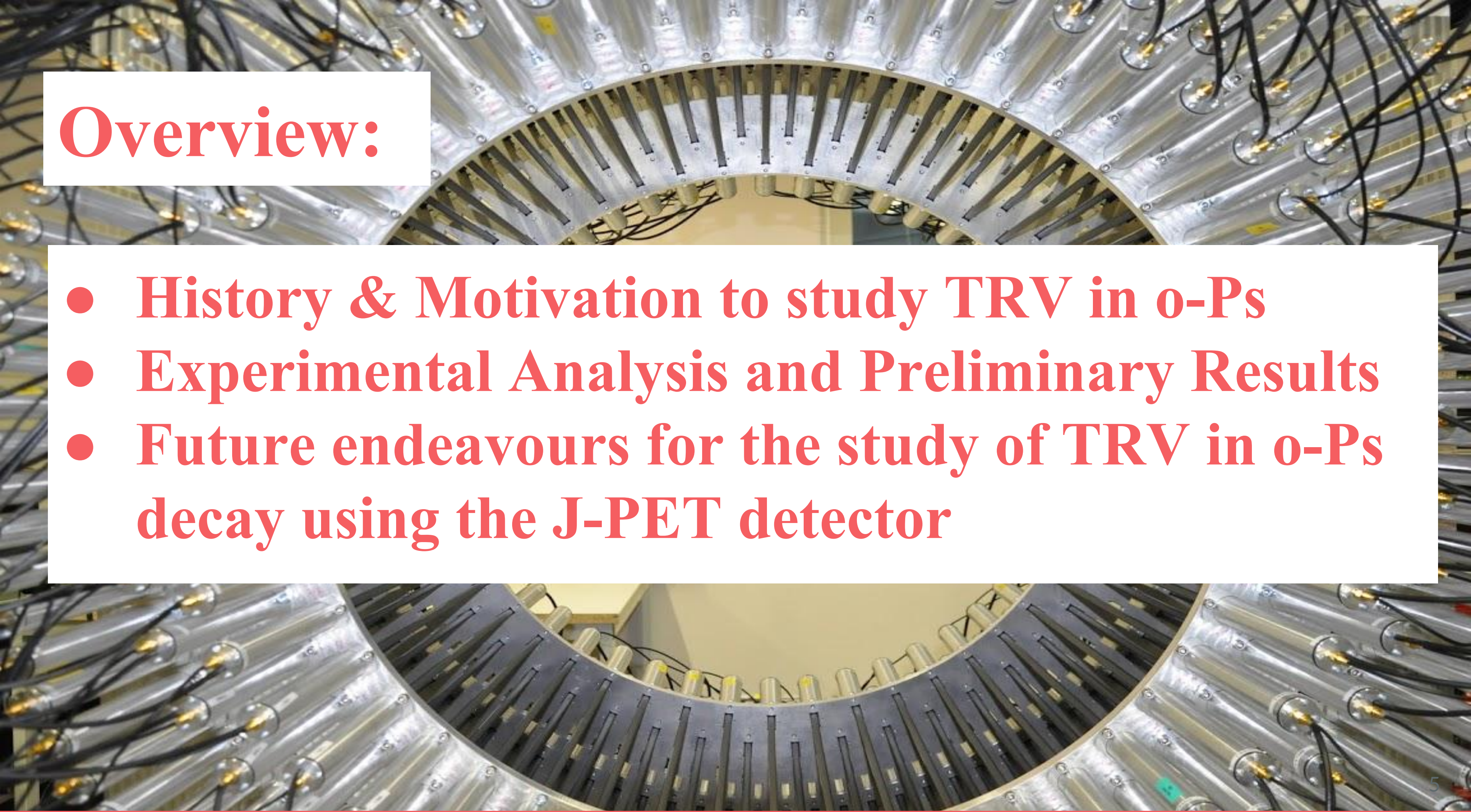


Overview:

- History & Motivation to study TRV in o-Ps
- Experimental Analysis and Preliminary Results
- Future endeavours for the study of TRV in o-Ps decay using the J-PET detector

History and Motivation!

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. Lee, *Columbia University, New York, New York*

AND

C. N. Yang,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

RECENT experimental data indicate closely identical masses[1] and lifetimes[2] of the $\theta^+(\equiv K_{\pi 2}^+)$ and the $\tau^+(\equiv K_{\pi 3}^+)$ mesons. On the other hand, analyses[3] of the decay products of τ^+ strongly suggest on the grounds of angular momentum and parity conservation that the τ^+ and θ^+ are not the same particle. This poses a rather puzzling situation that has been extensively discussed.[4]

One way out of the difficulty is to assume that parity is not strictly conserved, so that θ^+ and τ^+ are two different decay modes of the same particle, which necessarily has a single mass value and a single lifetime. We wish to analyze this possibility in the present paper against the background of the existing experimental evidence of parity conservation. It will become clear that existing experiments do indicate parity conservation in strong and electromagnetic interactions to a high degree of accuracy, but that for the weak interactions (i.e., decay interactions for the mesons and hyperons, and various Fermi interactions) parity conservation is so far only an extrapolated hypothesis unsupported by experimental evidence. (One might even say that the present $\theta-\tau$ puzzle may be taken as

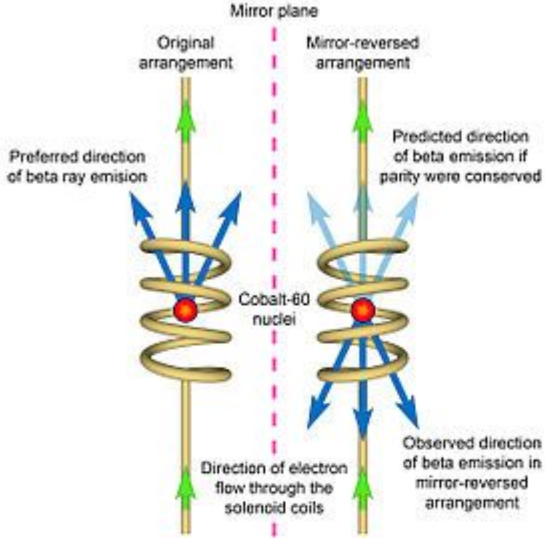
PRESENT EXPERIMENTAL LIMIT ON PARITY NONCONSERVATION

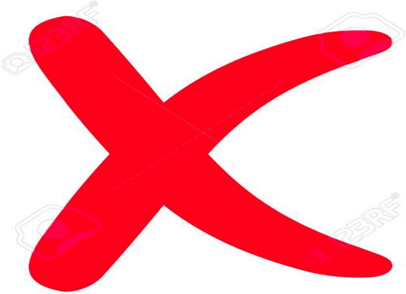
If parity is not strictly conserved, all atomic and nuclear states become mixtures consisting mainly of the state they are usually assigned, together with small percentages of states possessing the opposite parity. The fractional weight of the latter will be called $\mathfrak{F}^2$. It is a quantity that characterizes the degree of violation of parity conservation.

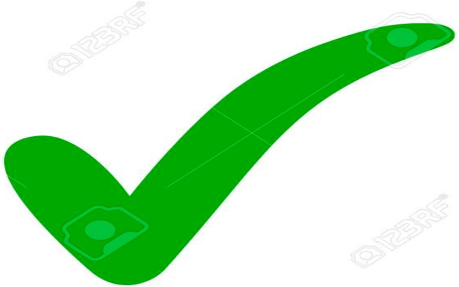
The existence of parity selection rules which work well in atomic and nuclear physics is a clear indication that the degree of mixing, $\mathfrak{F}^2$, cannot be large. From such considerations one can impose the limit $\mathfrak{F}^2 \lesssim (r/\lambda)^2$, which for atomic spectroscopy is, in most cases, $\sim 10^{-6}$. In general a less accurate limit obtains for nuclear spectroscopy.

Parity nonconservation implies the existence of interactions which mix parities. The strength of such interactions compared to the usual interactions will in general be characterized by $\mathfrak{F}$, so that the mixing will be of the order $\mathfrak{F}^2$. The presence of such interactions would affect angular distributions in nuclear reactions. As we shall see, however, the accuracy of these experi-

Dr. Chien Shiung Wu







Positronium systems for symmetry tests:

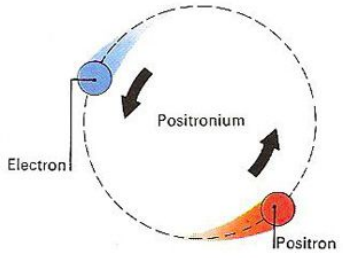
- Hamiltonian eigenstates of P, C, CP operators
- The lightest known atom and anti-atom
- The simplest atomic system with charge conjugation eigenstates.
- Electrons and positrons are the lightest leptons hence, they do not decay into lighter particles via weak interaction
- Weak interaction leads to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



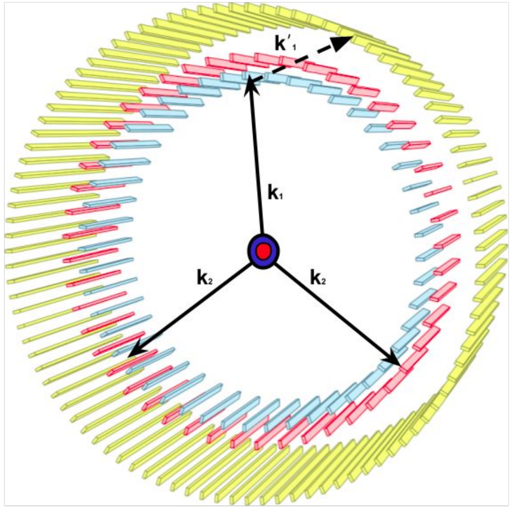
- Purely Leptonic state!
- Breaking of T and CP was observed but only for processes involving quarks.
- So far, breaking of these symmetries was not observed for purely leptonic systems.
- 10^{-9} vs upper limits of $3 * 10^{-3}$ for T, CP, CPT

(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:



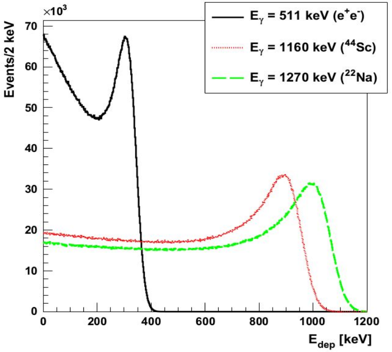


Figure 1: Schematic of the J-PET detector with a positron source (red) placed in the center, covered in XAD-4 porous polymer (blue).

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

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

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

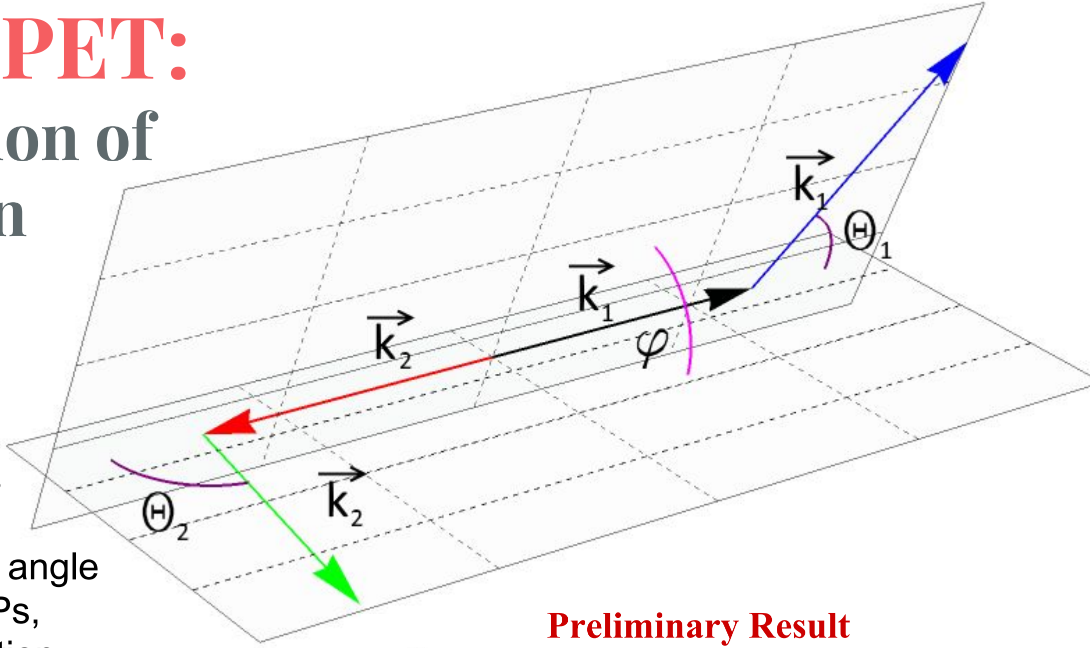
Table 2: Time Reversal Symmetry Odd-Operator

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

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

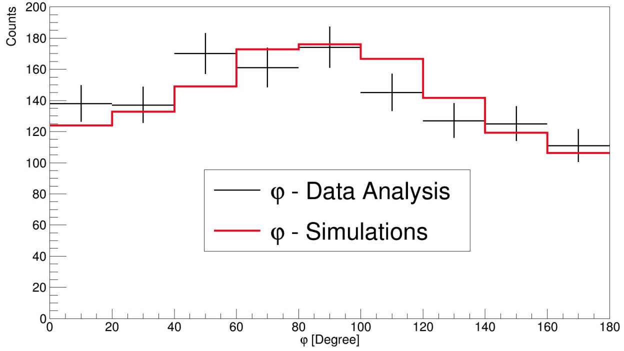
Unique Feature of J-PET:

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 '$\boldsymbol{\varphi}$'.
- The orthogonality in the measurement of $\boldsymbol{\varphi}$ 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.

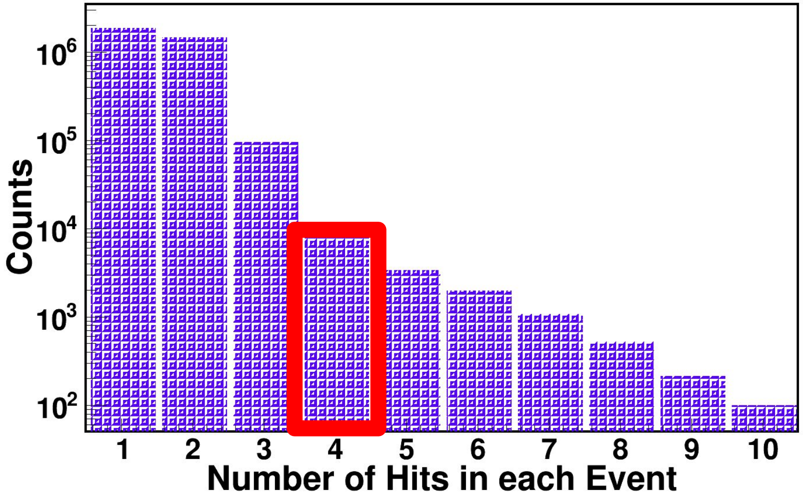
Preliminary Result



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

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

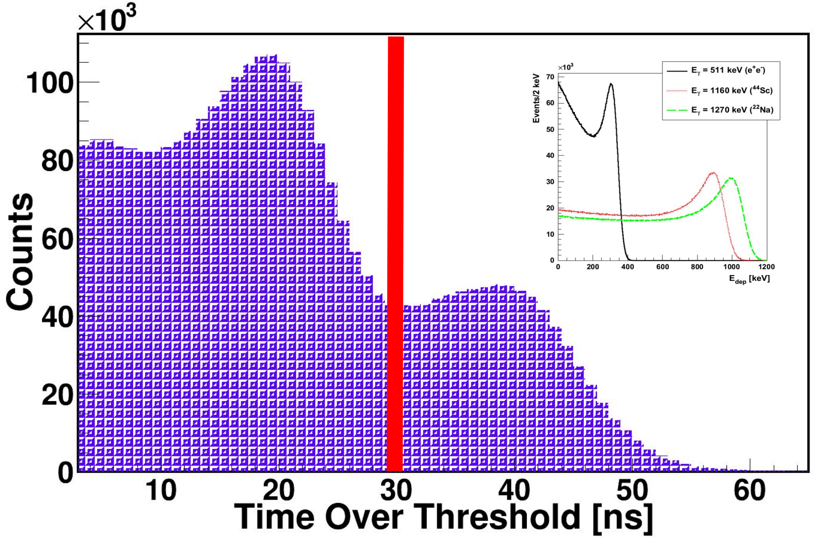
Hit Multiplicity:



The signal (hit) multiplicity distribution shows that the requirement of four hits in one event reduces the measured data sample by a factor of about 10^2.

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

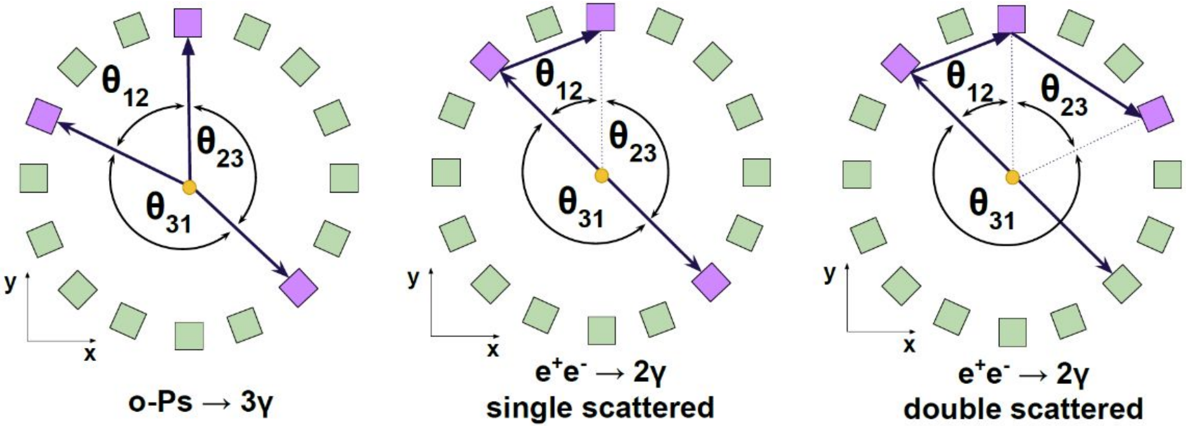
Energy Deposition:

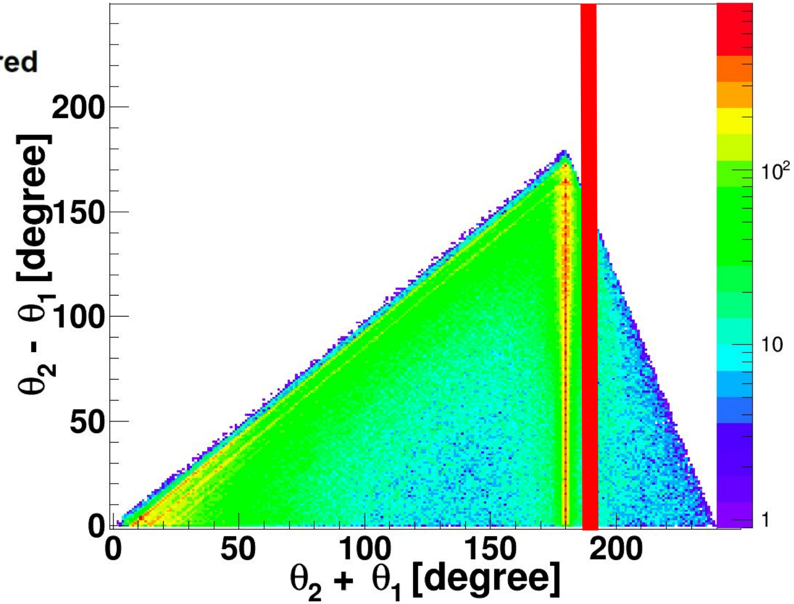


The de-excitation photon is identified using the time-over-threshold (TOT) measurement which is related to the energy deposited in the scintillator

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

Relative azimuthal angles of the interacting photons in an event:



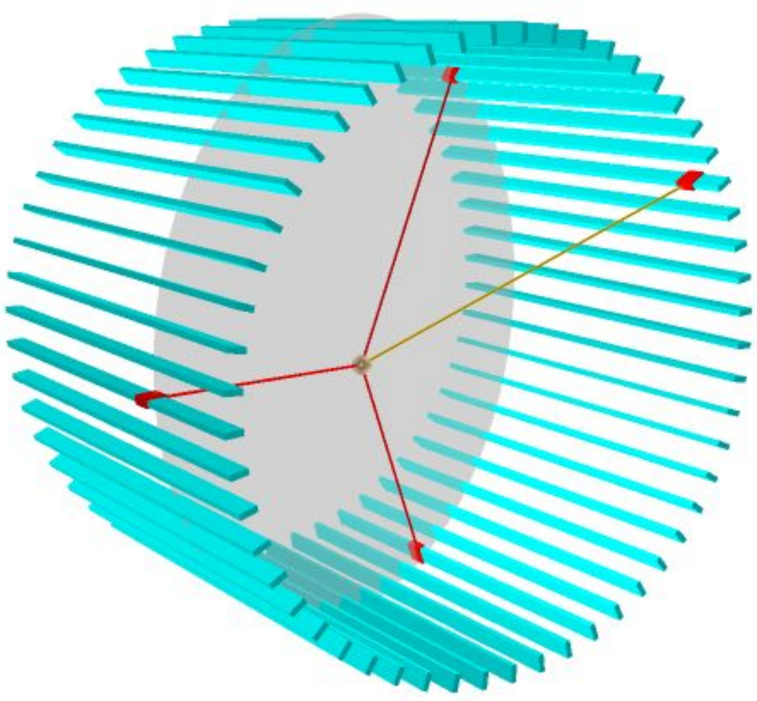


- Distribution of o-Ps → 3γ (greater than 180°) as a function of θ_{12} vs θ_{23} angle.
- Events, where two of the gamma from $e^+e^- \rightarrow 2\gamma$ annihilation is registered in the detector while the other is scattered and cause signals in two detectors, lies on the band at 180°

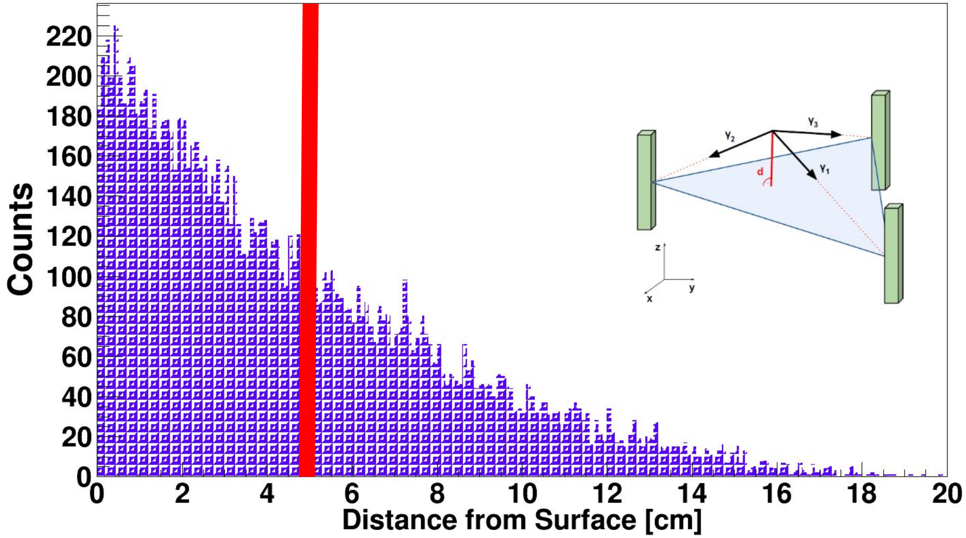
D. Kaminska et al., Eur. Phys. J. C 76, 445 (2016)

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

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.

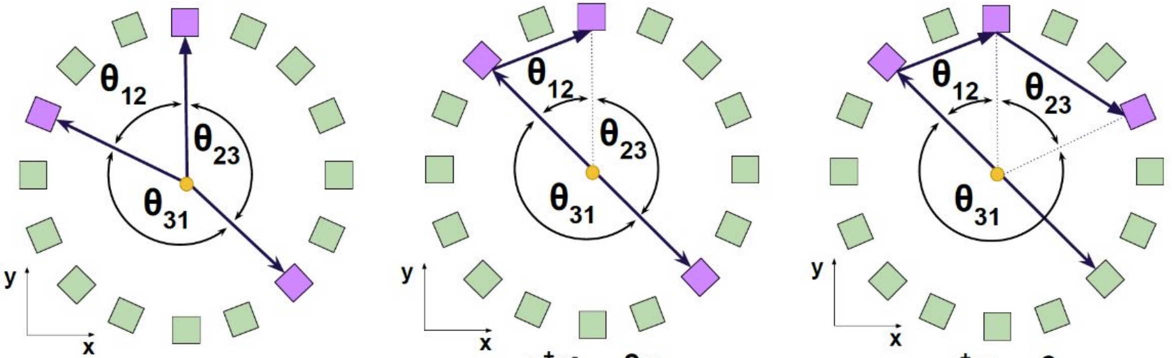


Energy of the photons from Kinematics:

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

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

$$E_3 = 2me\,\{(1 + \cos\theta_{12}) / (1 + \cos\theta_{12} - \cos\theta_{13} - \cos\theta_{23})\}$$



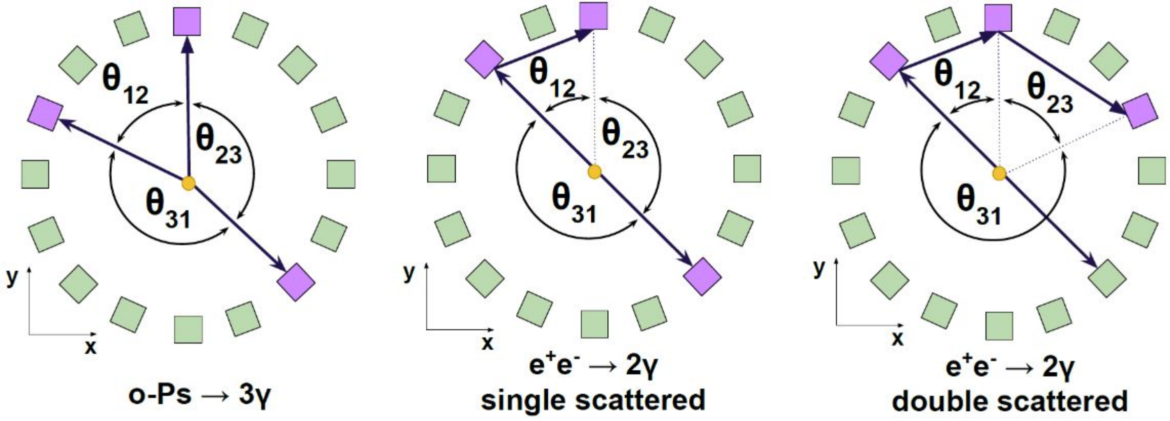
o-Ps → 3γ

$e^+e^- \to 2\gamma$ single scattered

$e^+e^- \to 2\gamma$ double scattered

Where,

$$\vec{E}_1 > \vec{E}_2 > \vec{E}_3$$



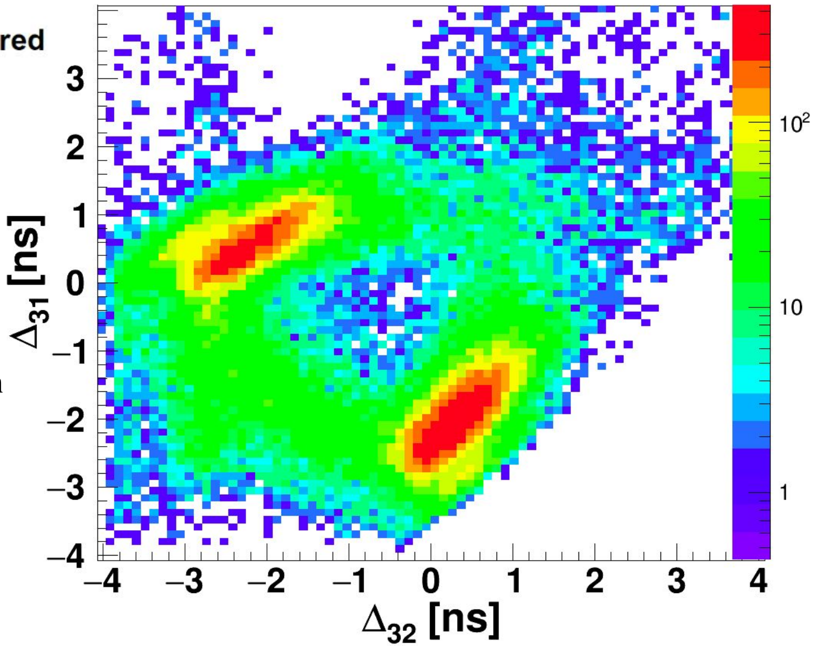
Correlating the primary & secondary photons using a time algorithm:

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

t_M = Measured Time Difference

t_C = Calculated Time

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

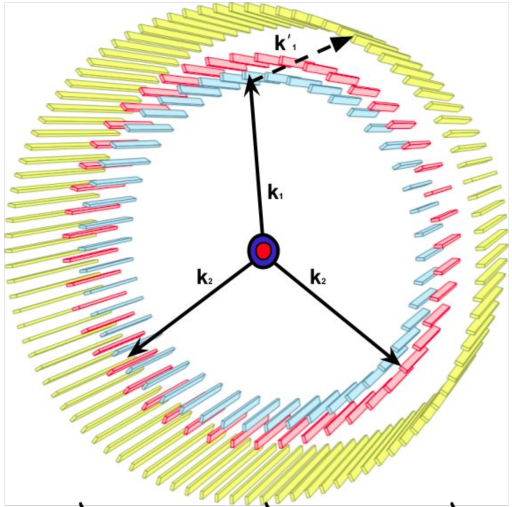


Expectation value of the operator:

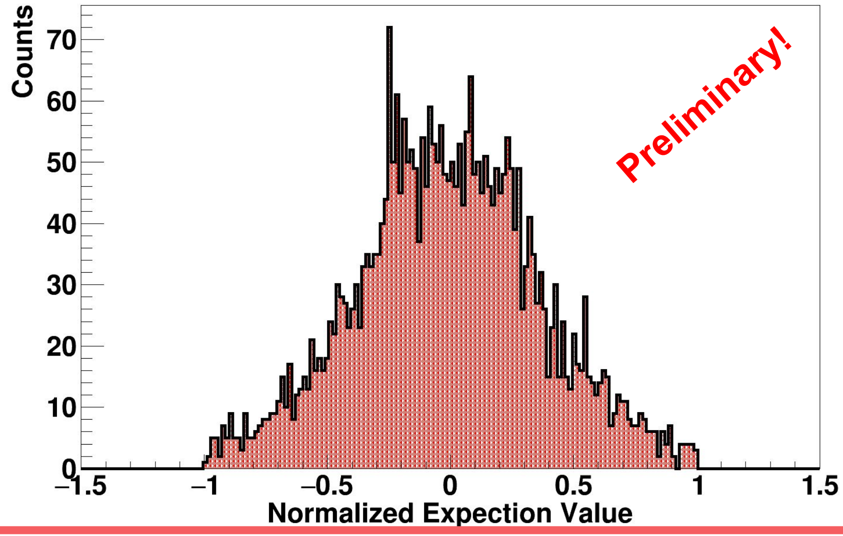
Table 2: Time Reversal Symmetry Odd-Operator

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

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



$$\vec{k_1} > \vec{k_2} > \vec{k_3}$$

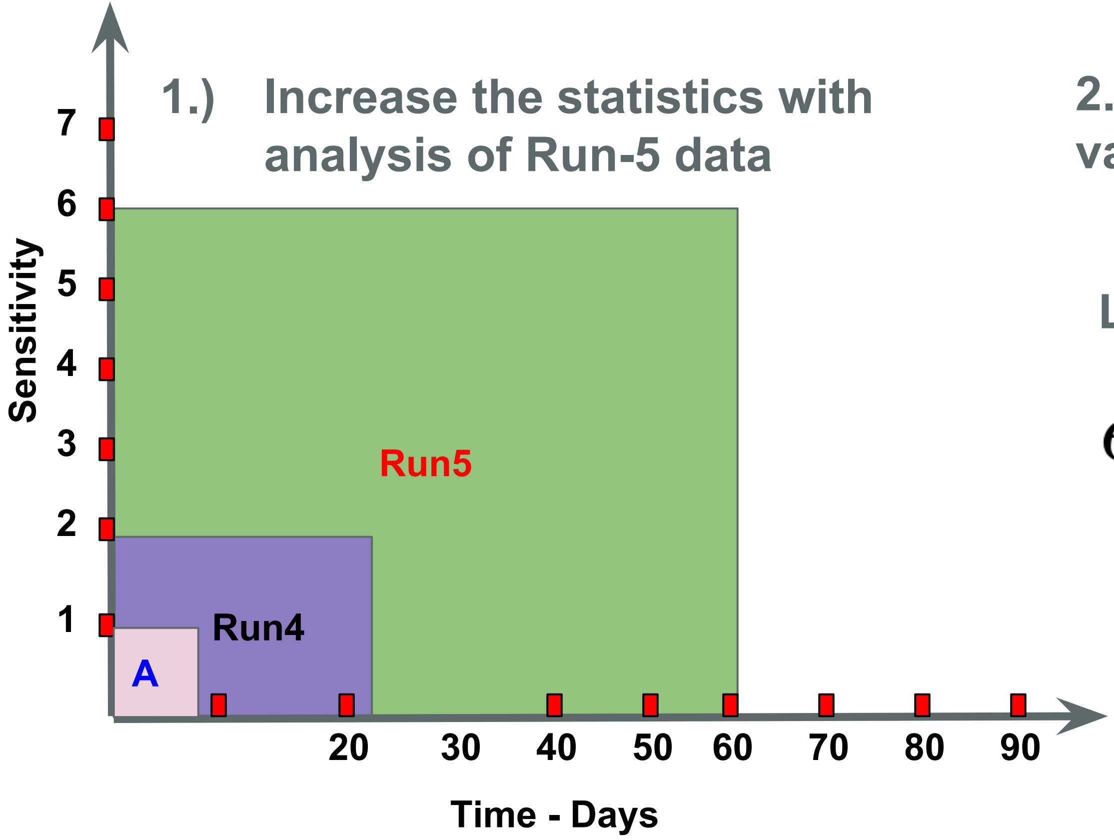


We see NO T - violation with the current stage of data analysis!

Mean = 10^{-3}

σ_s = 6.5×10^{-3}

Steps to improve the statistics:



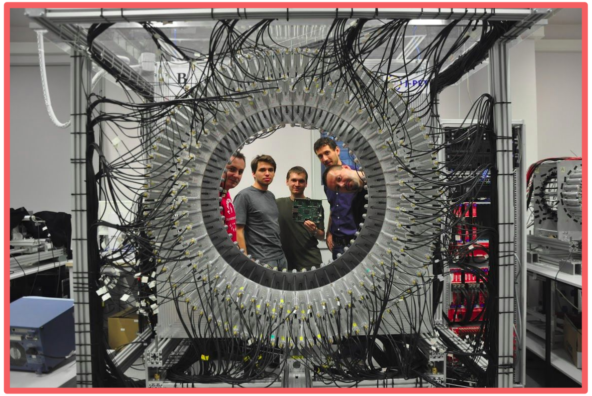
2.) Observing expectation values of various independent combinations

Like,

$$\vec{\epsilon_1} \cdot \vec{k_2} \;\; \& \;\; \vec{\epsilon_2} \cdot \vec{k_1} \;\; \text{etc..}$$

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!