Test of discrete symmetries with J-PET

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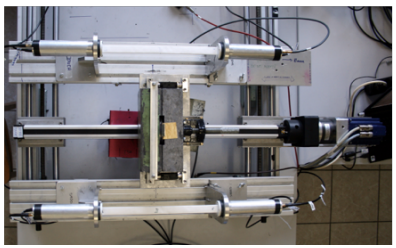
on behalf of the J-PET collaboration

1. **J**agiellonian **P**ositron **E**mission **T**omograph
2. Positronium atom decays
3. Tests of discrete symmetries
4. Future perspectice : Portable detection modules

Jagiellonian Positron Emission Tomograph

2012

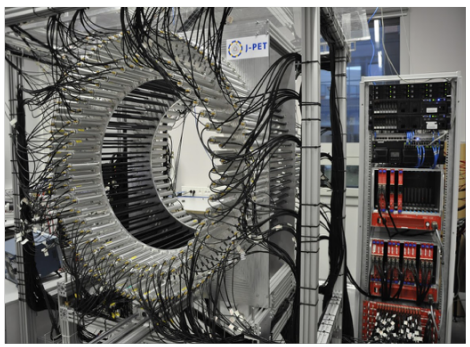


Characterize scintillator properties

Energy resolution, hit time, ..

192 strips

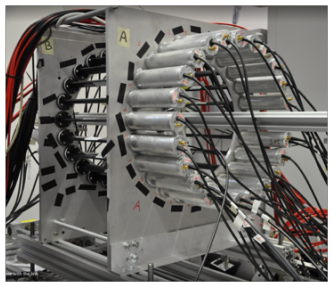
2016



Current version

Tests on discrete symmetries

2014



24 strips

Data acquisition for multi-modules

24 modules, each with 13 scintillators

2018

Modular PET – ready for first data campaign

- **2012** : First prototype with 2 plastic strips read by vacuum photomultipliers.
- **2014** : Data acquisition was successfully tested with multiple module system.
- **2016** : Prototype optimized to study the decays of positronium atoms
- **2018-2021** : Modular protoype - major changes in terms of SiPMs readout.

Key features

- 192 **detection modules** arranged in 3 Layers.
- Each module is made made of **plastic scintillators** (50 x 1.9 x .7 cm^3) and **2 photomultipliers** on each end.
- Trigger less and reconfiguration DAQ
- **T**ime **O**ver **T**hreshold (**TOT**) *Measure of energy deposition**
- Multiple photon detection in a **single event**
- Ang. reso.($\approx 1^0$)
  Good time reso. ($\approx$200 ps)

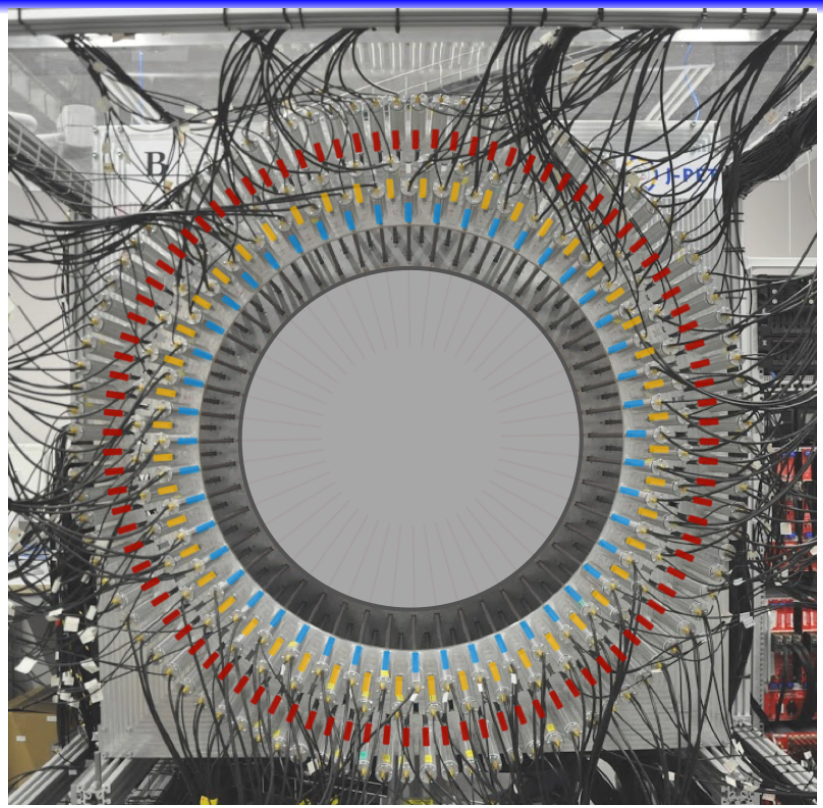
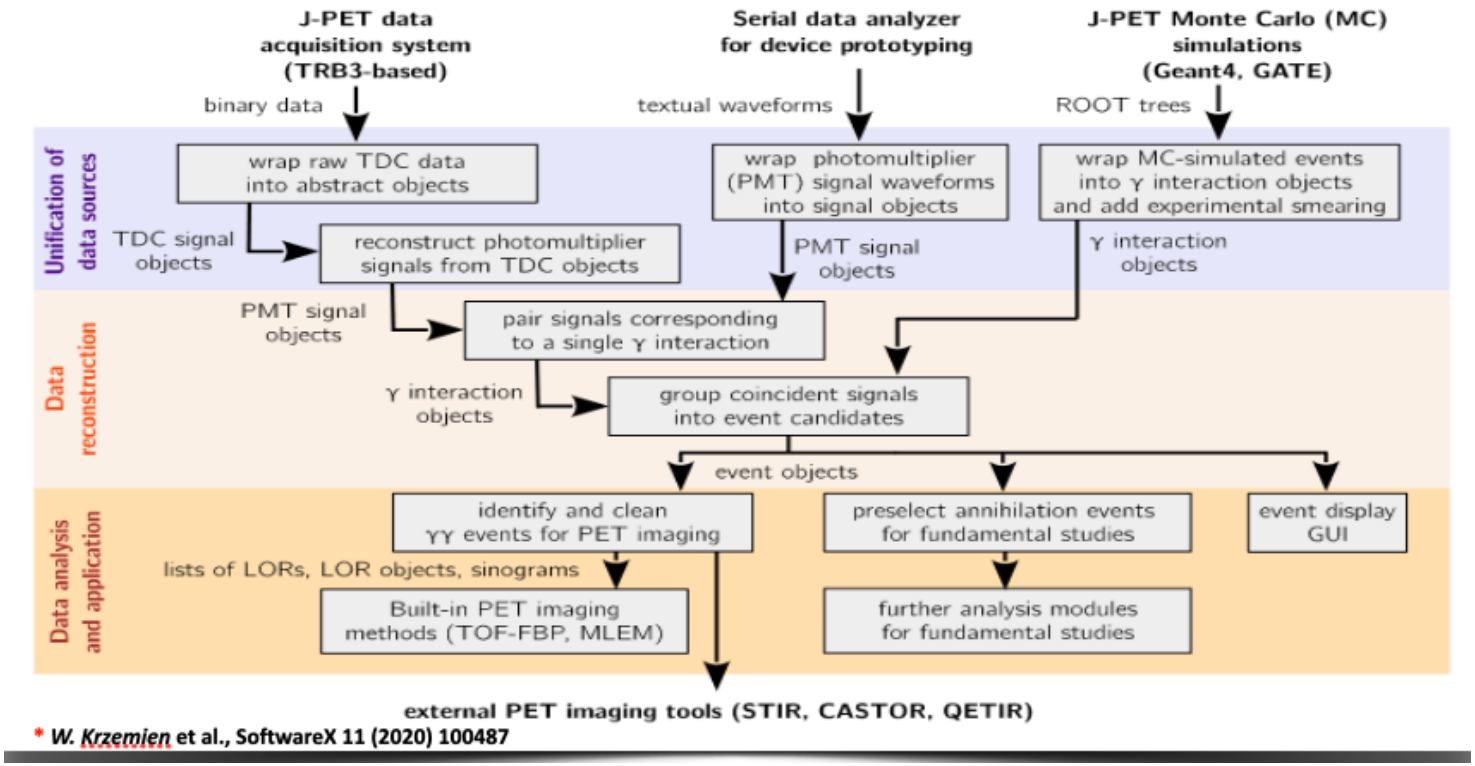


Figure: 3 Layers prototype

$$\text{Eres.}(\sigma_E/E) = 0.044/\sqrt{(E(MeV))}$$

* S. Sharma..,P.Moskal et al., EJNMMI Physics 7, 39 (2020)

Data Acquisition and Analysis : J-PET framework*



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

- J-PET Analysis Framework can be categorized in three sequential steps : DAQ (FPGA based), reconstruction of signal events and data analysis
- Mainly written in **C++11** using heavily the **ROOT** and **BOOST** libraries
- Dedicated MC simulations based on **Geant4** toolkit and **GATE** package

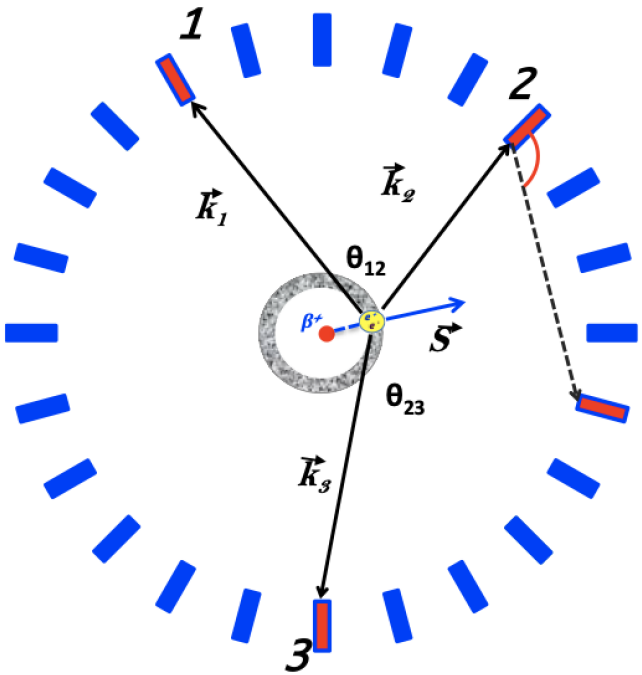
Positronium Decays : Applications in **Fundamental** physics

- First time detected in Gas by Martin Deutsch
  Nobel prize in 1956 for discovering Ps
- Hydrogen like atom without nuclei : purely leptonic object
  particle : e^- and anti-particle : e^+
- Eigenstate of C,P,CP operators
- Undergoes self-annihilation into gamma quanta.
  Number of annihilated photons followd the charge parity conservation.
- Formed in two gnd. states:

para-Positronium(p-Ps - .125 ns)	ortho-Positronium(o-Ps - 142 ns)
(S =0, m_Z = 0).	(S =1, m_Z = -1, 0, 1)
Even no of photons 2,4,.. **Charge Conj.**	Odd no of photons 3,5,..

- J-PET qualifies to perform the
  tests on discrete symmetries in the decays of o-Ps atoms

Tests of discrete symmetries in the decays of o-Ps atoms



Target chambers

- Odd symmetry operators can be constructed using *momentum vectors of anni. photons*($\vec{k}_i$) and *Spin of Ps atoms*($\vec{S}$).

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

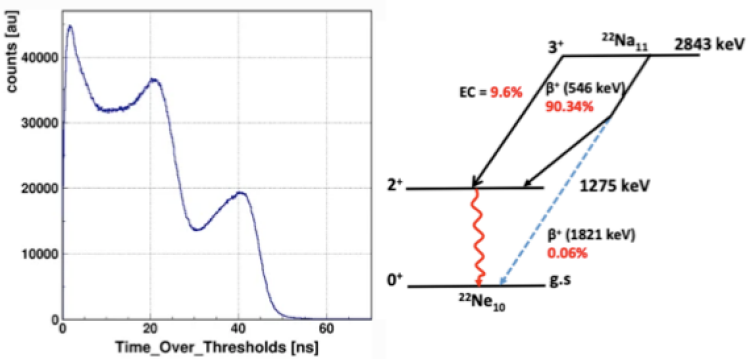
Table: Operators

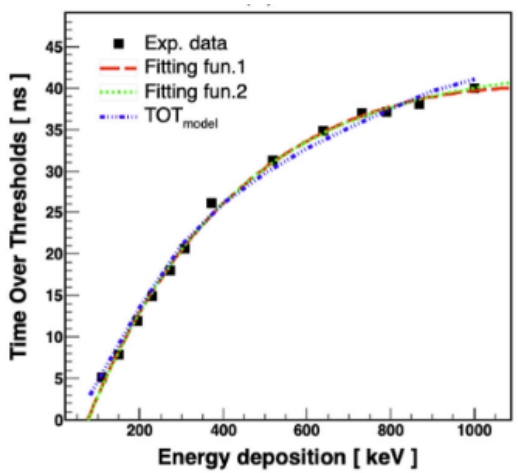
Odd symmetric	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	−	+	−	−
$\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	+	−	+	−
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)$	+	−	−	−	+

Control Spectra for data analysis

Time Over Thresholds

Measure of energy depositions

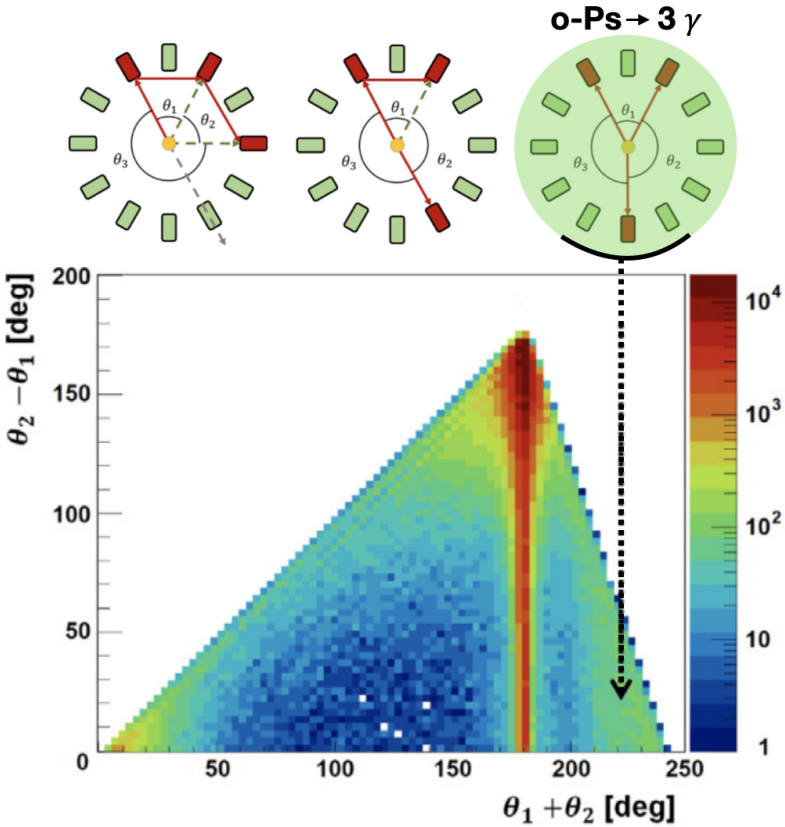




EJNMMI Physics 7, 39 (2020)

Azimuth angles

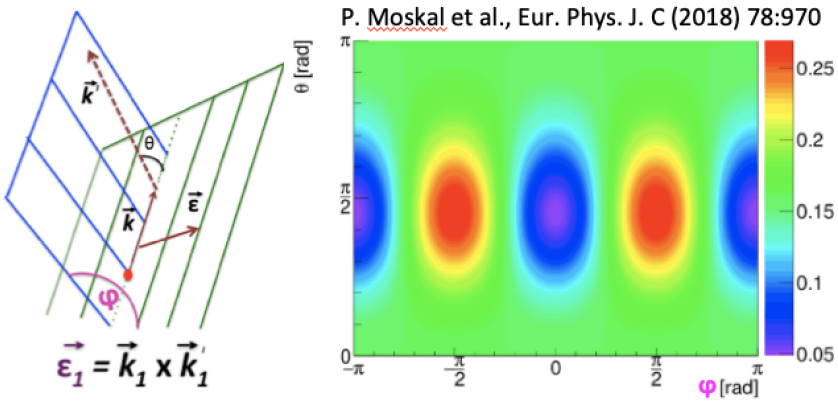
Angular correlation b/w anni. photons



K. Dulski et al, NIM A(in press)

Tests on discrete symmetries using the photons' polarization

- J-PET allows to register primary and scattered photon
- Photon (low energetic) most likely scattered in plane $\perp_{er}$ to electric vector(dir^n of the linear polarization).
- Photon's polarization direction -



With access to *photon polarization direction*, more operators are proposed*:

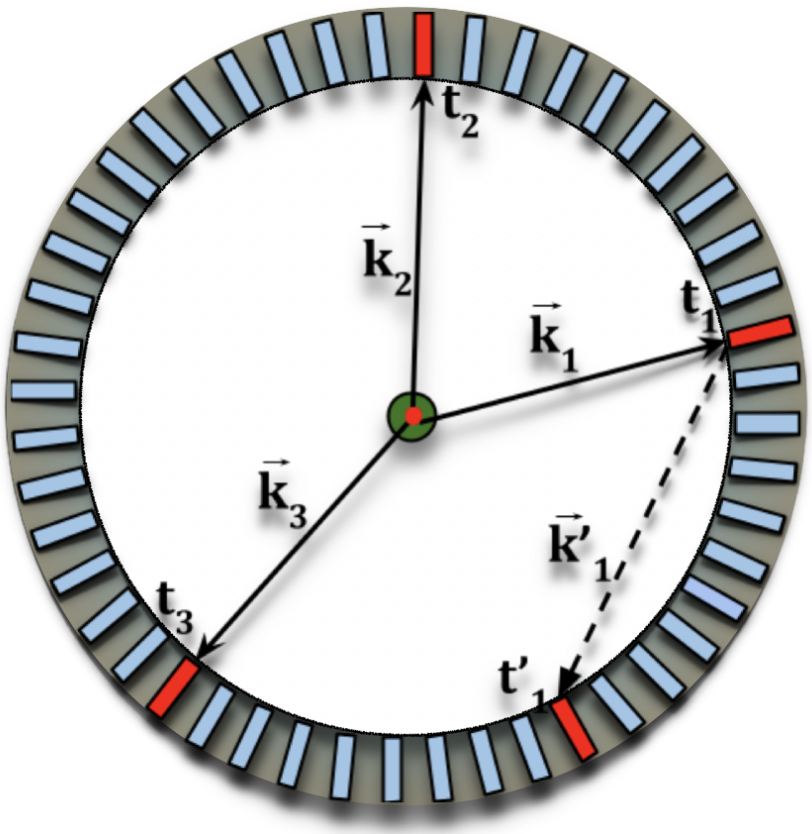
Table: Operators

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

*Acta Phys. Pol. B 47, 509(2016)

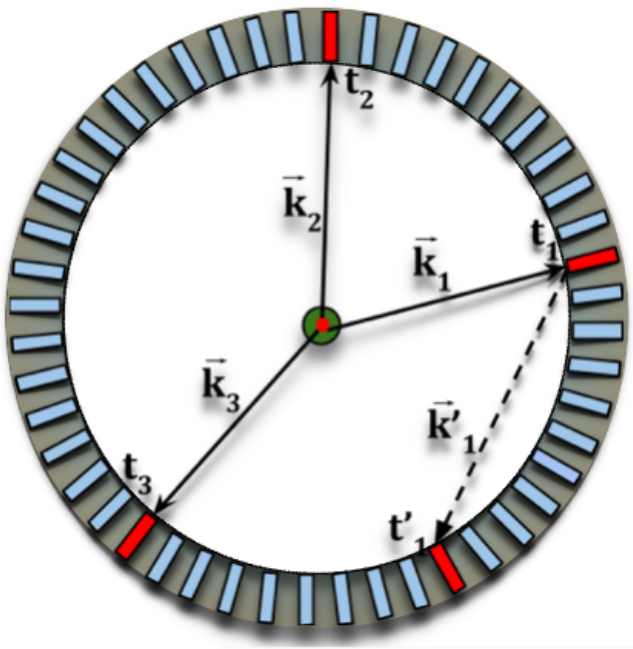
Tests on discrete symmetries using the photons' polarization

$(\vec{k}_2 \cdot \vec{\epsilon}_1)$

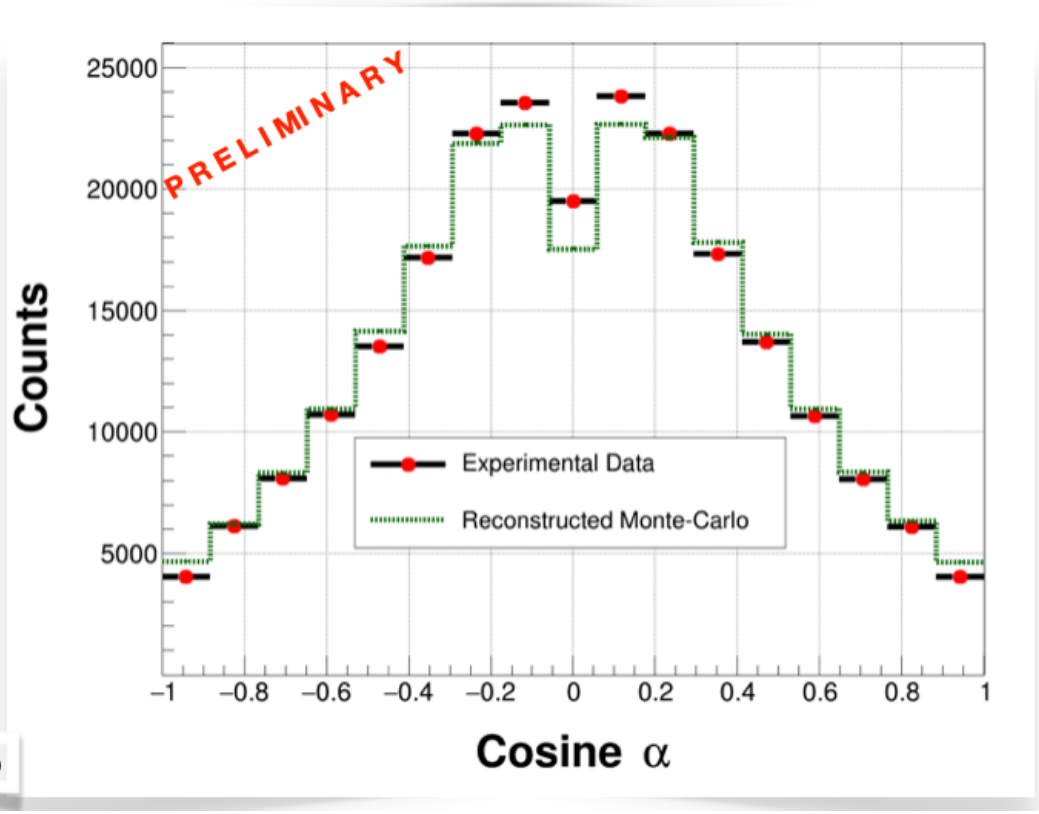


- Events with 4 hits are selected. Out of 4, 3 hits are by the o-Ps annihilation photons and and scattering of either of them.
- Scattered photon is associated with its primary based on the **scatter test**
- Photon polarization direction is estimated: $(\vec{\epsilon}_1 = \vec{k}_1 \times \vec{k}_{1'})$
- Calculate the expectation value of the operator $<\vec{k}_2 \cdot \vec{\epsilon}_1>$

Tests on discrete symmetries using the photons' polarization



Courtesy of J. Raj, PhD student in J-PET group



Expectation value = 3×10^{-4} +/- 0.0003(Stat)

Modular J-PET : *Portable tomograph (AFOV 50cm)*

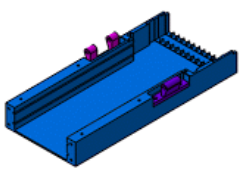


Figure: Digital J-PET

- Composed of **24 individual modules**

- Each module is made of **13** plastic scintillators (50 x 24 x 6 cm^3)
- Each side of scintillator is read out by **matrix of SiPMs**
- Modular construction allows to configure as **one layer** (24) or **multiple layers** (e.g., 8, 16 and thus requirement specific)
- Modules can be operated individually enabling to utilize as multi-role detector
- Easy to transport (full barrel around 60 kg)

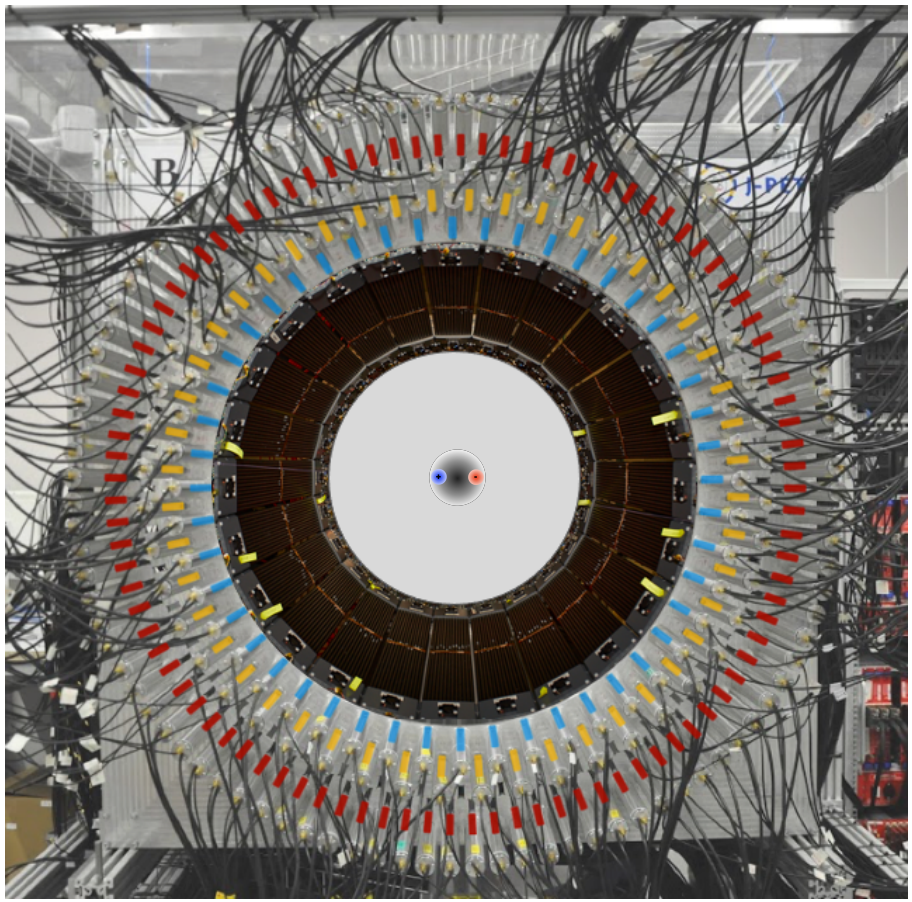


Figure: Modular + 3layers

- J-PET has potential to perform test of discrete symmetries.
- Modular prototype with AFOV 50 cm is already commisioned and started to collect the data as a standalone layer.
- 24 modules can be reconfigured in multiple layers and can be transported to use in other experimental facilities interested in the the detection of $\mathbf{e^+e^-}$ anni. in full phase space.
- **It is estimated that using the modular J-PET with 3 layers prototype will enhance the sensitivity by an order of magnitude.**

More details : http://koza.if.uj.edu.pl/