Review of physics program at J-PET

Eryk Czerwiński
on behalf of the J-PET Collaboration

MESON 2023
June 22nd

Outline

Subject of studies: positronium

Detector: J-PET

Covered topics:

Discrete symmetries: CPT, CP

Rare decays:

Search for Dark Matter

Test of nrQED

Entanglement of annihilation photons

Dalitz plot (test of C symmetry)

...

Positronium (Ps)

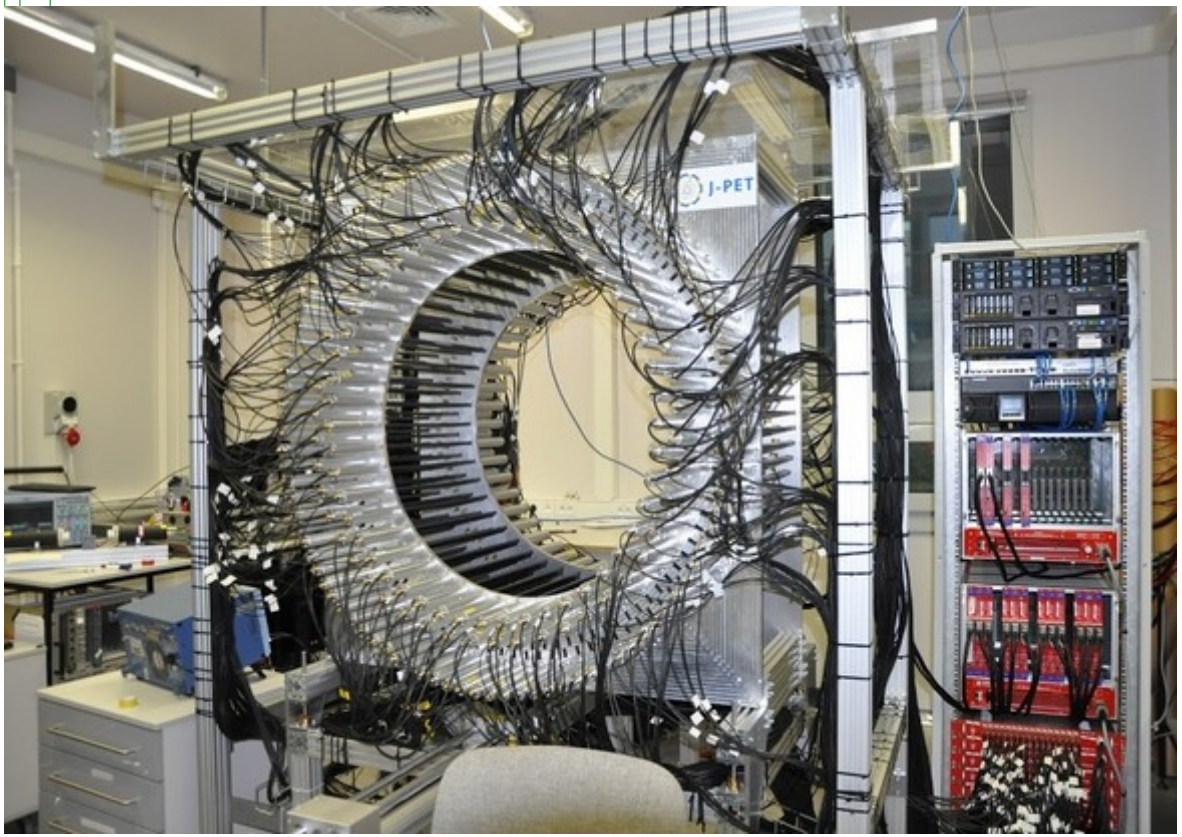
para-positronium (p-Ps)	↑↓	$2n\gamma$	CP = +1	$\tau \approx 0.125$ ns
ortho-positronium (o-Ps)	↑↑	$(2n+1)\gamma$	CP = -1	$\tau \approx 142$ ns

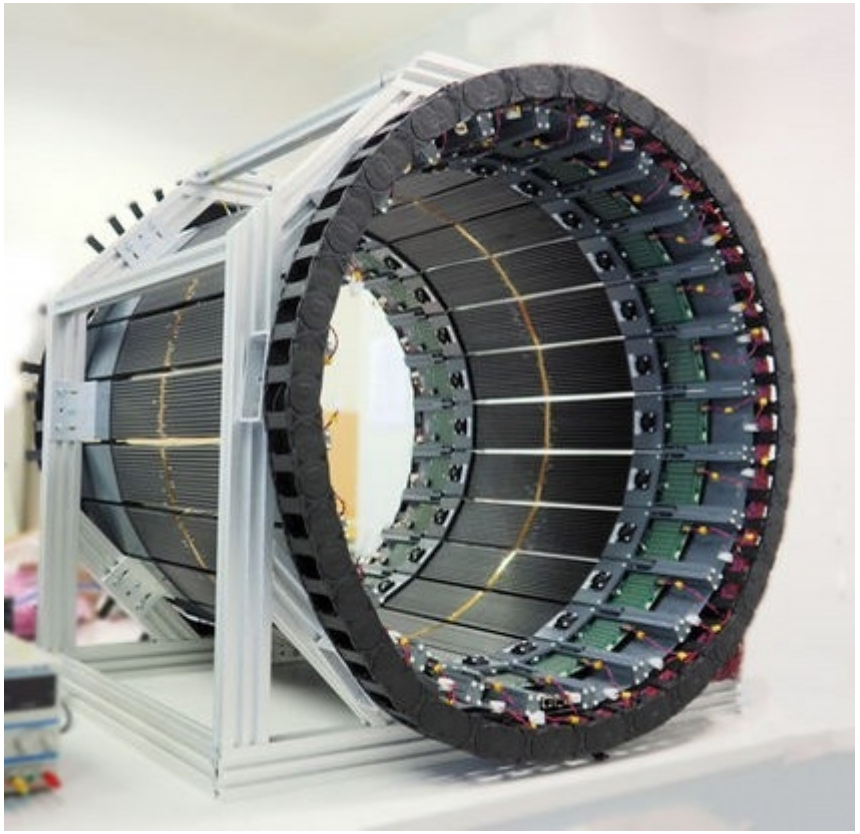
- purely leptonic (e+e-) bound state
- C, P, CP operators and $\mathcal{H}$ eigenstate
- the lightest atom
- undergoes self-annihilation
- e+ and e- do not decay into lighter particles via weak interaction, 10^{-14} violation level due to the weak interaction

  [M. Sozzi, Discrete Symmetries and CP Violation, Oxford University Press (2008)]
- no charged particles in the final state ($2*10^{-10}$ radiative corrections)

Jagiellonian PET

First PET from plastic scintillators

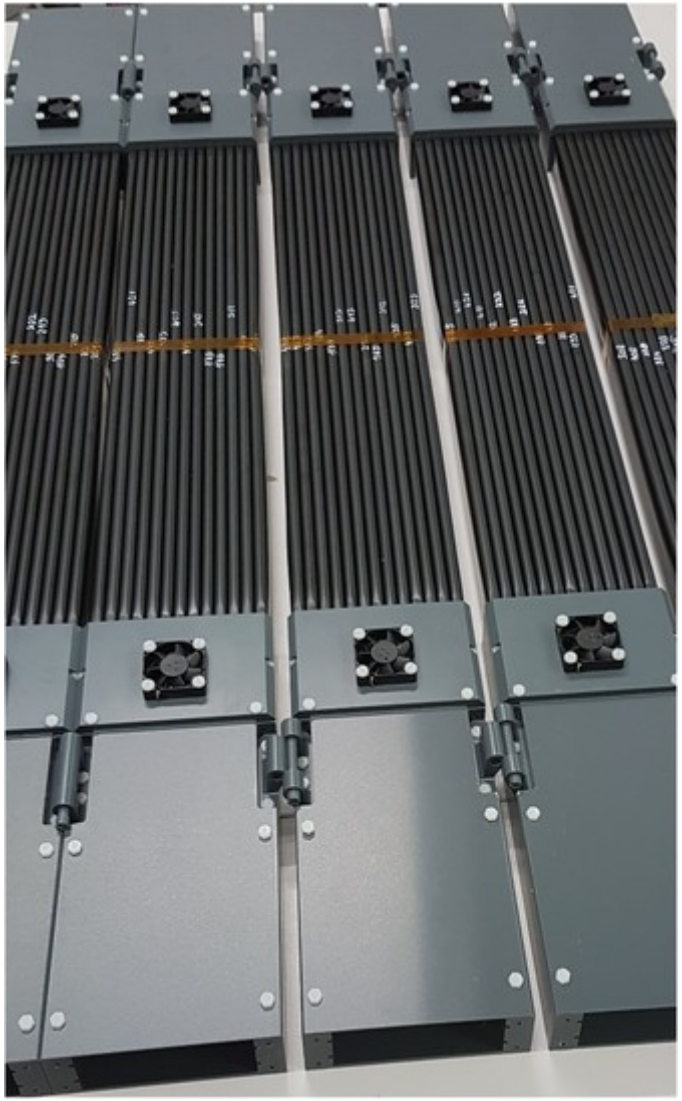


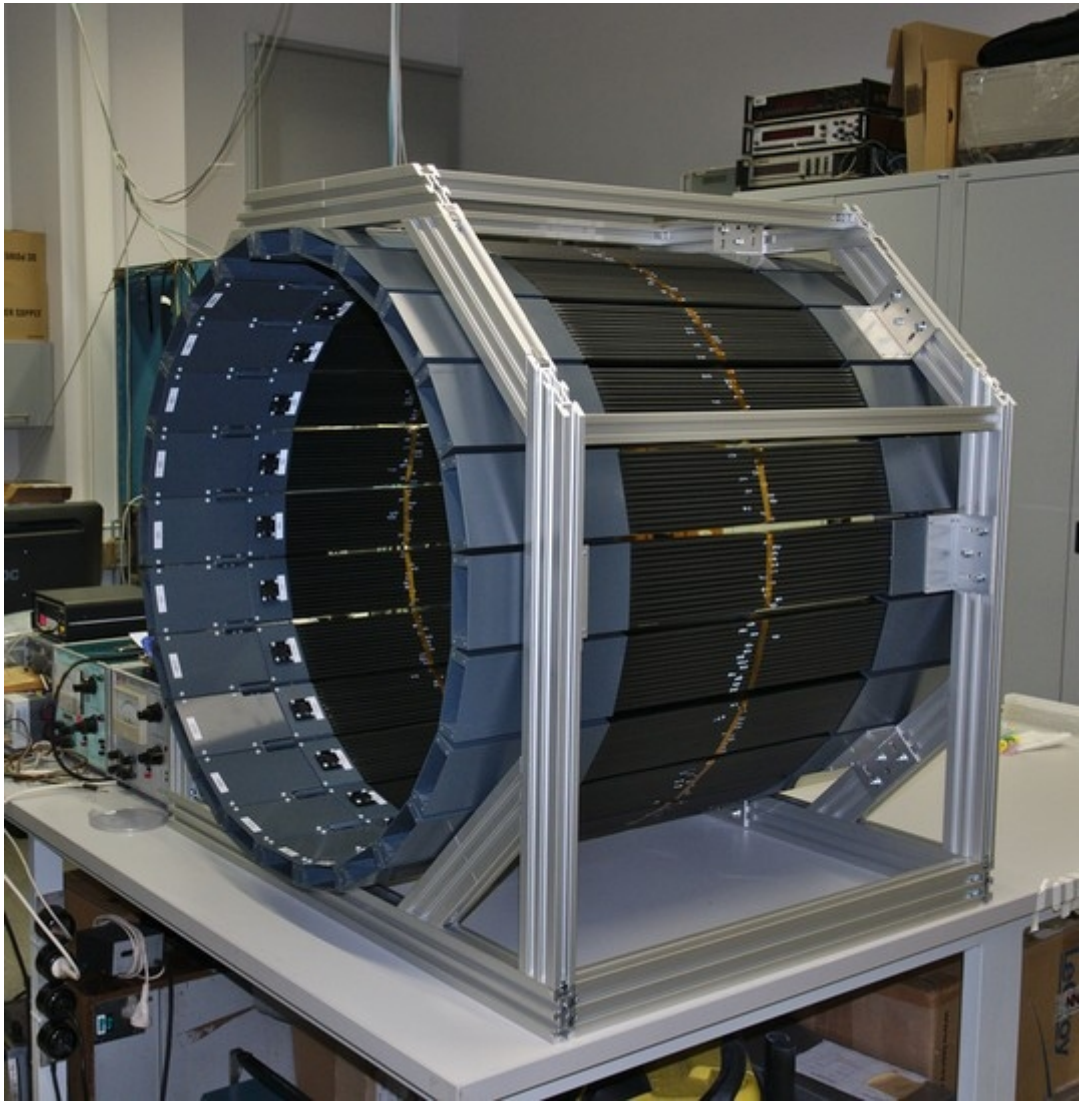


2016, 192 plastic strips, PMT

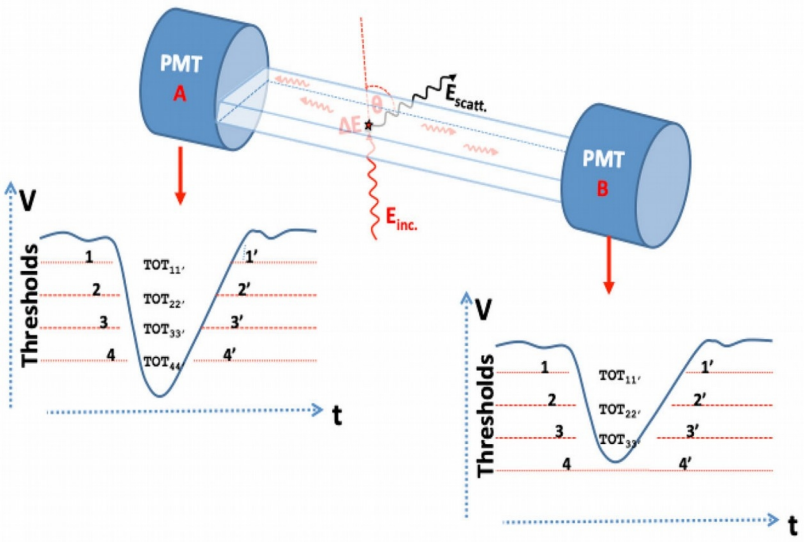
2019, 312 plastic strips, SiPM

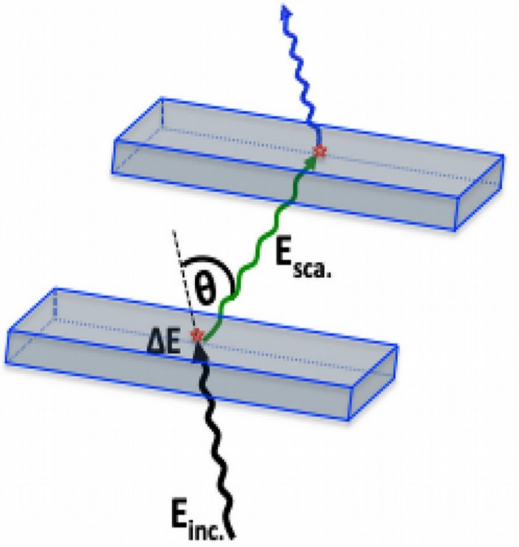
Modular J-PET

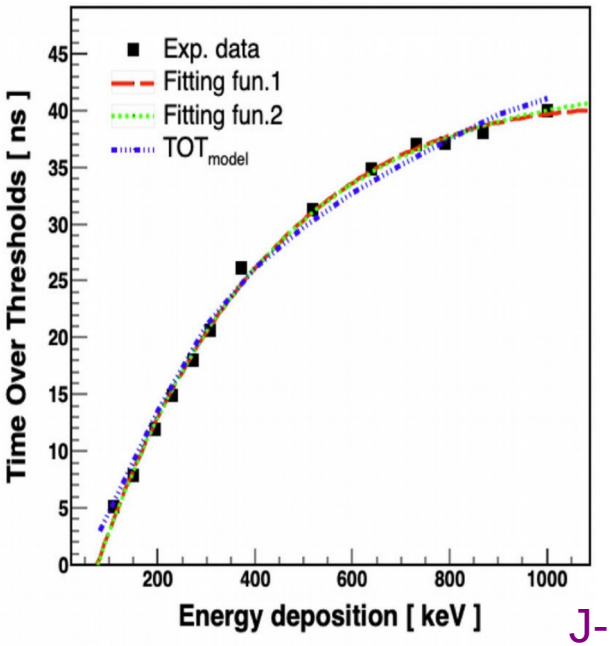


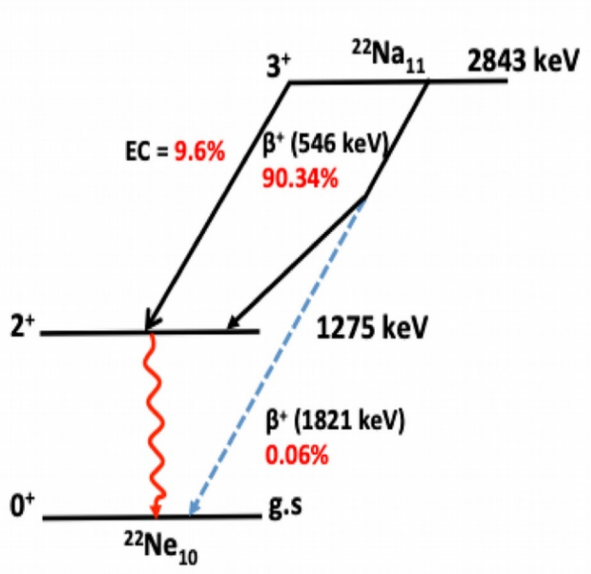


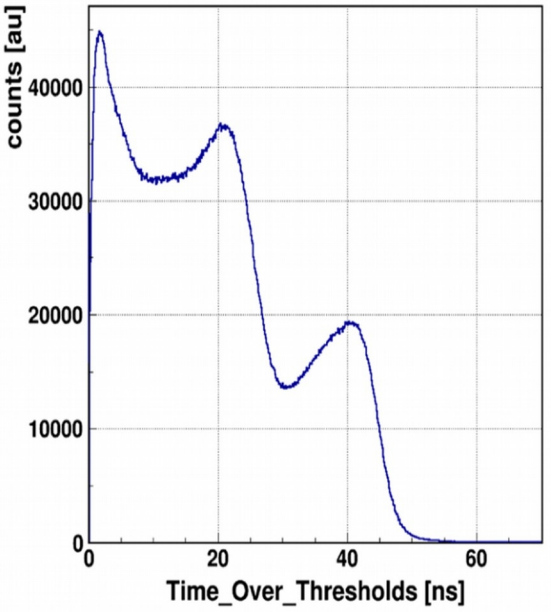
TOT for energy mesurement





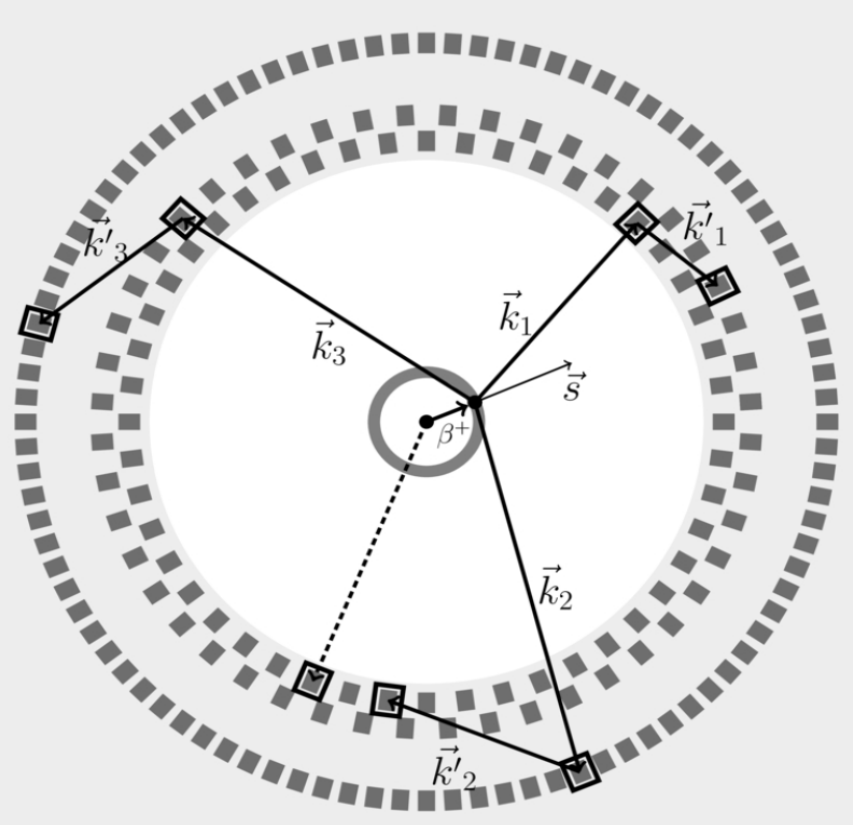


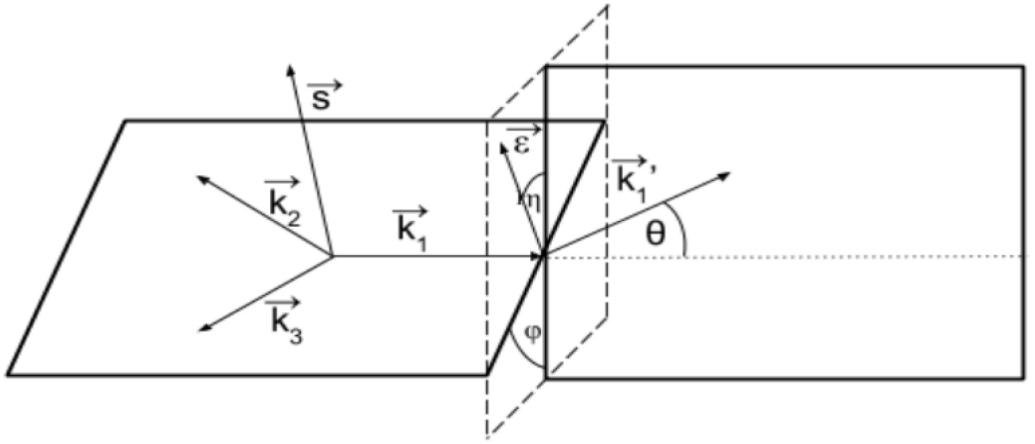




J-PET: EJNMMI Phys. 7, 39 (2020)
J-PET: EJNMMI Phys. 10(28) (2023)

Determination of polarization of anihilation γ





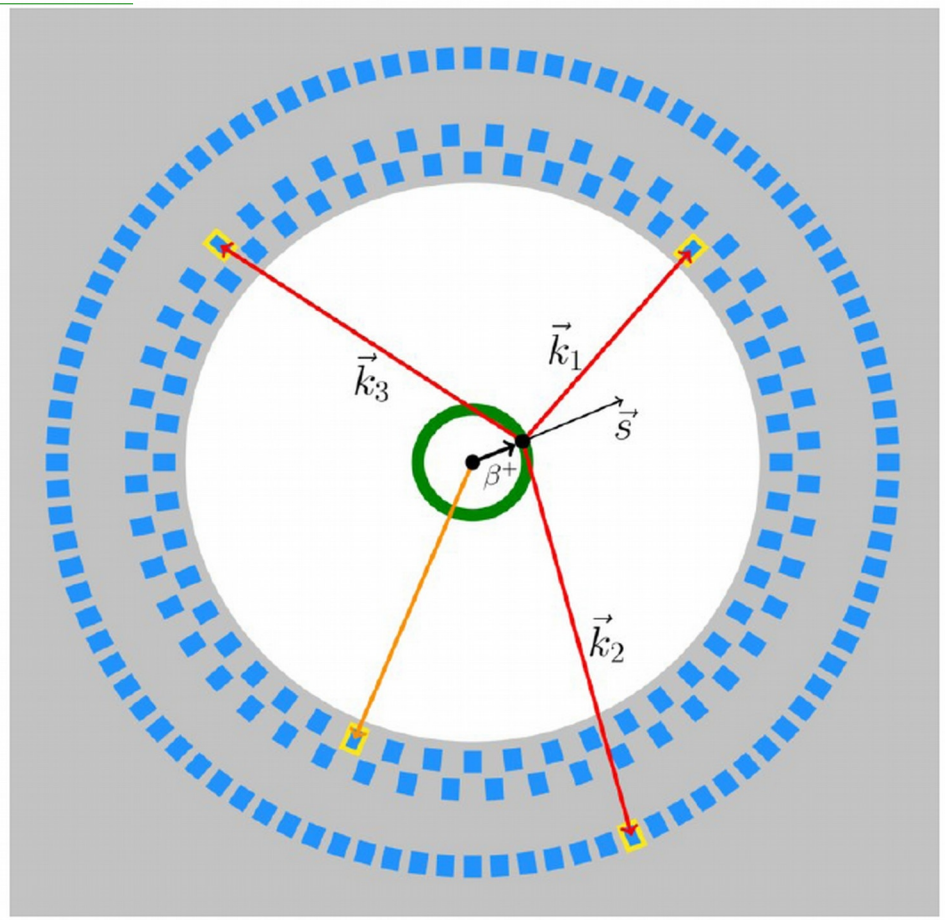
$$\frac{d\sigma}{d\Omega}(E,\theta,\eta) = \frac{r_0^2}{2}\left(\frac{E'}{E}\right)^2\left(\frac{E}{E'}+\frac{E'}{E}-2\sin^2\theta\cos^2\eta\right)$$

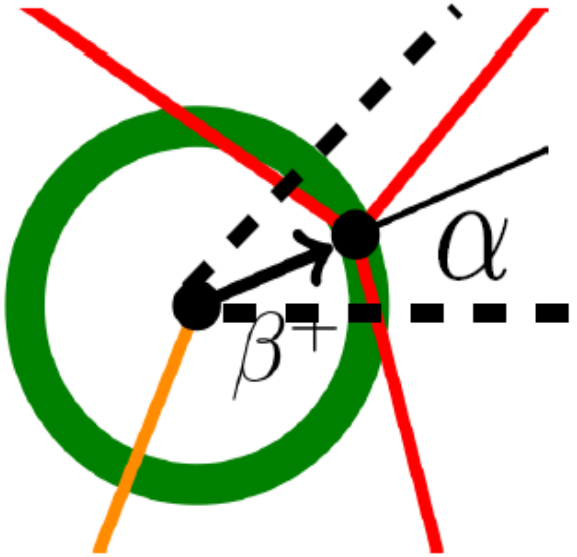
$$E'(E,\theta) = \frac{E}{1+\frac{E}{m_e c^2}(1-cos\theta)}$$

For a given scattering angle θ, cross-section is maximum for η = π/2 angle.

J-PET: P. Moskal et al., Acta Phys. Polon. B 47 (2016) 509
J-PET: P. Moskal et al., Eur. Phys. J. C78 (2018) 970

Determination of o-Ps polarization

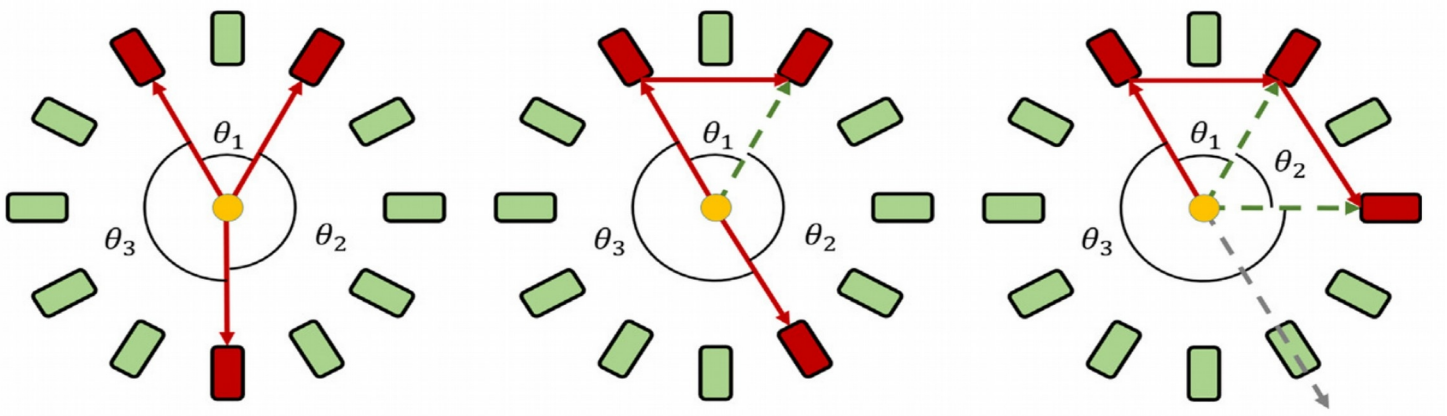


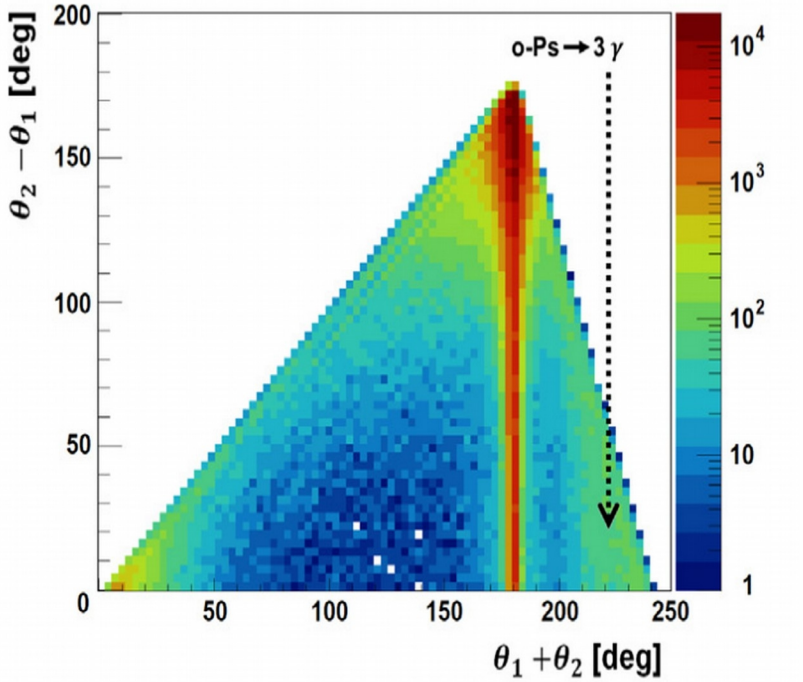


$$P = \frac{v}{c}(1 + \cos\alpha)/2$$

J.PET: A. Gajos al., Nucl. Inst. and Meth. A819 (2016) 54-59
J-PET: P. Moskal et al., Acta Phys. Polon. B 47 (2016) 509

o-Ps detection





J-PET: K. Dulski et al., NIM A 1008 (2021) 165452

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Discrete symmetries

Discrete symmetries are scarcely tested with leptonic systems

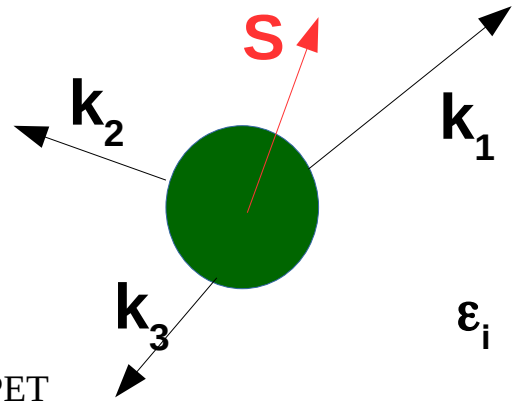
- Prominent results from neutrinos oscillation experiments
  Dirac phase, δ_{CP} ~3σ level [T2K, Nature 580 (2020) 339]
- Electron EDM < 1.1x10 $^{-29}$ [ACME, Nature 562 (2018) 355]

Positronium – the lightest purely leptonic bound state, the only system consisting of charged leptons used for tests of CP and CPT to date.

Possible tests of discrete symmetries in the positronium system:

- Searches for prohibited positronium annihilations
  [A.P. Mills and S. Berko, Phys. Rev. Lett. 18 (1967) 420]
- SME-based searches for CPT violation proposed with positronium spectroscopy
  [V. A. Kostelecký and A.J. Vargas, Phys. Rev. D92 (2015) 056002]
- Searches for non-vanishing symmetry-odd correlations (in use at J-PET)

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

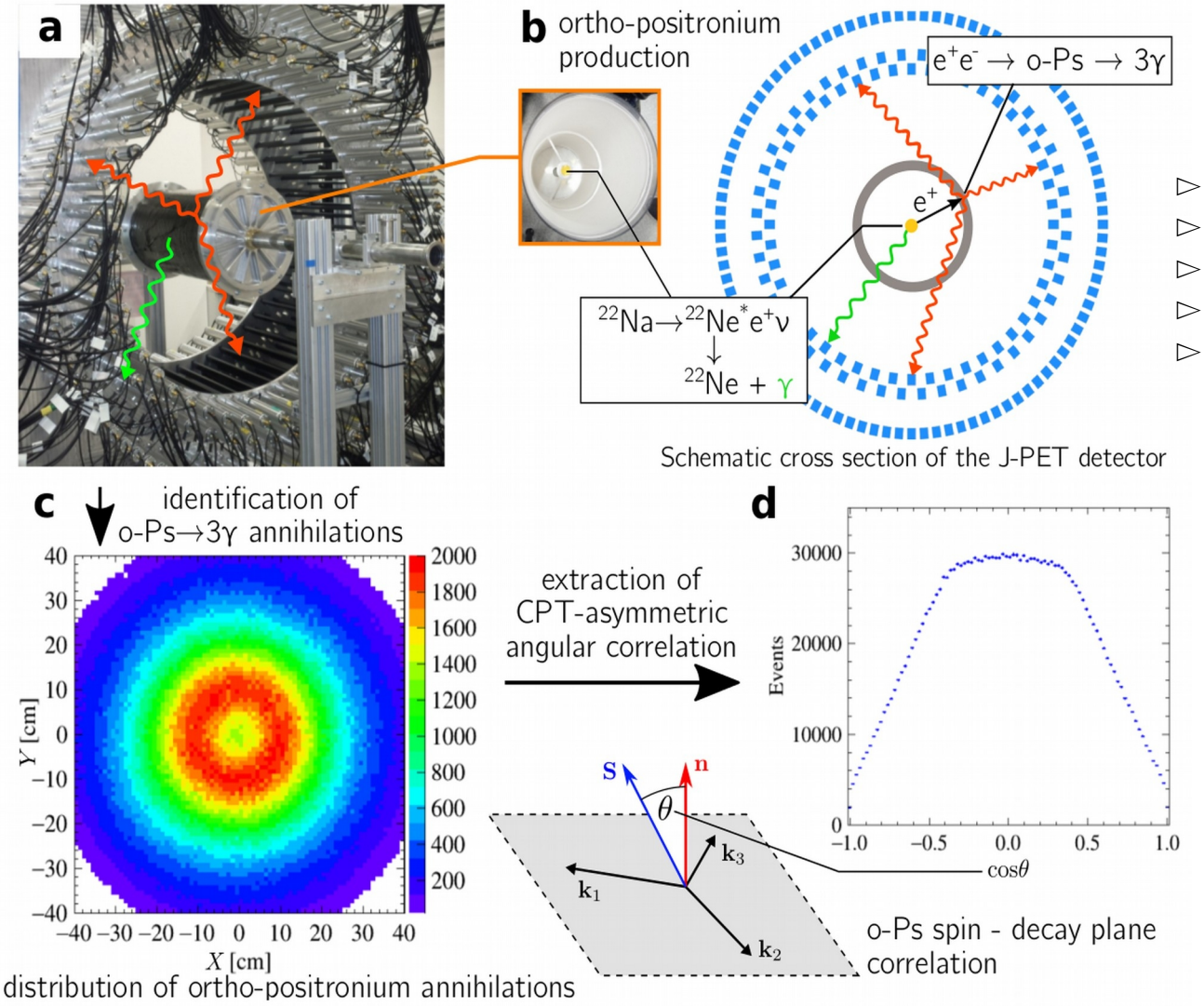


$k_1 > k_2 > k_3$

$\varepsilon_i = k_i \times k'_i$

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

CPT symmetry test



Selection criteria for 26 days measurement:

- TOT and hit time widows
- rejection of secondary Compton scatterings
- cut on LOR, sum of 2D and 3D angles
- total effective polarisation 37.4 %
- 7.3×10^6 event candidates

$\langle O_{CPT} \rangle = 0.00025 \pm 0.00036$

$C_{CPT} = \langle O_{CPT} \rangle / P = 0.00067 \pm 0.00095$

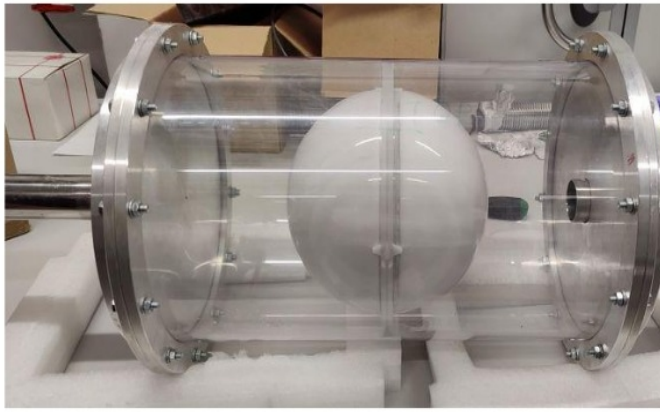
J-PET: P. Moskal et al.,
Nature Communications 12 (2021) 5658

$C_{CPT} = \langle \mathbf{S} \cdot (\mathbf{k_1} \times \mathbf{k_2}) \rangle = 0.0026 \pm 0.0031$

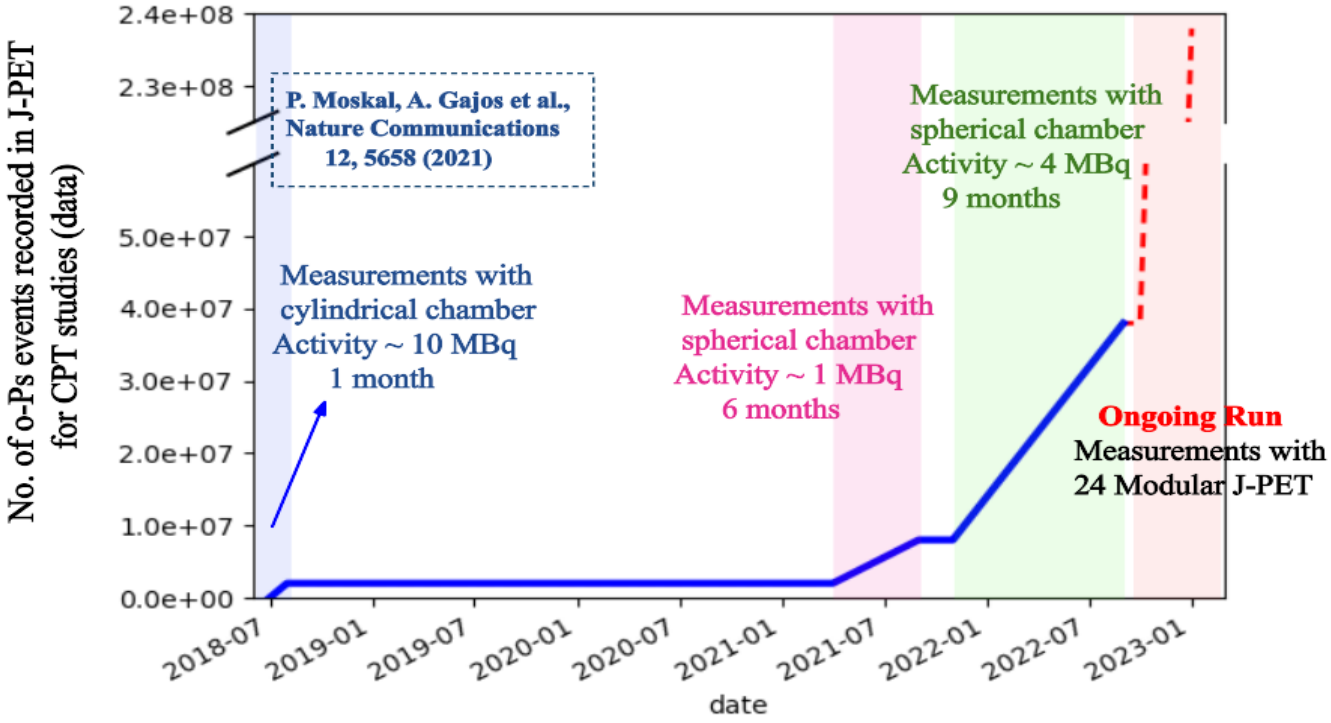
[P.A. Vetter, S.J. Freedman,
Phys. Rev. Lett. 91 (2003) 263401]

CPT test – next generation

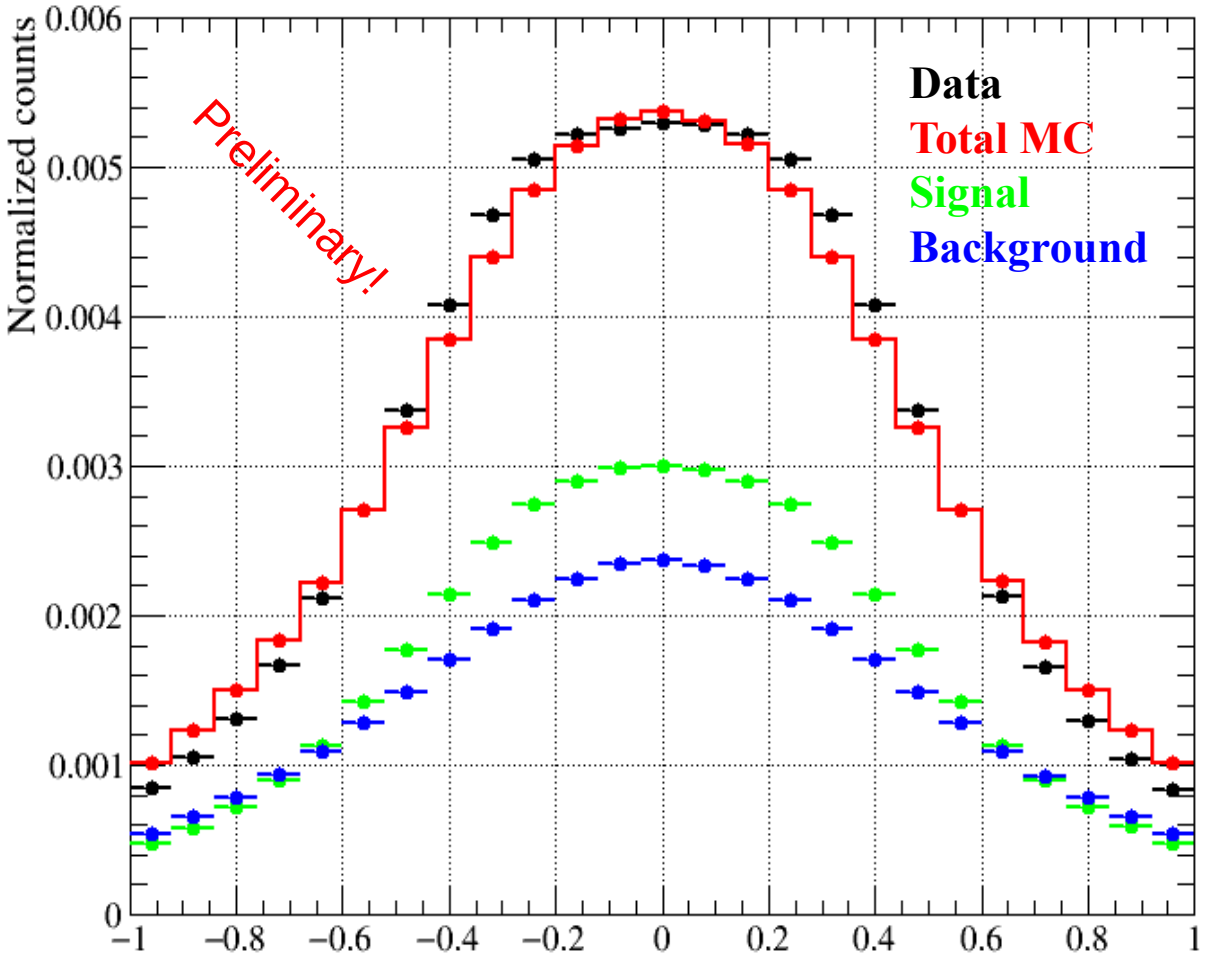
26 days → 9 months and still ongoing
10 MBq → 4 MBq of source activity
cylindrical → spherical annihilation chamber



Setup of annihilation chamber



CPT test – next generation



► The angular distribution between Spin and annihilation plane orientation of selected o-Ps event.

► Plot for 2.8 x 10^6 identified o-Ps$\rightarrow 3\gamma$ events in data.

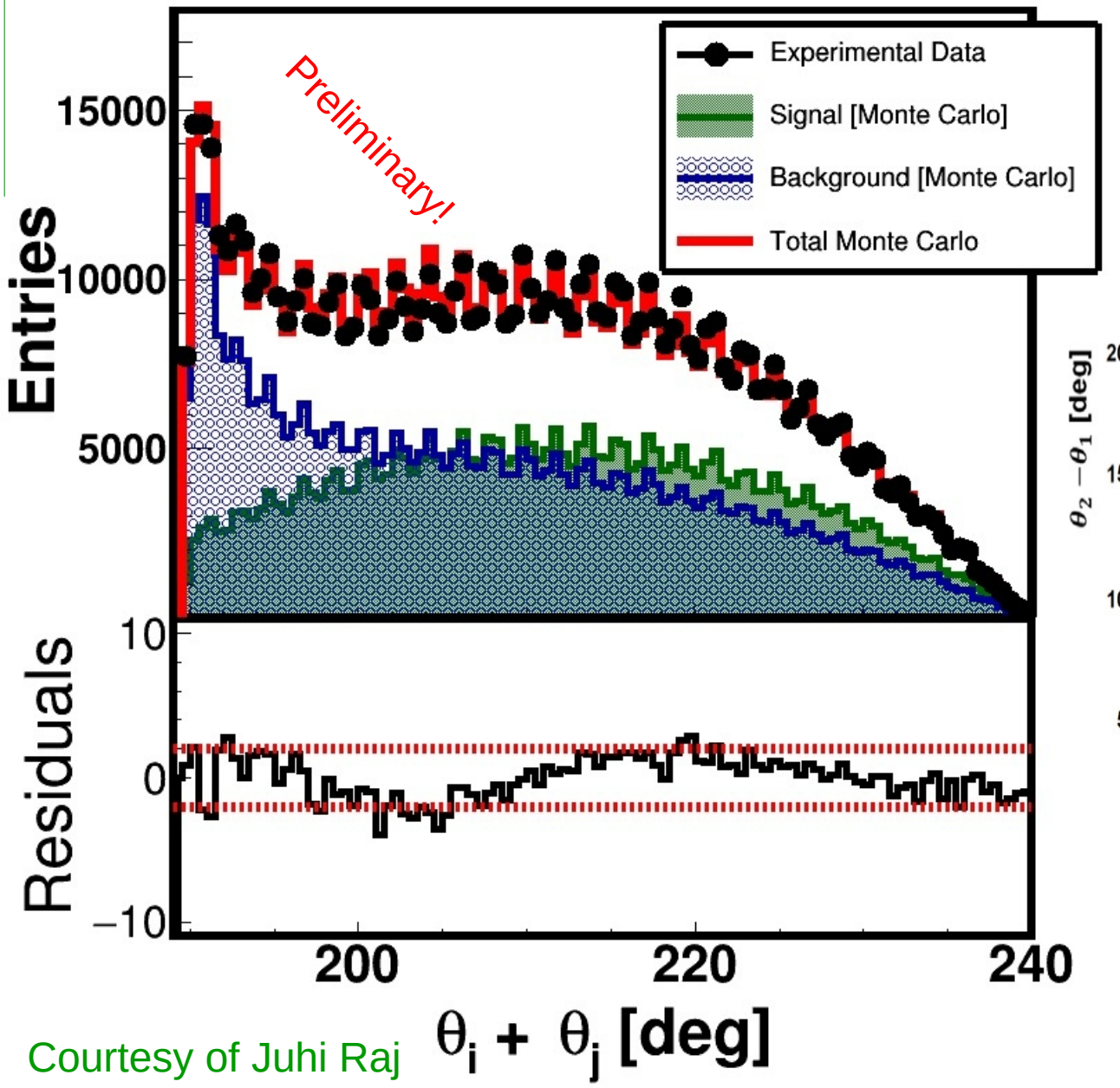
► Signal and Background is normalized to Total Monte Carlo.

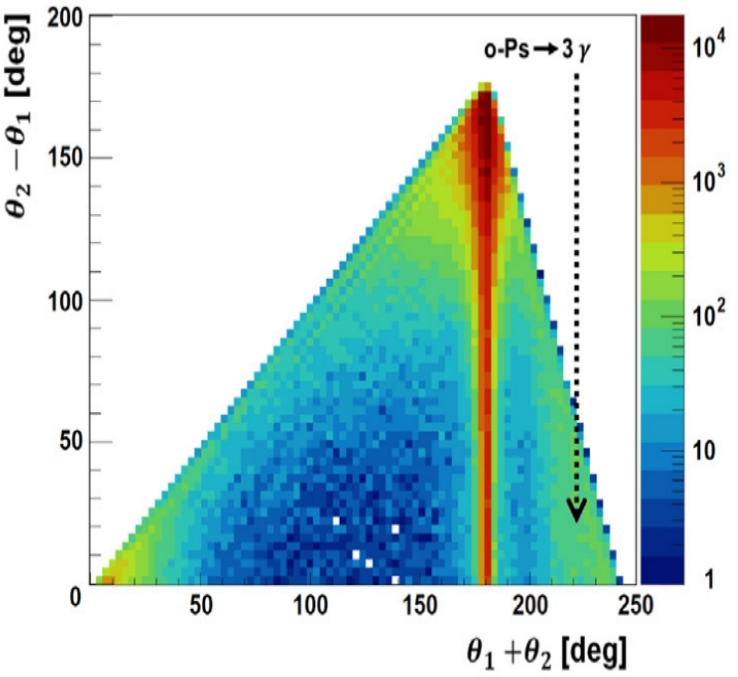
► Presented data results is from 30% of the data collected for CPT symmetry test with J-PET and spherical annihilation chamber.

$$O_{CPT} = \hat{S}.\frac{(k_1 \times k_2)}{|\vec{k_1} \times \vec{k_2}|} = cos\theta$$

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

CP, P, T symmetry test

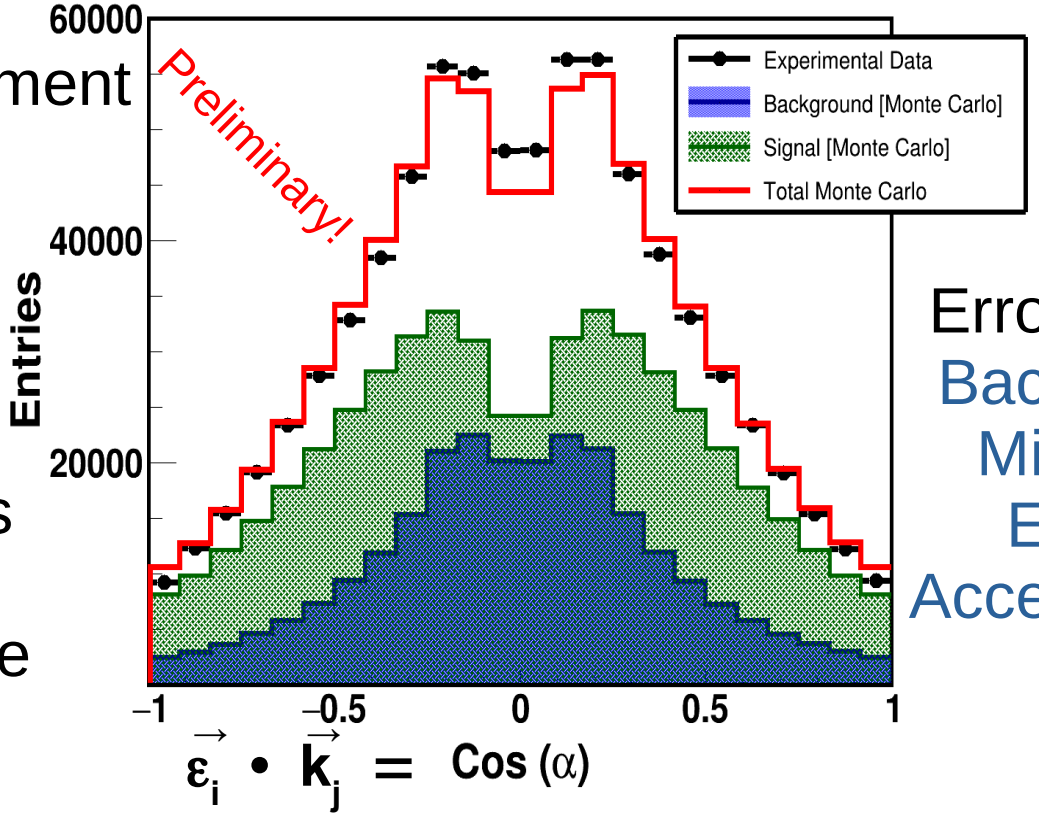




Courtesy of Juhi Raj

CP, P, T symmetry test

122 days of measurement
Selection based on:
- hit position
- TOT
- sum of 3D angles
- emission time of annihilation gammas
- distance of the annihilation plane



Error Composition:
Background = 6 %
Miss-Reco = 2 %
Efficiency = 2 %
Acceptance = 14 %
Data = 76 %

J-PET: $C_{CP} = \langle\, \varepsilon_i \cdot \mathbf{k}_j \,\rangle = 0.0005 \pm 0.0007_{stat}$ syst. error negligible

Preliminary!

$$C_{CP} = \langle\, (\mathbf{S} \cdot \mathbf{k}_1)(\mathbf{S} \cdot (\mathbf{k}_1 \times \mathbf{k}_2)) \,\rangle = 0.0013 \pm 0.0022$$

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

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Search for Dark Matter

Mirror Matter was proposed as an explanation of Parity symmetry violation
[T.D., Yang C. N. Phys. Rev. 1956. V. 104. P. 254.]

Each particle has a mirror partner with the same properties and opposite chirality (left/right – handed).

Mirror particles interact with normal matter mainly through gravity → Dark Matter candidates

See talk of Elena Perez del Rio, session A7, 26 Jun 2023, 17:50
Dark Matter and rare decay searches of the ortho-Positronium with the J-PET detector

$$\Gamma(\text{o-Ps} \to 3\gamma, 5\gamma) = \frac{2\left(\pi^2 - 9\right)\alpha^6 m_e}{9\pi}\left[1 + A\frac{\alpha}{\pi} + \frac{\alpha^2}{3}\ln\alpha + B\left(\frac{\alpha}{\pi}\right)^2 - \frac{3\alpha^3}{2\pi}\ln^2\alpha + C\frac{\alpha^3}{\pi}\ln\alpha + D\left(\frac{\alpha}{\pi}\right)^3 + \ldots\right]$$

$$\Gamma = 7.039979(11) \times 10^6\,\mathrm{s}^{-1}$$

[S.D. Bass, Acta Phys. Pol. B 50, 1319 (2019)]

$$\Gamma = 7.0401 \pm 0.0007 \times 10^6\,\mathrm{s}^{-1}$$

[Y. Kataoka, S. Asai, T. Kobayashi, Phys. Lett. B671, 219 (2009)]

$$\Gamma = 7.0404 \pm 0.0010 \pm 0.0008 \times 10^6\,\mathrm{s}^{-1}$$

[R.S. Vallery, P.W. Zitzewitz, D.W. Gidley, Phys. Rev. Lett.90, 203402(2003).]

Theory predictions 100 times more precise.

Courtesy of Elena Perez del Rio

Test of nrQED

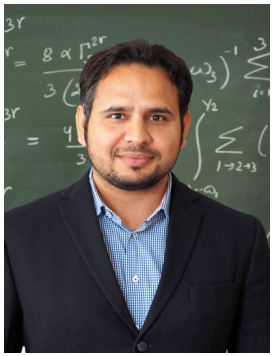
► Accurate measurement of the decay rate of Ps atoms is the rigorous test for validating the QED.

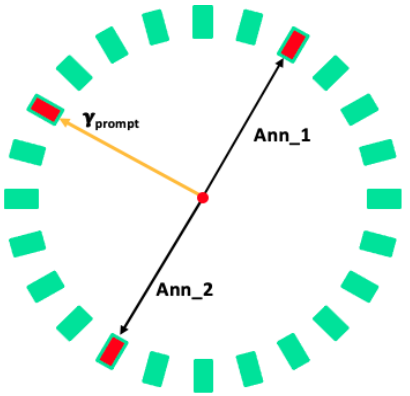
► The decay rate of o-Ps can be calculated exactly with the help of the formalism of non-relativistic QED (nrQED).

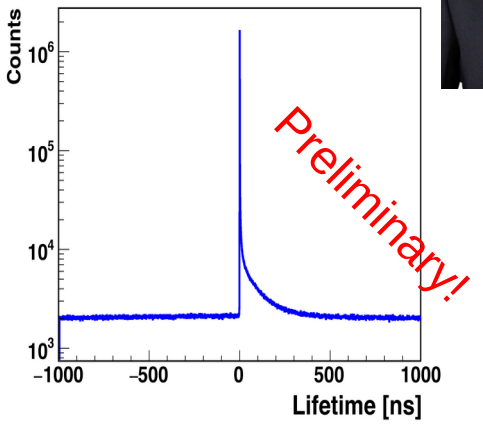
► It can be affected by several factors, such as the properties of bound state wavefunction, electromagnetic coupling, and relativistic corrections.

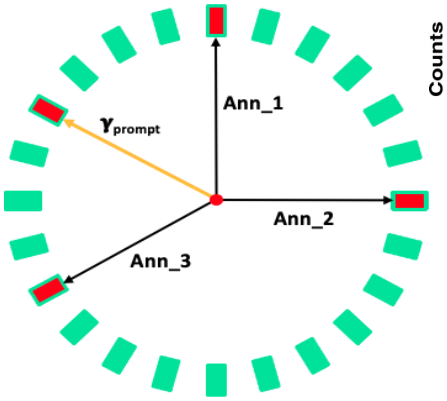
► Our goal is to measure the decay rate using the J- PET detector and to test the nrQED predictions.

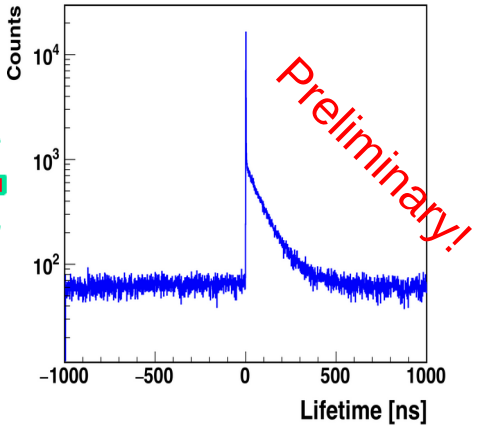
See talk of Sushil Sharma,
session A3, 23 Jun 2023, 16:00
Test for non-relativistic QED in decays of Positronium atoms











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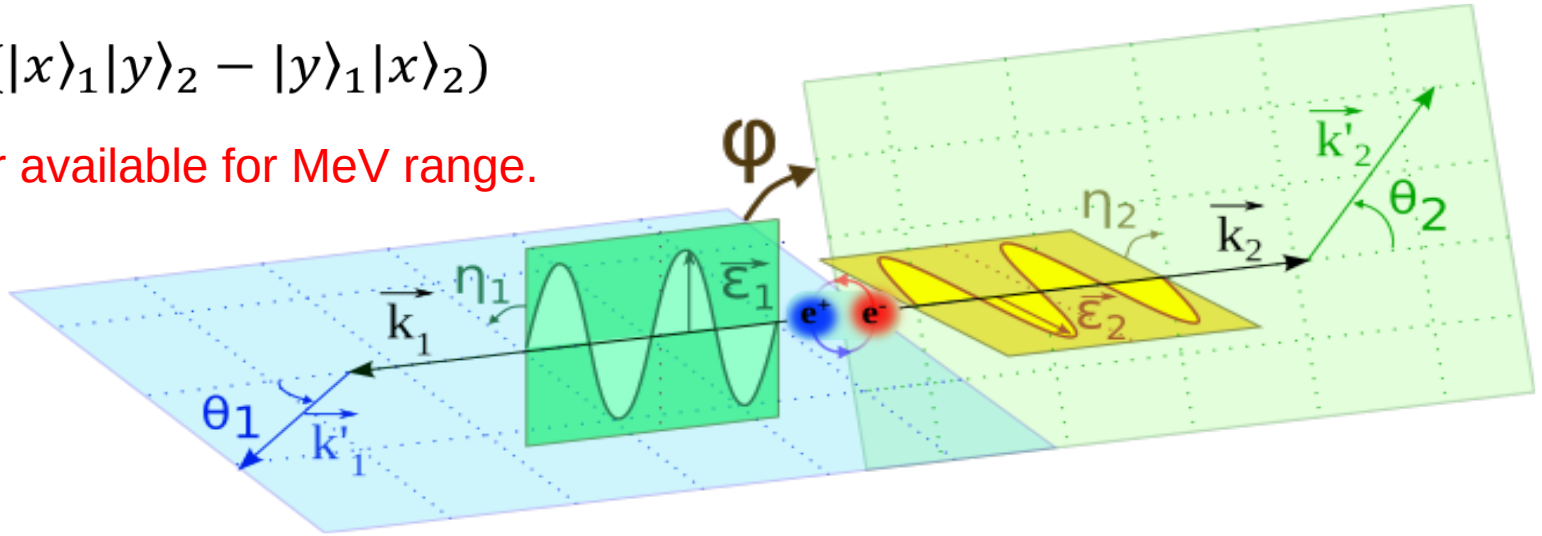
Entanglement of annihilation photons

State vector of annihilation photons emitting with entangled polarization (**orthogonal**)

$$\Psi = \frac{1}{\sqrt{2}} \left(|x\rangle_1 |y\rangle_2 - |y\rangle_1 |x\rangle_2\right)$$

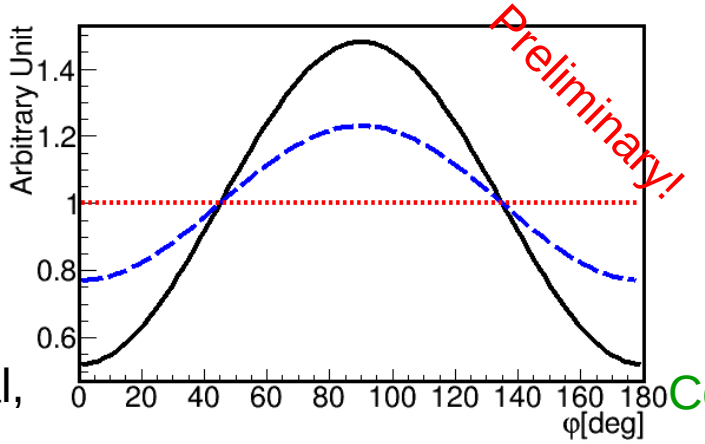
No polarizer available for MeV range.



$$\frac{d^2\sigma_{double}}{d\Omega_1\Omega_2} = \frac{r_0^4}{16}\left[\frac{\{(1-cos\theta_1)^3+2\}\{(1-cos\theta_2)^3+2\}}{(2-cos\theta_1)^3(2-cos\theta_2)^3} - \frac{sin^2\theta_1 sin^2\theta_2}{(2-cos\theta_1)^2(2-cos\theta_2)^2}\,\boldsymbol{cos(2\phi)}\right]$$

Assymetric ratio:

$$R = \frac{d\sigma_{\varphi=90}}{d\sigma_{\varphi=0}}$$



For $\theta_1 = \theta_2 = 81.7$

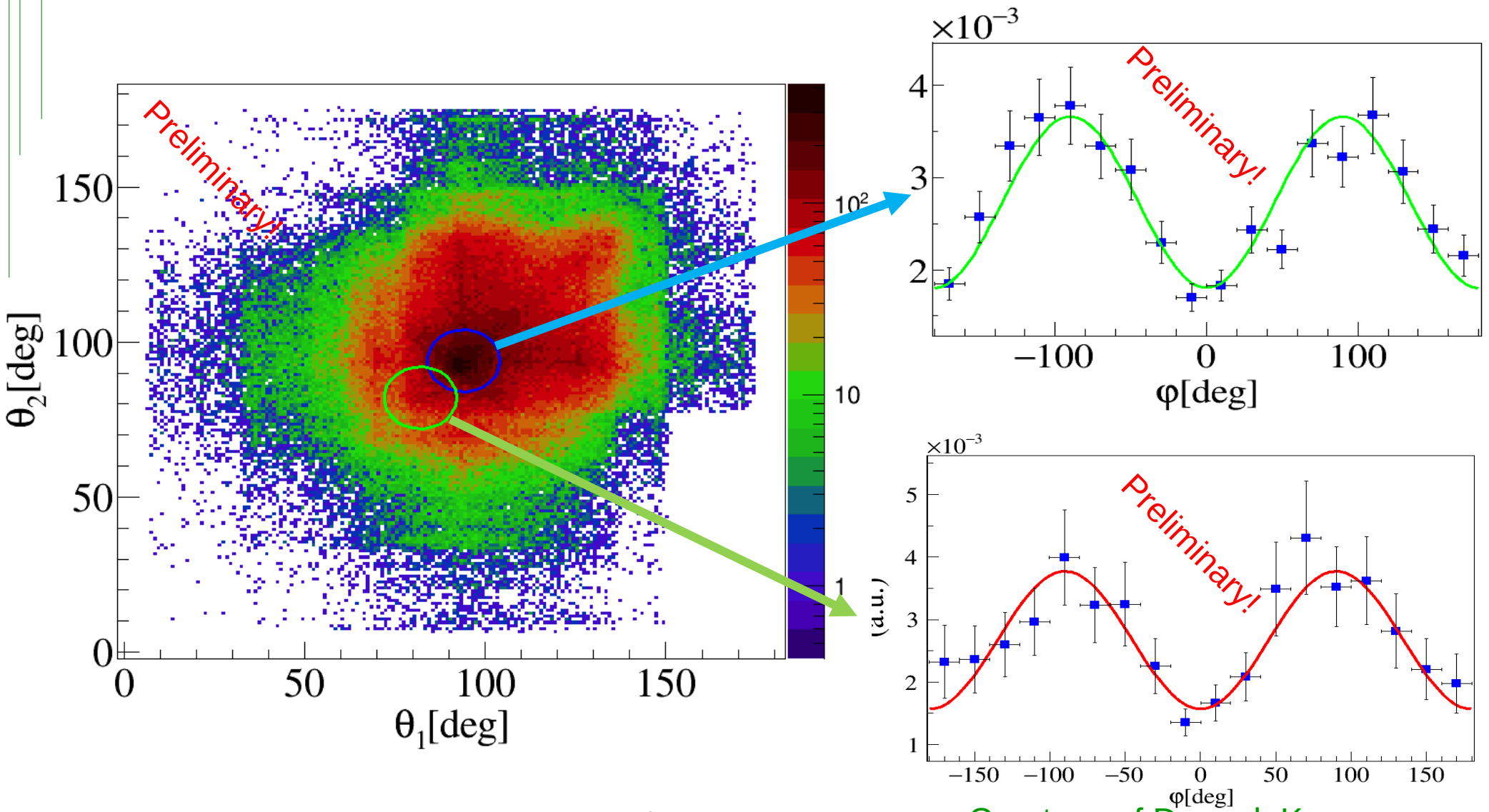
R = 2.85 for entangled state

R = 1.63 for separable state

Courtesy of Deepak Kumar

[S. Sharma, D. Kumar, P. Moskal, Acta Phys. Pol. 3 (2022) 142]

Entanglement of annihilation photons



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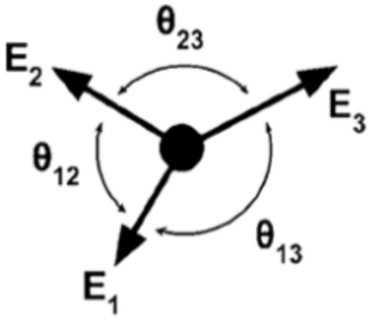
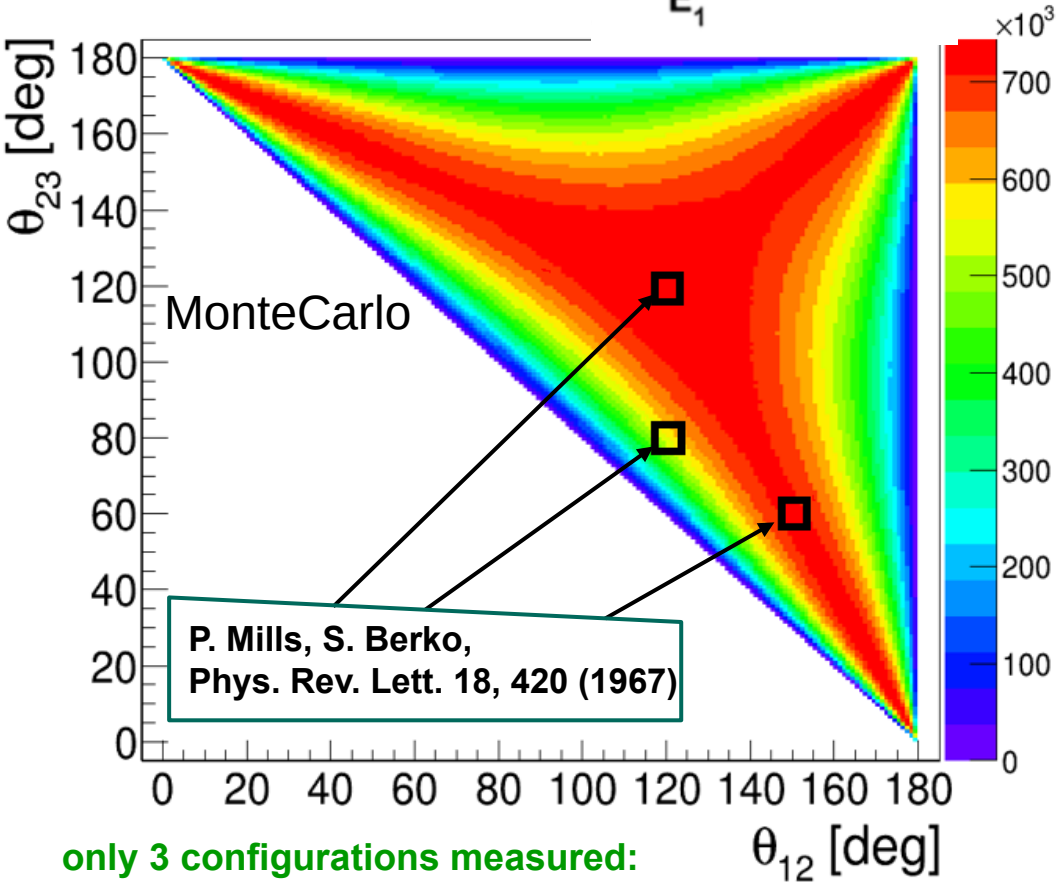
Dalitz plot

o-Ps $\rightarrow \gamma_1\gamma_2\gamma_3$





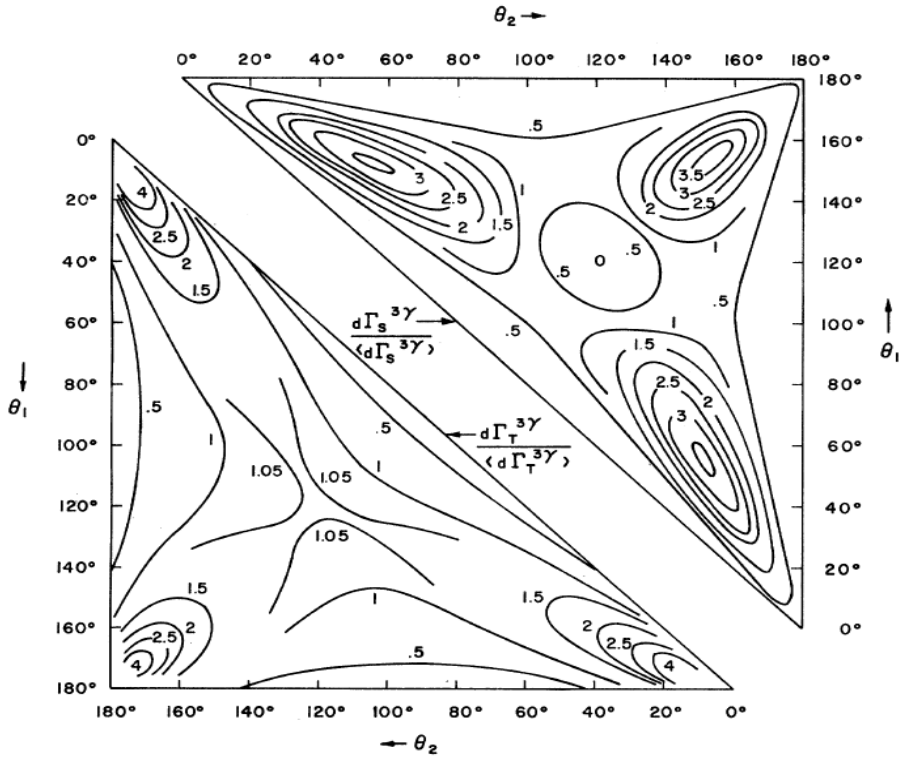
only 3 configurations measured:
120°,120°,120° , 60°,150°,150°
90°,120°,150°

$$\theta_{12} = cos^{-1}\left(\frac{p_3^2-p_1^2-p_2^2}{2p_1p_2}\right)$$
$$\theta_{23} = cos^{-1}\left(\frac{p_1^2-p_2^2-p_3^2}{2p_2p_3}\right)$$
$$\theta_{31} = cos^{-1}\left(\frac{p_2^2-p_1^2-p_3^2}{2p_1p_3}\right)$$

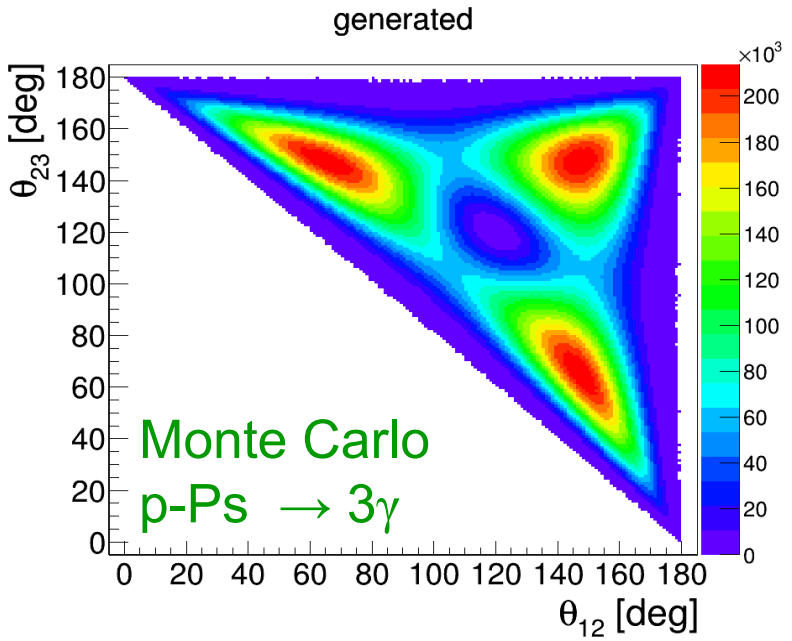
$$E_1 = -2m_e\frac{-\cos\theta_{13}+\cos\theta_{12}\cos\theta_{23}}{(-1+\cos\theta_{12})(1+\cos\theta_{12}-\cos\theta_{13}-\cos\theta_{23})},$$
$$E_2 = -2m_e\frac{\cos\theta_{12}\cos\theta_{13}-\cos\theta_{23}}{(-1+\cos\theta_{12})(1+\cos\theta_{12}-\cos\theta_{13}-\cos\theta_{23})},$$
$$E_3 = 2m_e\frac{1+\cos\theta_{12}}{1+\cos\theta_{12}-\cos\theta_{13}-\cos\theta_{23}}.$$

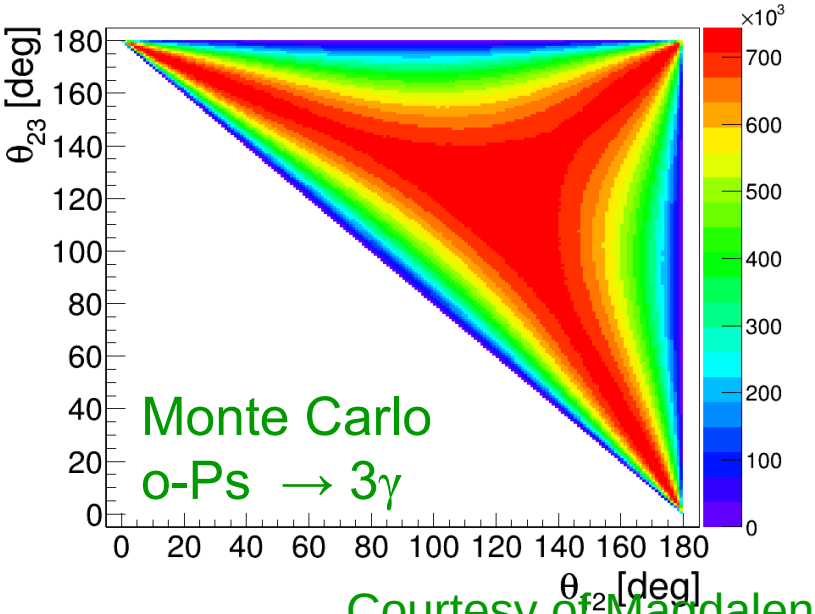
Courtesy of Magdalena Skurzok

Dalitz plot



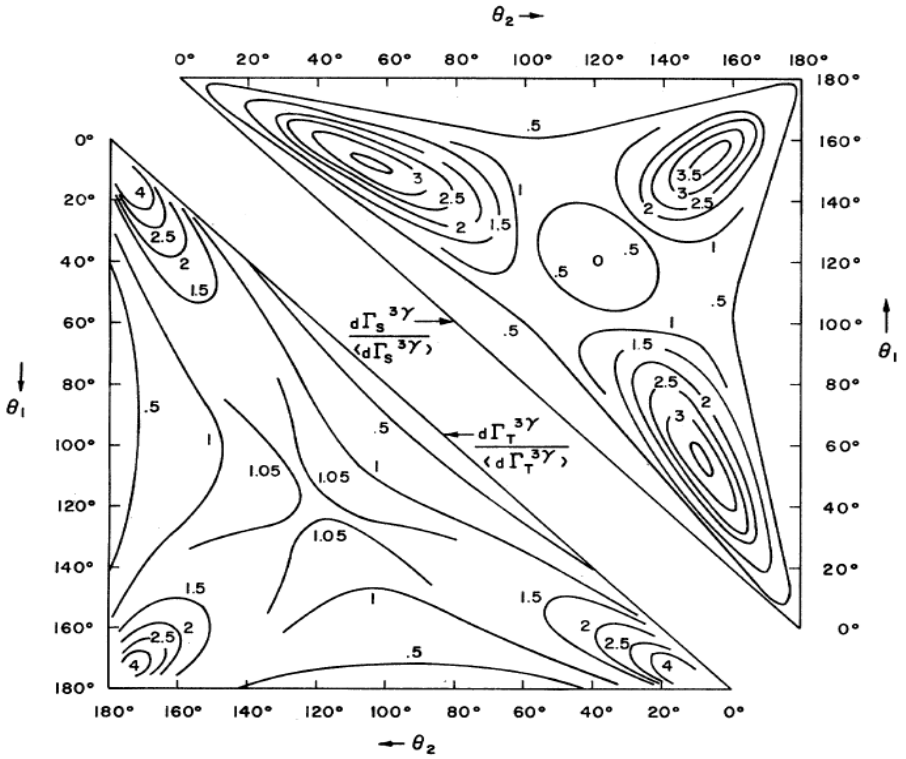
P. Mills, S. Berko,
Phys. Rev. Lett. 18, 420 (1967)



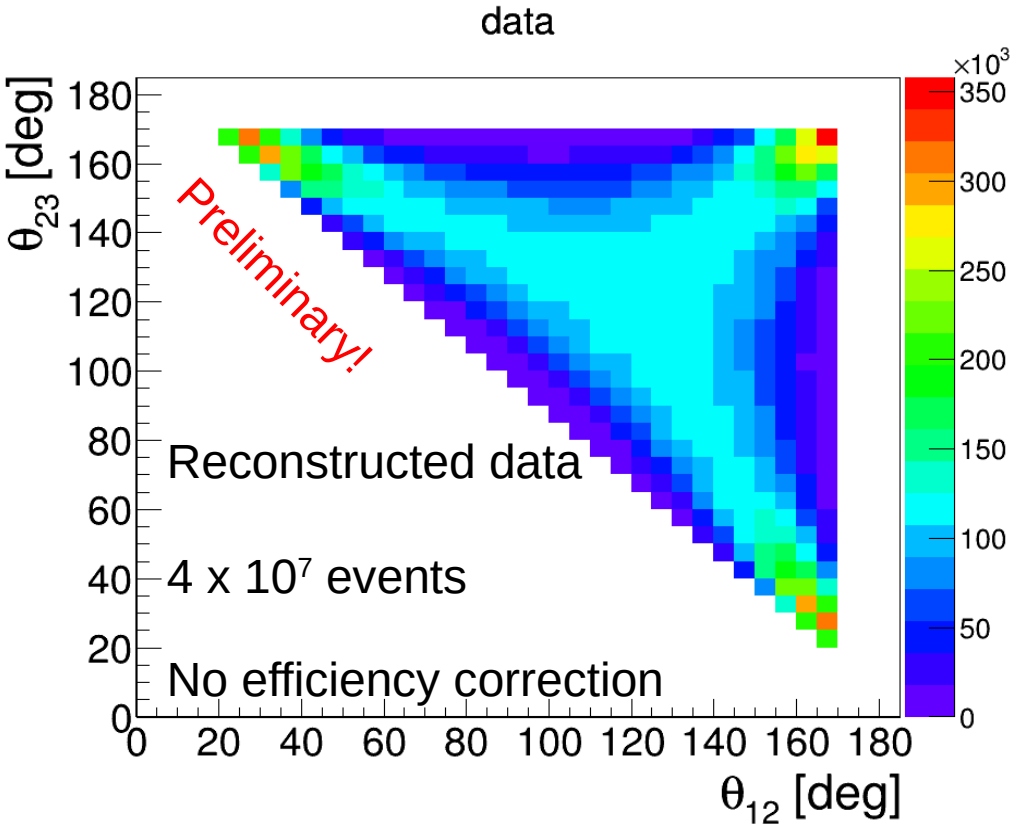


Courtesy of Magdalena Skurzok

Dalitz plot



P. Mills, S. Berko,
Phys. Rev. Lett. 18, 420 (1967)



$BR(p\text{-}Ps \rightarrow 3\gamma)/BR(p\text{-}Ps \rightarrow 2\gamma) < 2.8 \times 10^{-6}$

Courtesy of Magdalena Skurzok

Summary

- Studies with positronium decays allow for broad range of physics research.

- J-PET detector determines o-Ps spin direction and polarization of annihilation γ on the event by event basis.

- Efficiency and acceptance of J-PET are non-zero for the whole phase-space of operators sensitive to P, T, CP and CPT symmetry violations.

- We are continuously collecting data (physics runs separated with bio-medical measurements).

[S. D. Bass, S. Mariazzi, P. Moskal, and E Stępień, Rev. Mod. Phys. 95 (2023) 021002]

- Third detector on the way! Total Body J-PET!

Thank you