J-PET: a new experimental facility for studies of discrete symmetries in charged leptons sector

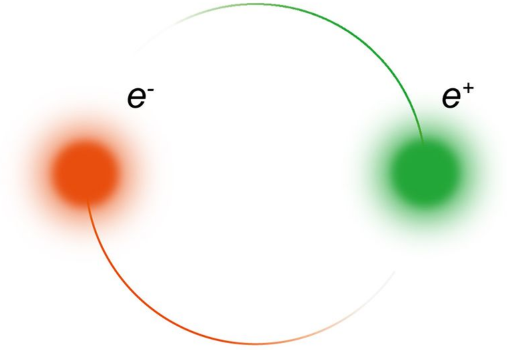
Szymon Niedźwiecki on behalf of the J-PET collaboration
18.05.2021 Meson 2021, Kraków, Poland

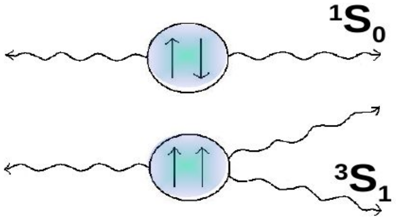
Plan of presentation

1. C-symmetry violation in positronium decay
2. J-PET detector overview
3. Preliminary results

Positrionium

- POSITRONIUM - the lightest purely leptonic object





due to Charge Conjugation C

$$|{}^1S_0\rangle \rightarrow 2\gamma, 4\gamma, \ldots \qquad |{}^3S_1\rangle \rightarrow 3\gamma, 5\gamma, \ldots$$

even number of photons — odd number of photons

- symmetric under the exchange of particles - anti-particles -> <u>is eigenstate of the charge conjugation op. C</u>

$$C|Ps> = (-1)^{L+S}|Ps>$$

eigenvalue of n photons $(-1)^n$

We can study **positronium decay to 3γ** with the **Dalitz Plot**

Ann. Rev. Nucl. Part. Sci 30,453 (1980)

Charge Conjugation Symmetry Test

J-PET

Study the **C symmetry** in the **leptonic system** searching for the C-forbidden decays of the POSITRONIUM

p-Ps -> 3γ

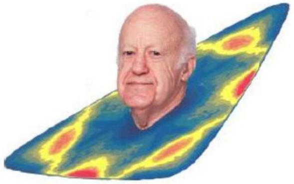


Image credit: Mike Pennington

C-symmetry:

- C-symmetry is violated in weak interactions

$$\nu_L \xrightarrow{C} \overline{\nu}_L$$

Left handed antineutrino does not exist!

- the best limit of the C-symmetry violation in the system of quarks (EM interactions)

$$\frac{\pi^0 \to 3\gamma}{\pi^0 \to 2\gamma} < 3.1 \times 10^{-8} \quad 90\% \text{ cl}$$

[PDG] P.A. Zyla et al., Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

- according to the SM predictions, *γ-γ* interaction or weak interaction can mimic the symmetry violation of the order of 10^{-9} and 10^{-14} , respectively

Phys. Rev. A 37, 3189 (1988), Z. Phys. C 41, 143 (1988), M. S Sozzi "Discrete Symmetries and CP violation"

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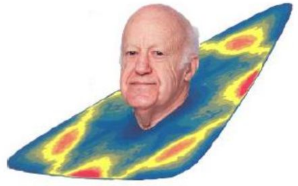
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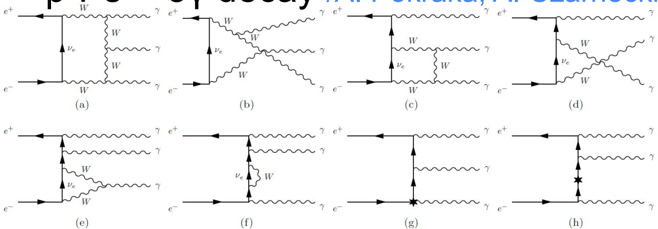
- p-Ps ->3γ can proceed through weak interactions - calculations with W-boson contribution to the p-Ps ->3γ decay /A. Pokraka, A. Czarnecki, Phys Rev. D 96, 093002 (2017)/



$$\text{Br}(\text{p-Ps} \to 3\gamma; W\text{-loops}) = \frac{\Gamma(\text{p-Ps} \to 3\gamma; W\text{-loops only})}{\Gamma(\text{p-Ps} \to 2\gamma)} \approx 4.4 \cdot 10^{-77}$$

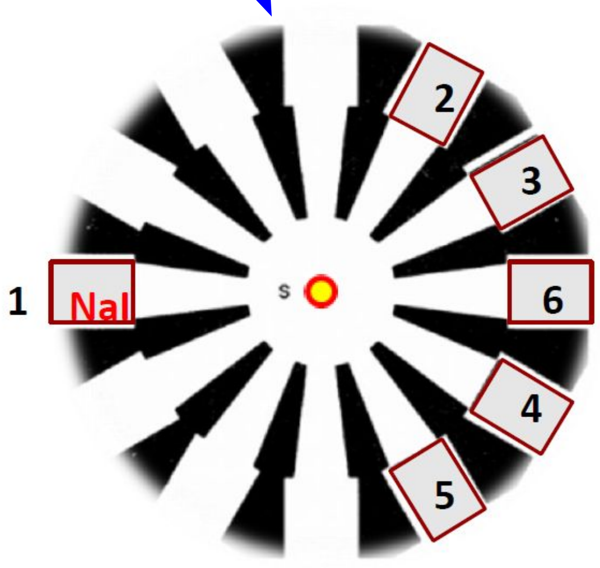
Charge Conjugation Symmetry Test

- experimental tests of C-symmetry in Ps decays

$$BR(\text{o-Ps} \to 4\gamma/\text{o-Ps} \to 3\gamma) < 2.6 \times 10^{-6} \quad \text{at} \quad 90\% \text{ C.L.}$$ [1] J. Yang et al., Phys. Rev. A 54, 1952 (1996)

$$BR(\text{p-Ps} \to 3\gamma/\text{p-Ps} \to 2\gamma) < 2.8 \times 10^{-6} \quad \text{at} \quad 68\% \text{ C.L.}$$ *the best limit for **p-Ps -> 3γ***
[2] **P. Mills, S. Berko, Phys. Rev. Lett. 18, 420 (1967)**

$$BR(\text{p-Ps} \to 5\gamma/\text{p-Ps} \to 2\gamma) < 2.7 \times 10^{-7} \quad \text{at} \quad 90\% \text{ C.L.}$$ [3] P. Vetter, S. Freedman, Phys. Rev. A 66, 052505 (2002)



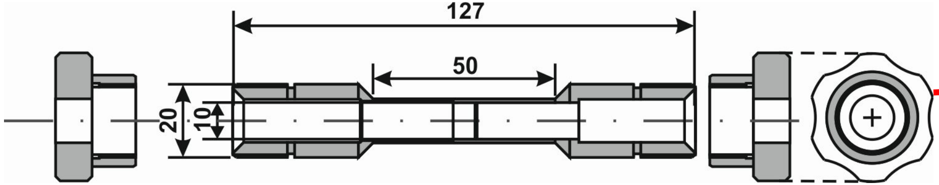
- Cu^{64} source (in gas chamber)
- 6 NaI(Tl) scintillators, multiple coinc. electronics
- NO quenching to suppress o-Ps-3γ

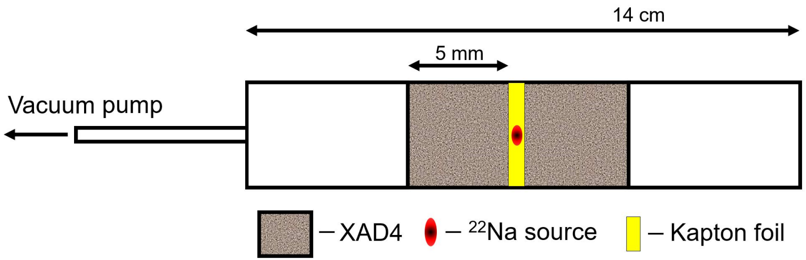
- the C forbidden p-Ps->3γ decay separated from the allowed o-Ps->3γ decay by studying angular distribution of 3 photons:
  - symmetric configuration (120°,120°,120°)
  - 60°,150°,150°
  - 90°,120°,150°

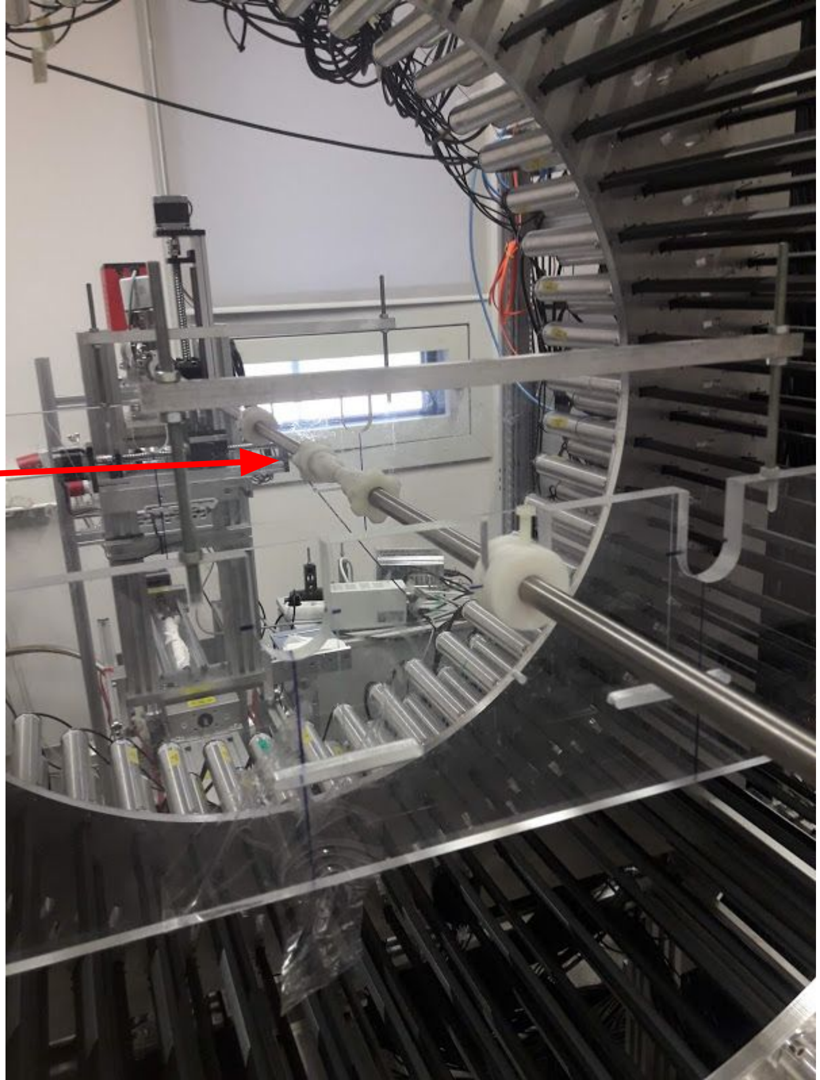
due to Bose statistic assumption C-nonconserving p-Ps->3γ must vanish

J-PET detector overview

Small annihilation chamber used for production of positronium:





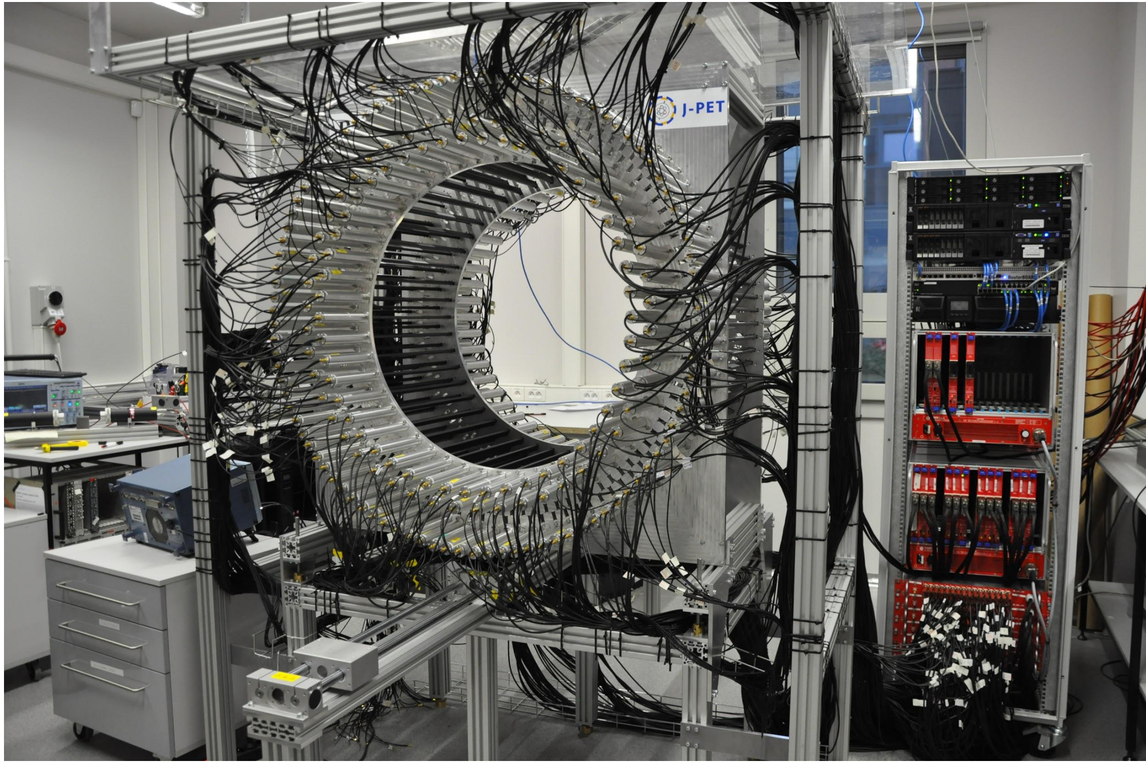


J-PET detector overview

192 BC420 scintillators
$7 \times 19 \times 500$ mm^3
85 cm radius

384 R9800 photomultipliers

1536 channels



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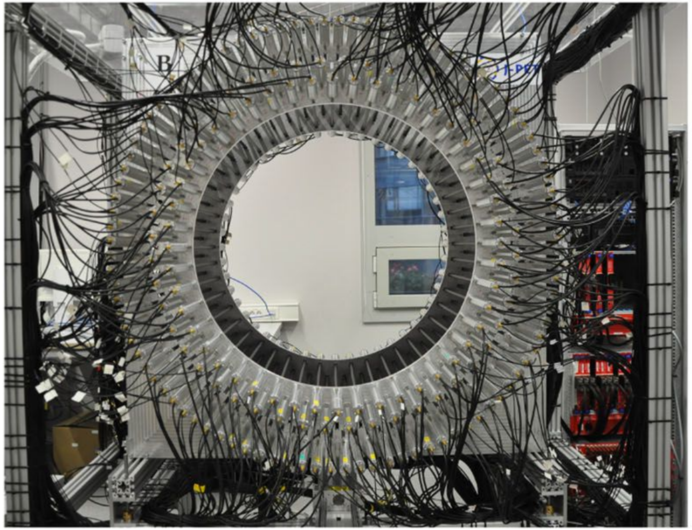
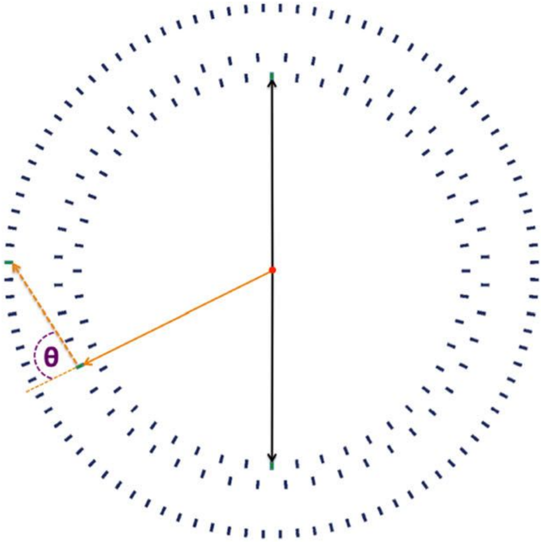
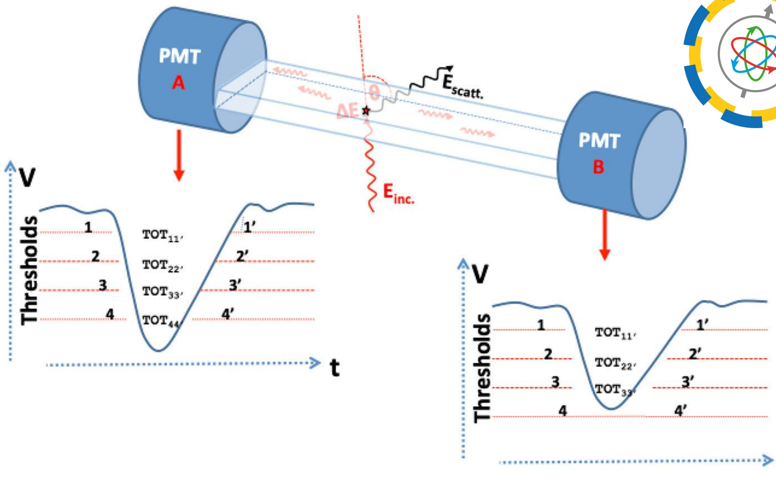
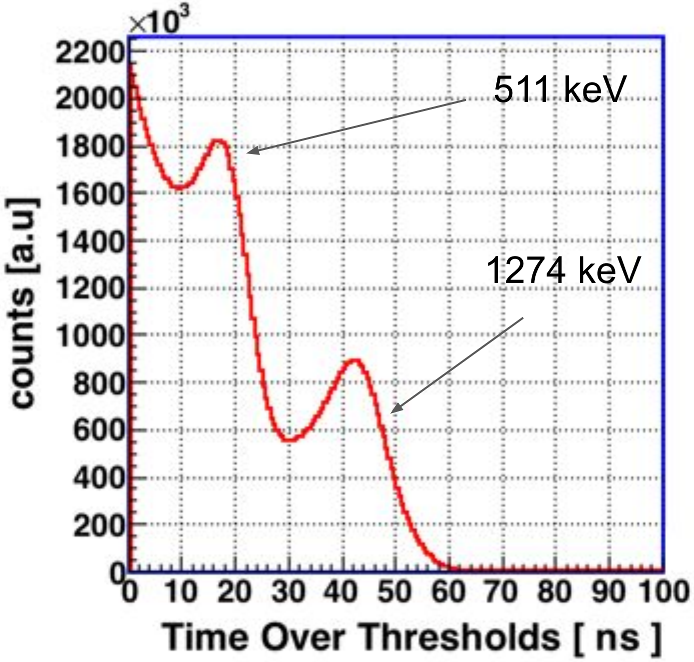




Detector performance: Time Over Threshold

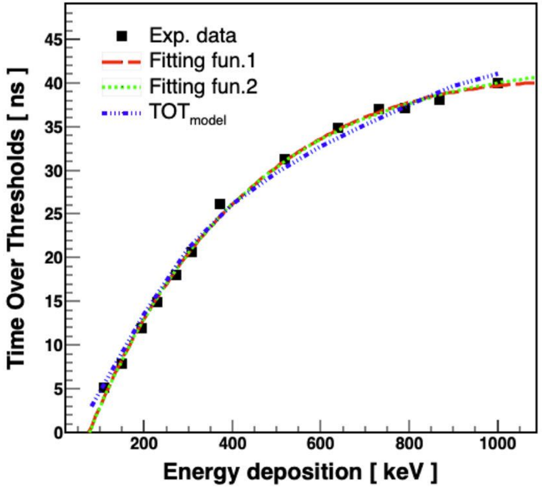


(a)



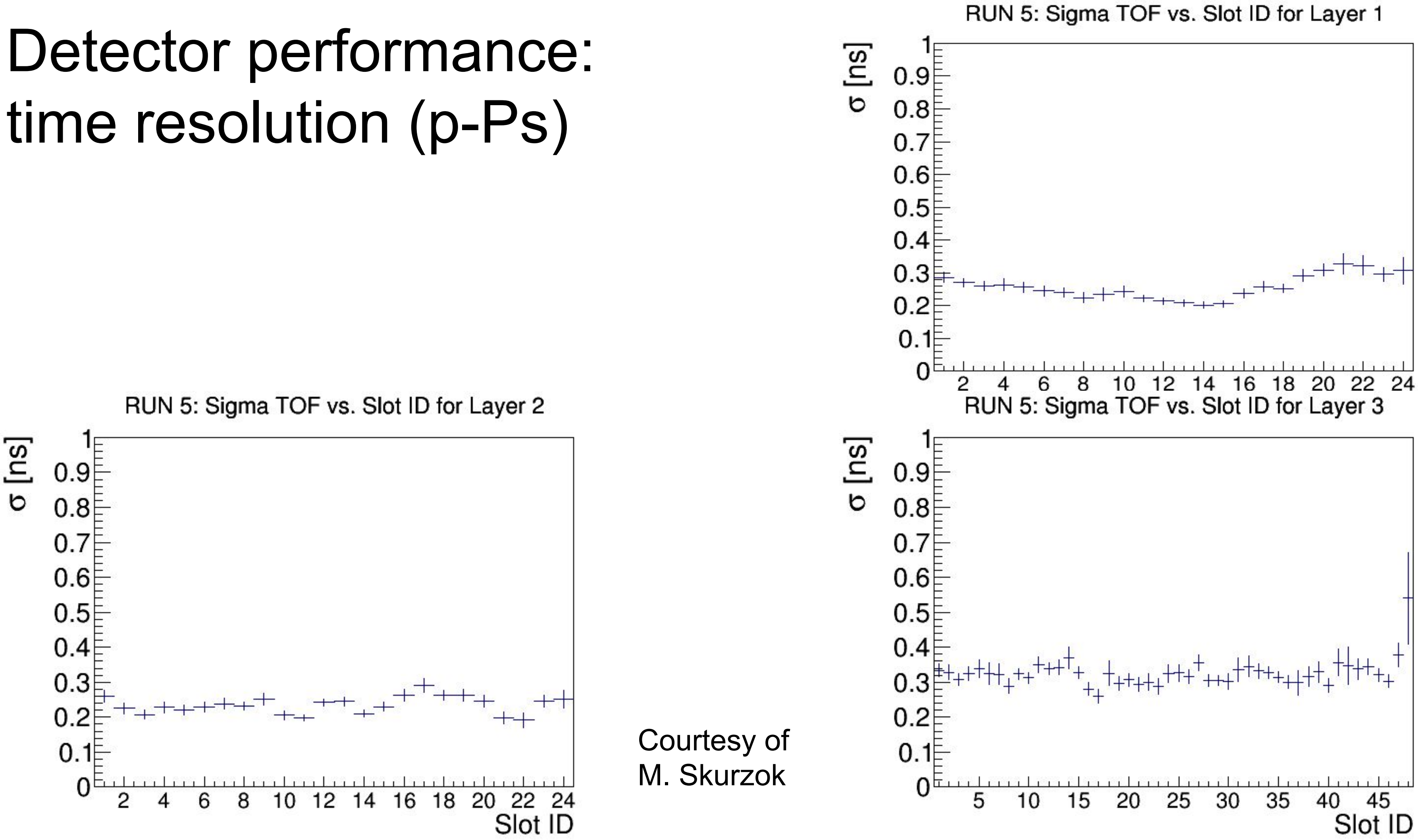
Courtesy of
S. Sharma

EJNMMI Phys. 7, 39 (2020)



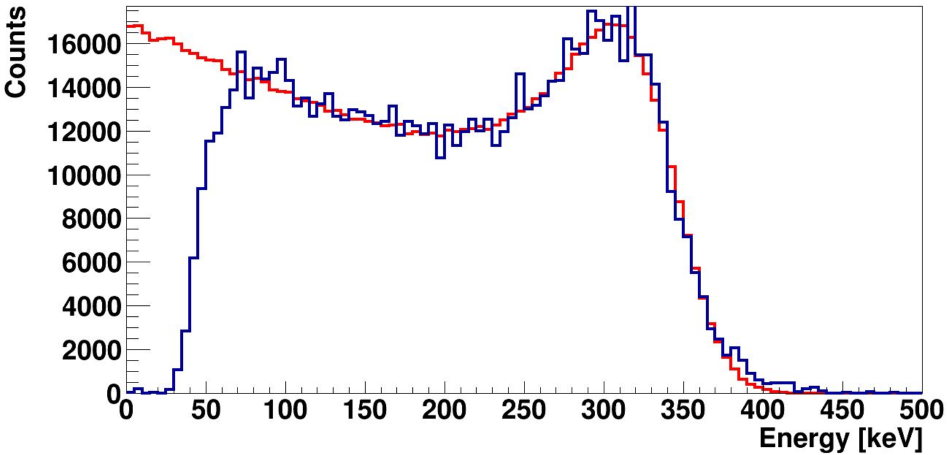
(b)

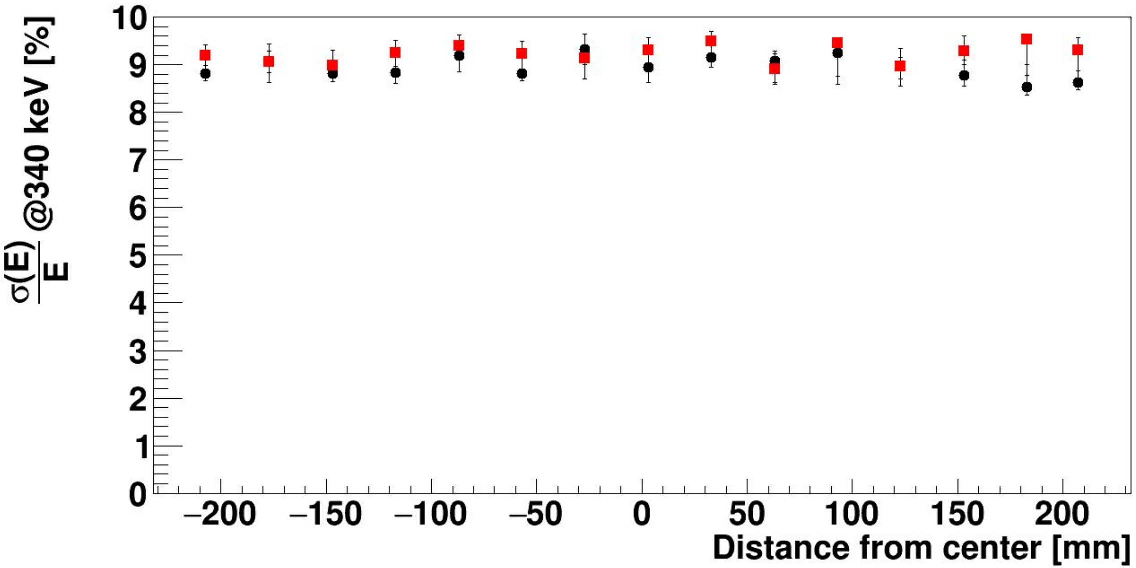
Detector performance: time resolution (p-Ps)



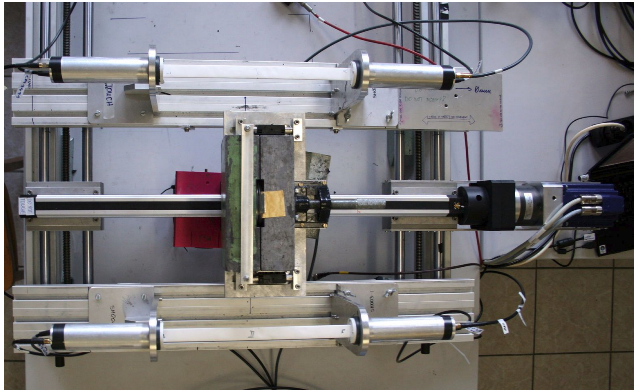
Courtesy of M. Skurzok

Detector performance: energy resolution (p-Ps)





Results from 2 strip studies:

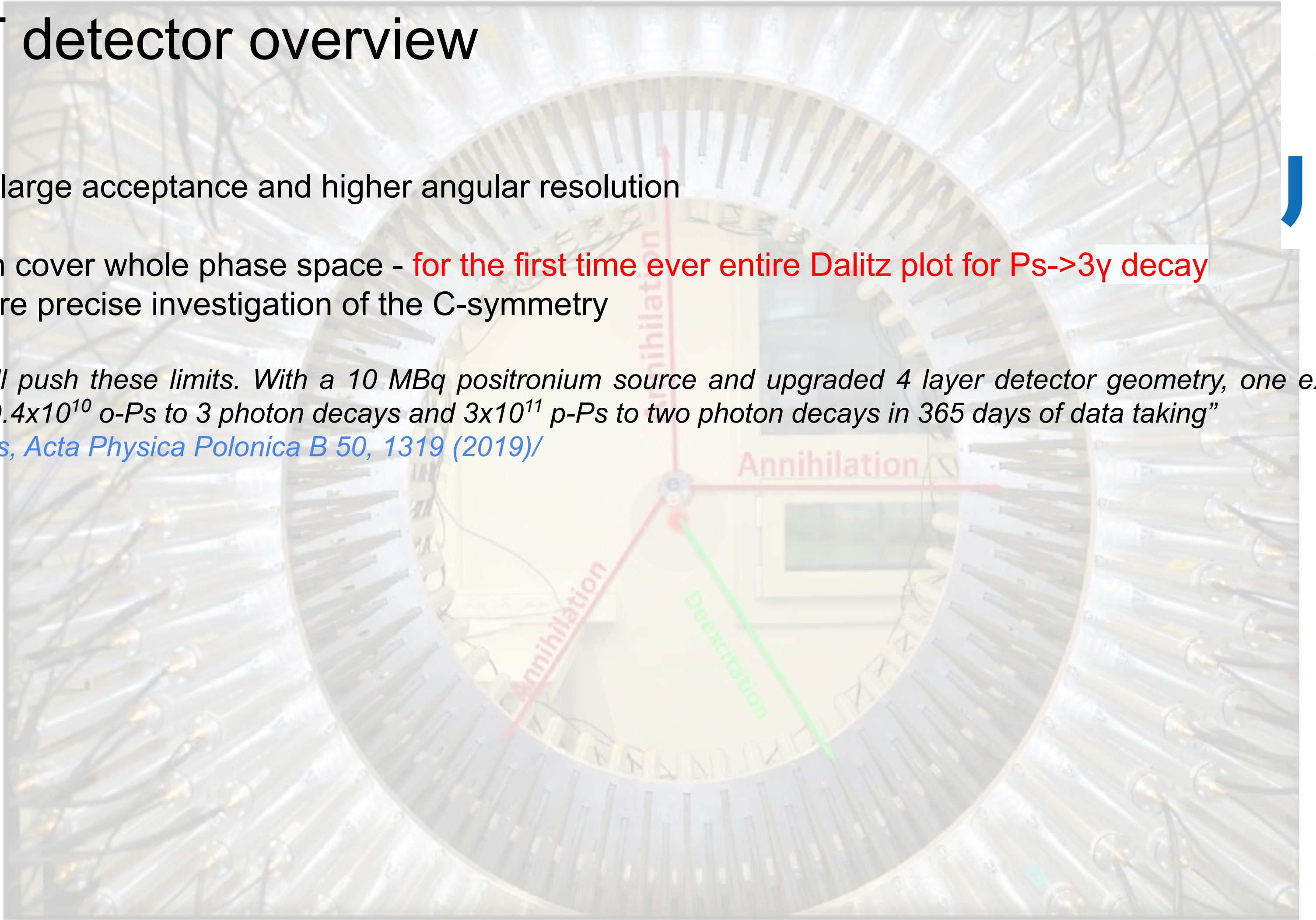


J-PET detector overview

J-PET - large acceptance and higher angular resolution

- can cover whole phase space - for the first time ever entire Dalitz plot for Ps->3γ decay
- more precise investigation of the C-symmetry

"J-PET will push these limits. With a 10 MBq positronium source and upgraded 4 layer detector geometry, one expects to measure 9.4x10^{10} o-Ps to 3 photon decays and 3x10^{11} p-Ps to two photon decays in 365 days of data taking"
/S. D. Bass, Acta Physica Polonica B 50, 1319 (2019)/



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Rough estimation of o-Ps->3 photon decays gathered up to now:

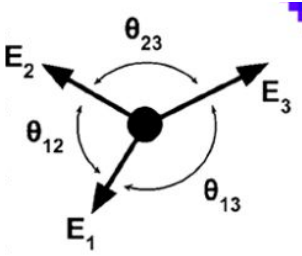
231 days of measurement

28.2×10^{6} o-Ps - from online monitoring spectra in period 22.06.20-1.03.21

for 231 days -> **10^{10} o-Ps**

Search for forbidden p-Ps -> 3γ decay

Simulations:



$$d\Gamma_S^{3\gamma} = \frac{g^2\Gamma_s^{2\gamma}}{8\alpha^2(2\pi)^6}(\omega_1\omega_2\omega_3)^3(\Sigma s_i)^2\left[\sum_{1\to2\to3}\left(\frac{1}{2}-\omega_3\right)^2(\omega_1-\omega_2)^2\right]d\theta_{12}d\theta_{13}d\Omega_1 d\varphi_1,$$

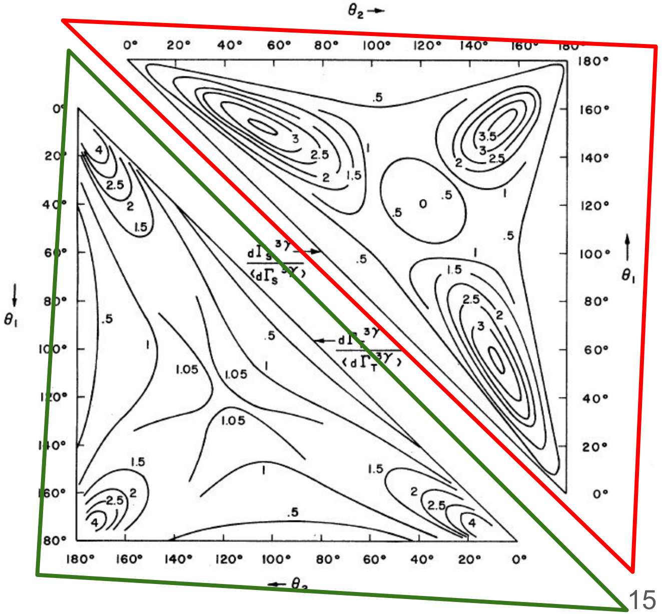
forbidden p-Ps->3γ

$$\Gamma_S^{3\gamma} = \frac{g^2\Gamma_s^{2\gamma}}{64\alpha^2(\pi)^4}\int_0^{1/2}d\omega\int_{1/2-\omega_1}^{1/2}(\omega_1\omega_2\omega_3)^2(\Sigma s_i)^2\left[\sum_{1\to2\to3}\left(\frac{1}{2}-\omega_3\right)^2(\omega_1-\omega_2)^2\right]d\omega_2$$

$$d\Gamma_T^{3\gamma} = \frac{8\alpha\Gamma_s^{2\gamma}}{3\alpha^2(2\pi)^4}(\omega_1\omega_2\omega_3)^{-1}\sum_{1\to2\to3}\omega_i^2\left(\frac{1}{2}-\omega_i\right)^2 d\theta_{12}d\theta_{13}d\Omega_1 d\varphi_1,$$

allowed o-Ps->3γ

$$\Gamma_T^{3\gamma} = \frac{4\alpha\Gamma_s^{2\gamma}}{3\pi^2}\int_0^{1/2}d\omega\int_{1/2-\omega_1}^{1/2}\sum_{1\to2\to3}\left(\frac{1}{2}-\omega_1\right)^2/(\omega_2\omega_3)^2 d\omega_2 \approx 0.898\cdot10^{-3}g^2\Gamma_s^{2\gamma}$$



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

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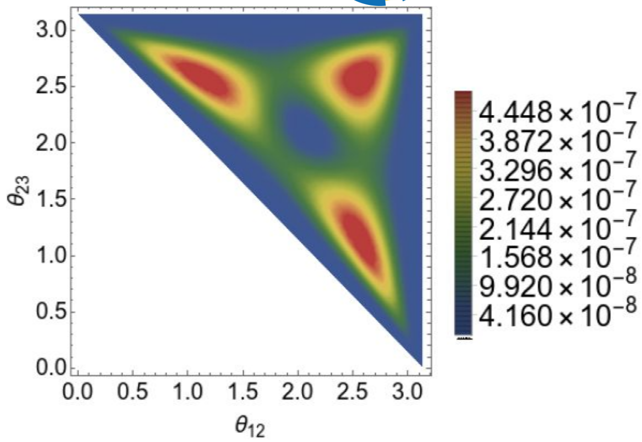
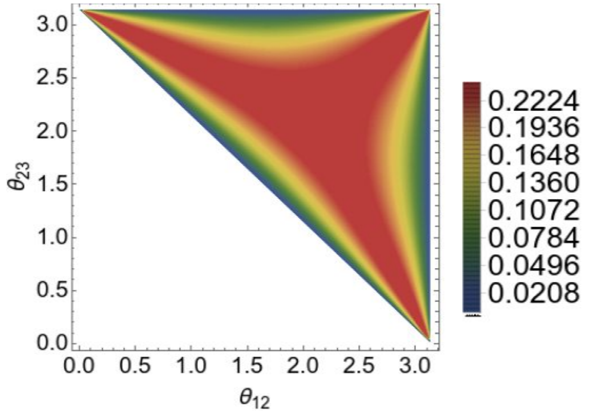


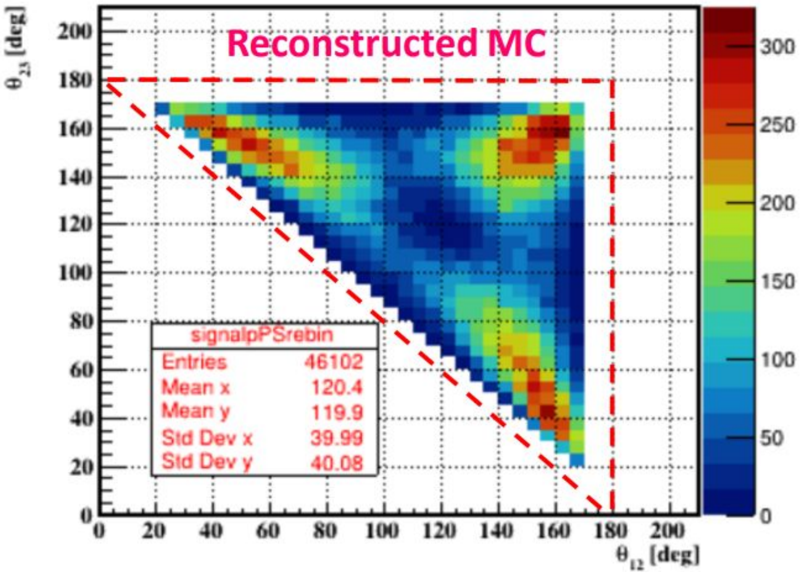


SIMULATIONS
J. Chhokar

Search for forbidden p-Ps -> 3γ decay

MC: 10^8 generated

Monte Carlo :$p - Ps \rightarrow 3\gamma$



1. **Z- Position of all hits in the detector** – to consider the scintillator active region only. (|Z|<23cm)
2. **All hits must be on different scintillators**(3 hits – 3 different Scintillator)
3. **Time Over Thresholds of all Hits** – to separate the annihilation and de-excitation photon (1<TOT<17 ns)

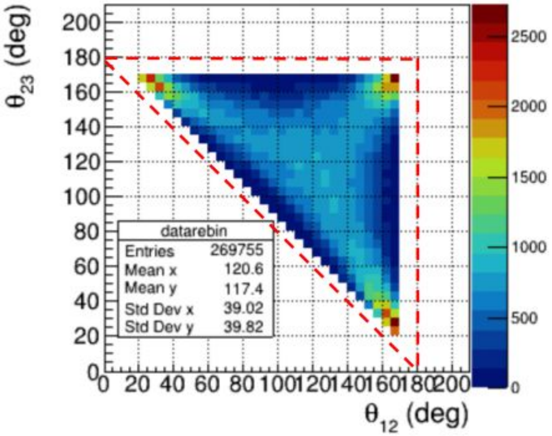
   OR

   Energy deposition of each photon - to select the annihilation candidate (20<E<340 keV) (MC)
4. **On distance between annihilation plane and the source** - (d<5cm)
5. **Difference between the third and first hit --** (corrected with TOF) (<1.5ns)
6. **Sum of the two smallest angle of o-Ps decaying into $3\gamma \geq 190°$--** due to conservation of momentum

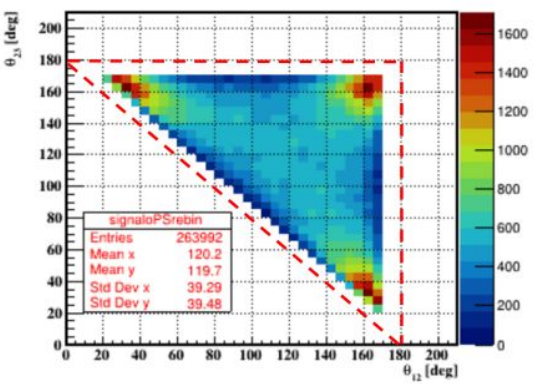
Search for forbidden p-Ps -> 3γ decay

Experimental Data Run9

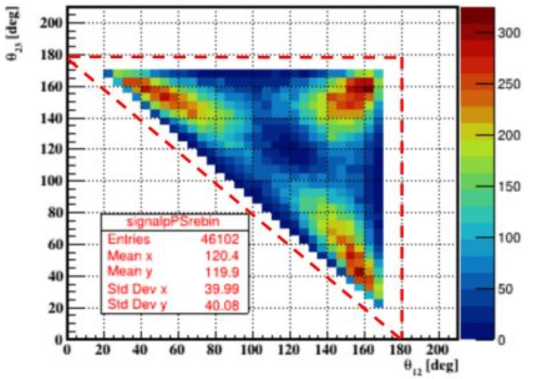
Simulated Monte Carlo



Monte Carlo $o{-}Ps \to 3\gamma$

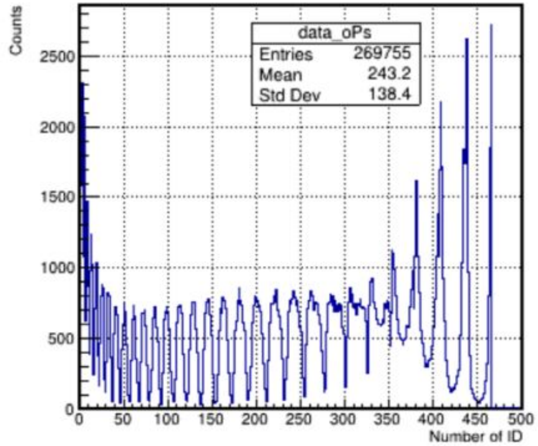


Monte Carlo :$p - Ps \to 3\gamma$

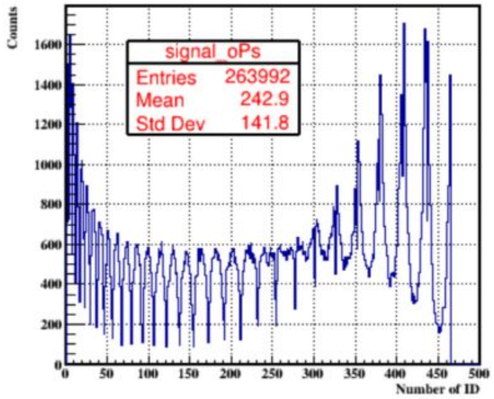


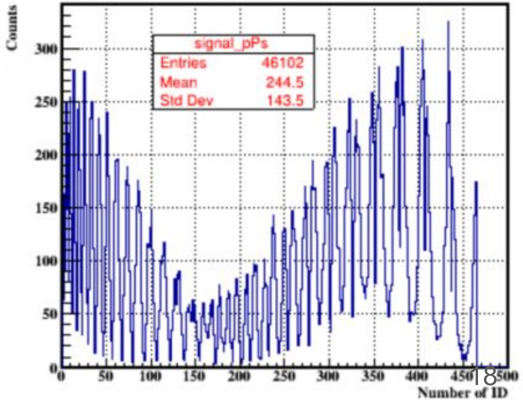
2D

PRELIMINARY



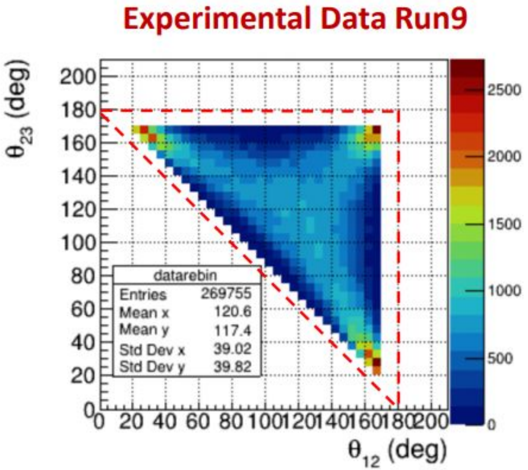
1D

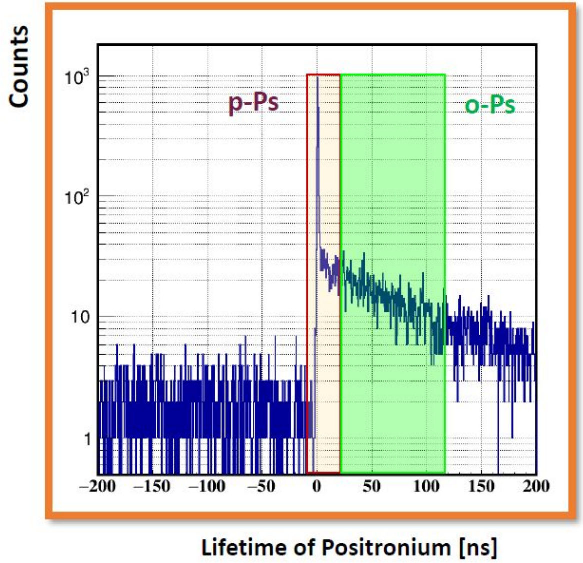




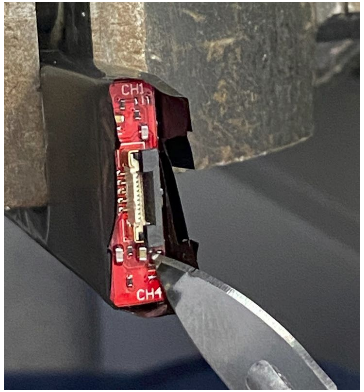
Summary

- One can study C-symmetry in charged lepton sector by measurement of Dalitz plot for positronium decay
- J-PET group is working on studying p-Ps->3γ decay using data from custom made annihilation chamber
- Initial results are promising, advanced data analysis is in progress



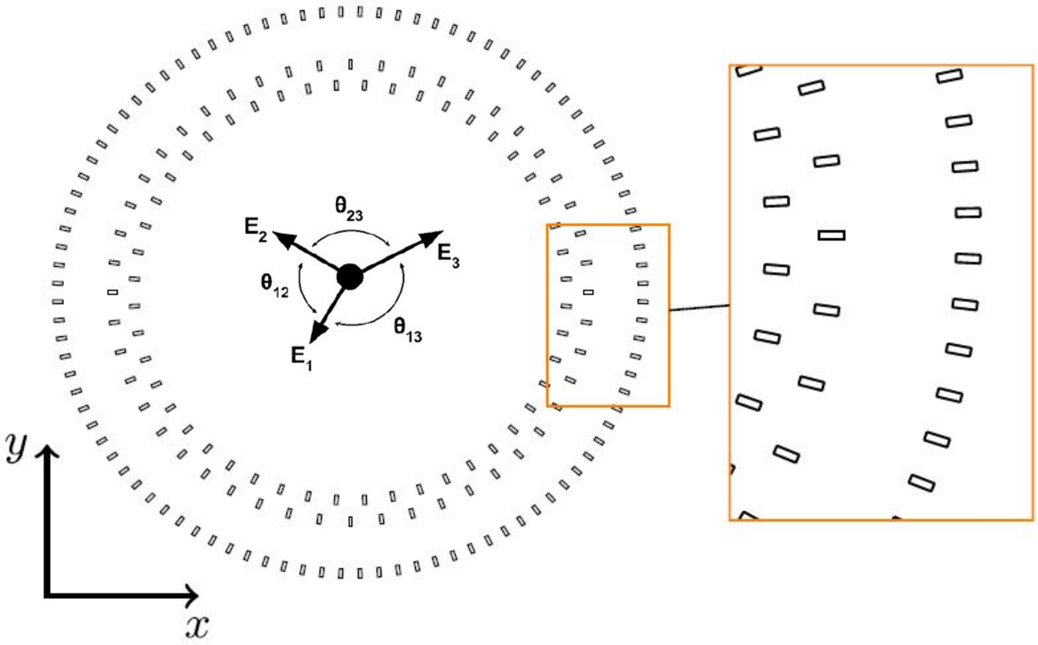


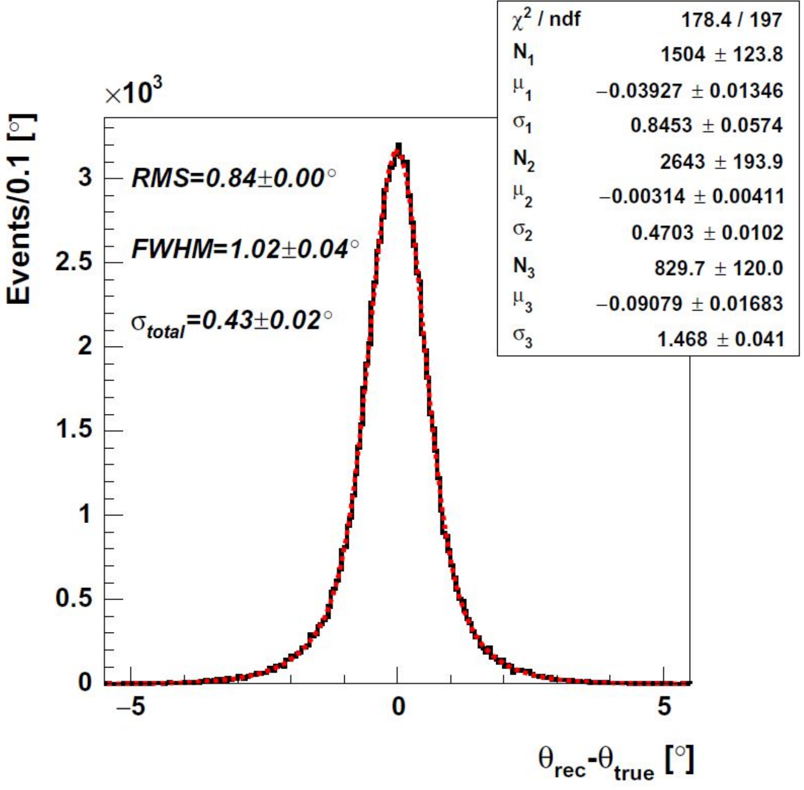
Thank you for your attention



Backup

Detector performance: angular resolution (o-Ps)

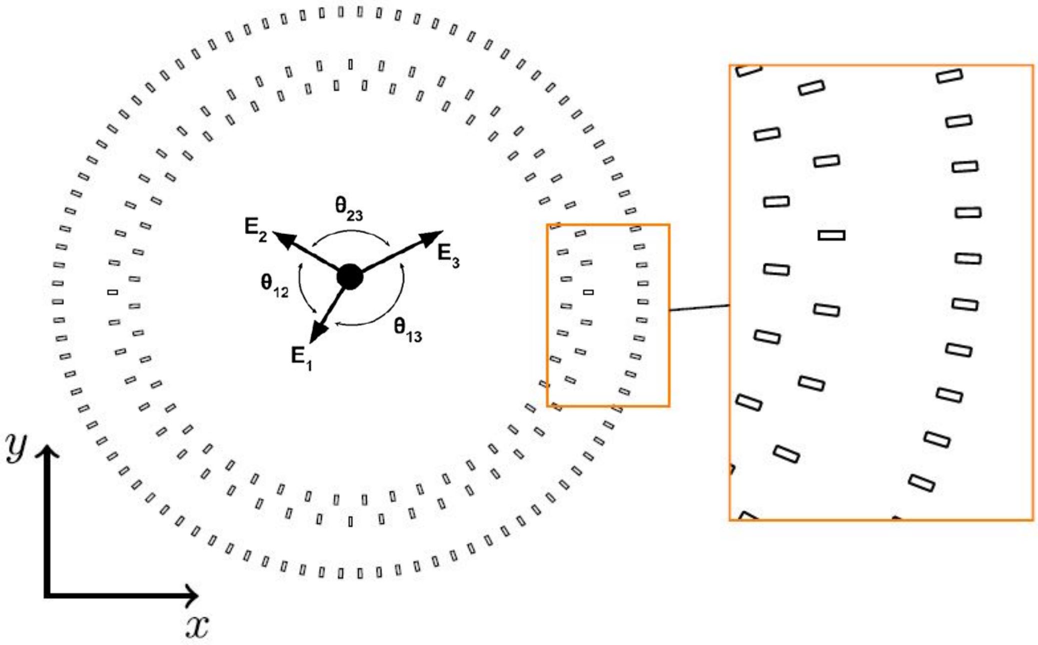


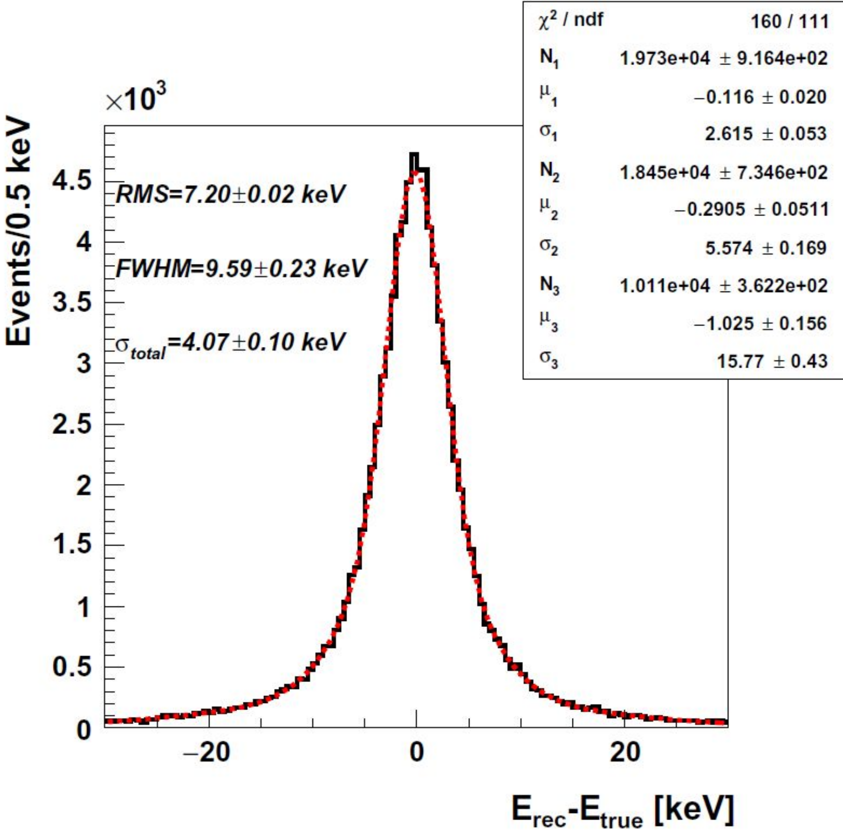


A feasibility study of ortho-positronium decays measurement with the J-PET scanner based on plastic scintillators

Eur. Phys. J. C (2016) 76:445
DOI 10.1140/epjc/s10052-016-429

Detector performance: energy resolution (o-Ps)





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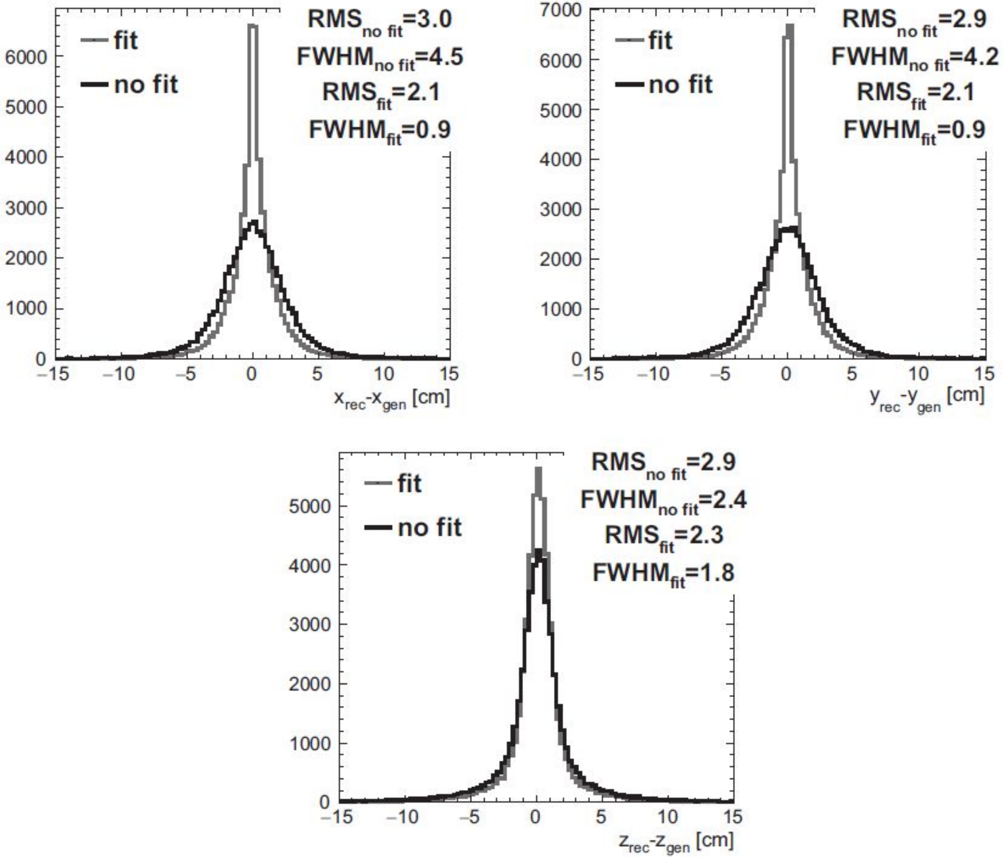
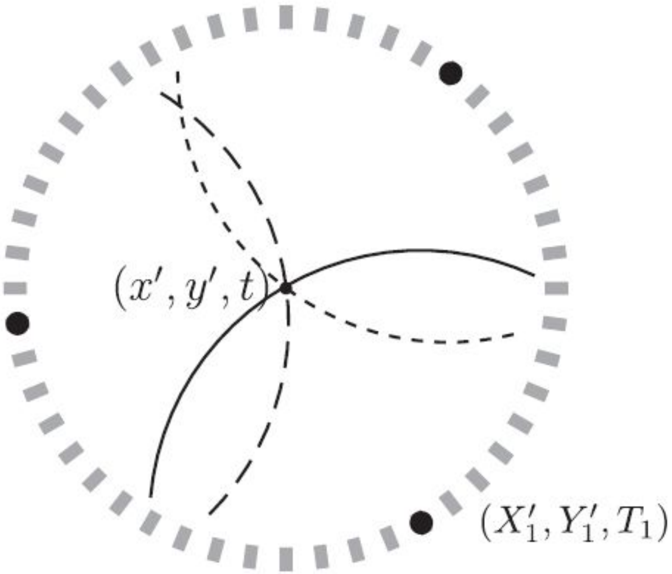
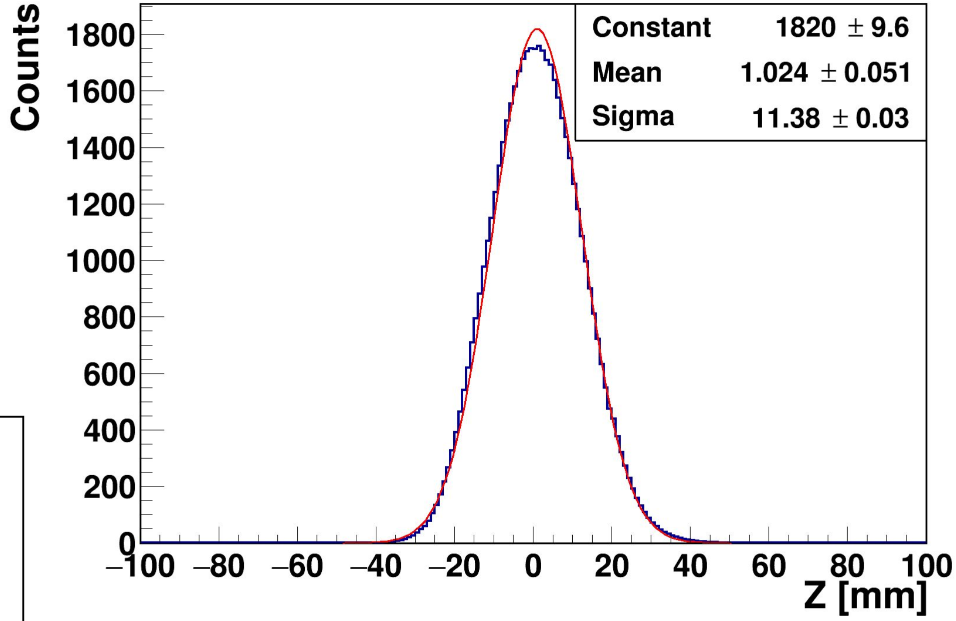
Detector performance: spatial resolution (o-Ps)

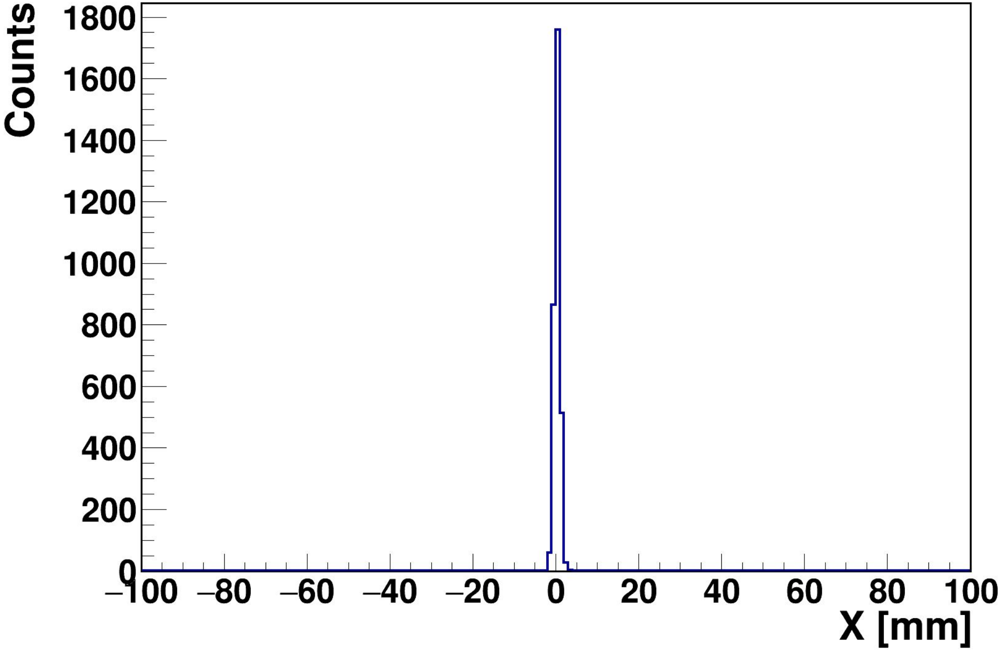




Trilateration-based reconstruction of ortho-positronium decays into three photons with the J-PET detector
Nuclear Inst. and Methods in Physics Research A 819 (2016) 54-59

Detector performance: spatial resolution (p-Ps)

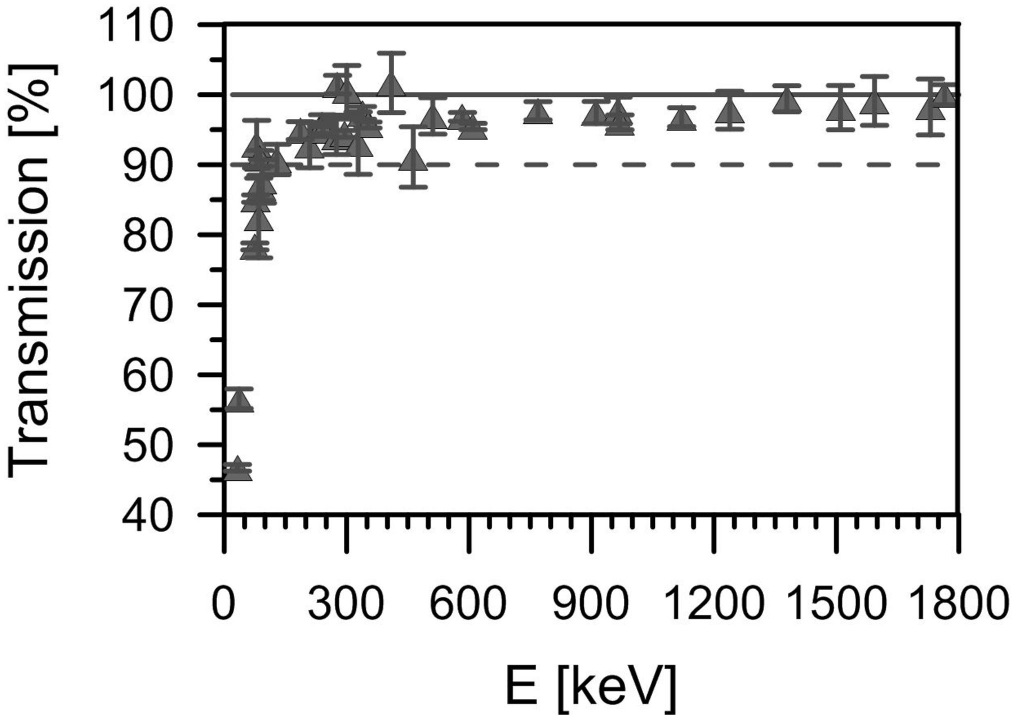




Resolution in XY in the order of source size (2-3 mm)
Resolution in Z ~ 1.2 cm

Preliminary Studies of J-PET Detector Spatial Resolution
Acta Phys. Polon. A 132, no. 5, 1645 (2017)

Transmission of gammas through aluminium



Acta Phys. Pol. B 51, 293 (2020)

Search for forbidden p-Ps -> 3γ decay

Simulations:

$$d\Gamma_S^{3\gamma} = \frac{g^2\Gamma_s^{2\gamma}}{8\alpha^2(2\pi)^6}(\omega_1\omega_2\omega_3)^3(\Sigma s_i)^2\left[\sum_{1\to2\to3}\left(\frac{1}{2}-\omega_3\right)^2(\omega_1-\omega_2)^2\right]d\theta_{12}d\theta_{13}d\Omega_1 d\varphi_1,$$

forbidden p-Ps->3γ

$$\Gamma_S^{3\gamma} = \frac{g^2\Gamma_s^{2\gamma}}{64\alpha^2(\pi)^4}\int_0^{1/2}d\omega\int_{1/2-\omega_1}^{1/2}(\omega_1\omega_2\omega_3)^2(\Sigma s_i)^2\left[\sum_{1\to2\to3}\left(\frac{1}{2}-\omega_3\right)^2(\omega_1-\omega_2)^2\right]d\omega_2$$

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

$$d\sigma_{3\gamma} = \frac{(2\pi)^2|M_{fi}|^2}{4I}\delta(k_1+k_2+k_3)\,\delta(\omega_1+\omega_2+\omega_3-2m)\frac{d^3k_1d^3k_2d^3k_3}{(2\pi)^9\,2\omega_1 2\omega_2 2\omega_3}$$

assuming that the decay rate $\Gamma_S^{3\gamma}$ and the cross-section are proportional...

amplitude for p-Ps->3γ

$$|M_{fi}|^2 = C(\omega_1\omega_2\omega_3)^2(s_1+s_2+s_3)^2\cdot$$
$$\cdot\left[(m-\omega_3)^2(\omega_1-\omega_2)^2+(m-\omega_1)^2(\omega_2-\omega_3)^2+(m-\omega_2)^2(\omega_3-\omega_1)^2\right]$$

E-p conservation laws

$$-p_i = p_j\cos\theta_{ij} + p_k\cos\theta_{ik}$$
$$E_1+E_2+E_3 = 2m.$$

$$\cos\theta_{13} = \frac{p_2^2-p_1^2-p_3^2}{2p_1p_3},$$
$$\cos\theta_{23} = \frac{p_1^2-p_2^2-p_3^2}{2p_2p_3}$$