# J-PET Monte Carlo simulation with the Geant4 package

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on behalf of the J-PET Collaboration

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# Outline

- Motivation
- Program architecture and simulated geometry
- Simulation of back-to-back and $3\gamma$ events
- Feasibility study of o-Ps$\rightarrow 3\gamma$ measurement with the J-PET detector

# Monte Carlo simulation is a support for...

- ... creating the calibration and reconstruction methods
  - additional reconstruction method of radiopharmaceutic position

    A. Gajos, *et al* Nucl. Instrum. Meth. A819, 54 (2016)
- ... searching for the physics beyond the Standard Model:
  - discrete symmetries violation

    W. Bernreuther, U. Low, J. P. Ma, O. Nachtmann, Z Phys. C, **41(1)**, 143 (1988)
  - extra dimensions

    S.L. Dubovsky, V.A. Rubakov, P.G. Tinyakov, Phys. Rev. D **62** (105011)
  - dark matter

    P. Crivelli, A. Belov, U. Gendotti, S. Gninenko and A. Rubbia, JINST **5**, P08001 (2010)
  - a new light vector gauge boson

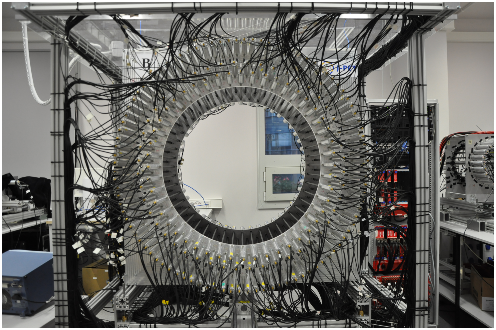
    S. N. Gninenko, N. V. Krasnikov, A. Rubbia, Modern Phys. Lett. A **17** , 1713 (2002)
- ... creating the diagnostic methods in medicine
  - morphometric imaging

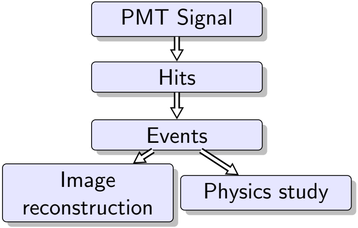
    P.Moskal *et al.*, Patent Application: PCT/PL2015/050038

Tools available on the market:

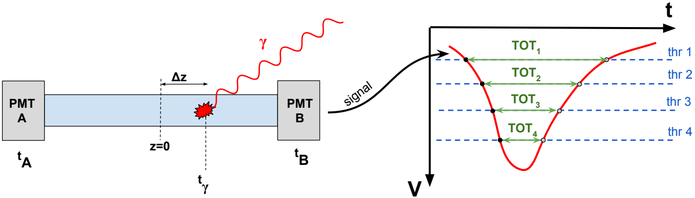
- Geant (general purpose)
- Gate (PET and SPET)
- Fred (Ion beam therapy)
- EGSnrc (it models the propagation of $\gamma$, $e^-$ and $e^+$ through matter)
- many more ...

# J-PET detector

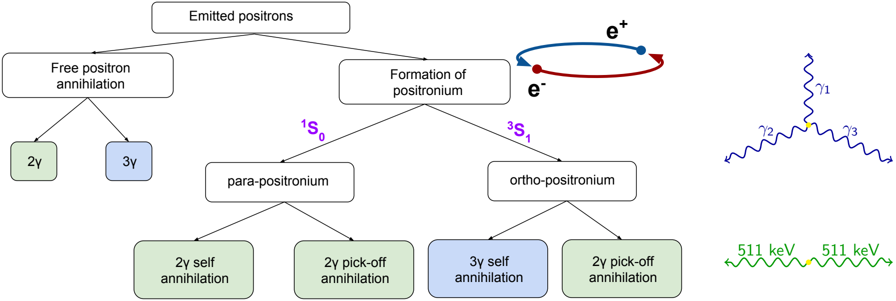





For details see a talk by Sz. Niedzwiecki on Monday



# Event types



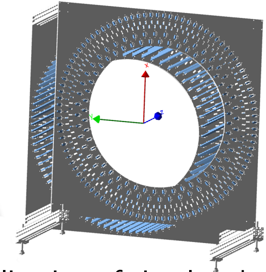

| Material | No Ps formed[1] | Water[1] | IC3100[2] | XAD-4[2] |
|---|---|---|---|---|
| $f_{3\gamma} = \sigma_{3\gamma}/\sigma_{2\gamma}$ | 0.27% | 0.52% | 16.9% | 28.9 % |

[1] *K. Merkurio et al.*, Phys. Med. Biol. **51**, N323 (2006)

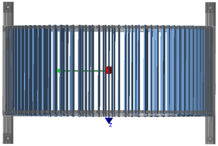
[2] *B. Jasiska et al.*, Acta Phys. Polon. B **47**, 453 (2016)

# Program architecture and simulated geometry

- code available at GitHub
  https://github.com/JPETTomography/J-PET-geant4.git
- required packages: geant.10.4, root6, cadmesh, cmake
- physics list: G4EmLivermorePolarizedPhysics (Livermore physics models with polarized photon models)
- the Monte Carlo simulations account for:
  - angular and energy distributions of gamma quanta originating from direct or ortho-positronium annihilation,
  - Compton interactions of emitted gamma quanta in the detector built from plastic scintillators,
  - determination of gamma quanta hit-position and hit-time in the detector with experimentally determined resolutions,
  - multiple scattering and accidental coincidences,

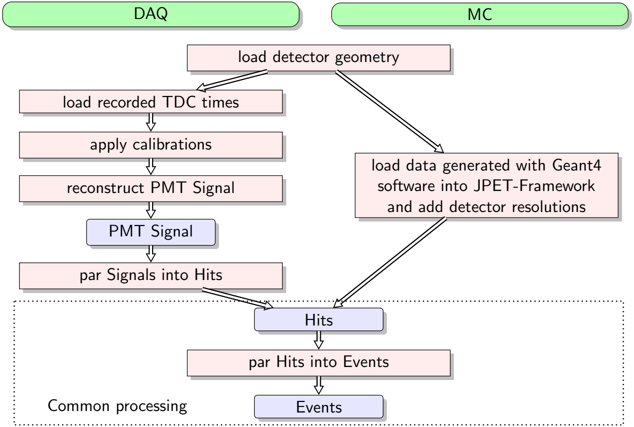


$\Updownarrow$ Visualization of simulated detector



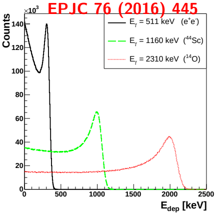
| Layer number | Layer radius with respect to the center of scintillator | Number of scintillators in the layer |
|---|---|---|
| 1 | 42.50 cm | 48 |
| 2 | 46.75 cm | 48 |
| 3 | 57.50 cm | 96 |

# Integration with J-PET analysis framework

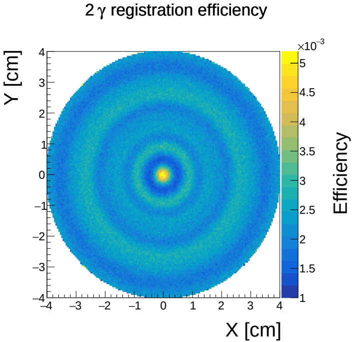



- provides adjustion of Geant MC output in framework structures (hit level)
- user can process MC in the same manner as collected data

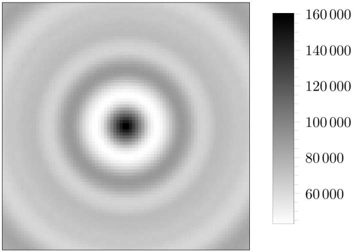
# Back to back events




- simulated two 511 keV back to back gamma quanta
- ⇐ emitted gamma quanta interact via Compton scattering
- ⇓ Sensitivity map in $x - y$ plane in the central part of the detector. Figure is made in a transverse view of the detector with 0.5 mm × 0.5 mm bin size.

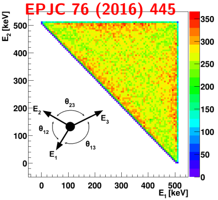



⇑ output from simulation

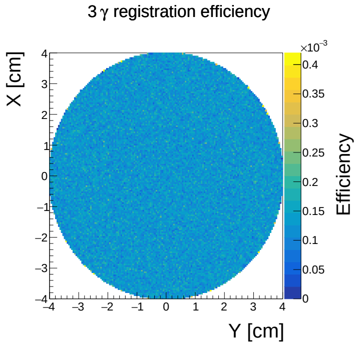


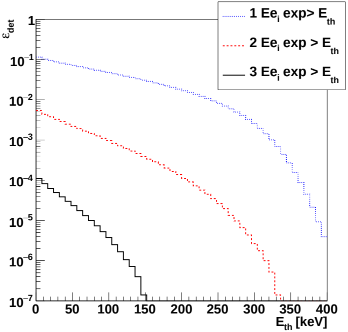

⇑ Strzelecki, A. Image reconstruction and simulation of strip Positron Emission Tomog- raphy scanner using computational accelerators PhD thesis (Jagiellonian University, 2016).

# o-Ps$\rightarrow$ 3$\gamma$ annihilation




- simulated two 511 keV back to back gamma quanta
- $\Leftarrow$ emitted gamma quanta interact via Compton scattering
- $\Downarrow$ Sensitivity map in $x-y$ plane in the central part of the detector. Figure is made in a transverse view of the detector with 0.5 mm $\times$ 0.5 mm bin size.



# Studies of discrete symmetries

$C_{CPT} = 0.0026 \pm 0.0031$ (for $\vec{S} \cdot \vec{k}_1 \times \vec{k}_2$)

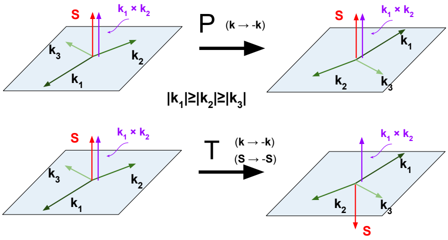
(P.A. Vetter et al., Phys. Rev. Lett. 91 (2003) 263401)

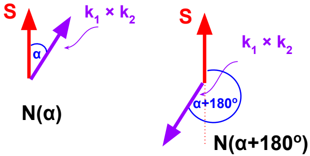
| Operator | C | P | T | CP | CPT |
|---|---|---|---|---|---|
| $\vec{S} \cdot \vec{k}_1 \times \vec{k}_2$ | $+$ | $+$ | $-$ | $+$ | $-$ |

SM: $10^{-9} - 10^{-10}$

effects of final state interaction

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

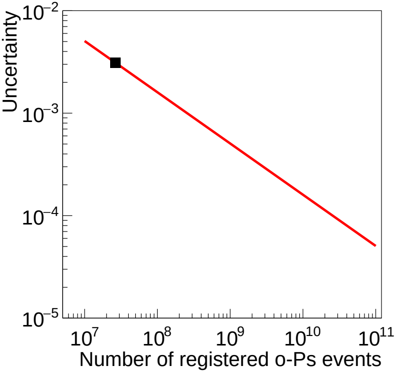



Observable: $A = \frac{N(\alpha)-N(\alpha+180)}{N(\alpha)+N(\alpha+180)}$

# Application example - $\mathcal{CPT}$ violation parameter

J-PET



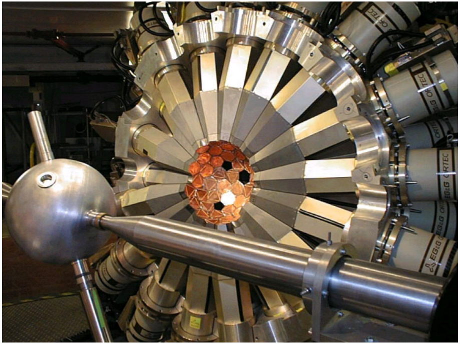

- $C_{CPT} = 0.0026 \pm 0.0031$ (for $\vec{S} \cdot \vec{k}_1 \times \vec{k}_2$)
  (P.A. Vetter et al., Phys. Rev. Lett. 91 (2003) 263401)
- $\Leftarrow$ Dependency between number of reconstructed o-Ps$\rightarrow 3\gamma$ events and the amplitude of $\mathcal{CPT}$ violating asymmetry uncertainty (red line). Plot is made assuming detection parameters as in Gammashpere detector. Result obtained by Vetter and Freedman is denoted by black square.
- $R_{o-Ps\rightarrow 3\gamma} = \mathcal{A} \cdot f_{o-Ps\rightarrow 3\gamma} \cdot \epsilon_{det}(th) \cdot \epsilon_{ana}$,
  - $\mathcal{A}$ - source activity
  - $f_{o-Ps\rightarrow 3\gamma}$ - fraction of o-Ps$\rightarrow 3\gamma$ annihilation
  - $\epsilon_{det}(th)$ - detection efficiency
  - $\epsilon_{ana}$ - analysis efficiency
- XAD-4 (10MBq, th=50keV):
  $R_{o-Ps\rightarrow 3\gamma} = 25$ events/s
  $\approx 1.5 \times 10^{7}$ events/week
- around 1.5 year of measurement is required to improve the previous result by an order of magnitude

# Thank you for your attention

# $C_{CPT}$ determination - Gammasphere experiment

J-PET

- measurement was performed at Gammasphere detector
- covers almost $4\pi$ around interaction point, but angular resolution is limited by crystals sizes ($\sim 4^{\circ}$)
- detects all three gamma quanta
- source activity is limited by signal pile-ups



picture adapted from www.physics.fsu.edu

Goal: determine the parameters of experiment that will improve sensitivity for CPT test

$$A = \frac{N_+ - N_-}{N_+ + N_-}$$

$$C_{CPT} = A/\langle P \rangle$$

$$C_{CPT} = 0.0026 \pm 0.0031 \quad (\text{for } \vec{S} \cdot \vec{k}_1 \times \vec{k}_2)$$

(P.A. Vetter et al., Phys. Rev. Lett. 91 (2003) 263401)

- $\langle P \rangle$: average polarization
- Gammasphere: 43% for $^{22}$Na and 61% for $^{68}$Ge. Determined on hemisphere
- J-PET: the uncertainty of determination of positron direction will amount to about 15°

| | **J-PET** | **Gammasphere** |
|---|---|---|
| Detector material | BC-420 | HPGe and BGO |
| Time resolution | 80 ps | 4.6 ns |
| Angular resolution (polar/azimuthal) | 1.4°/0.5° | 4°/4° |
| Source activity | 10 MBq | 1 MBq (limited by pile-ups) |