J-PET Monte Carlo simulation with the Geant4 package

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on behalf of the J-PET Collaboration

25 September 2019
Frascati

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

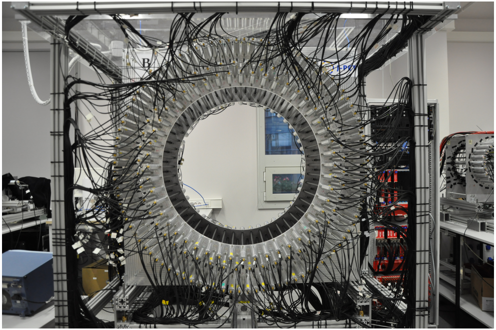
    S. N. Gninenko, N. V. Krasnikov, A. Rubbia, Modern Phys. Lett. A **17** , 1713 (2002)
- ... creating the diagnostic methods in medicine
  - morphometric imaging

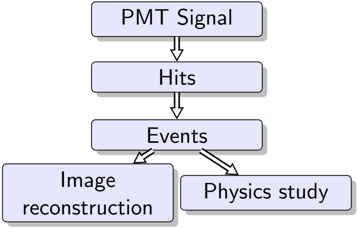
    P.Moskal *et al.*, Patent Application: PCT/PL2015/050038

Tools available on the market:

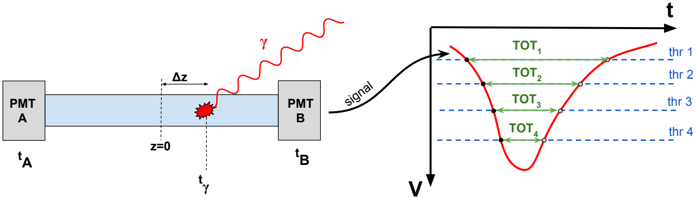
- Geant (general purpose)
- Gate (PET and SPET)
- Fred (Ion beam therapy)
- EGSnrc (it models the propagation of γ, e^- and e^+ through matter)
- many more ...

J-PET detector

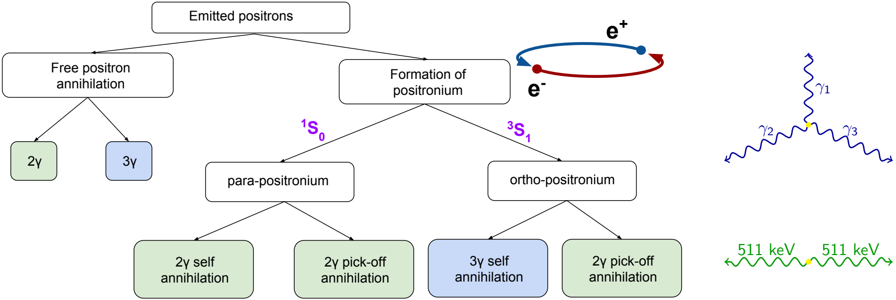




For details see a talk by P. Moskal on Monday



Event types

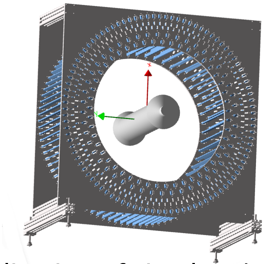


Material	No Ps formed[1]	Water[1]	IC3100[2]	XAD-4[2]
$f_{3\gamma} = \sigma_{3\gamma}/\sigma_{2\gamma}$	0.27%	0.52%	16.9%	28.9 %

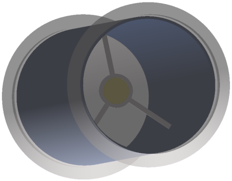
[1] *K. Merkurio et al.*, Phys. Med. Biol. **51**, N323 (2006)
[2] *B. Jasińska et al.*, Acta Phys. Polon. B **47**, 453 (2016)

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,



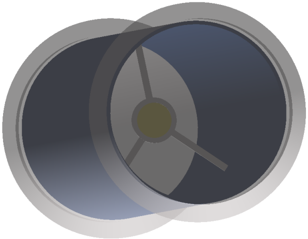
$\Updownarrow$ Visualization of simulated detector

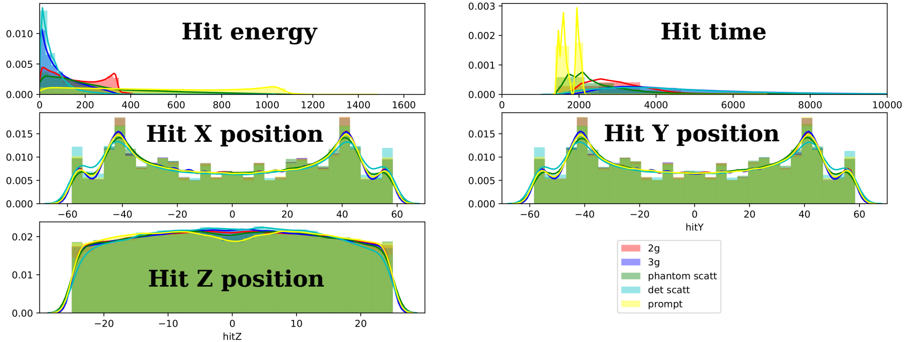


Event classification

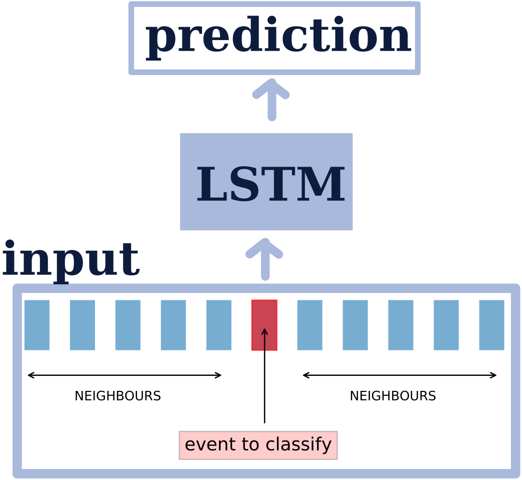
Goal: distinguish between following categories:

- 2γ
- 3γ
- prompt γ
- phantom scatterings
- detector scatterings



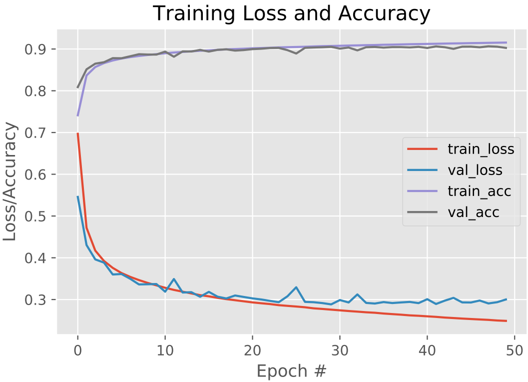


Machine Learning classifier



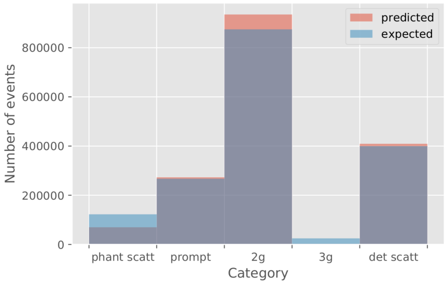
- MC for run6
  - large annihilation chamber
  - prompt from the center
- variables for each hit:
  - deposited energy,
  - registration time
  - position coordinates
- used Long Short Term Memory (LSTM) layer
- the series of hits is fed into network

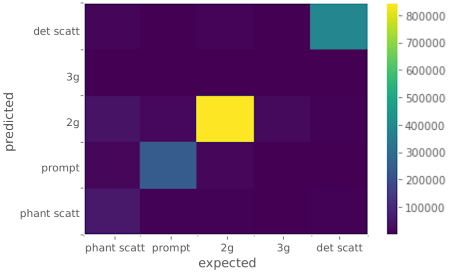
Learning process



- loss
  - this score is minimized and a perfect cross-entropy value is 0
- accuracy
  - to judge the performance of model ($\frac{\text{correctly classified events}}{\text{all events}}$)

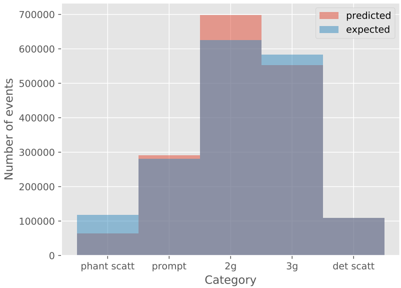
Classifiers - run6 (3γ: 0.3%)

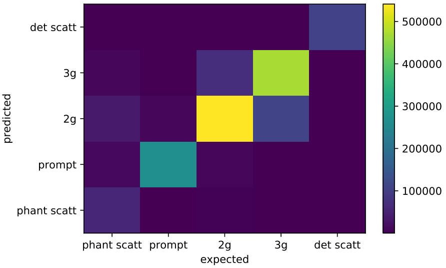




- loss 29.1 %
  - this score is minimized and a perfect cross-entropy value is 0
- accuracy 90.6%
  - to judge the performance of model ($\frac{\text{correctly classified events}}{\text{all events}}$)

Classifiers - run6 (3γ: 40%)





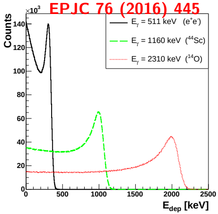
- loss 37.2%
  - this score is minimized and a perfect cross-entropy value is 0
- accuracy 84.3%
  - to judge the performance of model ($\frac{\text{correctly classified events}}{\text{all events}}$)

Summary

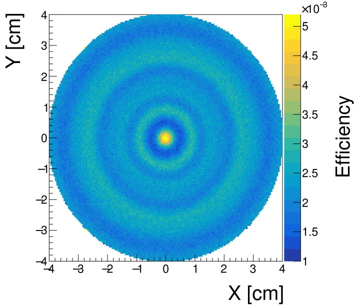
- J-PET-Geant4 is a Monte Carlo simulation program designed for the J-PET detector created in Geant4 toolkit.
- Software is maintained within public repositories on GitHub: https://github.com/JPETTomography
- Many contributing members

Thank you for your attention

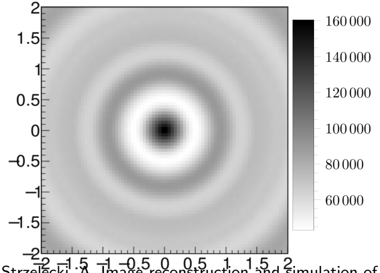
Back to back events



- 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.

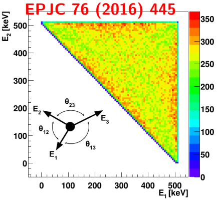


$\Uparrow$ output from simulation



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

o-Ps$\to 3\gamma$ annihilation



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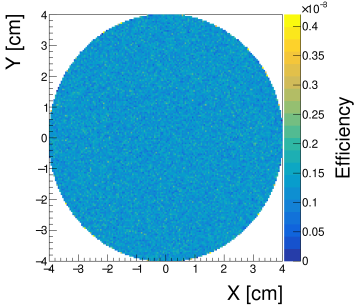
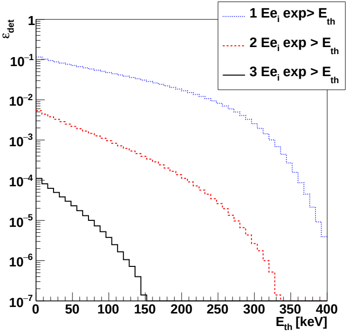




Studies of discrete symmetries

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

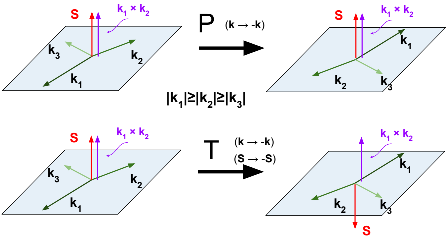
(P.A. Vetter et al., Phys. Rev. Lett. 91 (2003) 263401)

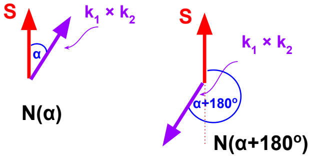
Operator	C	P	T	CP	CPT
$\vec{S}\cdot\vec{k}_1 \times \vec{k}_2$	$+$	$+$	$-$	$+$	$-$

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

effects of final state interaction

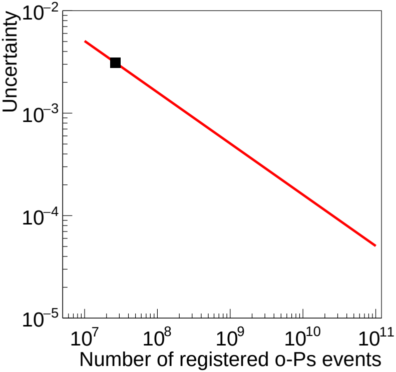
(W. Bernreuther et al., Z. Phys. C 41 (1988) 143)





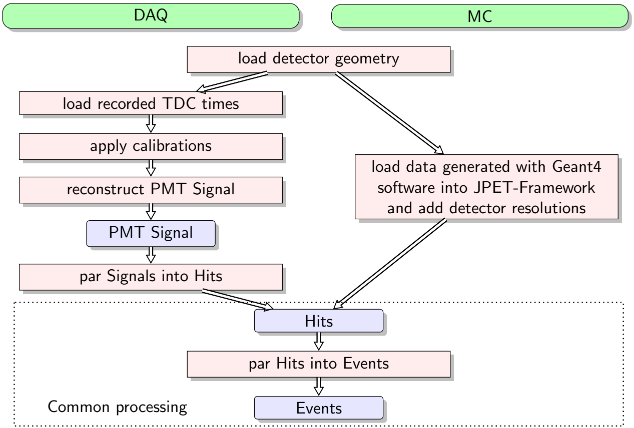
Observable: $A = \frac{N(\alpha) - N(\alpha+180)}{N(\alpha)+N(\alpha+180)}$

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



- $C_{CPT} = 0.0026 \pm 0.0031$ (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
  - ϵ_{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

Integration with J-PET Analysis Framework



- J-PET Framework is the analysis environment written in C++ for the low- and high-level data processing.
- provides adjusting of Geant MC output in framework structures (hit level)
- user can process MC in the same manner as collected data