



Studies of attenuation and detector geometry effects in two- and three-gamma positronium decays towards $3\gamma/2\gamma$ imaging using the Total-Body J-PET tomograph

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Total Body J-PET detector

J-PET:

- Positron Emission Tomography detector based on plastic scintillators
- Cost-efficient
- Multi-photon detection

Medical imaging:

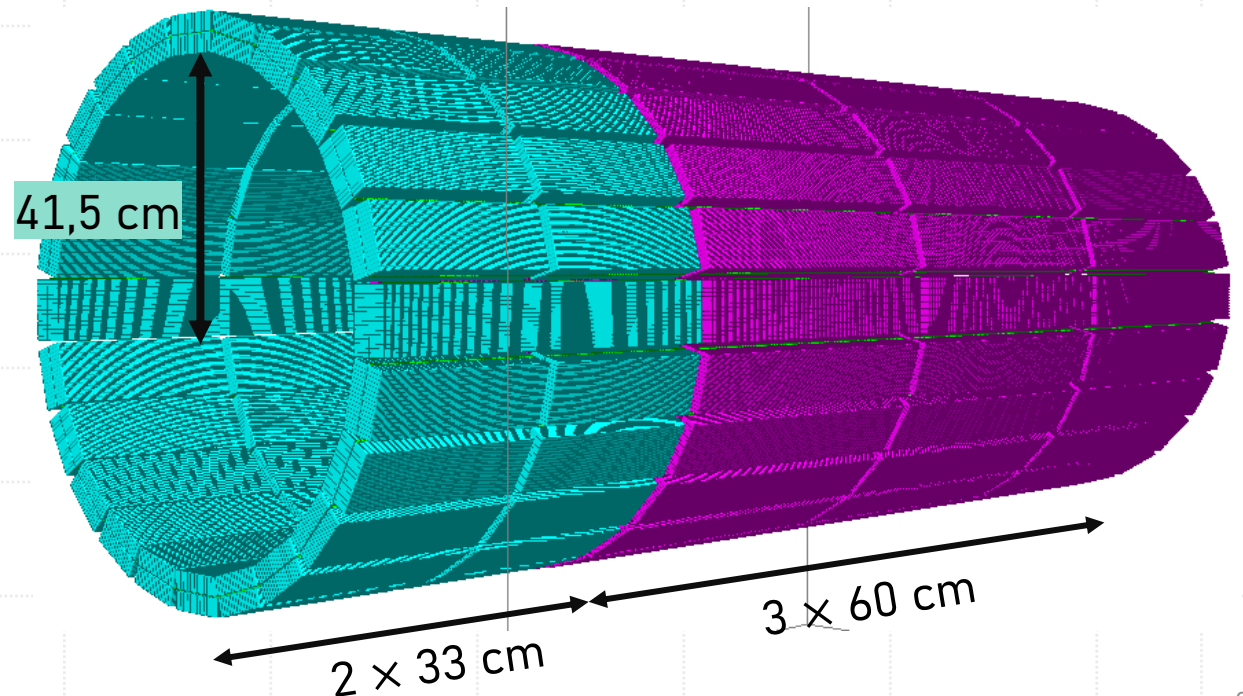
- **Total body PET**
- **Positronium Imaging**

Fundamental physics:

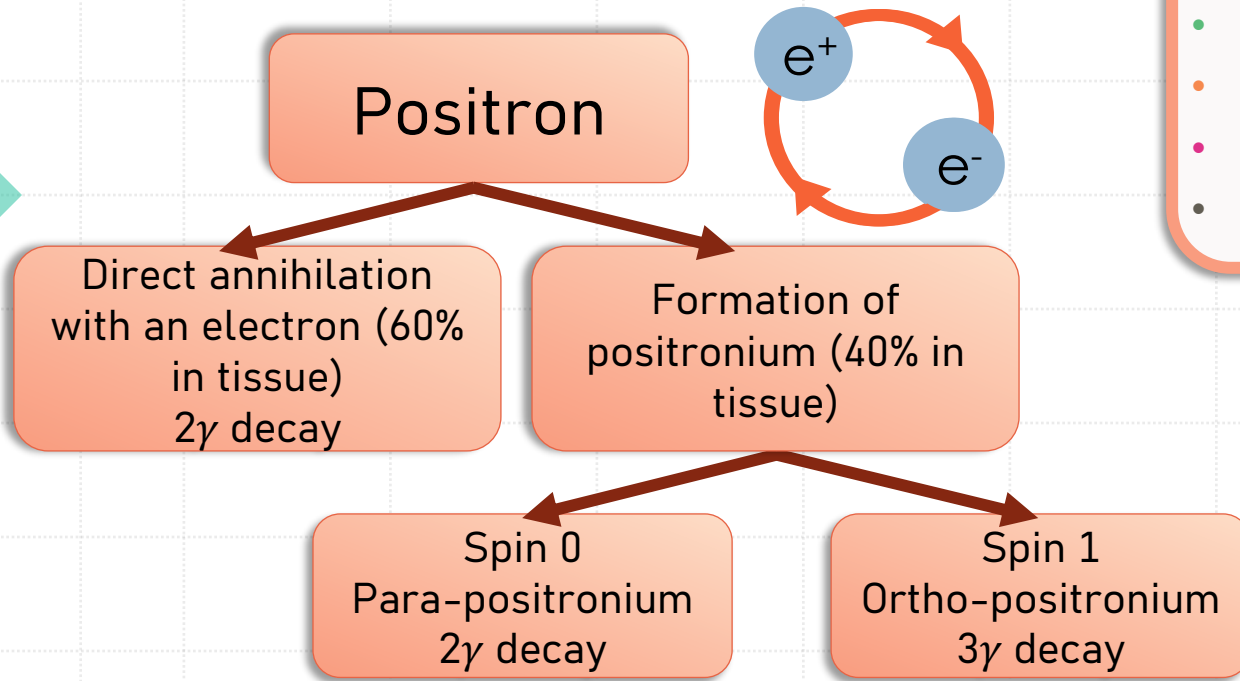
- Quantum entanglement
- Discrete symmetries

Total Body J-PET design:

- Plastic scintillator strips with dimensions 30×6 mm and 330 or 600 mm length
- 5 rings with 24 modules:
 - 2 rings with 330 mm strips
 - 3 rings with 600 mm strips
- 2 layers
- 16 scintillator strips per layer
- Total AFOV 254 cm



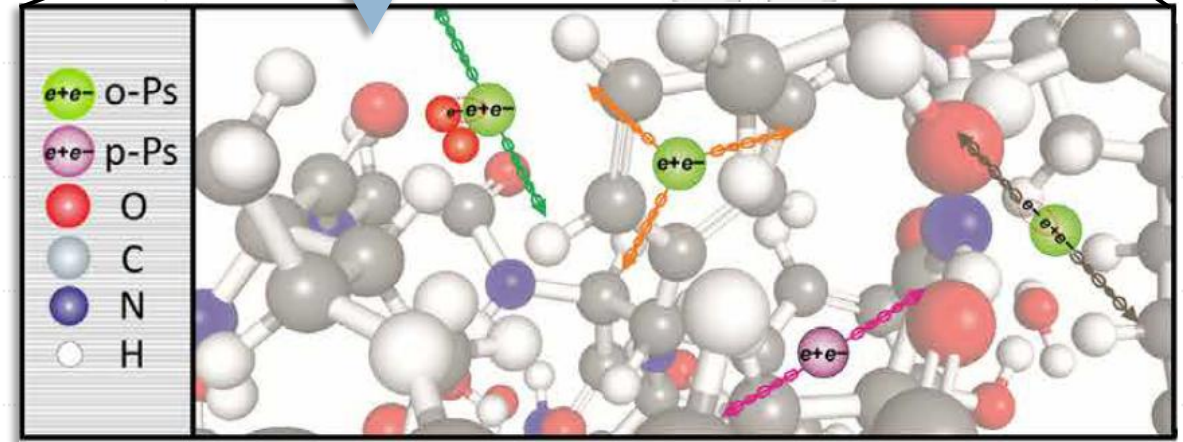
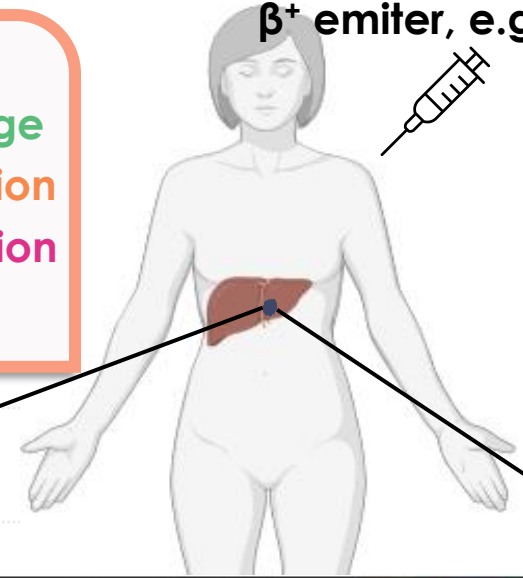
Positronium imaging



Positronium in the tissue:

- o-Ps $\rightarrow 2\gamma$ spin-exchange
- o-Ps $\rightarrow 3\gamma$ self-annihilation
- p-Ps $\rightarrow 2\gamma$ self-annihilation
- o-Ps $\rightarrow 2\gamma$ pick-off

Radiopharmaceutical β^+ emitter, e.g. ^{68}Ga



J-PET collaboration:

- Promising results reported by Moskal et al. in Refs. [2, 3] regarding **Positronium Lifetime Imaging**
- Development of a complementary positronium imaging method based on the **$3\gamma/2\gamma$ annihilation ratio** $\rightarrow$ needed corrections for physical processes (e.g. **attenuation**)

Volume of free spaces $\uparrow$
Oxygenation $\downarrow$

o-Ps lifetime $\uparrow$

$3\gamma/2\gamma$ ratio $\uparrow$

[2] P. Moskal et al. Science Advances 10 (2024), eadp2840

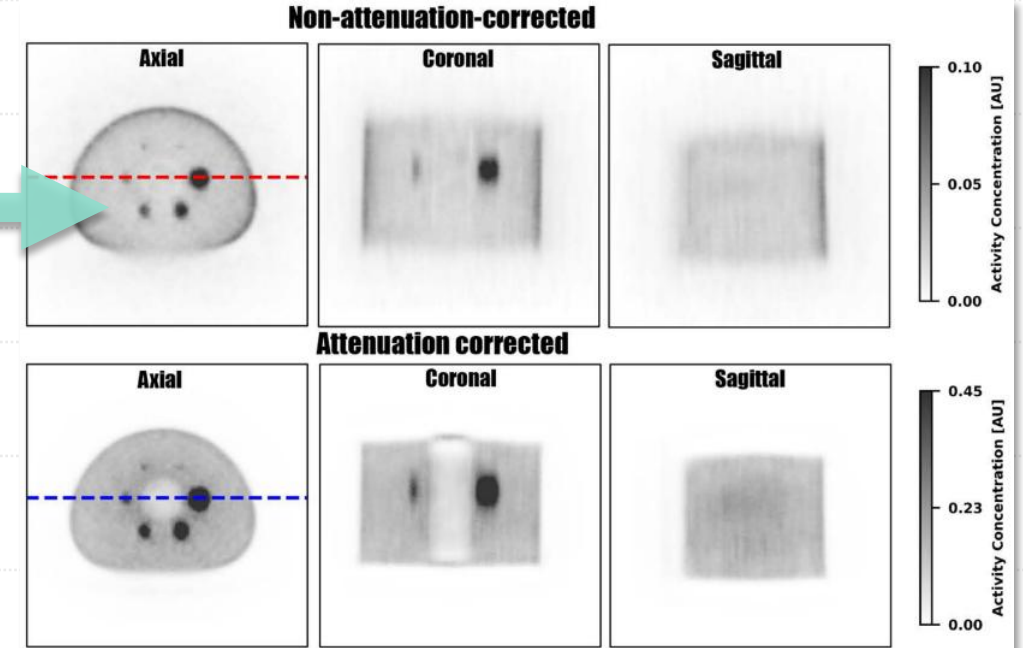
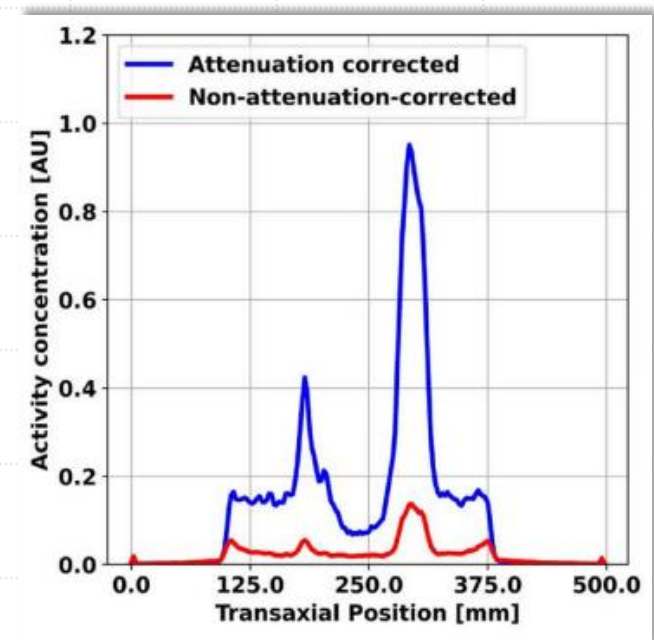
[3] P. Moskal et al. Science Advances 7 (2021), eabh4394

Attenuation correction

Absorption of gamma quanta in tissues

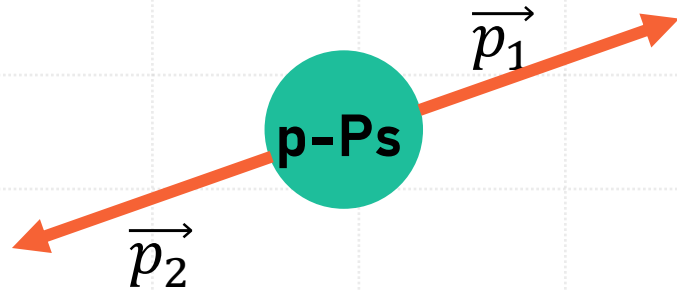
Underestimation of radiopharmaceutical concentration in deeper tissues

- J-PET: CT-based attenuation correction **for two-gamma imaging** [4]
- Standard attenuation maps – **not sufficient** for three-gamma imaging
- Absorption map → a basis for developing 3 γ attenuation correction



Monte Carlo simulation

Para-positronium

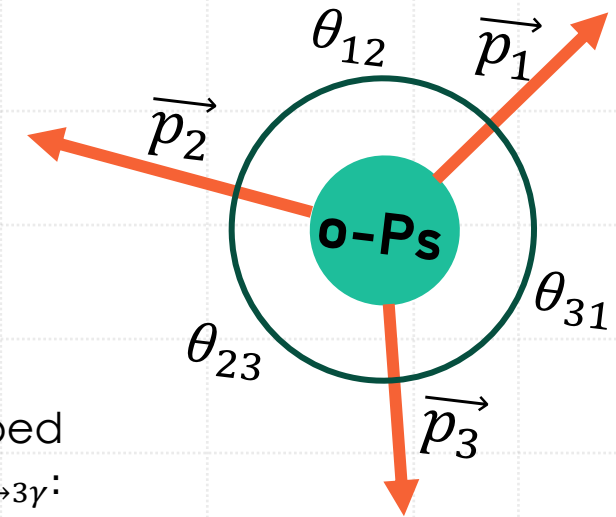


Isotropic decay into 2 back-to-back photons with energies of 511 keV

Decay simulation:

1. Randomizing the direction of $\vec{p}_1$
2. Assigning the energy of 511 keV
3. Determining the momentum $\vec{p}_2 = -\vec{p}_1$

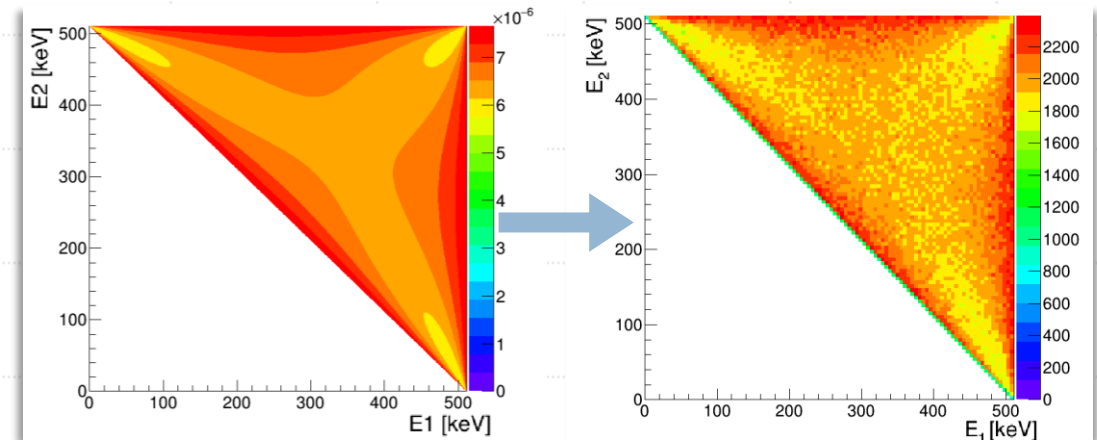
Ortho-positronium



Decay into 3 photons described with the matrix element $M_{oPs \rightarrow 3\gamma}$:

$$M_{oPs \rightarrow 3\gamma} = \left(\frac{m_e - E_1}{E_2 E_3} \right)^2 + \left(\frac{m_e - E_2}{E_1 E_3} \right)^2 + \left(\frac{m_e - E_3}{E_1 E_2} \right)^2,$$

where m_e - electron mass, E_1, E_2, E_3 - gamma quanta energies



Theory [5]

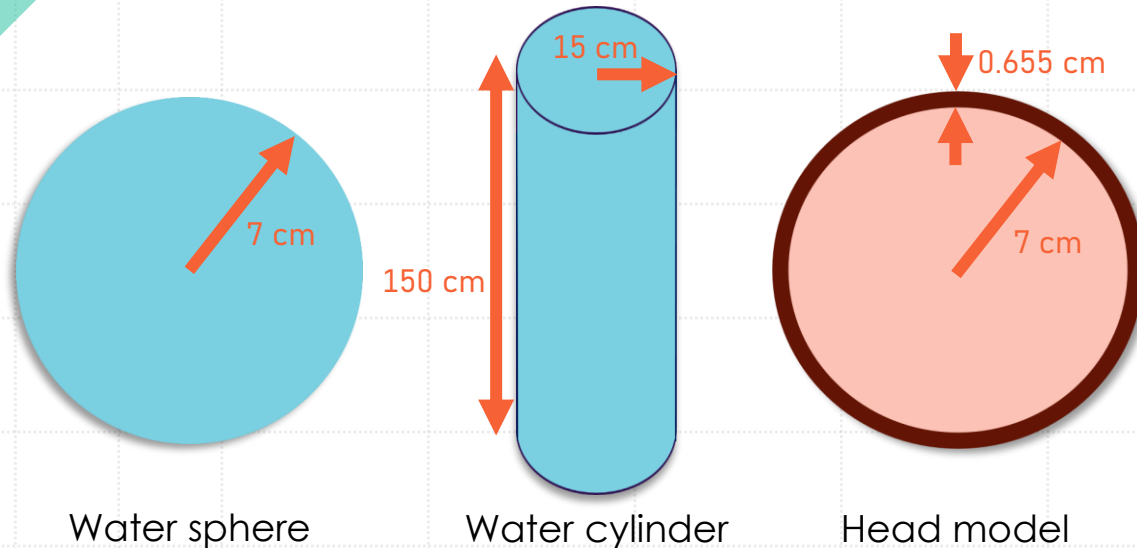
Simulation

[5] G. S. Adkins Phys. Rev. A 72 (2005), 4903

[6] K. Kasperska, M. Skurzok, P. Moskal Bio-Algorithms and Med-Systems vol. 21, Special Issue (2025), 42

Phantom models

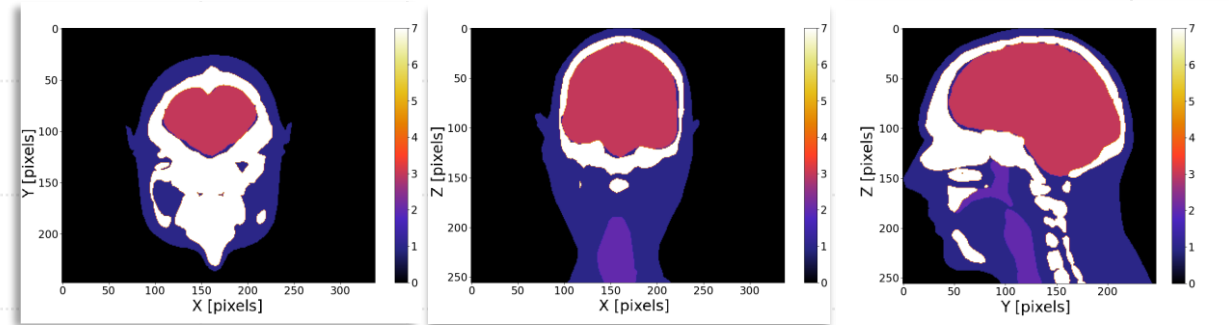
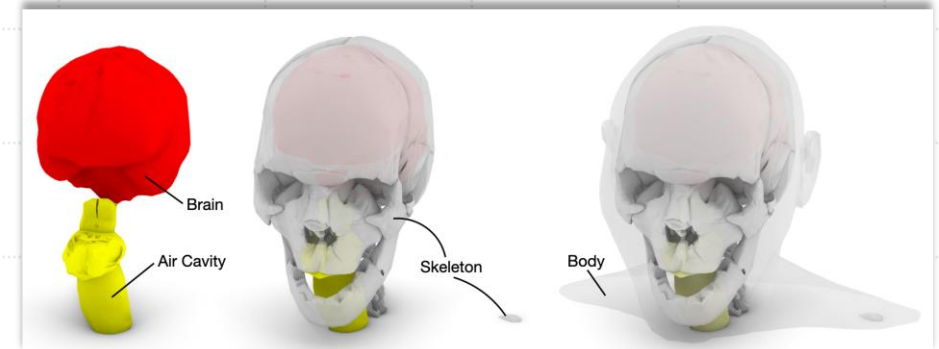
Simplified models



Simplified models were implemented in the toy Monte Carlo simulation. The results were validated through comparison with analogous simulations performed using the **GATE** toolkit [7].

- [7] S. Jan et al. Physics in Medicine and Biology 49 (2004), 4543
- [8] B. Auer et al. Physics in Medicine & Biology 68.7 (2023), 075015
- [9] B. Auer <https://github.com/BenAuer2021/Mesh-based-Human-Phantom-for-Simulation>

Human body phantom



Mesh-based **XCAT** phantom (mesh50_XCAT) developed and maintained by B. Auer [8, 9]

Source – voxelized version of the phantom

Simulations performed using the **GATE** toolkit [7] on CYFRONET AGH computing cluster (computational grants no. PLG/2024/017688 and PLG/2025/018762)

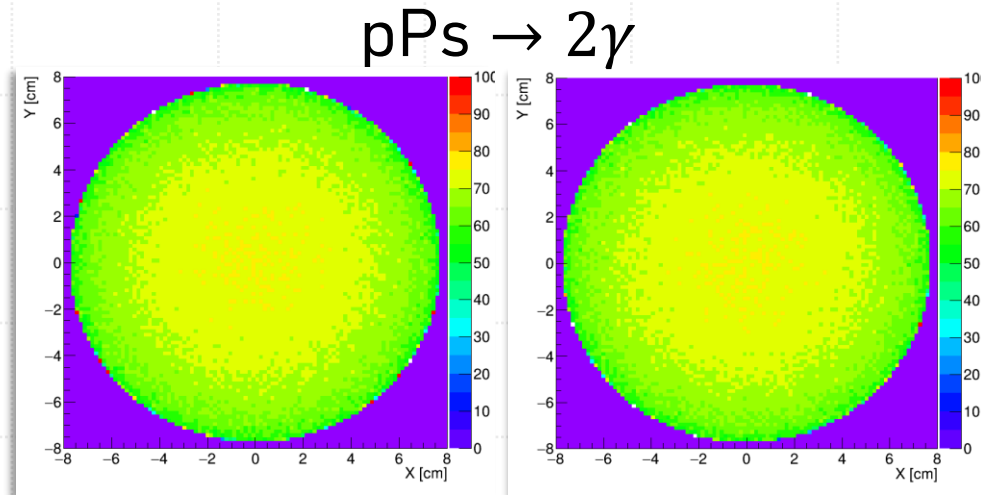
Results – simplified models

Simplified head model

- Percentage of gamma quanta pairs or triplets, from which **at least one** of the photons **interacted** with the model
- Specific to the annihilation point
- 10^7 events

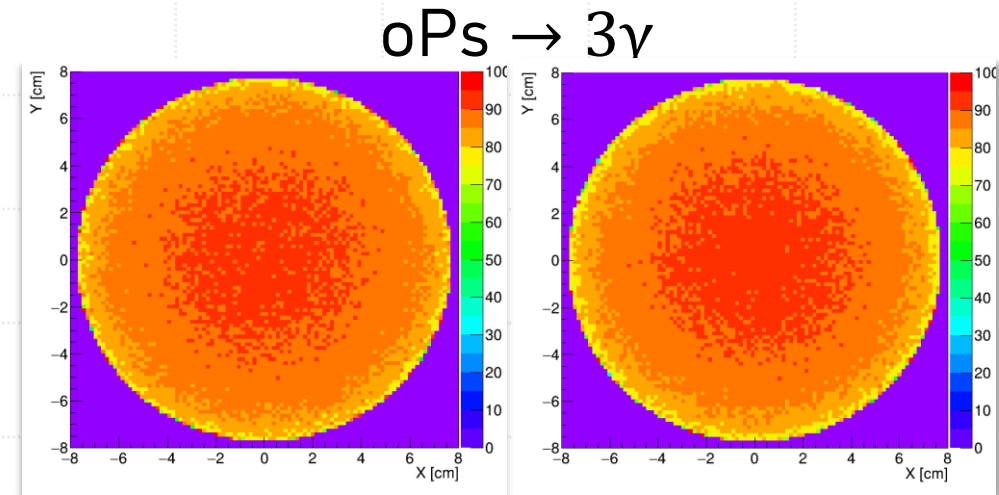
Surviving photon multiplets within the whole model

	Toy MC	GATE
p-Ps	30%	30%
o-Ps	12%	12%
$3\gamma/2\gamma$	0.39	0.39



Toy MC

GATE



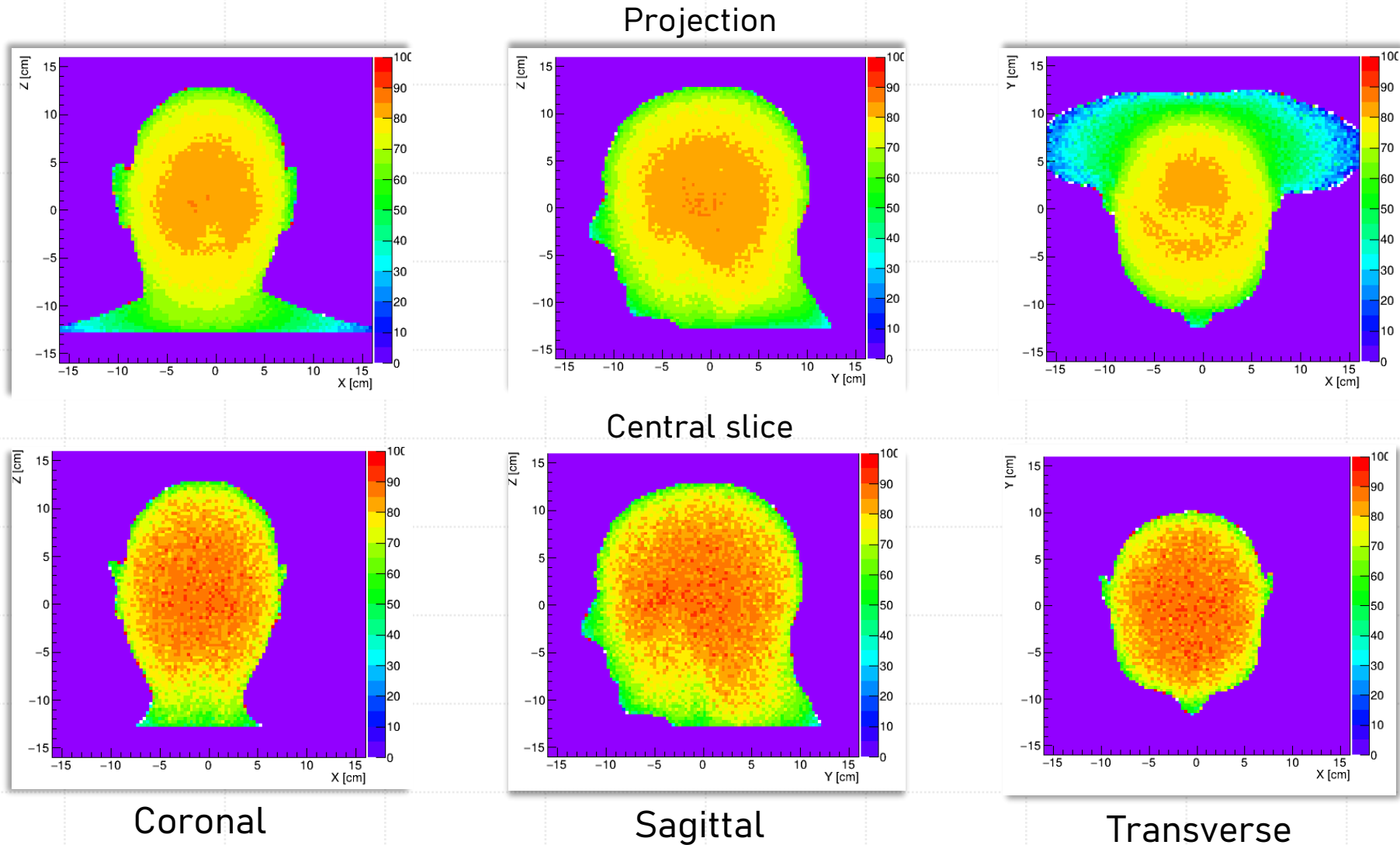
Toy MC

GATE

Results -XCAT phantom



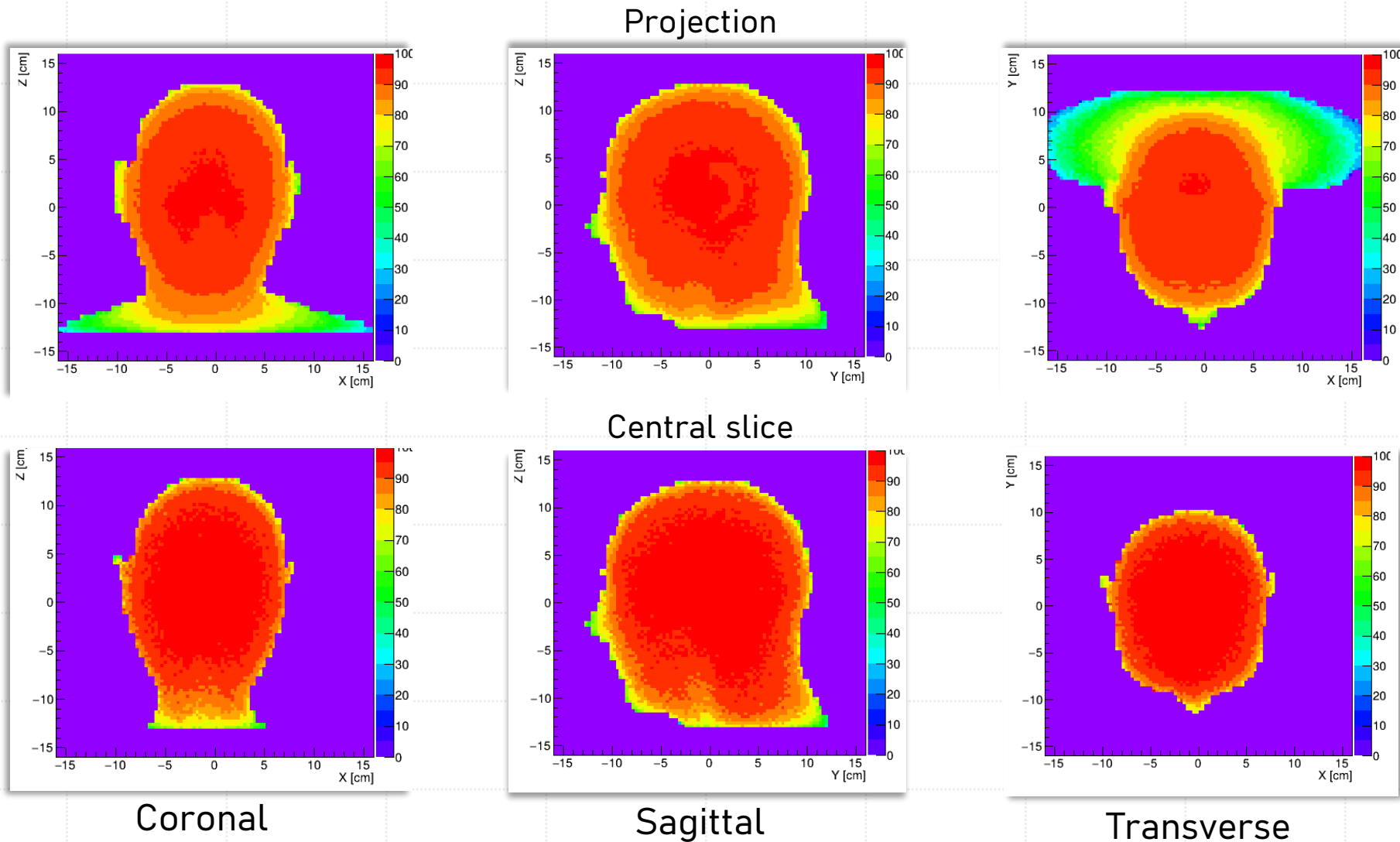
10^7 events, 25% pairs not absorbed



Results -XCAT phantom



$4.435 \cdot 10^7$ events, 10% triplets not absorbed



Introducing TB-J-PET detector effects into the simulation

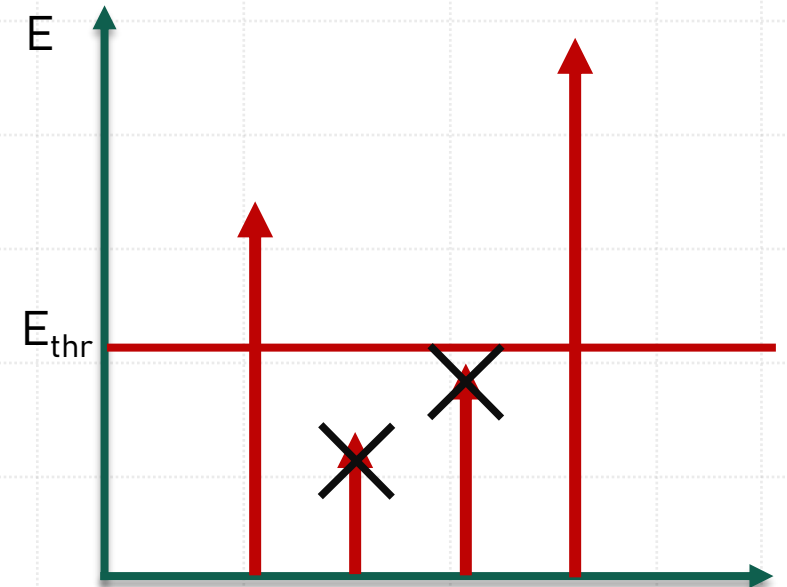
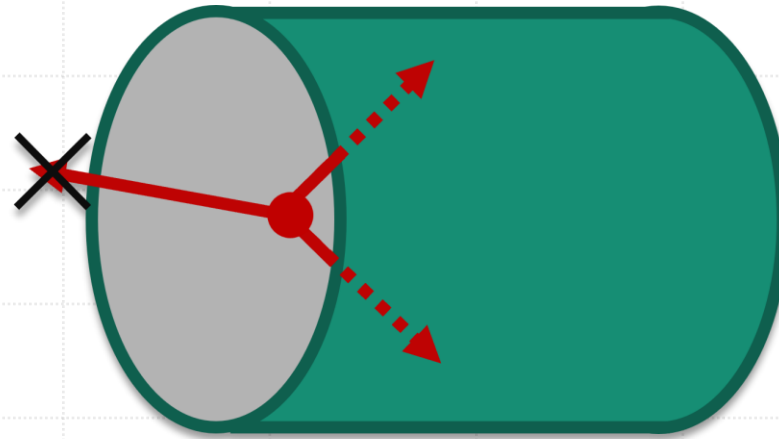
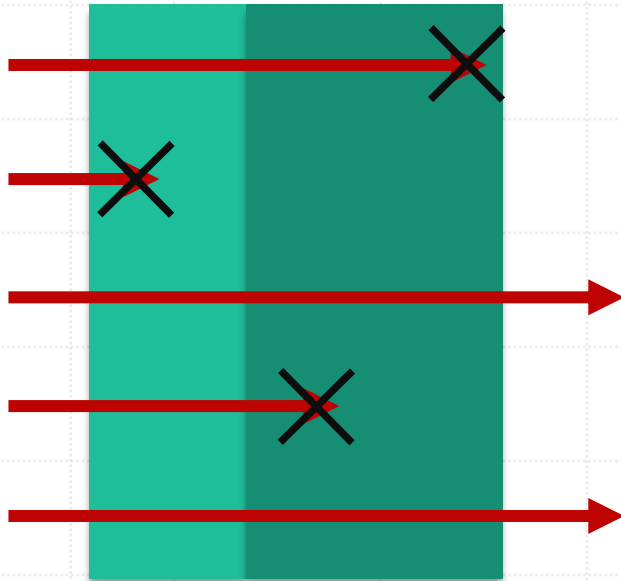
absorption

+

geometrical acceptance

+

detection energy thresholds

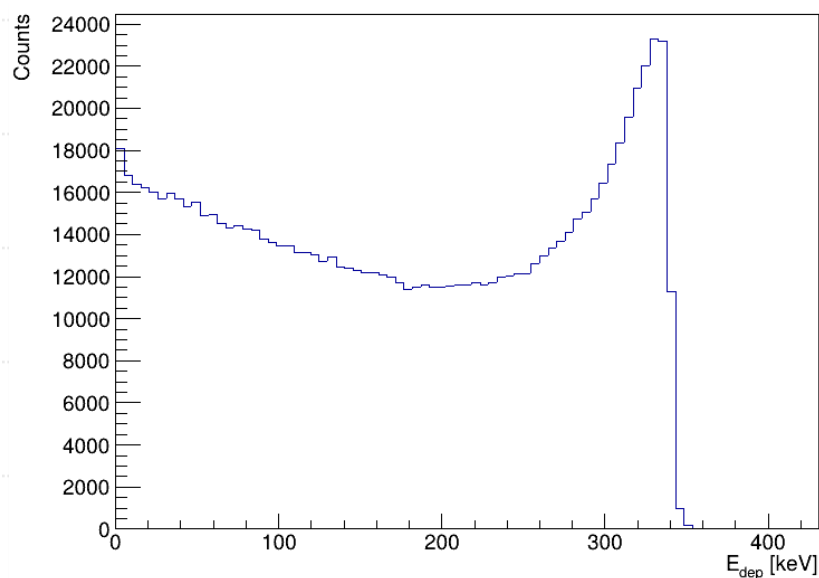


Results -XCAT phantom

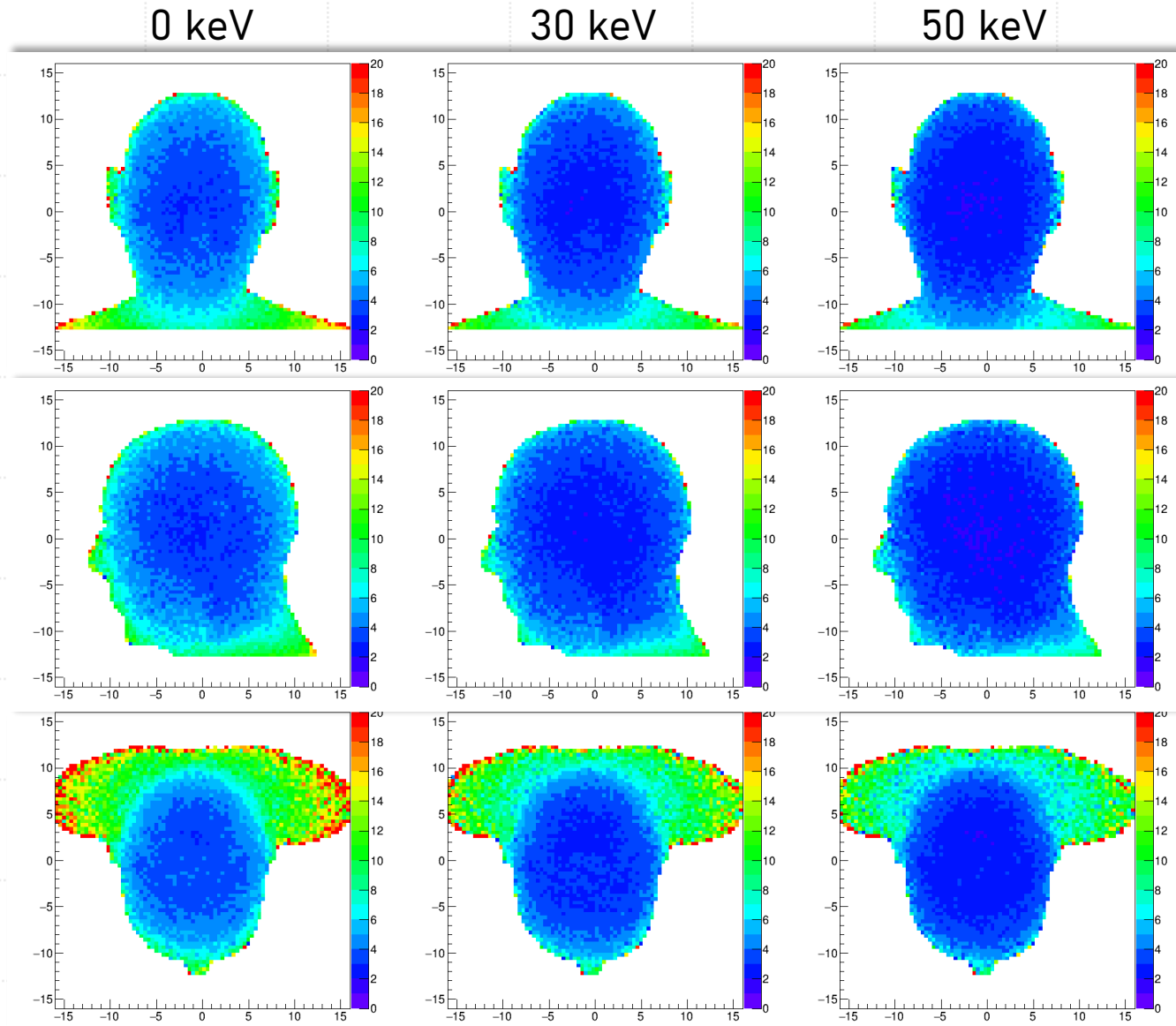
10^7 events



Energy deposition threshold:



Photon Energy deposition



Coronal

Sagittal

Transverse

Registered events:

4.7%

3.8%

3.3%

Results -XCAT phantom

$4.435 \cdot 10^7$ events

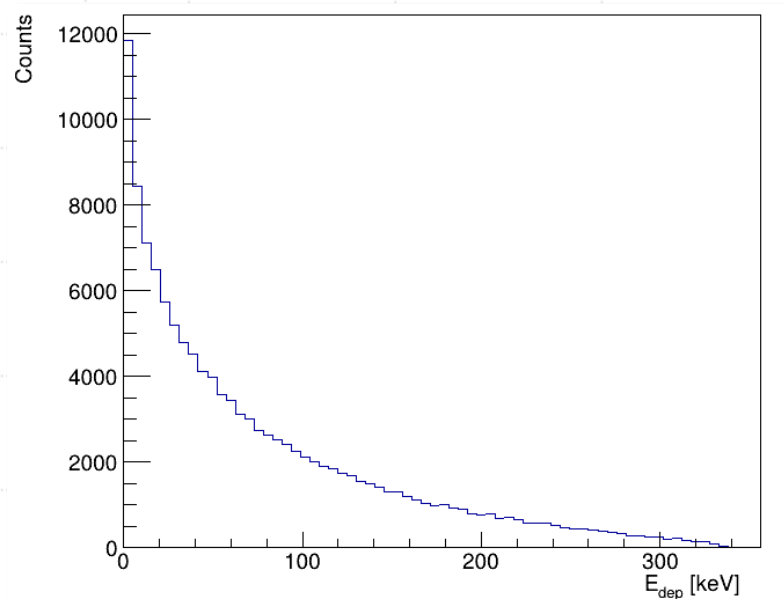
$o\text{-Ps} \rightarrow 3\gamma$

Energy deposition threshold:

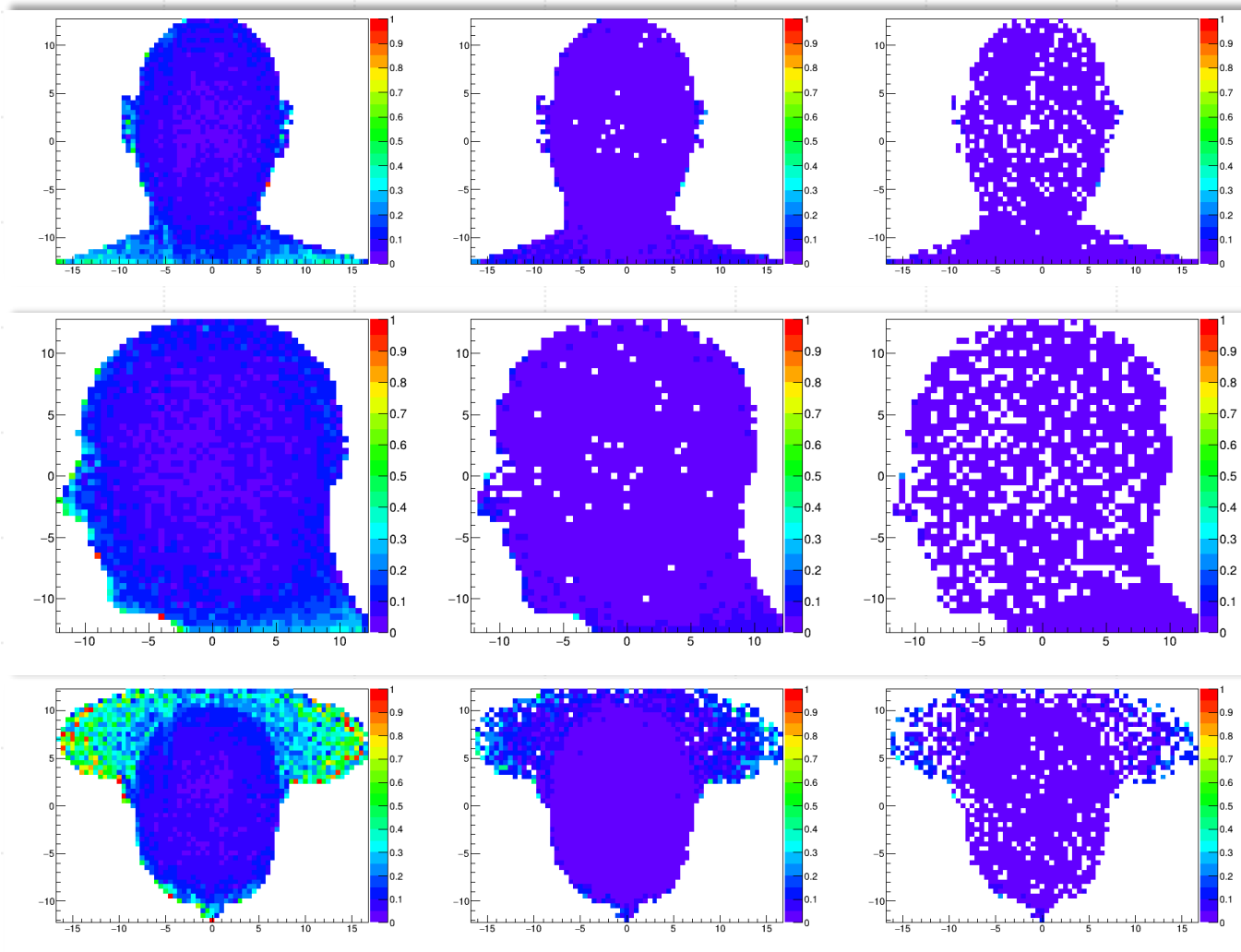
0 keV

30 keV

50 keV



Photon Energy deposition



Coronal

Sagittal

Transverse

Registered events:

0.094%

0.022%

0.009%

Summary and perspectives



Study of gamma absorption from $p\text{-Ps} \rightarrow 2\gamma$ and $o\text{-Ps} \rightarrow 3\gamma$ decays in different phantoms – a foundation for developing attenuation maps required for tomographic image correction

Used custom-developed toy MC simulation and GATE simulation toolkit to create emission-point-specific absorption maps

According to expectations – absorption of 3γ events significantly higher than that of 2γ events due to their lower energies

Significantly lower detection efficiency for 3γ events, due to limited detector acceptance

Small increases of energy thresholds cause substantial decrease of 3γ detection efficiency, while 2γ detection remains largely unaffected

Simulations using whole-body XCAT human Phantom



Simulations using a Phantom created based on the patient's CT scan



Thank you for your attention!

Acknowledgements

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