Analyzing scanning tables data using neural networks

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L'intelligence artificielle appliquée aux détecteurs semi-conducteurs,

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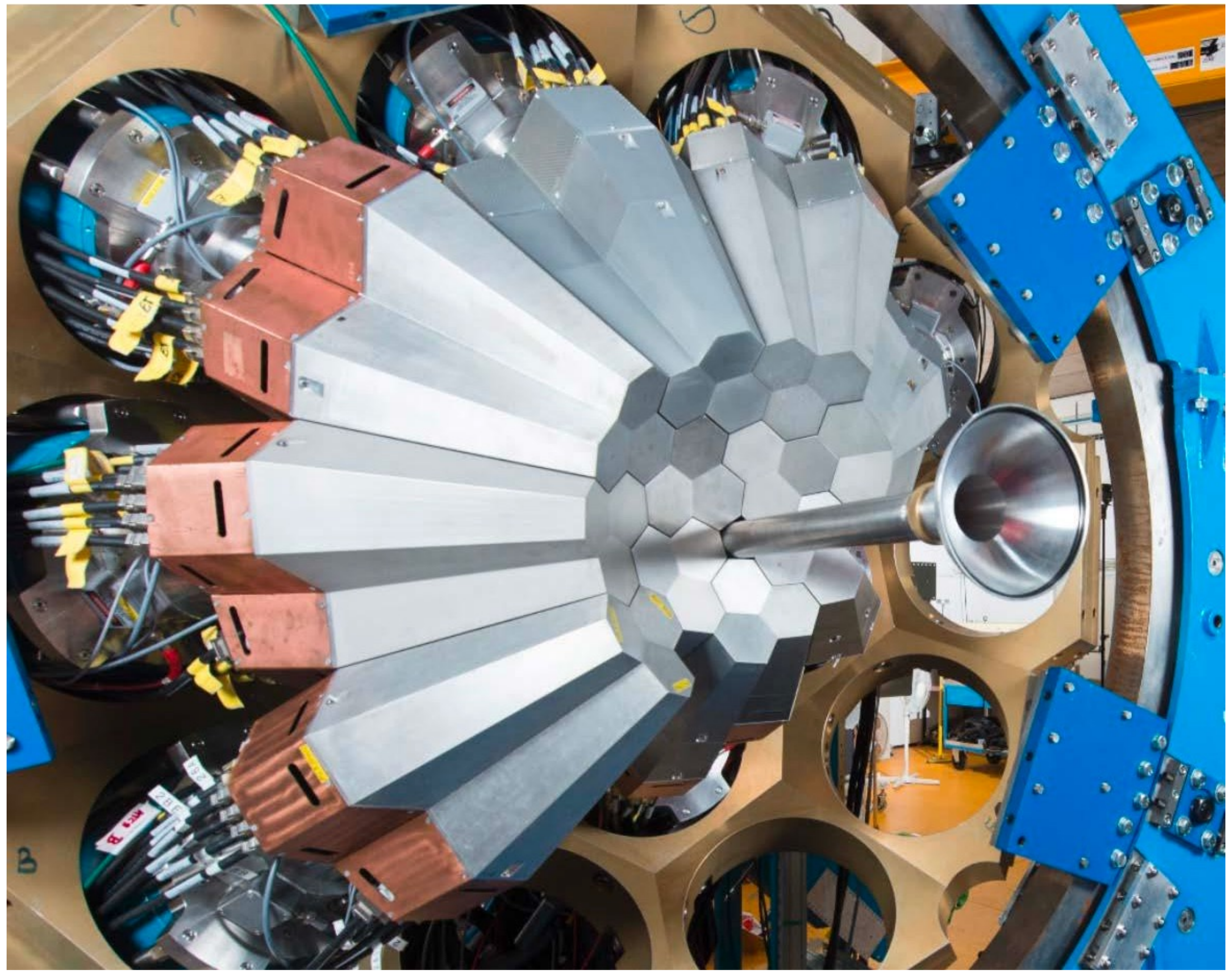
AGATA: State of the art for in beam gamma-ray spectroscopy

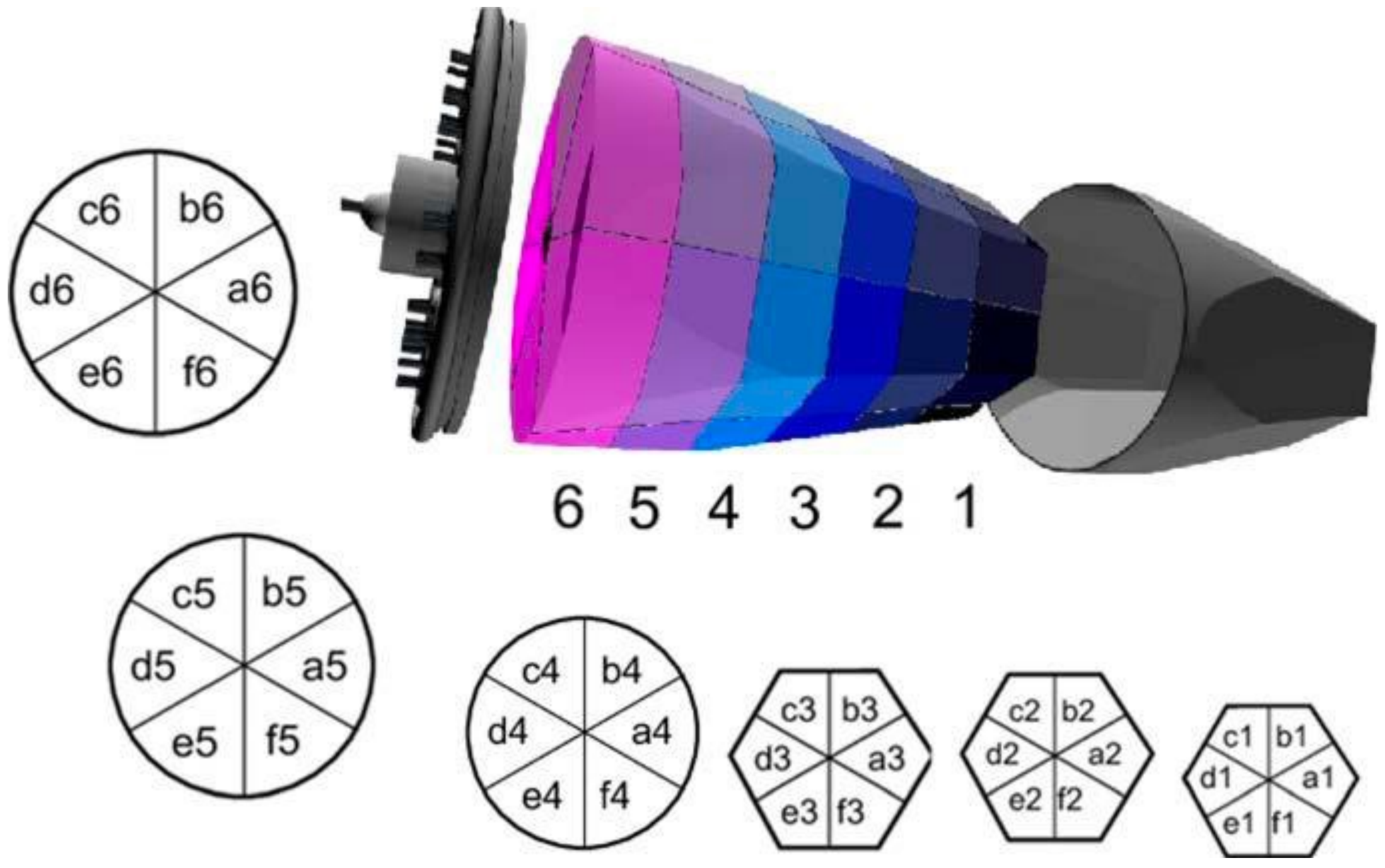
The AGATA array

- ➥ Consists of 50 **HPGe detectors**
  - ➥ (180 are planned to complete 4π sphere)
- ➥ Capable of **tracking gamma rays** in the Ge volume

AGATA crystals

- ➥ **Electric segmentation** in 6 layers and 6 sections
- ➥ **37 signals** for each gamma-ray interaction:
  - ➥ 36 segments
  - ➥ 1 signal for the full volume (core signal)

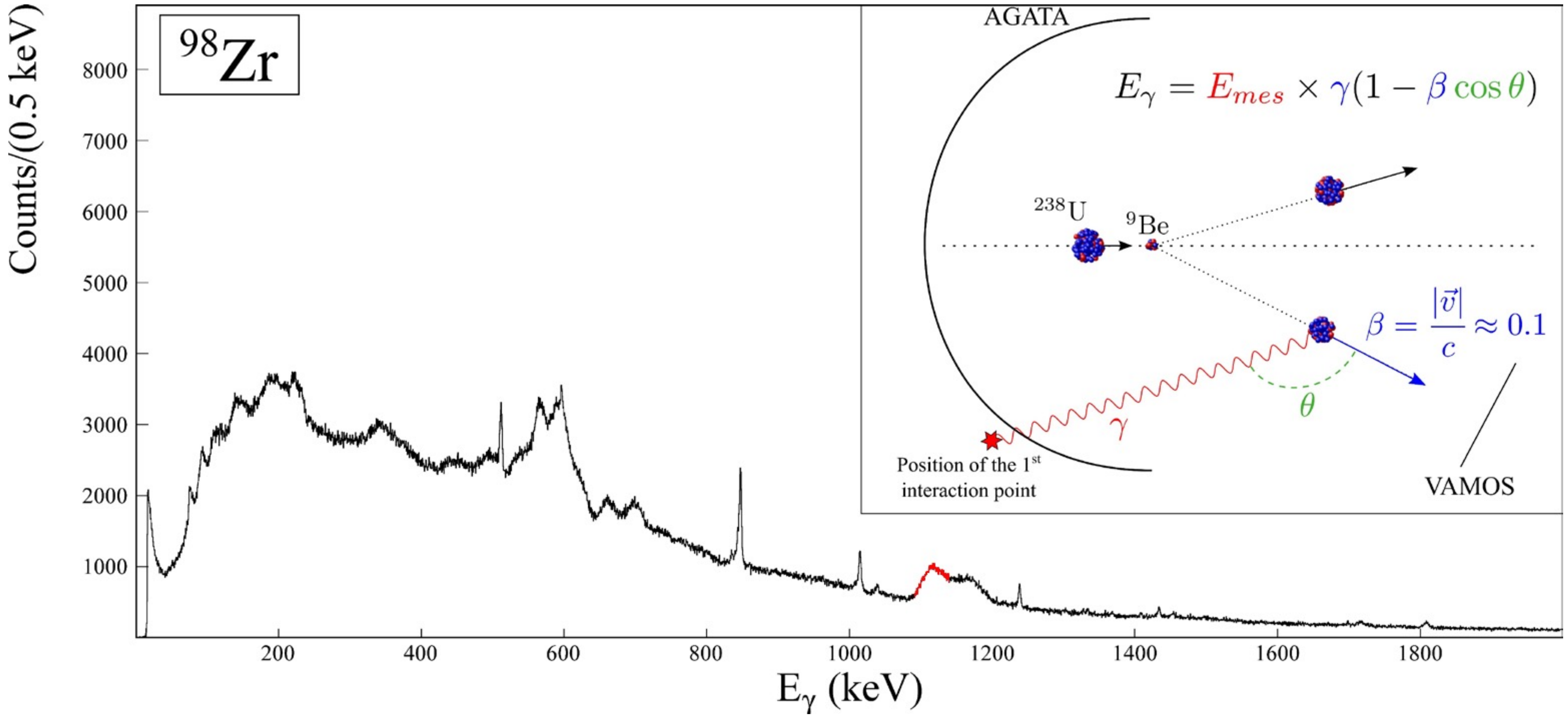




In-beam Gamma-ray spectroscopy

Doppler effect in γ-ray spectroscopy

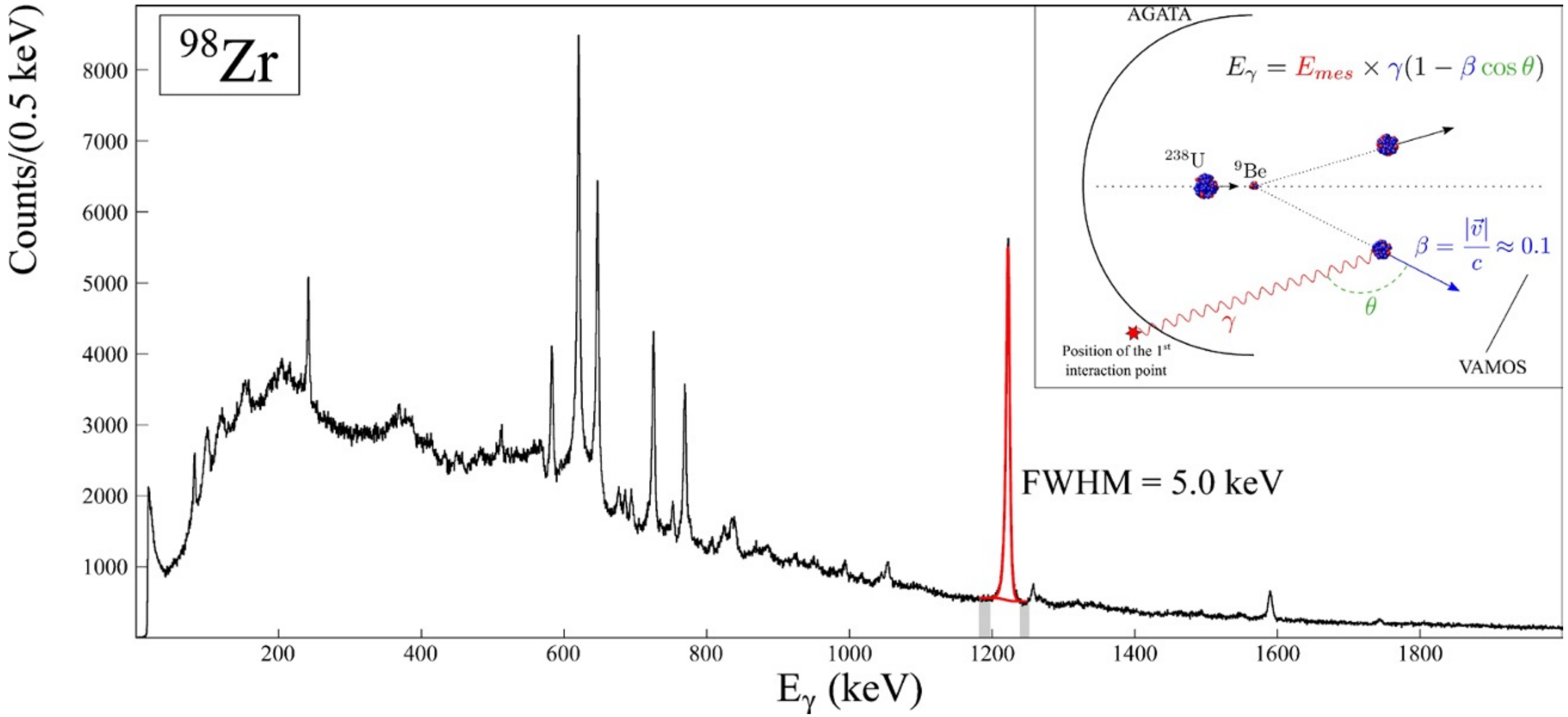
➡ Product nuclei are emitted at **high velocities**, leading to **significant Doppler broadening**.
➡ Visible peaks correspond to the ambient nuclear background of the experimental hall.
➡ In-flight emission transitions — **the scientific focus** — are **not exploitable in their current state**.



In-beam Gamma-ray spectroscopy

Doppler effect in γ-ray spectroscopy

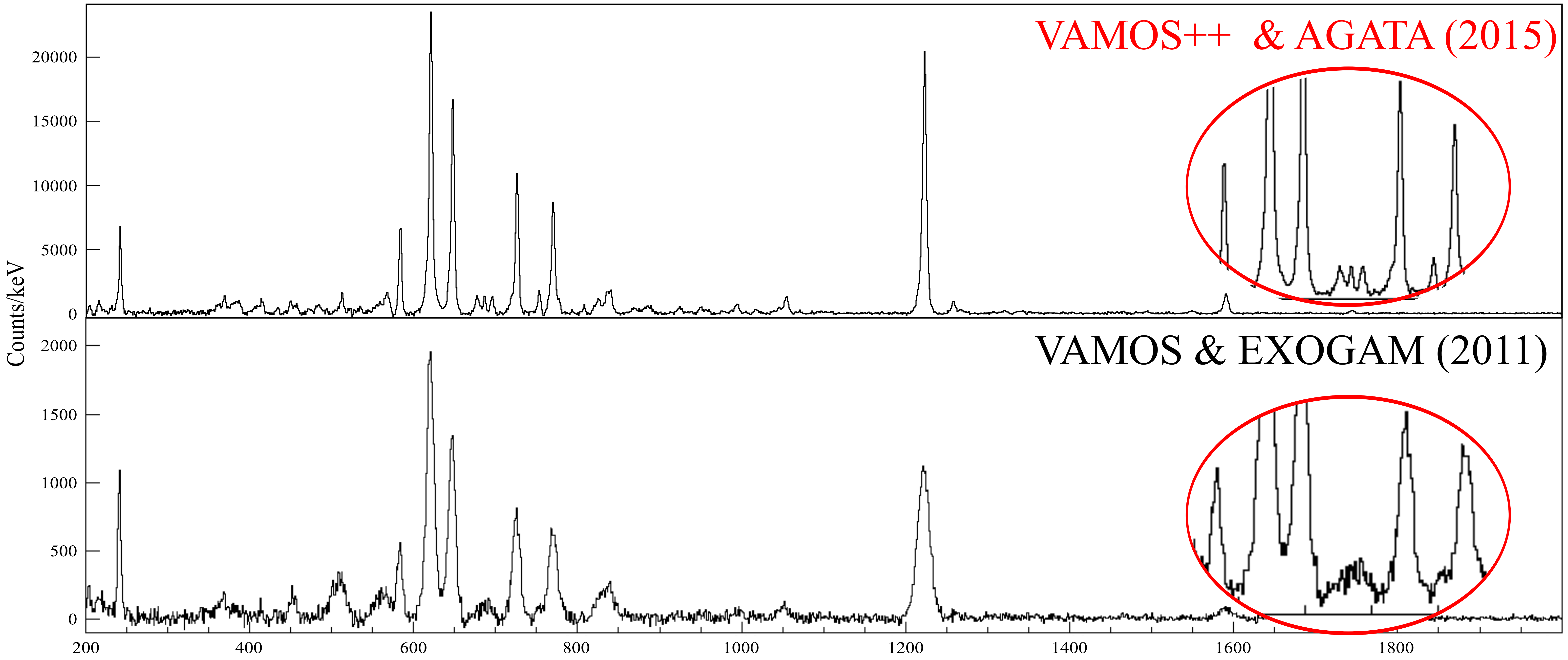
➡ Doppler correction requires knowledge of the **first γ-ray interaction point**.
➡ A final **energy resolution of 5 keV at 1223 keV** can thus be achieved.



In-beam Gamma-ray spectroscopy

Doppler effect in γ-ray spectroscopy

- ➡ Doppler correction requires knowledge of the **first γ-ray interaction point**.
- ➡ A final **energy resolution of 5 keV at 1223 keV** can thus be achieved.
- ➡ **AGATA's position resolution enabled a breakthrough in γ-ray spectroscopy sensitivity**.



How is the position of γ-ray interactions determined with AGATA ?

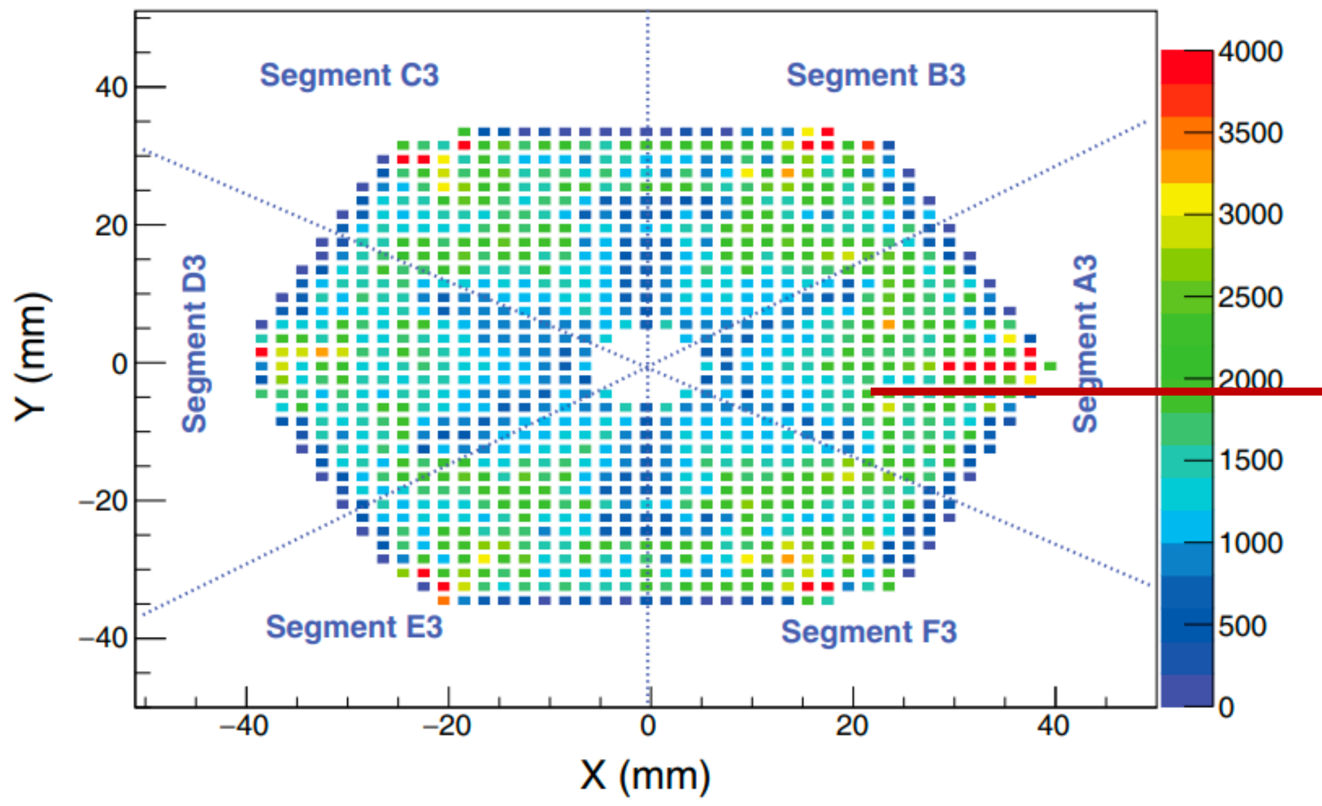
The Pulse Shape Analysis algorithm (PSA)

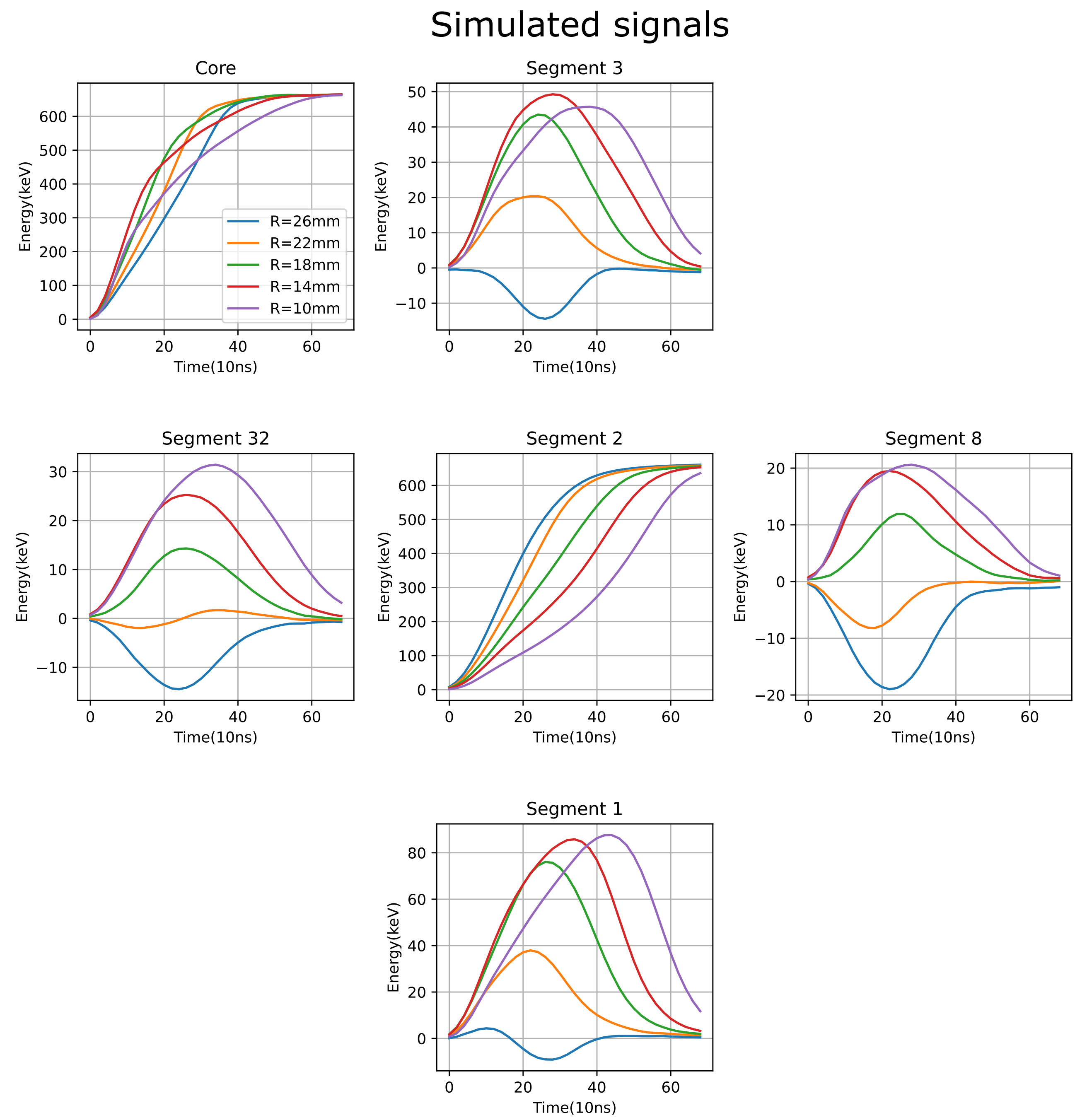
➤ Simulated database of signals:

➥ 2 mm Cartesian grid.
➥ 700-2000 simulated signals per segment.

➥ **Net charge** is collected only on the **core** and on the **fired segment** where the interaction occurs

➥ **Neighboring** segments exhibit **transient signals** due to the drift of charge carriers in the electric field





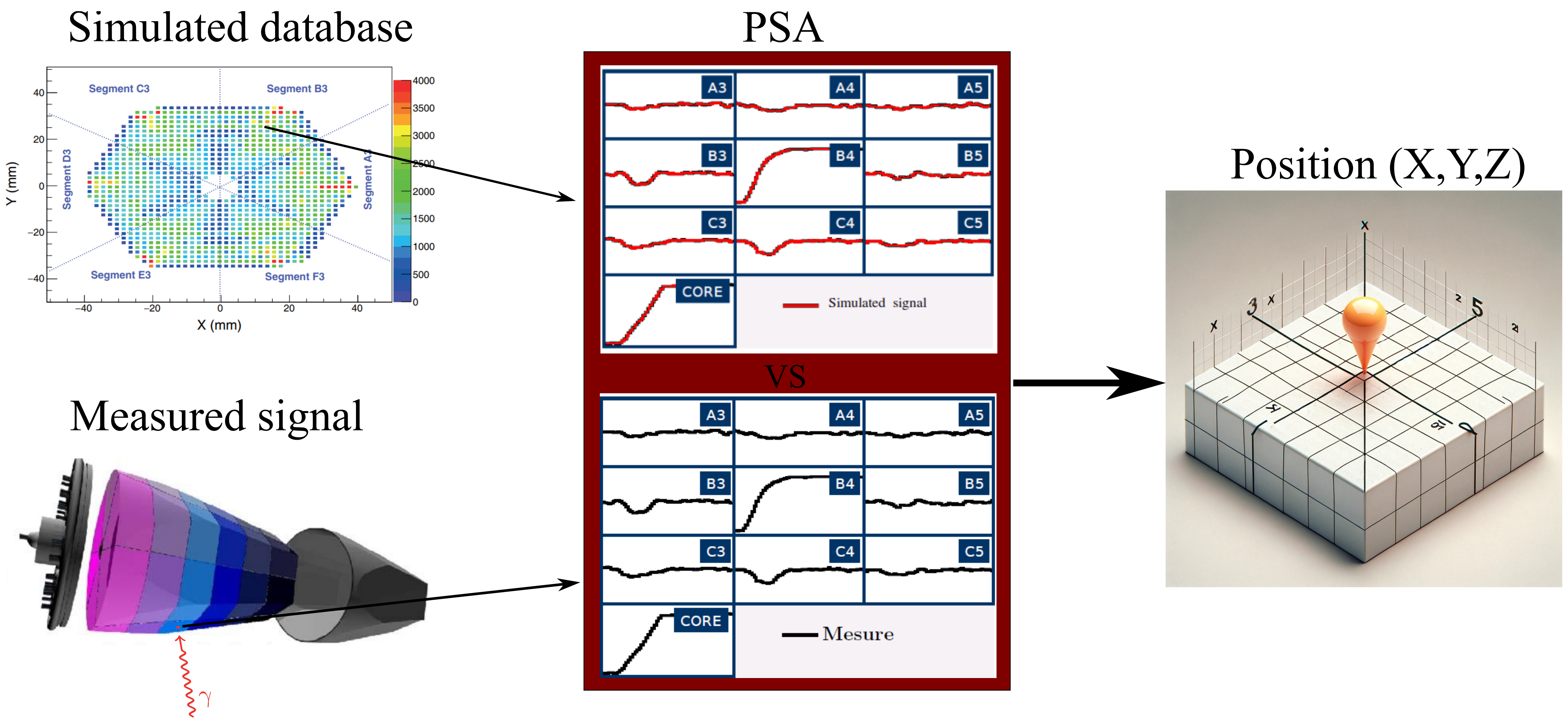
How is the position of γ-ray interactions determined with AGATA ?

The Pulse Shape Analysis algorithm (PSA)

➤ Grid Search algorithm for position extraction:

➥ The measured signal is compared to simulated signals using **χ^2 minimization**

➥ Average **position resolution of ~5 mm** over the detector volume.



What can be improved ?

➤ Is the PSA working ? YES

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YES, with a scanning table !

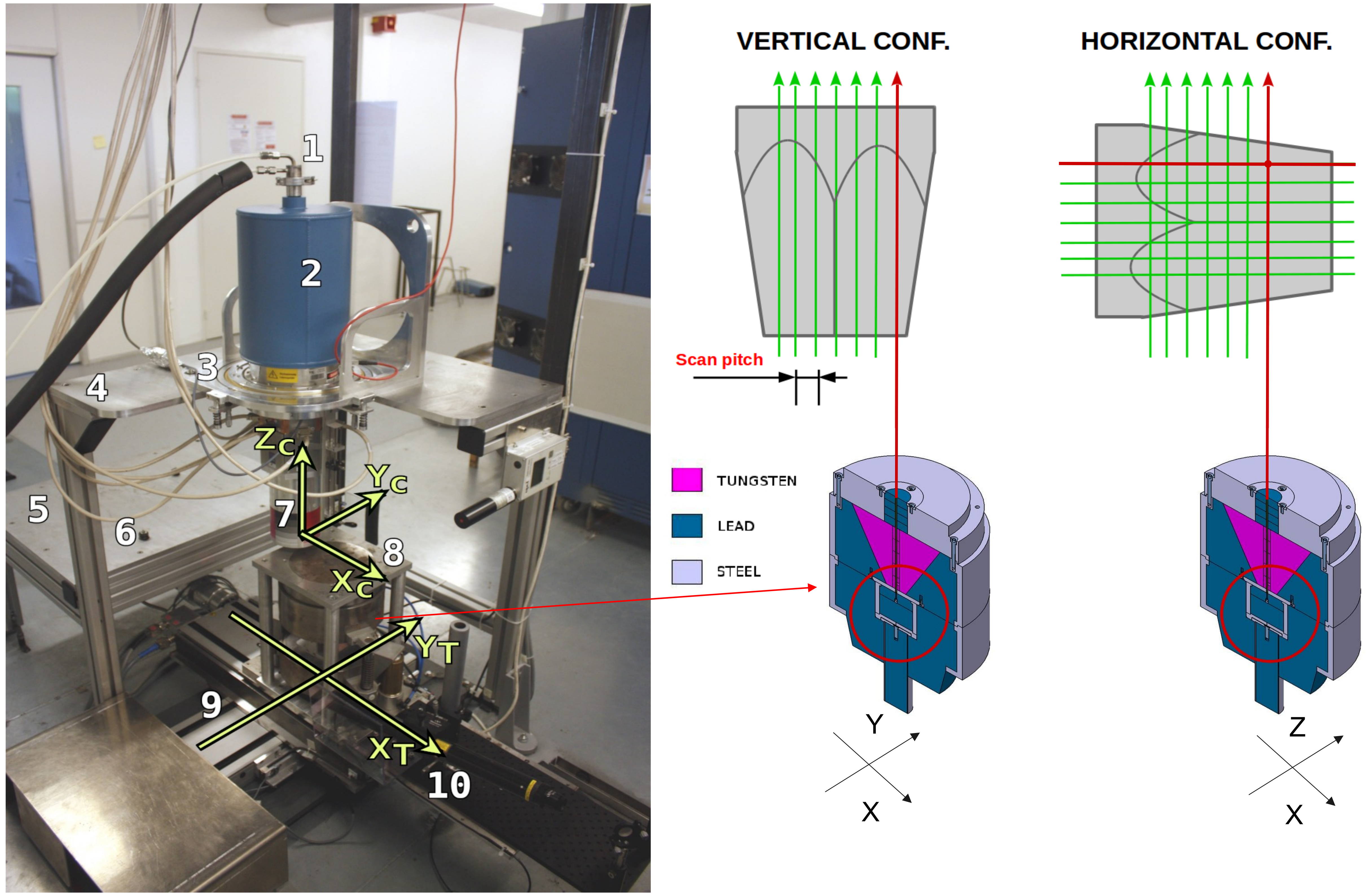
The Strasbourg scanning table

➤ Scanning capabilities:

- ➥ Motorized collimator (10 µm precision)
- ➥ Detector in vertical or horizontal position
- ➥ Laser alignment system

➤ Scanning concept:

➥ **3D** scan exists but are very time consuming. Full volume cannot be scanned in 3D.
➥ **Combination of two 2D scans** (vertical and horizontal)
➥ **3D basis** obtained by Pulse Shape Comparison Scanning method (**PSCS**)

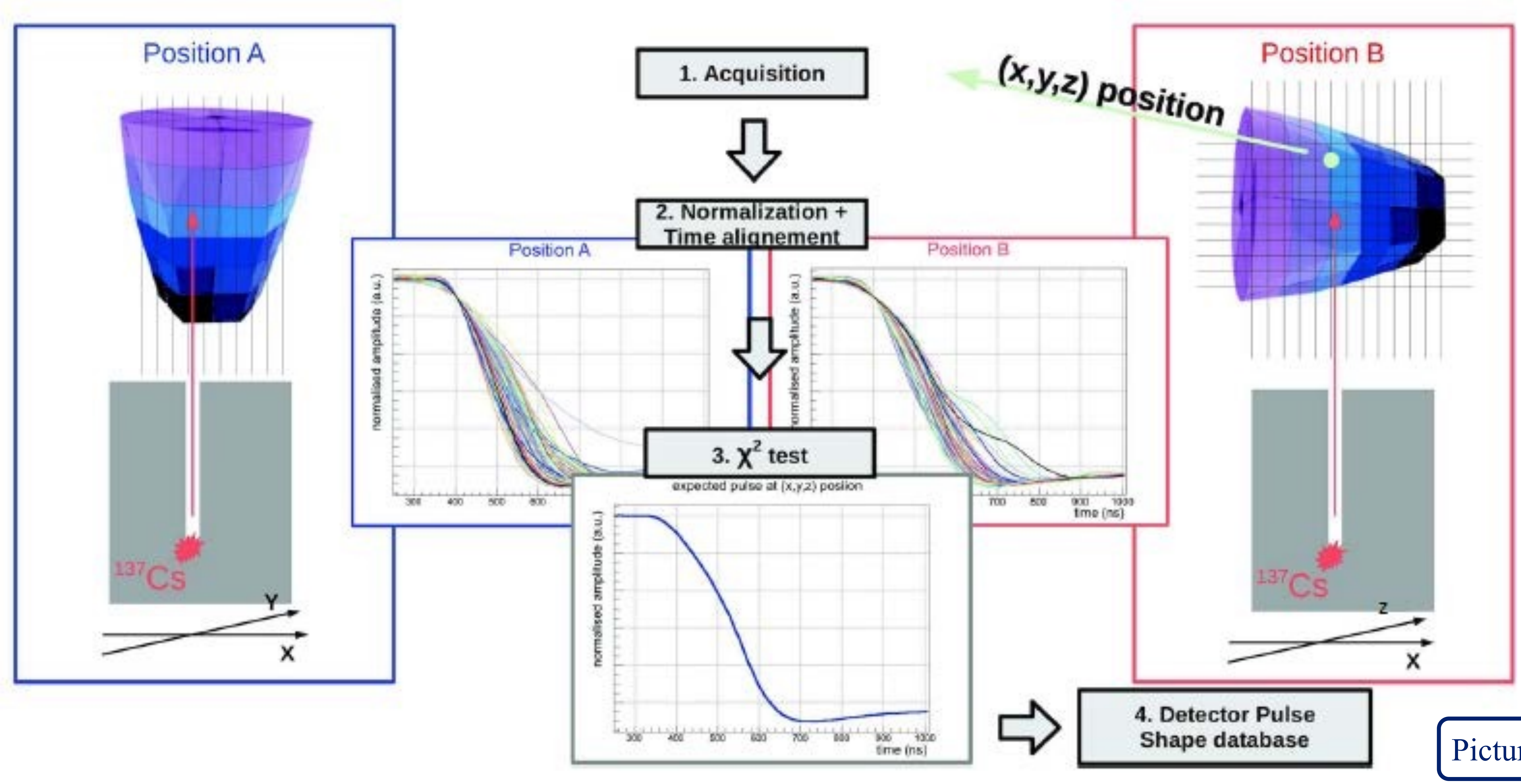


B. De Canditiis and G. Duchêne, Eur. Phys. J. A 56 (2020)

The Pulse Shape Comparison Scanning method (PSCS)

- 1 horizontal scan + 1 vertical scan
- the 3D basis is obtained by a combined analysis of both data-sets.
- Validated and published method, but time consuming (5 days for the PSCS analysis)

B. De Canditiis et al., Eur. Phys. J. A 57 (2021), B. De Canditiis and G. Duchêne, Eur. Phys. J. A 56 (2020)

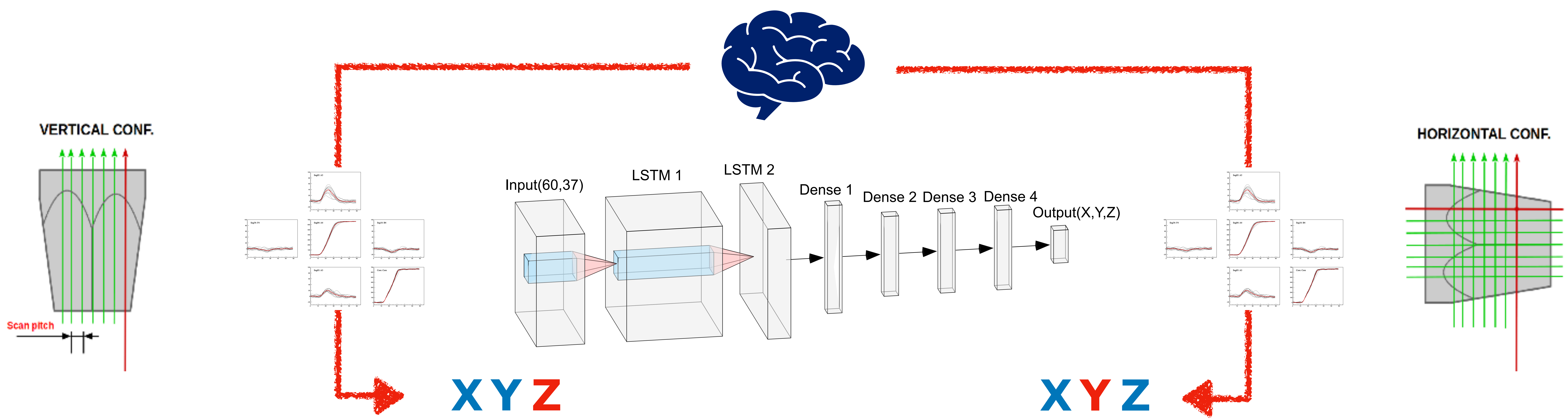


Picture from Michael Ginsz's PhD thesis

New method proposed @ IP2I based on neural networks

- **2 Long short-term memory (LSTM) layers** were used as starting point.
  - ➥very robust against time misalignment
- 4 dense layers are added to obtain a 3D output (X,Y,Z)
- **Masked loss function:** calculated only for the two known axes
  - ➥ this allows the network to learn patterns of each dataset without affecting the other.

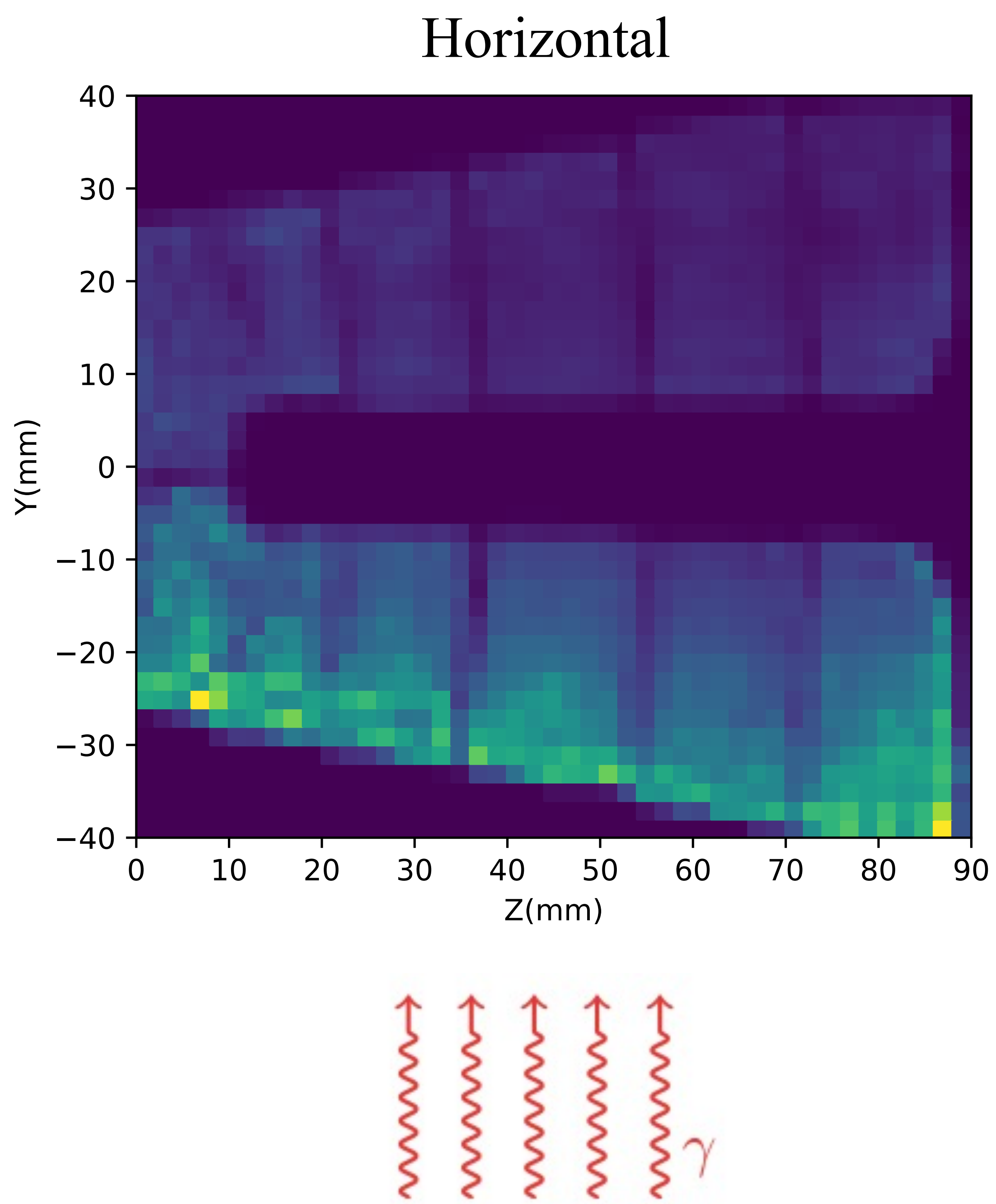
Trained Neural network

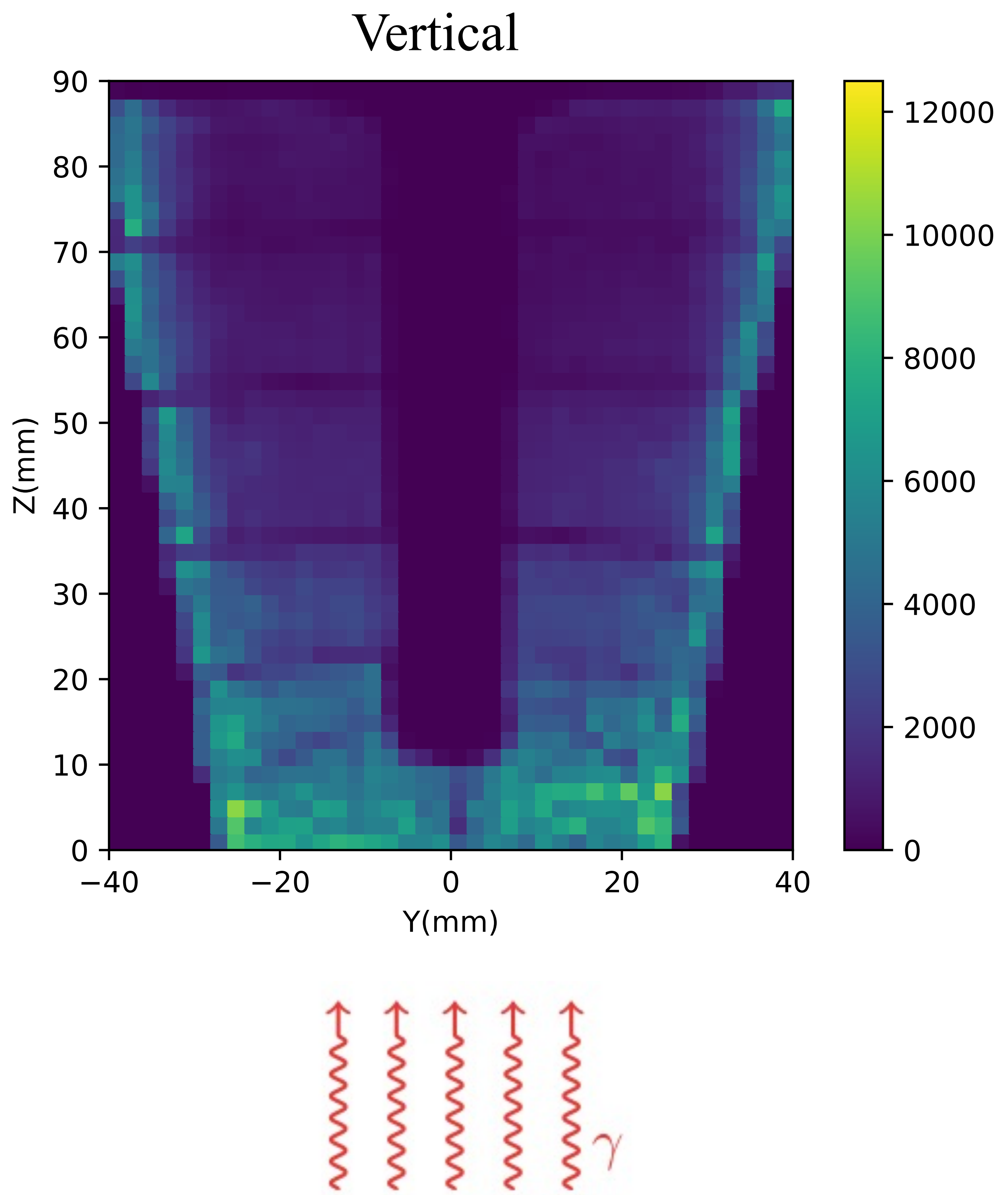


Neural network results

➤ The distribution of the **predicted positions conforms with the attenuation of the gamma rays.**

Predicted positions in (Y,Z) plane for X in [-3 mm ; 3 mm]

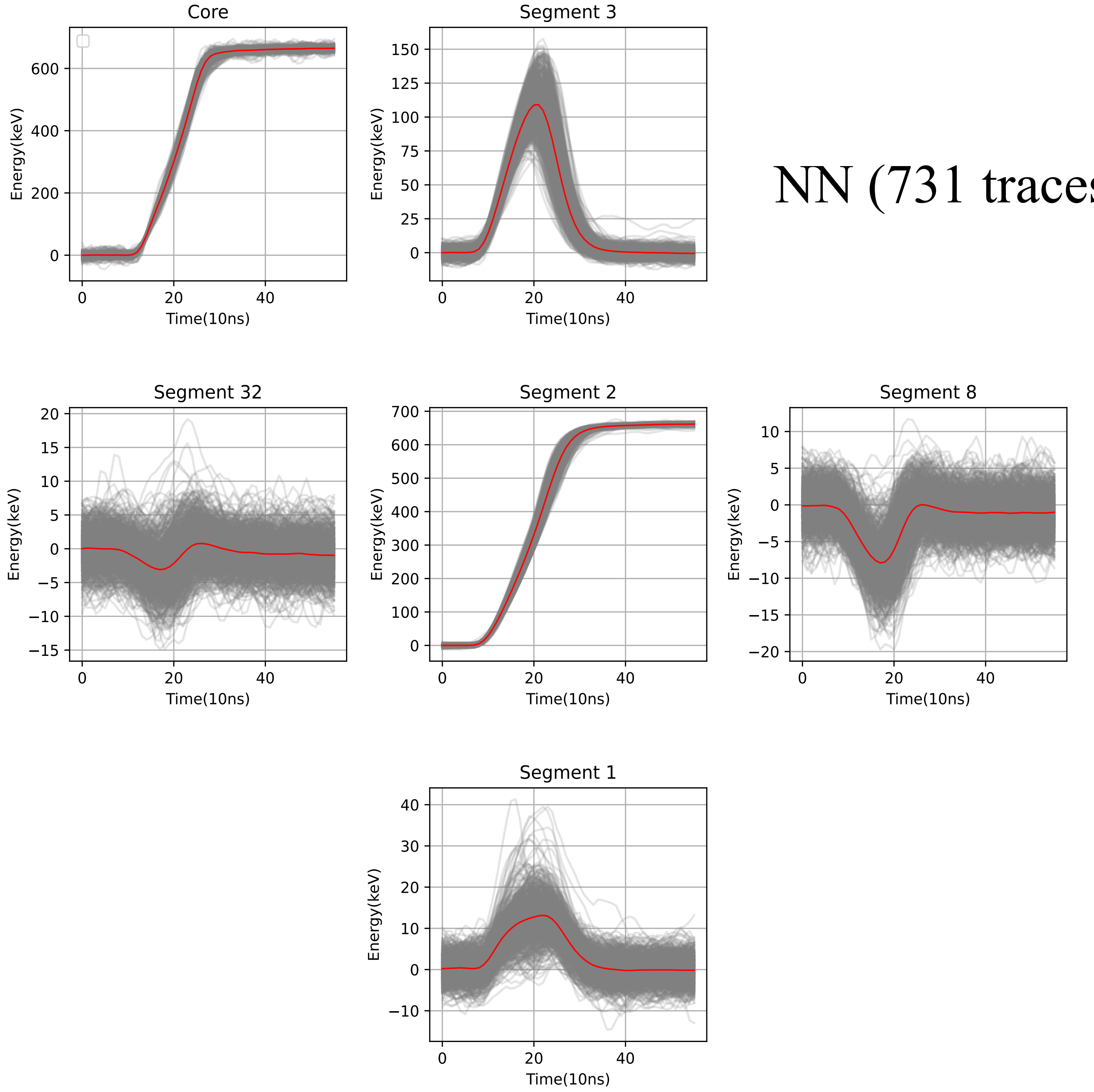




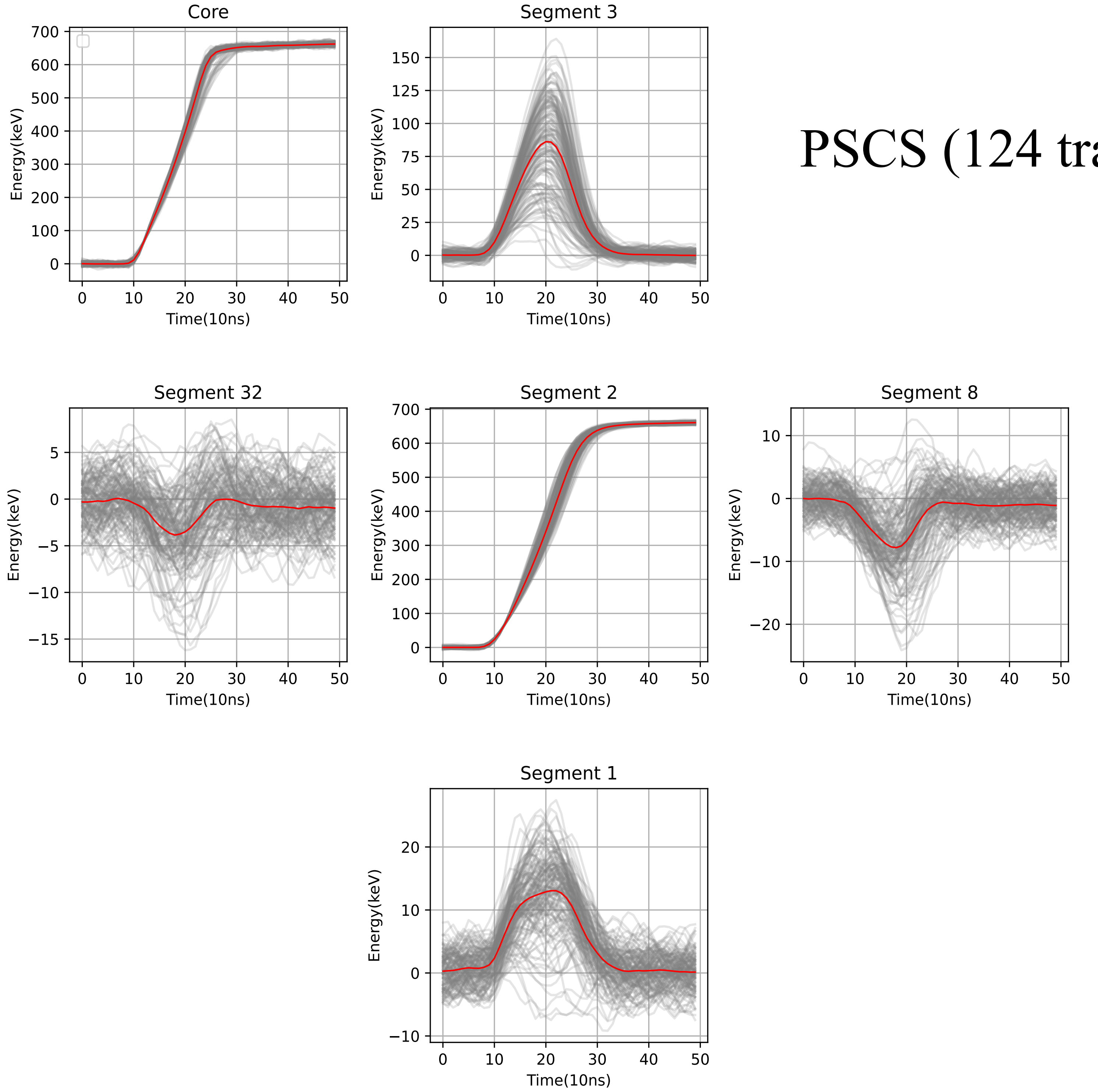
Model consistency: Neural Network vs PSCS

- **Signals predicted at the same position should have the same shape**.
- Average trace between Neural network and PSCS looks similar but **more statistics and less fluctuations in NN**

Traces predicted at position (22,0,34) in segment 2



NN (731 traces)

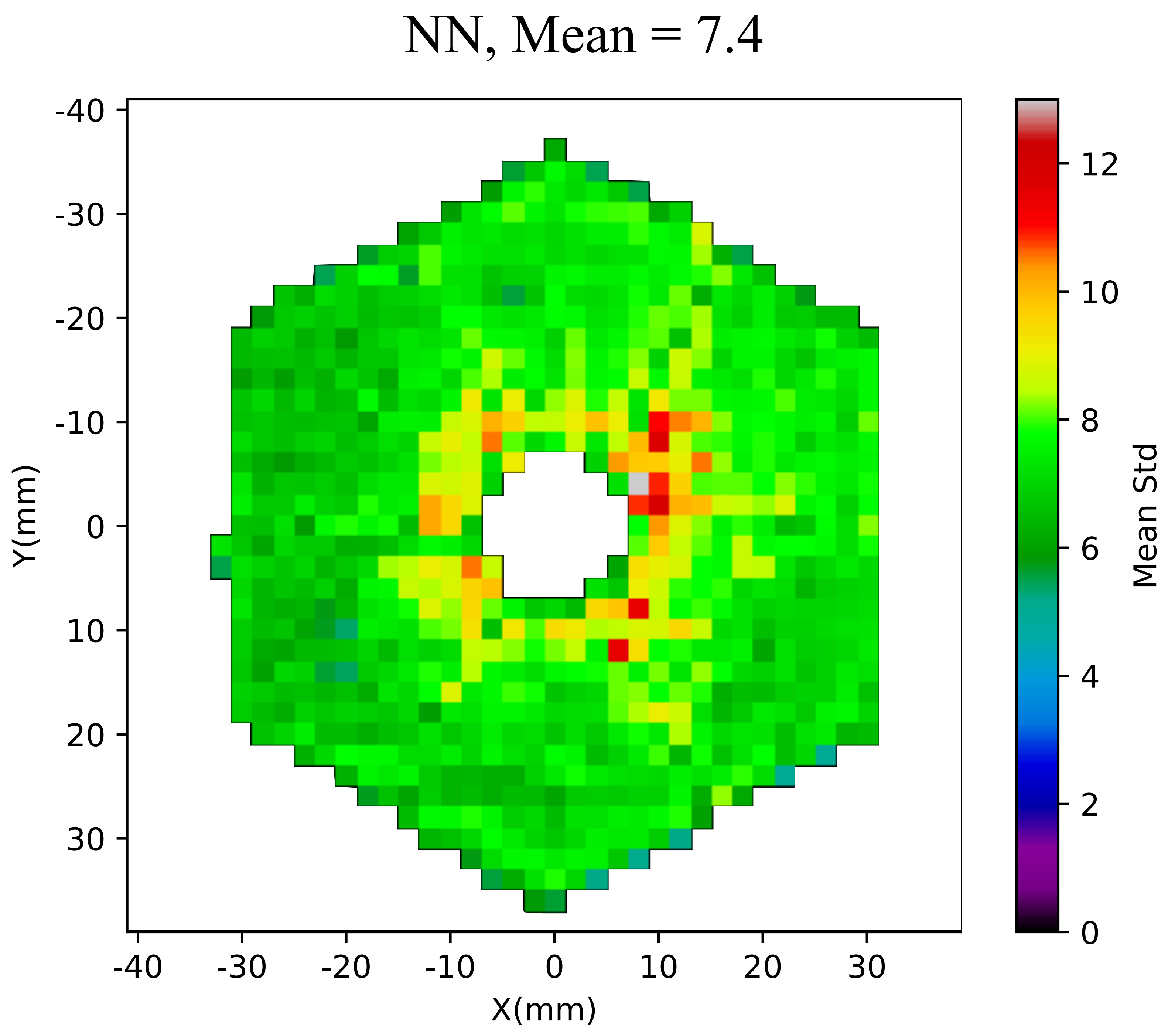


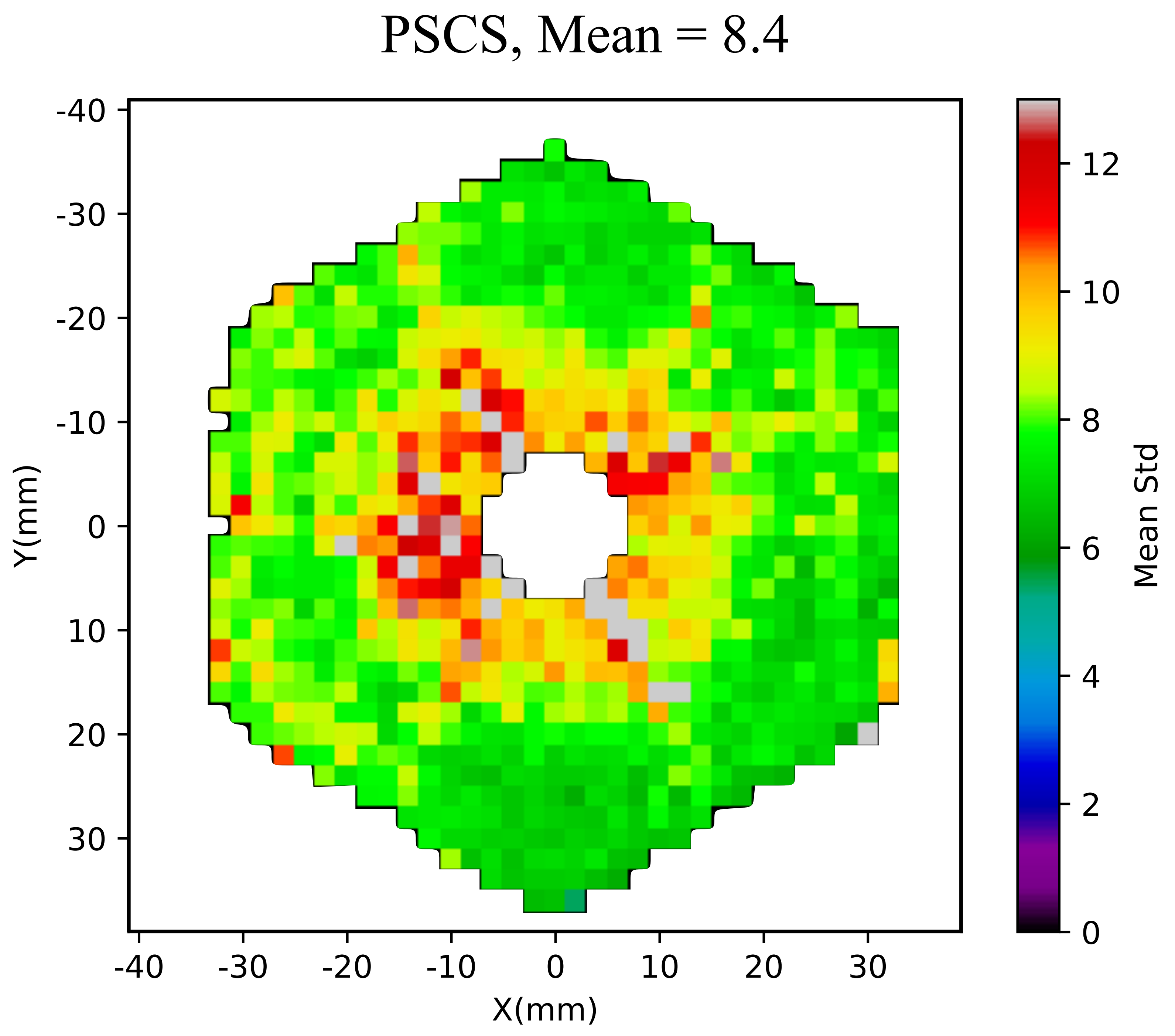
PSCS (124 traces)

Model consistency: Neural Network vs PSCS

- The **mean standard deviation** of the signals predicted at the same position is used to **evaluate the model consistency**.
- The **Neural Network shows better homogeneity** than the PSCS.

Mean Std of the traces per pixel at Z=30mm

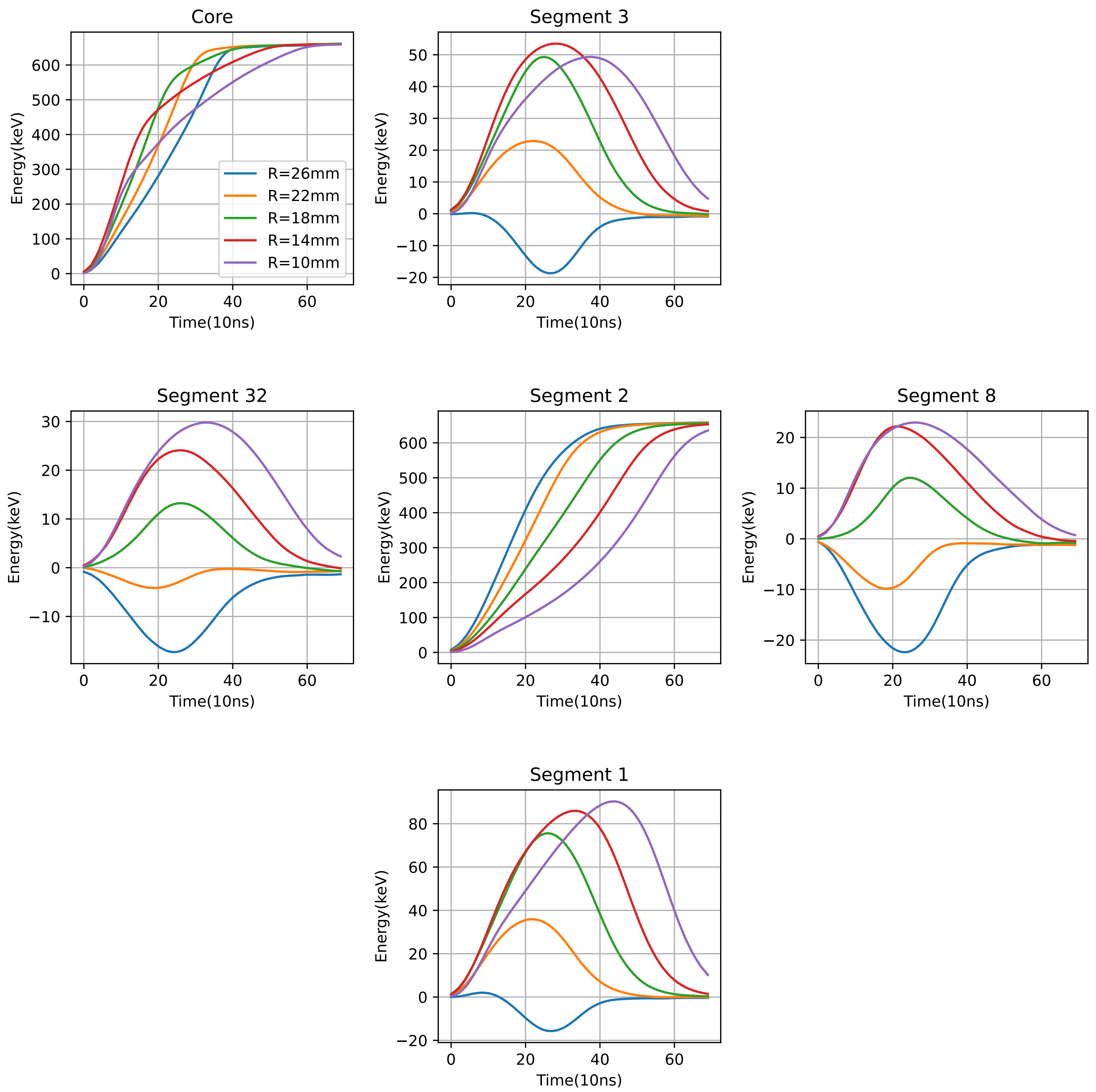




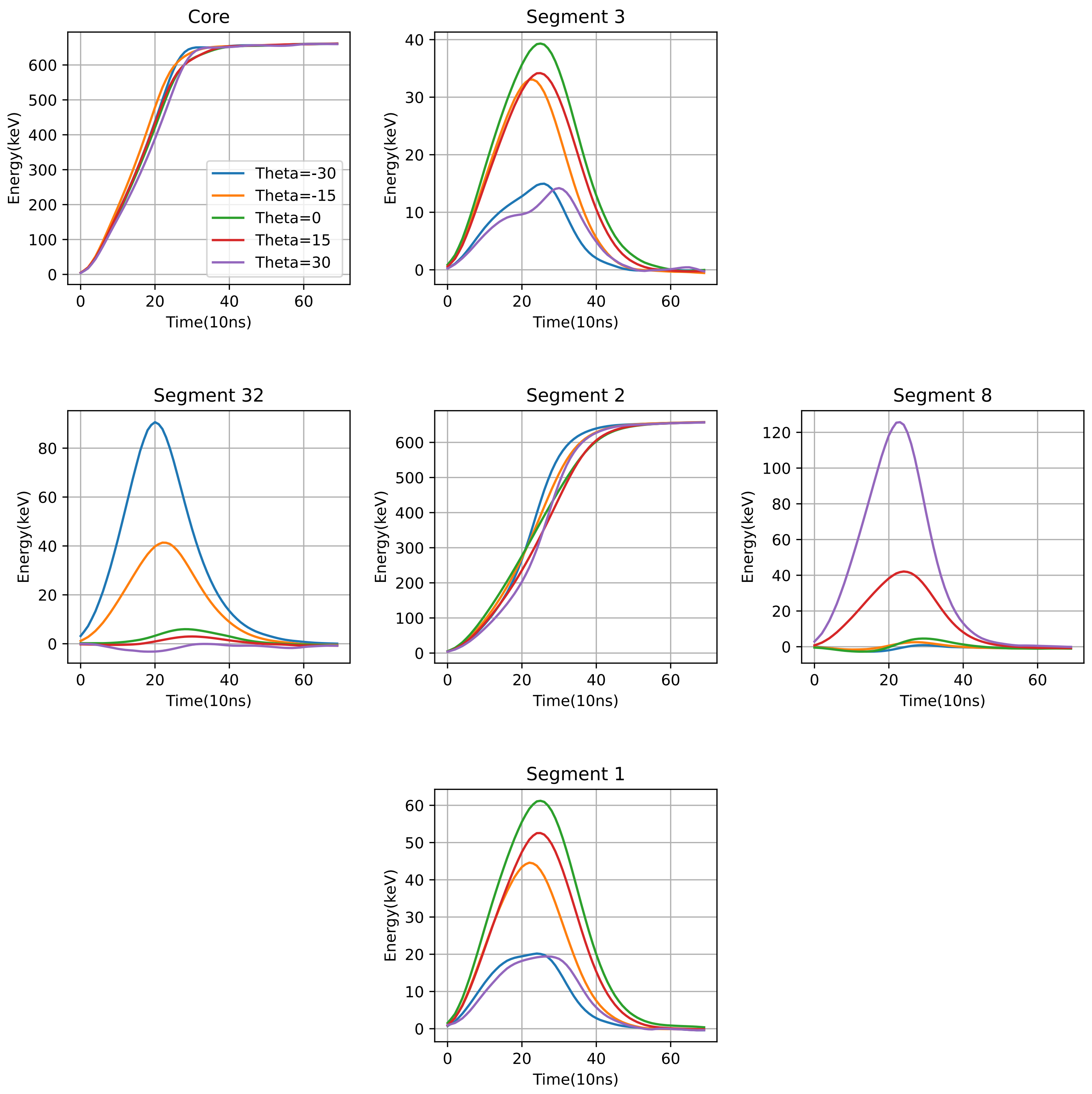
The NN Experimental basis

➤ **We now have an experimental signal basis covering the full crystal volume**

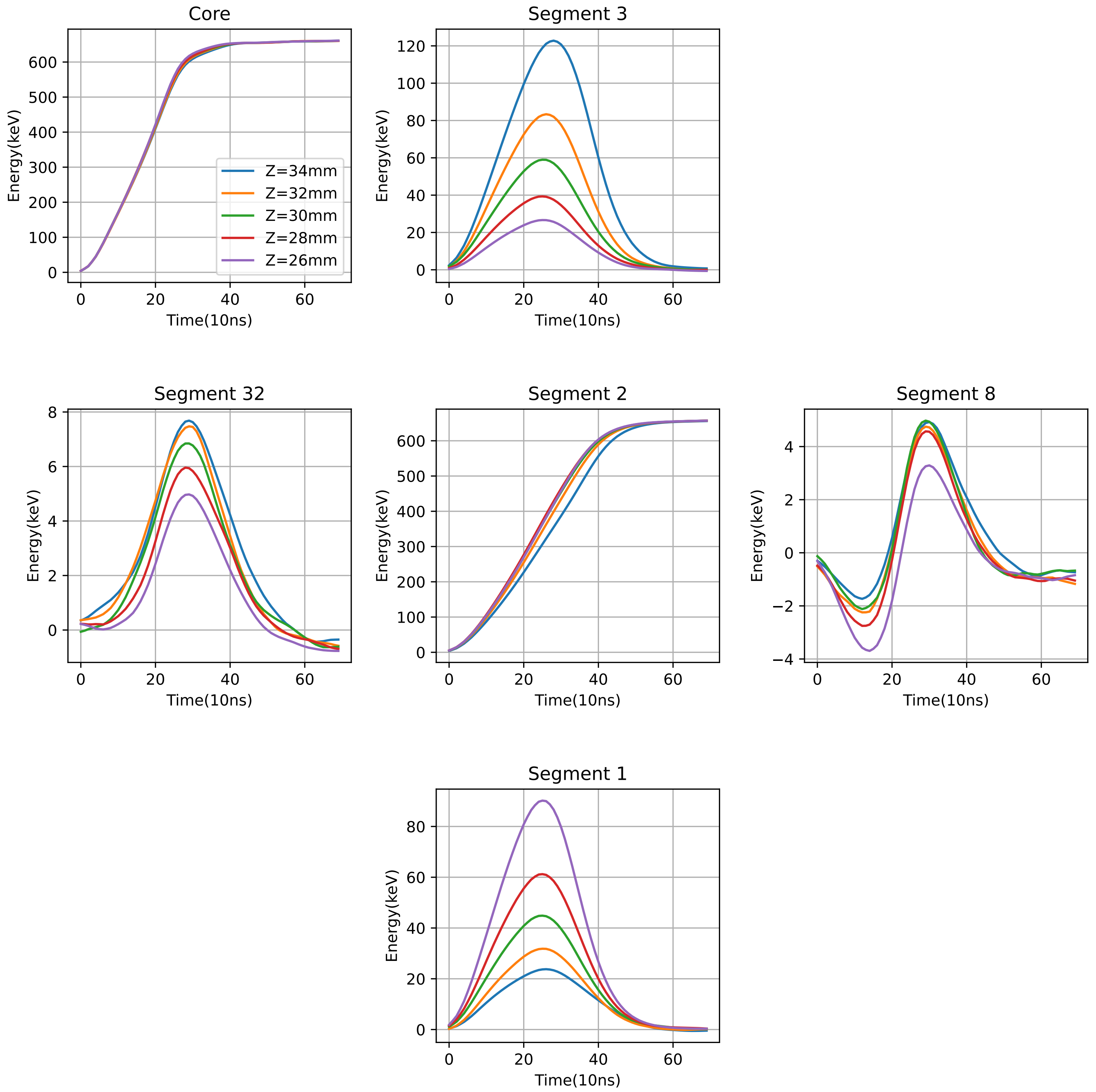
Signal Variation with Radius



Signal Variation with Theta

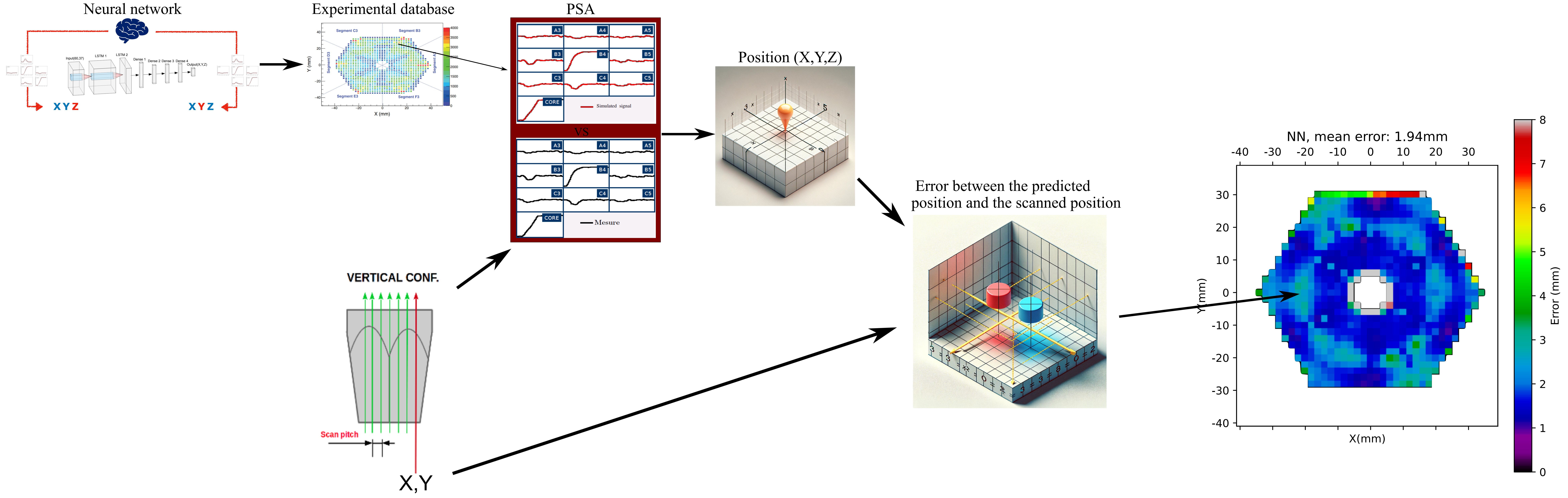


Signal Variation with Depth



Testing experimental databases using PSA results

- ➤ We can now perform the AGATA PSA using experimental bases !
  - ➥ The basis is switched between ADL, NN and PSCS
  - ➥ PSA results are then compared

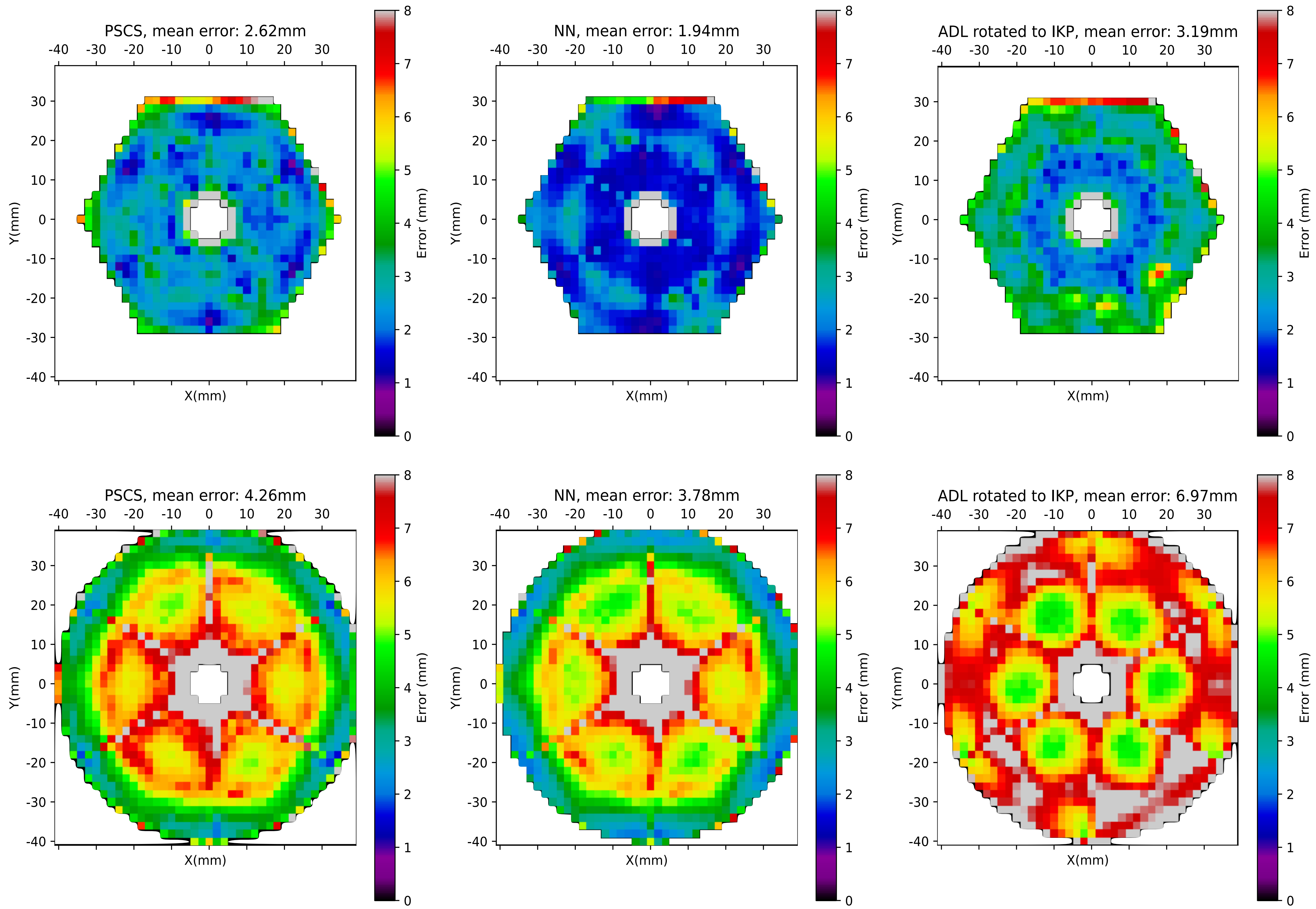


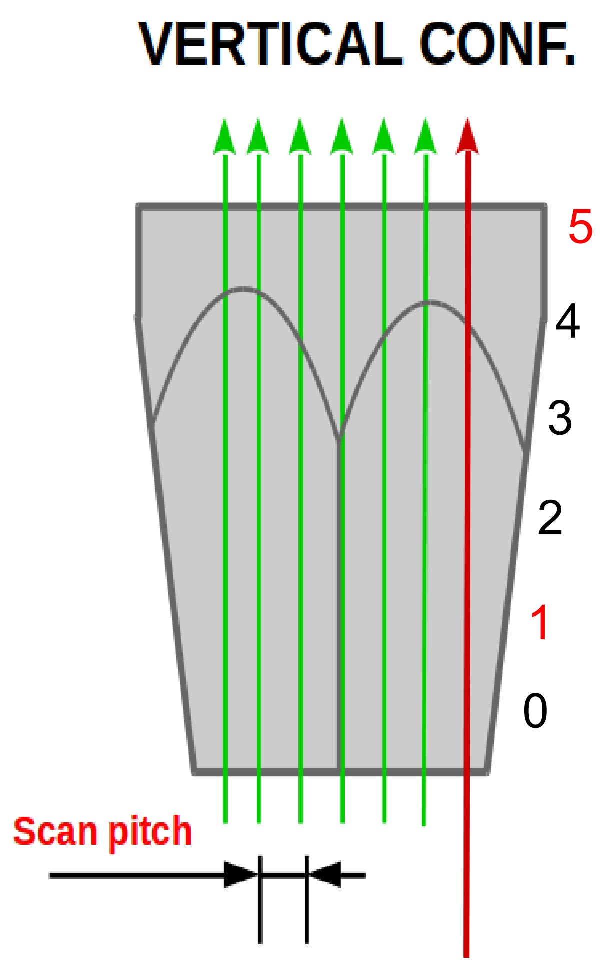
PSA vs Scanning position

➤ **PSA with NN basis outperforms** the **PSCS** basis and the **simulated ADL** basis

Layer 1

Layer 5

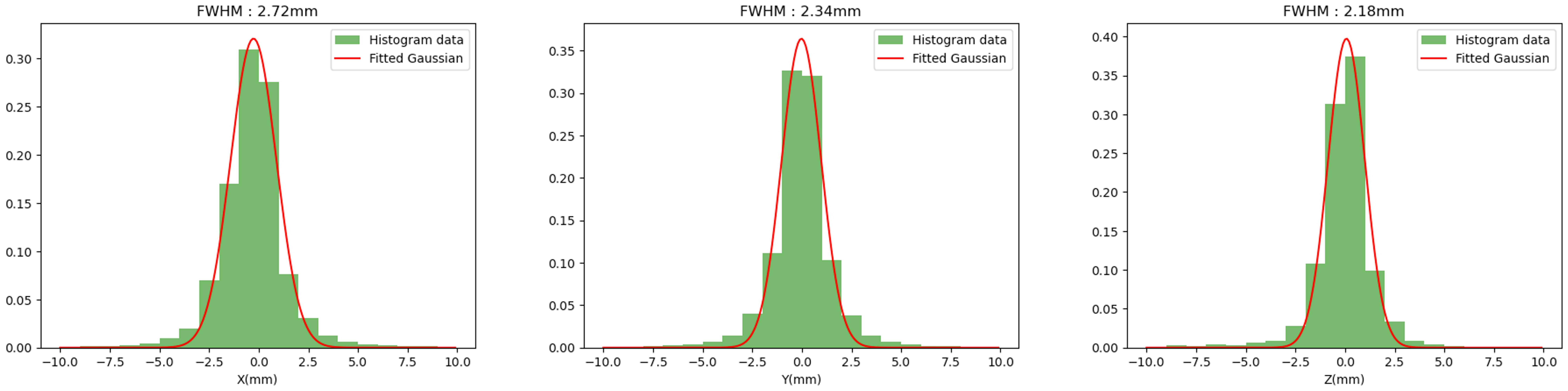




Results

- **Average PSA Position resolution (FWHM):**
  - ➥ NN: **2.4 mm**
  - ➥ ADL **4.9 mm**

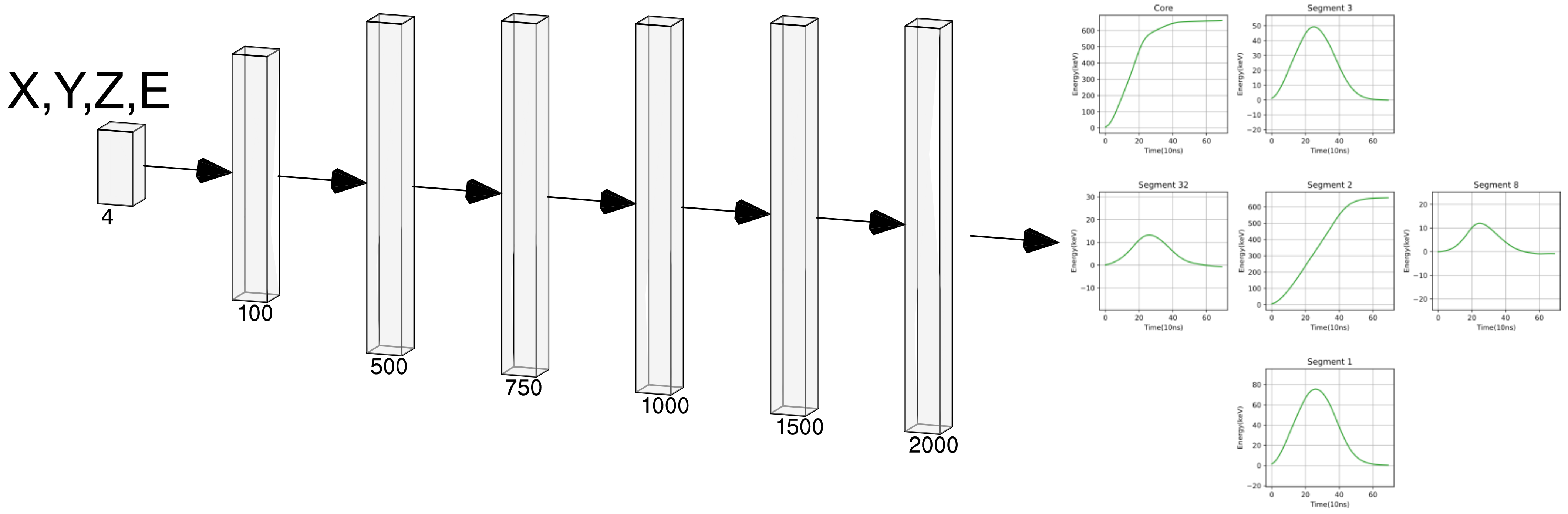
- **In-beam spectroscopy resolution (^{98}Zr at 1222 keV, FWHM):**
  - ➥ NN: **3.9 keV**
  - ➥ ADL **4.3 keV**

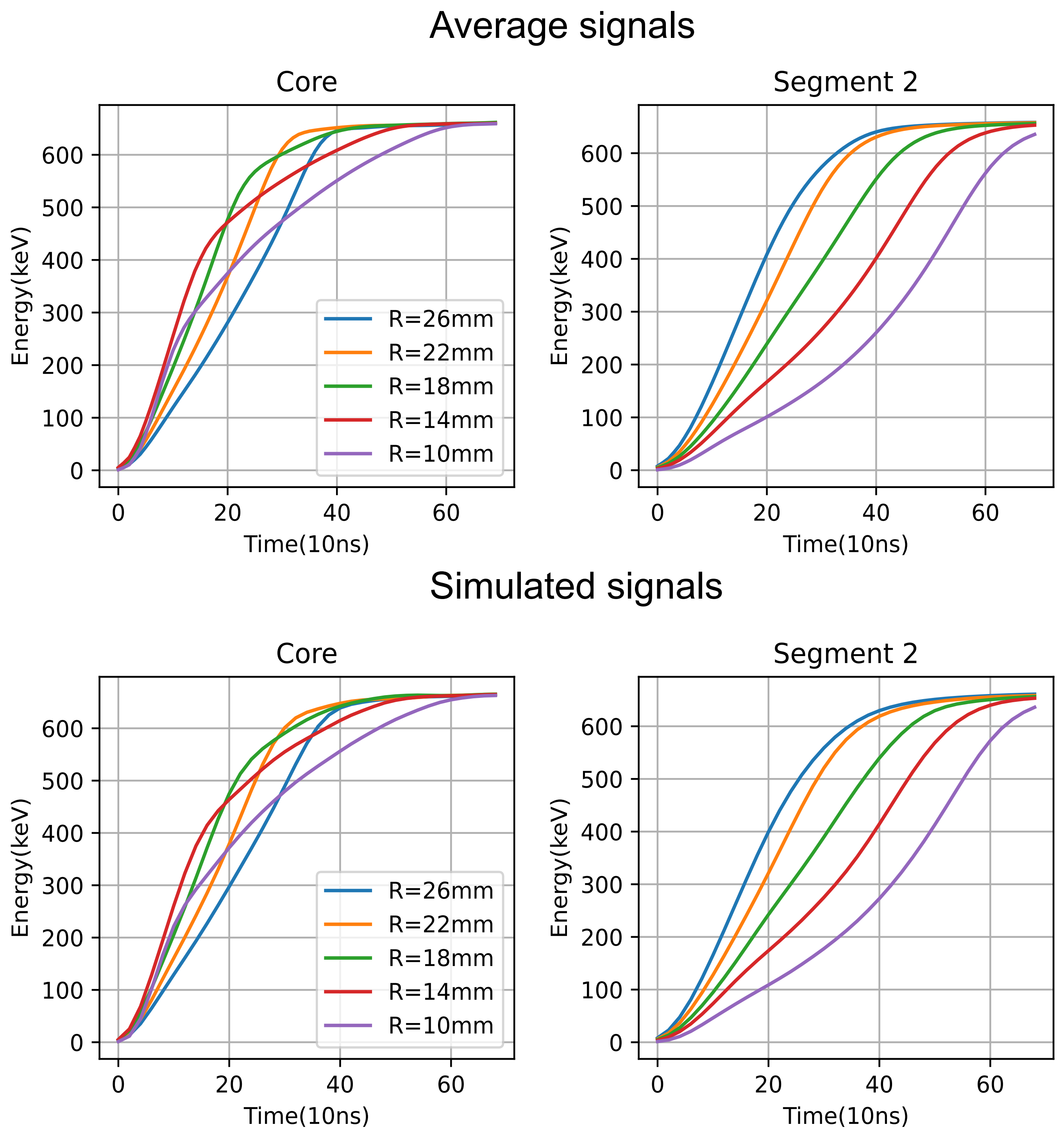


Supplementary result: development of a signal generator

- **Main Outcome: generation of labeled experimental data**
  - ➥ opens the door to new developments, such as a **signal generator** (simulate a signal for any [X,Y,Z] input)

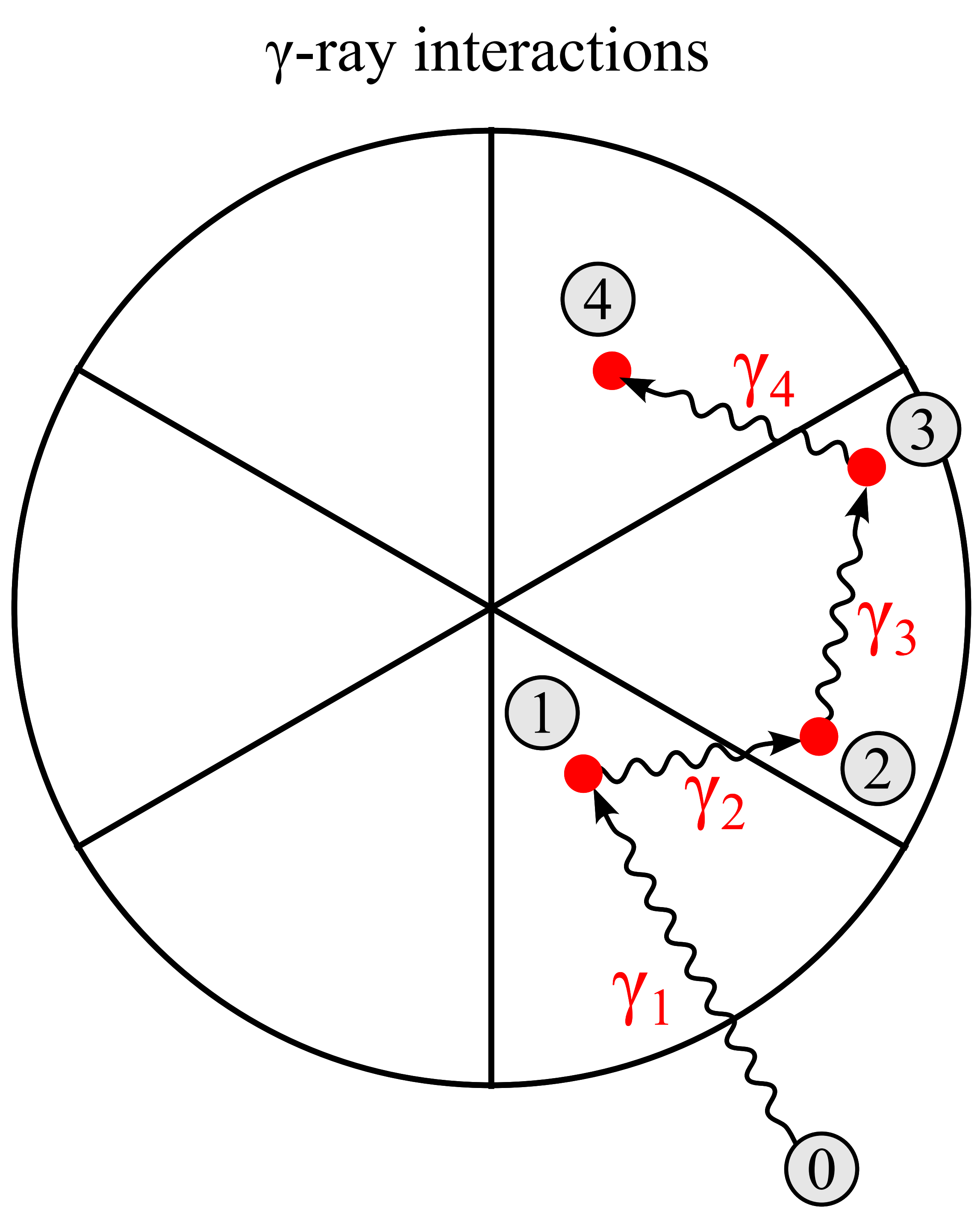
- **Potential applications:**
  - ➥ Handling **non-Cartesian PSA grid search**
  - ➥ Managing **multiple interactions per segment** (not currently considered in AGATA)

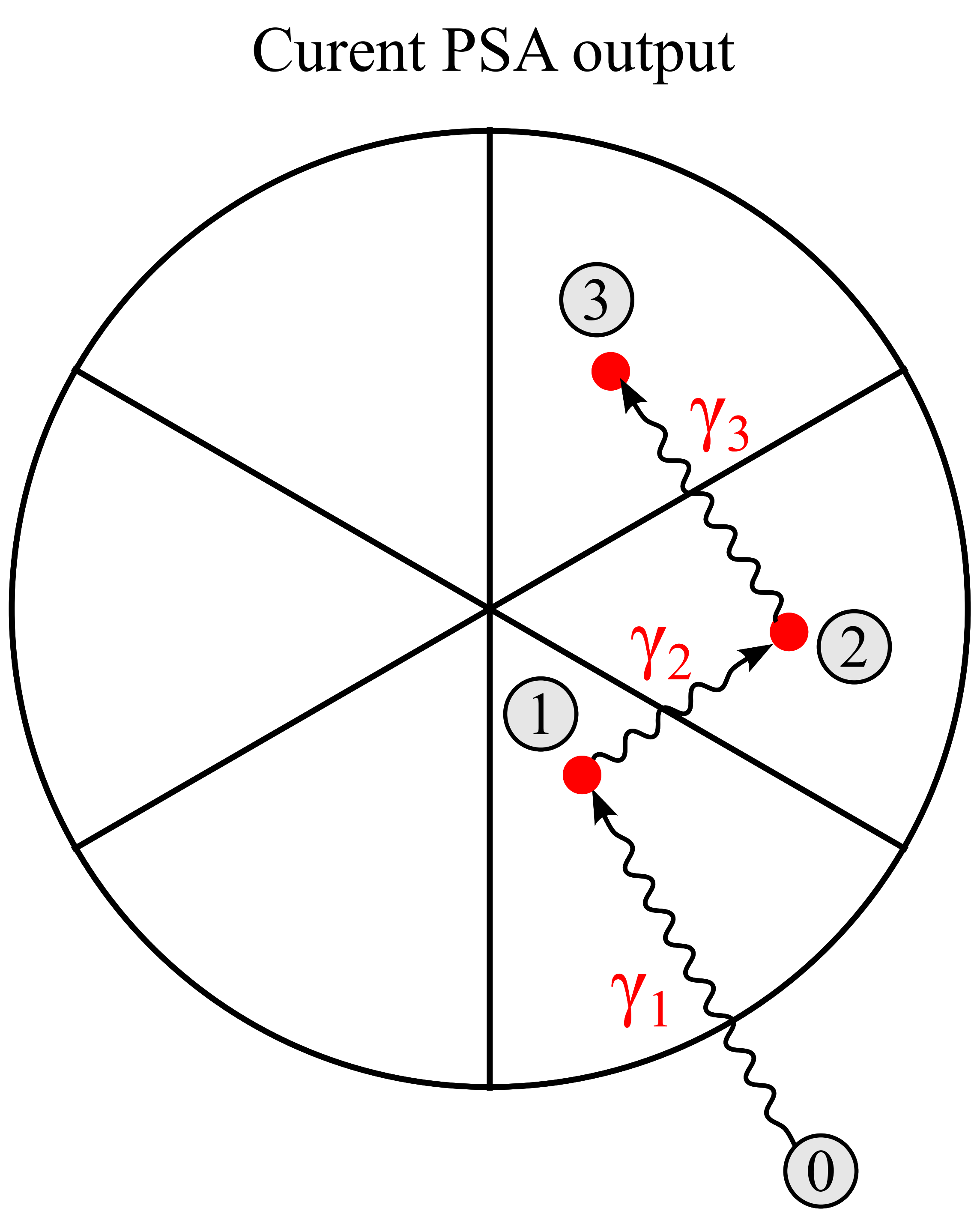




How to treat multi hits in one segment ?

- **The multi hit problem:**
  - ➥ A significant fraction of γ-rays undergo **multiple interactions within the same segment**
  - ➥ **Grid search cannot handle multi-hit** events due to the **combinatorial explosion** of possibilities
  - ➥ The **current PSA treats these events as a single interaction**:
    - ➥ **Degraded position resolution**

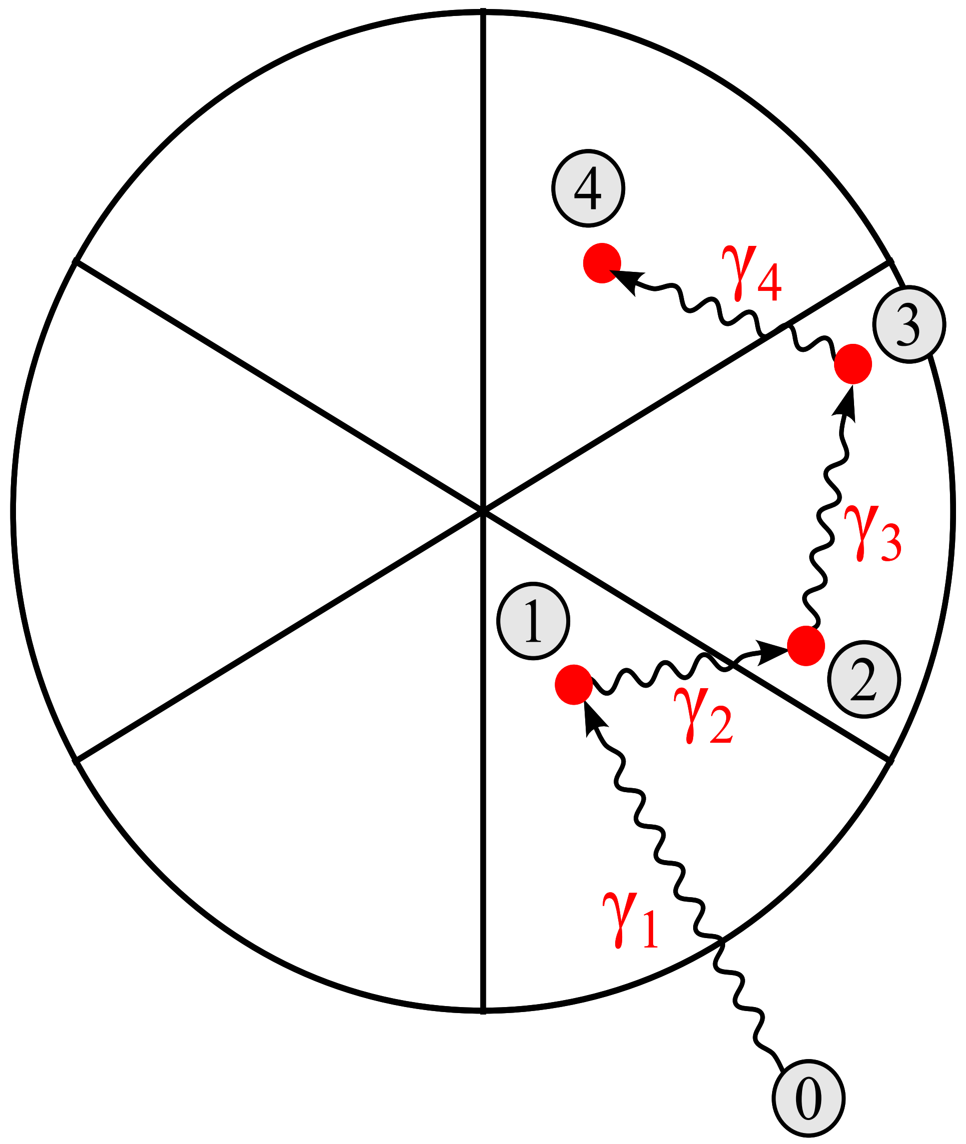




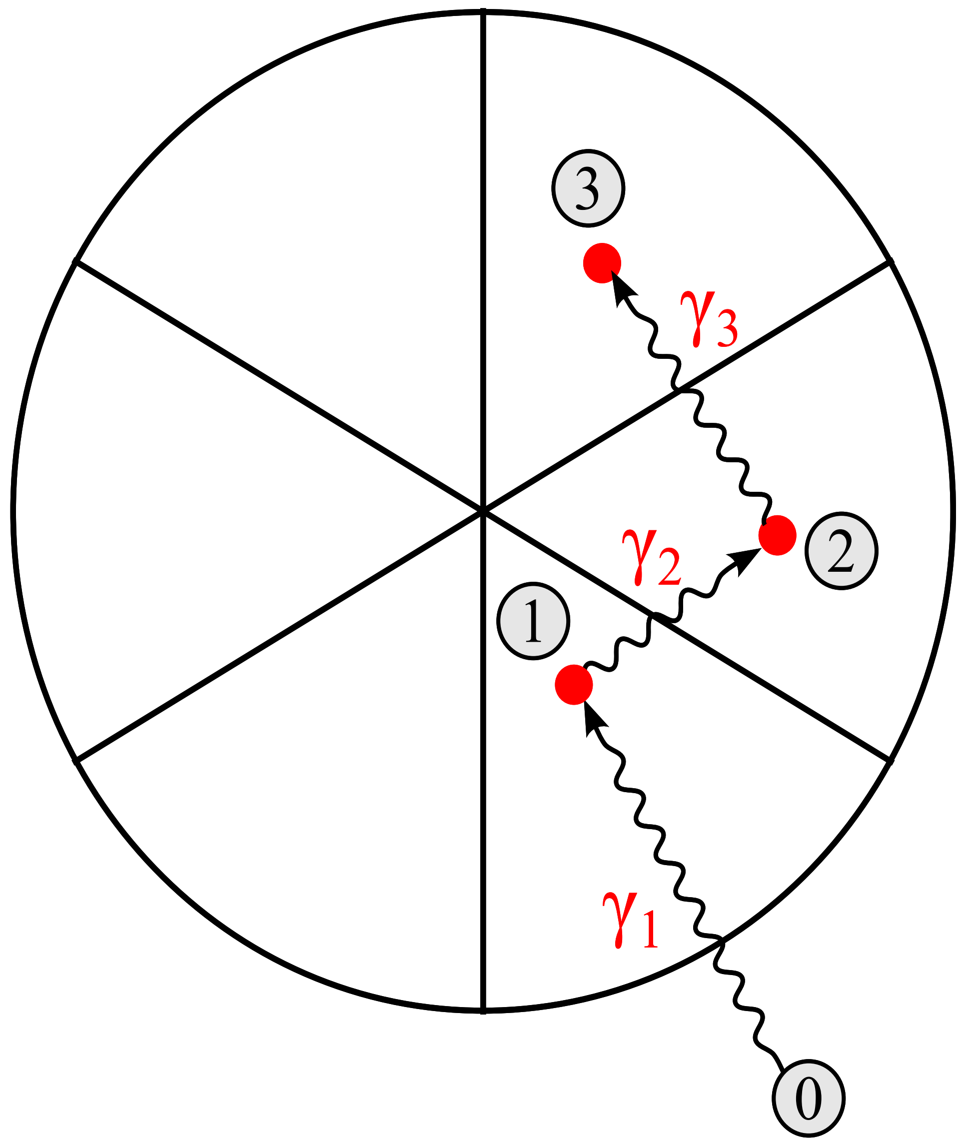
How to treat multi hits in one segment ?

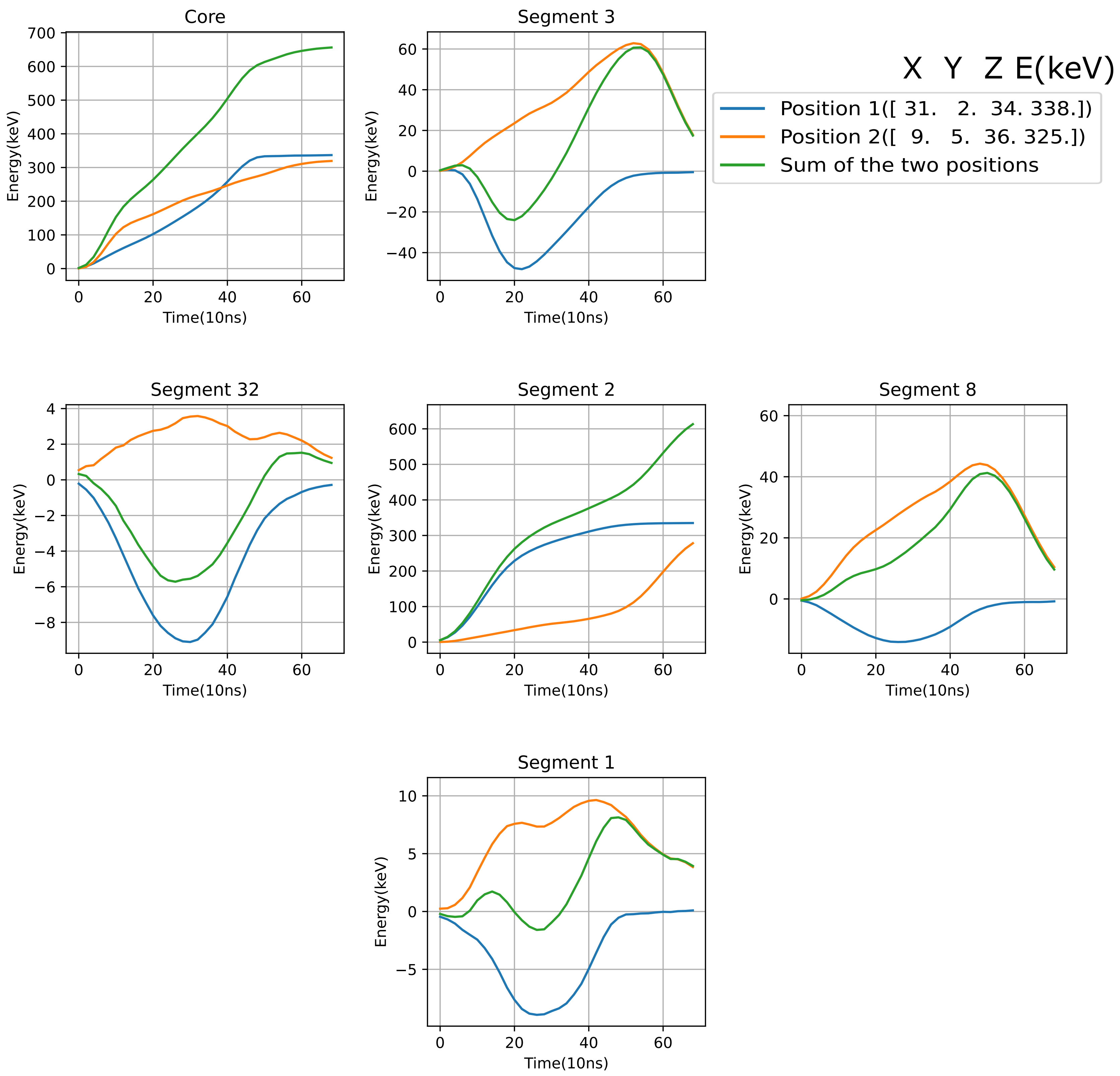
- **New ML-based approach to address the problem:**
  - A **synthetic dataset** was generated to **mimic two-interactions-per-segment events**
    - The signal generator adds two signals from the same segment to create an artificial two-hit event
    - Each combined signal is associated with **two positions and energies** (X_1,Y_1,Z_1,E_1 and X_2,Y_2,Z_2,E_2)

γ-ray interactions



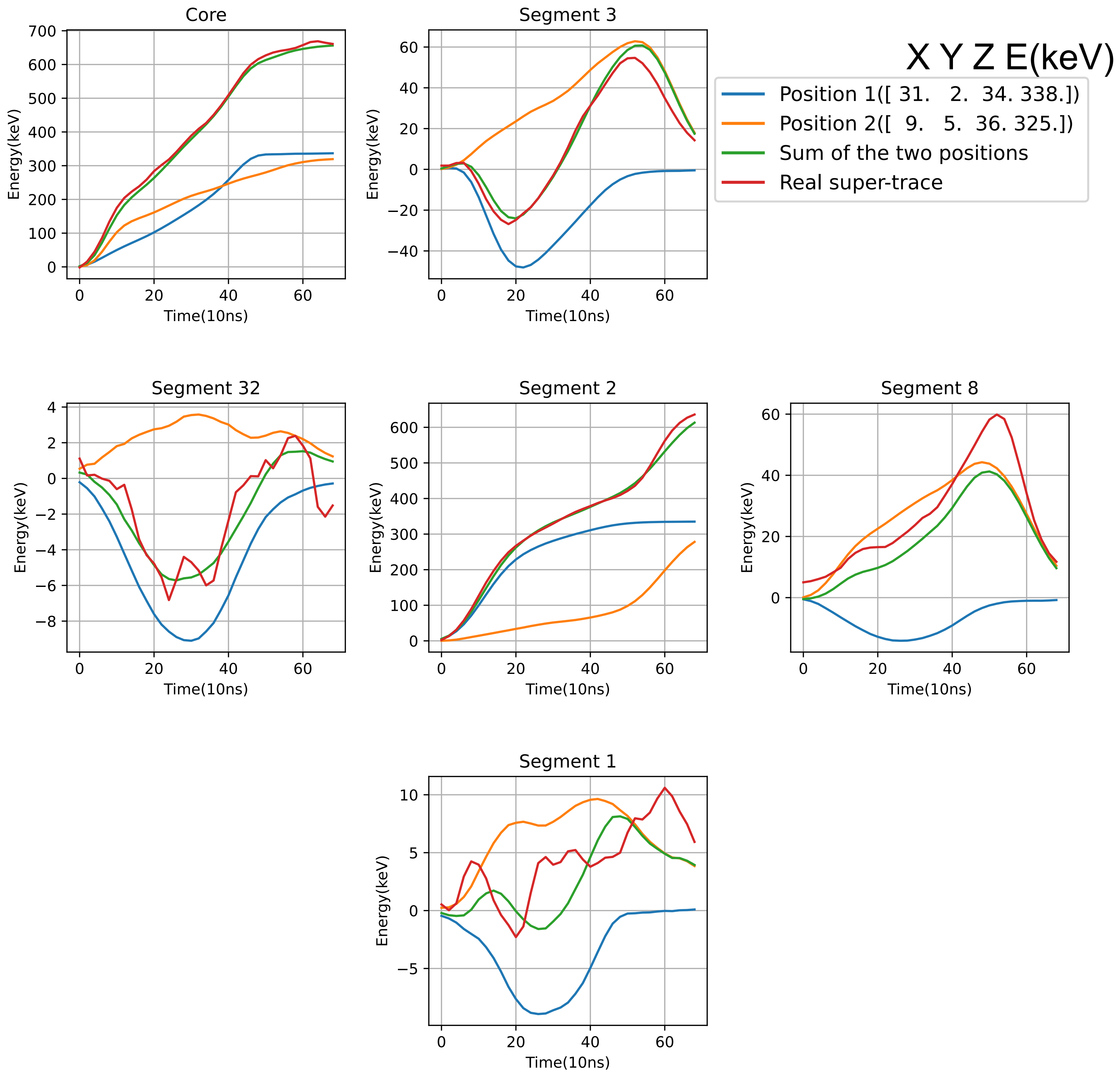
Curent PSA output





Two hits in one segment NN

- A neural network was trained to **predict** the **position** and **deposited energy** of **each interaction**
- The model was then **applied to real data not included in the (synthetic) training set**
  - ➡ Two simulated signals were generated using the predicted positions from the two-hit NN
  - ➡ The **sum of the two simulated signals** closely **matches the actual two-hit signal**



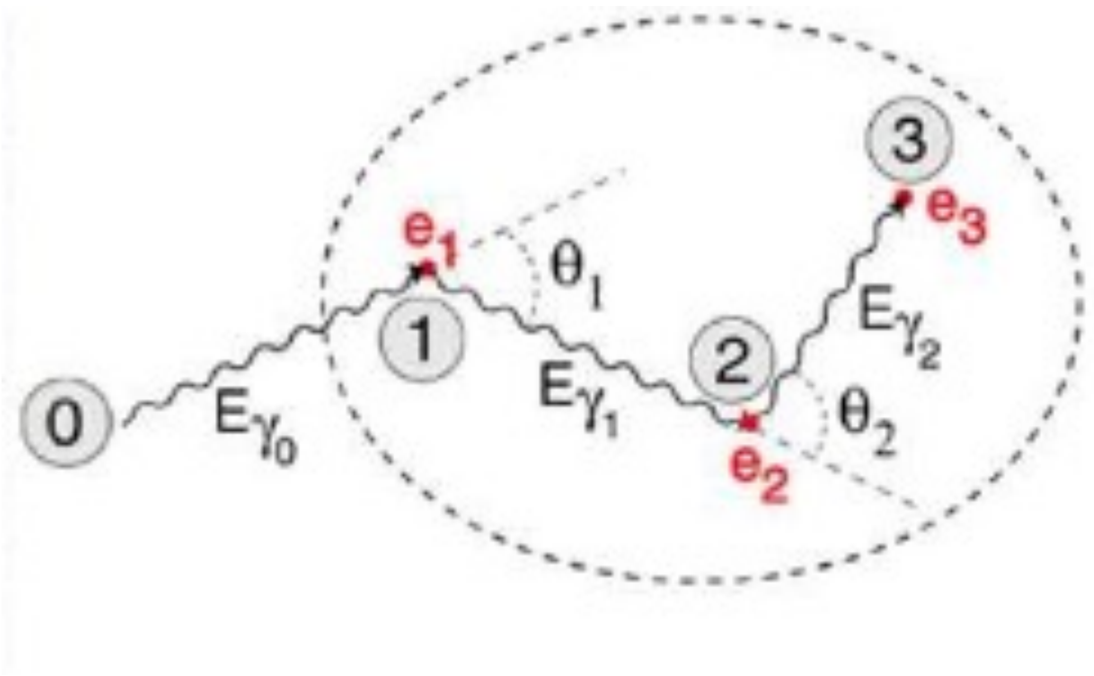
Two hits in one segment NN

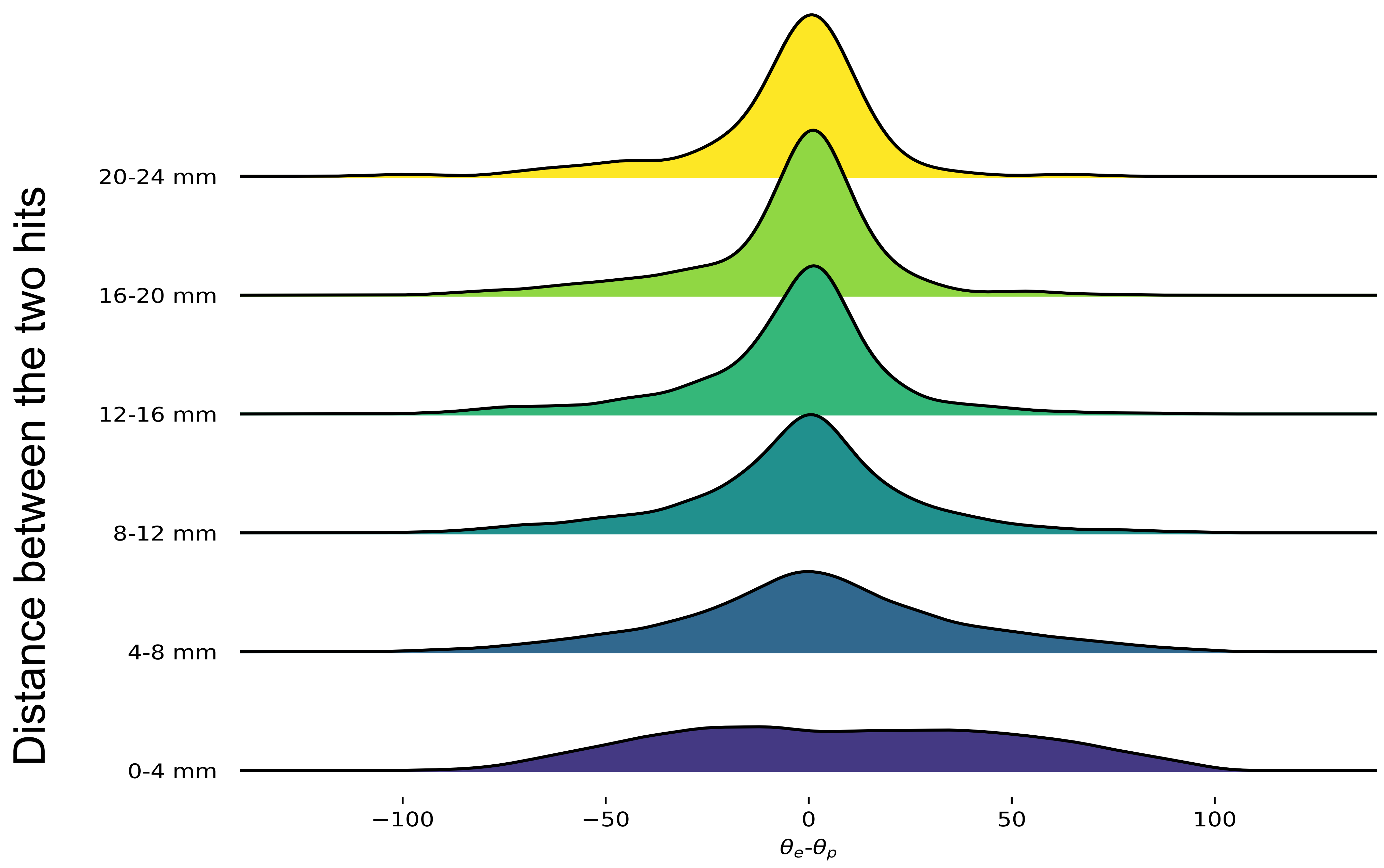
➤ **Experimental validation of the results**

➥ The angle between interactions can be calculated:
- using the **Compton scattering formula**, and
- using the **reconstructed interaction positions**

➥ Although the full ground truth is unknown, results can be validated by checking their **consistency with the Compton formula**

$$\cos\theta = 1 + m_e c^2 \left(\frac{1}{E_\gamma - E_1} - \frac{1}{E_\gamma} \right)$$





Conclusions and perspectives

Conclusions:

- A neural network was trained to process the Strasbourg scanning table data
- Training takes 12 hours, and processing takes 2 hours (vs. 5 days with PSCS)
- The NN showed **better consistency** and **accuracy** than the PSCS method
- Experimental signal bases were generated using both the NN and PSCS, and applied to the PSA
- The **NN-based basis improved the experimental resolution** compared to the default AGATA simulated basis
- A neural network capable of **simulating real signals** was successfully trained
- A neural network was trained on synthetic data to **handle two interactions per segment**
    - ➥ This model showed a **28% improvement** over the one-interaction-per-segment network

Perspectives:

- Developing an **online two-interaction-per-segment algorithm** would be a major breakthrough for AGATA
- Further work is required to finalize the method initiated in this study

NUCLÉAIRE & PARTICULES

AGATA ADVANCED GAMMA TRACKING ARRAY

Merci !