



# INVESTIGATING THE GIANT DIPOLE RESONANCE OF $^{164}\text{Dy}$ USING NRF

**M. Heumüller**<sup>1,✉</sup>, J. Kleemann<sup>1</sup>, N. Pietralla<sup>1</sup>, A. D. Ayangeakaa<sup>2,3</sup>, S. W. Finch<sup>2,4</sup>,  
D. Gribble<sup>2,3</sup>, J. Hauf<sup>1</sup>, J. Isaak<sup>1</sup>, X. K.-H. James<sup>2,3</sup>, R. V. F. Janssens<sup>2,3</sup>,  
S. R. Johnson<sup>2,3</sup>, T. Kowalewski<sup>2,3</sup>, B. Löher<sup>5</sup>, O. Papst<sup>1</sup>, K. Prifti<sup>1</sup>, A. Saracino<sup>2,3</sup>,  
D. Savran<sup>5</sup>, N. Sensharma<sup>2,3</sup>, V. Werner<sup>1</sup>

<sup>1</sup>IKP, TU Darmstadt

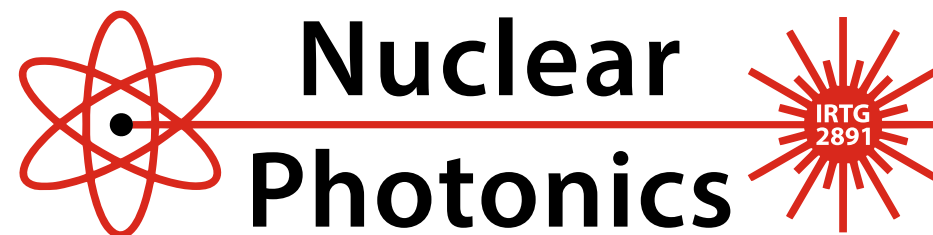
<sup>2</sup>TUNL, Durham, NC, USA

<sup>3</sup>U. of NC, Chapel Hill, USA

<sup>4</sup>Duke U., Durham, NC, USA

<sup>5</sup>GSI, Darmstadt, Germany

✉mheumueller@ikp.tu-darmstadt.de



# THE GIANT DIPOLE RESONANCE

- Fundamental nuclear excitation
- Dominates photoresponse of all nuclei
- Located between 10 and 30 MeV, dependent on atomic mass  $A$
- Geometrical Model: Oscillation of proton against neutron body
- 99% particle emission, 1%  $\gamma$ -decay
- Extensively investigated, but still not fully understood

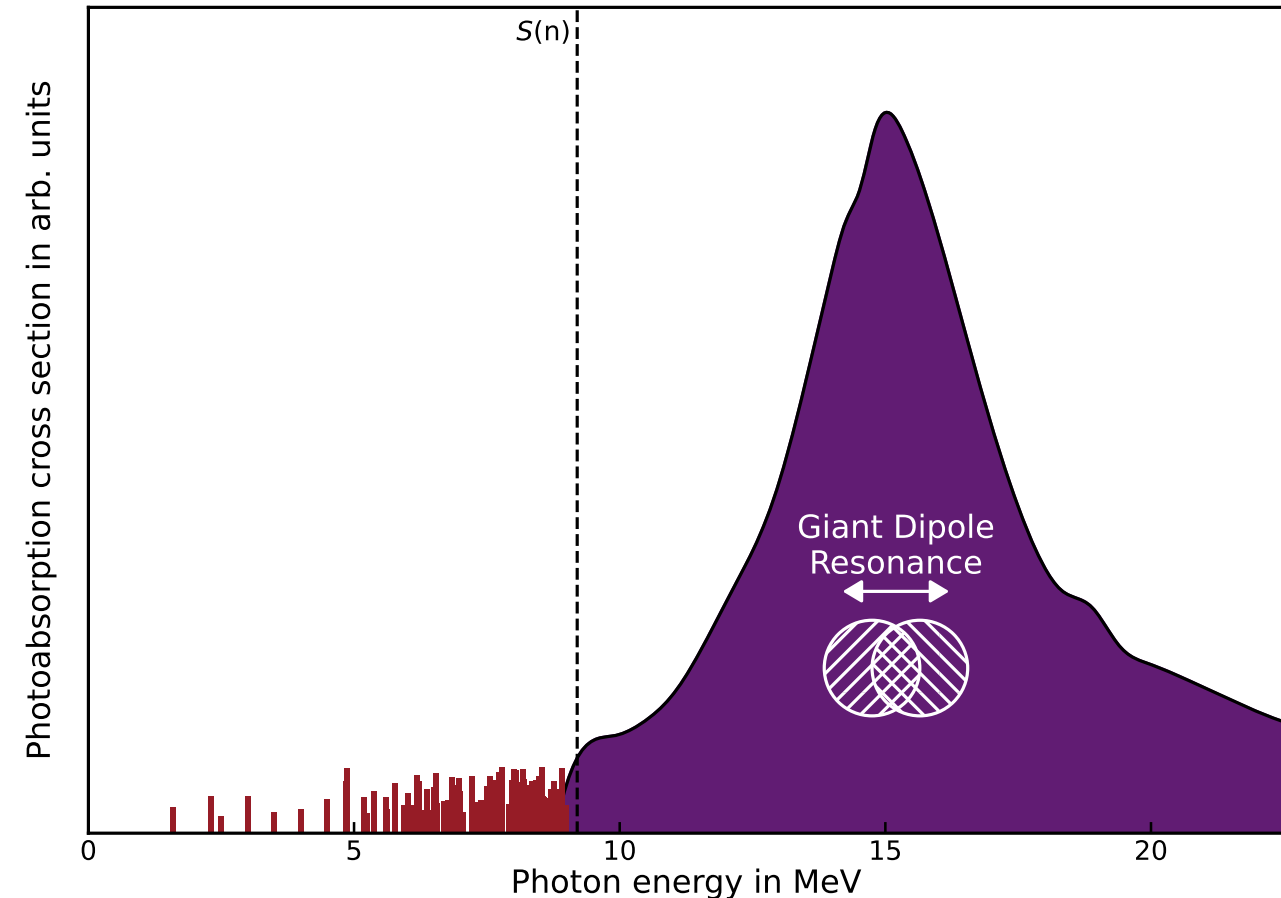
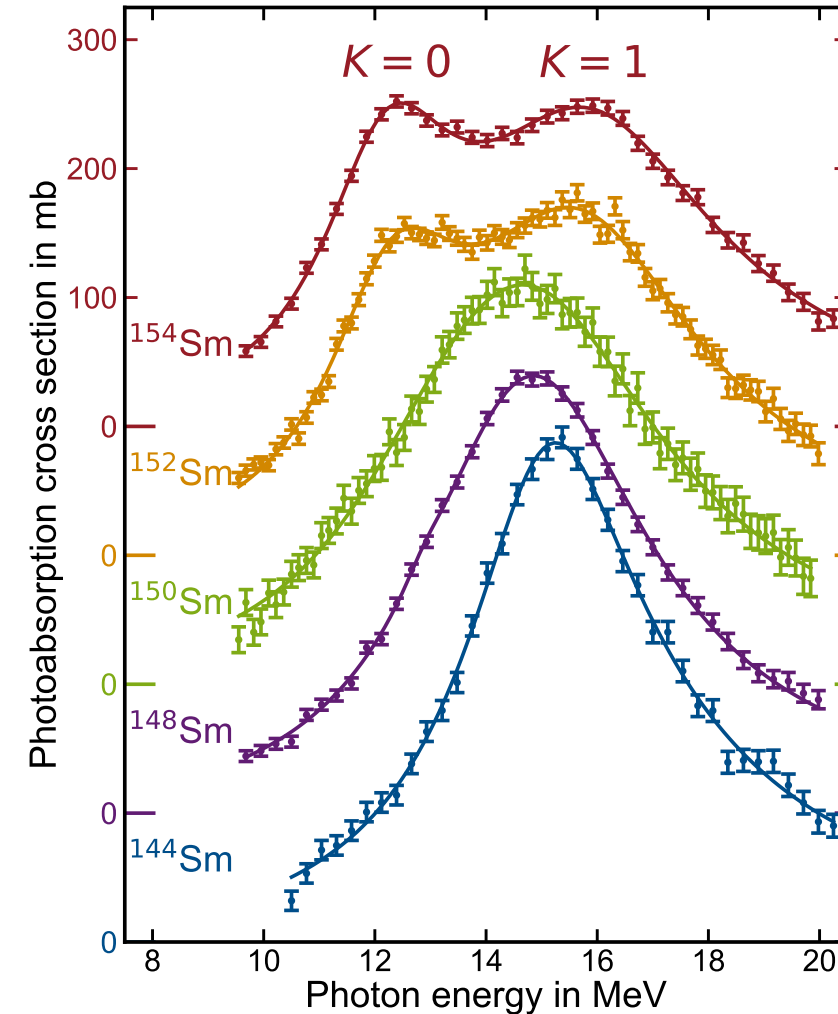
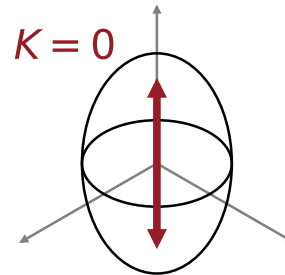


Figure adapted from J. Kleemann *et al.*, Dissertation (2024)

# THE GIANT DIPOLE RESONANCE

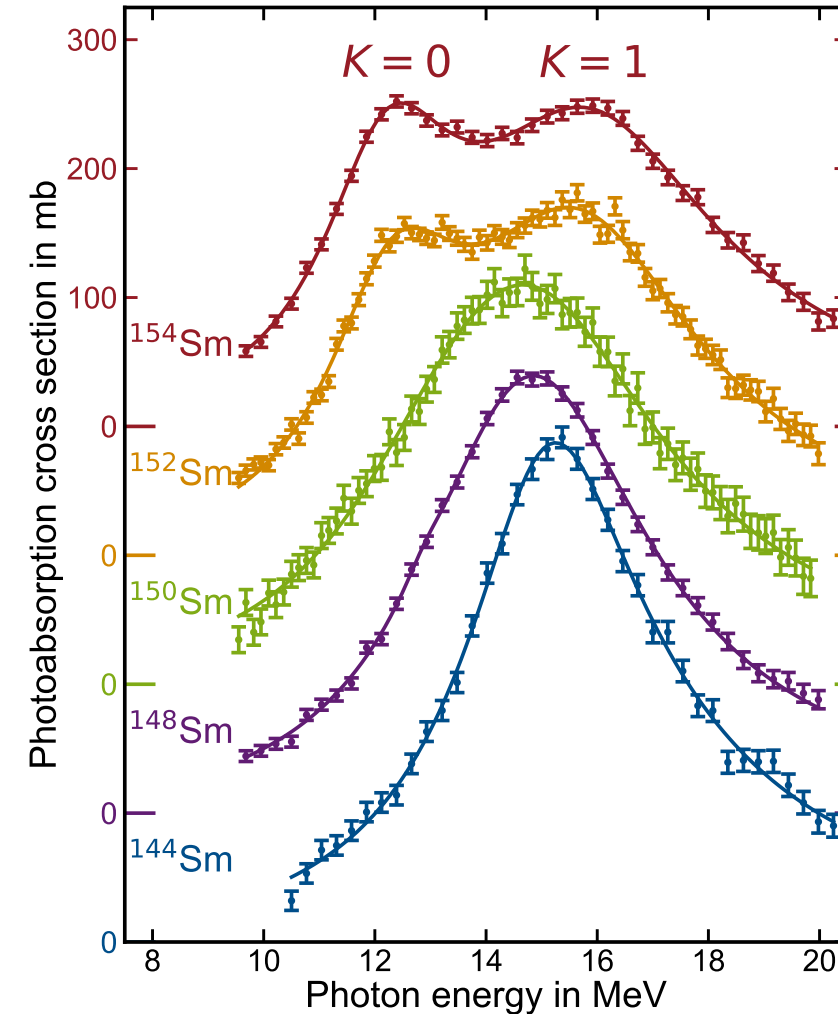
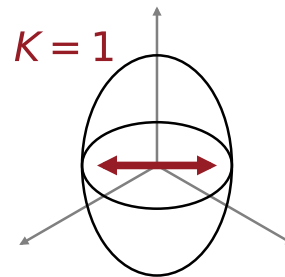
- Splitting of  $\sigma_{\text{Abs}}(E)$  in deformed nuclei
- Geometrical: Oscillation along different symmetry axes with distinct frequencies
- Axial deformation:
  - Oscillation  $\parallel$  symmetry axis ( $K = 0$ )
  - Oscillation  $\perp$  symmetry axis ( $K = 1$ )
- $\sigma_{\text{Abs}}(E)$  can be described as sum of up to three Standard Lorentzians (SLO)
- Geometrical Model makes predictions for  $\gamma$ -decay



Data from P. Carlos *et al.*, Nucl. Phys. A **225**, 171 (1974)  
Figure adapted from J. Kleemann *et al.*, Dissertation (2024)

# THE GIANT DIPOLE RESONANCE

- Splitting of  $\sigma_{\text{Abs}}(E)$  in deformed nuclei
- Geometrical: Oscillation along different symmetry axes with distinct frequencies
- Axial deformation:
  - Oscillation  $\parallel$  symmetry axis ( $K = 0$ )
  - Oscillation  $\perp$  symmetry axis ( $K = 1$ )
- $\sigma_{\text{Abs}}(E)$  can be described as sum of up to three Standard Lorentzians (SLO)
- Geometrical Model makes predictions for  $\gamma$ -decay



Data from P. Carlos *et al.*, Nucl. Phys. A **225**, 171 (1974)  
Figure adapted from J. Kleemann *et al.*, Dissertation (2024)

# PHOTODECAY OF THE GDR

- First systematic study of  $\gamma$ -decay behavior by J. Kleemann *et al.*
- $\gamma$ -decay into ground state and first excited  $2^+$  (elastic and Raman scattering)
- Experiment validates the Geometrical Model predictions for  $^{154}\text{Sm}$  and  $^{140}\text{Ce}$

J. Kleemann *et al.*, Dissertation (2024)  
J. Kleemann *et al.*, Phys. Rev. Lett. **134**, 022503 (2025)

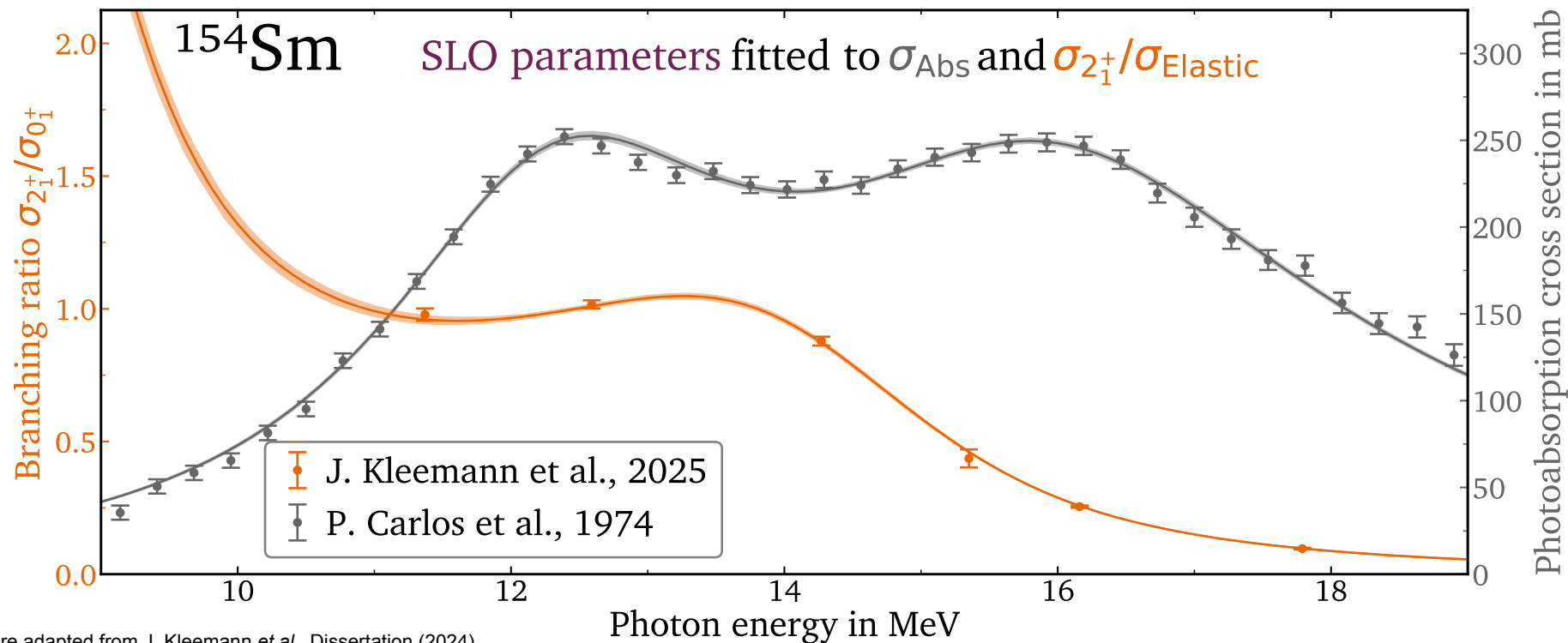
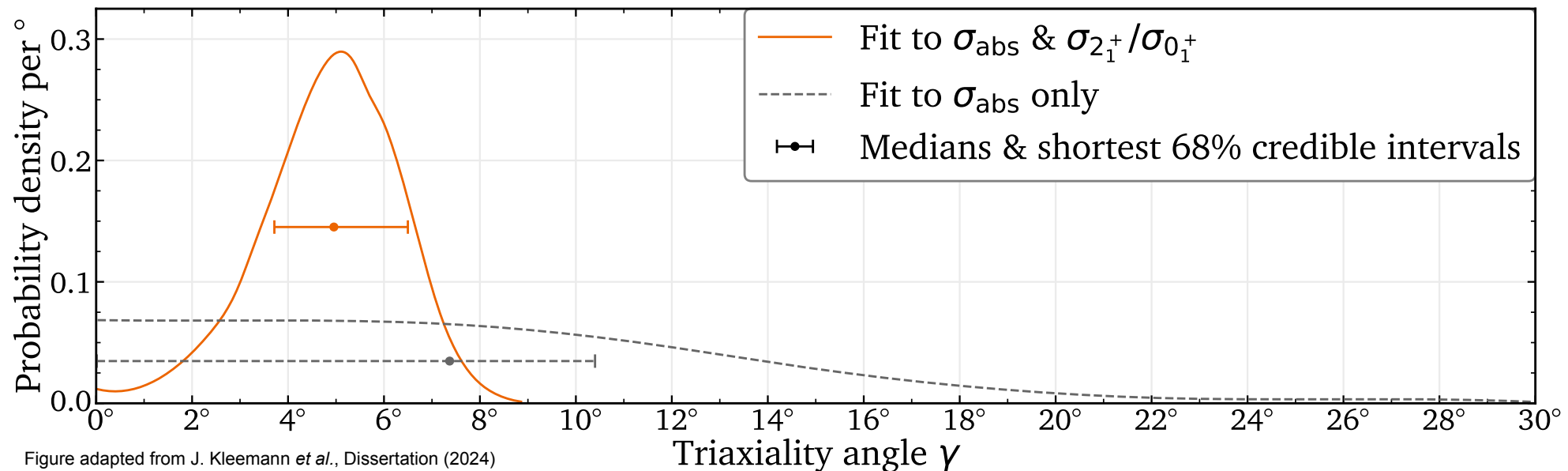


Figure adapted from J. Kleemann *et al.*, Dissertation (2024)

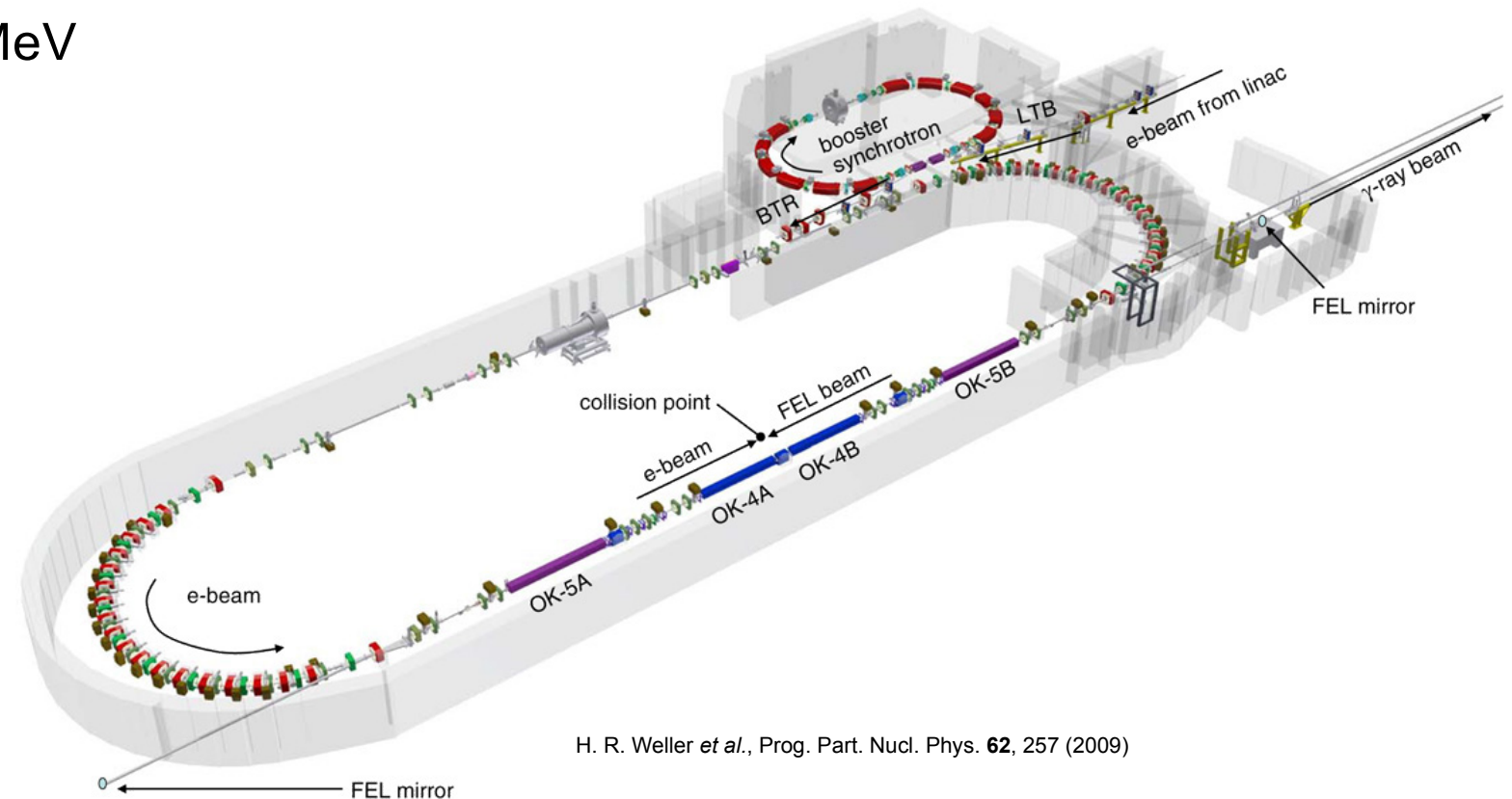
# PHOTODECAY OF THE GDR

- First systematic study of  $\gamma$ -decay behavior by J. Kleemann *et al.* J. Kleemann *et al.*, Dissertation (2024)  
J. Kleemann *et al.*, Phys. Rev. Lett. **134**, 022503 (2025)
- $\gamma$ -decay into ground state and first excited  $2^+$  (elastic and Raman scattering)
- Experiment validates the Geometrical Model predictions for  $^{154}\text{Sm}$  and  $^{140}\text{Ce}$
- Very sensitive to nuclear shape, determination of shape parameters like degree of triaxiality  $\gamma$
- Probing more triaxial nucleus  $^{164}\text{Dy}$  (Suspected  $\gamma = 7.3^\circ$ ) T. Otsuka *et al.*, arXiv 2303.11299, 1 (2025)



# HIGH INTENSITY $\gamma$ -RAY SOURCE

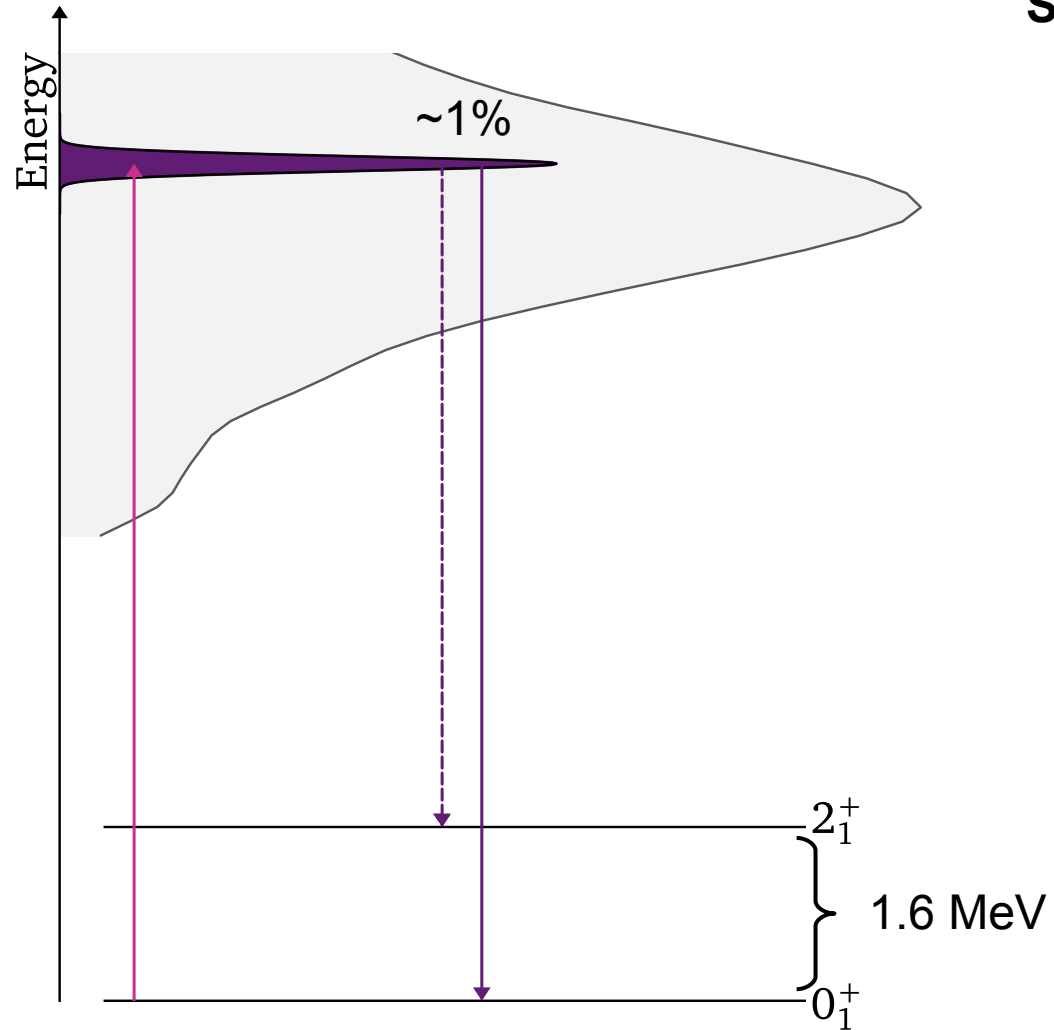
- Production of photons using laser-Compton back-scattering
- Tunable energies from 1-100 MeV
- Linear and circular polarization
- Beam FWHM of  $\sim 2\%$ 
  - Quasi-monochromatic



H. R. Weller *et al.*, Prog. Part. Nucl. Phys. **62**, 257 (2009)

# EXPERIMENTAL METHOD

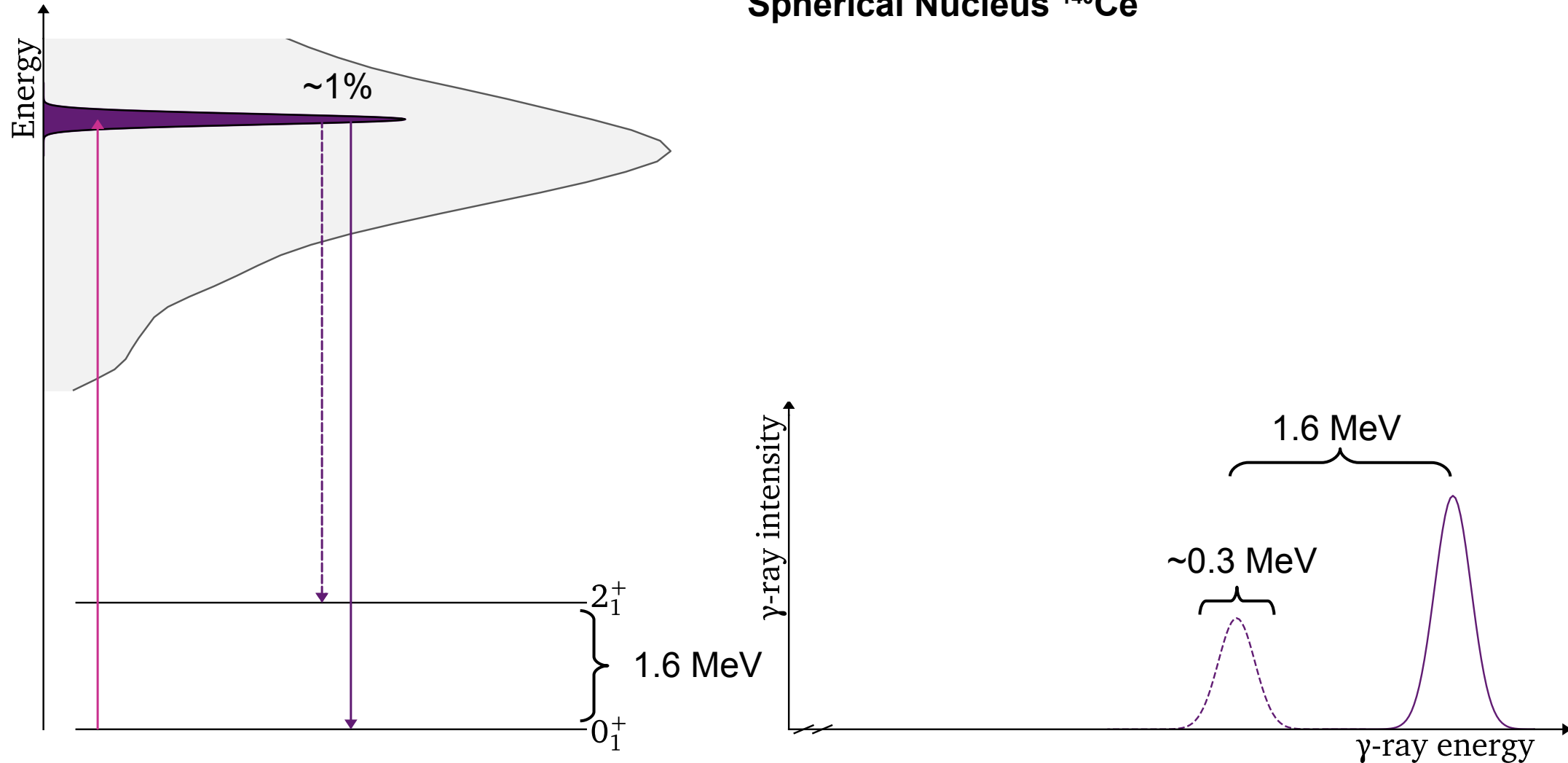
Spherical Nucleus  $^{140}\text{Ce}$



# EXPERIMENTAL METHOD



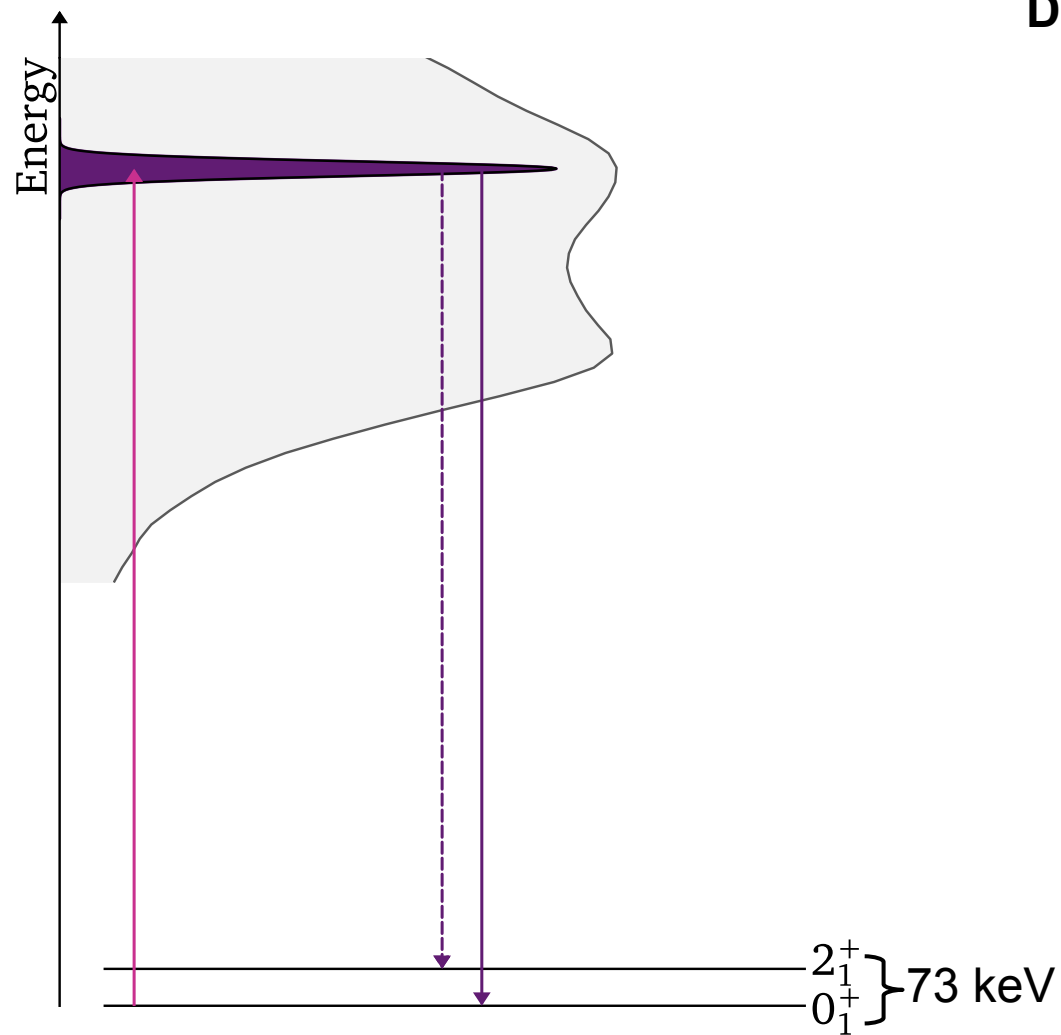
Spherical Nucleus  $^{140}\text{Ce}$



# EXPERIMENTAL METHOD



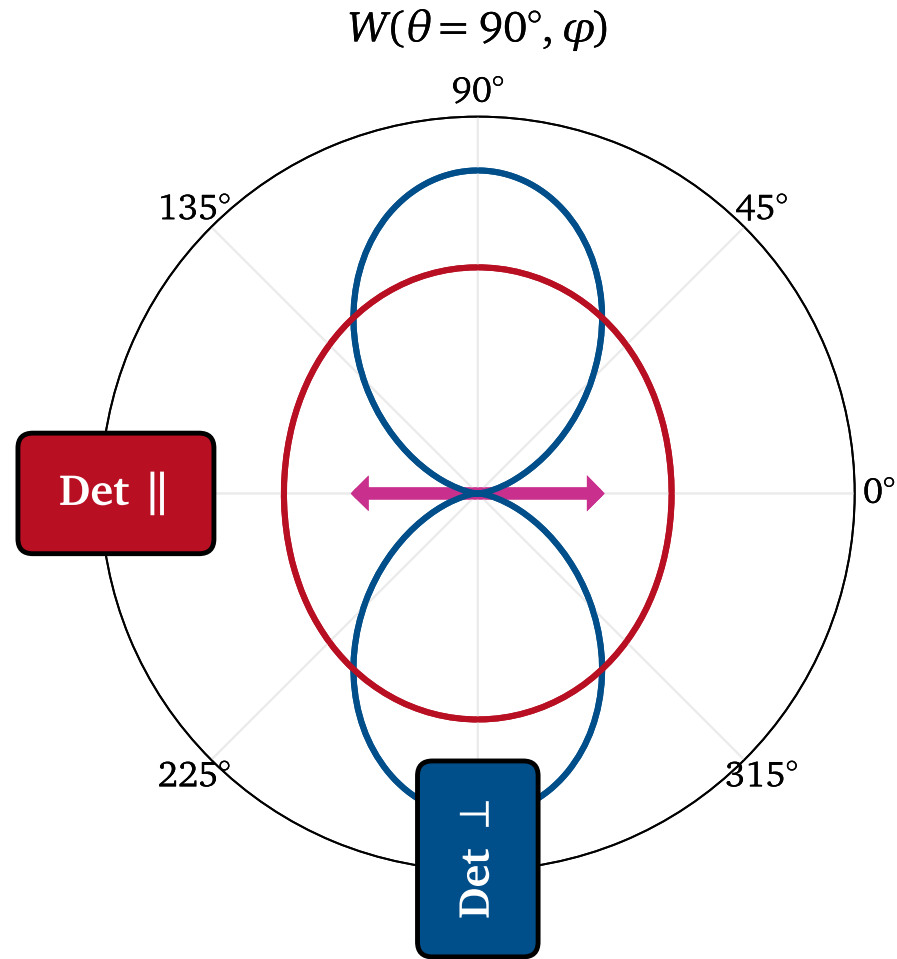
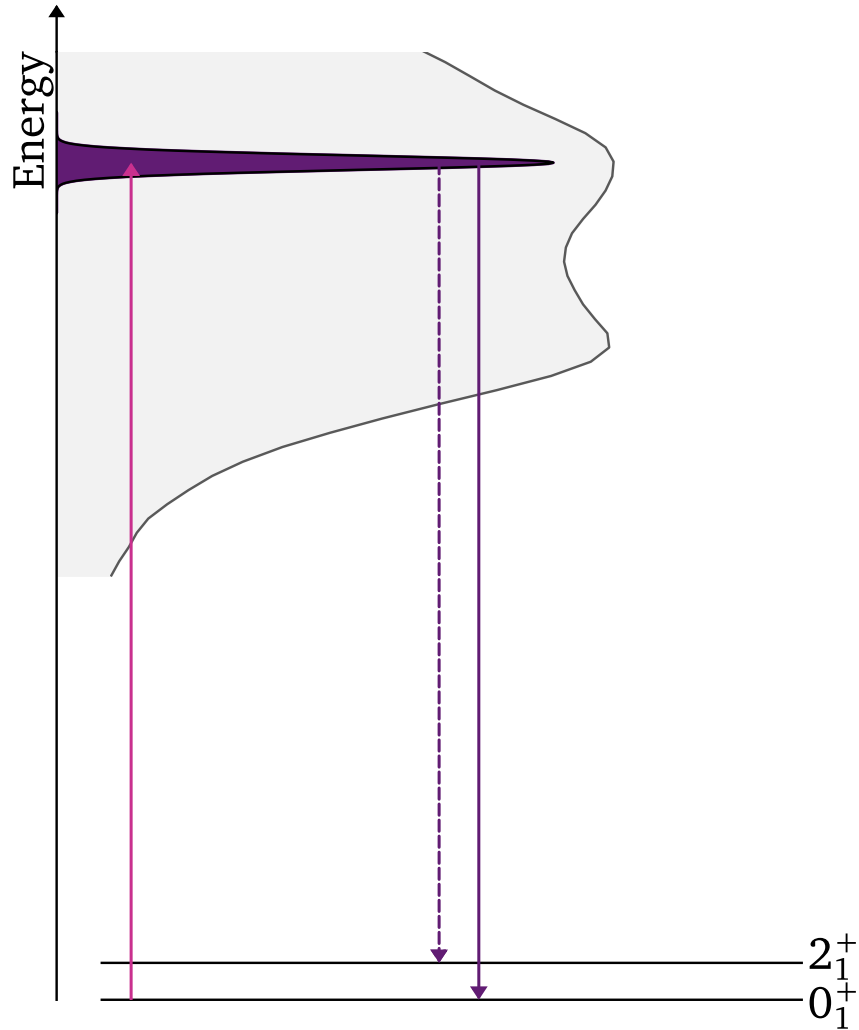
## Deformed Nucleus $^{164}\text{Dy}$





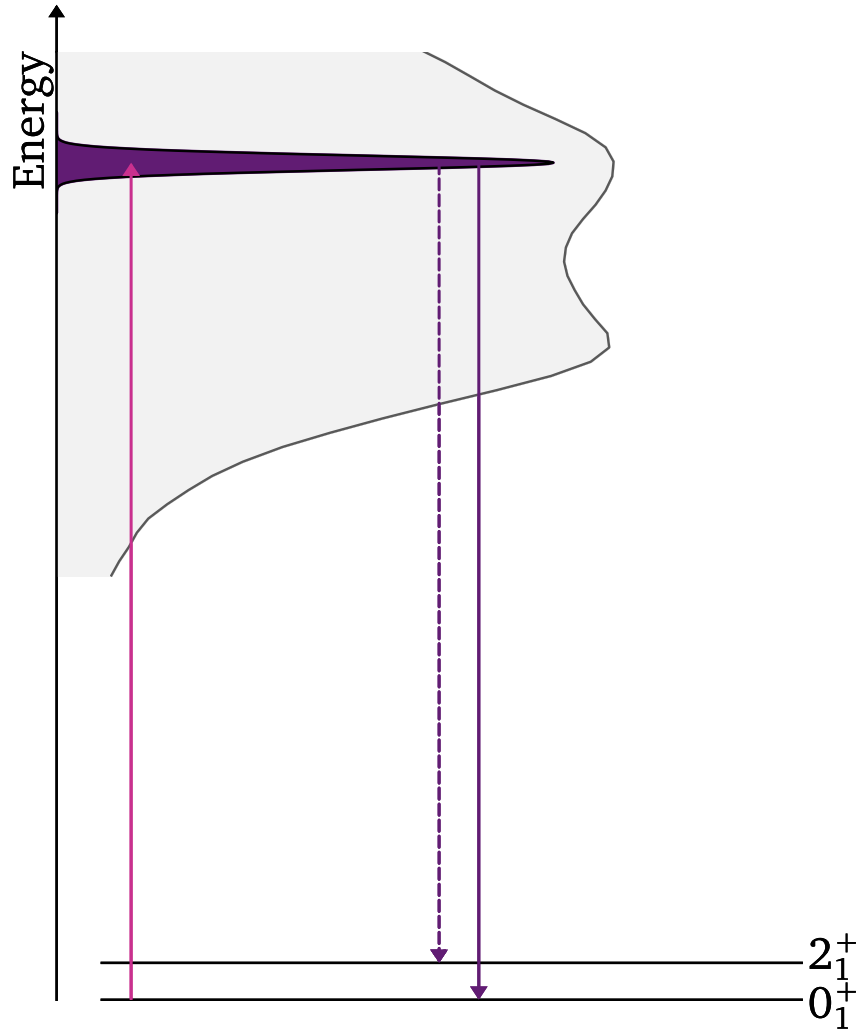
# ANGULAR DISTRIBUTION

Deformed Nucleus  $^{164}\text{Dy}$

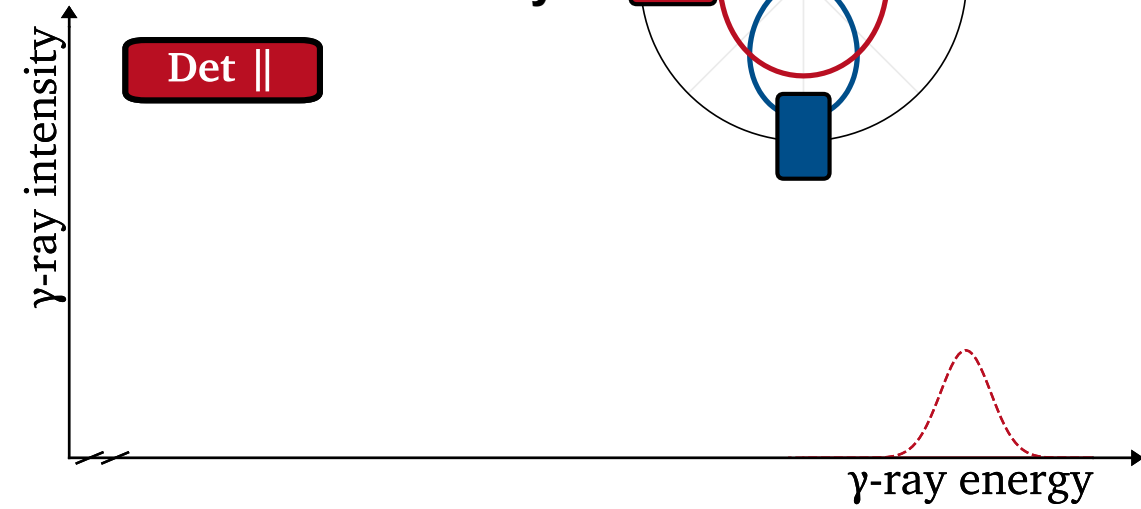


↔ Beam polarization    — Elastic scattering    —  $2_1^+$  Raman scattering

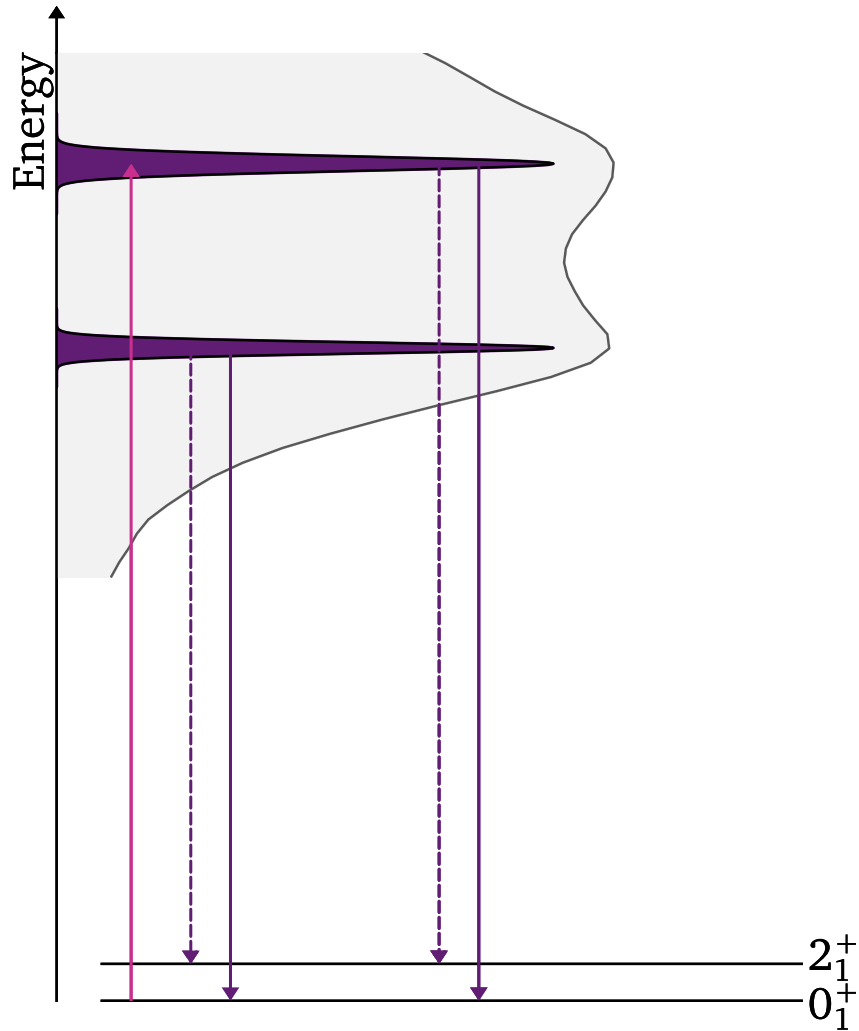
# EXPERIMENTAL METHOD



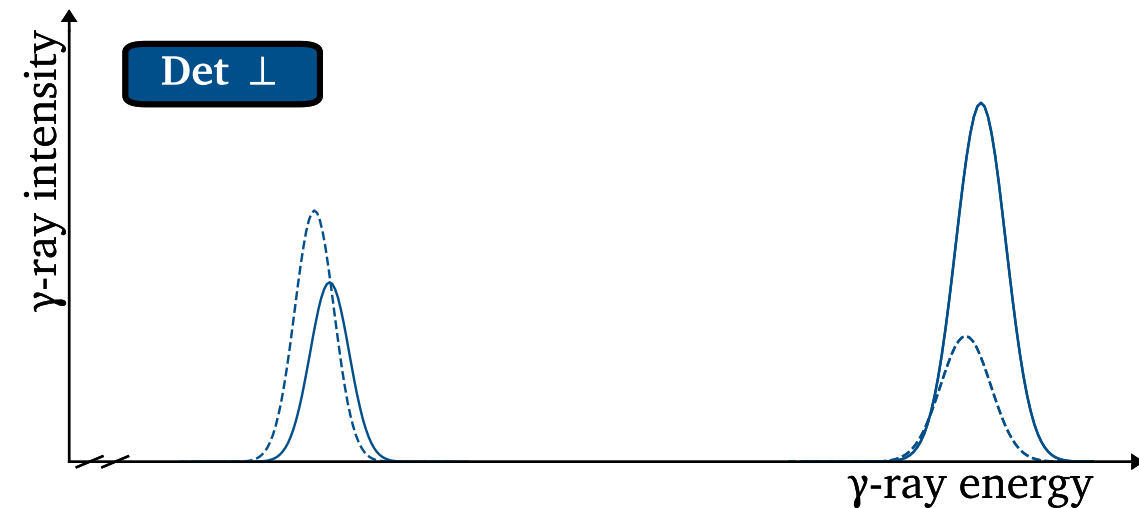
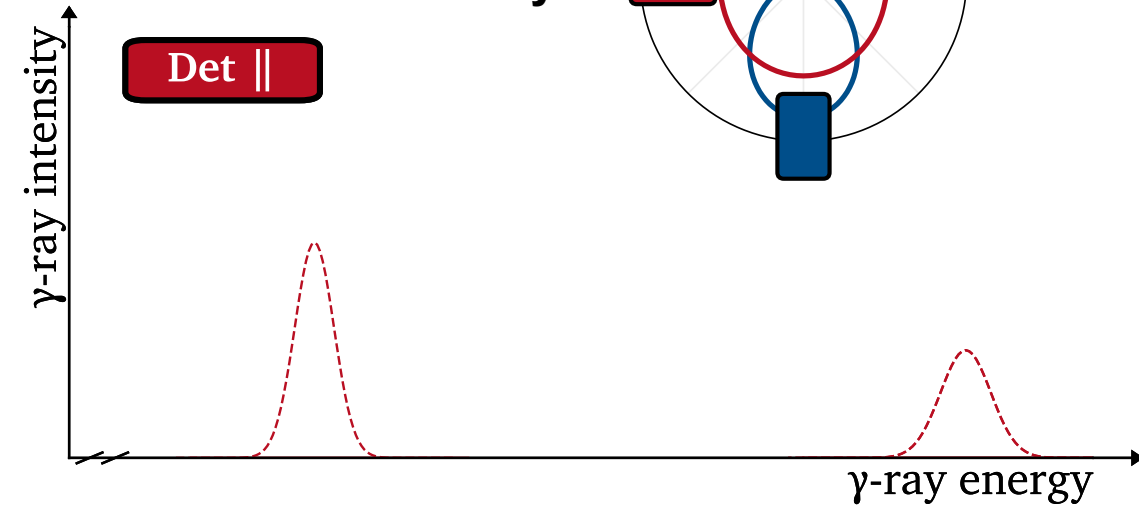
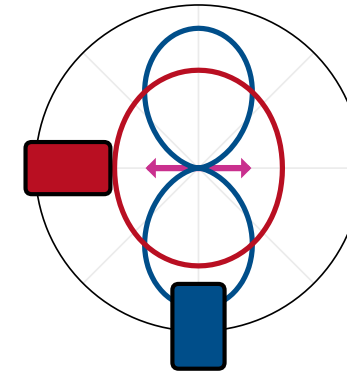
Deformed Nucleus  $^{164}\text{Dy}$



# EXPERIMENTAL METHOD

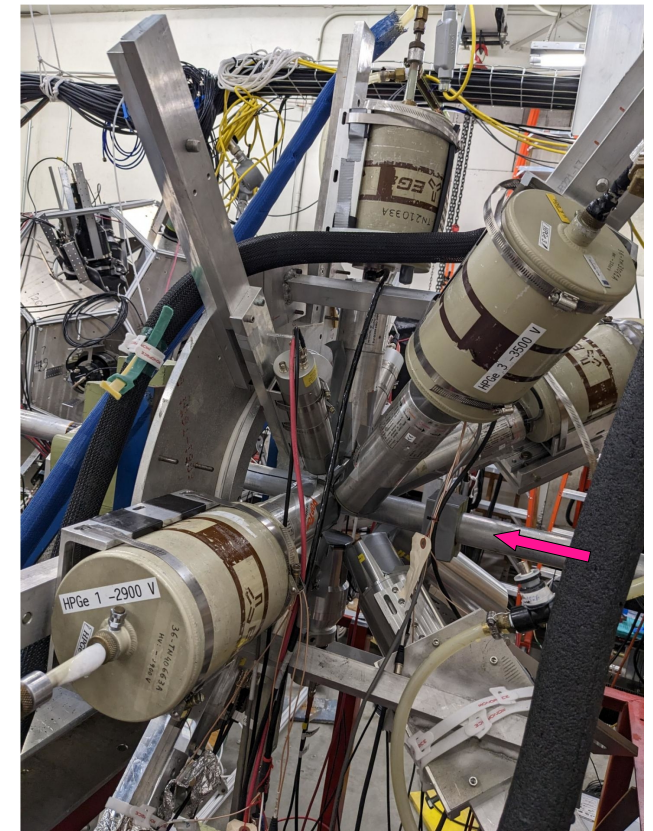
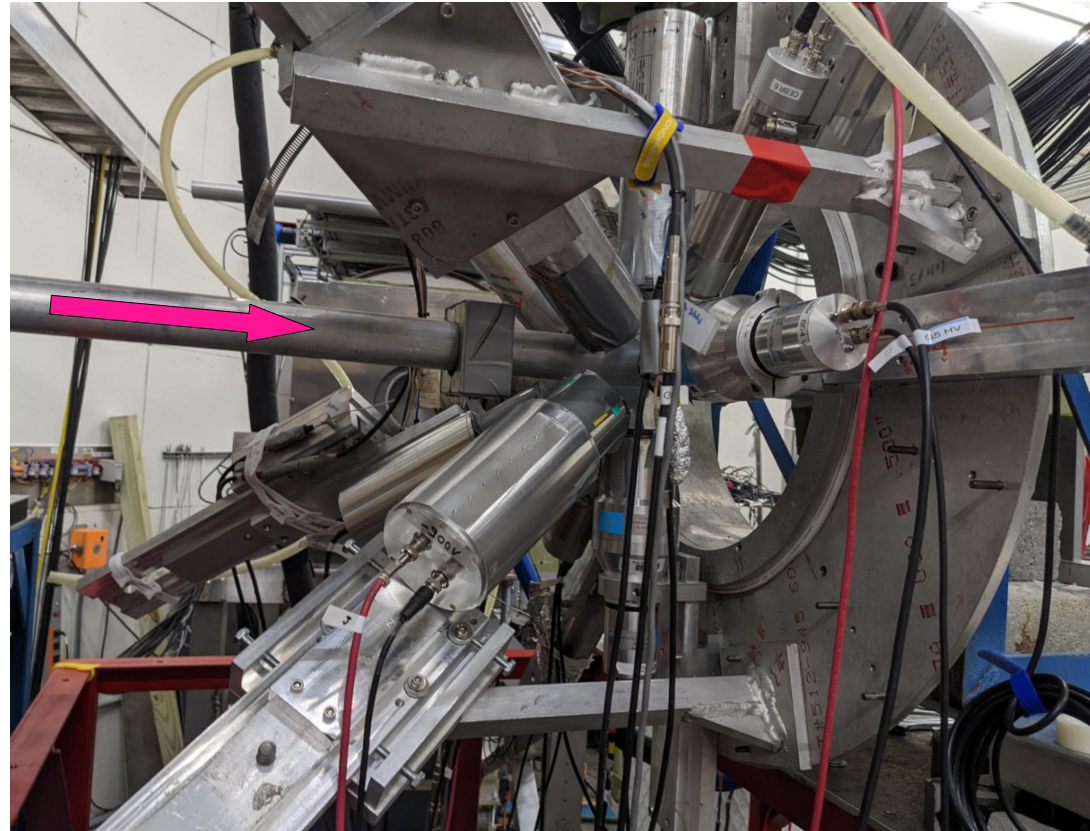


Deformed Nucleus  $^{164}\text{Dy}$

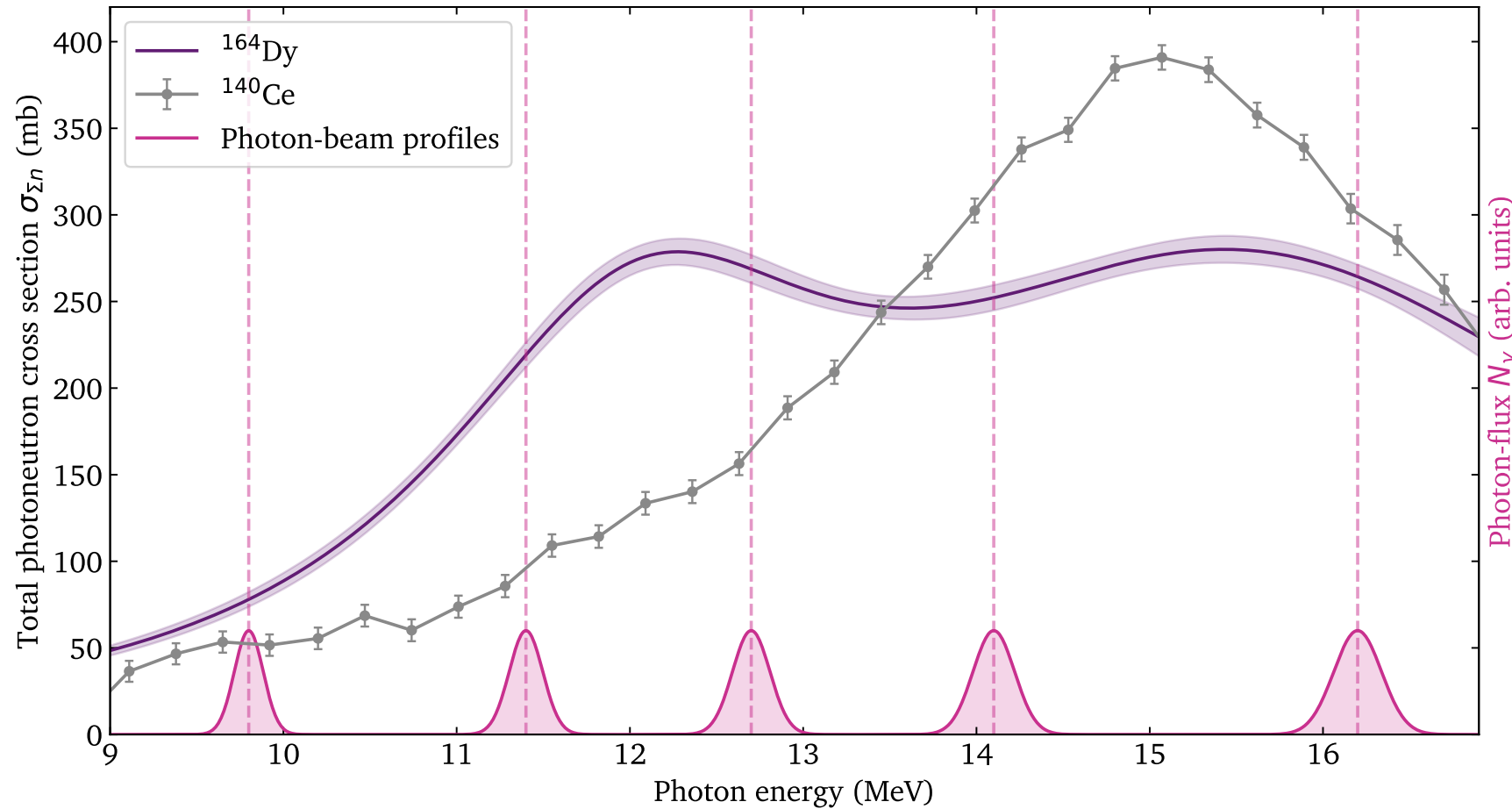


# $\gamma^3$ SETUP

- Detectors:
  - 4 HPGe
  - 4 LaBr<sub>3</sub>
  - 3 CeBr<sub>3</sub>
- Placed:
  - Perpendicular to beam line ( $\theta = 90^\circ$ )
  - Backward angles ( $\theta = 135^\circ$ )



# CONDUCTED MEASUREMENTS



- $^{164}\text{Dy}$  and  $^{140}\text{Ce}$  target
- 5 beam energies
- Linear and circular polarization
- ~3-4 hours per measurement

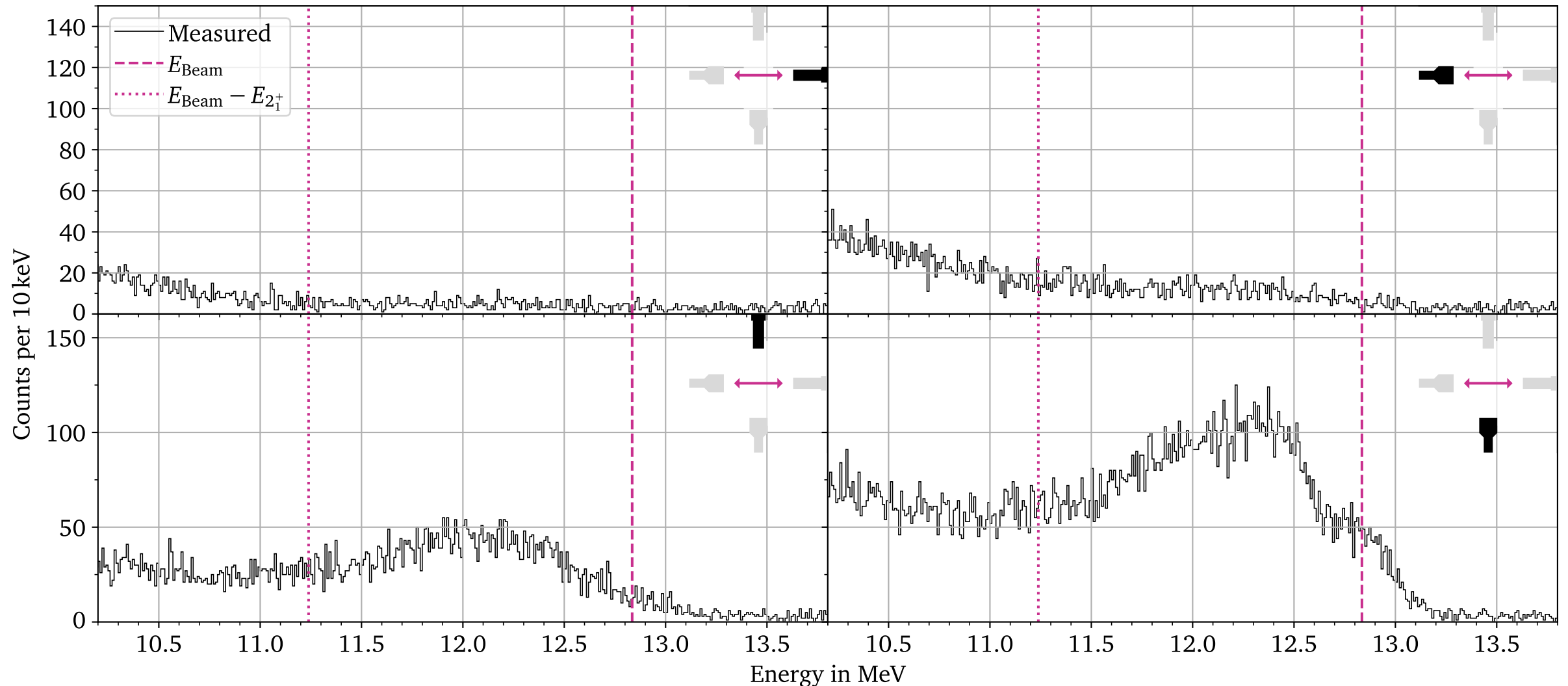


# EXAMPLE SPECTRA

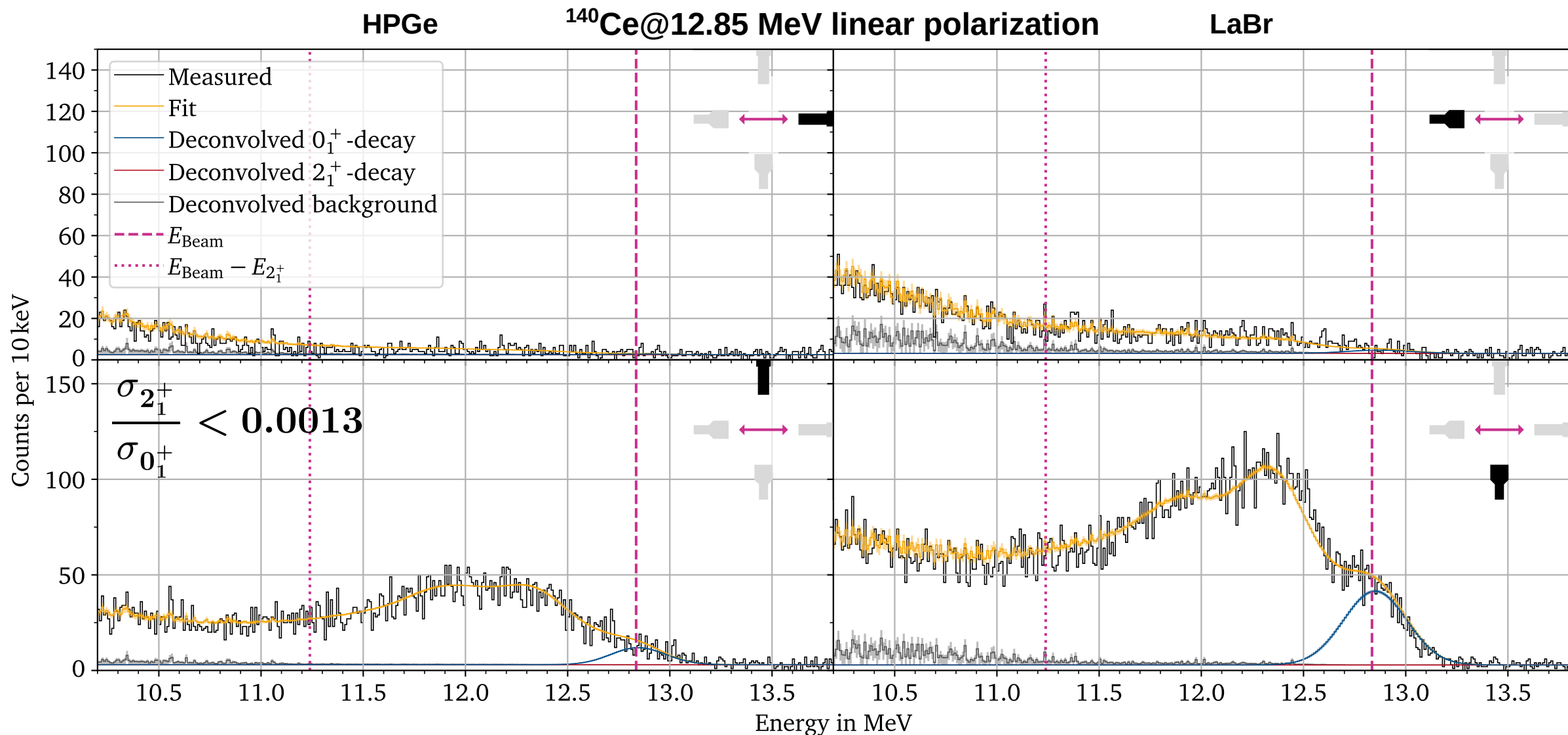
HPGe

$^{140}\text{Ce}$ @12.85 MeV linear polarization

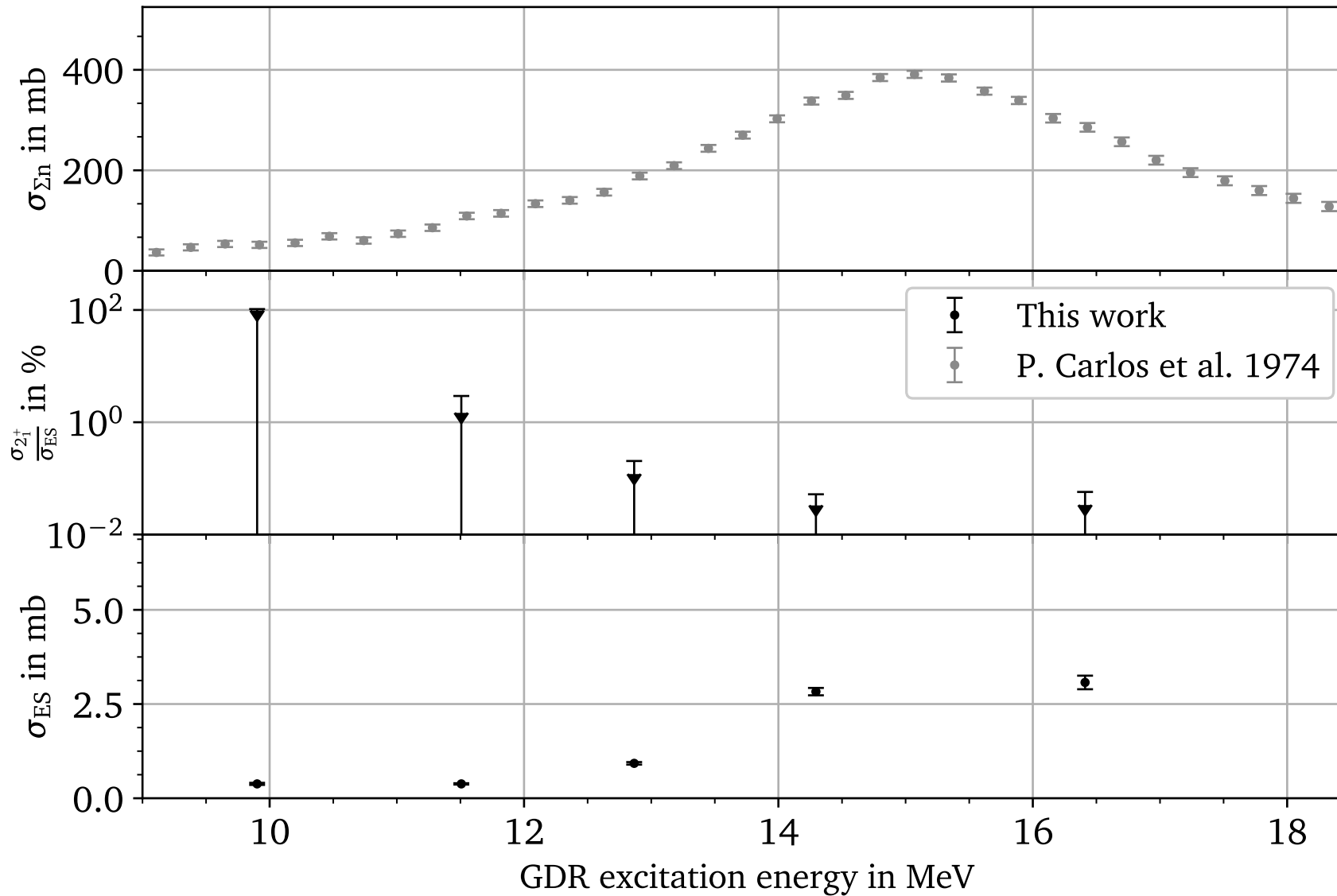
LaBr



# DECONVOLVED SPECTRA

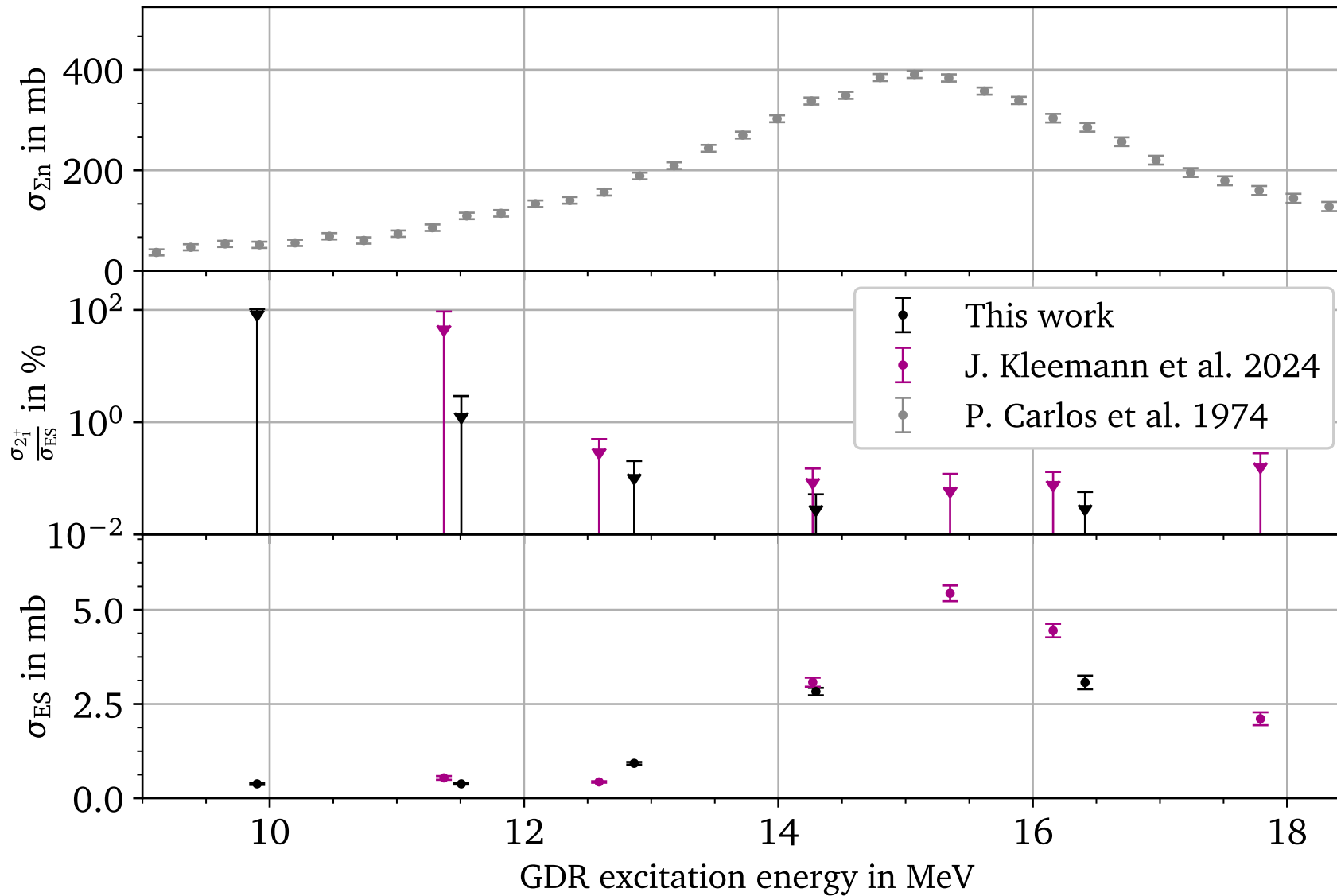


# RESULTS $^{140}\text{Ce}$



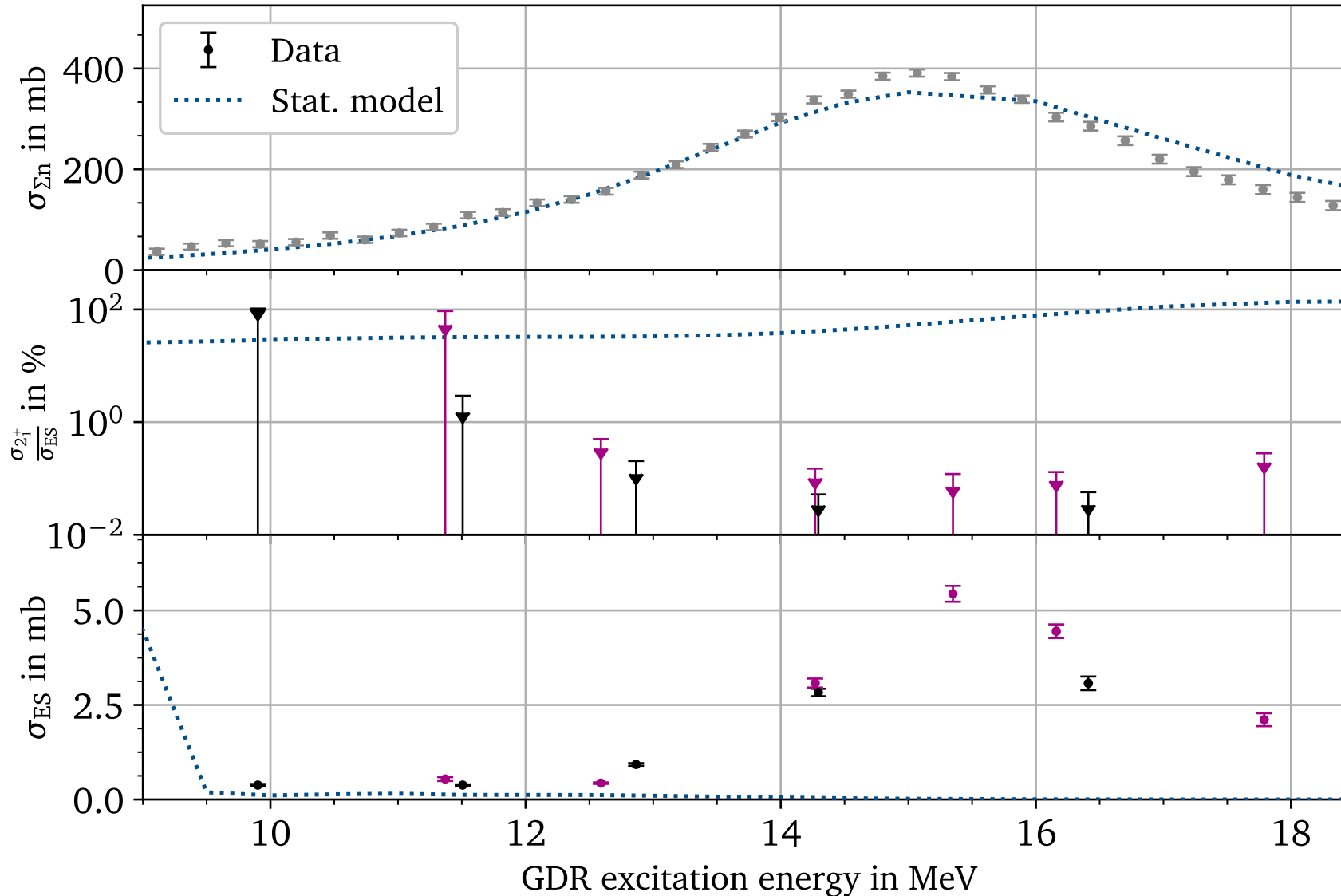
- Deconvolution yields  $\sigma_{2^+}/\sigma_{ES}$
- Photon flux determination via gold activation measurement  
→ Total  $\sigma_{ES}$

# RESULTS $^{140}\text{Ce}$



- Deconvolution yields  $\sigma_{2^+}/\sigma_{ES}$
- Photon flux determination via gold activation measurement  
→ Total  $\sigma_{ES}$
- Agree and improve on data from J. Kleemann

# RESULTS $^{140}\text{Ce}$



- Deconvolution yields  $\sigma_{2^+}/\sigma_{ES}$
- Photon flux determination via gold activation measurement  
→ Total  $\sigma_{ES}$
- Agree and improve on data from J. Kleemann
- Statistical model cannot reproduce the data

# GEOMETRICAL MODEL FORMALISM

- Photoabsorption cross section sum of up to three SLO's:  $\sigma_{\text{Abs}}(E) = \sum_{k=1}^3 \sigma_k^{\text{SLO}}(E) = \sum_{k=1}^3 \frac{\hat{\sigma}_k}{1 + \left(\frac{E - \hat{E}_k}{E\hat{\Gamma}_k}\right)^2}$
- Elastic scattering cross section:  $\sigma_{\text{ES}} = \frac{8\pi}{3} |f_{\text{ENRF}} + f_{\text{T}}|^2$

# GEOMETRICAL MODEL FORMALISM

- Photoabsorption cross section sum of up to three SLO's:  $\sigma_{\text{Abs}}(E) = \sum_{k=1}^3 \sigma_k^{\text{SLO}}(E) = \sum_{k=1}^3 \frac{\hat{\sigma}_k}{1 + \left(\frac{E - \hat{E}_k}{E\hat{\Gamma}_k}\right)^2}$
- Elastic scattering cross section:  $\sigma_{\text{ES}} = \frac{8\pi}{3} |f_{\text{ENRF}} + f_{\text{T}}|^2$

Optical theorem:

$$\text{Im}(f(E)) = \frac{E}{4\pi\hbar c} \sigma_{\text{Abs}}(E)$$



Kramers-Kronig relation:

$$\text{Re}(f(E)) = \frac{2E^2}{\pi} \mathcal{P} \int_0^\infty \frac{\text{Im}(f(\mathcal{E}))}{\mathcal{E}(\mathcal{E}^2 - E^2)} d\mathcal{E}$$

Thomson:

$$f_{\text{T}} = -\frac{Z^2 \alpha \hbar c}{Mc^2}$$

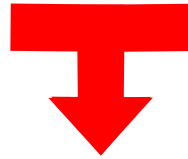
$$\Rightarrow f_{\text{ENRF}}(E) = \frac{E}{4\pi\hbar c} \left( i - \frac{E^2 - \hat{E}^2}{E\Gamma} \right) \sigma_{\text{Abs}}(E)$$

# GEOMETRICAL MODEL FORMALISM

- Photoabsorption cross section sum of up to three SLO's:  $\sigma_{\text{Abs}}(E) = \sum_{k=1}^3 \sigma_k^{\text{SLO}}(E) = \sum_{k=1}^3 \frac{\hat{\sigma}_k}{1 + \left(\frac{E - \hat{E}_k}{E\hat{\Gamma}_k}\right)^2}$
- Elastic scattering cross section:  $\sigma_{\text{ES}} = \frac{8\pi}{3} |f_{\text{ENRF}} + f_{\text{T}}|^2$

Optical theorem:

$$\text{Im}(f(E)) = \frac{E}{4\pi\hbar c} \sigma_{\text{Abs}}(E)$$



Kramers-Kronig relation:

$$\text{Re}(f(E)) = \frac{2E^2}{\pi} \mathcal{P} \int_0^\infty \frac{\text{Im}(f(\mathcal{E}))}{\mathcal{E}(\mathcal{E}^2 - E^2)} d\mathcal{E}$$

Thomson:

$$f_{\text{T}} = -\frac{Z^2 \alpha \hbar c}{Mc^2}$$

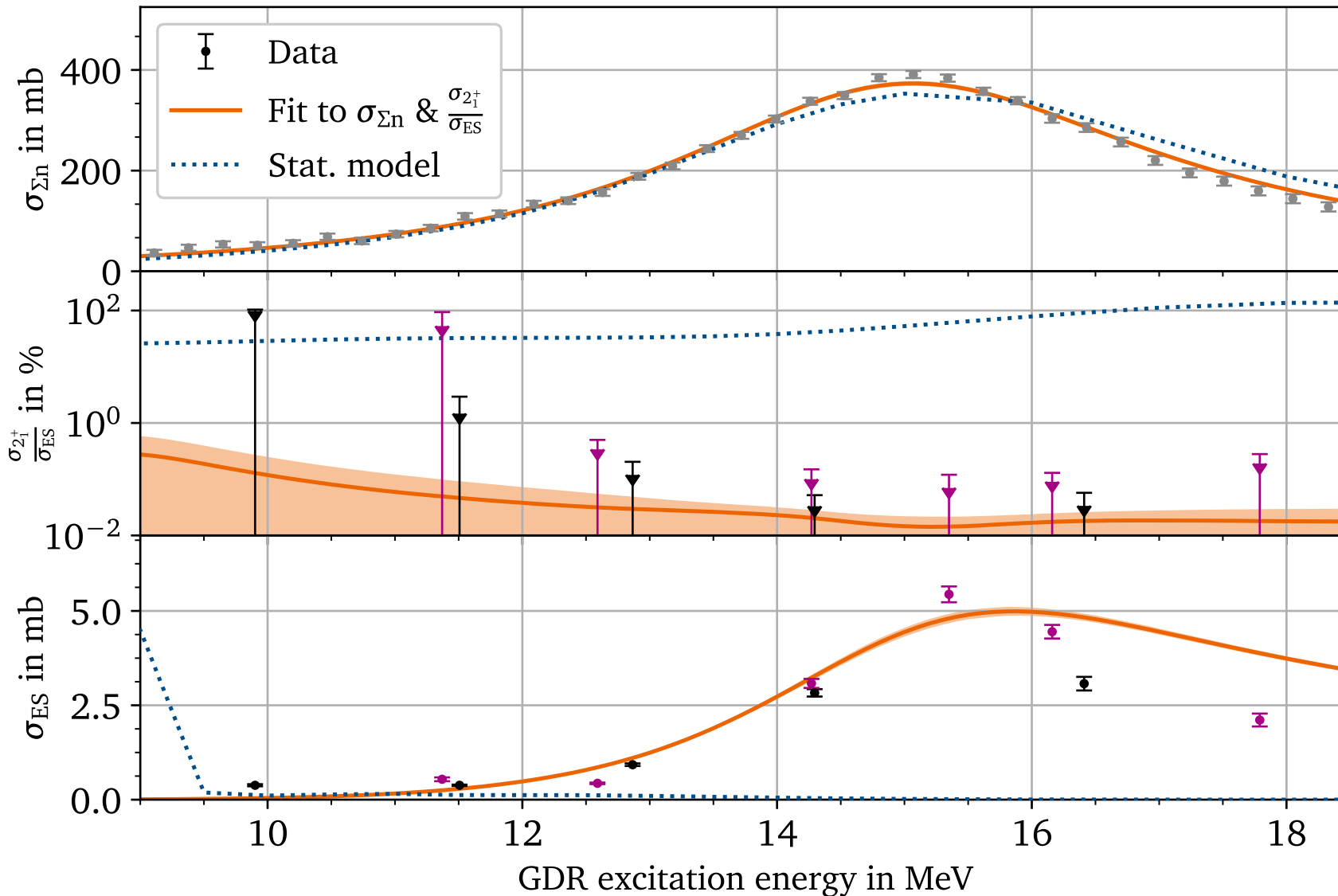
$$\Rightarrow f_{\text{ENRF}}(E) = \frac{E}{4\pi\hbar c} \left( i - \frac{E^2 - \hat{E}^2}{E\Gamma} \right) \sigma_{\text{Abs}}(E)$$

- Inelastic scattering cross section from coupling of GDR to rotational motion:

$$\sigma_{2_1^+} = \frac{4\pi}{3} \sum_{k,l=1}^3 |f_k^{\text{ENRF}}(E) - f_l^{\text{ENRF}}(E)|^2$$

**Elastic and inelastic scattering cross sections dependent on SLO parameters!**

# RESULTS $^{140}\text{Ce}$



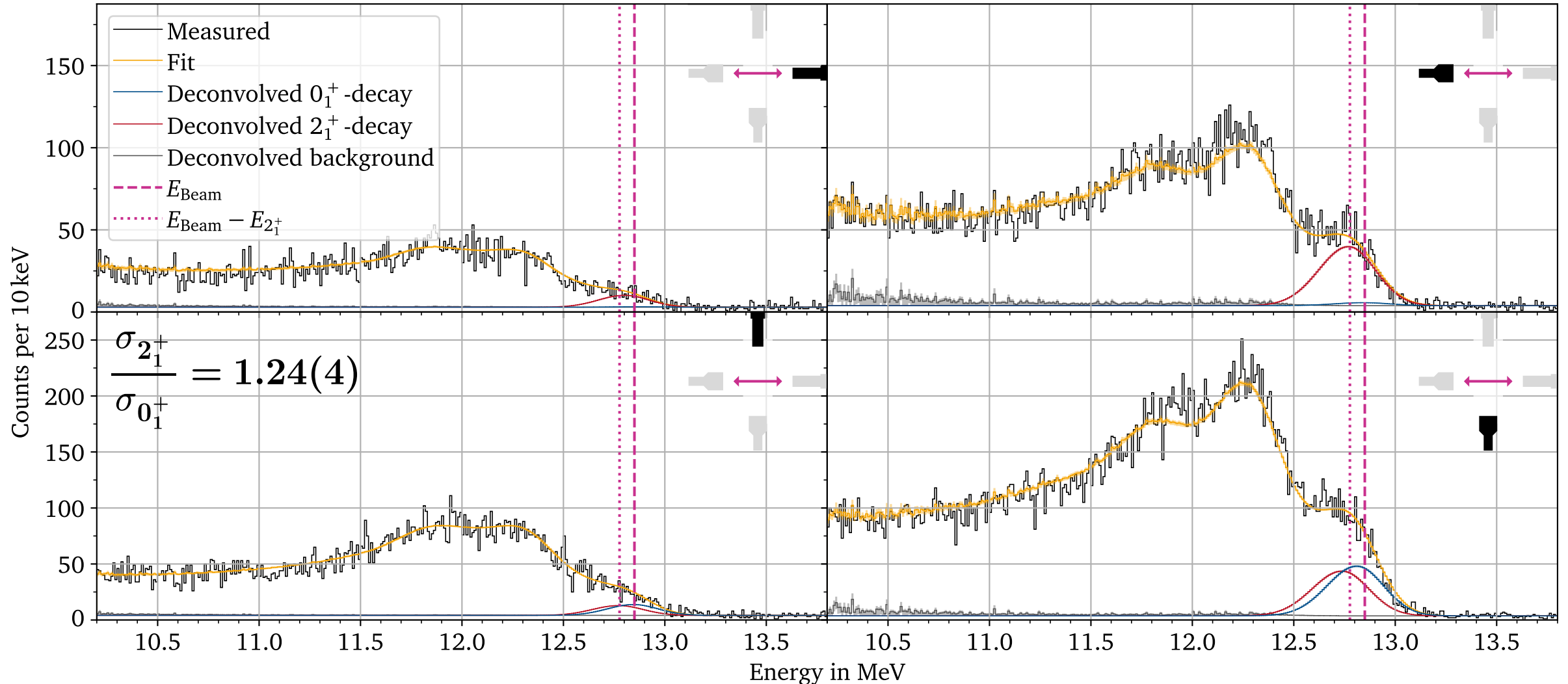
- Deconvolution yields  $\sigma_{2+}/\sigma_{ES}$
- Photon flux determination via gold activation measurement  
→ Total  $\sigma_{ES}$
- Agree and improve on old data
- Statistical model cannot reproduce the data
- Geometrical Model fit describes the data accurately

# DECONVOLVED SPECTRA

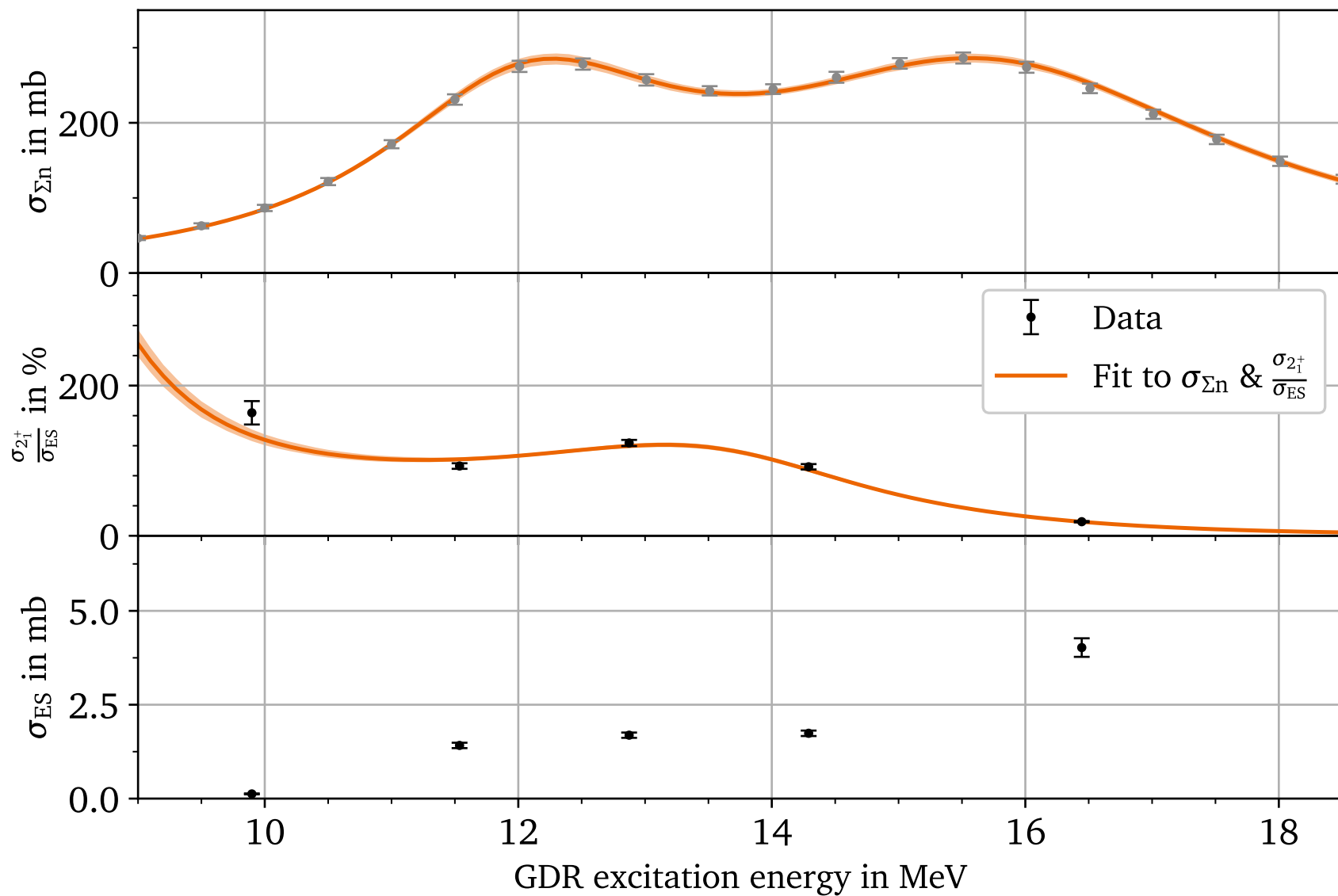
HPGe

$^{164}\text{Dy}$ @12.85 MeV linear polarization

LaBr

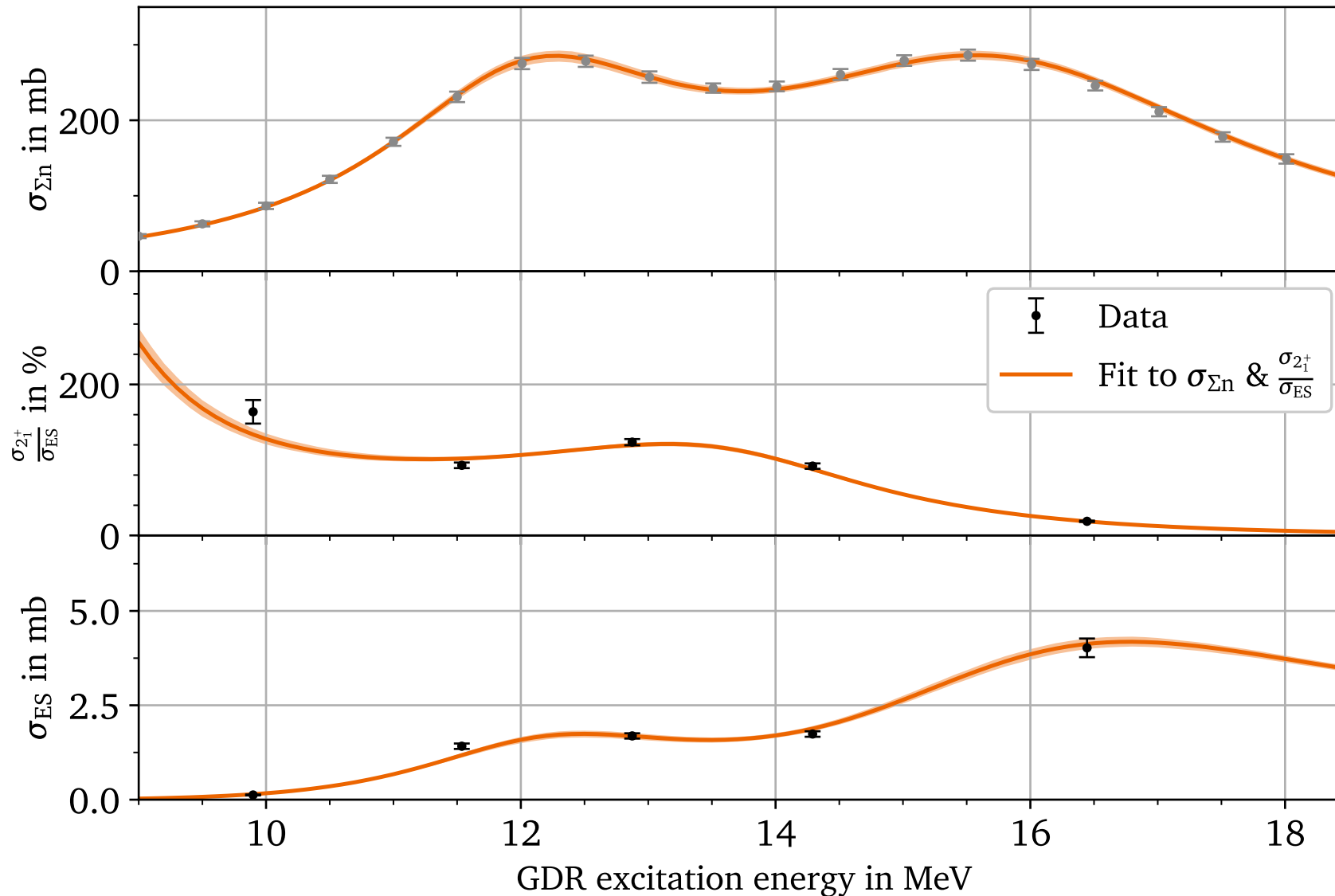


# RESULTS $^{164}\text{Dy}$



- Fit of Geometrical Model predictions for a triaxial nucleus
- Assume same width  $\Gamma_2 = \Gamma_3$  and amplitude  $\sigma_{0,2} = \sigma_{0,3}$

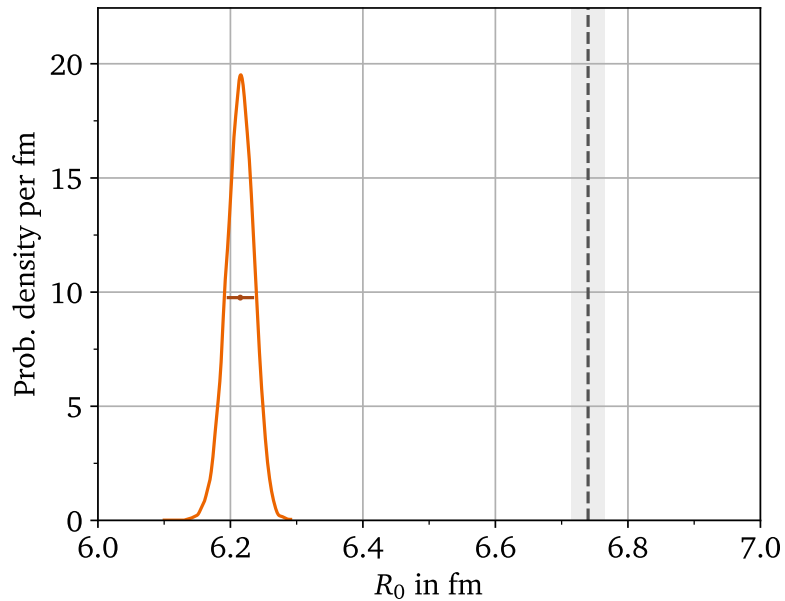
# RESULTS $^{164}\text{Dy}$



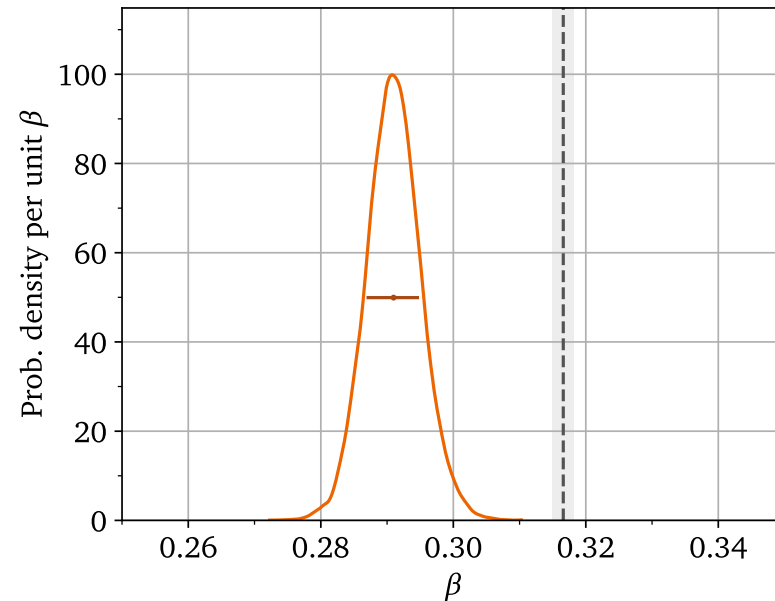
- Fit of Geometrical Model predictions for a triaxial nucleus
- Assume same width  $\Gamma_2 = \Gamma_3$  and amplitude  $\sigma_{0,2} = \sigma_{0,3}$
- Fit predictions for  $\sigma_{ES}$  describe the data precisely

# SHAPE PARAMETERS OF $^{164}\text{Dy}$

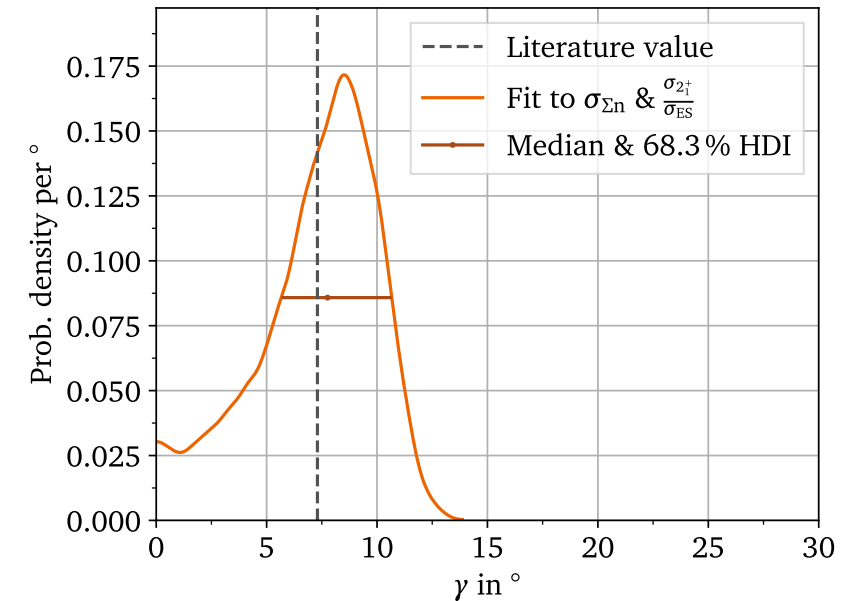
- Shape parameter predictions possible from Geometrical Model fits
- Results align reasonably well with literature values
- Triaxiality estimated to be  $\gamma = 7.6^{\circ+2.9}_{-2.1}$



I. Angeli, At. Data and Nuc. Data Tables **87**, 185 (2004)



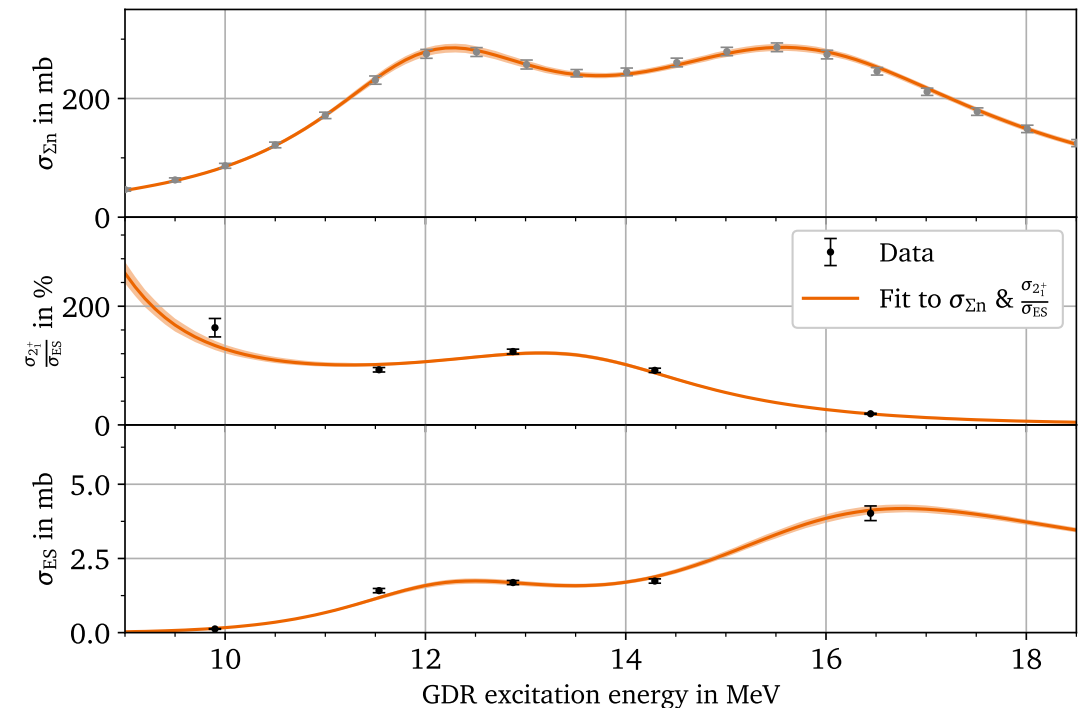
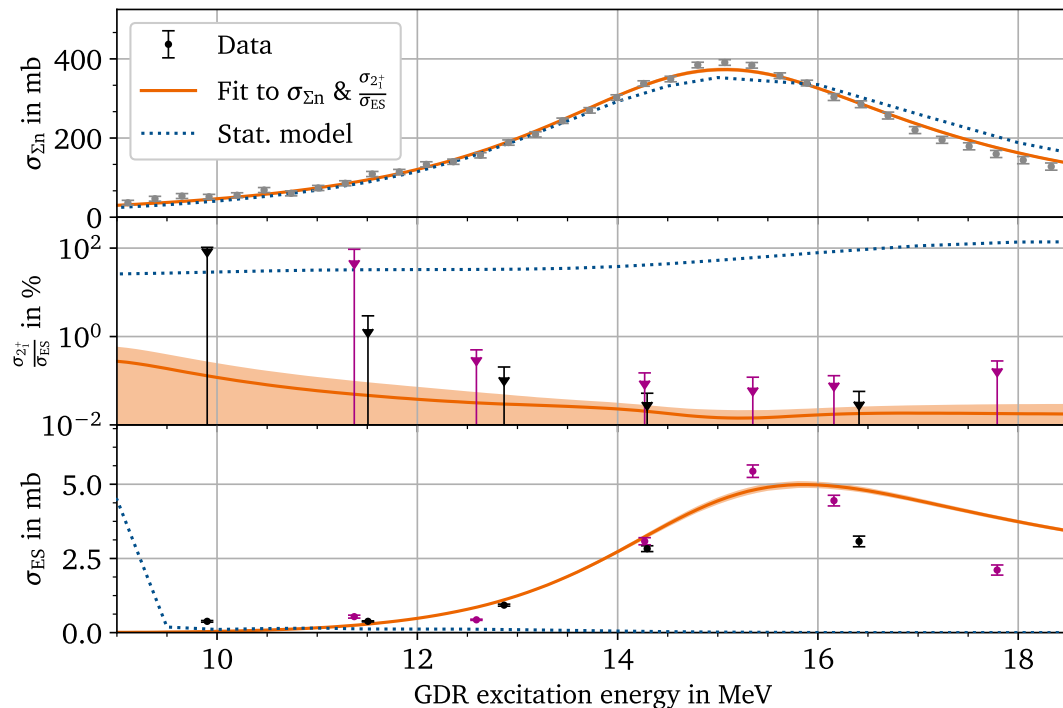
B. Singh and J. Chen, Nucl. Data Sheets **147**, 1 (2018)



T. Otsuka et al., arXiv **2303.11299**, 1 (2025)

# CONCLUSION

- Successful experiment measuring the  $\gamma$ -decay of the GDR of  $^{164}\text{Dy}$
- $^{140}\text{Ce}$  results agree and improve on previous data from J. Kleemann
- $^{140}\text{Ce}$  and  $^{164}\text{Dy}$  results can be accurately described by Geometrical Model fits
- Shape parameters can be estimated, triaxiality of  $\gamma=7.6^{+2.9}_{-2.1}$





# INVESTIGATING THE GIANT DIPOLE RESONANCE OF $^{164}\text{Dy}$ USING NRF

**M. Heumüller**<sup>1,✉</sup>, J. Kleemann<sup>1</sup>, N. Pietralla<sup>1</sup>, A. D. Ayangeakaa<sup>2,3</sup>, S. W. Finch<sup>2,4</sup>,  
D. Gribble<sup>2,3</sup>, J. Hauf<sup>1</sup>, J. Isaak<sup>1</sup>, X. K.-H. James<sup>2,3</sup>, R. V. F. Janssens<sup>2,3</sup>,  
S. R. Johnson<sup>2,3</sup>, T. Kowalewski<sup>2,3</sup>, B. Löher<sup>5</sup>, O. Papst<sup>1</sup>, K. Prifti<sup>1</sup>, A. Saracino<sup>2,3</sup>,  
D. Savran<sup>5</sup>, N. Sensharma<sup>2,3</sup>, V. Werner<sup>1</sup>

<sup>1</sup>IKP, TU Darmstadt

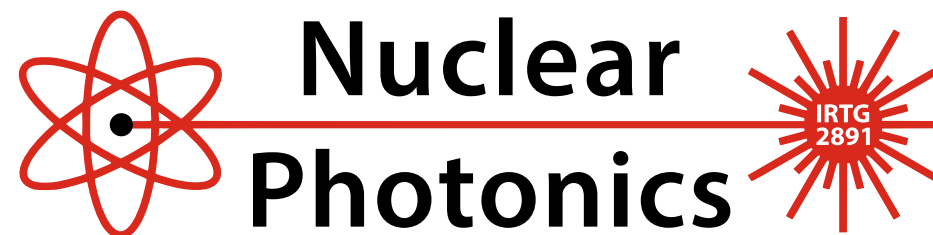
<sup>2</sup>TUNL, Durham, NC, USA

<sup>3</sup>U. of NC, Chapel Hill, USA

<sup>4</sup>Duke U., Durham, NC, USA

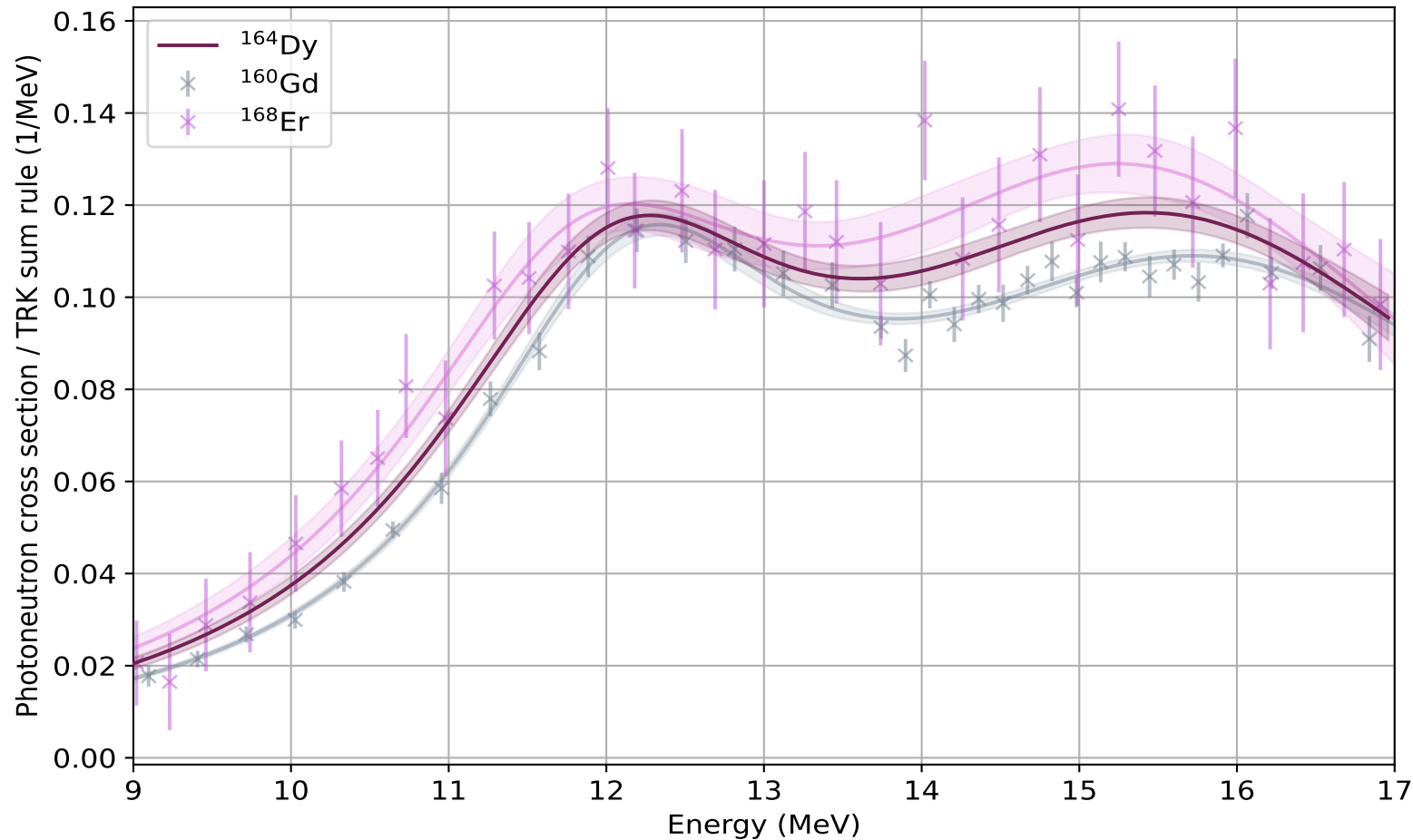
<sup>5</sup>GSI, Darmstadt, Germany

✉mheumueller@ikp.tu-darmstadt.de



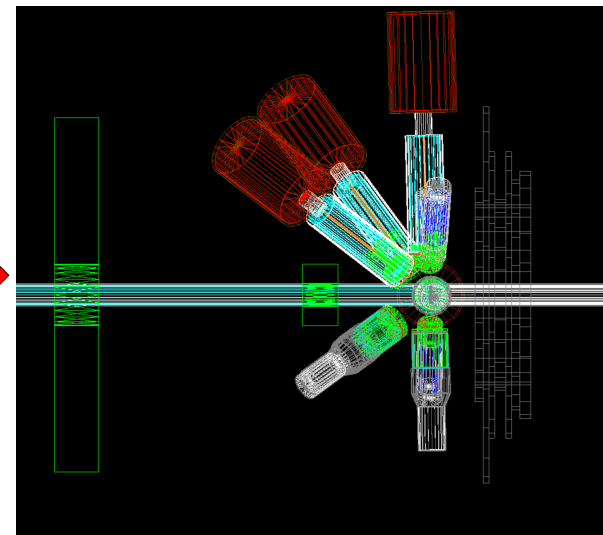
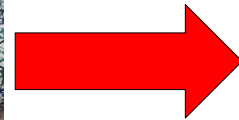
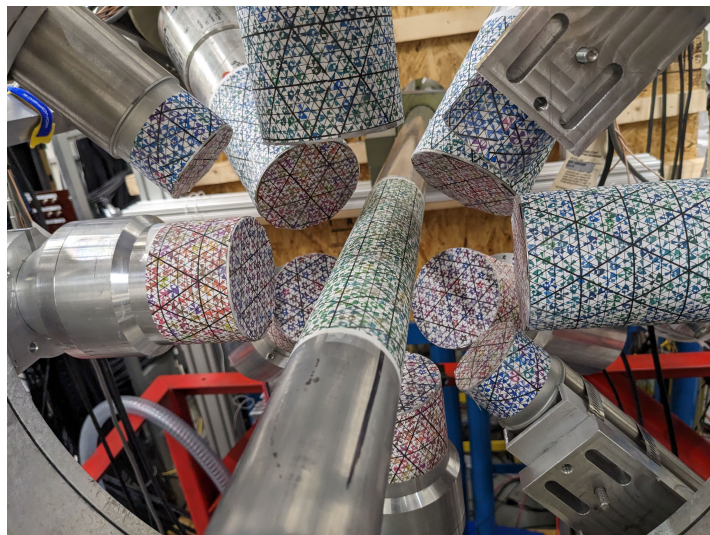
# THE GIANT DIPOLE RESONANCE OF $^{164}\text{Dy}$

- Suspected triaxility of  $\gamma = 7.3^\circ$   
T. Otsuka et al., arXiv [2303.11299](https://arxiv.org/abs/2303.11299), 1 (2025)
- GDR of  $^{164}\text{Dy}$  never measured in detail
- Photoneutron cross section of  $^{160}\text{Gd}$  and  $^{168}\text{Er}$  measured  
B. L. Berman et al., Phys. Rev. **185**, 1576 (1969)  
G. Gurevich et al., Nucl. Phys. A **351**, 257 (1981)
- Averaged cross section as approximation for  $\sigma_{\text{Abs}}$  of  $^{164}\text{Dy}$
- Validity can later be tested with data from this work

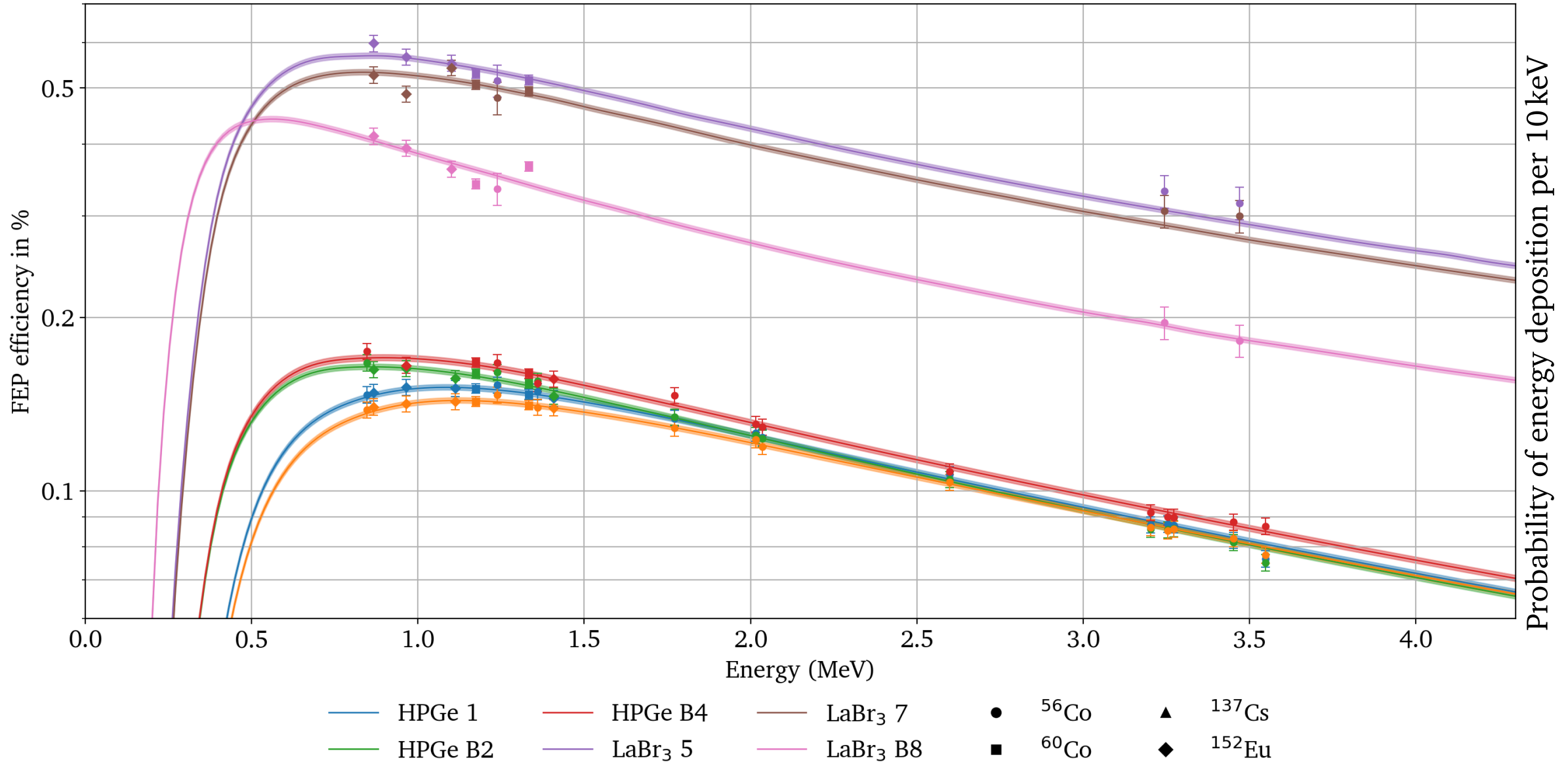


# PHOTOGRAMMETRY

- Analysis and deconvolution of NRF spectra need precise knowledge about the setup geometry for detector response simulations
- Photogrammetry enables detailed measurement of positions and angles
- Implementation into GEANT4



# DETECTOR RESPONSE





# DECONVOLUTION PROCEDURE

- GEANT4 simulations  $\Rightarrow$  Response matrices  $\mathbf{R}_{0_1^+}$ ,  $\mathbf{R}_{2_1^+}$ ,  $\mathbf{R}_{\text{BG}}$  for each detector
- Model for incident  $\gamma$ -ray radiation:

$$I_{0_1^+} \cdot \mathcal{N}(E_{\text{Beam}}) + I_{2_1^+} \cdot \mathcal{N}(E_{\text{Beam}} - E_{2_1^+}) + \text{BG}$$

- Final fit functions for convoluted spectra:

$$\mathbf{R}_{0_1^+} \cdot [I_{0_1^+} \cdot \mathcal{N}(E_{\text{Beam}})] + \mathbf{R}_{2_1^+} \cdot [I_{2_1^+} \cdot \mathcal{N}(E_{\text{Beam}} - E_{2_1^+})] + \mathbf{R}_{\text{BG}} \cdot \text{BG}$$

- Deconvolve using Bayesian fits to all detectors simultaneously

# OUTLOOK

- Beam monitor analysis to optimize deconvolutions
- Similar experiments on the Samarium isotopic chain conducted in December 2025

