



L International Meeting  
on Fundamental Physics  
and XV CPAN Days

2 — 6 October 2023



# Advances in the development of Compton cameras for treatment verification

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Instituto de Física Corpuscular (IFIC, CSIC-UV)

<http://ific.uv.es/iris>

# Outline

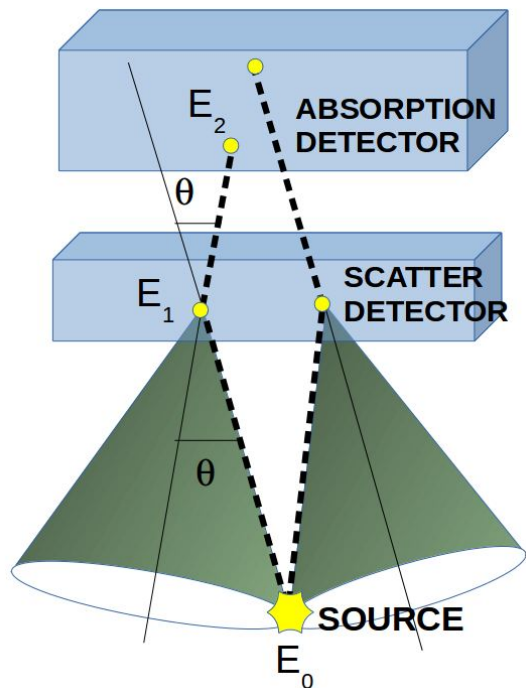
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From:	To:
MACACO III	MACACO III+
MACACOp	FALCON

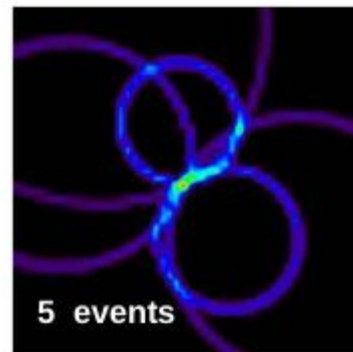
+

- Hadron therapy treatment monitoring.
- Radionuclide therapy assessment.
- Conclusions and outlook.

# Compton camera



## Backprojection



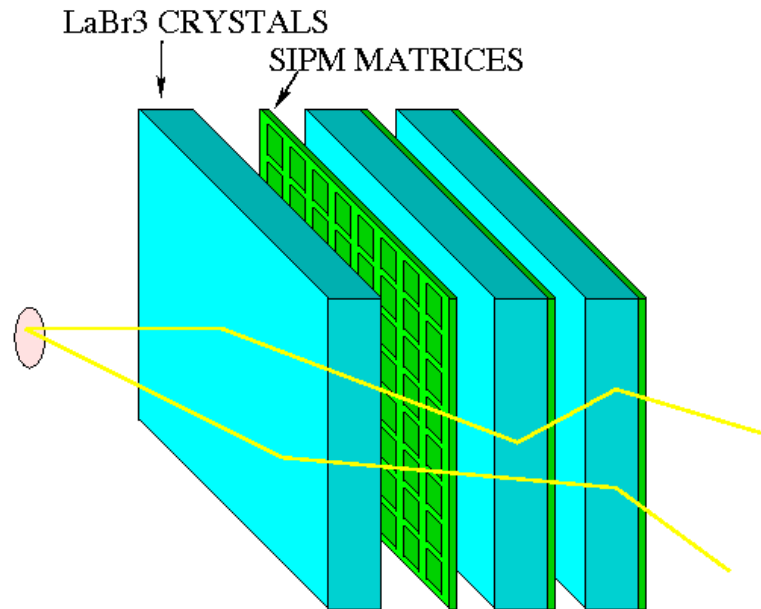
## + Image reconstruction

$$\lambda_j^{n+1} = \frac{\lambda_j^n}{s_j} \sum_{i=0}^N \frac{t_{ij}}{\sum_k t_{ik} \lambda_k^n}$$

List mode ML-EM

# MACACO

## Medical Applications CompAct COmpton camera



Fast response  
2/3 planes + no absorption required

MACACO III (AliVATA) vs. MACACO<sub>p</sub> (PetSys)

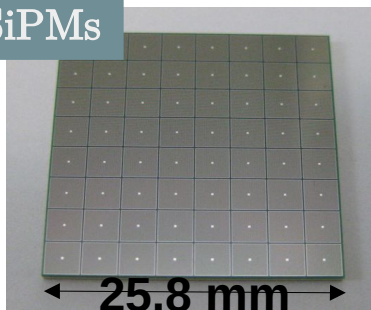
# MACACO III

## Detectors

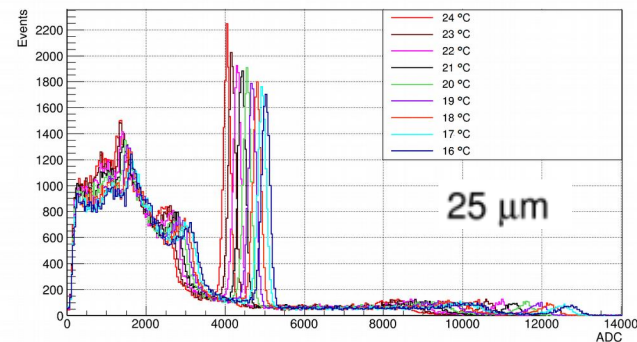
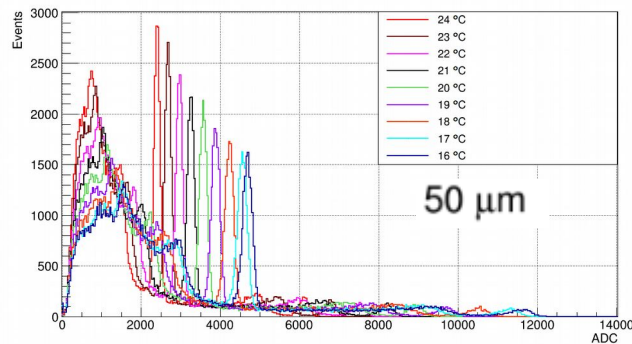
LaBr<sub>3</sub>



SiPMs



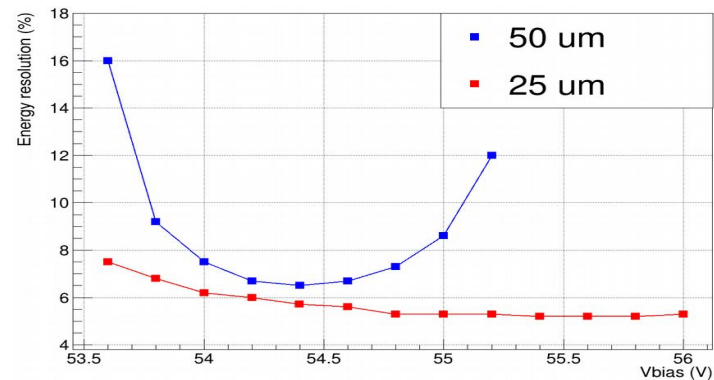
8 x 8 channels



S13360-3025CS (25  $\mu\text{m}$ )

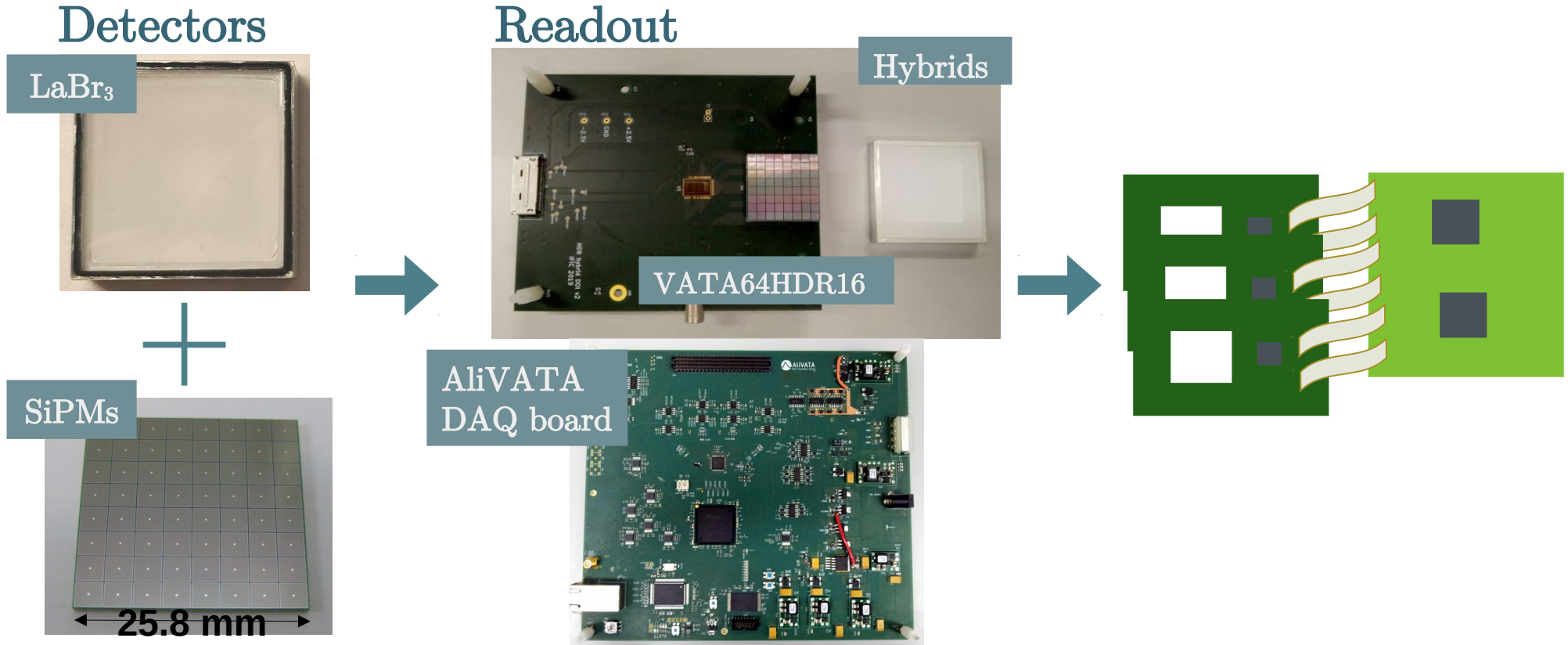
VS

S13361-3050AE-08 (50  $\mu\text{m}$ )

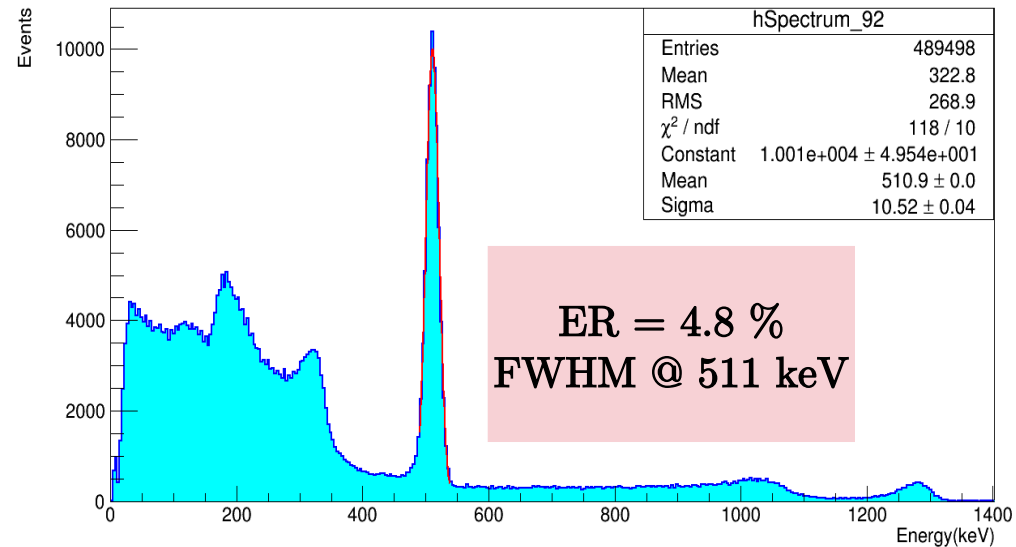


L. Barrientos et al. Rad. Phys. Chem. 2023

# MACACO III



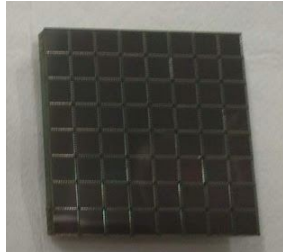
# MACACO III



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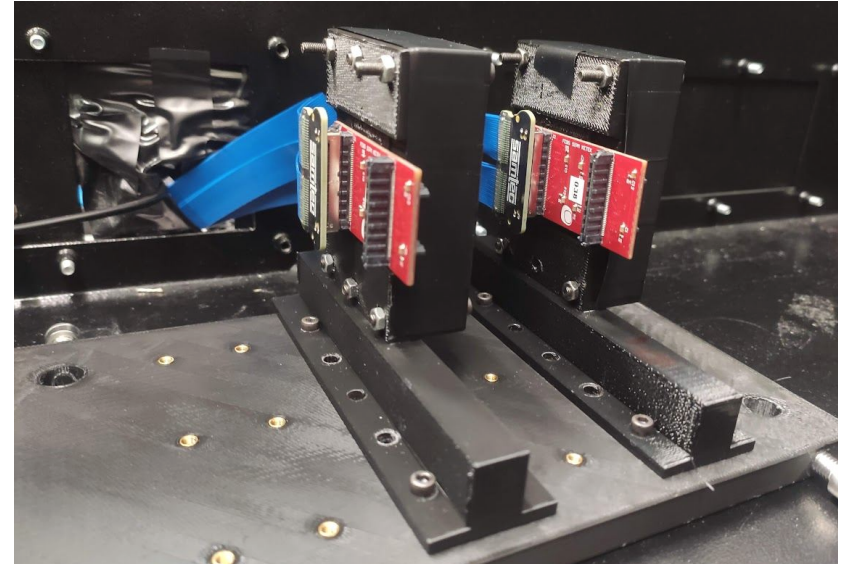
monolithic  
**LaBr<sub>3</sub>:Ce**



**8 x 8 SiPM  
array**  
PA3325-WB-0808

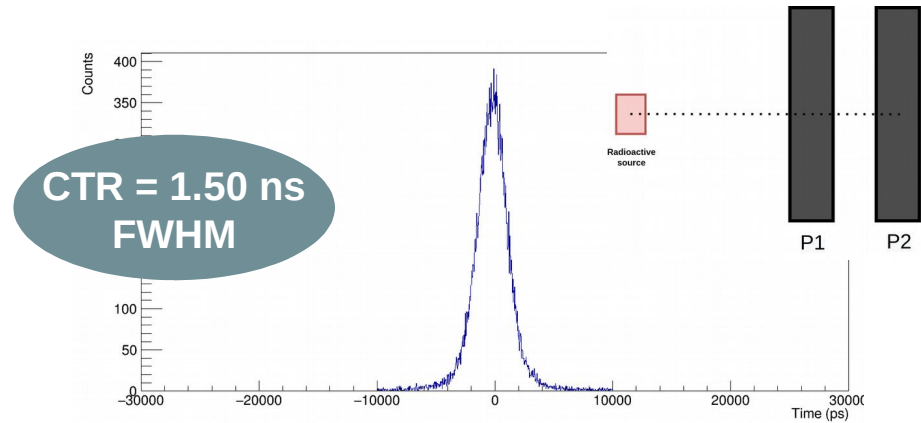
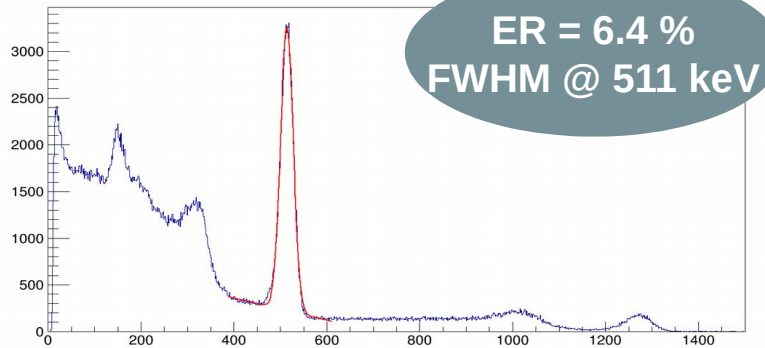


**TOFPET2  
ASIC**



R. Viegas et al. Radiat. Phys. Chem. 2022





Better time resolution, readout speed and dynamic range



R. Viegas et al. Radiat. Phys. Chem. 2022

# Prototypes

## MACACO III



Readout electronics:  
**ASIC VATA64HDR1**

ER: **5.2 % FWHM @511 keV**

TR: **24 ns**

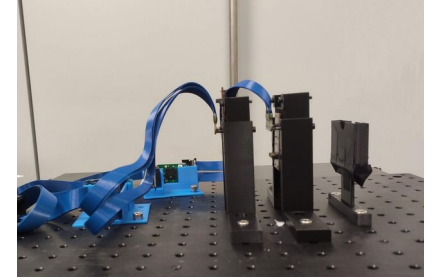
Dynamic range: **-20 pC to 55 pC**

Readout speed: **55 kHz/channel**



**Barrientos et al.**  
**Radiat. Phys. Chem. 2023**

## MACACOp



Readout electronics:  
**TOFPET2 ASIC**

ER: **6.4 % FWHM @511 keV**

TR: **1.5 ns**

Dynamic range: **up to 1500 pC**

Readout speed: **600 kHz/channel**

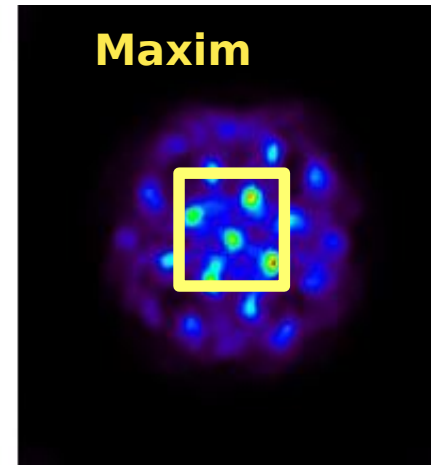
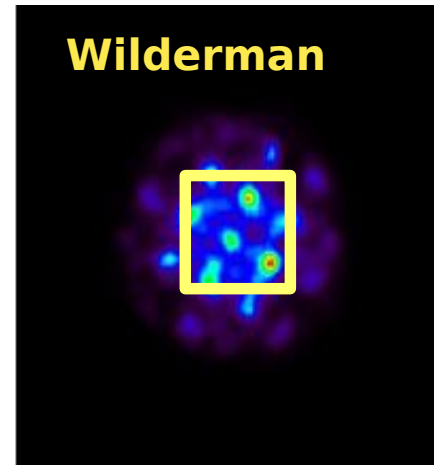
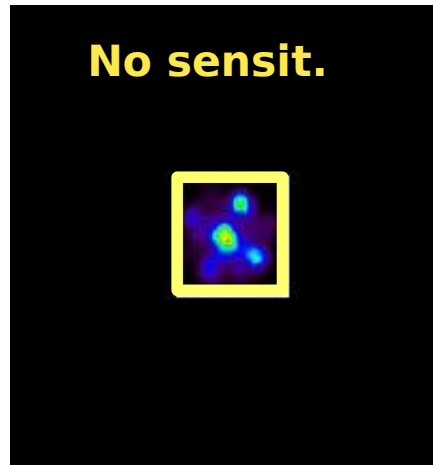
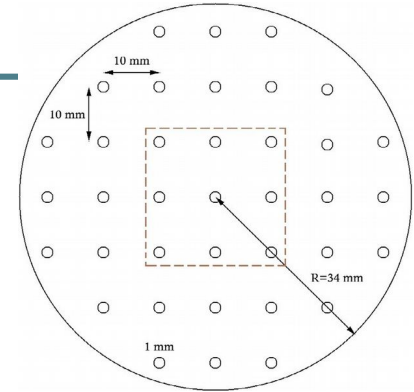


**Viegas et al.**  
**Radiat. Phys. Chem. 2022**

# Image reconstruction

Sensitivity model for 2- and 3- interaction events

Array of 37  
Na-22  
point-like  
sources

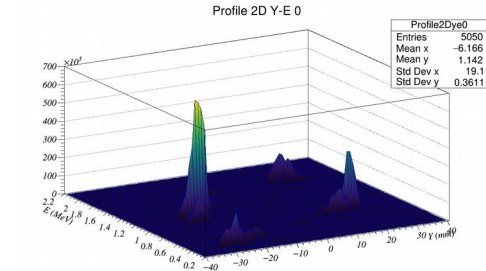
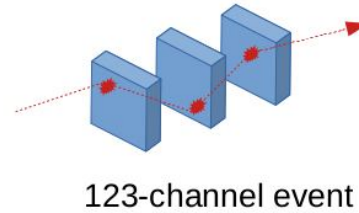
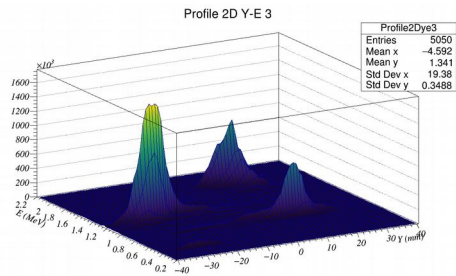
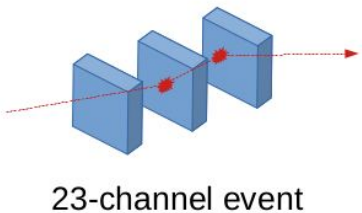
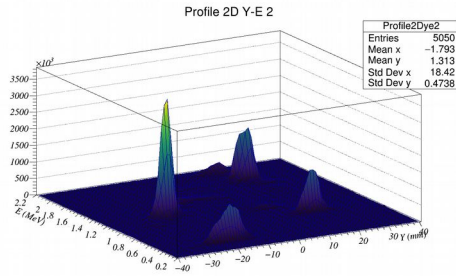
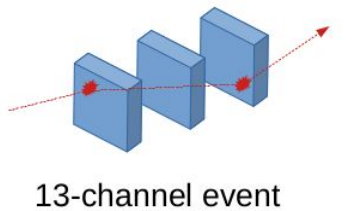
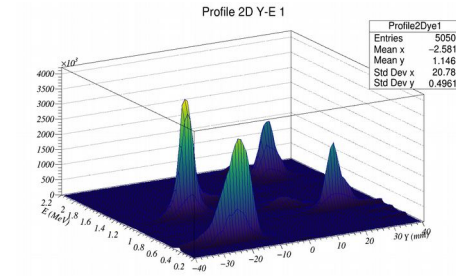
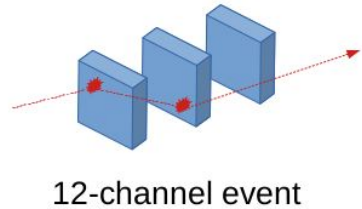


E. Muñoz et al. Phys. Med. Biol. 2018.

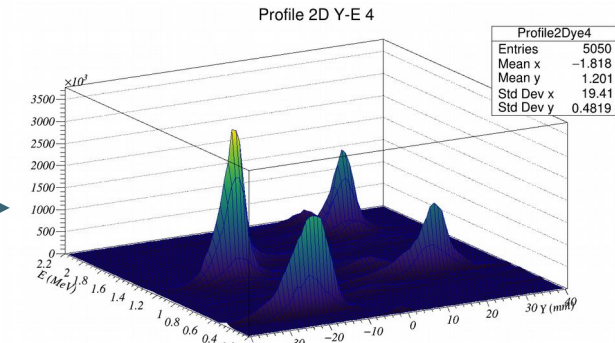
# Image reconstruction

## Joint reconstruction of 2- and 3-interaction events

Y-88 + Na-22



Joint Reconstruction

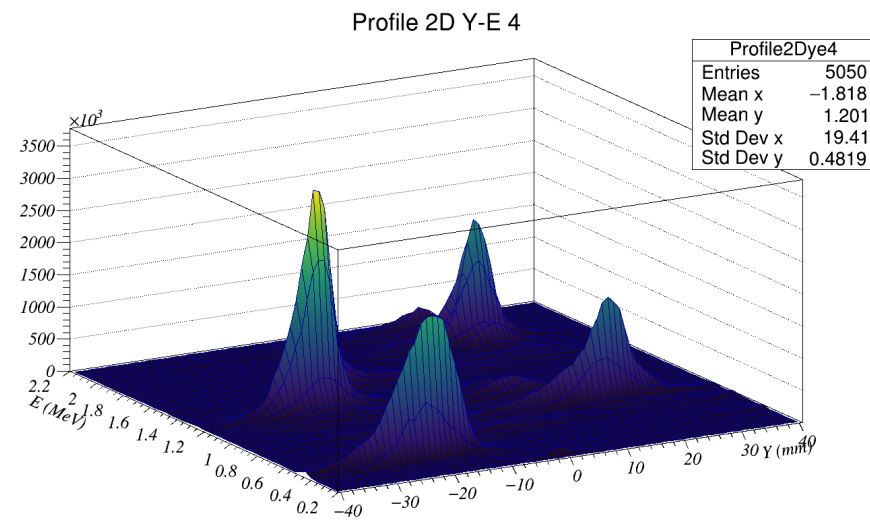
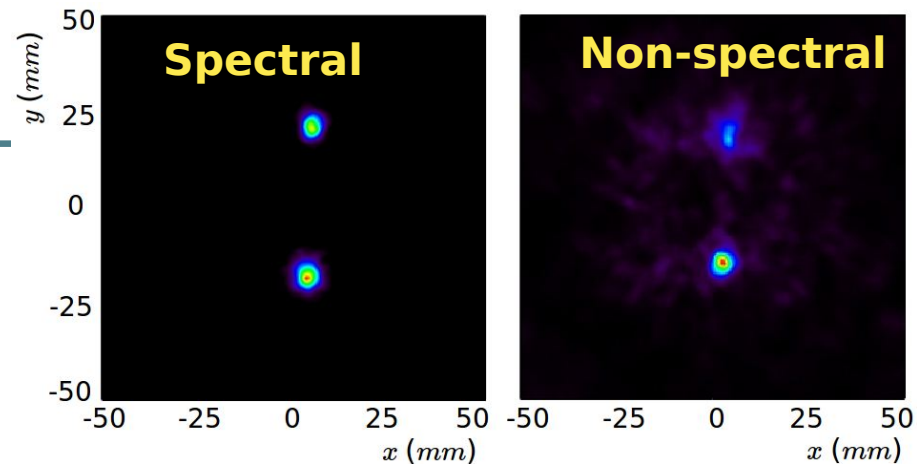
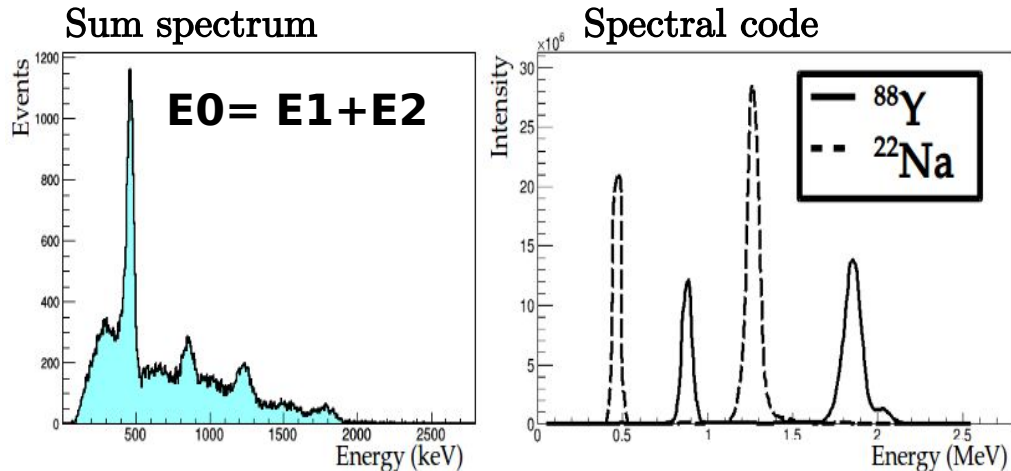


J. Roser et al. Phys. Med. Biol. 2022

# Image reconstruction

Spectral code: position and energy distributions

Simultaneous reconstruction of  
Y-88 (898, 1836 keV) + Na-22 (511, 1275 keV)



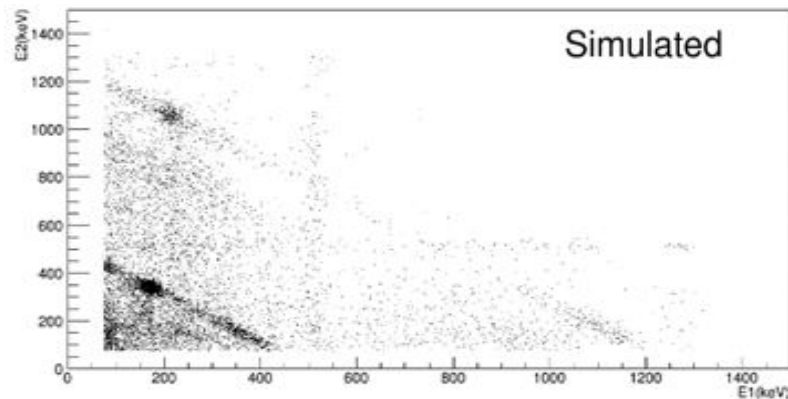
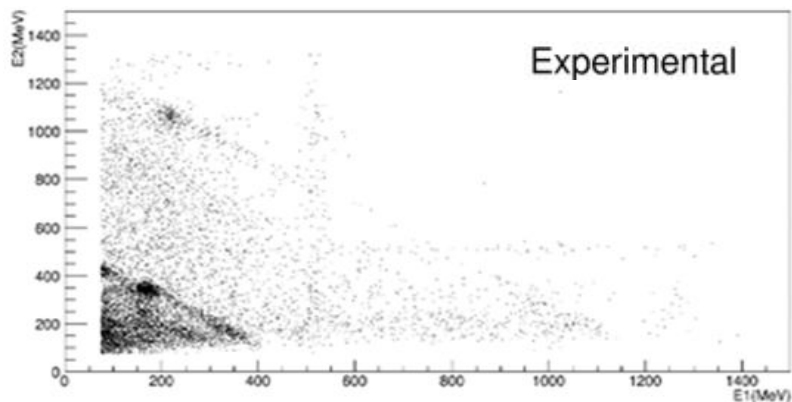
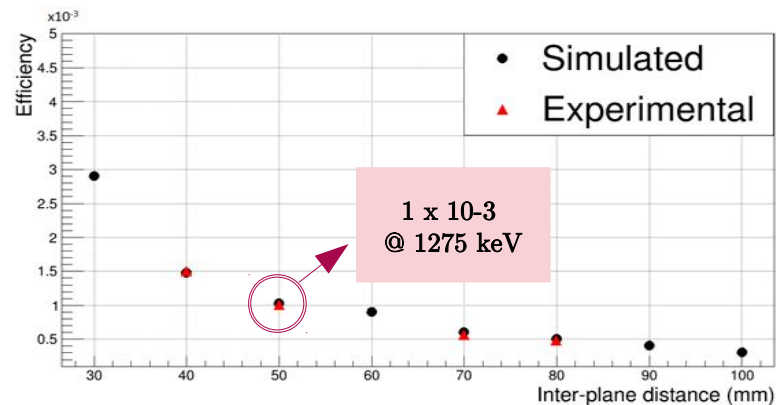
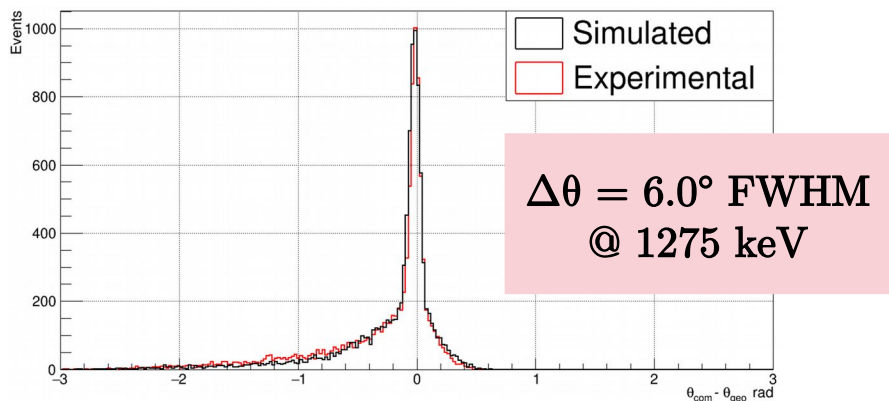
E. Muñoz et al. Phys. Med. Biol. 2020

# GATE simulations

## Comparison with MACACO III

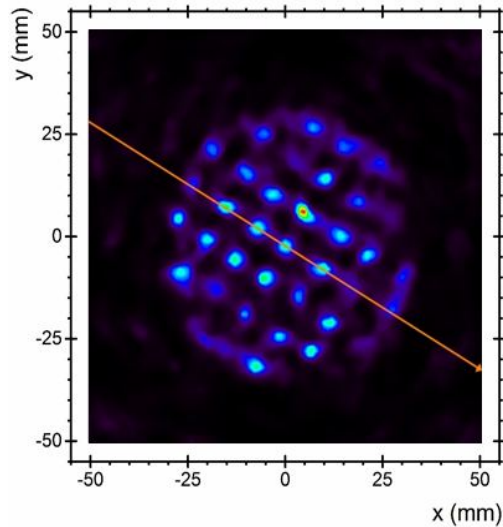


Excellent agreement between experimental results and GATE v8.2 simulations.

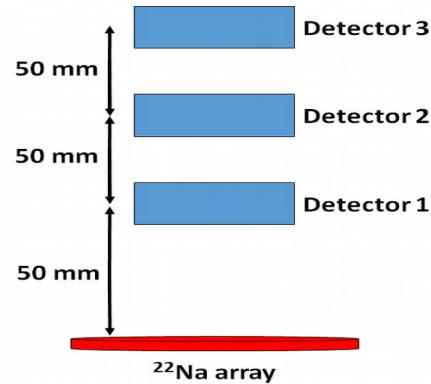
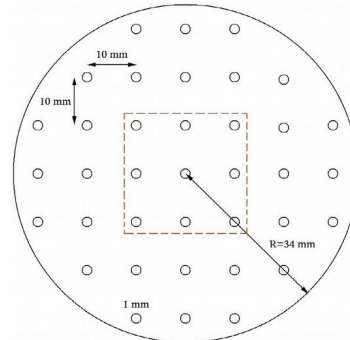


# Prototypes

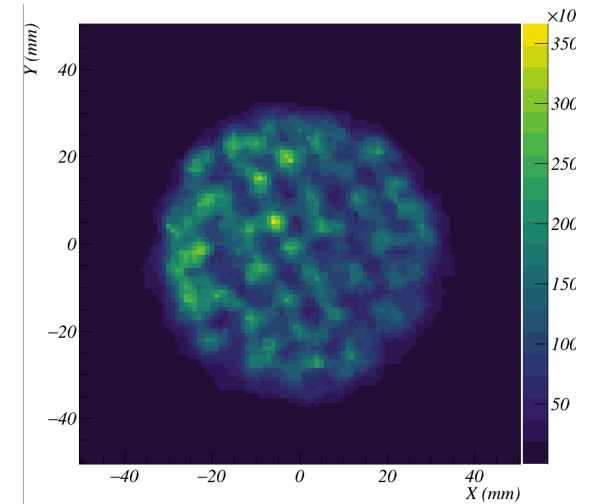
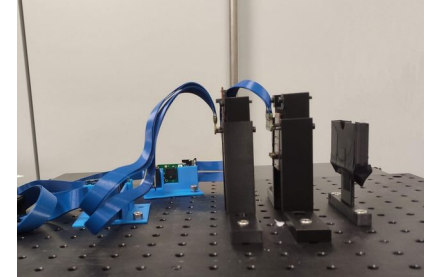
MACACO III



Array of 37 Na-22 point-like sources

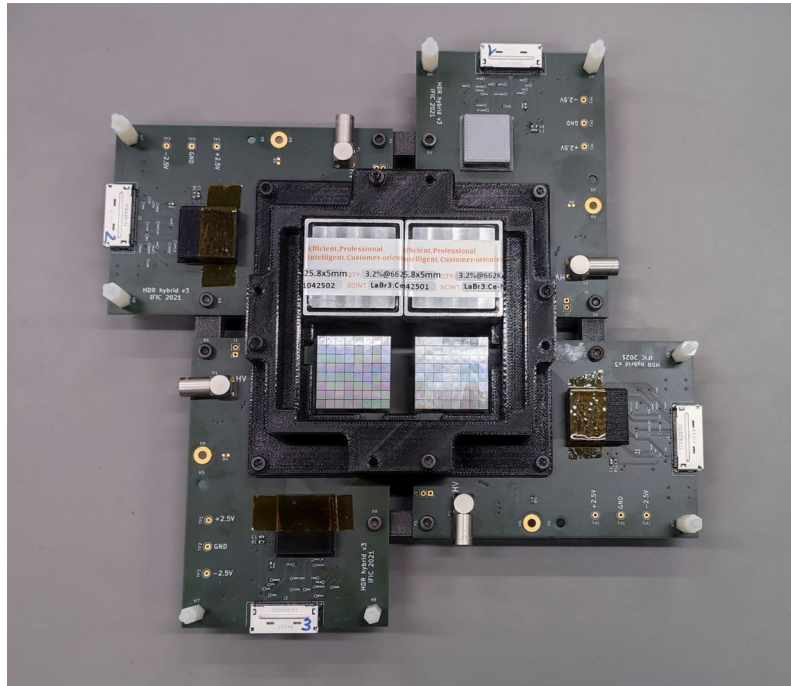


MACACO<sub>p</sub>

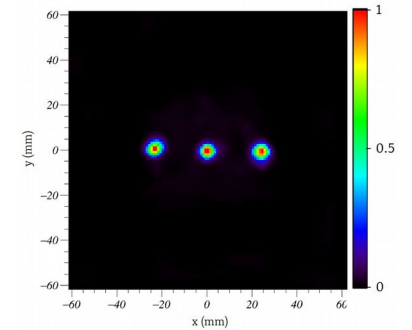
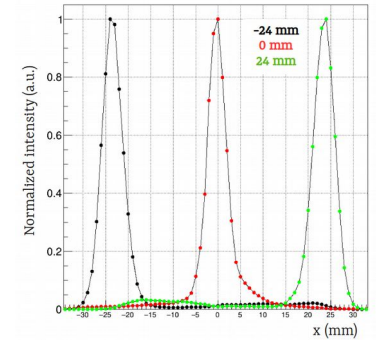


# Prototypes

## MACACO III+

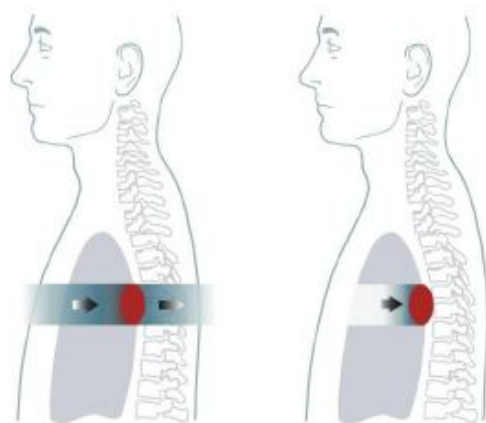


## FALCON



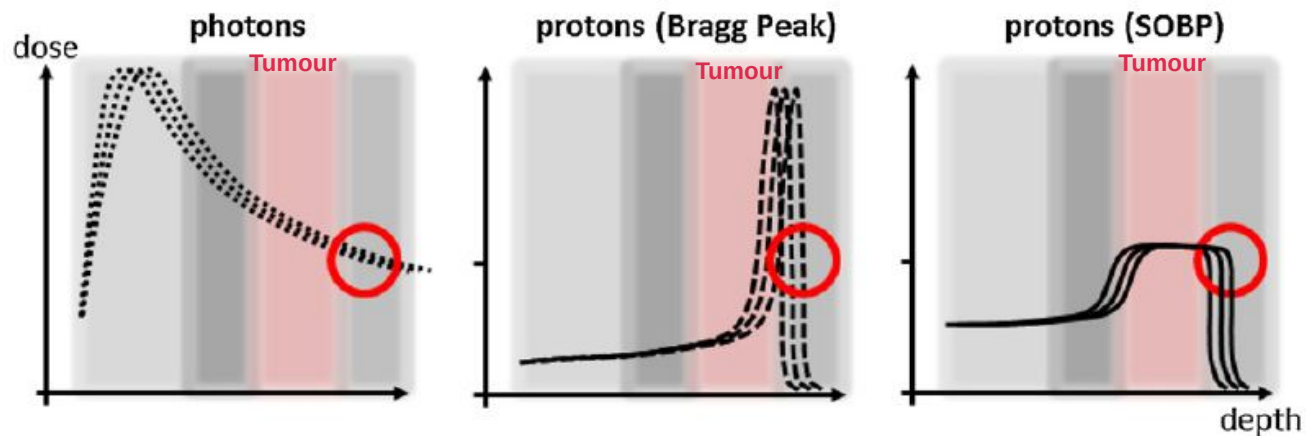
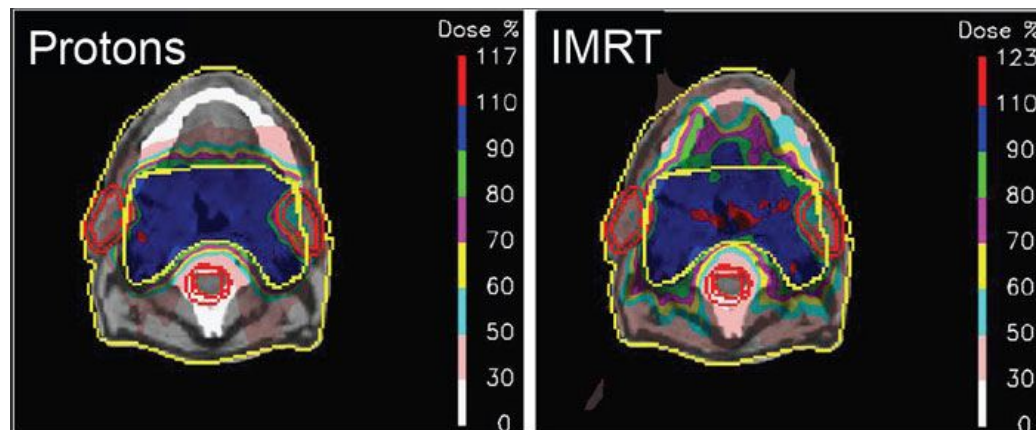


# Hadron therapy treatment monitoring



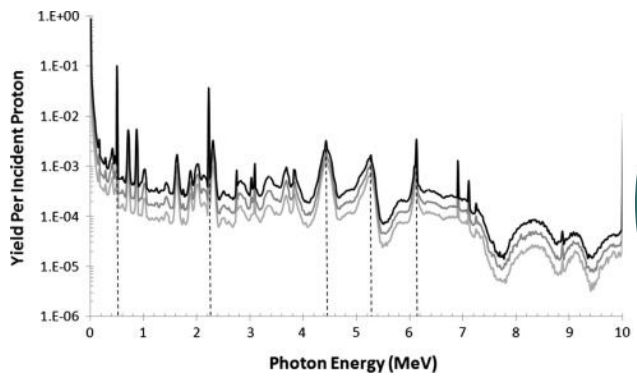
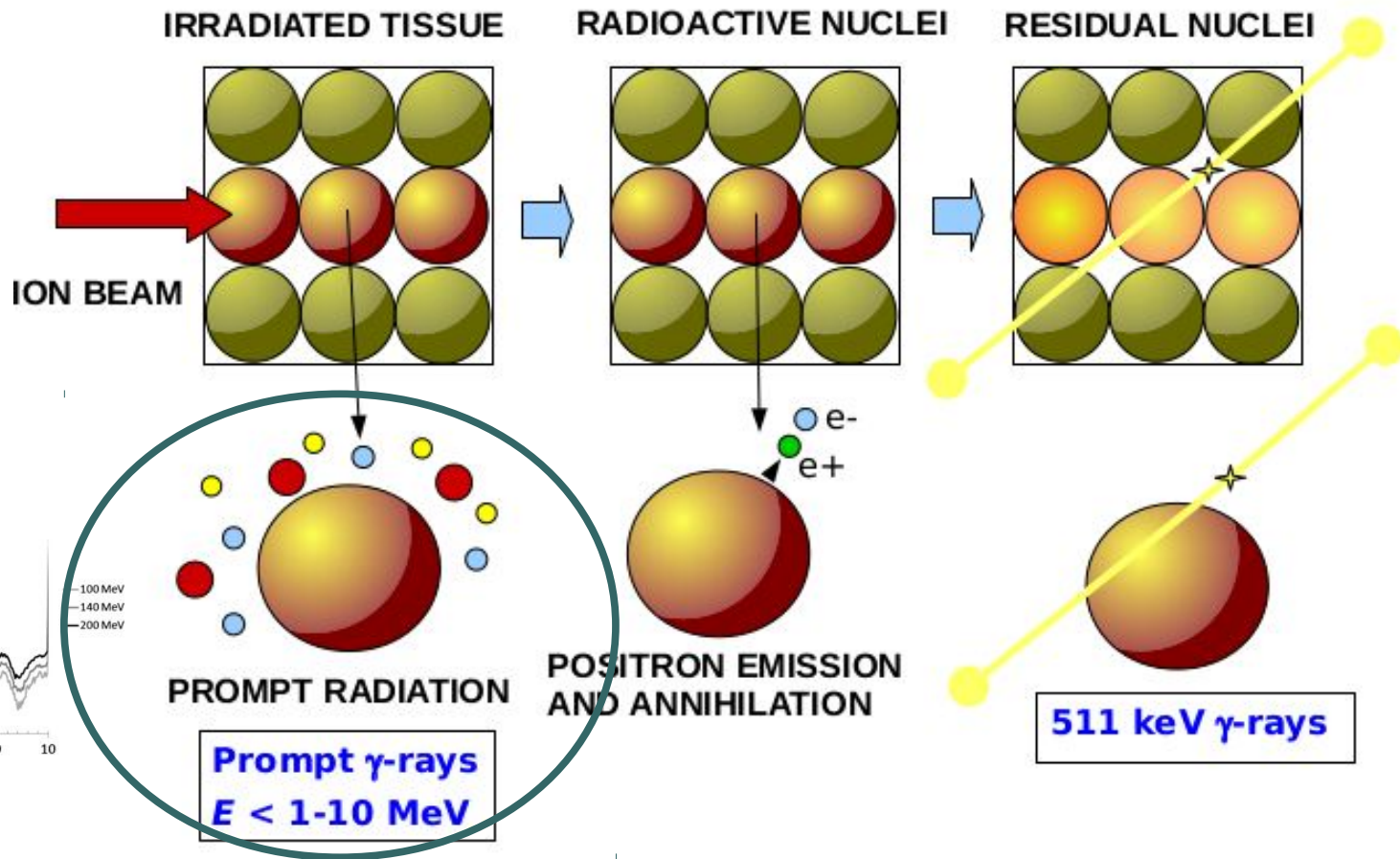
Conventional: X-Rays

Ion Radiation



Large safety margins applied

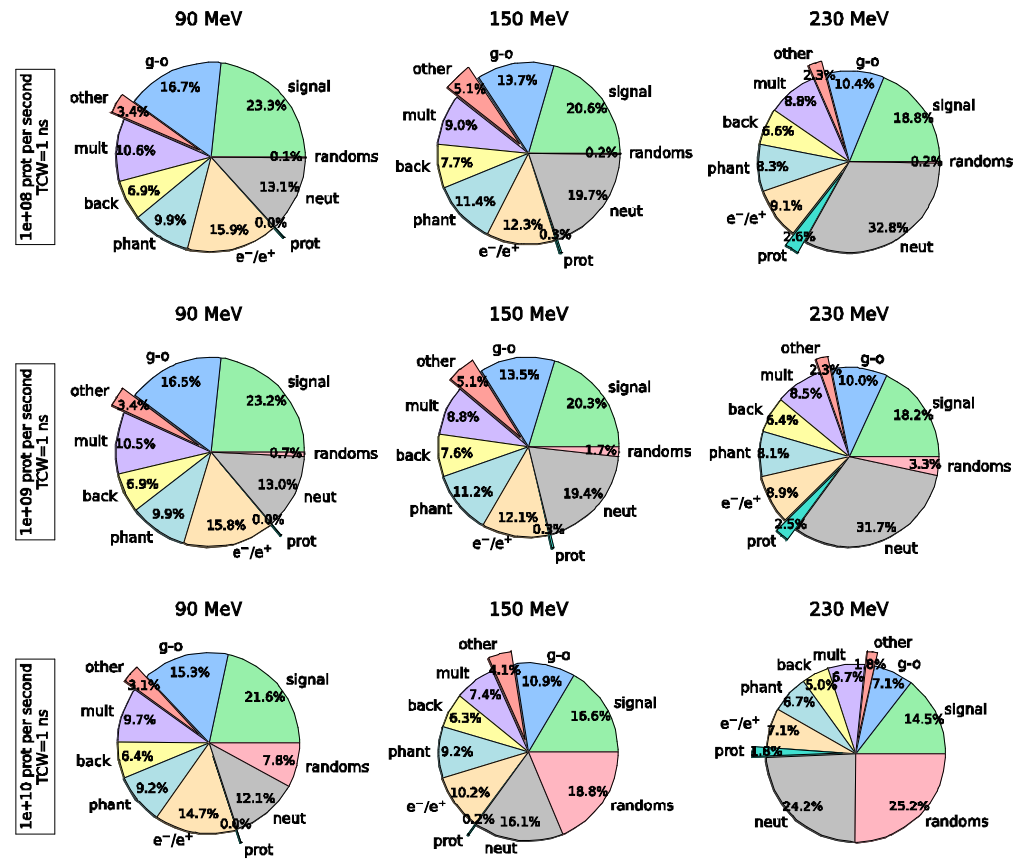
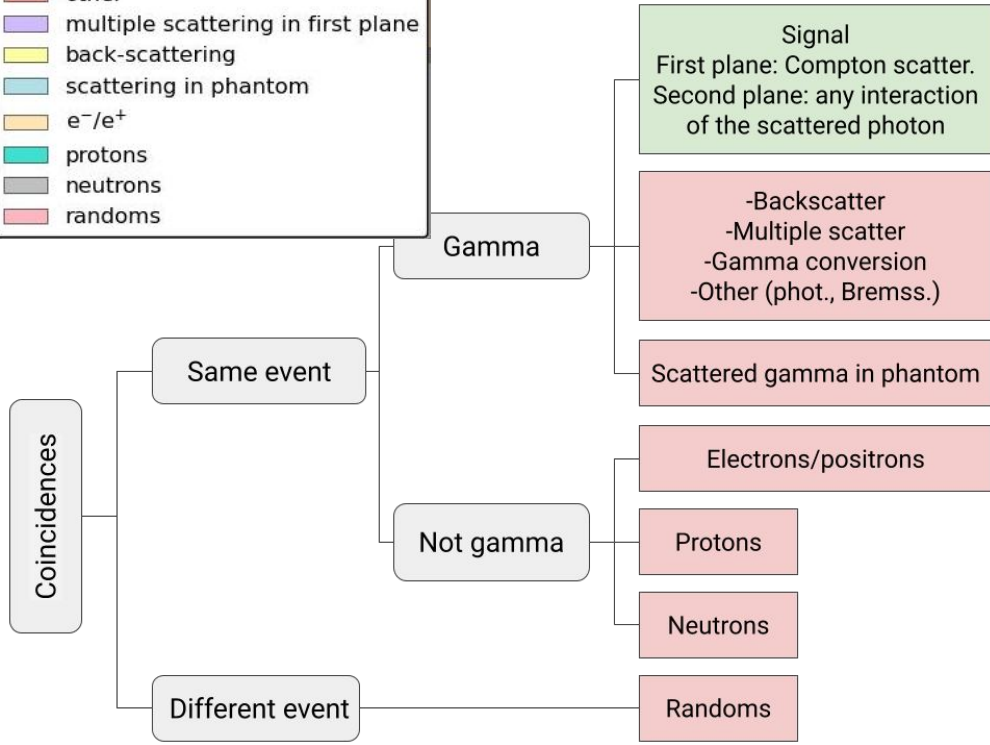
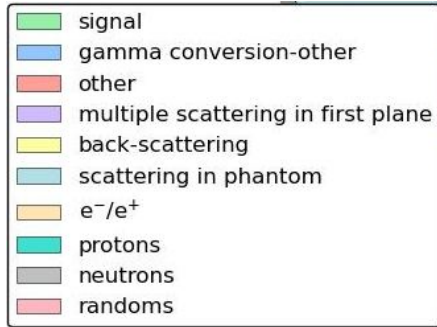
# Hadron therapy treatment monitoring



**Prompt  $\gamma$ -rays**  
 $E < 1-10$  MeV

**511 keV  $\gamma$ -rays**

# Background studies – background composition



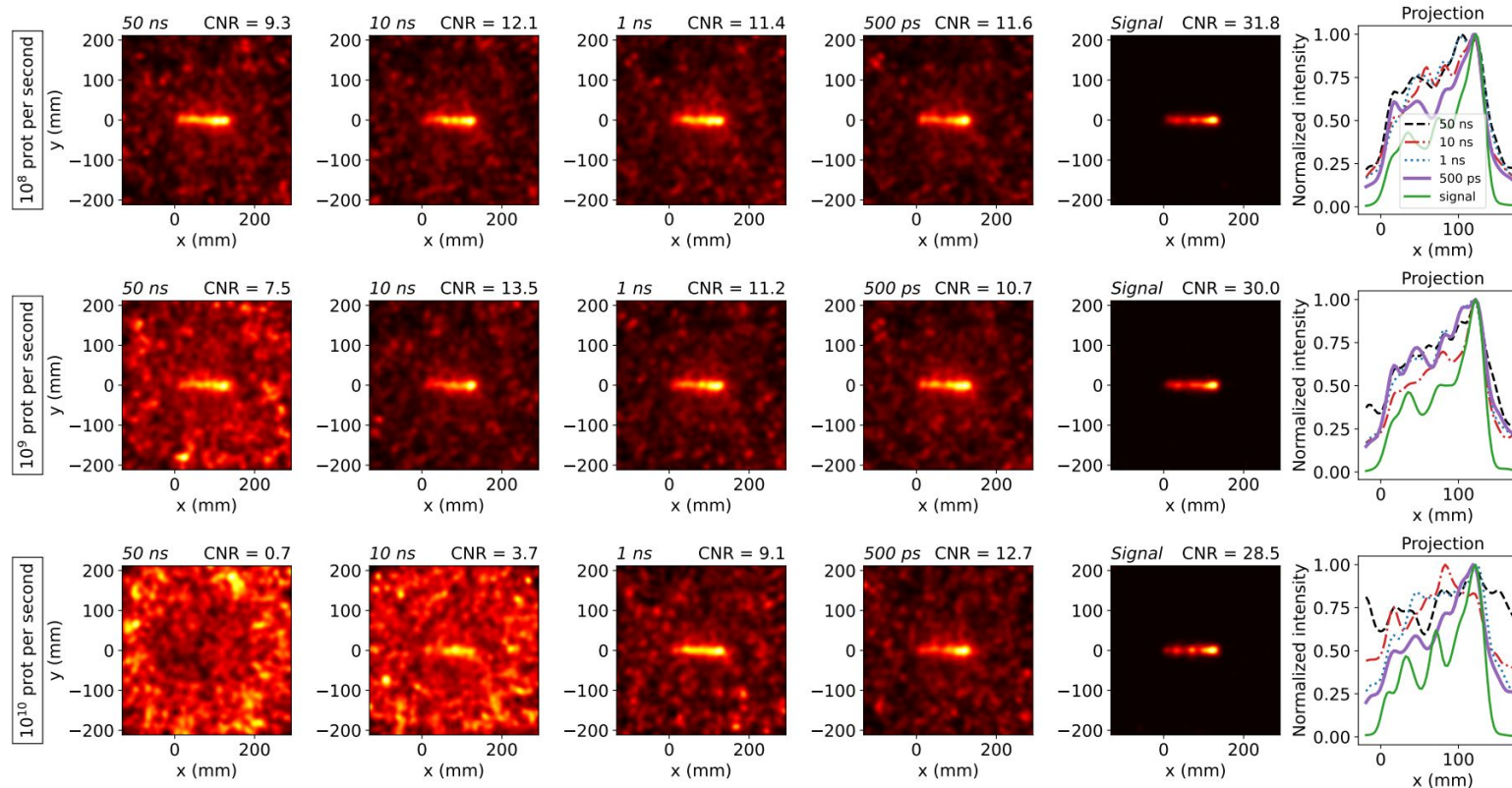
M. Borja et al. PMB 2023

# Background studies – influence on images

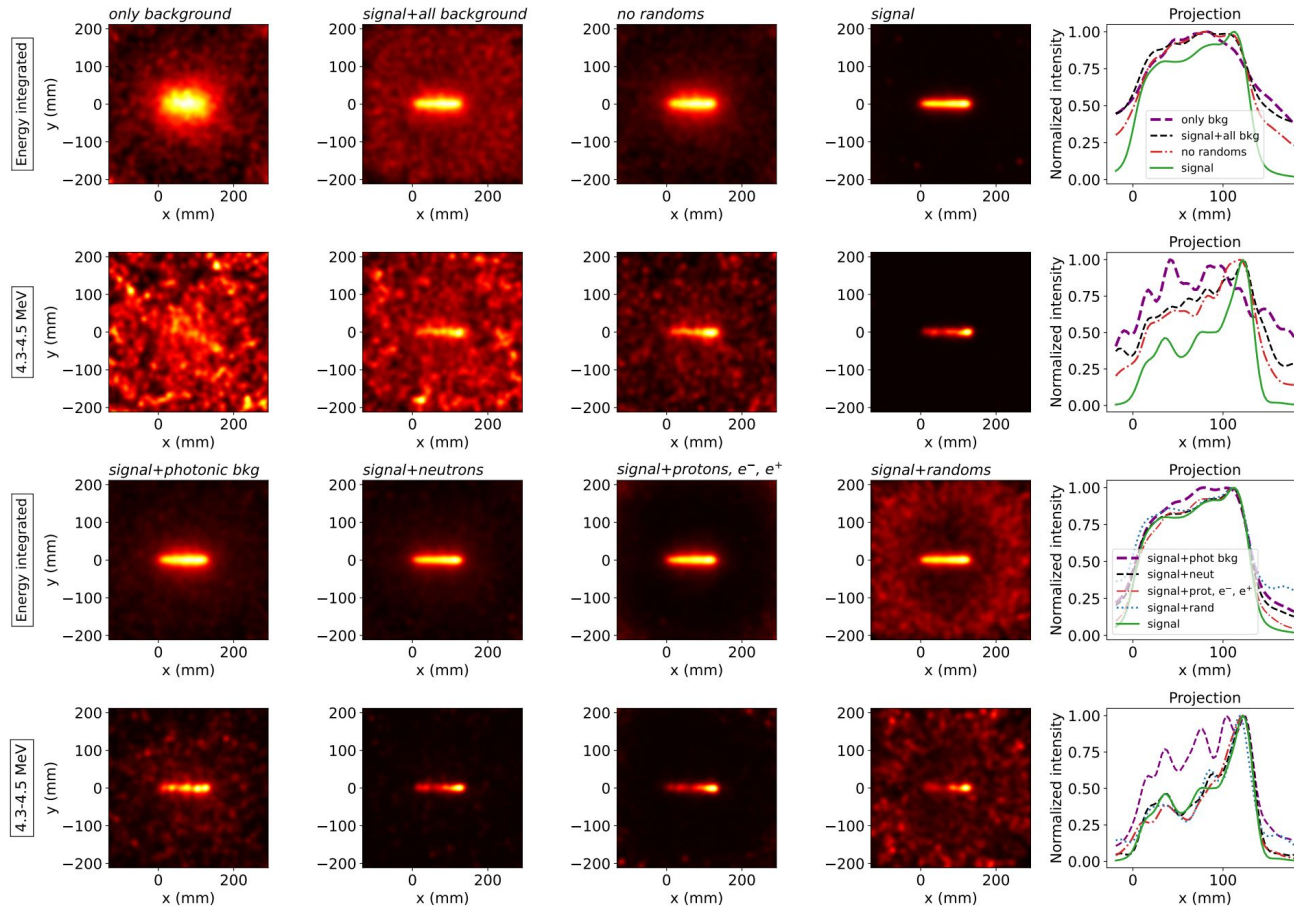
Coincidence window @ 150 MeV



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# Background studies – influence on images



Influence of different types of background

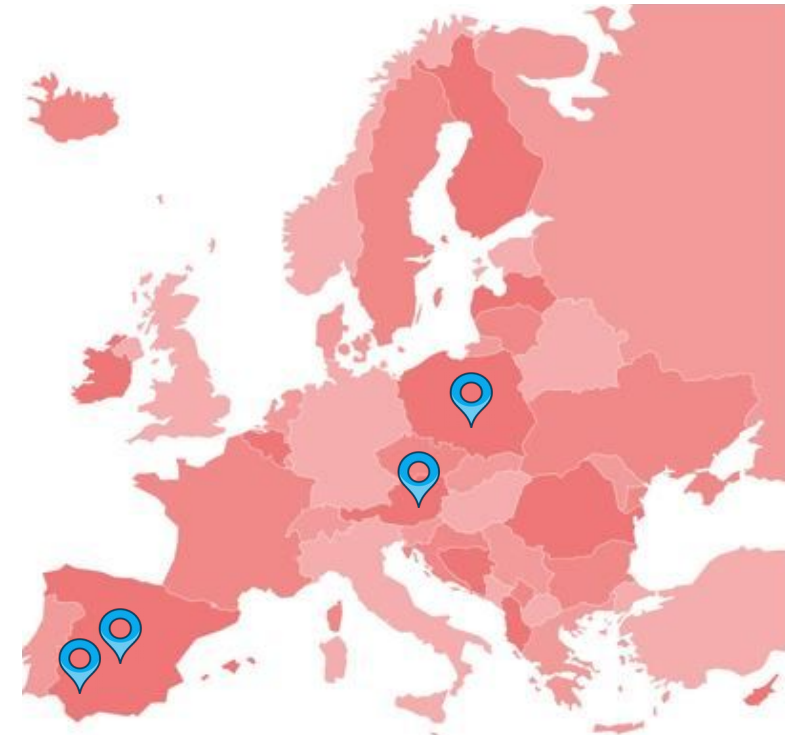


M. Borja et al. PMB 2023

# In-beam experiments

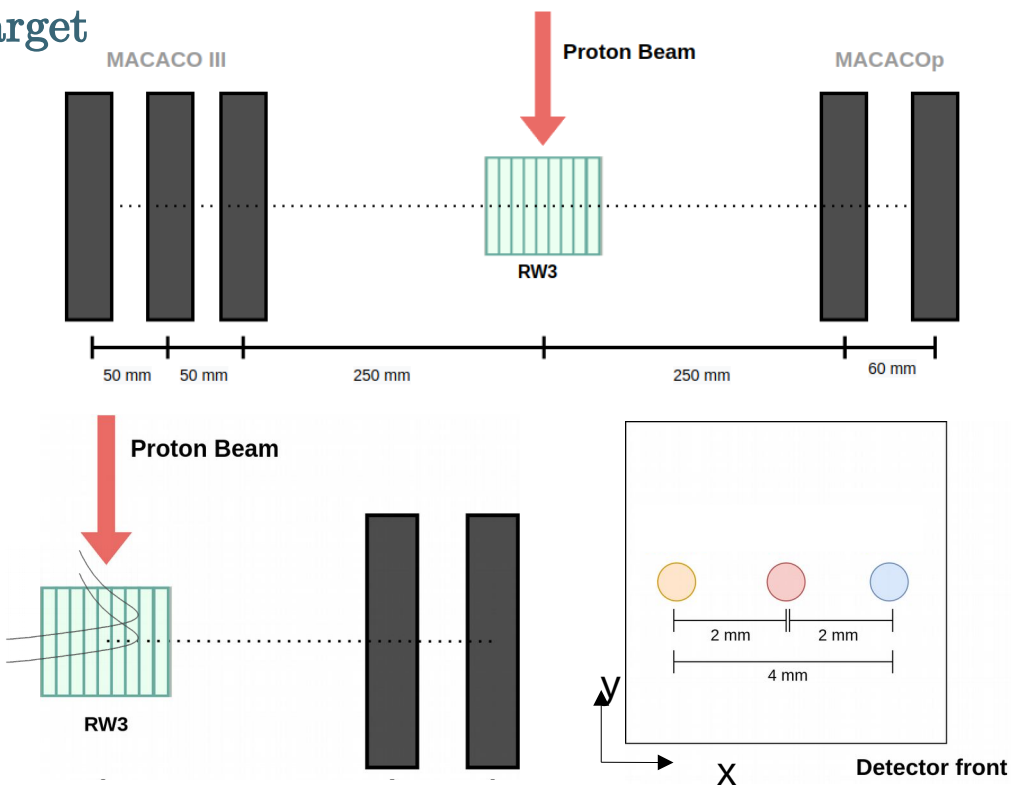
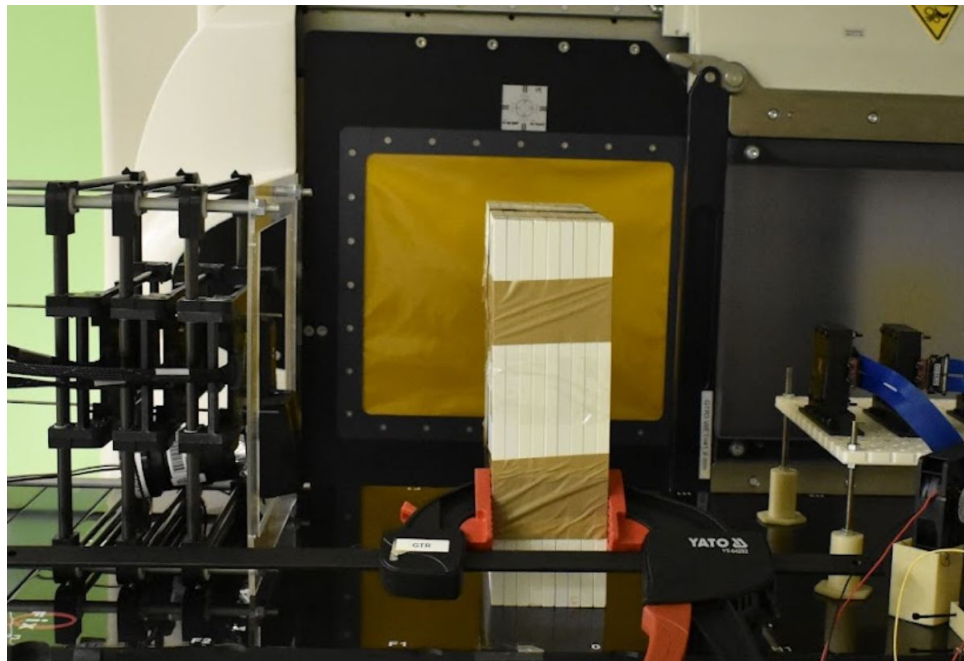
Tests with the current prototypes: Spanish National Accelerator Centre (CNA) and proton therapy centres

Center	Accelerator	Target	Energy (MeV)
CNA	Cyclotron	Graphite	18
CCB	Cyclotron (Proteus C-235)	RW3	88.38 – 91.62
QuirónSalud	Synchrocyclotron (S2C2)	RW3	70-90
MedAustron	Synchrotron-based particle accelerator	ARDOS	99.6



# In-beam experiments CCB (Krakow, Poland)

Proton beam with different energies on RW3 target  
[Cyclotron]

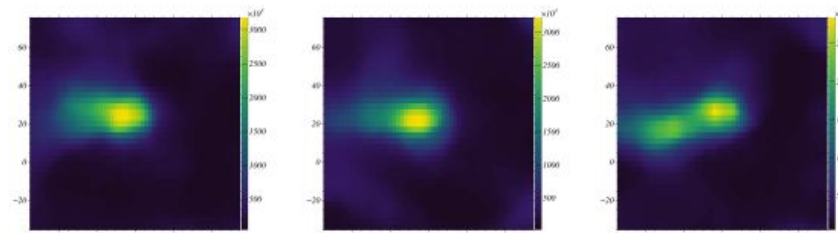


In collaboration with Hubert Jabłoński, Renata Kopeć, Dawid Krzempek and Natalia Mojżeszek,  
from Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland

# In-beam experiments CCB (Krakow, Poland)

90 MeV  
 $I = 90 \text{ pA}$

## MACACO III

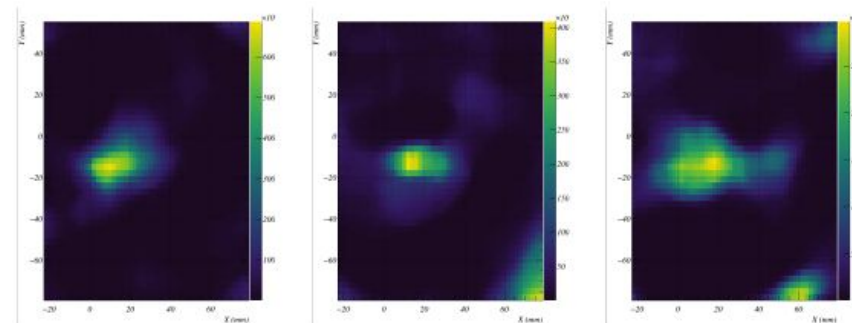


88.38 MeV

90 MeV

91.62 MeV

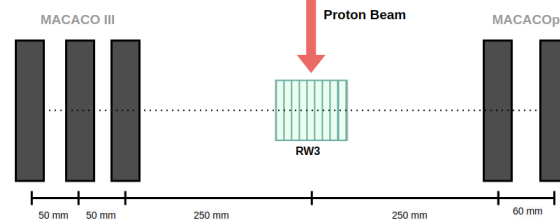
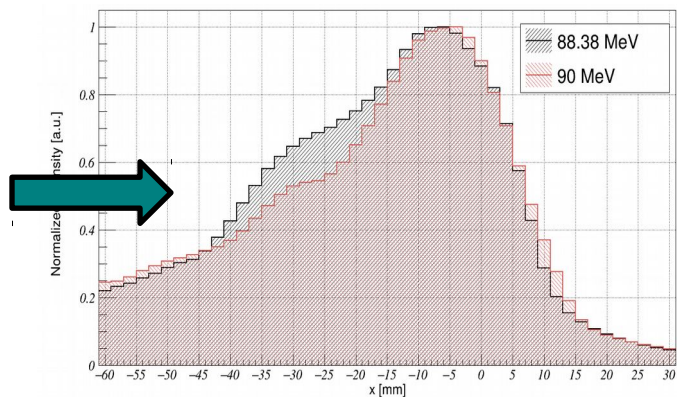
## MACACOp



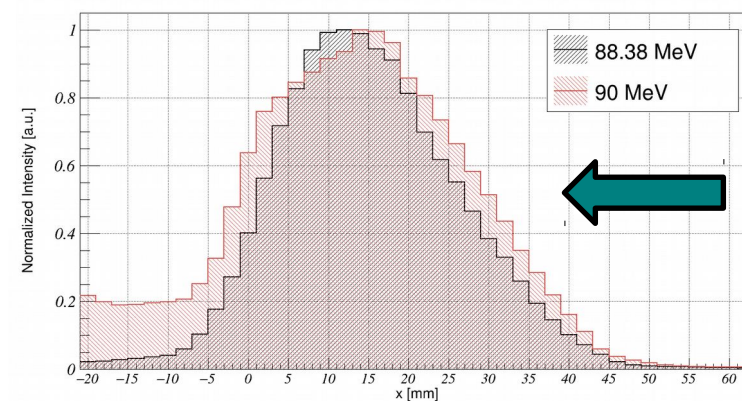
88.38 MeV

90 MeV

91.62 MeV



Neural networks for event selection

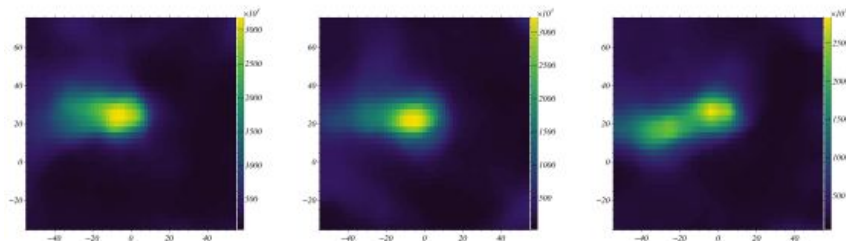




# In-beam experiments CCB (Krakow, Poland)

90 MeV  
 $I = 90 \text{ pA}$

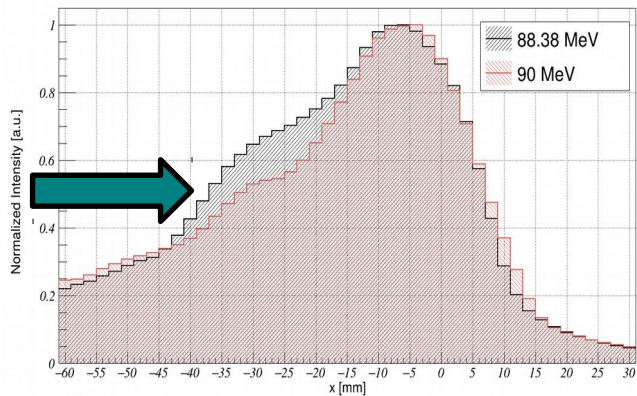
## MACACO III



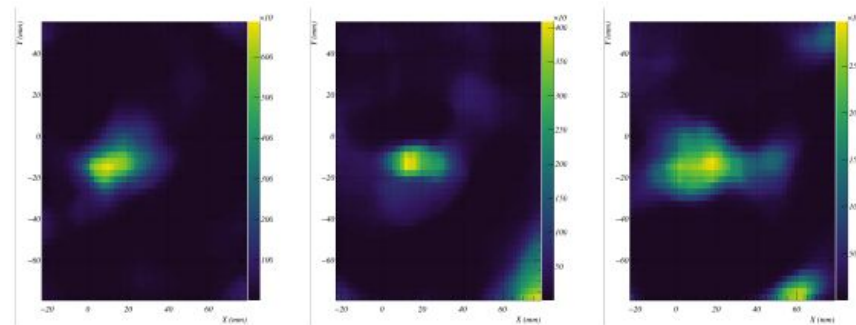
88.38 MeV

90 MeV

91.62 MeV



## MACACOp

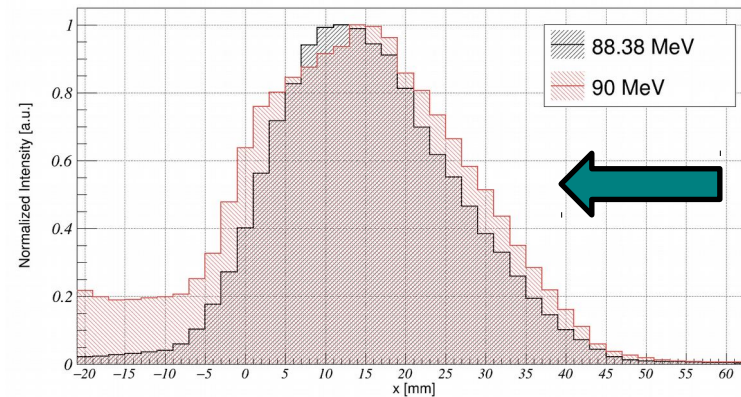


88.38 MeV

90 MeV

91.62 MeV

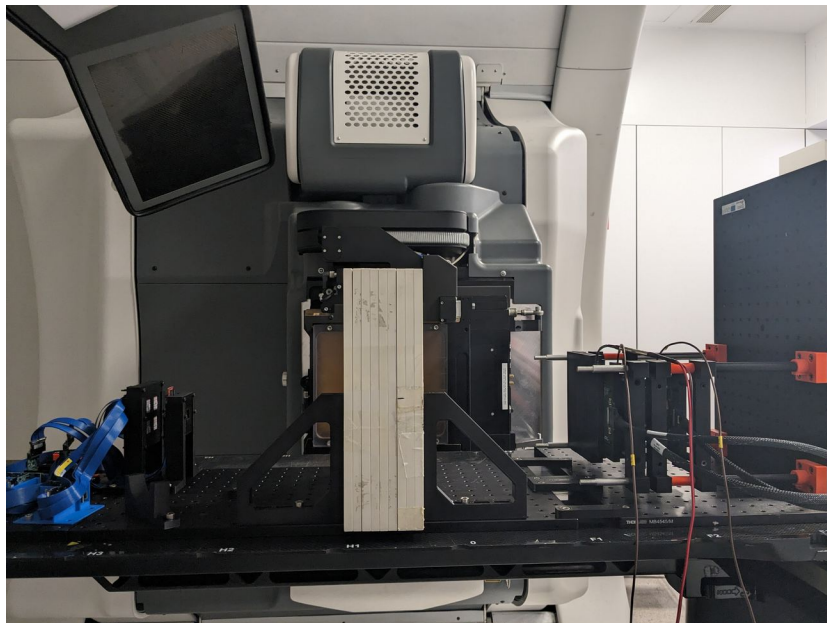
2 mm steps detected  
with both systems



# In-beam experiments Quirónsalud (Madrid, Spain)

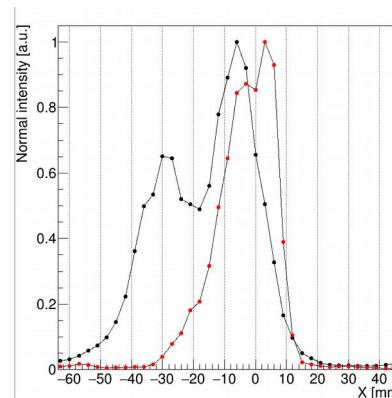
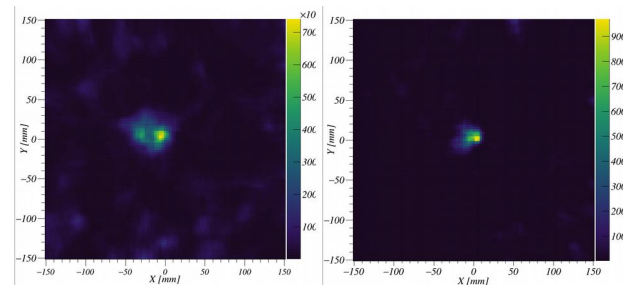
70 – 90 MeV

Proton beam with different energies on RW3 target  
[Synchrocyclotron]



In collaboration with A. Mazal and J.A. Vera-Sánchez,  
from Centro de Protonterapia Quirónsalud, Madrid, Spain

FALCON



15 mm  
shift

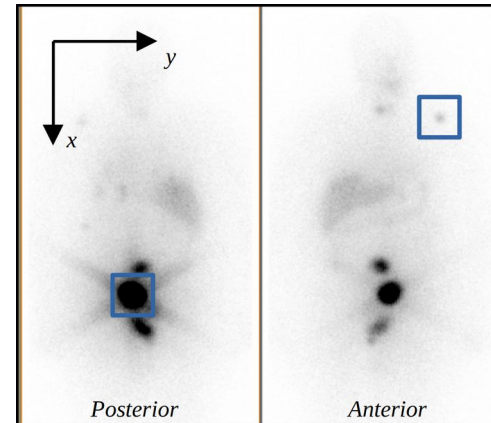
Preliminary

# Radiopharmaceutical imaging

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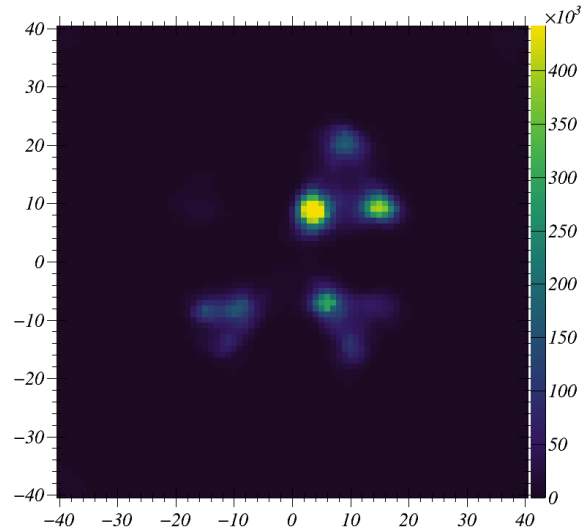
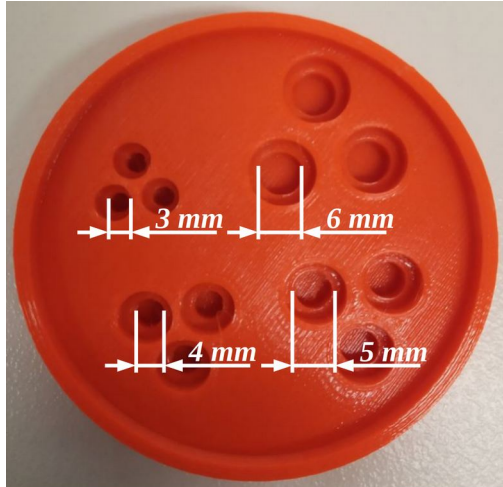
- ▶ Radionuclide therapy is expanding due to its good results.
- ▶ Imaging can be used to visualize their distribution in the body and carry out dosimetry employing secondary gamma radiation.
- ▶ More challenging than diagnostic imaging since photon energies and activities are not optimized for gamma cameras.

Gamma camera images of a patient treated with  $^{131}\text{I}$ -NaI



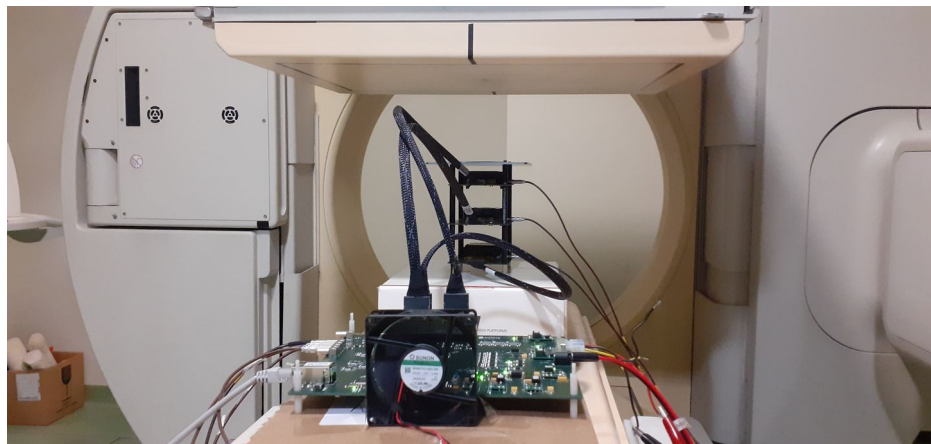
# Radiopharmaceutical imaging

Phantom filled with  $^{18}\text{F}$ -FDG  
(511 keV)



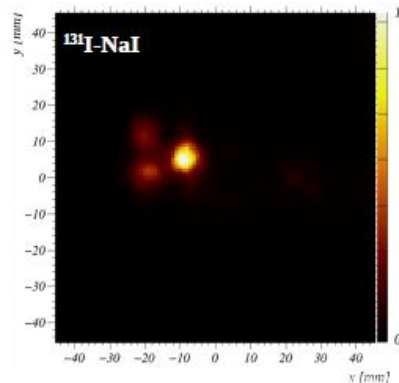
# Tests in La Fe hospital (Valencia)

Phantom filled with  $^{131}\text{I}$ -NaI (364 keV)

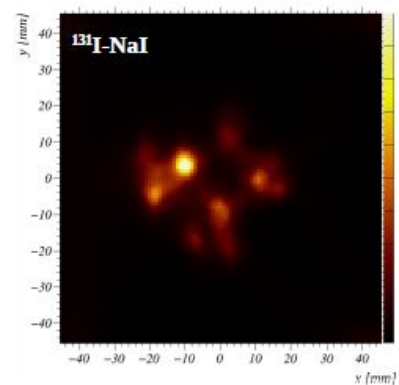


In collaboration with Irene Torres-Espallardo, José Manuel Calatayud, Pilar Bello y Stefan Prado from La Fe (Valencia).

Compton camera

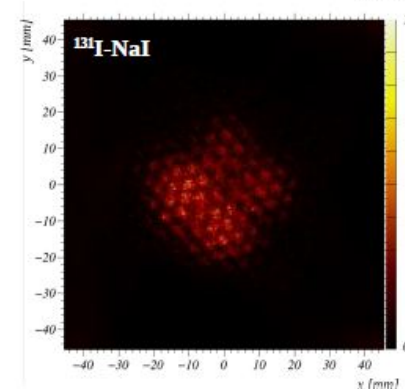
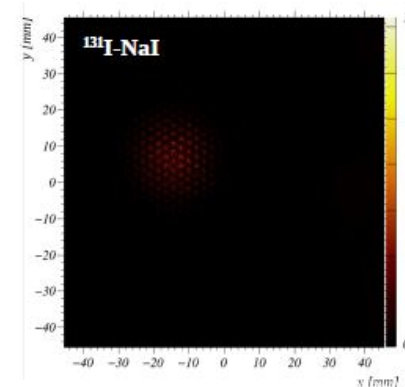


One sector



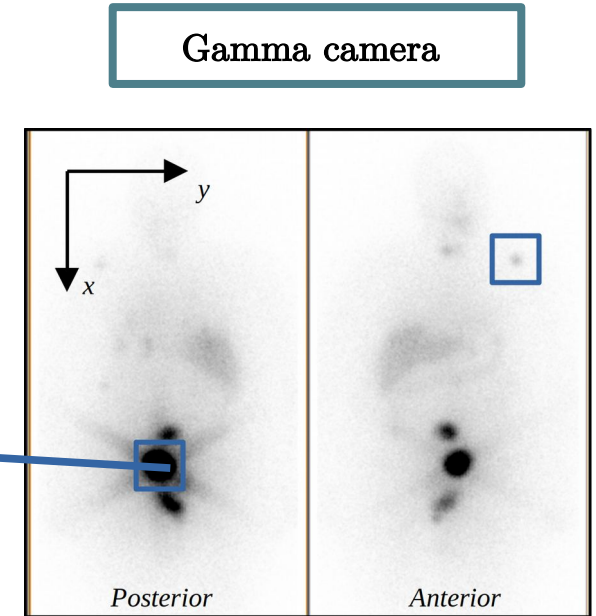
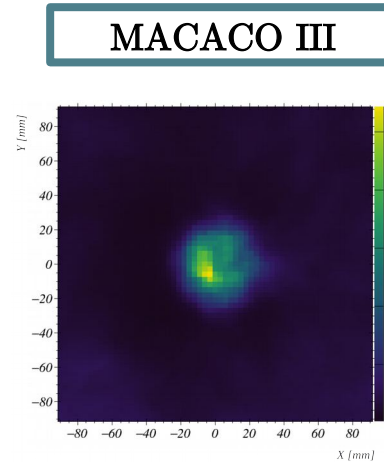
All sectors

Gamma camera  
Bright View XCT (Philips)



# Tests in La Fe hospital (Valencia)

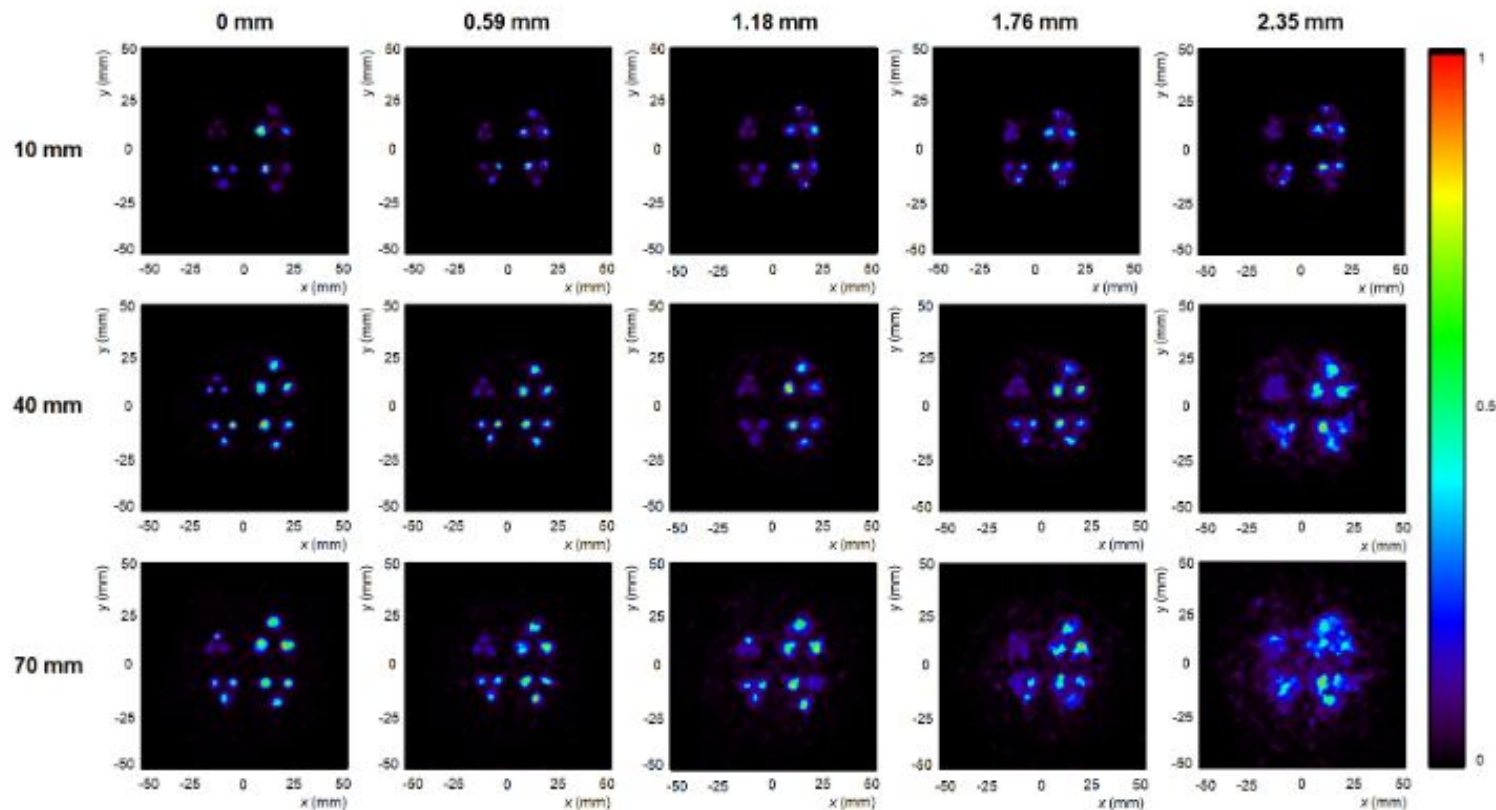
- ▶ Metastatic lesions from patients treated with  $^{131}\text{I}$ -NaI after thyroid gland resection
- ▶ Initial activity (total): 150 mCi
- ▶ MACACO III @  $\sim 70$  mm.



Sacrum lesion

# Further studies

Spatial resolution @ 1275 keV

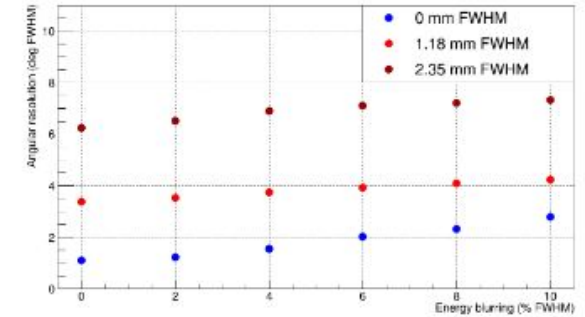
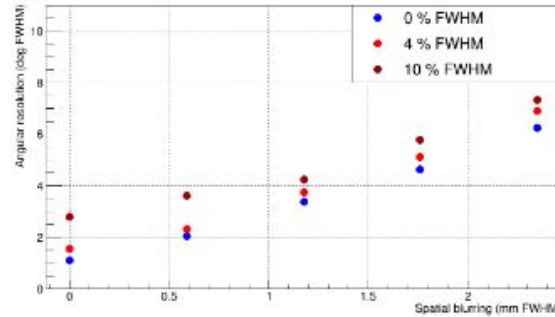
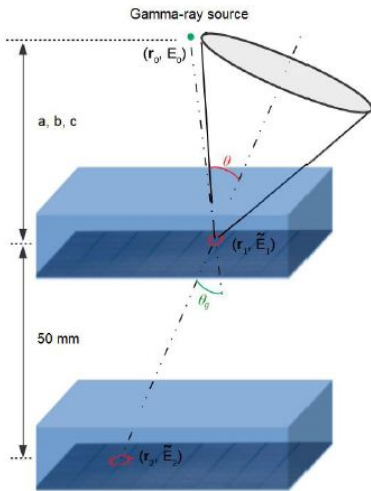


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# Angular Resolution Measure (ARM)

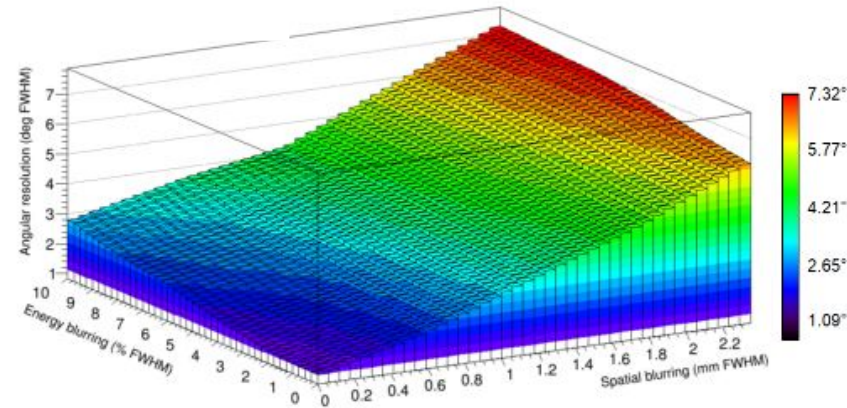
ARM vs. spatial and energy resolution

$$\text{ARM} = \theta_c - \theta_g$$



(b)

@1275 keV



(c)



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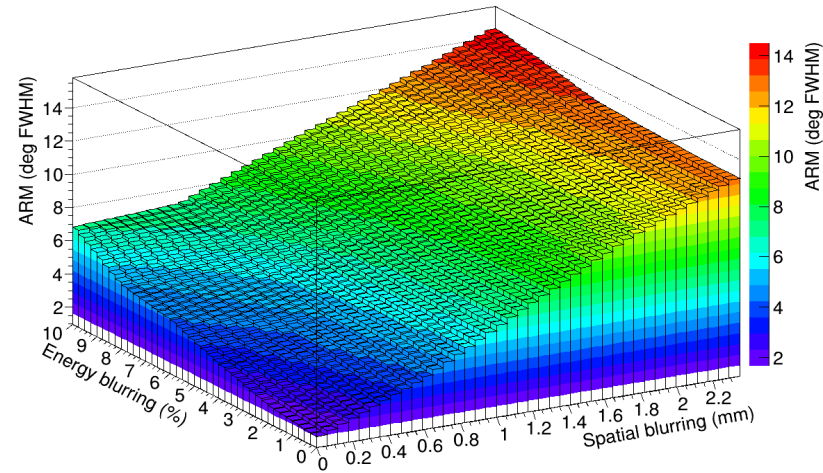
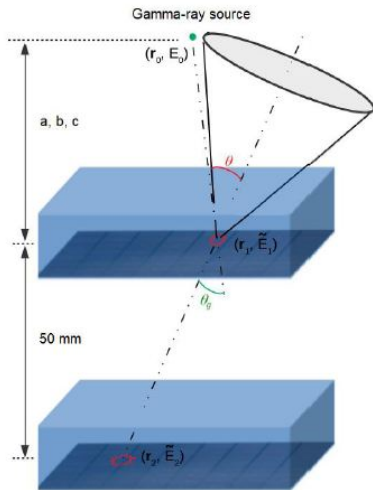


# Angular Resolution Measure (ARM)

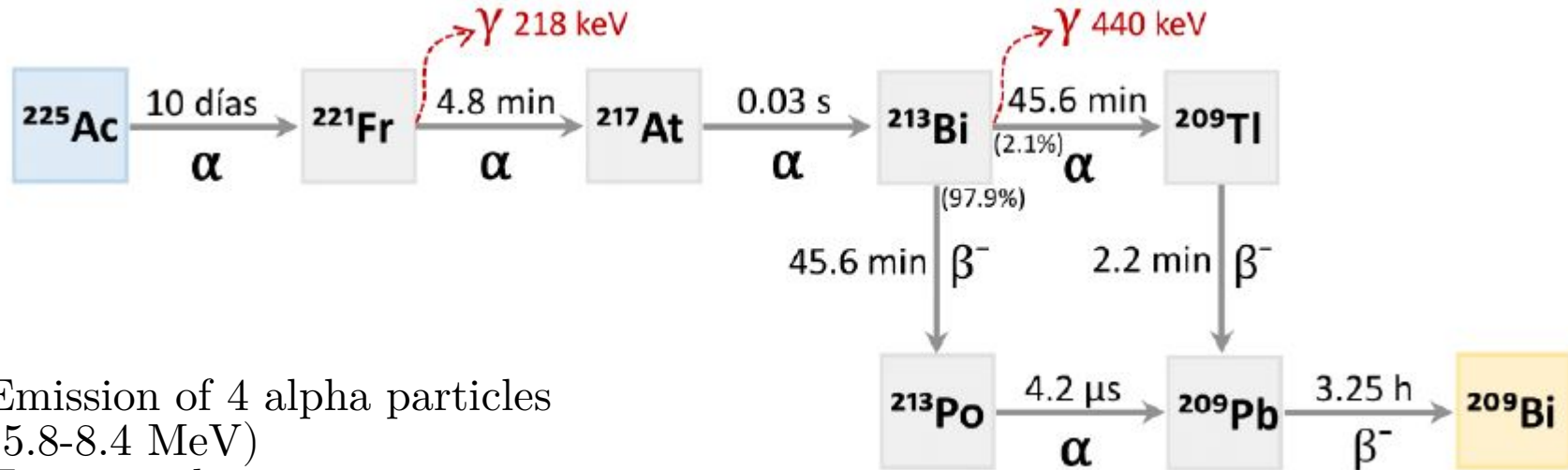
ARM vs. spatial and energy resolution

$$\text{ARM} = \theta_c - \theta_g$$

@440 keV



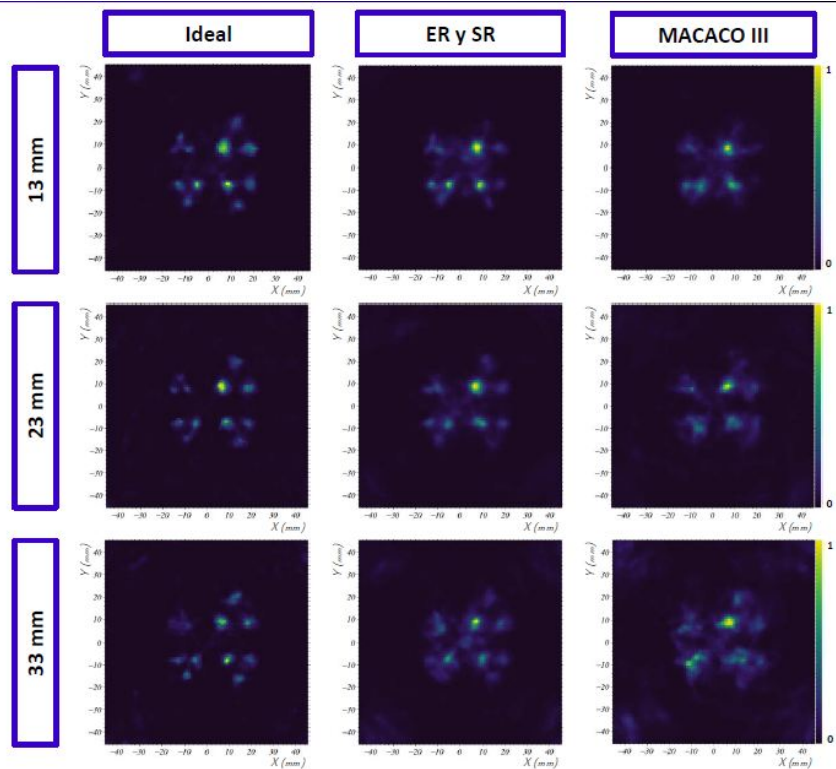
# Ac-225



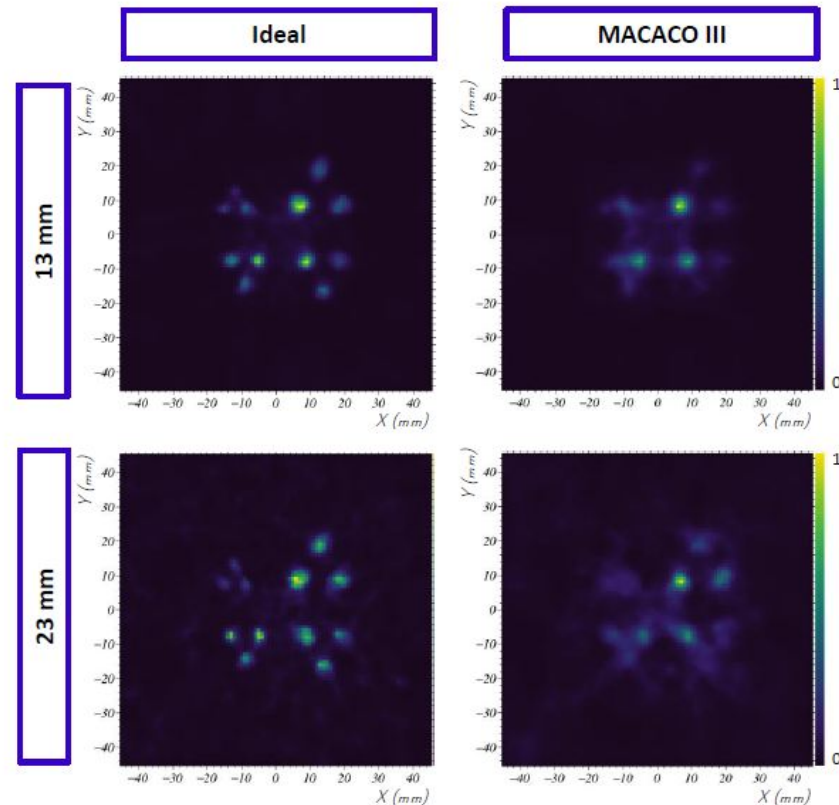
- Emission of 4 alpha particles (5.8-8.4 MeV)
- $T_{1/2} = 10$  days

# Ac-225 Gate simulations

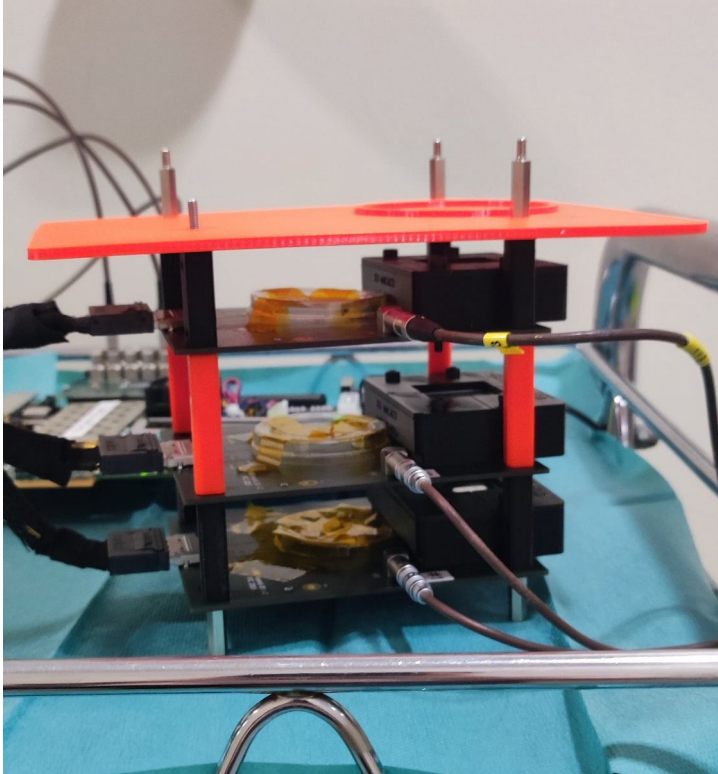
## MACACO III



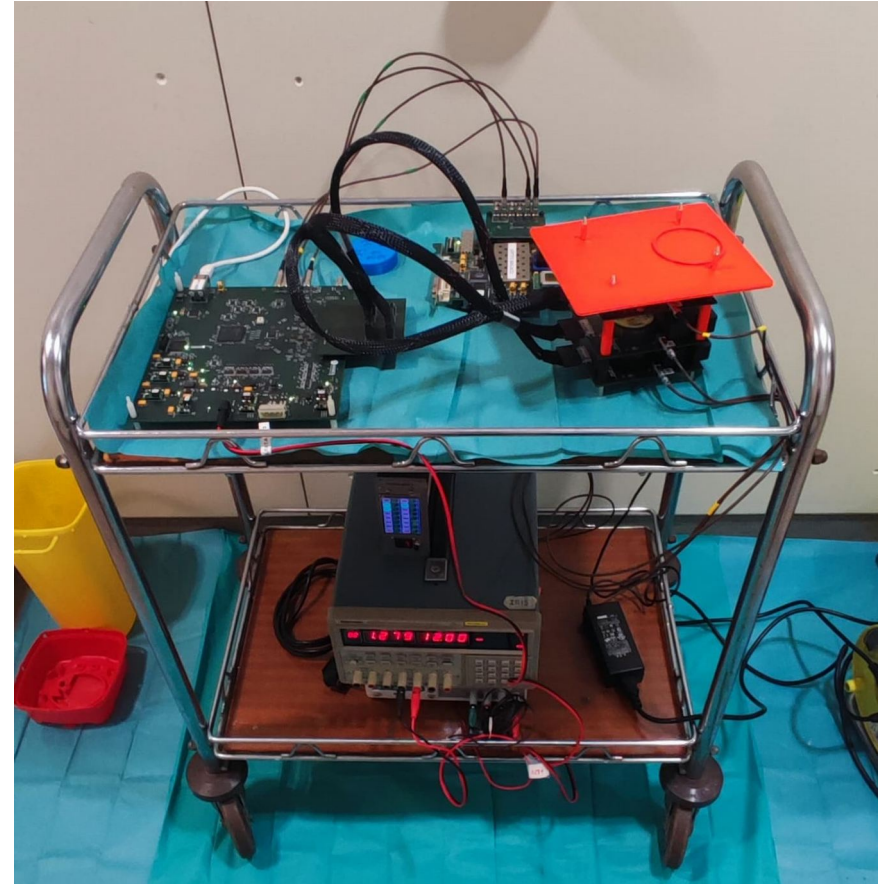
## MACACO III+



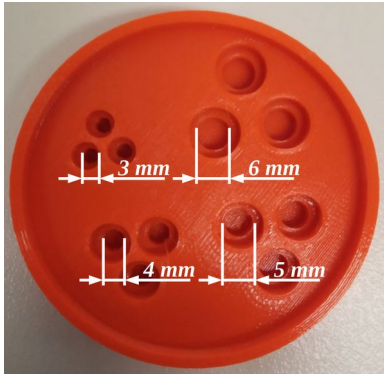
# Ac-225 Measurements at Léon Bérard hospital (Lyon)



In collaboration with Ane Etxebeste, David Sarrut, Jean Noël Badel from Creatis and Léon Bérard hospital (Lyon).

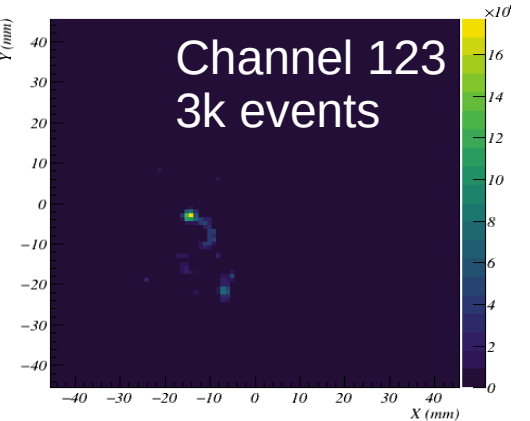
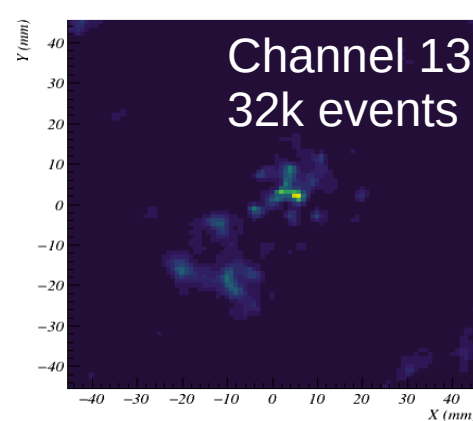
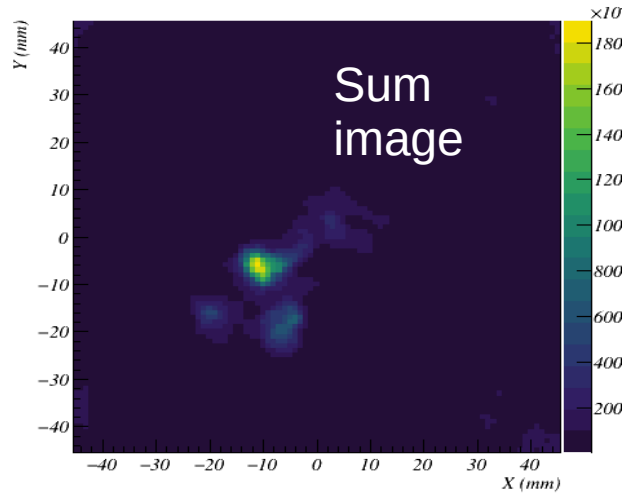
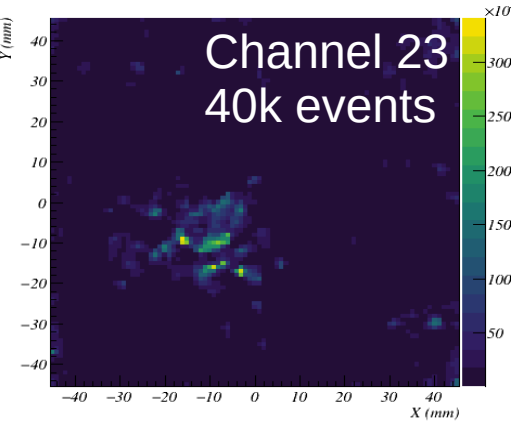
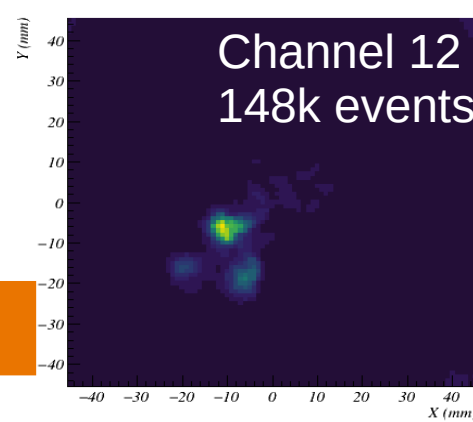


# Ac-225 Measurements at Léon Bérard hospital (Lyon)



6 mm  
rods

Preliminary



# Conclusions

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- ▶ The IRIS group has developed a Compton camera suitable for photon imaging in the range of 300 keV – 7 MeV.
- ▶ Application to hadron therapy treatment monitoring has achieved promising results. Collaboration with protontherapy centres is ongoing (CCB in Krakow, Quironsalud in Madrid).
- ▶ Initial results for radiopharmaceutical imaging are very encouraging. Collaboration with La Fe hospital in Valencia and Léon Bérard hospital in Lyon.
- ▶ Further improvement of the system performance and test in clinical sites are ongoing.



G. Llosá



A. Ros

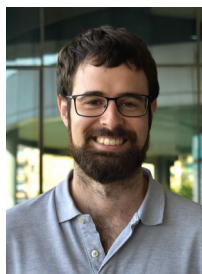


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M. Borja-Lloret



R. Viegas



J. Pérez Curbelo



C. Senra



J. V. Casaña

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  - Generalitat Valenciana, Prometeo CIRPOM/2022/70.

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# Medical Physics Days. CNA, Sevilla 29 Nov-1 Dec

## IV Jornadas RSEF / IFIMED de Física Médica

29 November 2023 to 1 December 2023

CNA, Sevilla

Europe/Madrid timezone

Overview

Scientific Programme

Call for Abstracts

Timetable

Book of Abstracts

Registration

Participant List

Contacto

✉ [iris@ific.uv.es](mailto:iris@ific.uv.es)

### Call for Abstracts



Abstracts should be no longer than 3000 characters including spaces and can be written in Spanish or English.

A summary or attached files are optional. Figures are allowed in the attachment.

The call for abstracts is open

You can submit an abstract for reviewing.

[Submit new abstract](#)

GEFM from RSEF

# Thank you

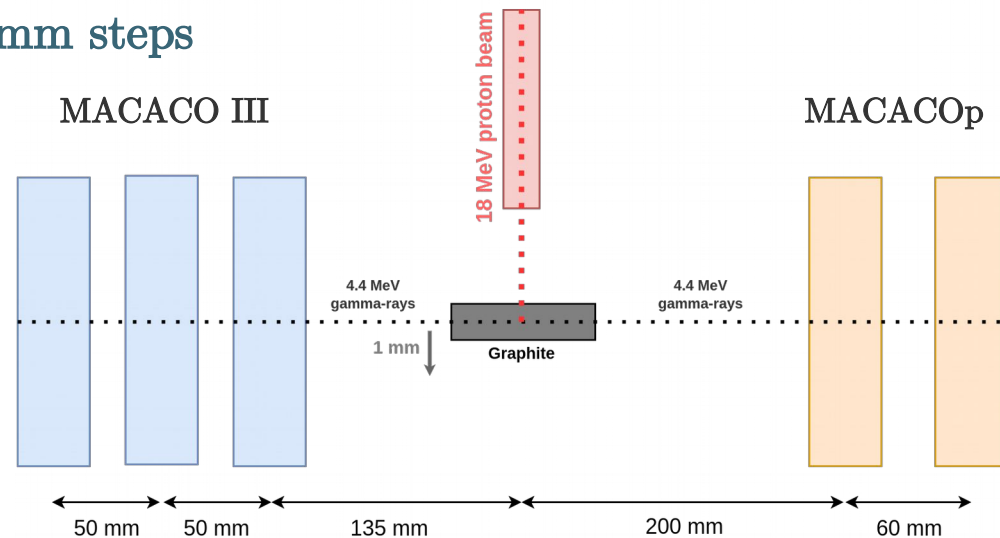
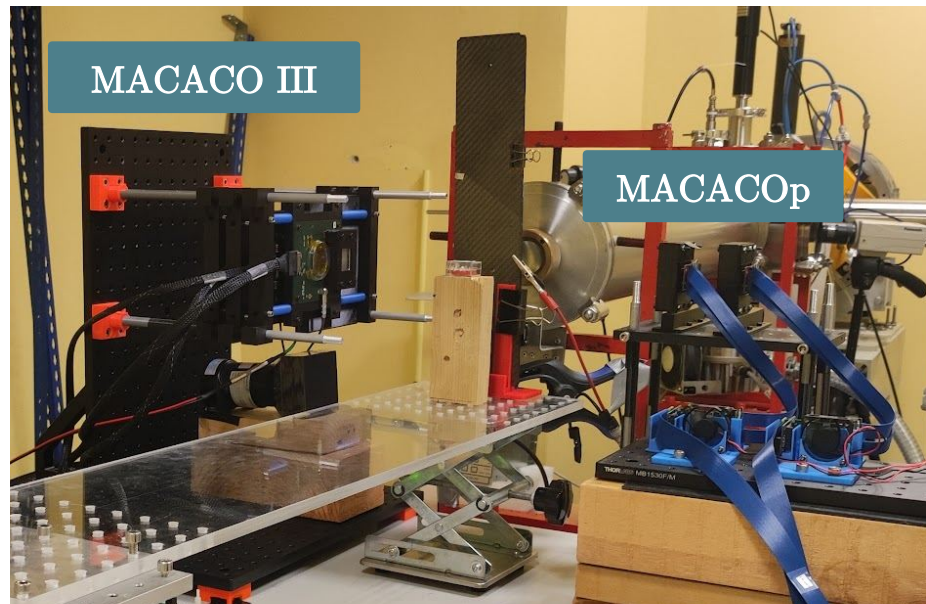
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[Gabriela.Ilosa@ific.uv.es](mailto:Gabriela.Ilosa@ific.uv.es)

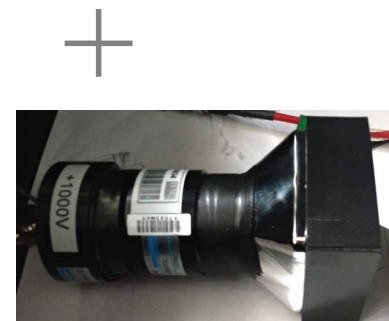
<http://ific.uv.es/iris>

# In-beam experiments CNA (Sevilla, Spain)

18 MeV protons on graphite positions with 1 mm steps

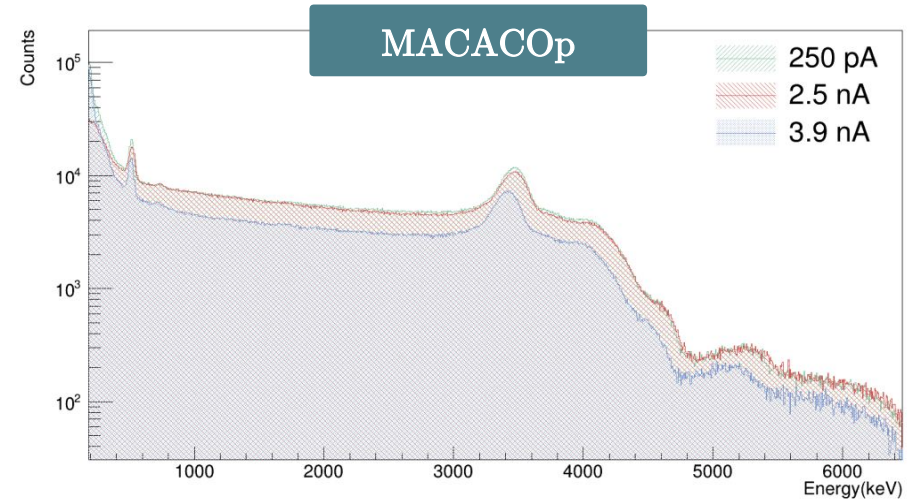
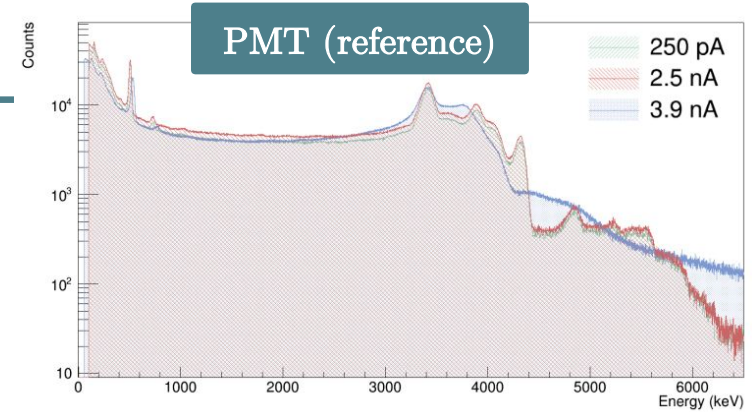
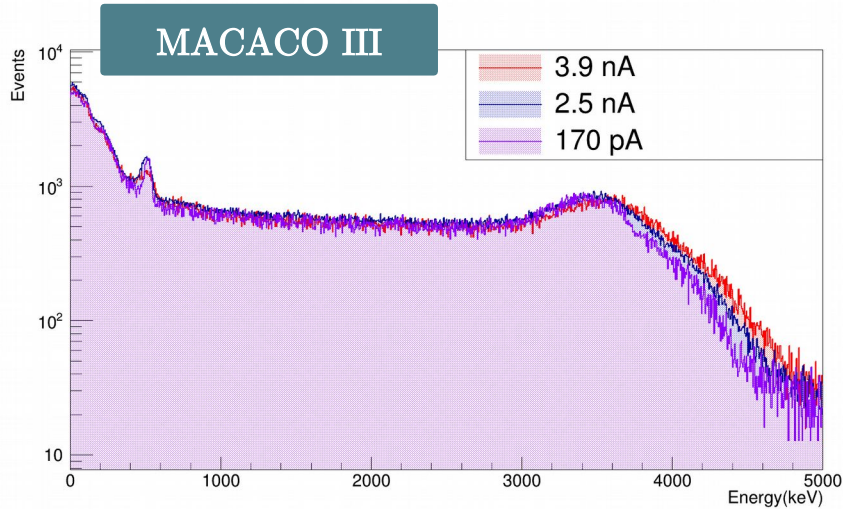


PMT + LaBr3  
 $51.2 \times 51.2 \times 10 \times \text{mm}^3$



# In-beam experiments CNA (Sevilla, Spain)

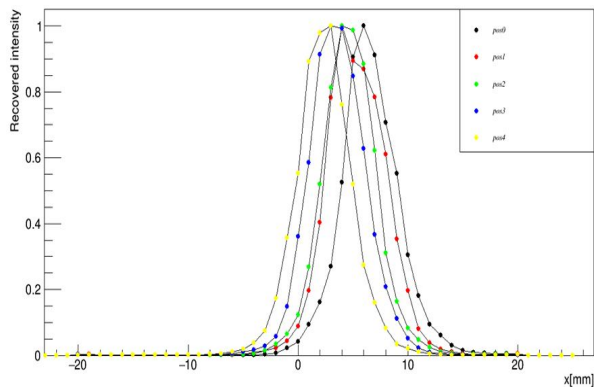
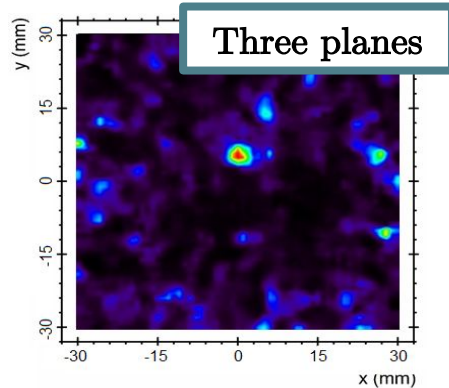
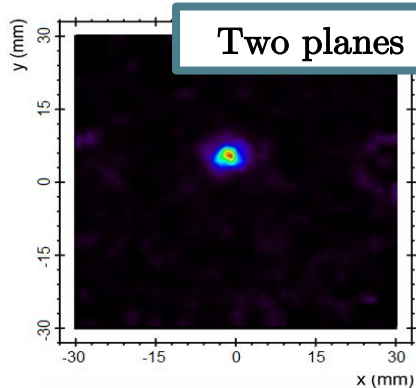
## Measured energy spectra



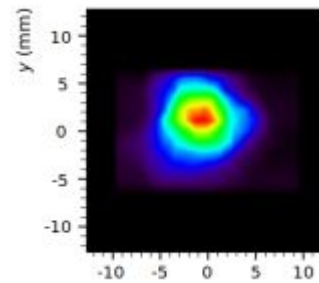
# In-beam experiments CNA (Sevilla, Spain)

18 MeV  
 $I = 2.5 \text{ nA}$

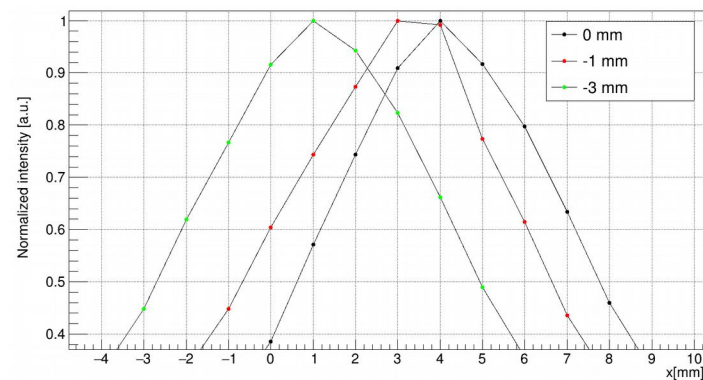
## MACACO III



## MACACOp



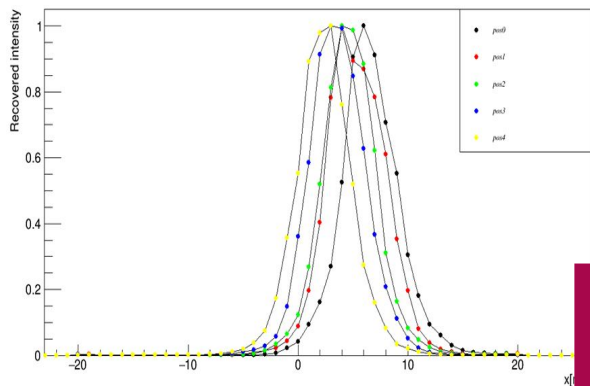
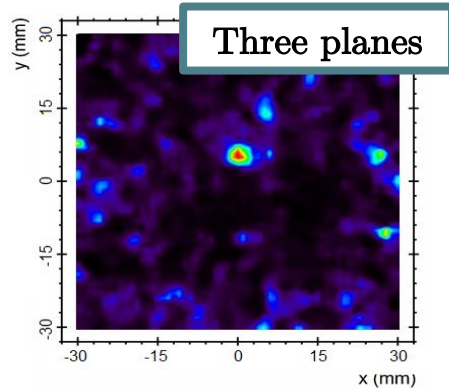
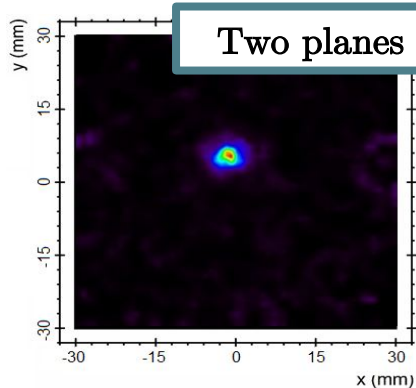
Target Separation ( $\pm 0.7 \text{ mm}$ )		
Expected	Max	R80 after Max
1 mm	1	1.1
2 mm	2	1.7
3 mm	3	2.8



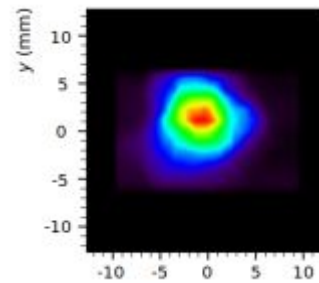
# In-beam experiments CNA (Sevilla, Spain)

18 MeV  
 $I = 2.5 \text{ nA}$

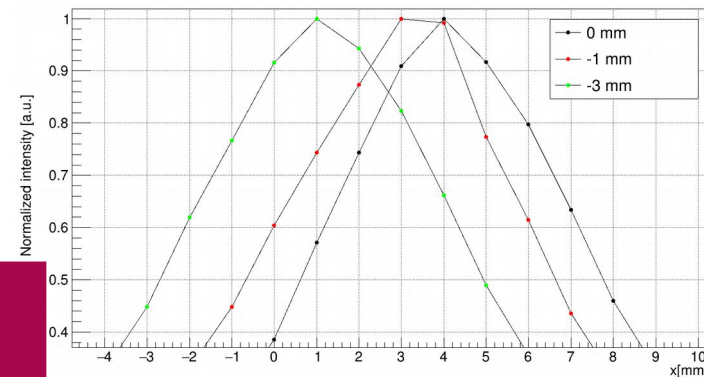
## MACACO III



## MACACOp

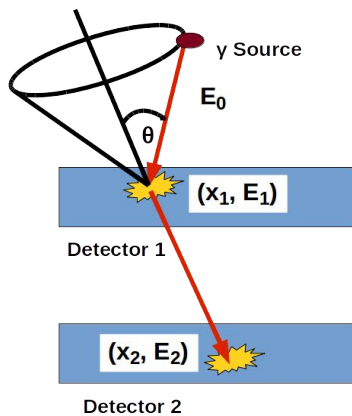


Target Separation ( $\pm 0.7 \text{ mm}$ )		
Expected	Max	R80 after Max
1 mm	1	1.1
2 mm	2	1.7
3 mm	3	2.8



1 mm steps detected  
with both systems

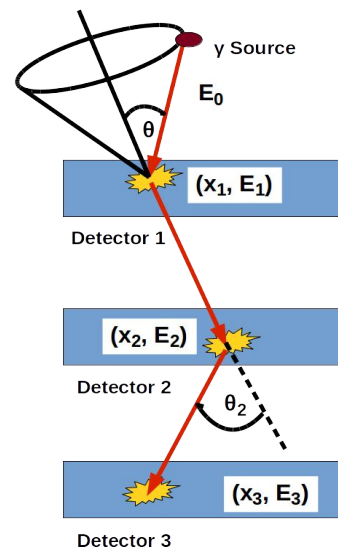
# Compton camera configurations



Scatterer + “absorber”  
2 interactions

$$\cos(\theta) = 1 - m_0c^2 \left( \frac{1}{E_0 - E_e} - \frac{1}{E_0} \right)$$

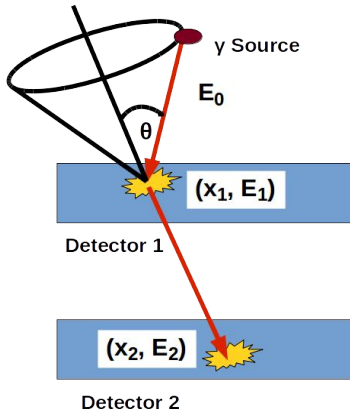
Multilayer  
3 int. in 3 detectors



$$\cos(\theta) = 1 - \frac{E_1 m_e c^2}{E_0 (E_0 - E_1)}$$

$$E_0 = E_1 + \frac{1}{2} \left( E_2 + \sqrt{E_2^2 + 4 \frac{E_2 m_e c^2}{1 - \cos(\theta_2)}} \right)$$

# Compton camera configurations



Scatterer + “absorber”  
2 interactions

Problem if the photon energy is  
unknown/high (MeV)

$$\cos(\theta) = 1 - m_0c^2 \left( \frac{1}{E_0 - E_e} - \frac{1}{E_0} \right)$$

Multilayer  
3 int. in 3 detectors

Energy determined  
Lower efficiency

$$\cos(\theta) = 1 - \frac{E_1 m_e c^2}{E_0 (E_0 - E_1)}$$

$$E_0 = E_1 + \frac{1}{2} \left( E_2 + \sqrt{E_2^2 + 4 \frac{E_2 m_e c^2}{1 - \cos(\theta_2)}} \right)$$

