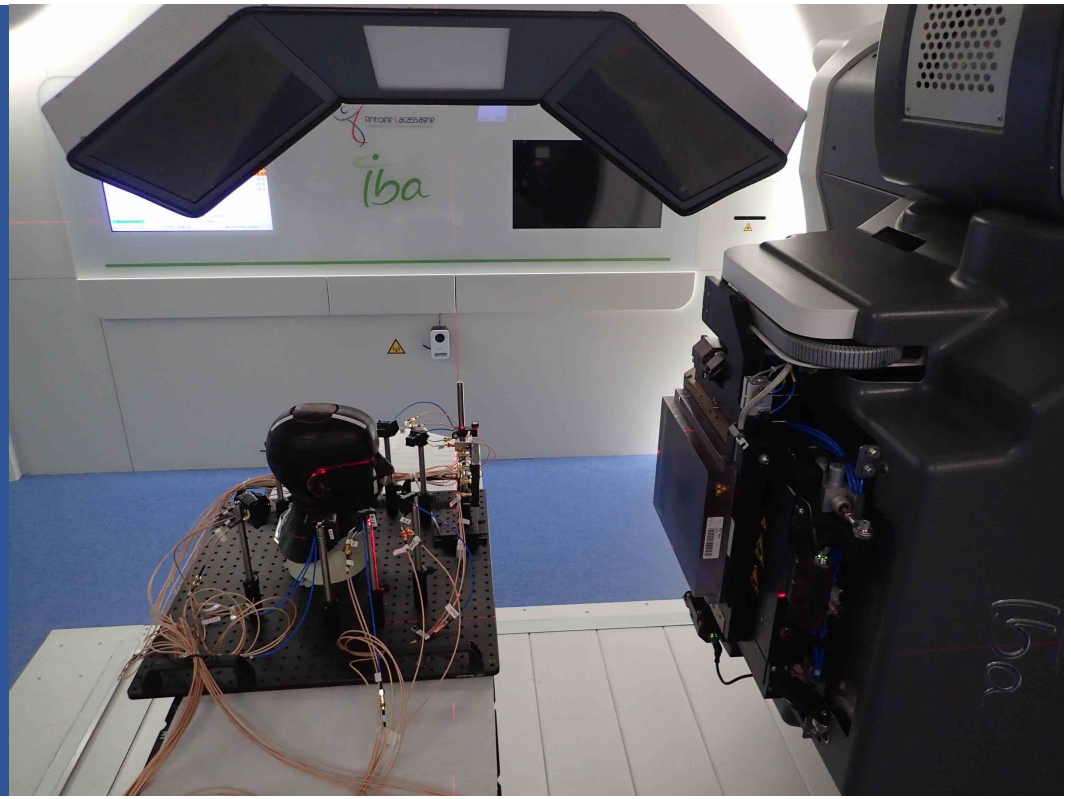
Prompt Gamma Timing and Time Imaging with the TIARA detector



Sara Marcatili, on behalf of the TIARA collaboration

CNAO-IN2P3 Collaboration meeting

5 March 2026

CNAO, Pavia

LPSC GRENOBLE | MODANE

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM

Antoine Lacassagne CENTRE DE LUTTE CONTRE LE CANCER unicancer NICE

TOR VERGATA UNIVERSITÀ DEGLI STUDI DI ROMA

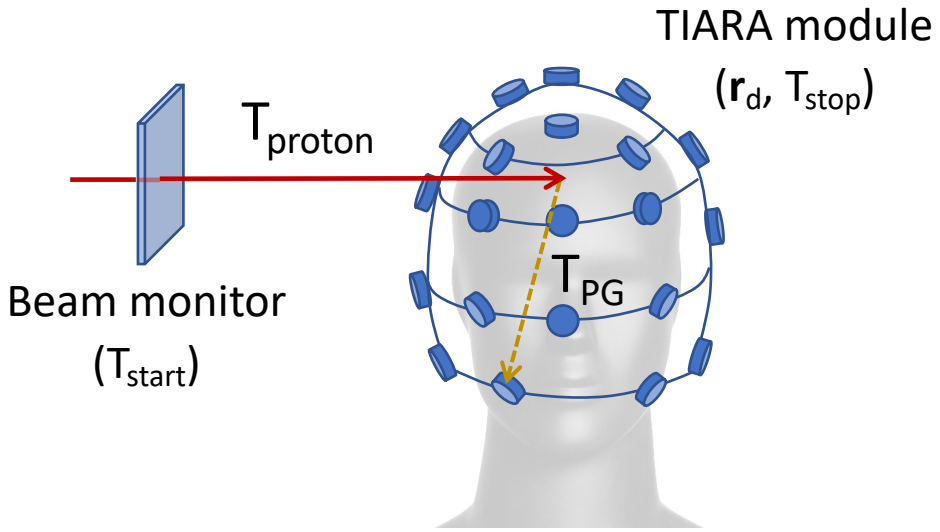
cnrs NUCLÉAIRE & PARTICULES

erc European Research Council Established by the European Commission

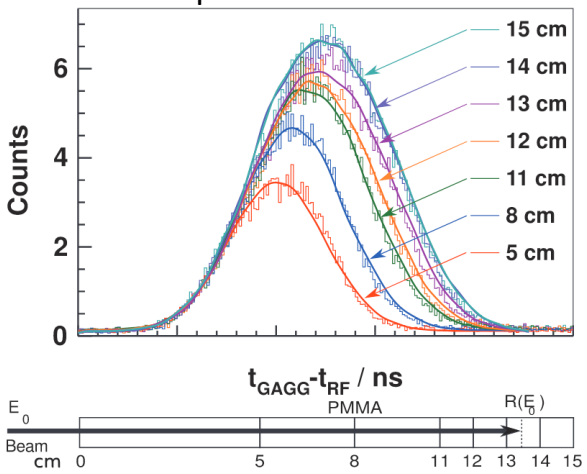
PGTI PROMPT GAMMA TIME IMAGING

Beyond Prompt Gamma Timing: detection principle

Prompt Gamma Timing



Example of TOF distributions



Golnik et al. Phys. Med. Biol. 59 (2014) 5300

$$TOF = t_{stop} - t_{start}$$

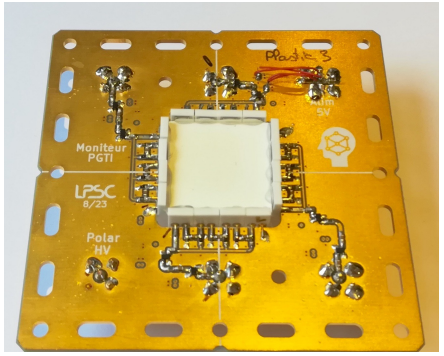
$$T_{proton}(\mathbf{r}_v, \mathbf{v}_p) + T_{PG}(\mathbf{r}_v, \mathbf{r}_d)$$

2 unknowns: $\mathbf{r}_v$ = PG vertex $\mathbf{v}_p$ =proton speed

The TIARA (Tof Imaging ARrAy) detector

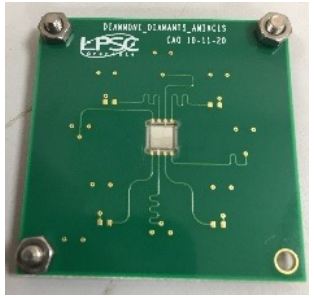
Fast beam monitors

Plastic-based for
low intensity

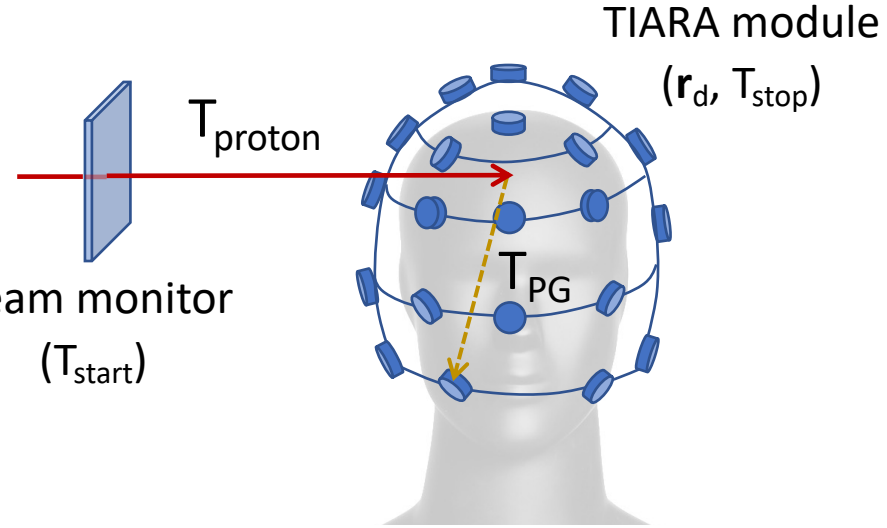


https://arxiv.org/abs/2411.07877

Diamond-based for
high intensity

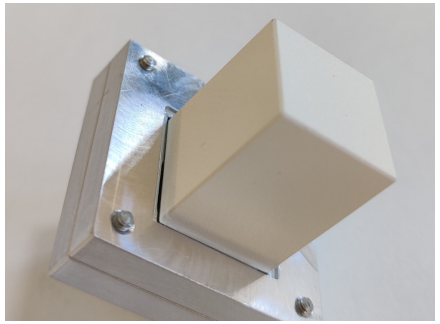


cf. Gallin-Martel's talk



Targeted coincidence time resolution (CTR):
~ **100 ps RMS** (235 ps FWHM)
for range uncertainty ~ mm

Cherenkov-based gamma detector



http://arxiv.org/abs/2601.20457

Adapted to all
intensities

Gamma module: understanding detector response

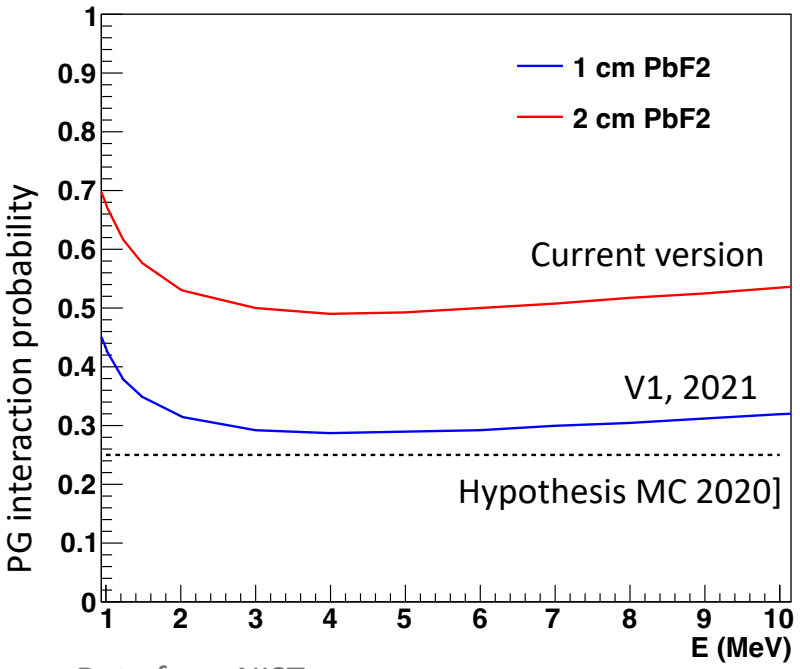
$$\epsilon = \epsilon_{geo} \times \epsilon_{int} \times \epsilon_{opt}$$

$$\epsilon \sim 0.45\%$$

Detector solid angle

- nb. Of PG modules
- distance from beam axis

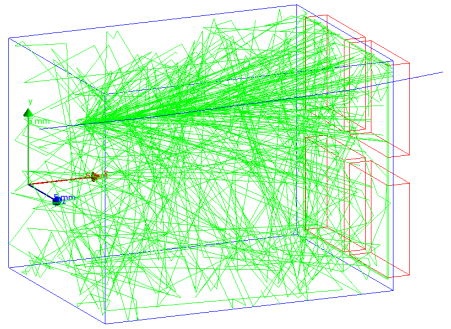
PG interaction probability



Data from NIST

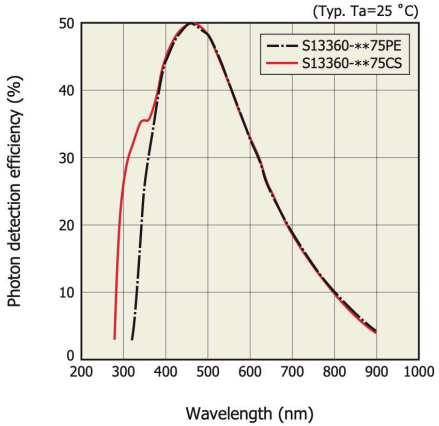
Probability that a particle interacting in the crystal is actually detected by the SiPM.

Nb of optical photons reaching the SiPm



G4 simulation

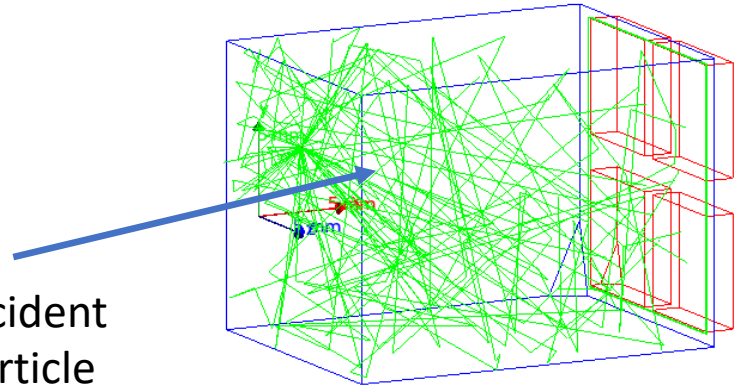
SiPM PDE

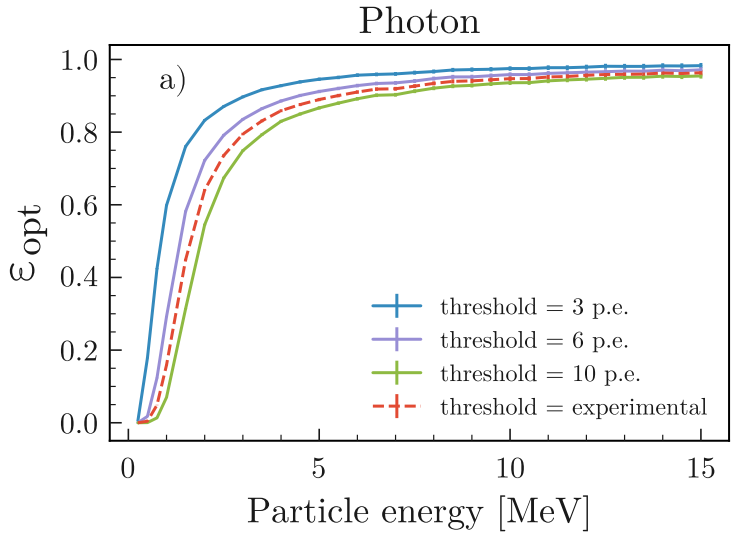


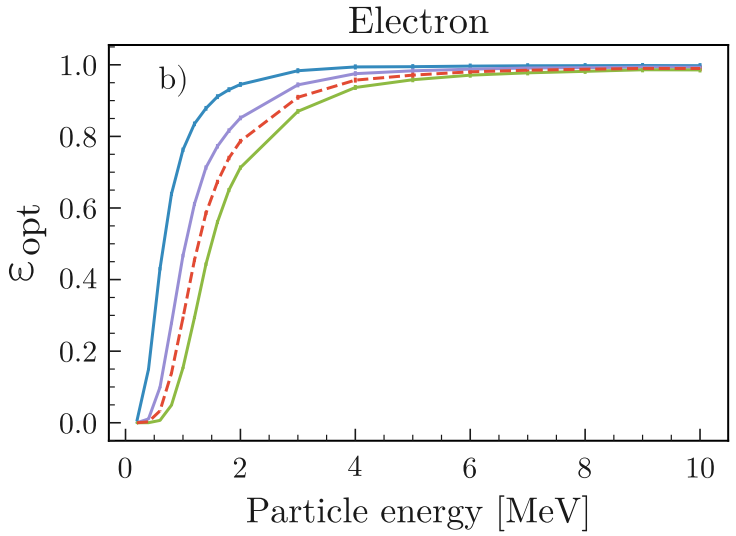
Post-analysis

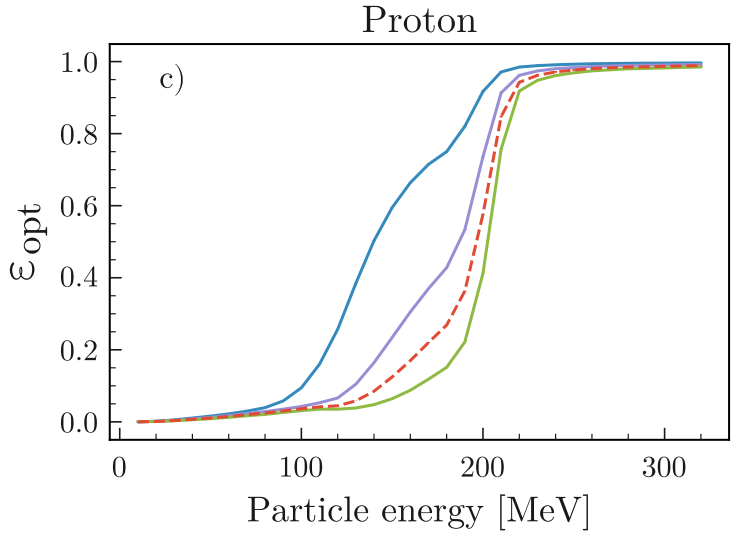
Gamma module optical response: particle sensitivity

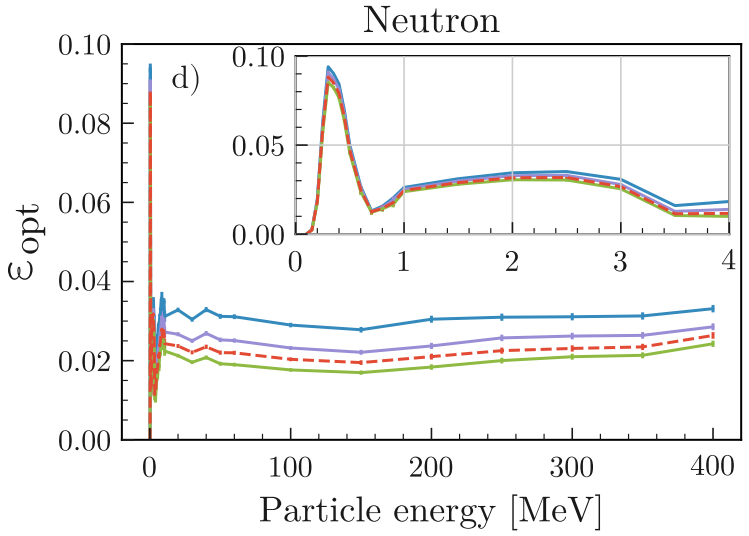
The optical detection efficiency is determined as a function of particle incident energy





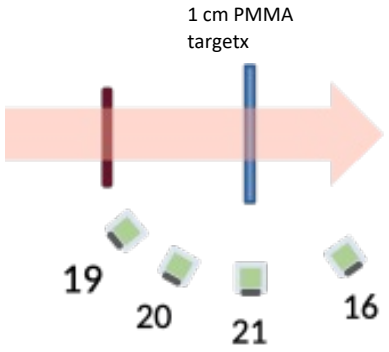




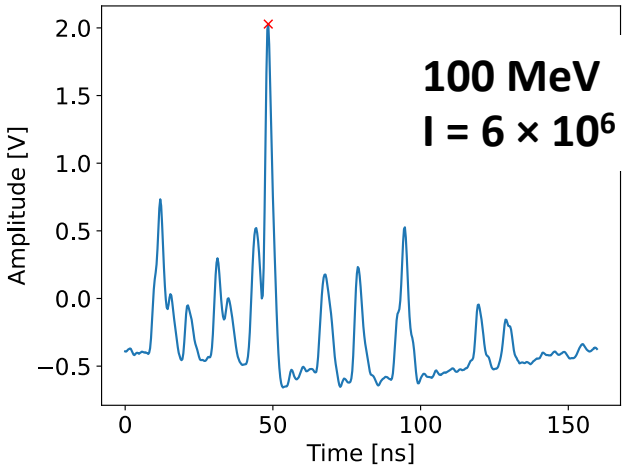


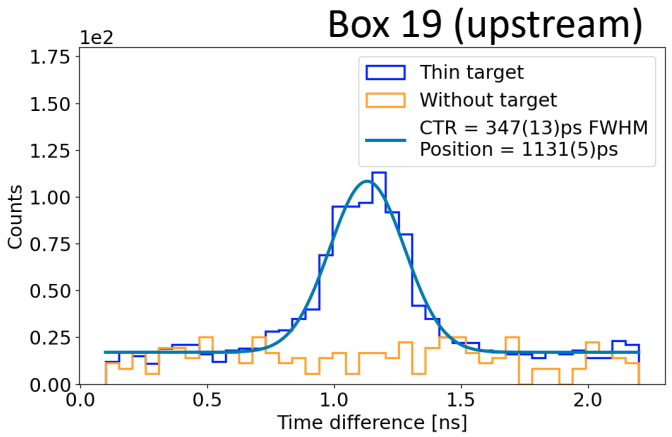
Protons at CNAO: time resolution and SNR

Time resolution



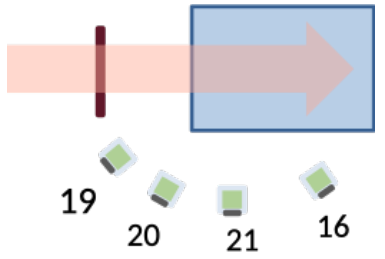
Signal from monitor not bunched at the gamma detector time-scale





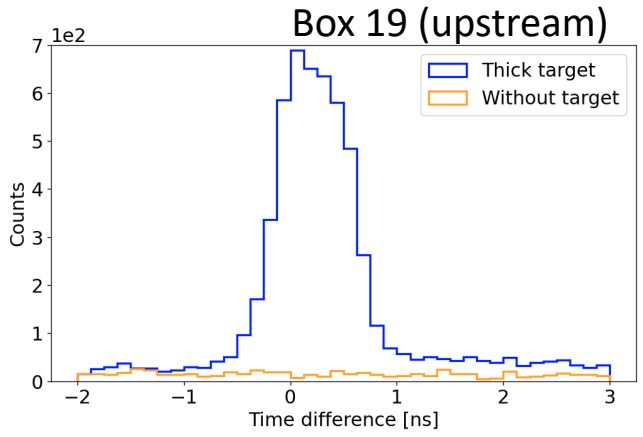
Time resolution slightly degraded (148 ps rms) as this is not Single Proton Regime.

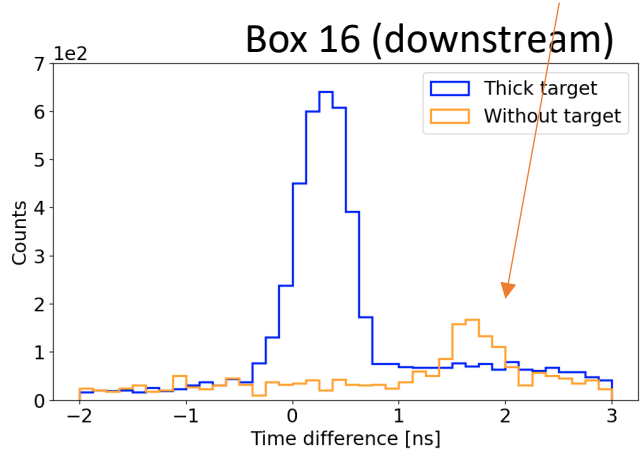
Signal-to-Noise Ratio



- Negligible background with target/patient in place
- Very high SNR both downstream and upstream

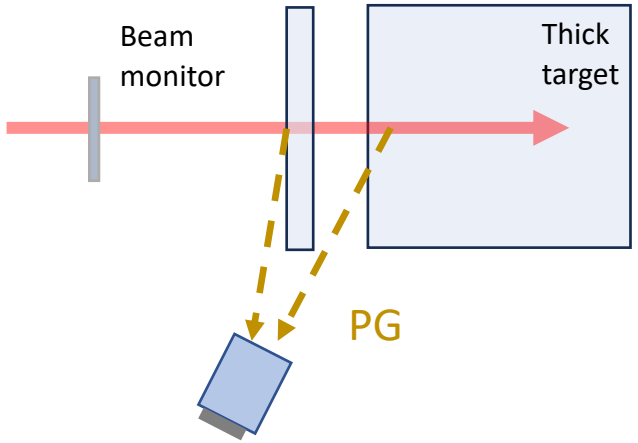
Protons from monitor stopped in the target

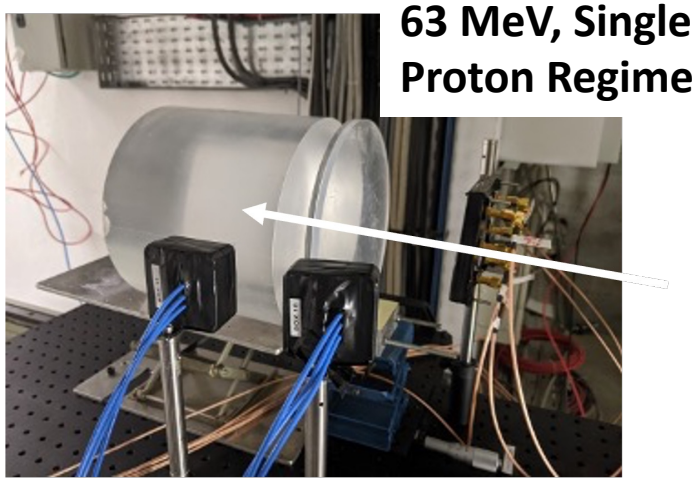




Range accuracy with protons (MEDICYC Cyclotron)

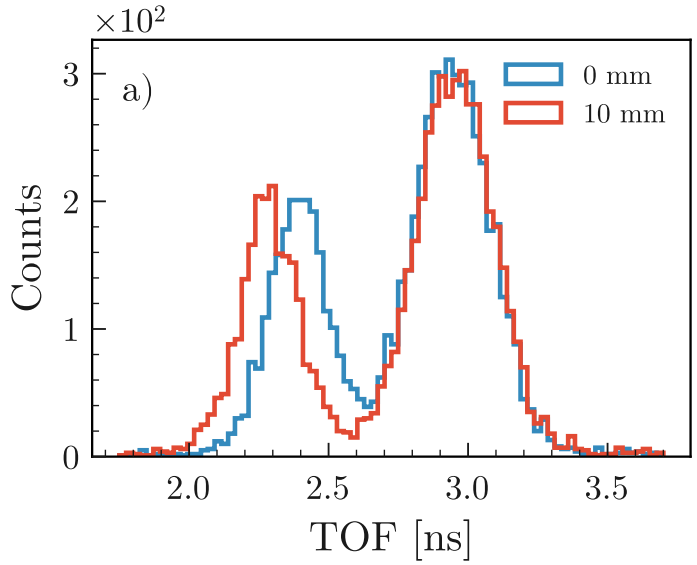
Variable thickness air gap to simulate a range shift

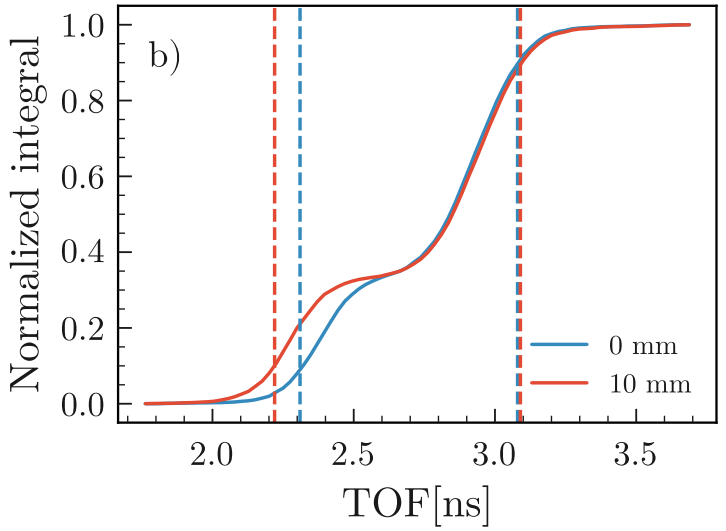


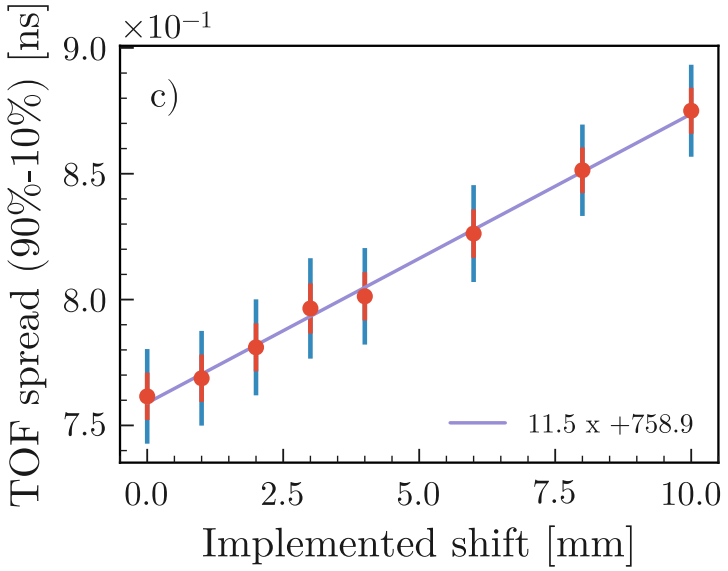


63 MeV, Single Proton Regime

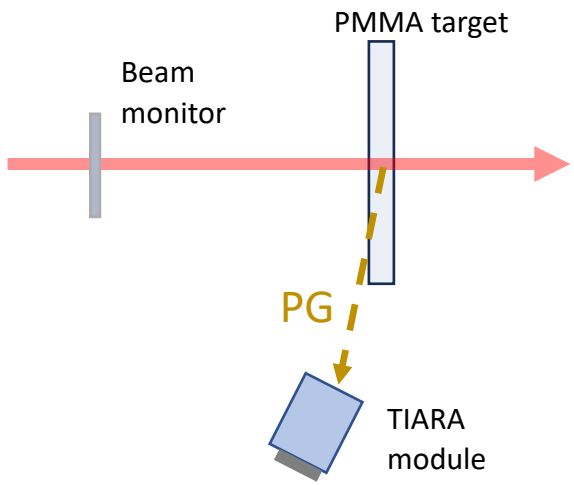
Nb. Of spots	1	2
Nb. of incident protons	1 x 10^7	2 x 10^7
Range accuracy at 2 σ (mm)	3.3 ± 0.1	2.3 ± 0.1



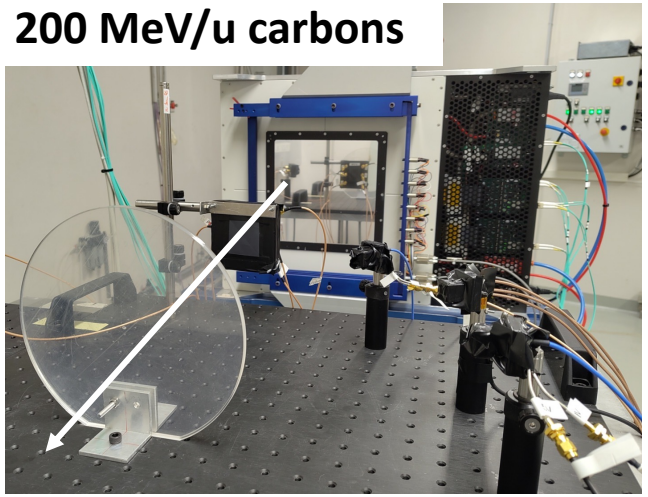




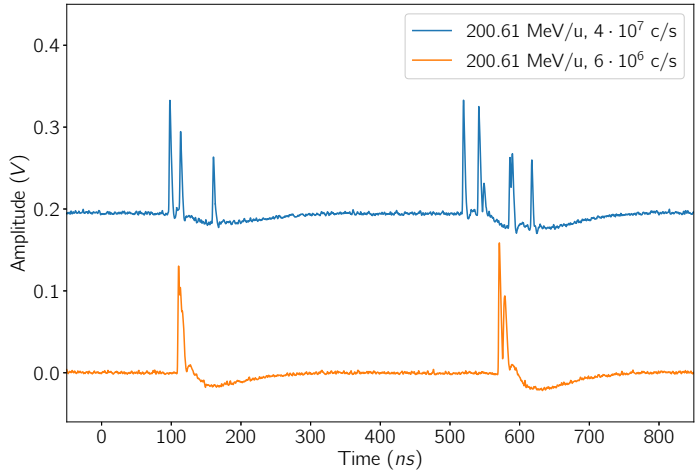
Carbons at CNAO: time resolution and intensity



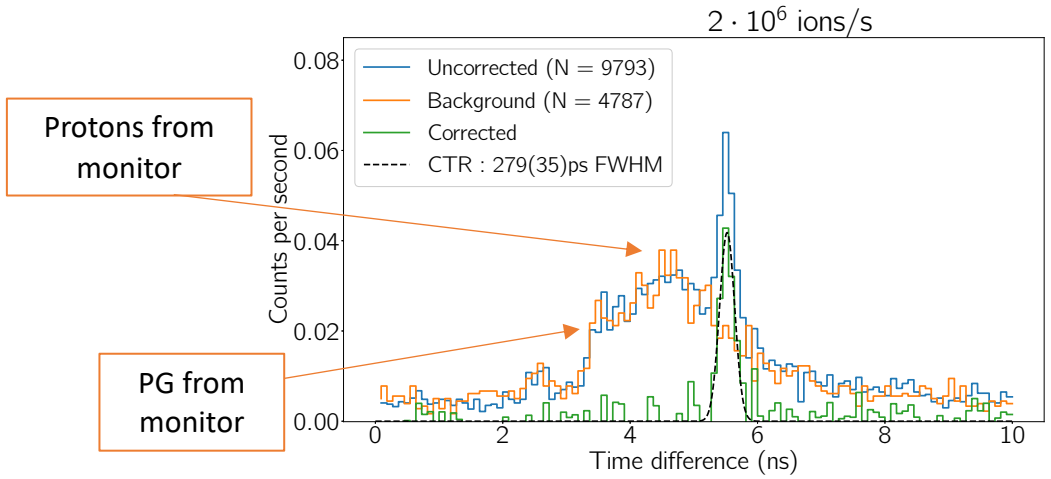
200 MeV/u carbons

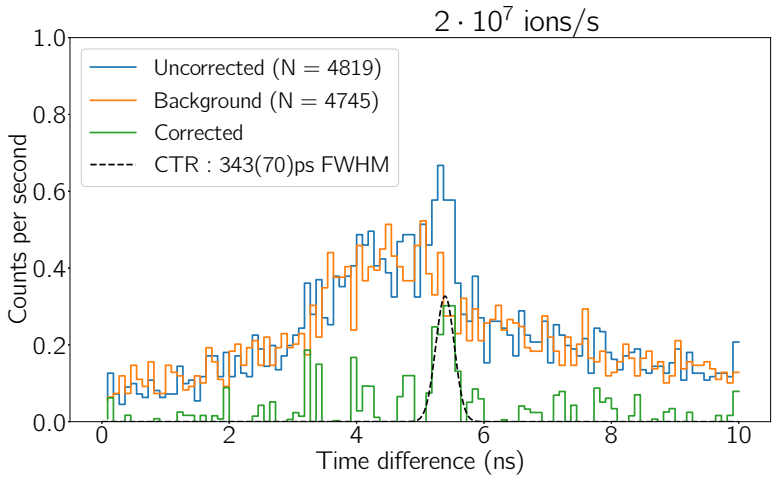


Beam monitor response



Coincidence Time Resolution

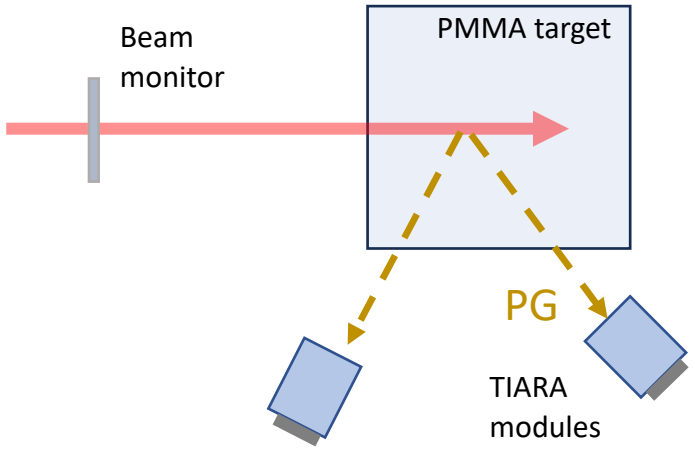




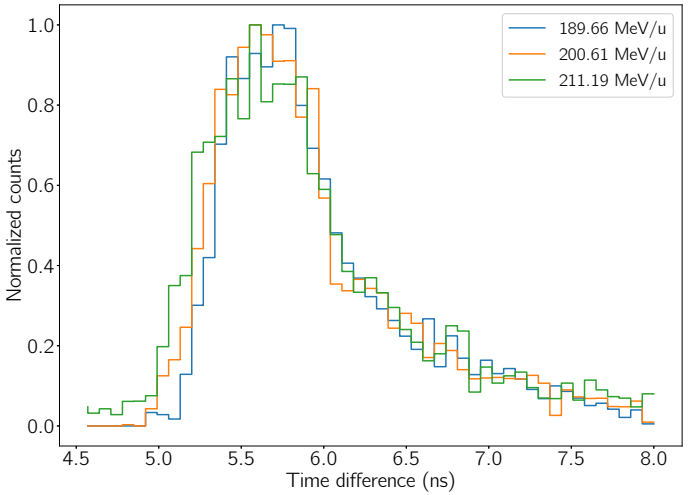
Coincidence Time Resolution

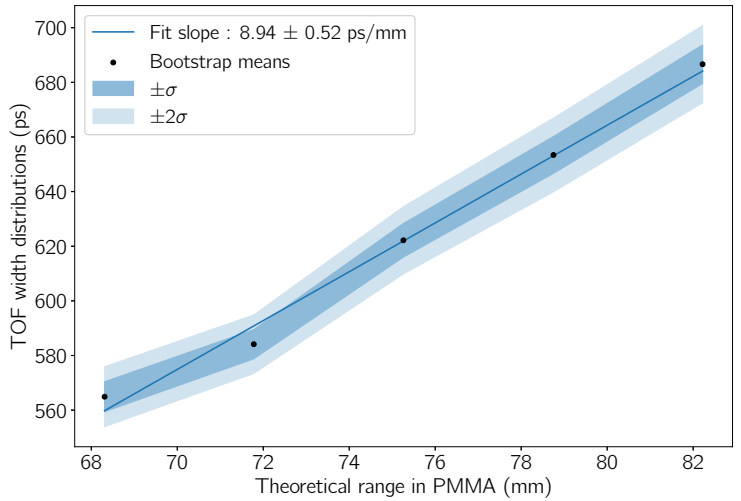
- better than proton's (347 ps FWHM)
- only slightly degraded at clinical intensity

Range accuracy with carbons (CNAO)

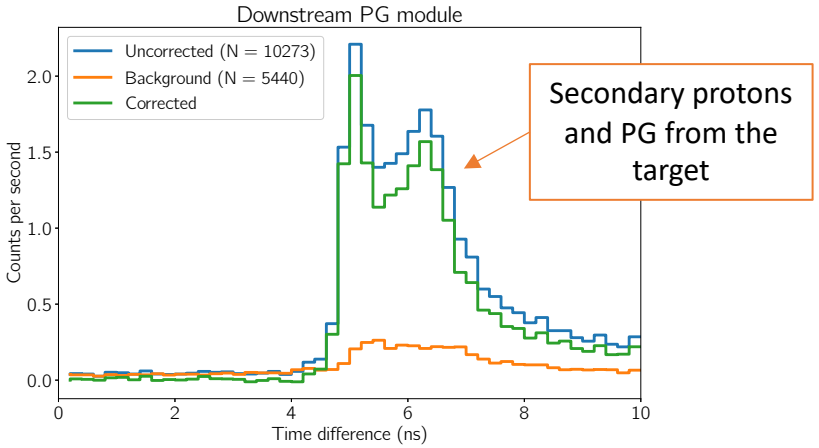


From 189 to 211 MeV/u to induce progressive range shifts of 3.5 mm in PMMA





Downstream detection not feasible



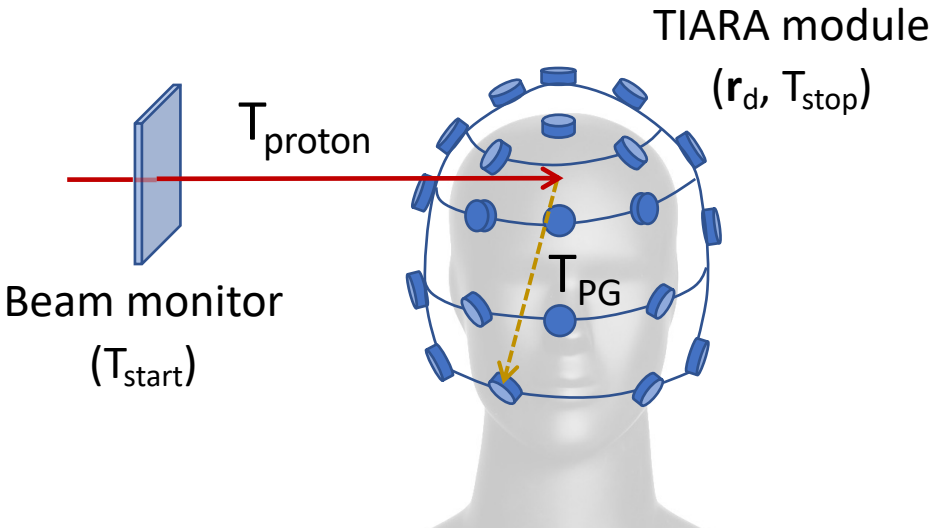
2σ range accuracy extrapolated to full TIARA detector

			$R_{acc,2\sigma}$ (mm)	
Clinical spots	Number of ions	N_{PG} (Counts)	$2 \cdot 10^6$ ions/s	$2 \cdot 10^7$ ions/s
1	$2.4 \cdot 10^6$	1400	5.42 ± 0.32	9.30 ± 0.70
2	$4.8 \cdot 10^6$	2800	3.76 ± 0.22	6.64 ± 0.50
4	$9.6 \cdot 10^6$	5600	2.68 ± 0.16	4.74 ± 0.36

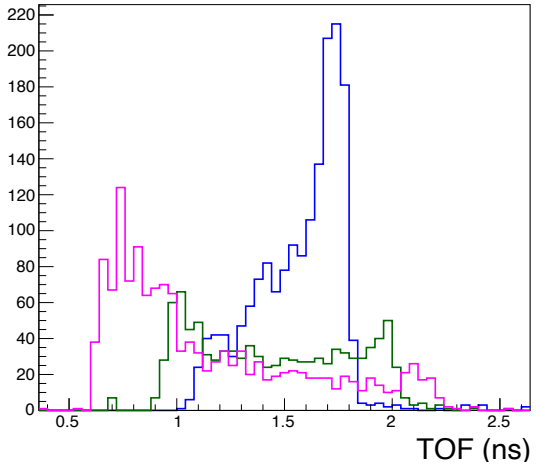
http://arxiv.org/abs/2602.18318

Beyond Prompt Gamma Timing

Prompt Gamma Time Imaging



INPUT: TOF
(one histo per detector)

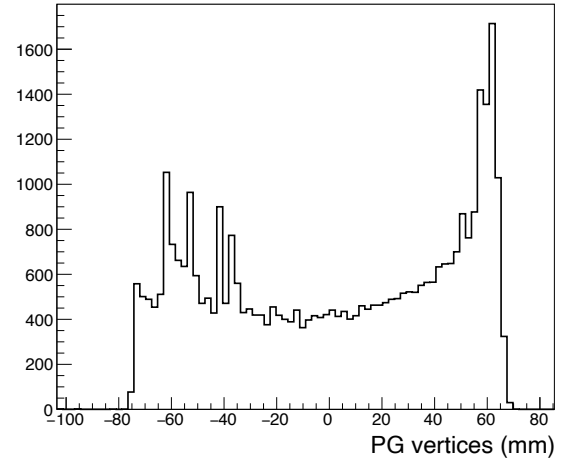


$$TOF = t_{stop} - t_{start} =$$

$$T_{proton}(\mathbf{r}_v, \mathbf{v}_p) + T_{PG}(\mathbf{r}_v, \mathbf{r}_d)$$

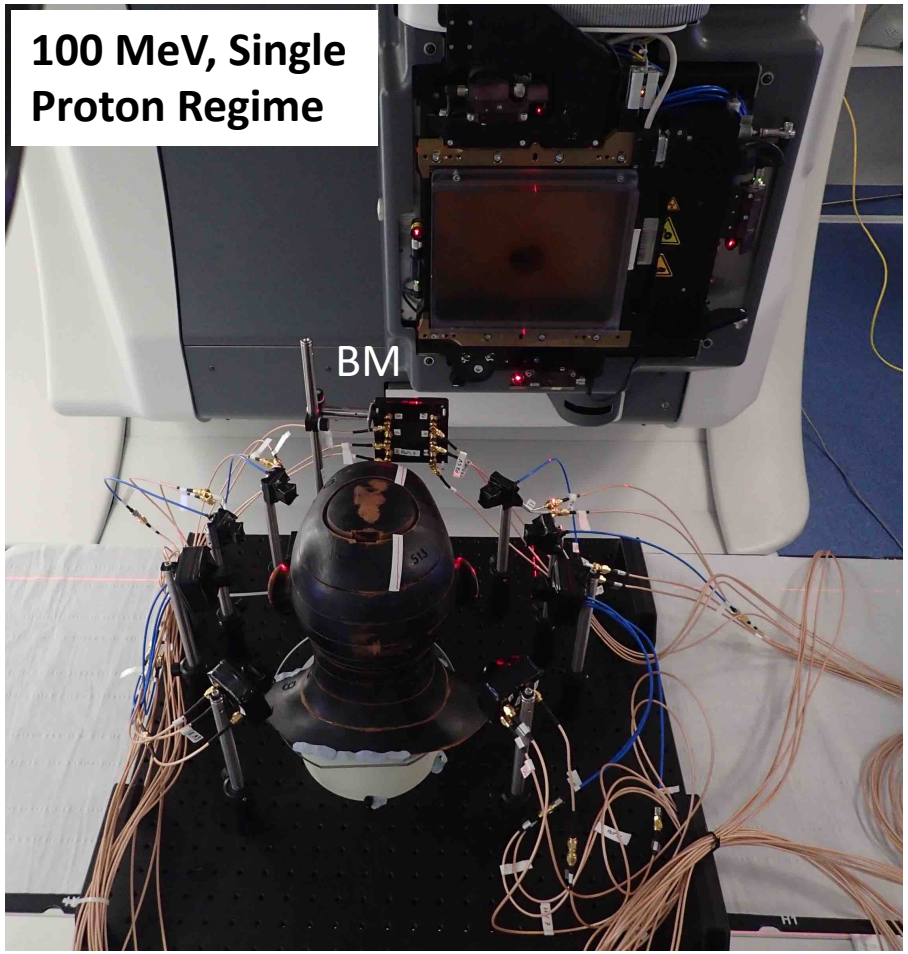
2 unknowns: $\mathbf{r}_v$ = PG vertex $\mathbf{v}_p$ =proton speed

OUTPUT: $\mathbf{r}_v$
(a unique PG vertex distribution)



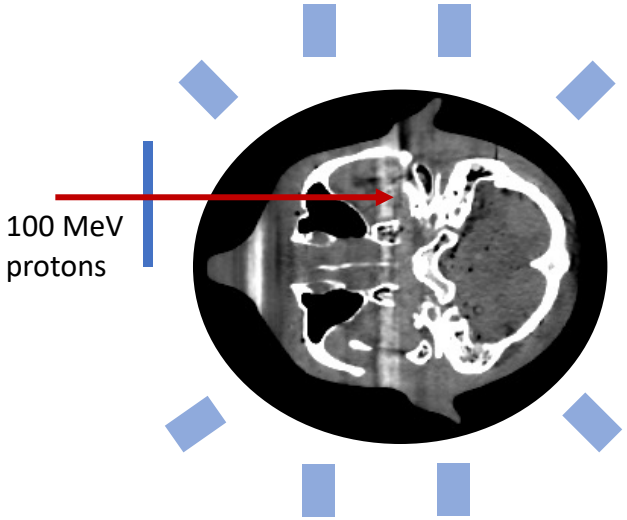
Determination of anatomical variations with PGTI

8 channels TIARA prototype



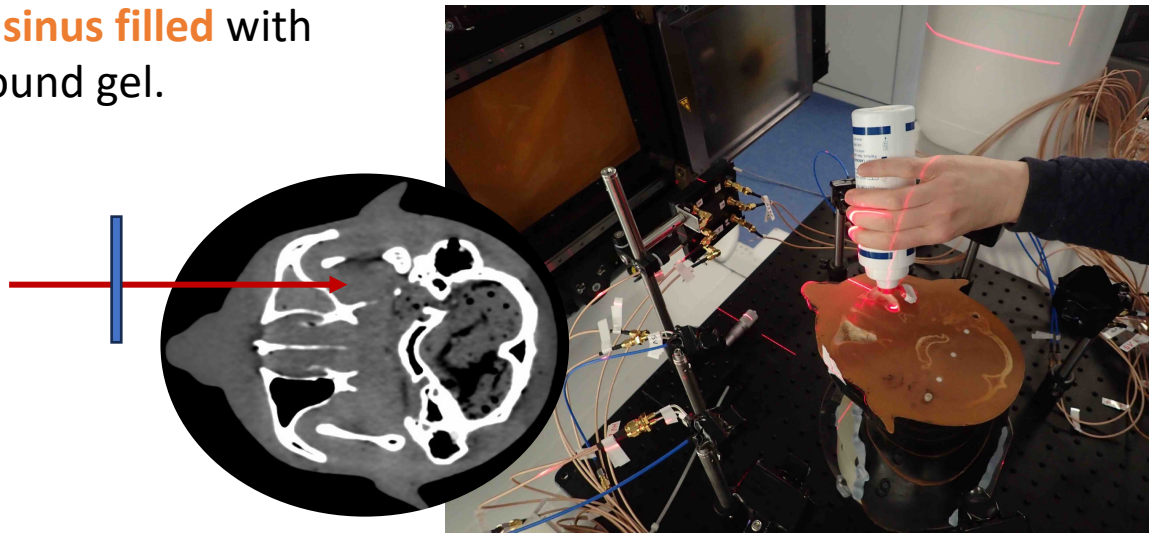
Treatment planning

Irradiation of RANDO anthropomorphic phantom with **sinus empty**…

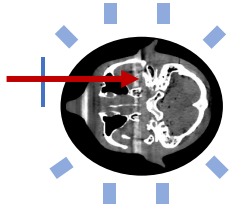


Treatment delivery

… and **sinus filled** with ultrasound gel.

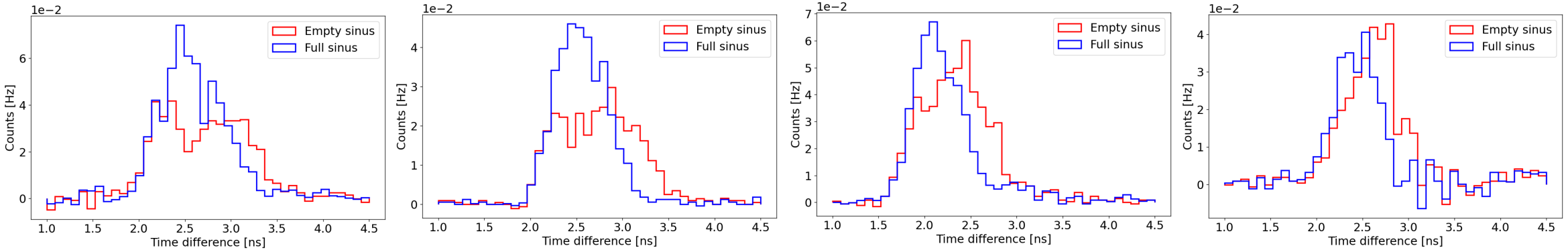


Determination of anatomical variation: TOF data

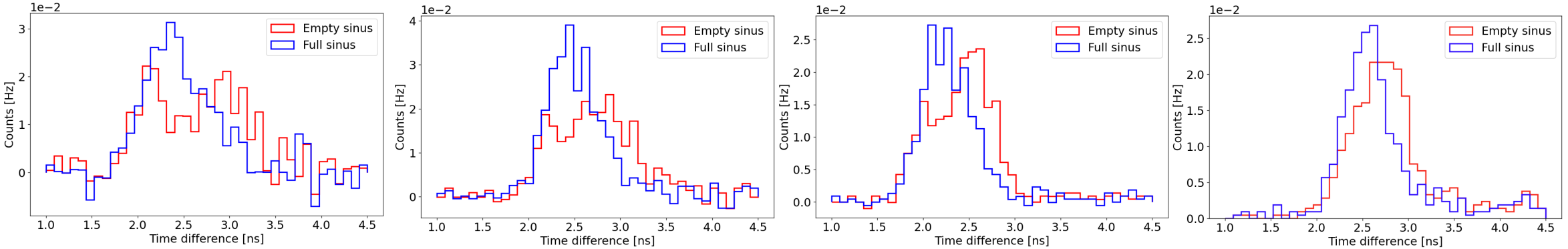


Between 500 and 1000 PGs per detector

All data after background subtraction: comparison sinus empty/filled

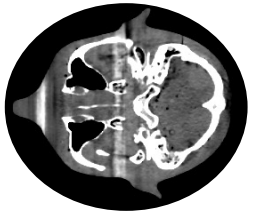


Beam direction

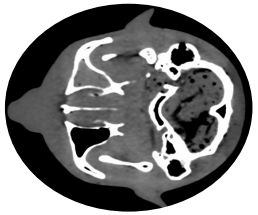


Determination of anatomical variation: reconstructed data

Possible clinical application



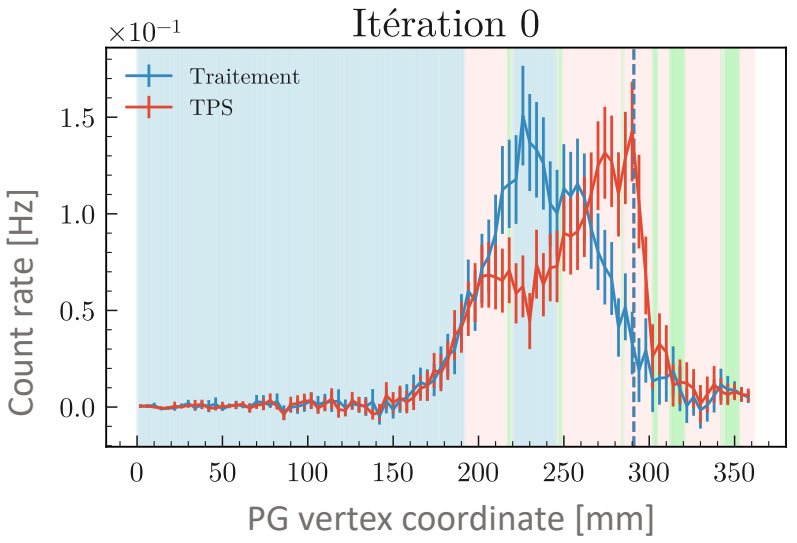
Treatment planning:
the sinus is empty



Treatment:
the sinus is filled (inflammation)

Prompt Gamma Time Imaging

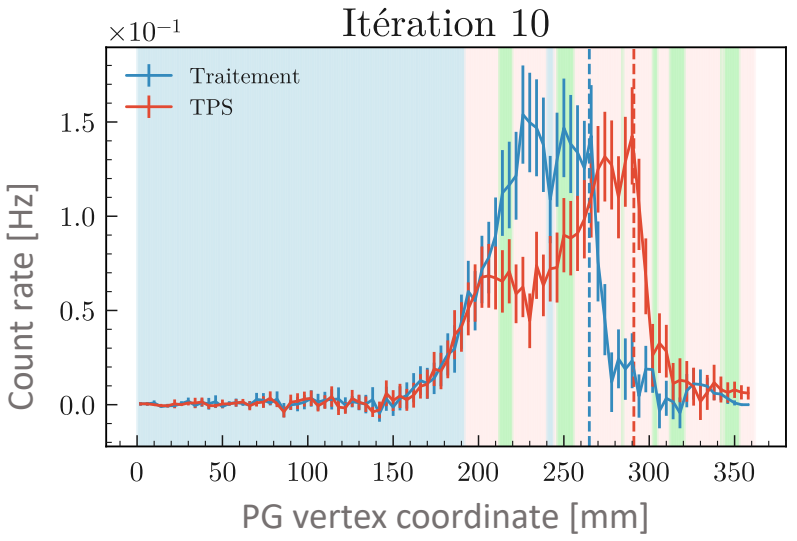
1) Iterative reconstruction of PG vertex distribution
2) Identification of anatomical change
3) Determination of proton velocity

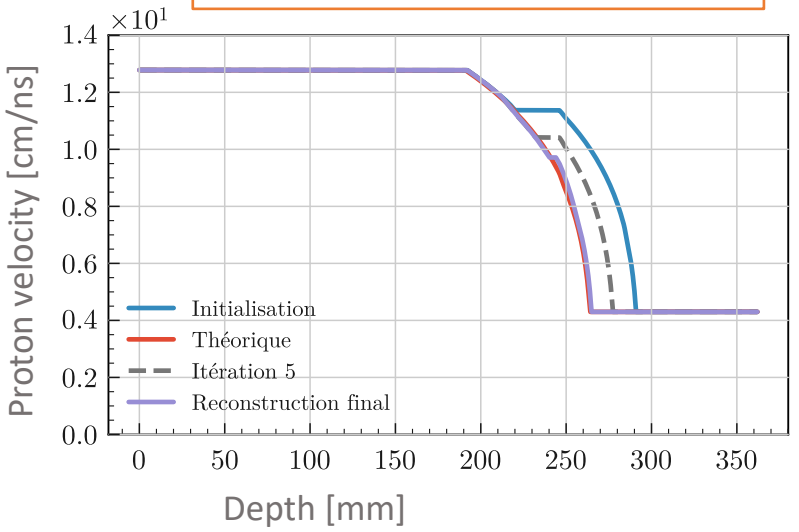


Air
Bone
Water-like

$$TOF = t_{stop} - t_{start} = T_{proton}(\mathbf{r}_v, \mathbf{v}_p) + T_{PG}(\mathbf{r}_v, \mathbf{r}_d)$$

Range shift
Actual = 27 ± 1 mm
Measured = 26 ± 4 mm





Conclusions

The use of **Cherenkov detectors** is promising to significantly increase the sensitivity of PG-based monitoring techniques:

- High detection efficiency (~ 0.45%)
- Higher SNR (no neutron detection)
- But sensitive to secondary protons in ^{12}C therapy

A first **8-channel prototype** has been **extensively tested**

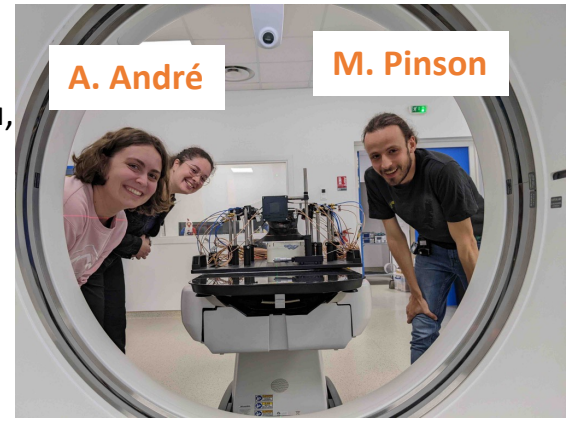
- **with protons at low intensity regime**, with cyclotrons, synchro-cyclotrons and synchrotrons .
- with carbon ions at CNAO

The PGTI reconstruction algorithm may allow to **identify anatomical changes** between treatment planning and delivery.

Acknowledgements and credits

The **TIARA Collaboration**

LPSC: S. Marcatili, **A. André**, G. Fanciulli, ML. Gallin-Martel, L Gallin-Martel, C. Hoarau, P. Kavrigin, J-F Muraz, P. Paris, **M. Pinson**
CPPM: Y. Boursier, C. Abid, M. Dupont, A. Garnier, C. Morel
CAL: D. Maneval
Roma Tor Vergata: N. Toschi, D. Psarras



Funding agencies

IRS – Initiative de Recherche Stratégiques (project ANR-15-IDEX-02)
M. Jacquet PhD thesis, ED physique
A. André PhD thesis, ED physique

PCSI TIARA (Convention n°20CP118-00)

ERC Starting Grant (project 101040381)

This work was partially supported by the **European Union (ERC project PGTI, grant number 101040381)**. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Research Council Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Beam time at CNAO and related travel expenses

2 internships

CAL/IN2P3 COMEX for the allocated beam time
Petter Hofverberg (CAL), **Marco Pullia** (CNAO) and their teams for the nice reception
Some of the results have been obtained at CNAO experimental facility built in collaboration with INFN