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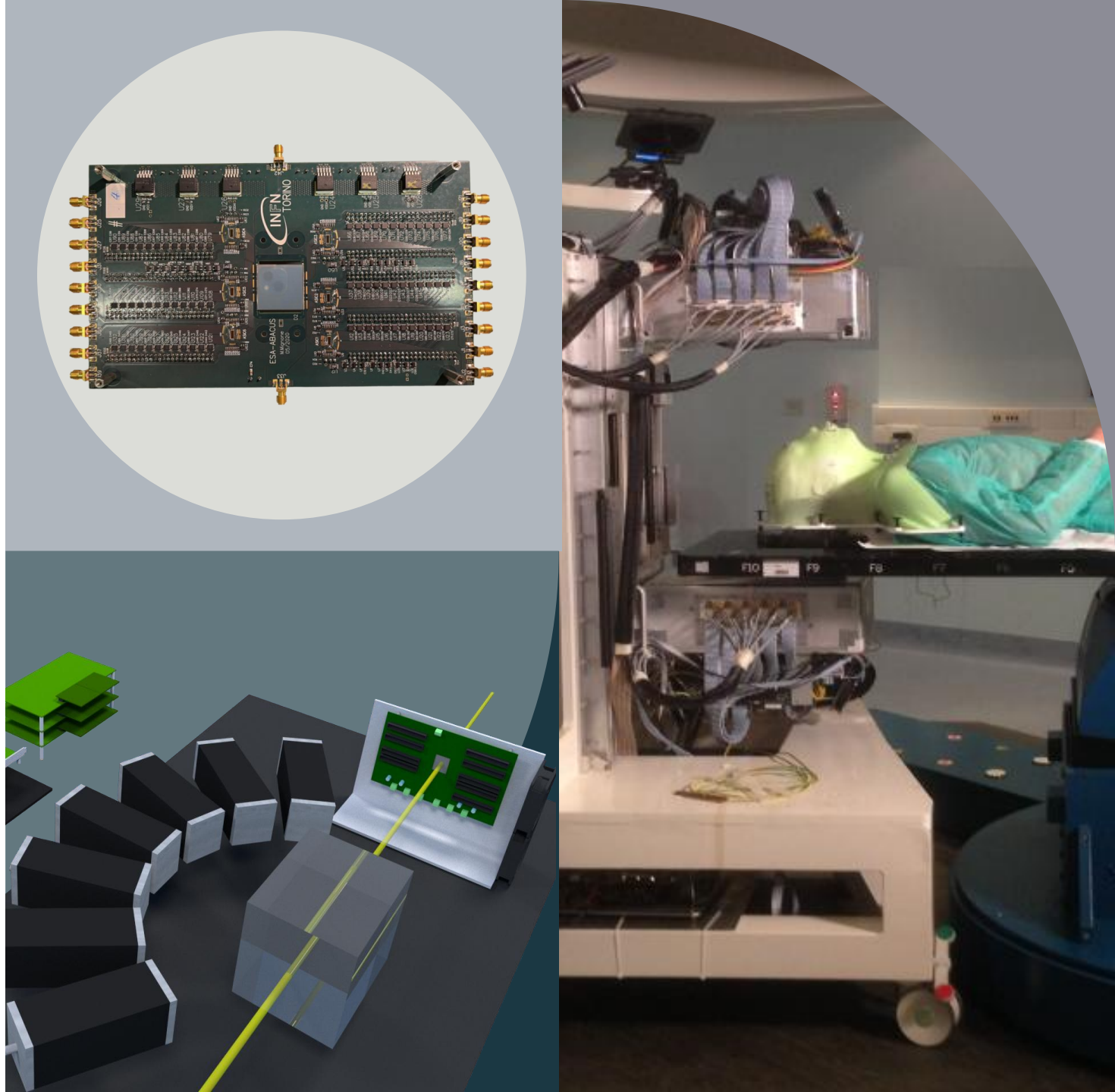
Istituto Nazionale di Fisica Nucleare

Update on beam monitors and range verification systems

V. Ferrero – Università degli Studi di Torino e INFN Sezione di Torino

CNAO – IN2P3 meeting 5th March 2026 *…follow-up of the October 2023 meeting*



NOVEL BEAM MONITORS

TREATMENT VERIFICATION SYSTEMS

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CNAO Centro Nazionale di Adroterapia Oncologica

RESEARCH ACTIVITIES FOR PARTICLE THERAPY IN THE MEDICAL PHYSICS GROUP AT UNITO AND INFN-TO:

NEW CHALLENGES IN PARTICLE THERAPY:

- Advanced treatment modalities (multiple rescanning, image-guided treatment)
- Fast pencil beam scanning
- Hypofractionation
- New accelerators

ADAPTIVE THERAPY

InSIDE

Superconducting Ion Gantry

honey

I3PET

FRIDA

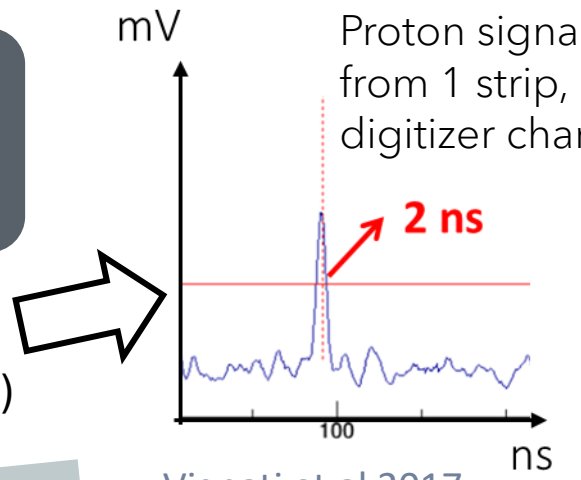
MIRO Minibeam Radiotherapy

MERLINO

RAPTOR

NOVEL BEAM MONITORS

- **PROTONS (60-230 MeV):**
  - Low Gain Avalanche Detectors (LGAD) segmented in strips
  - Thickness → 50 μm
  - Internal gain → 10
- **CARBON IONS (115-400 MeV/u)**
  - Strip segmented n-on-p diode sensors
  - Thickness → 60 μm

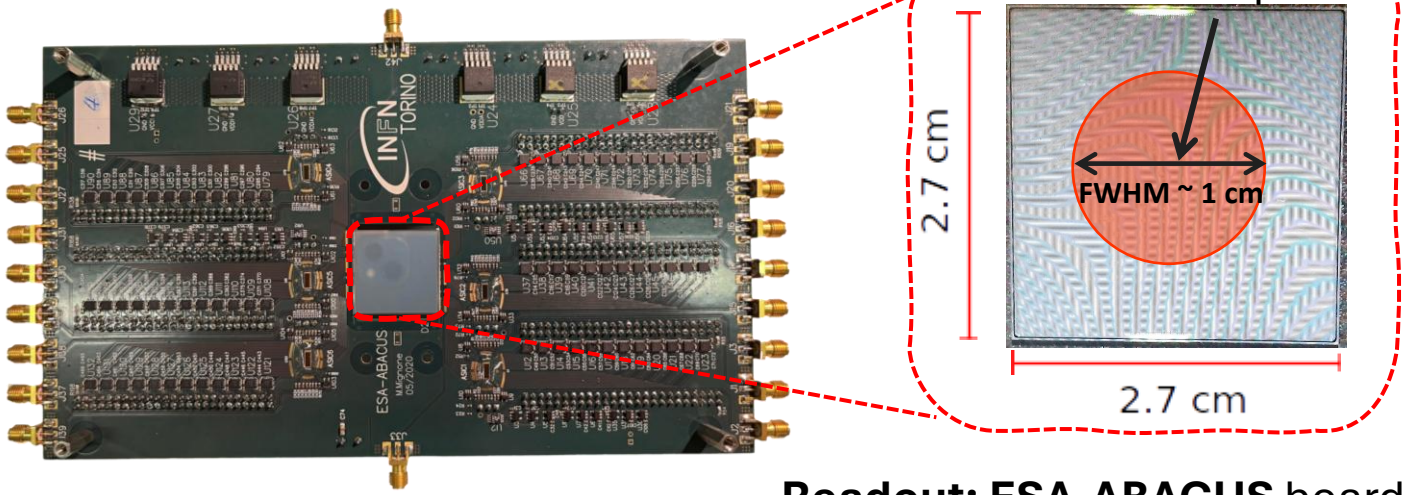


Vignati et al 2017 JINST 12 C12056

Tests @CNAO

Sensitivity → single particle
Collection times → ~1 ns
Time resolution → 30 ps

- **Single particle discrimination**
- **Different beam fluence rates:**
  - **Protons (10^9 protons/s)**
  - **Carbon ions ($5x10^7$ ions/s)**

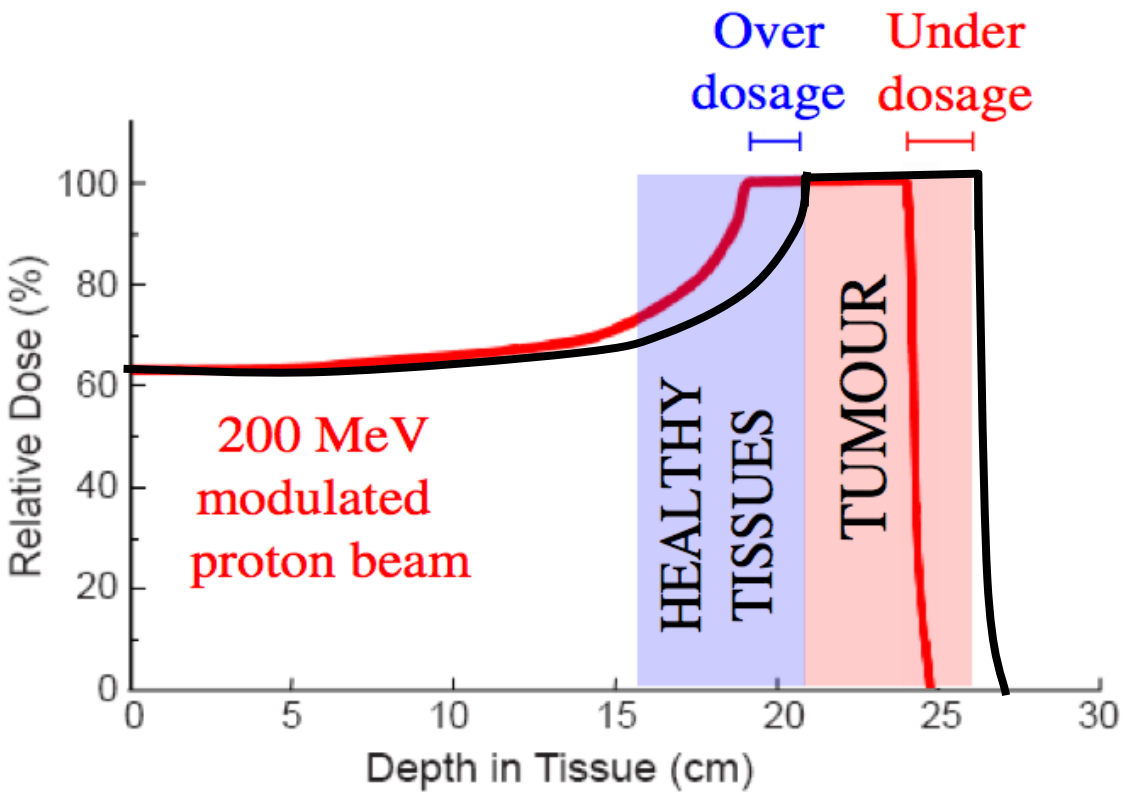


Readout: ESA-ABACUS board (110 nm CMOS technology)

MAIN CHALLENGES:

- **Signal pile-up**
  - fast sensors & segmentation
  - fast readout electronics
- **Readout complexity**
  - number of channels
  - dead time
  - data throughput
- **Limited size**

TREATMENT VERIFICATION SYSTEMS



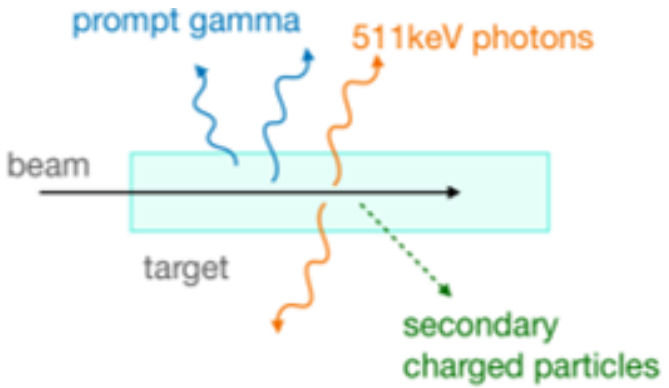
Zhu X, Fakhri GE. *Theranostics. 2013;3(10):731-740.*

Charge particle therapy → very sensitive to any source of deviation with respect to the treatment planning

- patient mispositioning
- organ motion
- anatomic changes
- tumor shrinking
- weight loss
- cavity filling

Range uncertainty estimation for **robust treatment plans 2.5-3% + 1-3 mm**

Treatment verification systems → towards adaptive treatment planning



TREATMENT VERIFICATION SYSTEMS

Secondary particle detection LaBr3(Ce) + PMT/SiPM

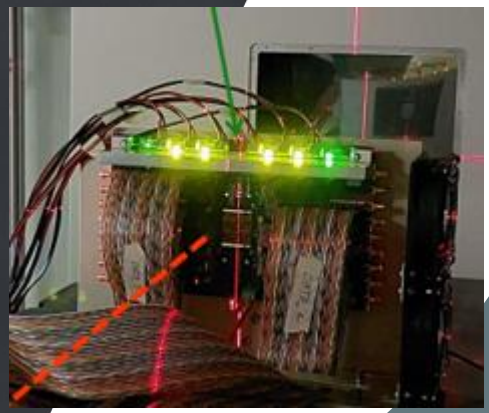
Primary particle detection ESA-ABACUS

t_0

$t\gamma_2$

$t\gamma_1$

$t\gamma_n$



$$TOF_n = t\gamma_n - t_0$$

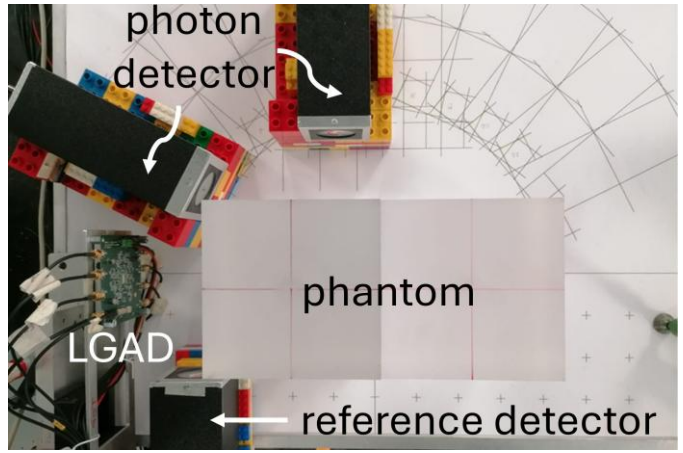
DAQ: digitizer
→ PicoTDC

TREATMENT VERIFICATION SYSTEMS

PGT measurement to:

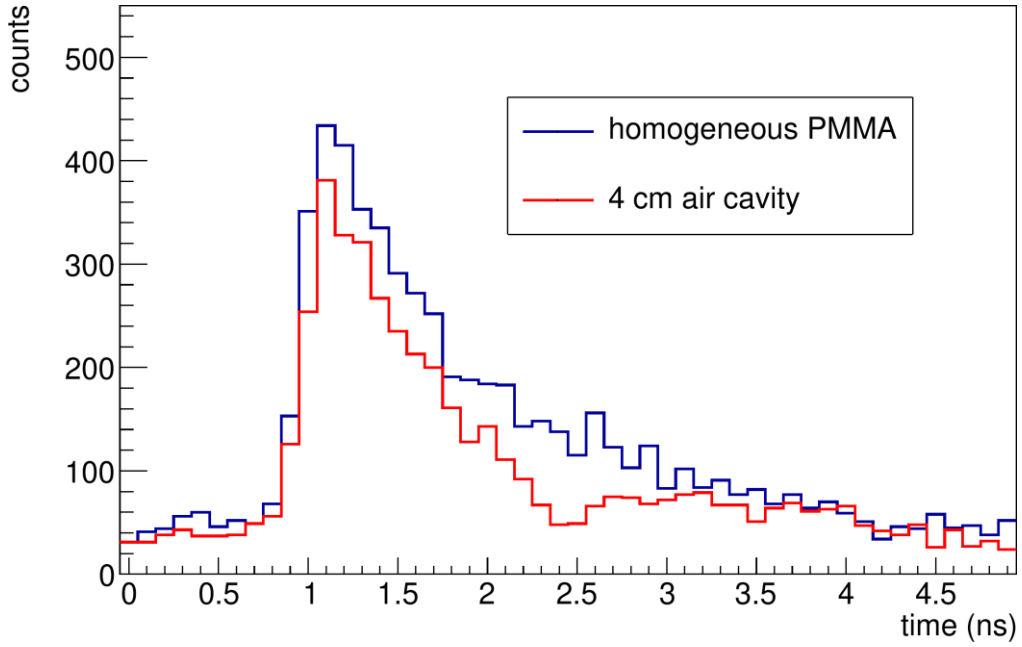
- **Assess the range (p and ^{12}C)**

Measurements at CNAO Centro Nazionale di Adroterapia Oncologica

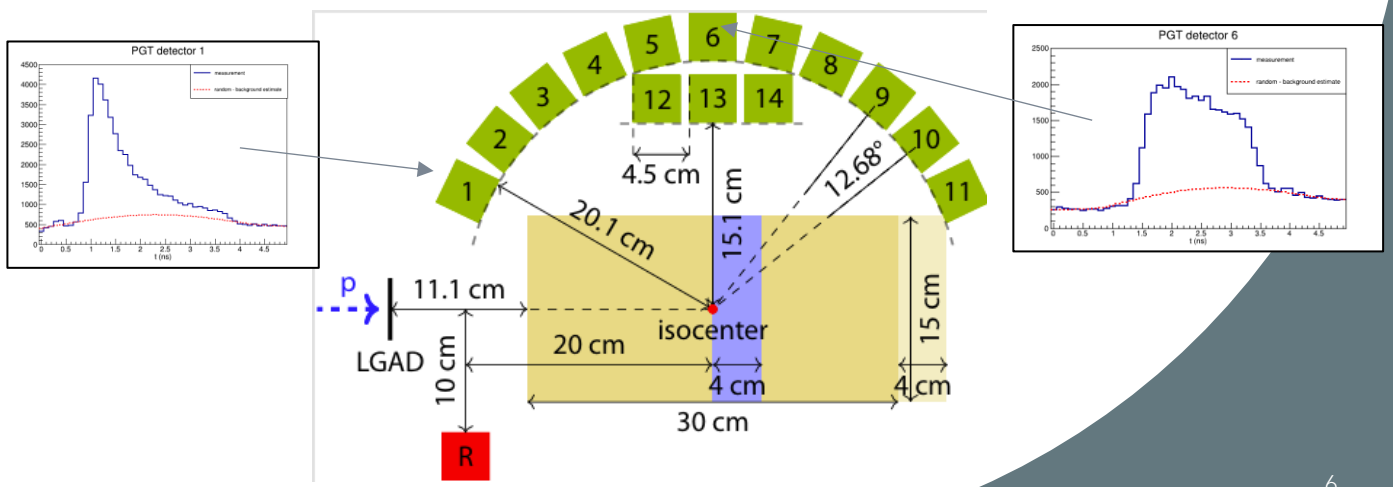


LaBr3:Ce + PMT
DAQ: digitizer

Protons, 227 MeV, $4 \cdot 10^7$ pps avg rate on homogeneous PMMA and on a 4-cm airgap PMMA



Measurements at different detector positions



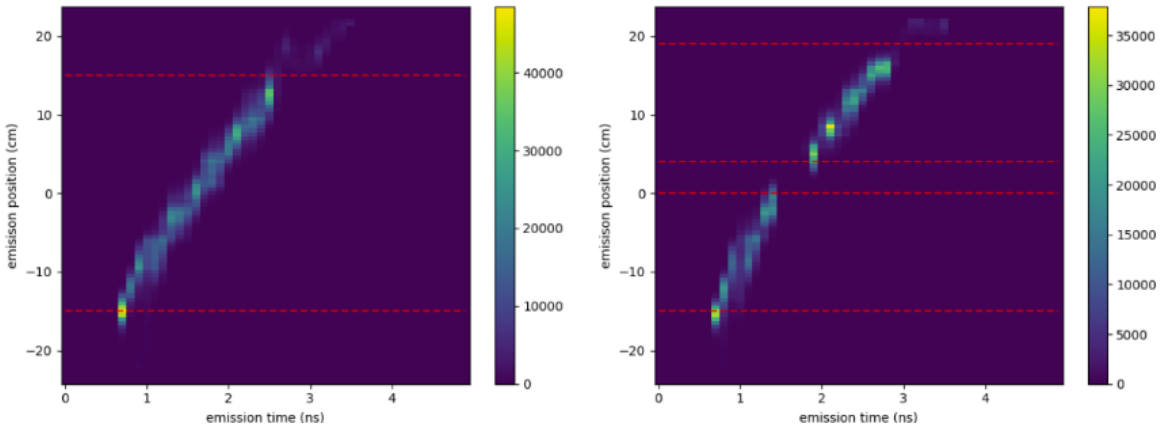
TREATMENT VERIFICATION SYSTEMS

PGT measurement to:

- **Assess the range (p and ^{12}C)**
- **Evaluate the stopping power (p)**

Measurements at CNAO
Centro Nazionale di Adroterapia Oncologica

227 MeV protons, $4 \cdot 10^7$ pps avg rate, on homogeneous PMMA (left) and on a 4-cm airgap PMMA (right)



Can we use it to measure different target's SP (metrological measure)?

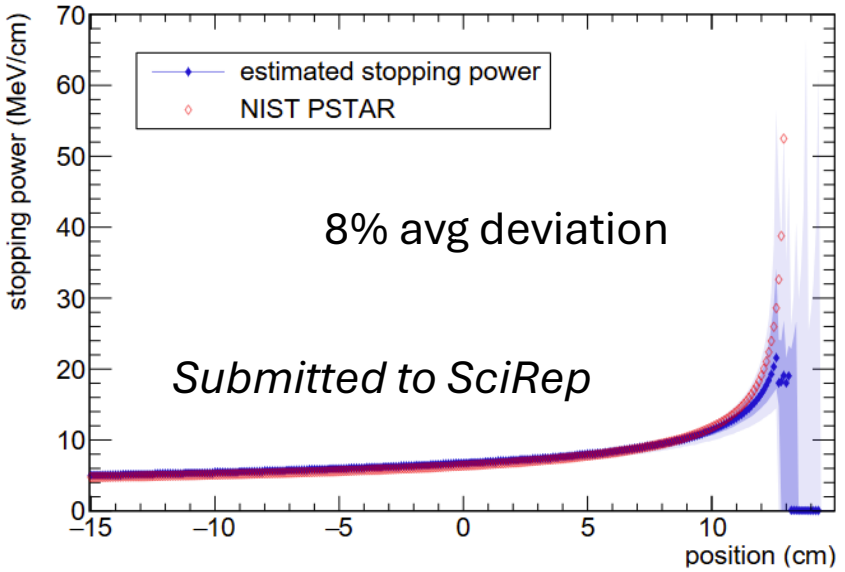
data

$$m_{jp}^{k+1} = \frac{m_{jp}^{k}}{S_{jp}} \sum_i \sum_d \frac{n*_{id}}{\sum_l \sum_t f_{idlt} m_{lt}^{k}} f_{idjp}$$

prompt photon
sensitivity
p: time bin (emission)
j: space bin (emission)
i: time bin (detection)
d: detector
SM

Spatiotemporal Emission Reconstruction (SER-PGT): an MLEM-based solution to reconstruct the particle range (Pennazio et al. PMB 2022)

Space and time: we have the particle motion!
(Ferrero et al. Front in Phys 2022)



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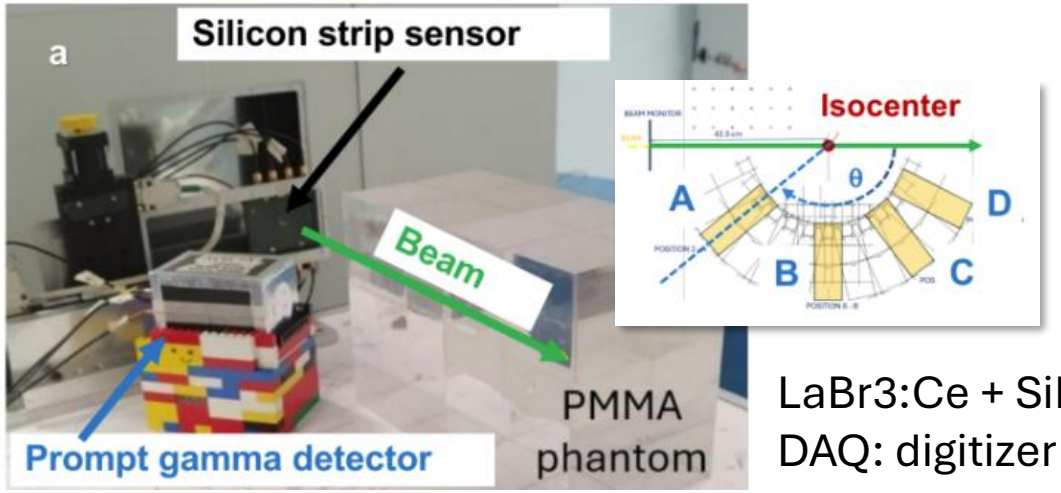
Work with M. Rafecas, Luebeck (Germany)

TREATMENT VERIFICATION SYSTEMS

PGT measurement to:

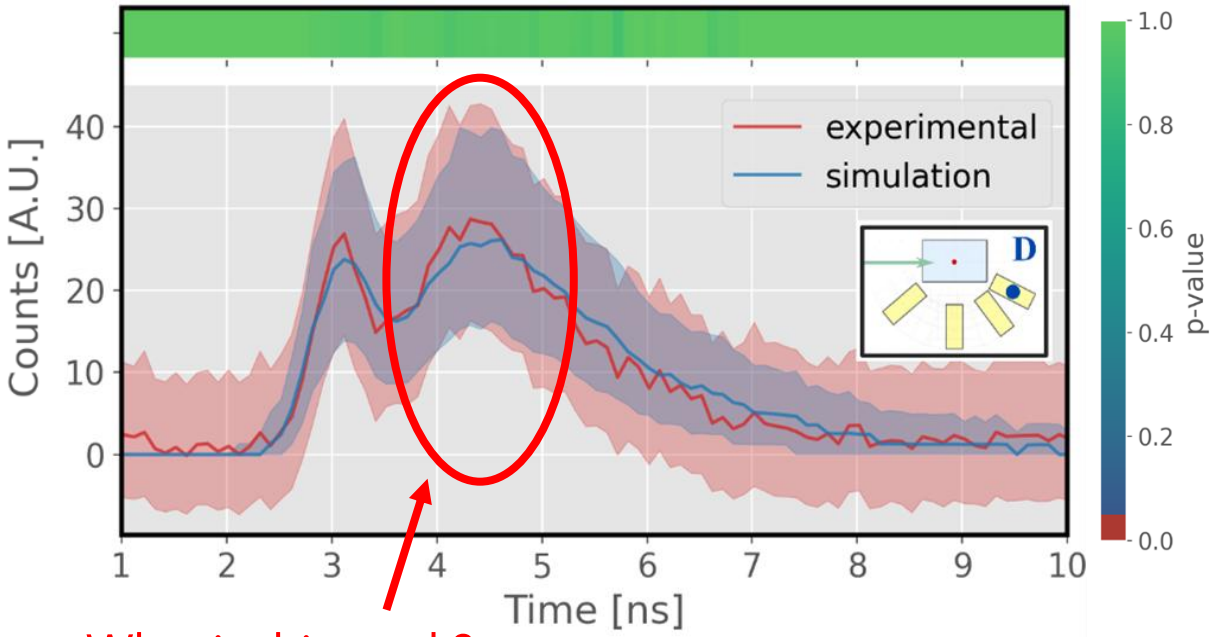
- **Assess the range (p and ^{12}C)**

Measurements at CNAO
Centro Nazionale di Adroterapia Oncologica



LaBr3:Ce + SiPM
DAQ: digitizer

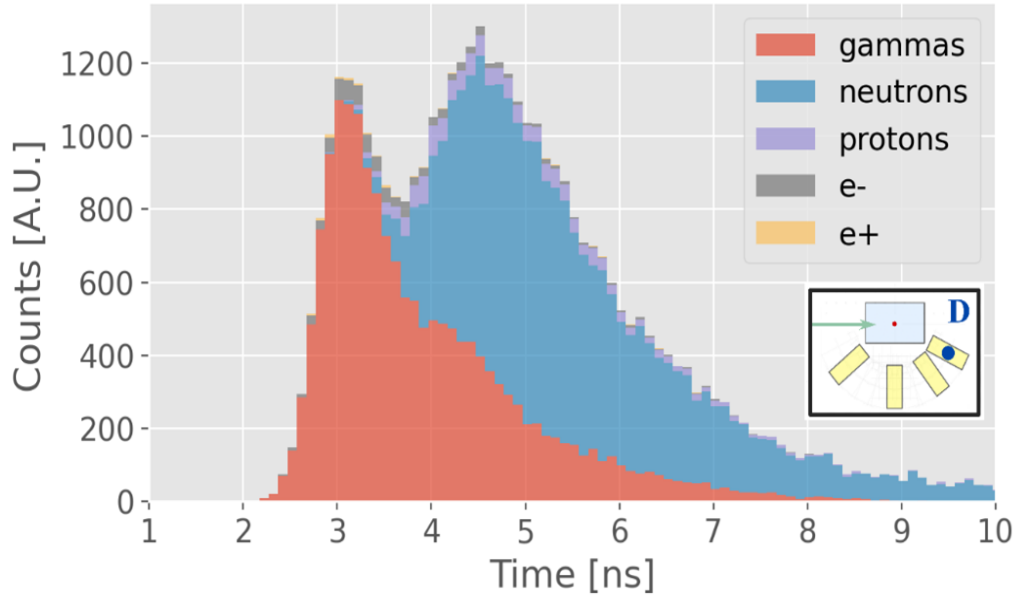
Carbon ions, 166 MeV/u, $5 \cdot 10^6$ pps avg rate on PMMA



What is this peak?

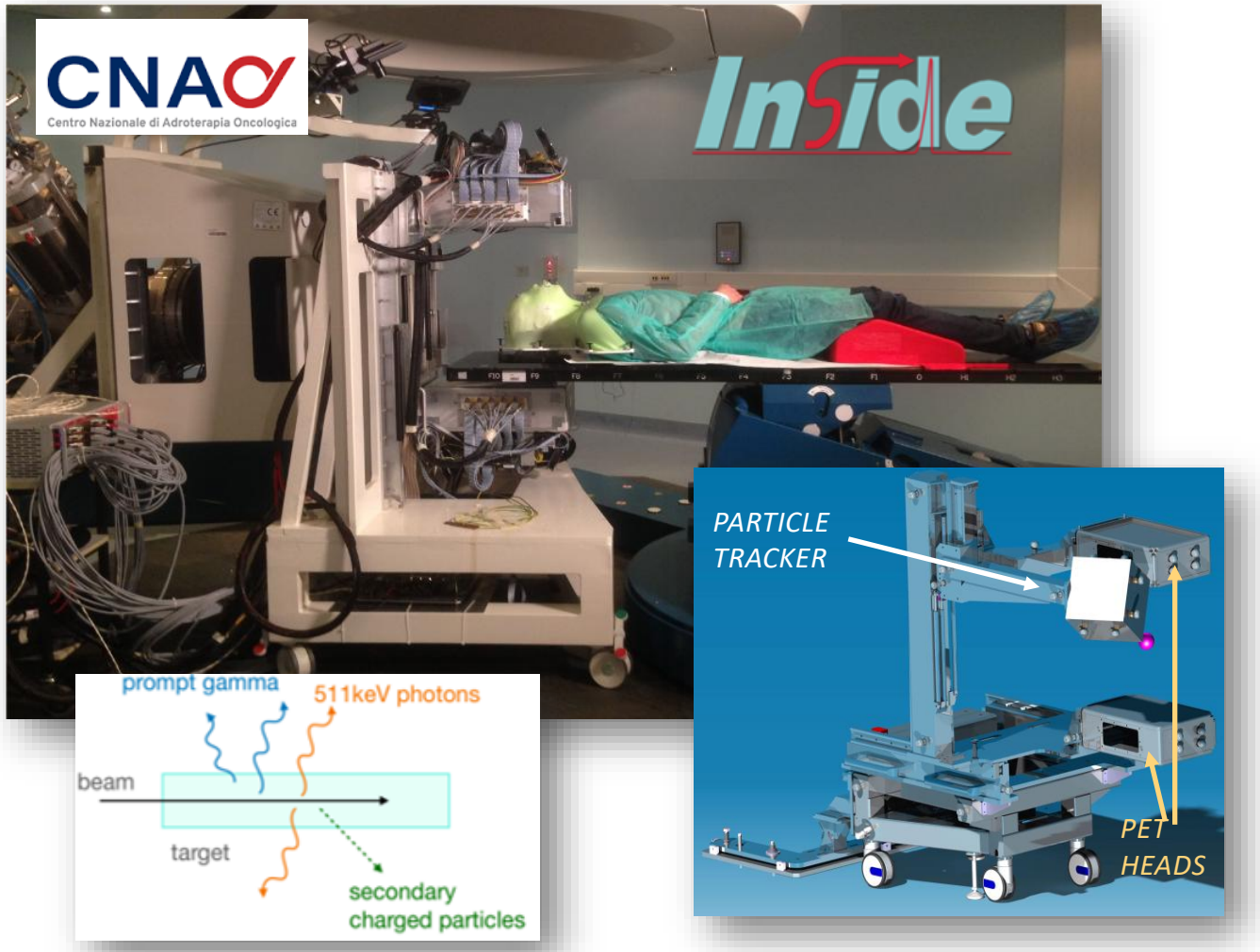
Bootstrapping of exp data (2000 datasets)
Shaded region: 95% confidence intervals

Geant4 simulation of particle contribution



Work by Iram B., submitted to PMB

TREATMENT VERIFICATION SYSTEMS



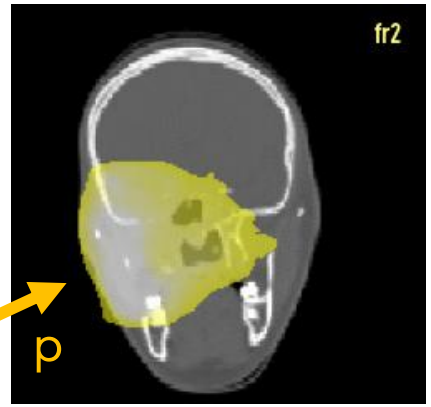
INSIDE - *INnovative Solutions for In-beam DosimEtry in hadrontherapy*

- **Bimodal system** (PET detector + particle tracker)
- **Integrated** in the treatment room

Observational **clinical trial**

40 patients:

- **Phase I**: 20 patients (10 p + 10 ^{12}C) enrolled between 2019 July and 2020 February
- **Phase II**: 20 patients (4 p + 3 ^{12}C), *ongoing*



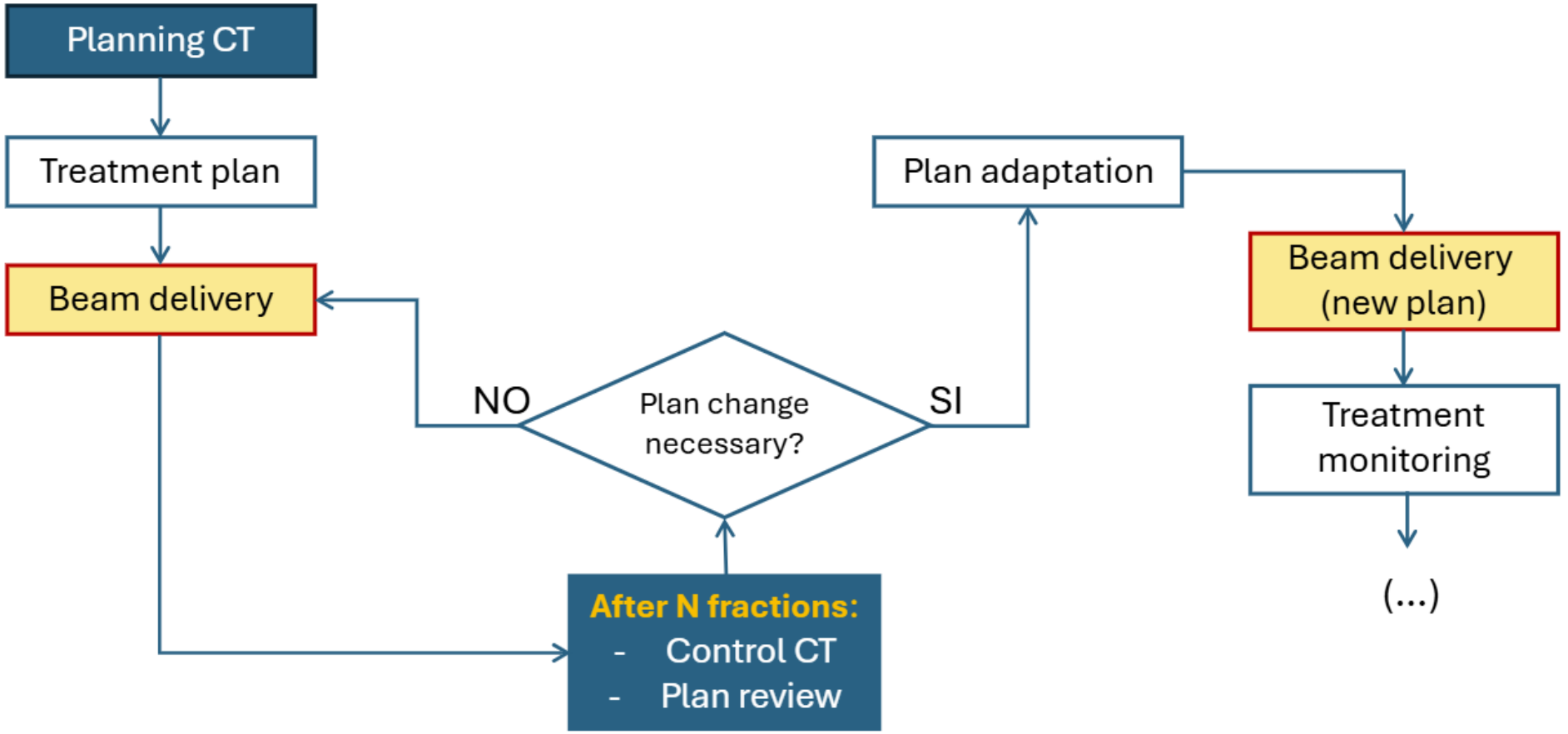
Adenoid cystic carcinoma, protons (35 fractions)

TREATMENT VERIFICATION SYSTEMS

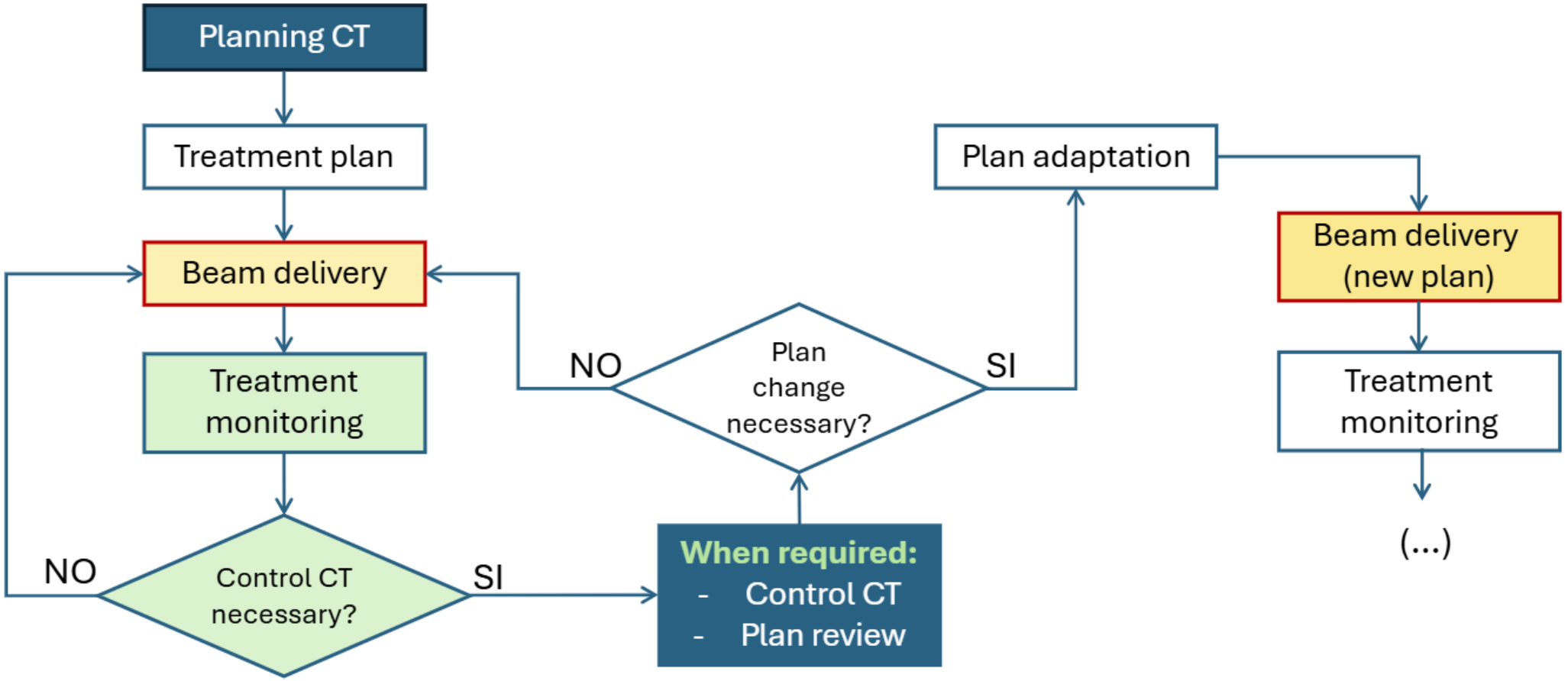
Pathology:

- ACC: adenoid cystic carcinoma (p or C)
- Adenocarcinoma (p or C)
- Bone sarcoma (p or C)
- Clivus chondrosarcoma (p or C)
- Clivus chordoma (p or C)
- ITAC: intestinal type adenocarcinoma (p or C)
- Meningioma (p)
- MMM: malignant mucosal melanoma (p or C)
- Mucoepidermoid carcinoma (p or C)
- Nasopharyngeal carcinoma (p)
- SCC: squamous cell carcinoma (p or C)
- SNEC: sinonasal neuroendocrine carcinoma (p or C)
- SNUC: sinonasal undifferentiated carcinoma (p or C)
- Soft tissue sarcoma (p or C)
- estensioneuroblastoma

TREATMENT VERIFICATION SYSTEMS



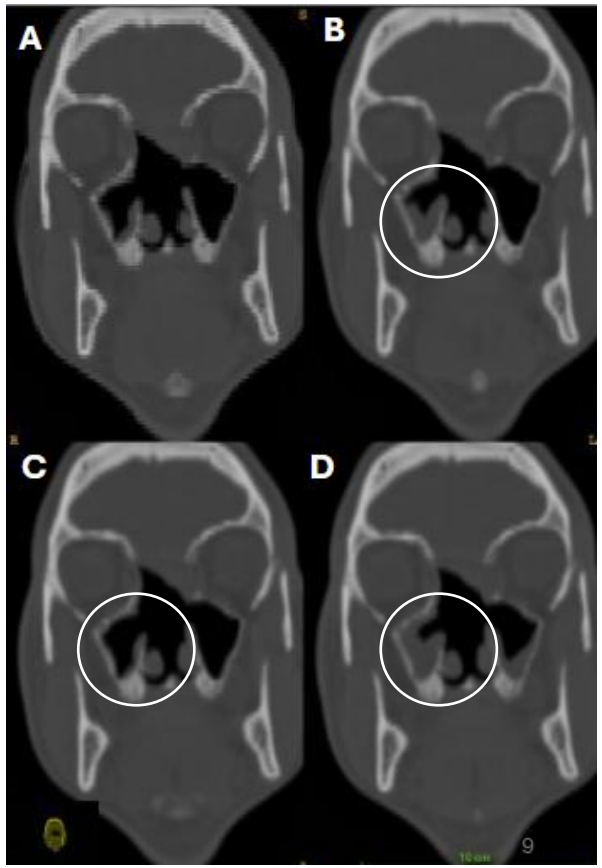
TREATMENT VERIFICATION SYSTEMS



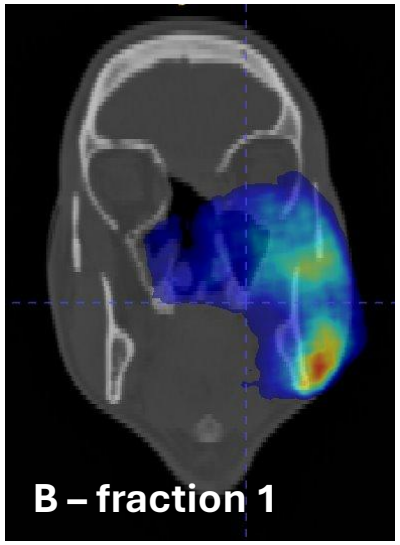
TREATMENT VERIFICATION SYSTEMS

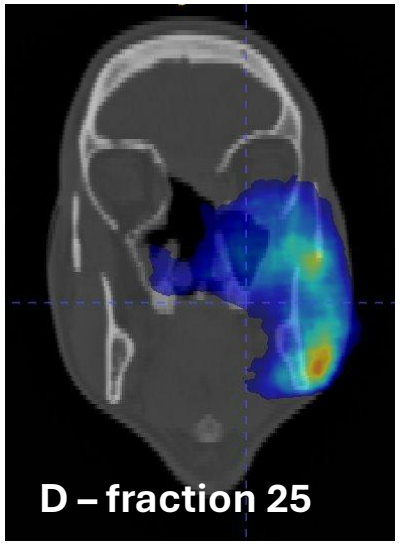
011P - estensionuroblastoma

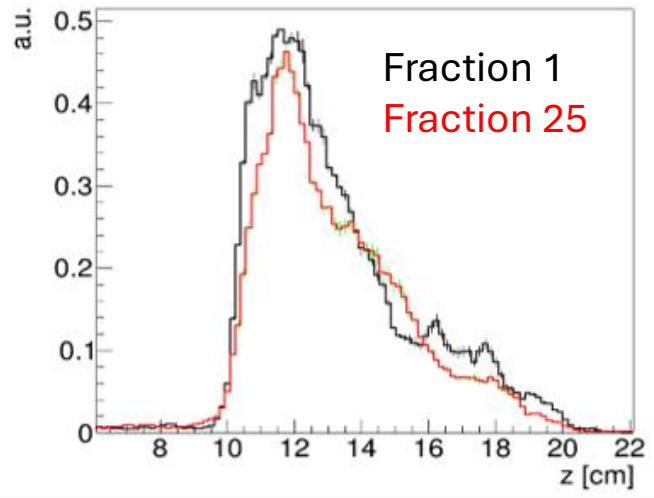
35 fractions – 5 days/week - prescribed dose = 70 GyE



A. PLANNING CT, 12/11/2025. Right cavity slightly filled, left cavity empty.
B. TREATMENT START: CONTROL CT, 26/11/2025. Moderate filling of right cavity.
C. Fraction 15: CONTROL CT, 18/12/2024. Emptying of right cavity (similar to planning CT).
D. Fraction 25: CONTROL CT, 03/01/2025. Severe filling of left and right cavities.







Outline

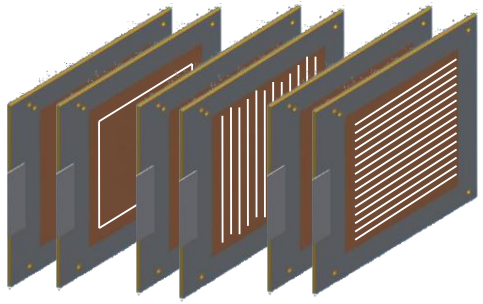
Short-term perspectives for beam monitors and range verification systems:

- Up to 6x6 cm^2 Si-based beam monitors with single particle sensitivity for commissioning of fixed beams and research setups
- Optimization of highly performing DAQ interfaced with both systems
- Investigation of innovative algorithms for image reconstruction

Long-term perspectives for beam monitors and range verification systems:

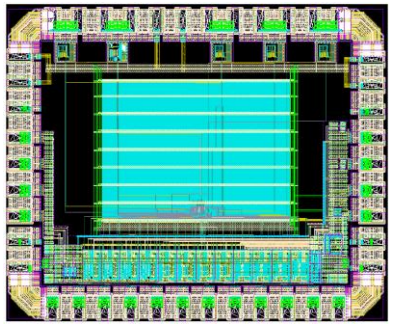
- Larger Si-based beam monitors
- Clinical use of range verification systems

In the meantime… *new front-end readout to boost performances of existing ionization chambers*



Gas-based detector (ionization chambers, MWPC, …)

NEW TERA ASIC CMOS 65 nm



Technology	CMOS **65 nm**
N. of channels	64
F_{MAX} Curr-To-Freq conv	**> 160 MHz**
Minimum Q_C	**~ 10 fC (1 count)**
Interface	SLVS
Transmission protocol	**Serial**
System clock	200 MHz
Clock I→f internal	Yes

First TERA in 65 nm expected at the end of 2026

Gruppo di Fisica Medica
UNITO e INFN TO