Plastic-scintillator based proton radiograhpy relying on time of flight measurement: the tofprad project

Yunsheng Dong, Rebecca Anzalone, Giuseppe Battistoni, Esther Ciarrocchi, Marco Francesconi, Luca Galli, Ana Maria Goanta, Nils Krah, Alessio Mereghetti, Silvia Muraro, Marco Pullia, Giacomo Traini, Matteo Morrocchi

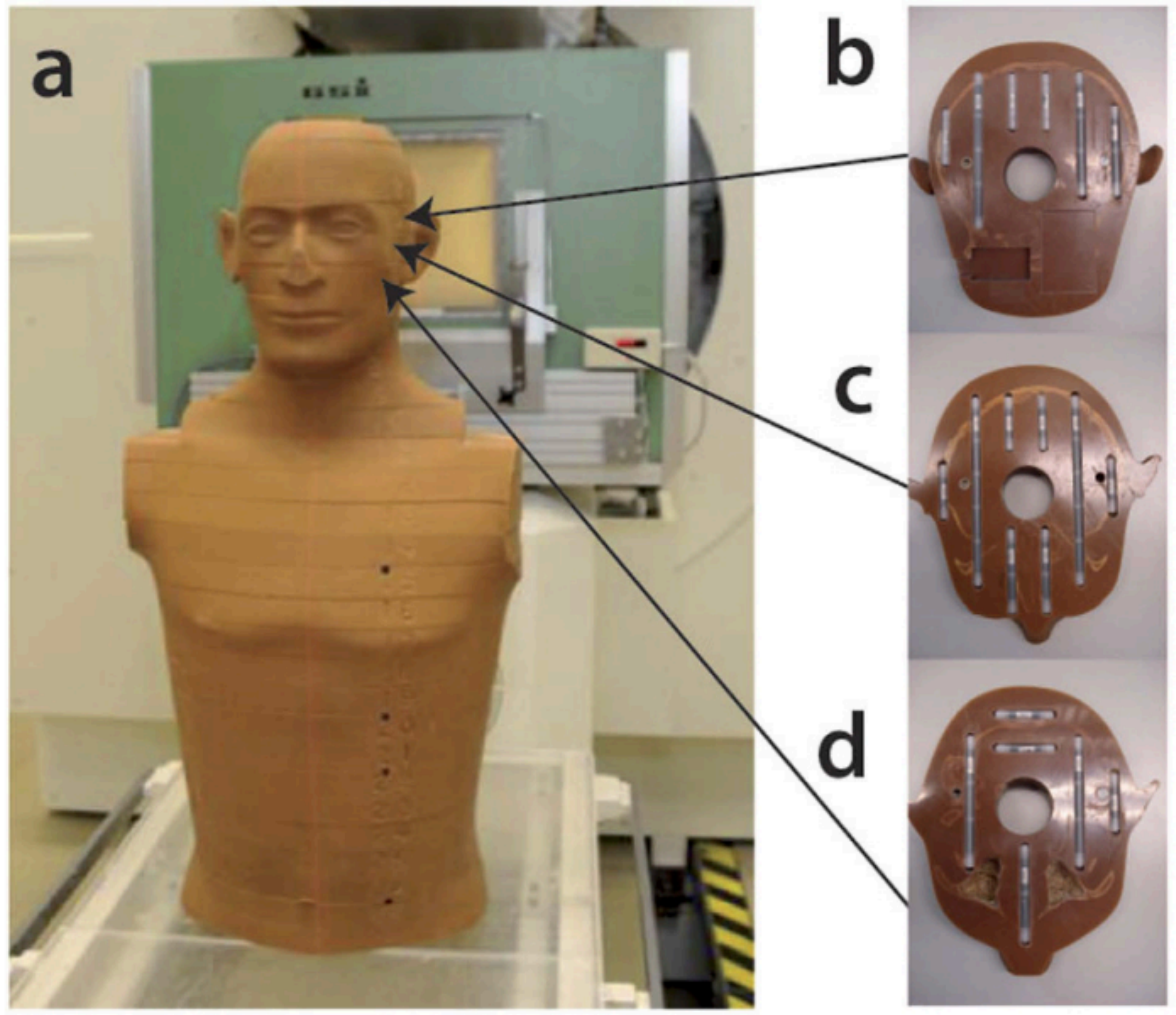
5th ion imaging workshop 2024

Outline

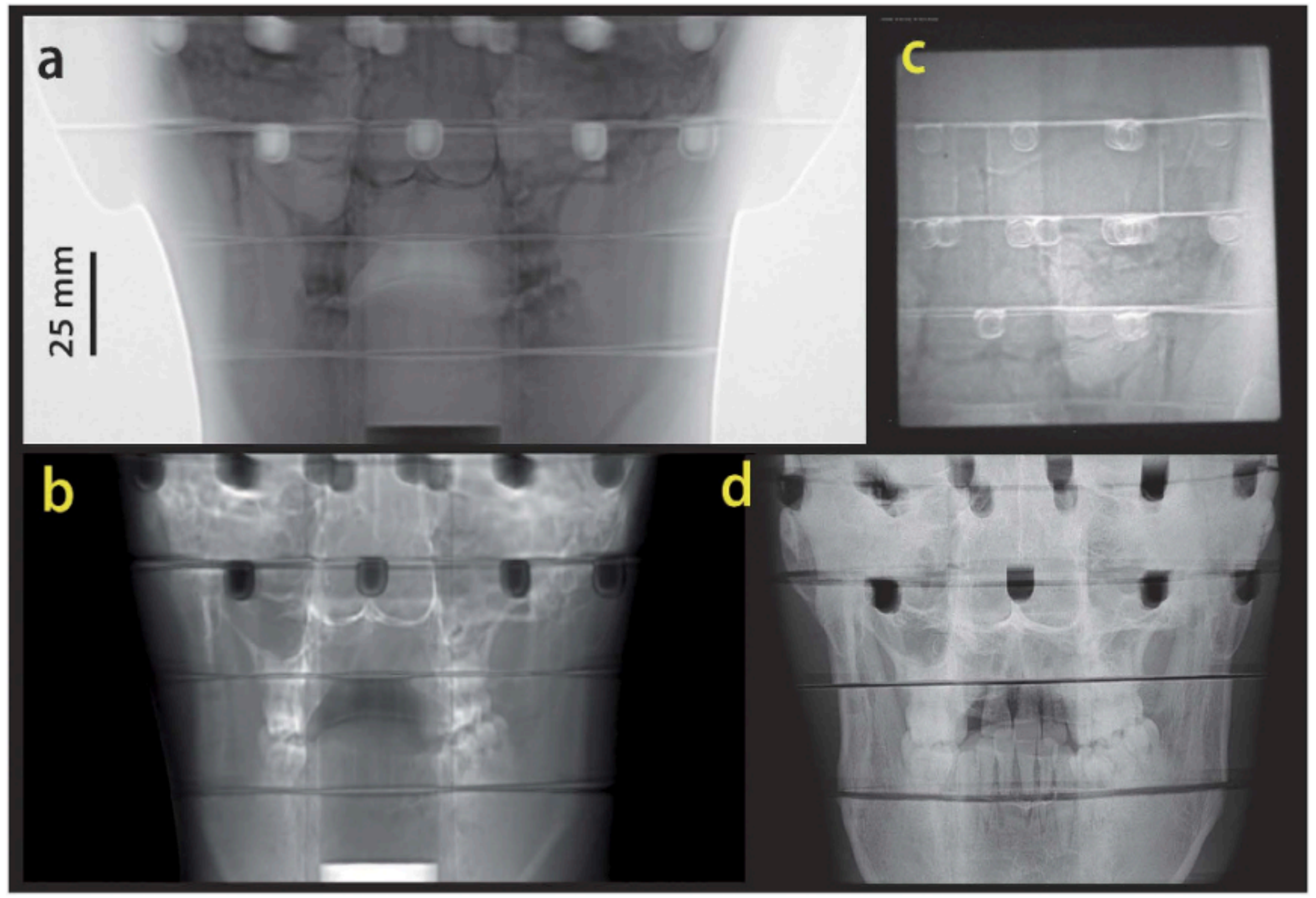
- Proton radiography
- TOFpRad project
- First data taking setup
- Preliminary results
- Conclusion and future perspectives

Proton radiography

Proton radiography: imaging technique based on the measurement of the energy loss



The Matroshka phantom (a) was used to simulate radiography. The phantom is divided into 25 mm thick slices. Three of them (b,c) contain cavities which were filled with thermoluminescent detectors for dose measurements.



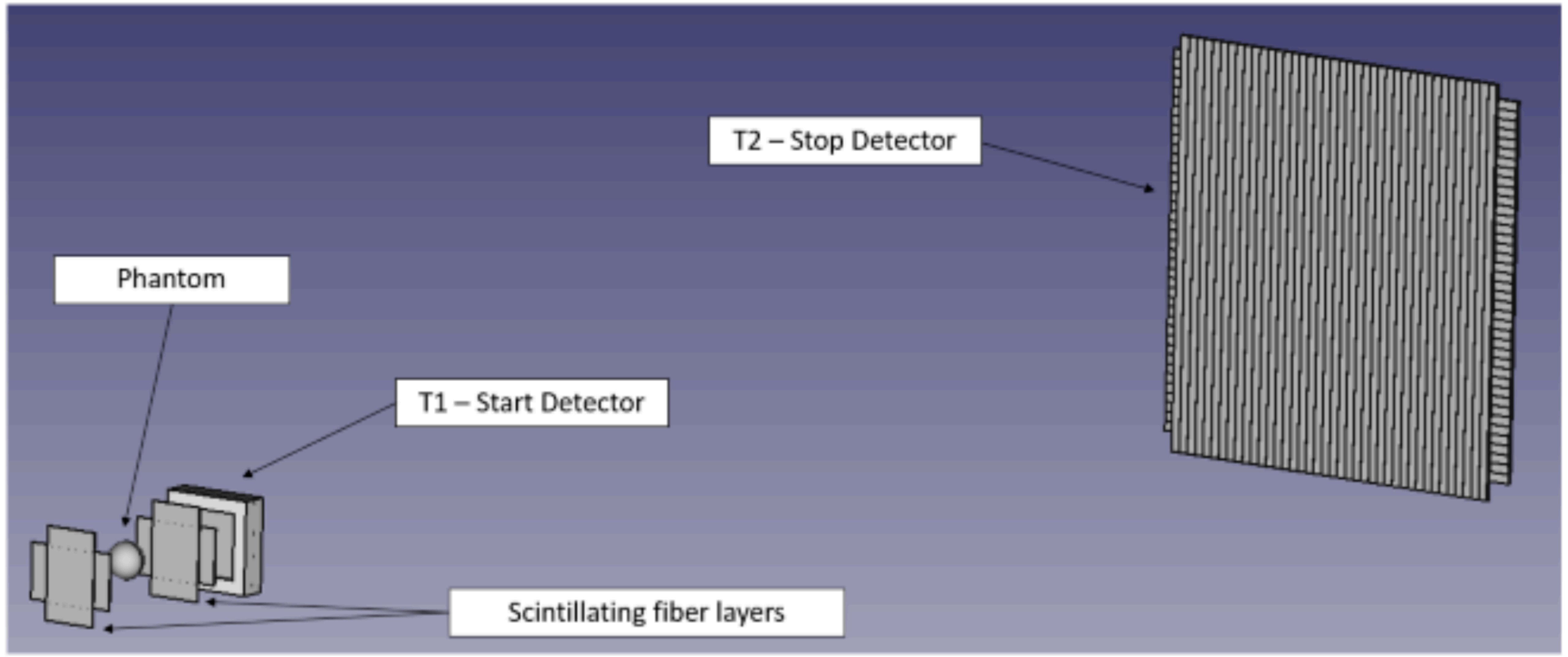
Images acquired from the radiography of the anthropomorphic phantom (Matroshka) head. (a) A merged radiograph. (b). Images converted to areal density (c). Unprocessed radiograph taken with 10mGy imaging dose. (d) X-ray image (70 kV, about 5μGy total dose).

Prall, M., Durante, M., Berger, T. et al. High-energy proton imaging for biomedical applications. Sci Rep 6, 27651 (2016). https://doi.org/10.1038/srep27651

- Direct measurement of proton stopping power, no need of HU conversion
- Typically measuring the particle residual kinetic energy with a calorimeter
- Slow for clinical applications
- Reference: Krah Nils et al. "Relative stopping power precision in Time-Of-Flight proton CT", 2021 Doi: https://doi.org/10.48550/arxiv.2112.11575

TOFpRad project

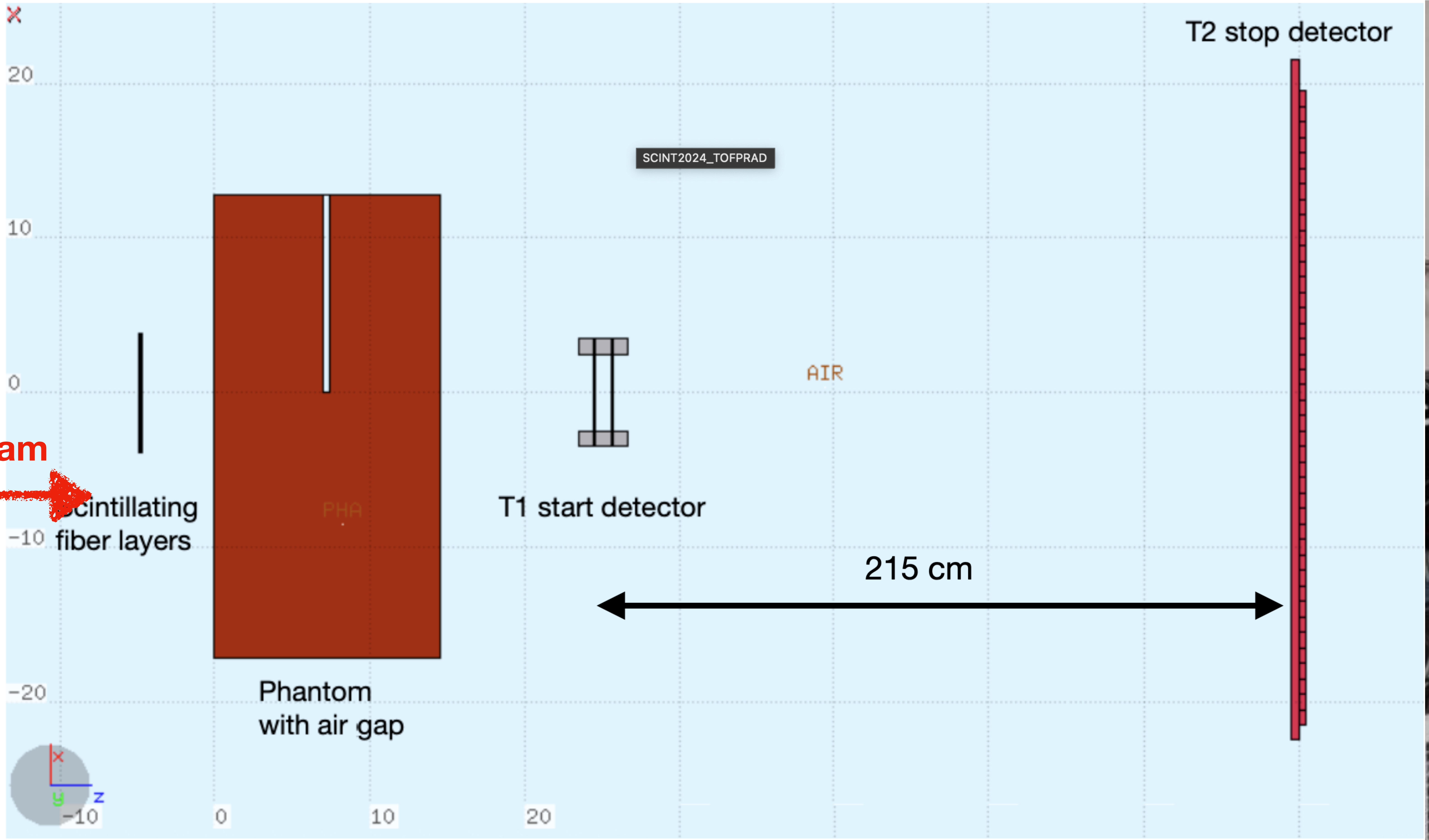
Goal: create Time of Flight (TOF) proton radiography system to support the planning and the verification of charge particle treatments



- Two fast plastic scintillator detectors for the TOF measurement
- a set of layers of plastic scintillator fibres for tracking purposes, both read with SiPMs
- Ekin from TOF (Time reso < 100ps/m)
- Develop a low-cost system, ensuring a larger rate capability (ideally ~1Mhz)

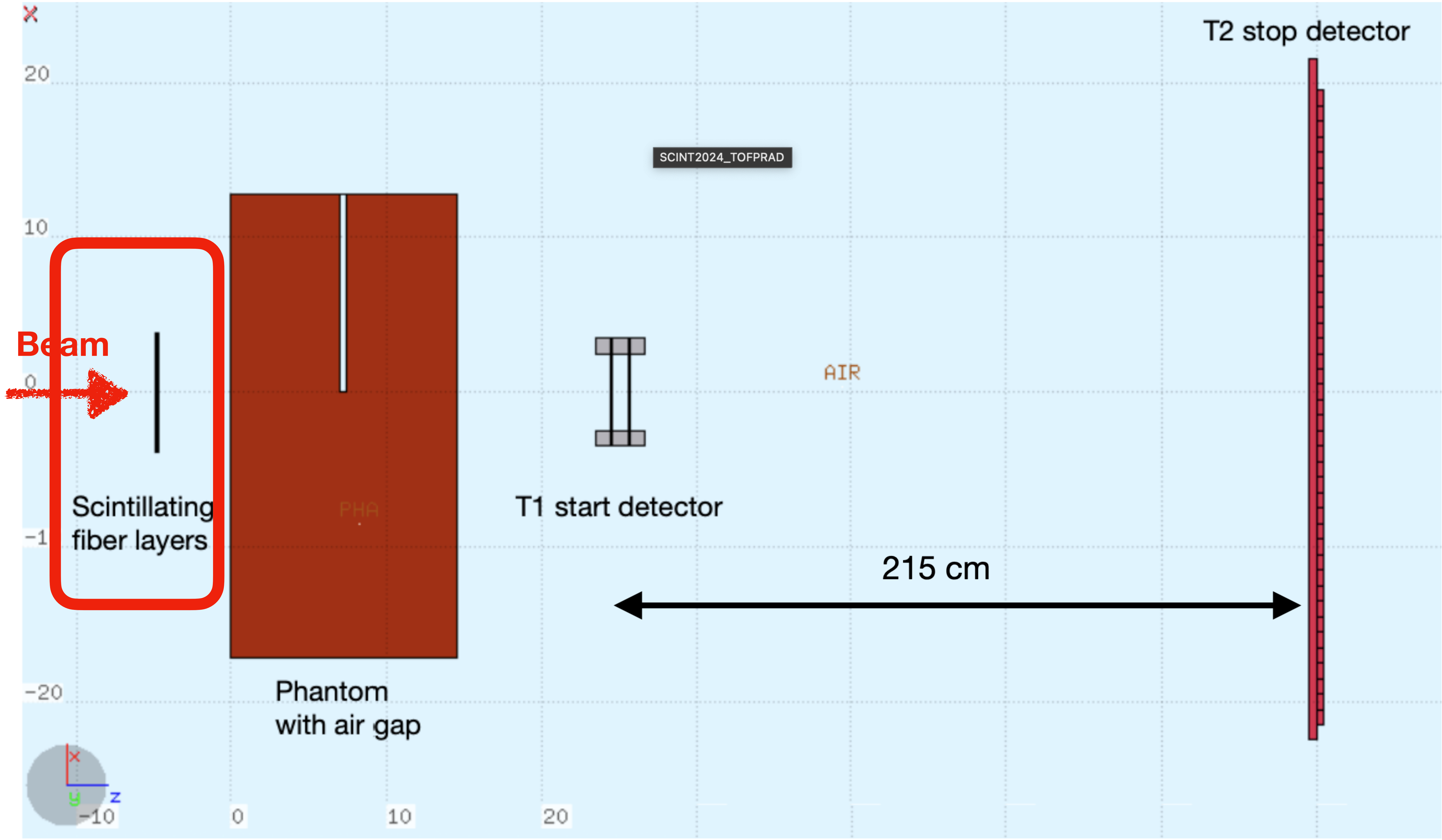
First experimental setup

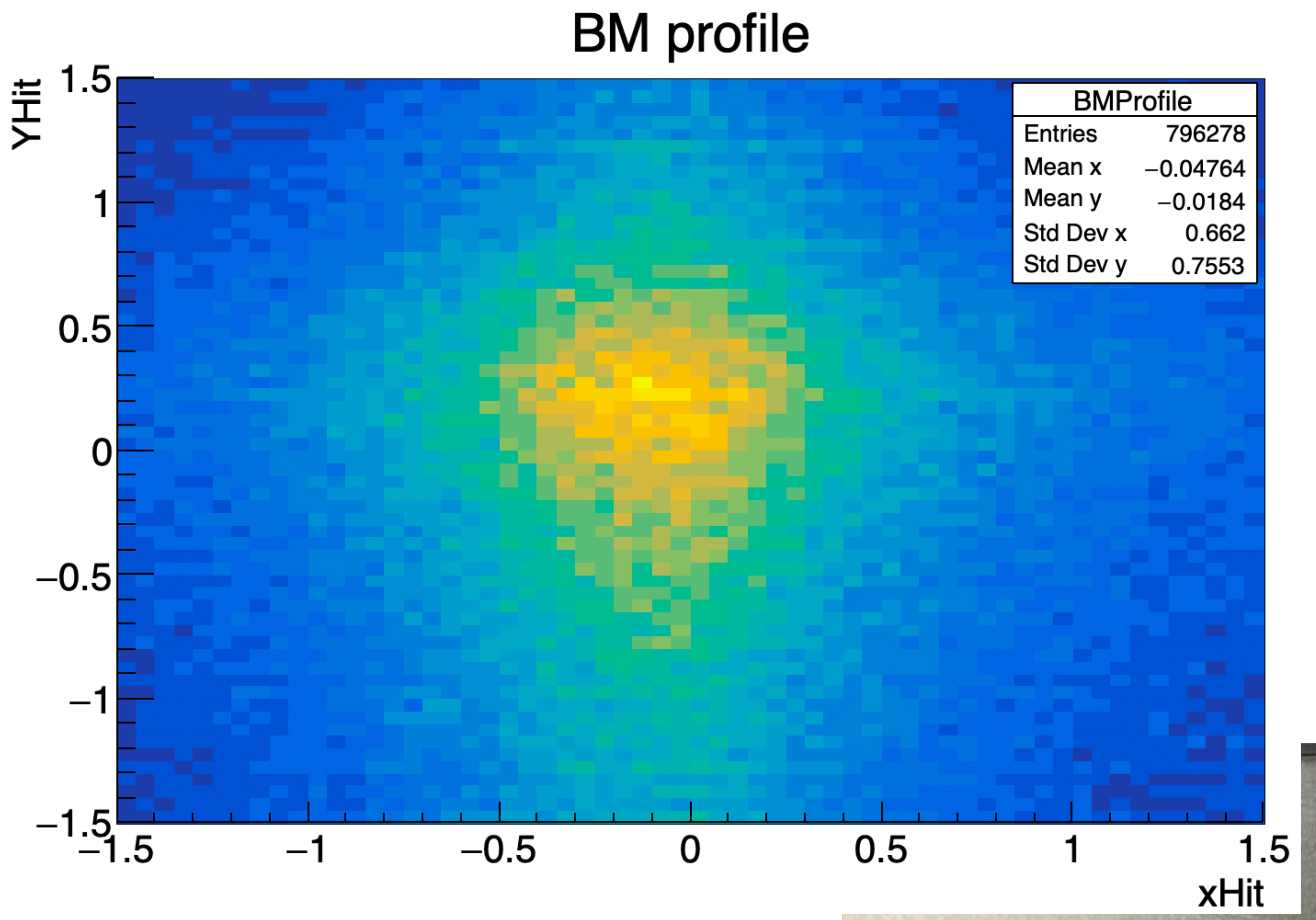
Preliminary TOF system tested at CNAO (Pavia) with P at 226.91 MeV, experimental setup with detectors developed for the FOOT* experiment (optimised for 3≤Z≤8)

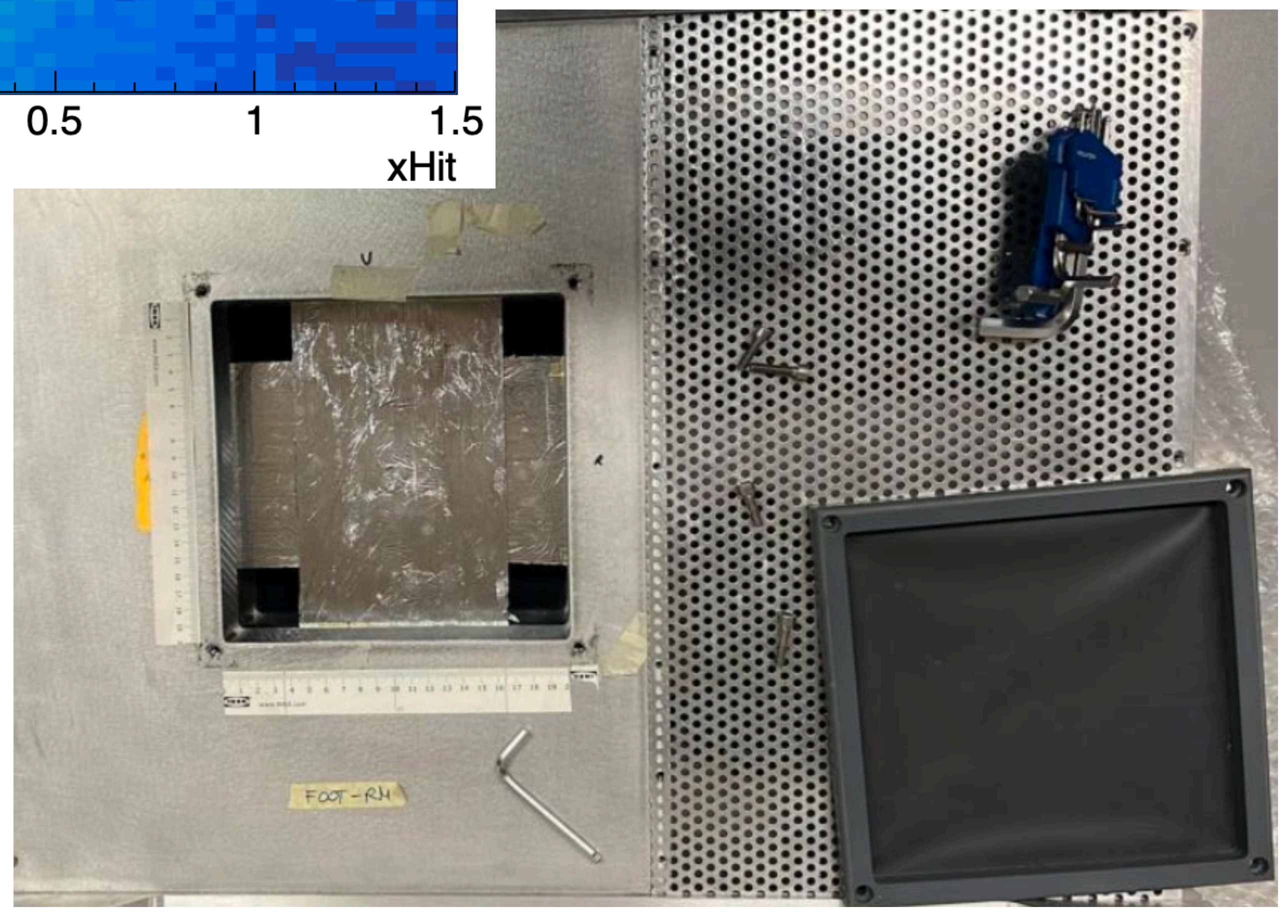


*Battistoni G, Toppi M, Patera V and The FOOT Collaboration (2021) Measuring the Impact of Nuclear Interaction in Particle Therapy and in Radio Protection in Space: the FOOT Experiment. *Front. Phys.* **8**:568242. doi: 10.3389/fphy.2020.568242

First experimental setup



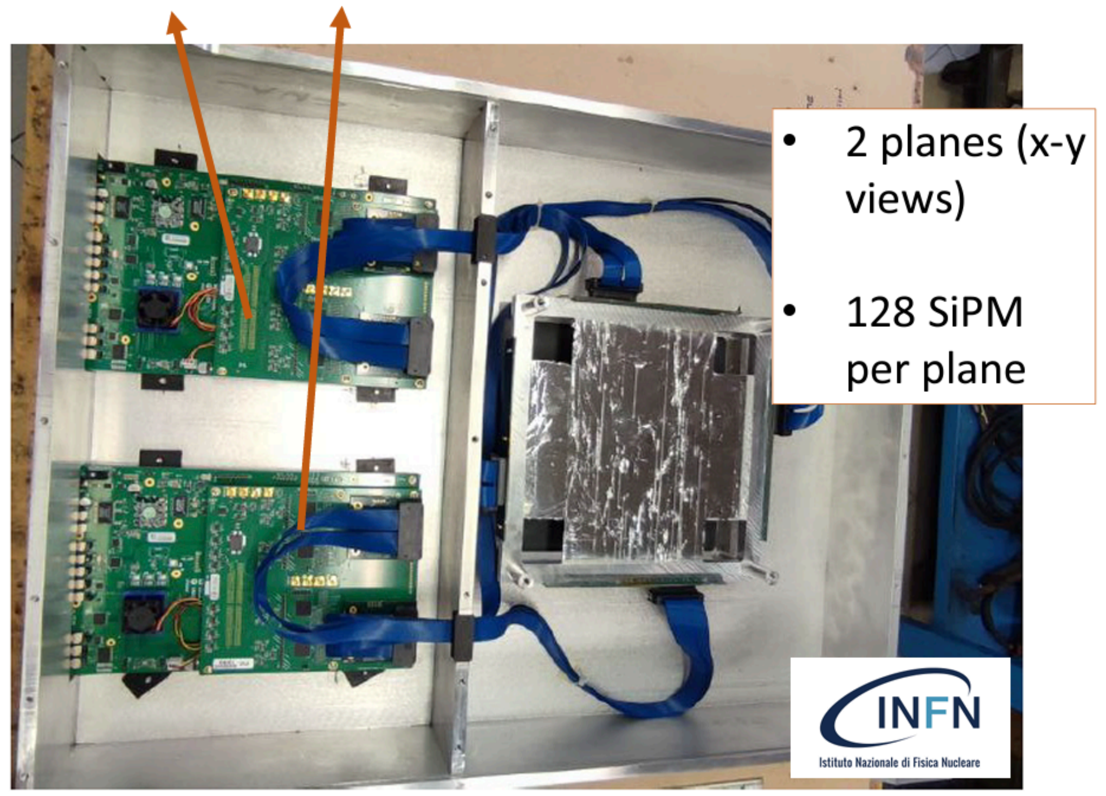


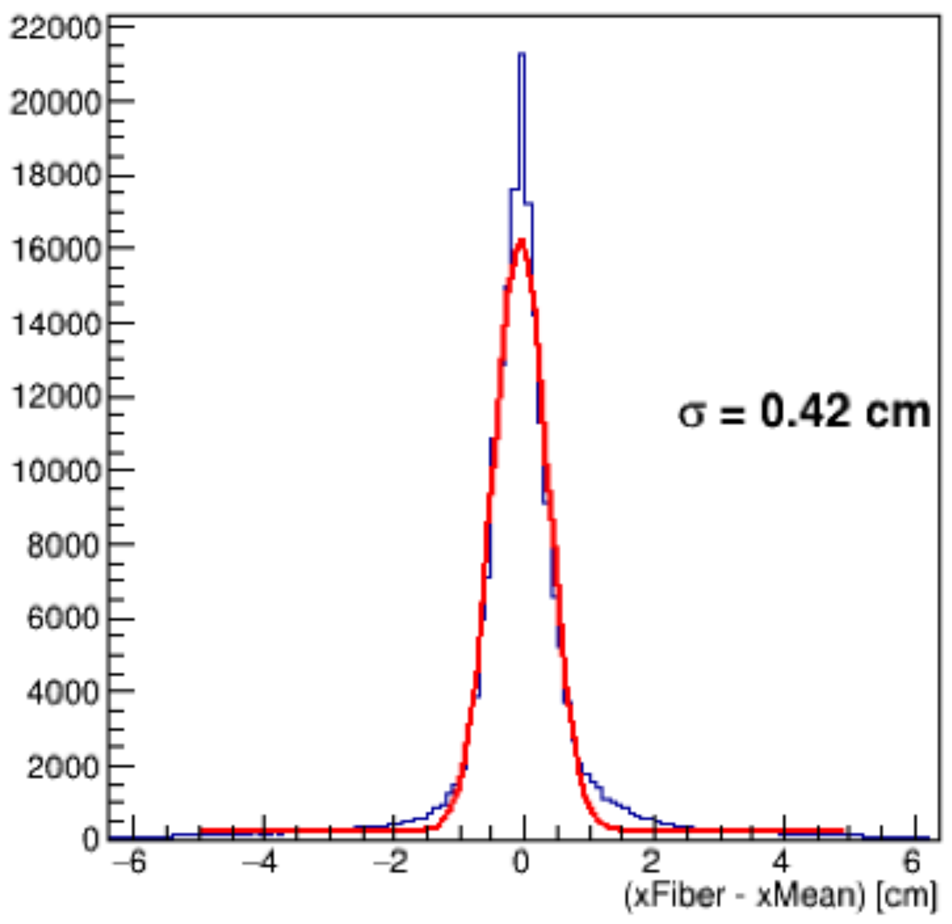


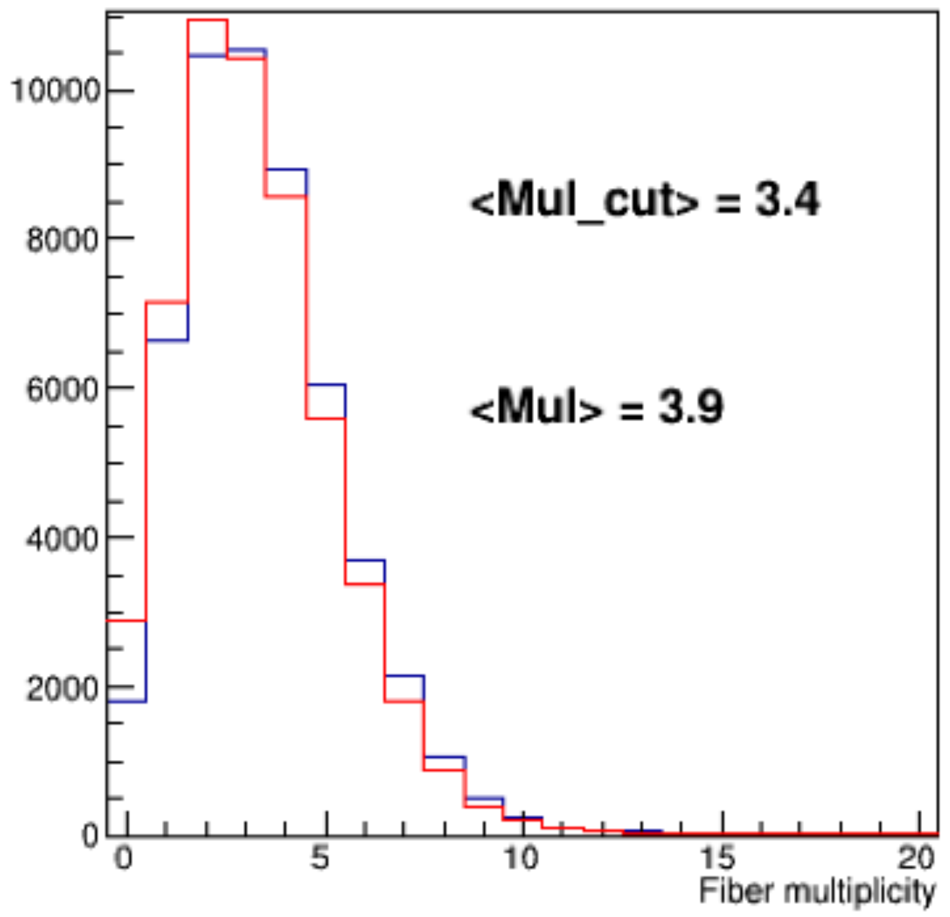
Beam monitor: two orthogonal planes of scintillating fiber layers with a thickness of 1 mm adopted to measure the initial particle position

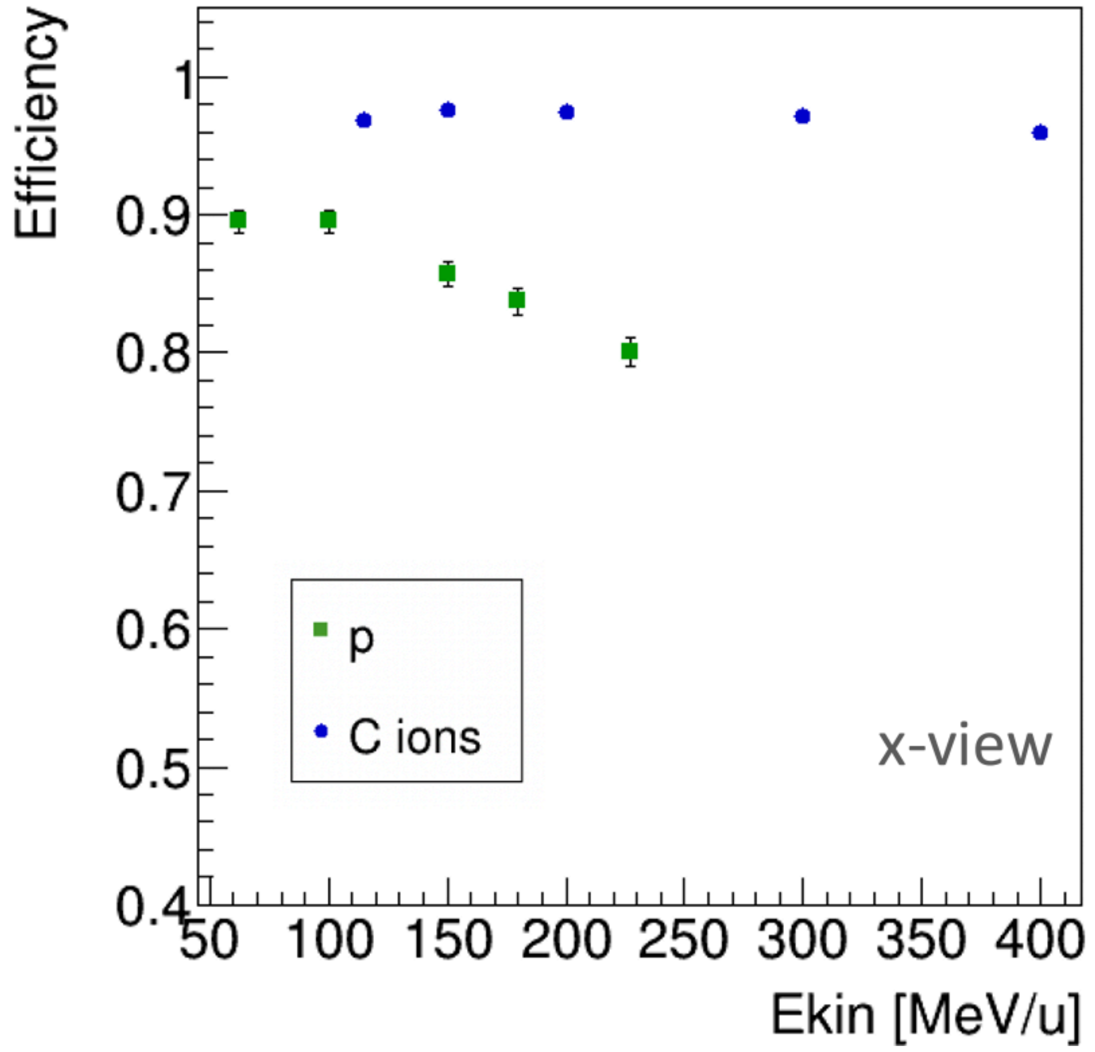
First experimental setup

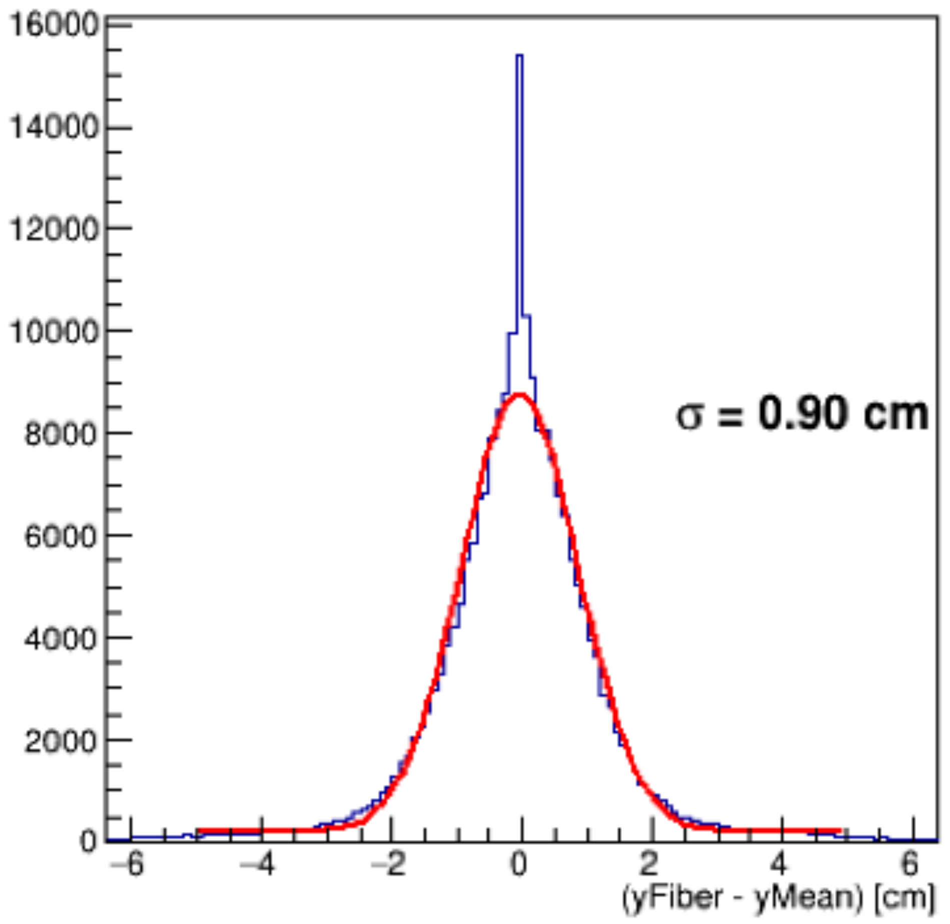
CAEN DT5550W (CITIROC ASICs for SiPM readout + customizable FPGA)

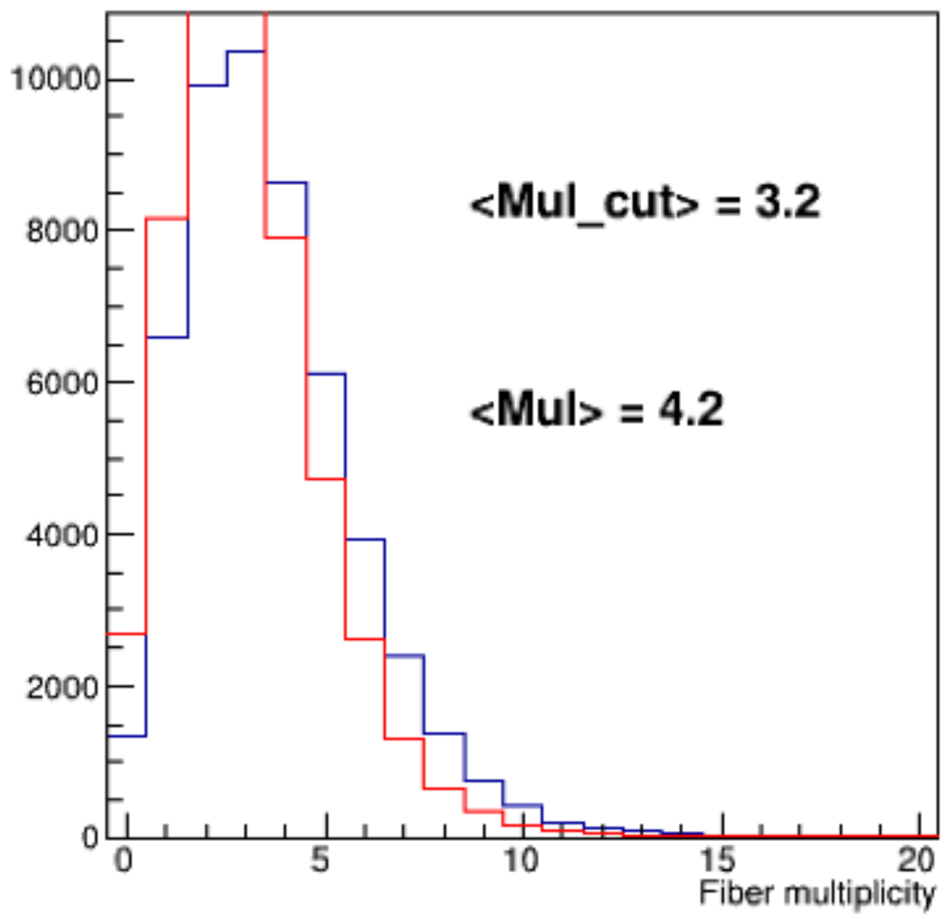






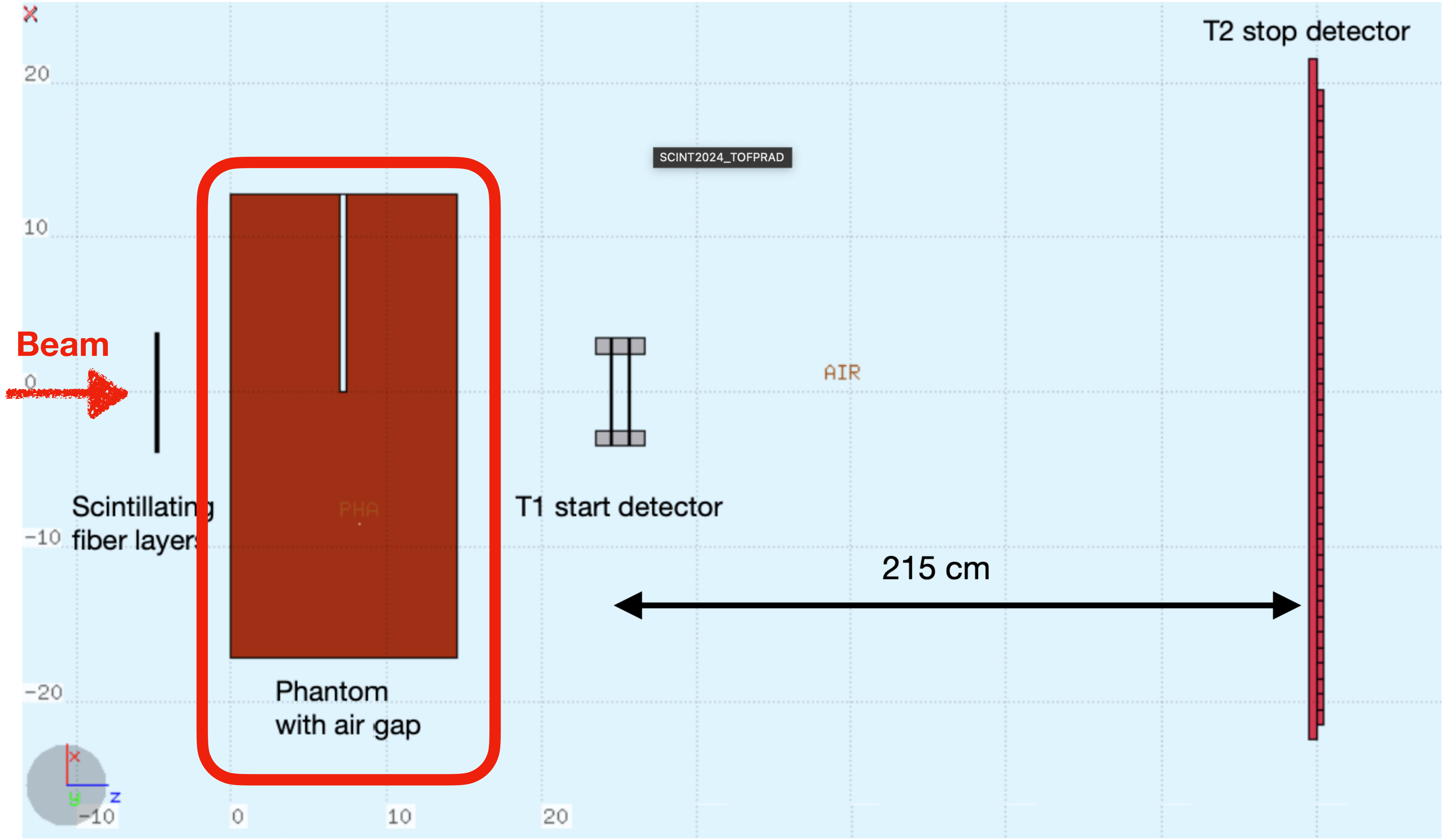






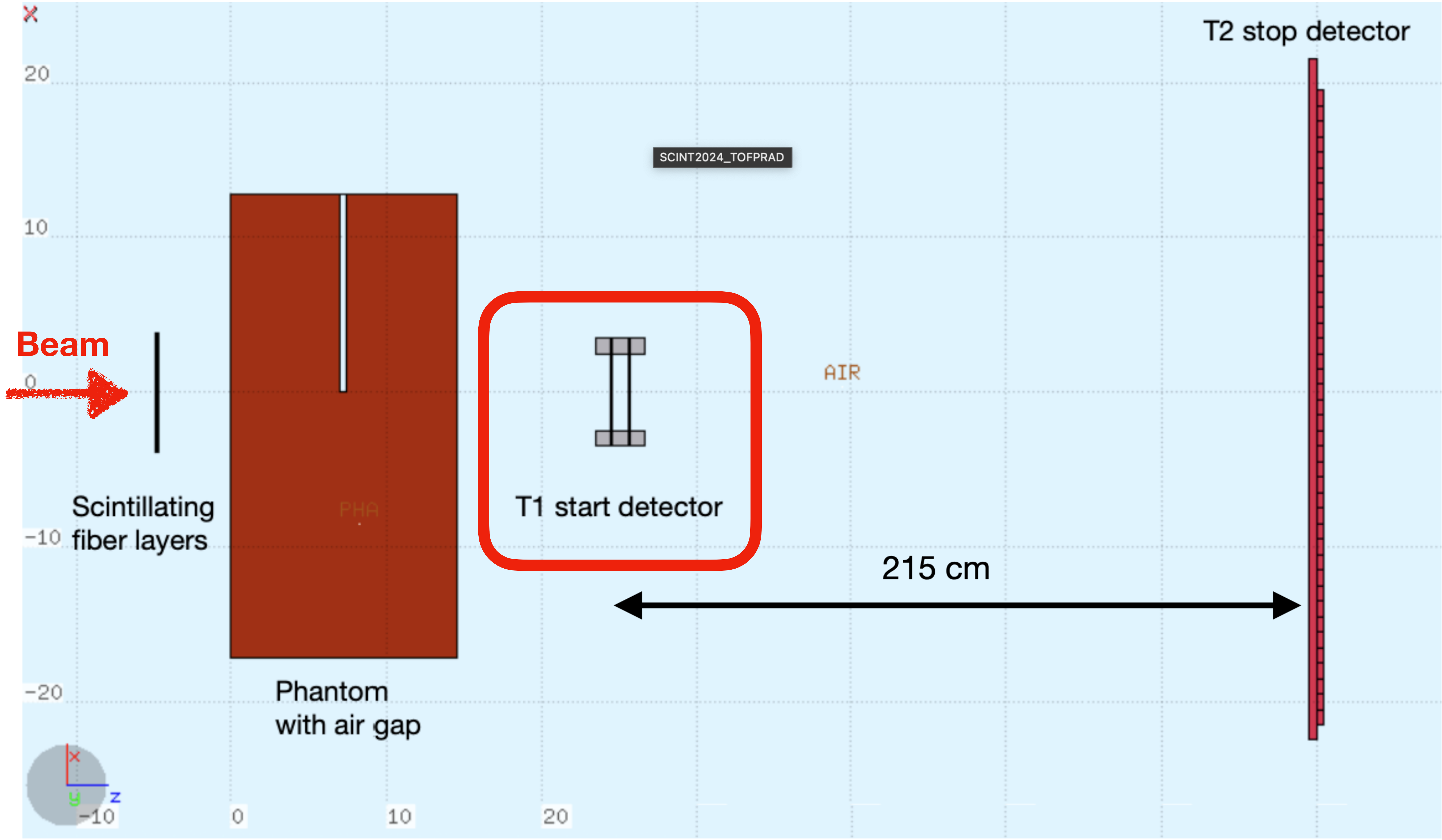
- Developed to monitor the beam in the CNAO XPR room @ low intensity (1~10^5 Hz)
- Event by event (TOFprad) or periodic acquisition
- Loss of efficiency on P due to cross talk
- Position resolution of few mm
- Differences in X and Y (under investigation)

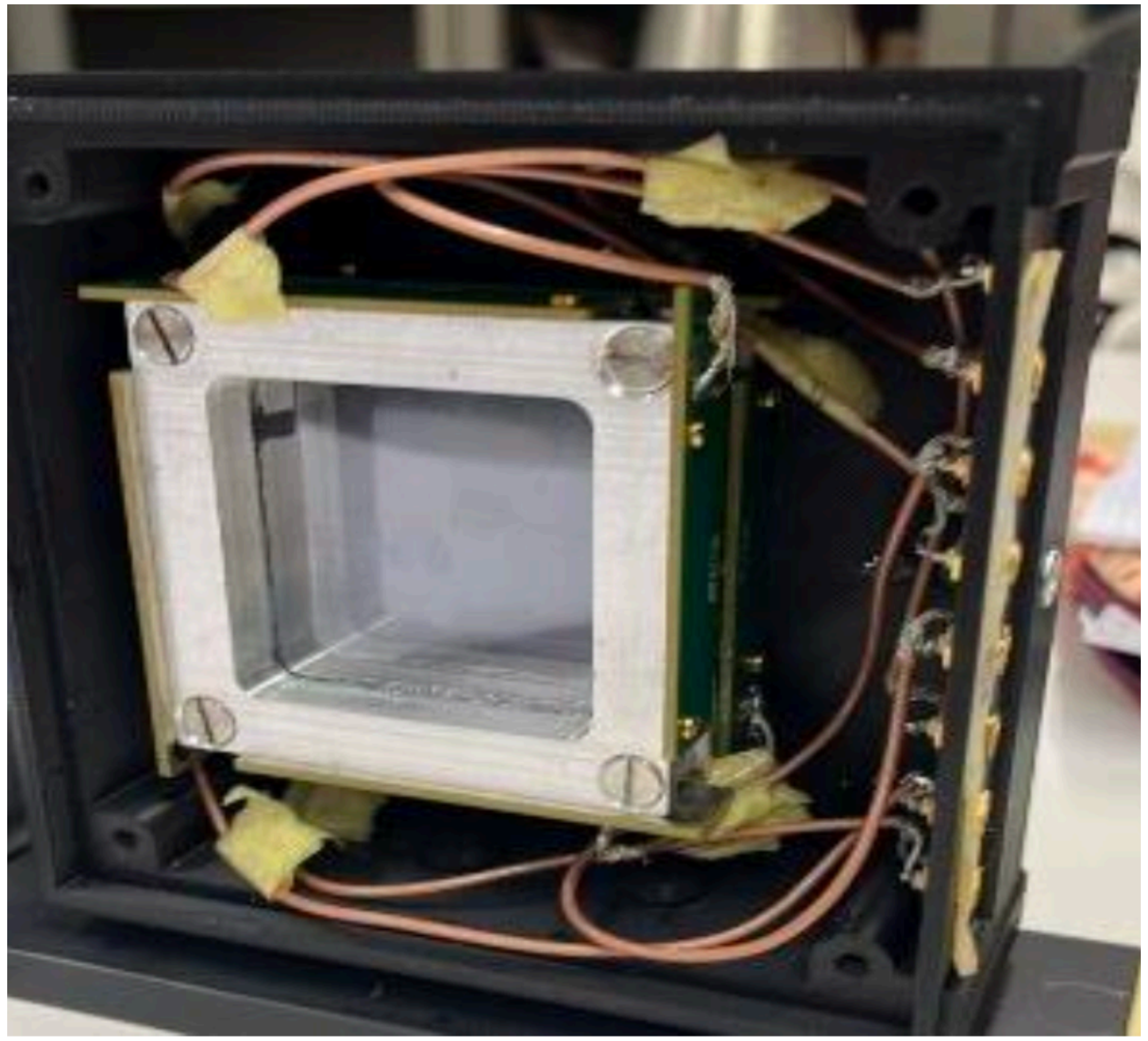
First experimental setup



Phantom: a 14.5 cm thick water-equivalent phantom (RW3) with air gaps of varying thicknesses (2-10 mm) positioned at different depths and across half of the transverse section within the water phantom

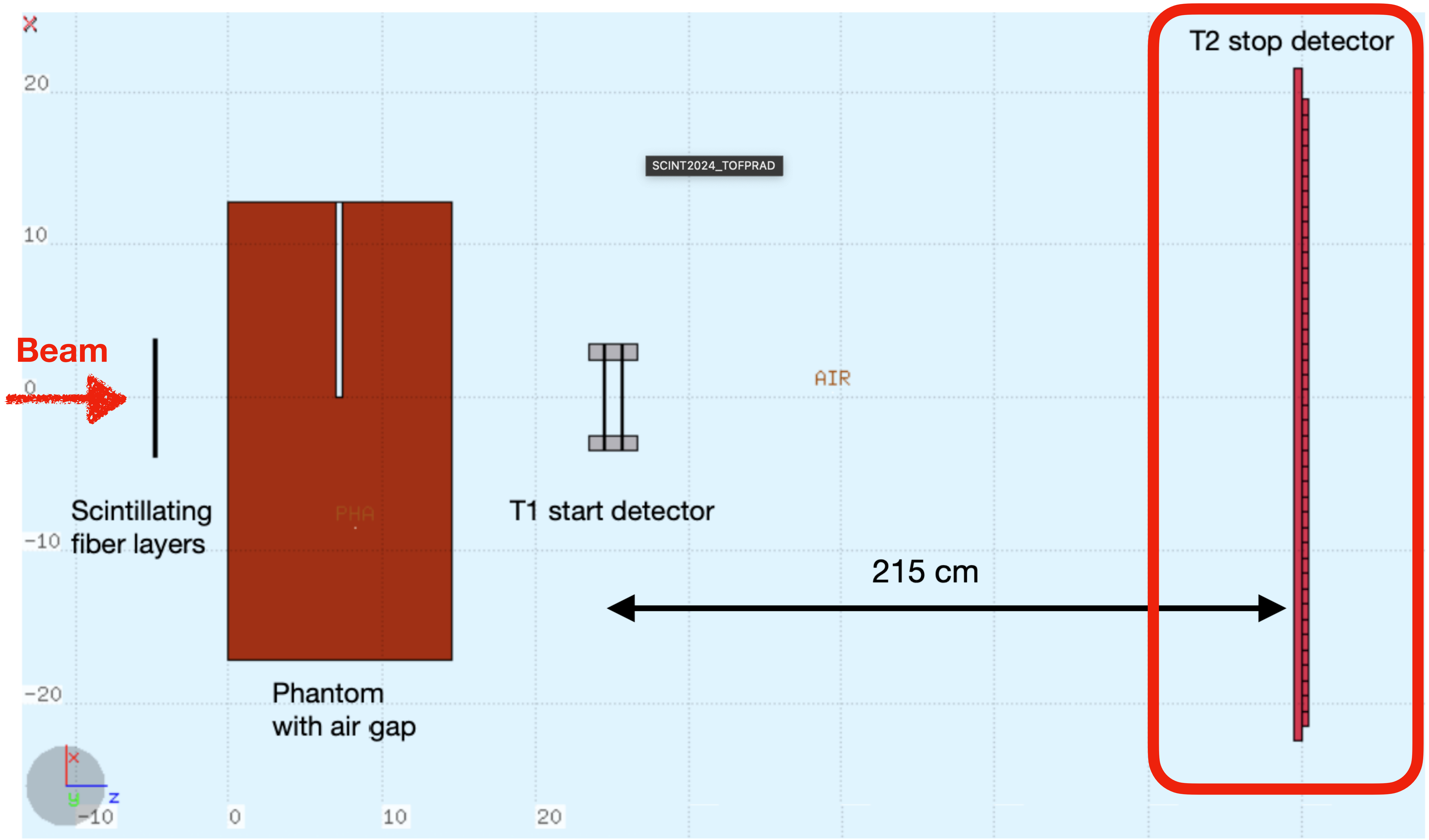
First experimental setup

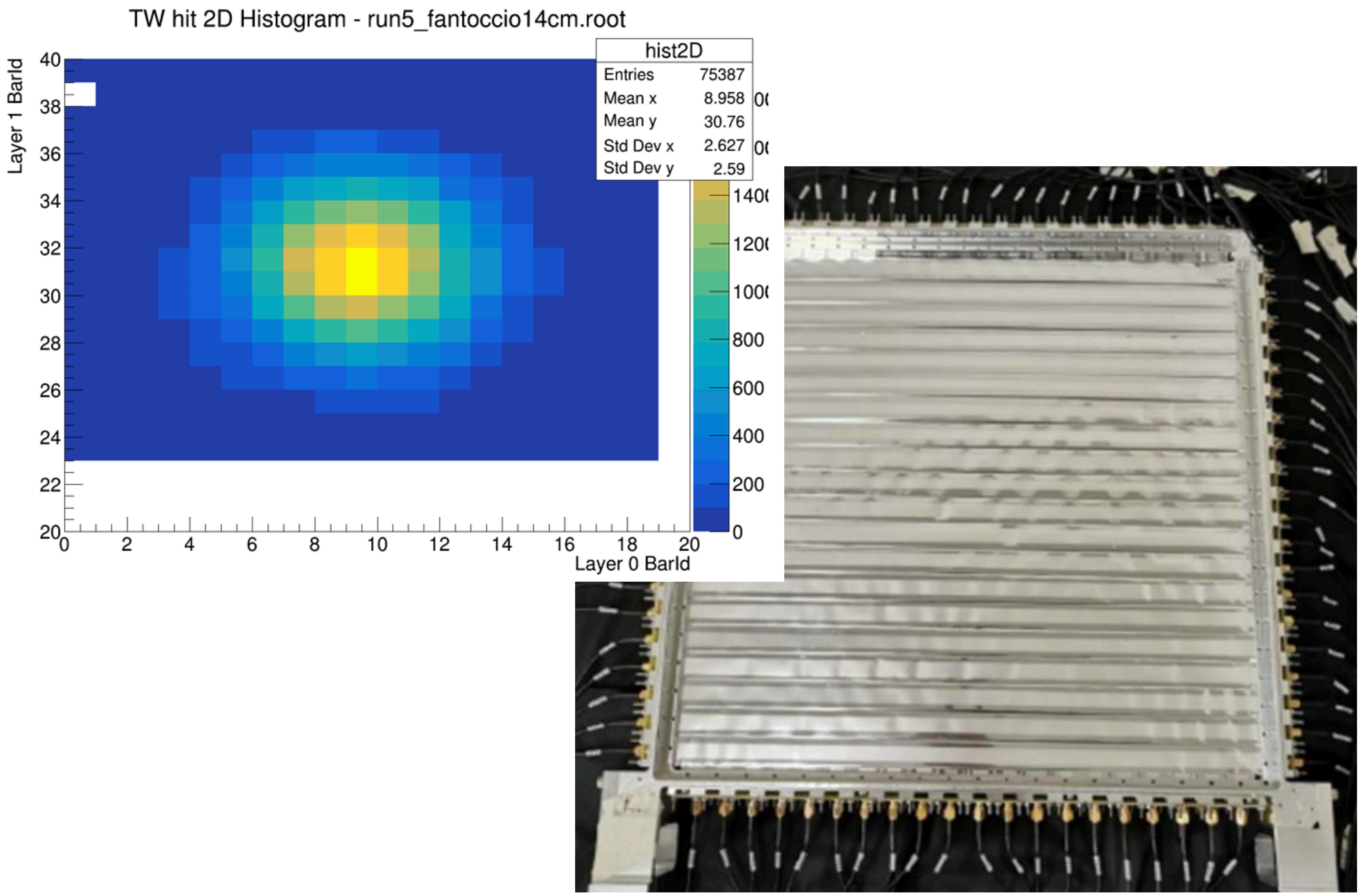




T1 start detector: two homogeneous layers of plastic scintillator (EJ-232 by Eljen Technology), each with a thickness of 500 μm, read-out by SiPMs (Advansid NUV3S) and used as TOF start detector

First experimental setup

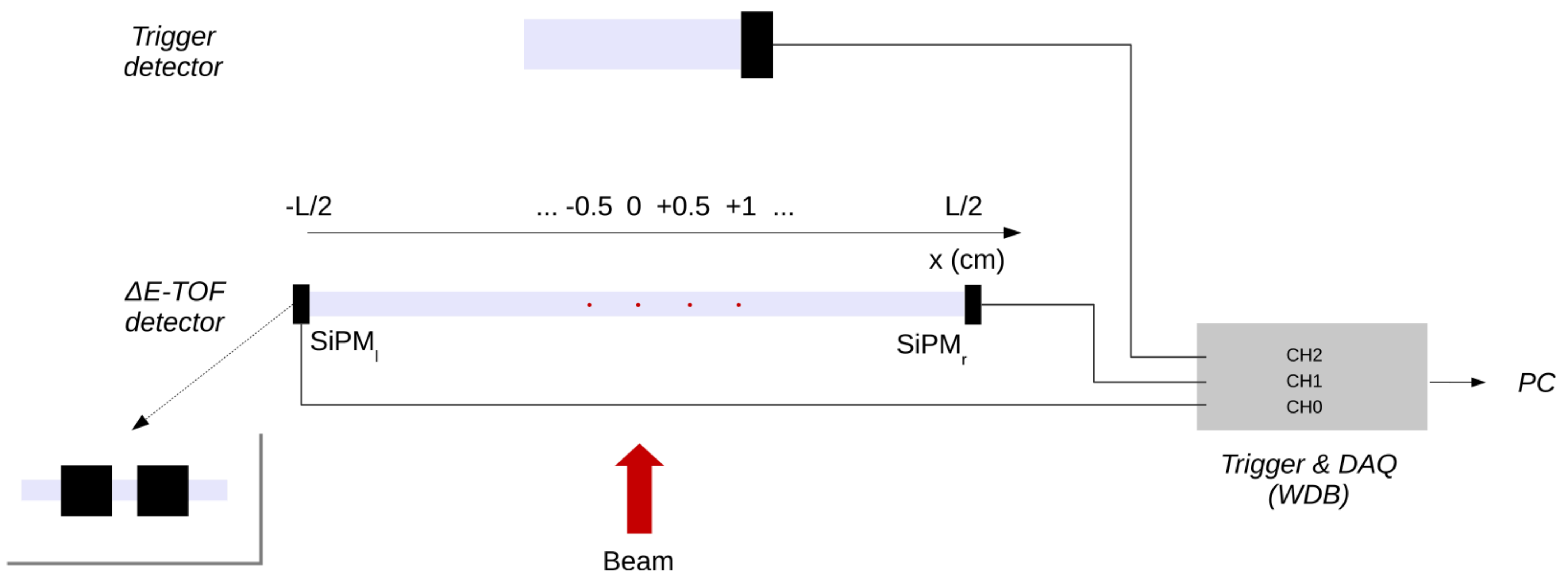


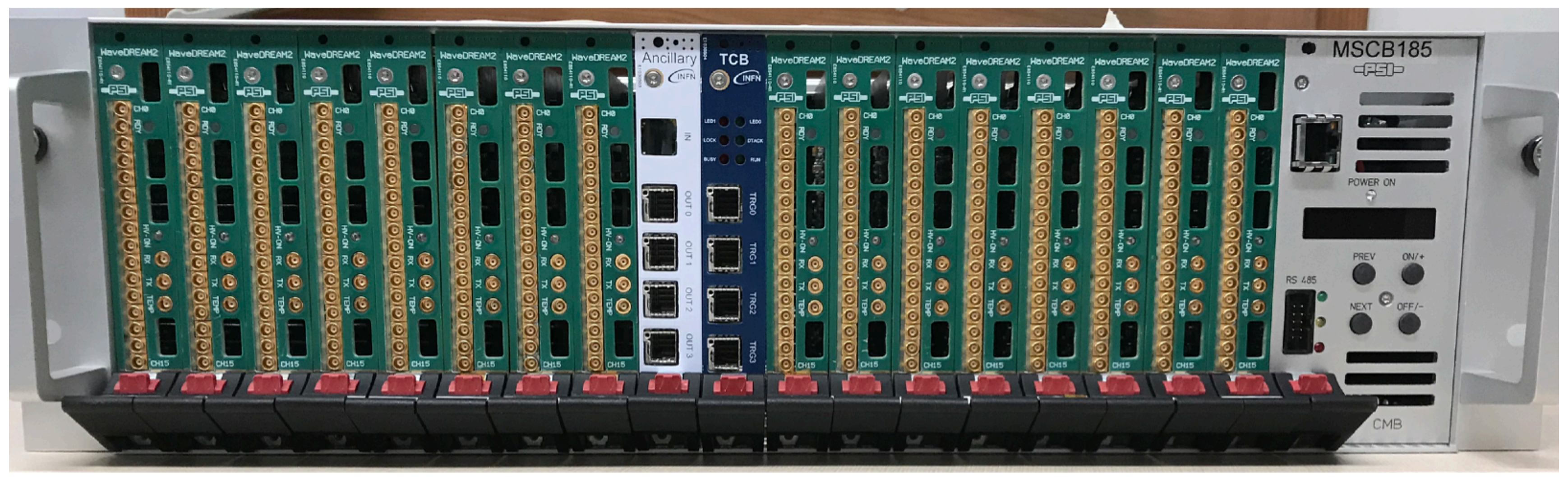


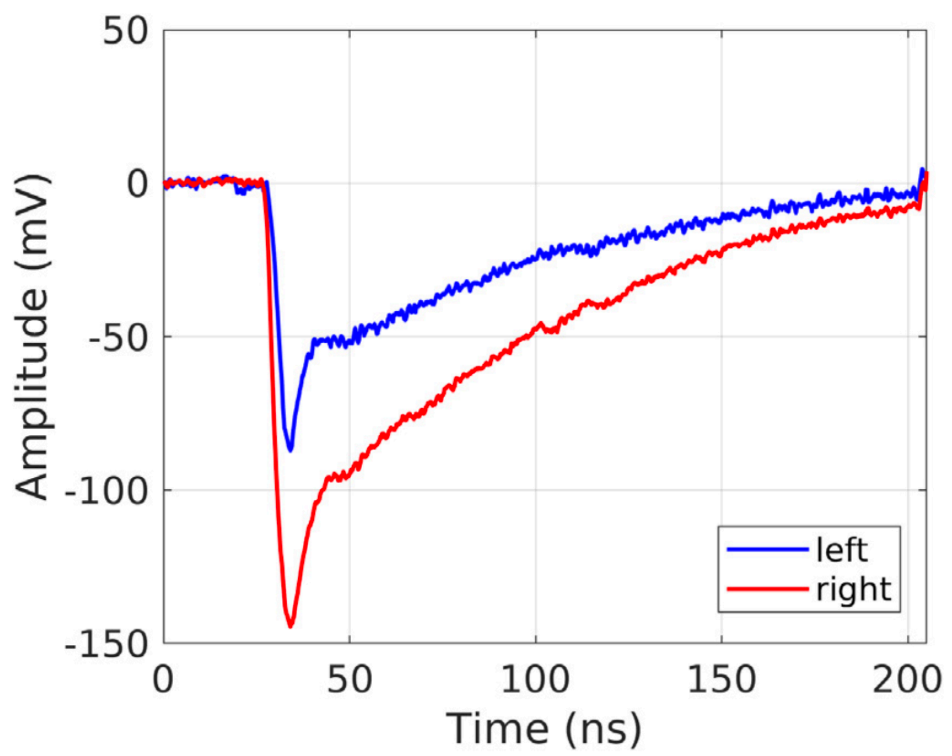
T2 stop detector: Two orthogonal layers of EJ-200 plastic scintillating bars (20 bars of 44x2x0.3 cm3 each) read with SiPMs on both sides. It is adopted as the final TOF measurement station

Reference: Morrocchi M. et al., "Performance evaluation of the TOF-Wall detector of the FOOT experiment", 2020 Doi: https://doi.org/10.1109/TNS.2020.3041433

First experimental setup



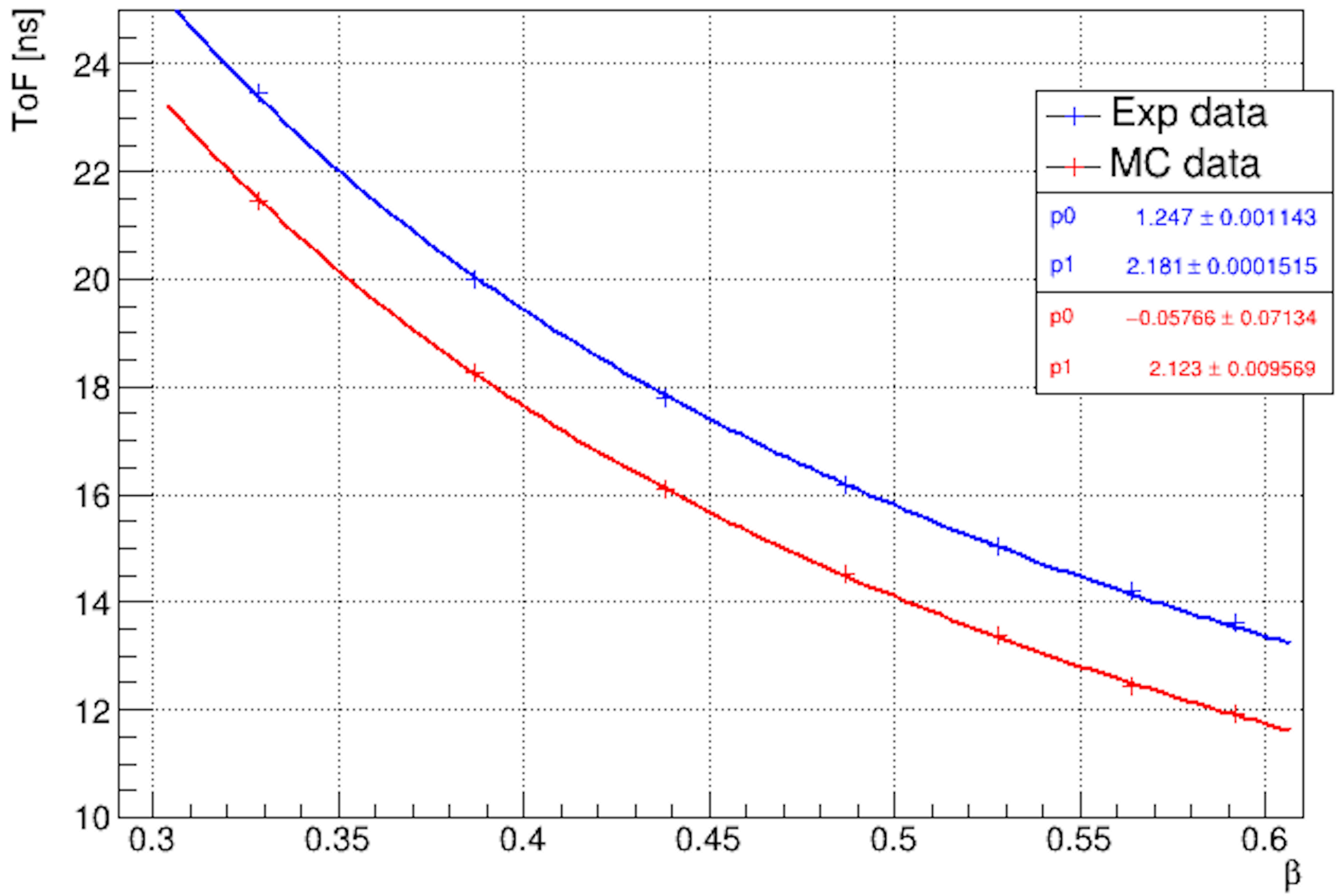




- Readout of T1 and T2 by means of WaveDAQ system
- Compact and highly integrated trigger and data acquisition system developed within the MEG II exp adopted in FOOT exp
- 16-10k channels
  1-5 GSPS Waveform digitiser
  80 MSPS for trigger processing
  0.5-100 input gain
  FPGA process ADC data in real time

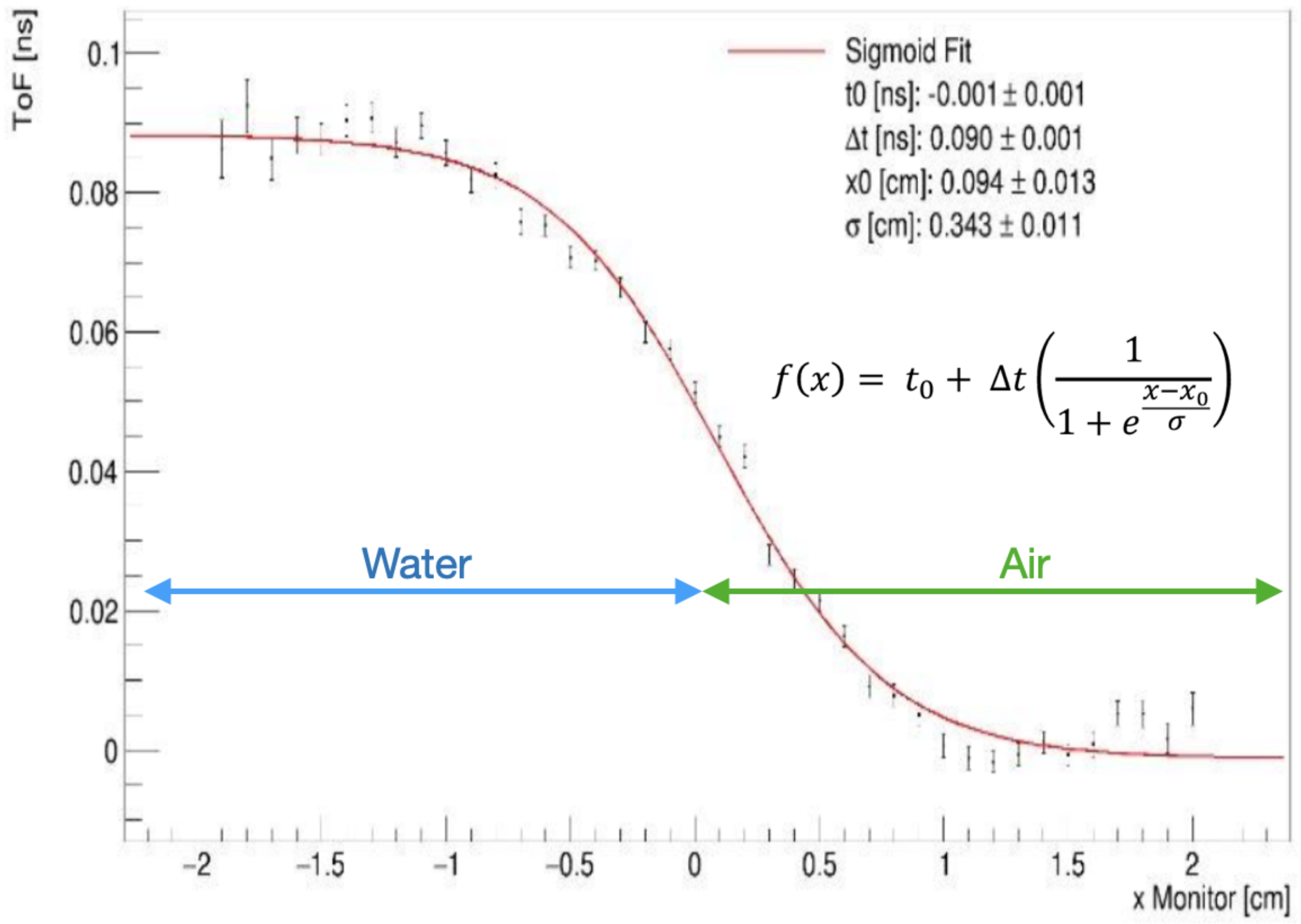
- Galli et al., “WaveDAQ: An highly integrated trigger and data acquisition system", NIM A, 2018, https://doi.org/10.1016/j.nima.2018.07.067

TOF calibration



- TOF calibration conducted with P at 62-228 MeV without phantom
- MC simulation by means of FLUKA
- ToF = $p_0 + p_1/\beta c$
  p_0~ns; p1~m (distance T1-T2)
- There is a difference of about 1.7 ns between MC and data
- TOF reso ~ 200 ps

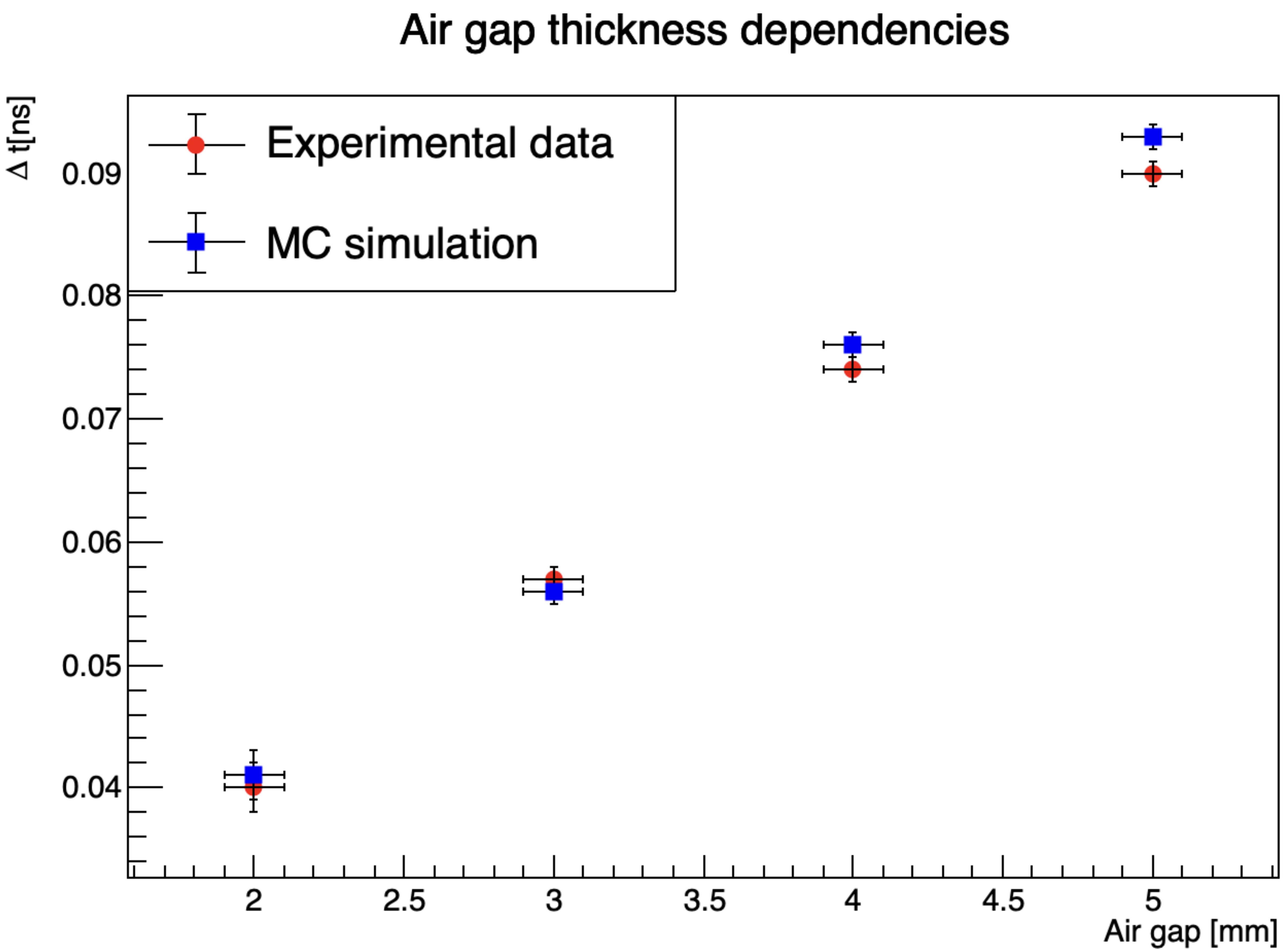
Air gap detection



- TOF vs beam position measurements fitted with a sigmoid function to extract the parameters and study the capability of the system to detect the air gap within the phantom

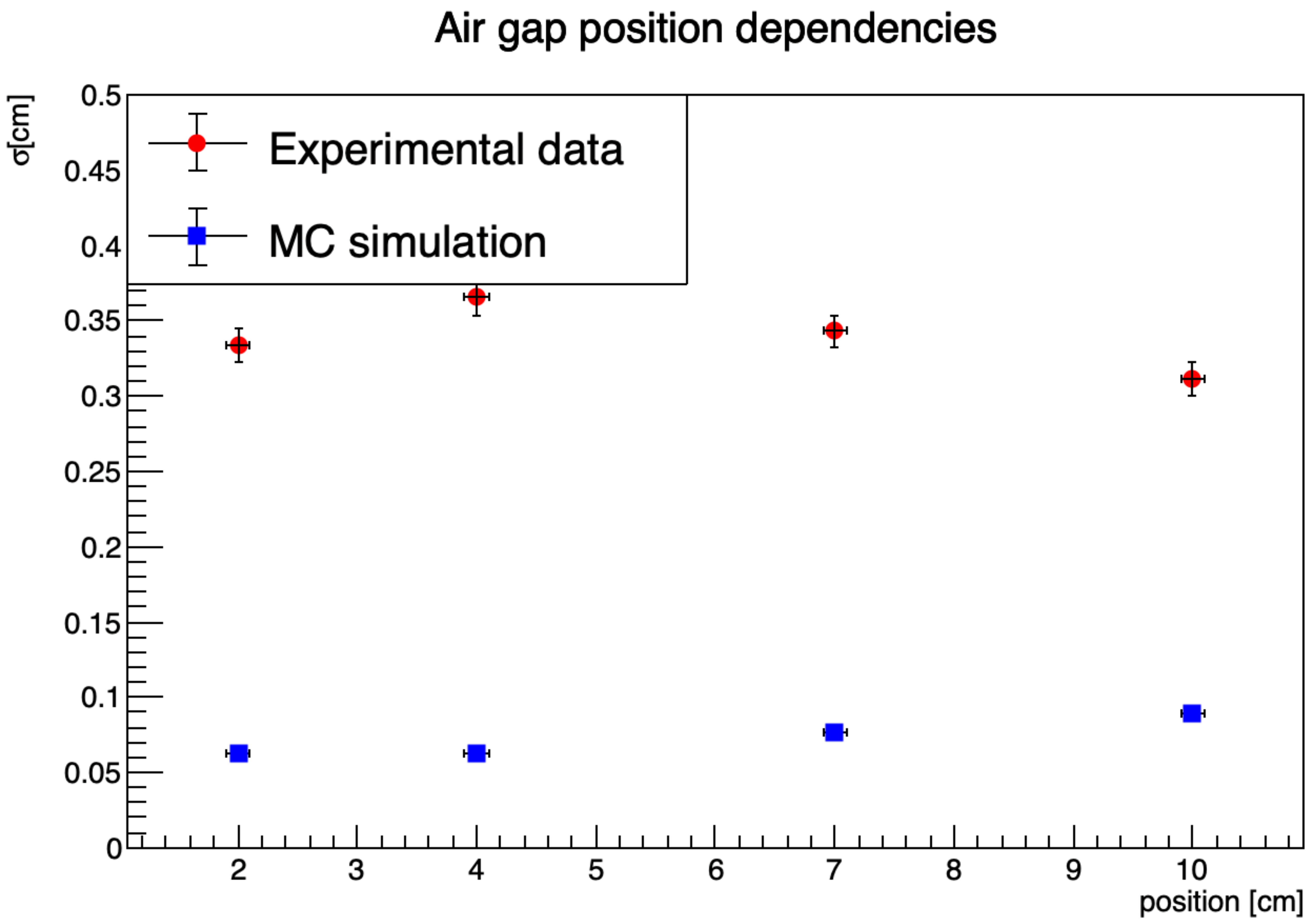
- T_0 ~ TOF meas at x—>∞
  Δt ~ time gap size
  X_0 ~ gap position ⊥ to the beam
  σ ~ spatial resolution (related to the gap position along the beam)

Air gap thickness detection



- Δt parameter increases with increasing air gap size
- No relevant changes for the other fit parameters
- Good agreement between data and MC simulations

Air gap depth detection



- σ parameter has a very small dependency on the gap depth position even in MC
- Not detectable by our preliminary TOF system
- Further studies ongoing

Conclusions and future perspectives

- We built and tested a plastic-scintillator based proton radiography prototype
- The prototype is able to detect an air gap of few millimetres in a water equivalent phantom
- The experimental results about the air gap thickness measurements are in good agreement with the MC simulation output
- The system seems unable to detect the depth of the air gap position along the beam direction
- A new T1 detector is under study to increase the spatial resolution
- A new DAQ system is under study to reach the clinical beam rates (next data taking at CNAO in November 24)

Thank you for the attention!

The research is funded by the grant PRIN: PROGETTI DI RICERCA DI RILEVANTE INTERESSE NAZIONALE

Bando 2022 TOFpRad

“TOFpRad: Time Of Flight Proton RADiography with plastic scintillators”

grant nr. 202293MEL9, CUP I53D23000970001

MUR PRIN

Back up

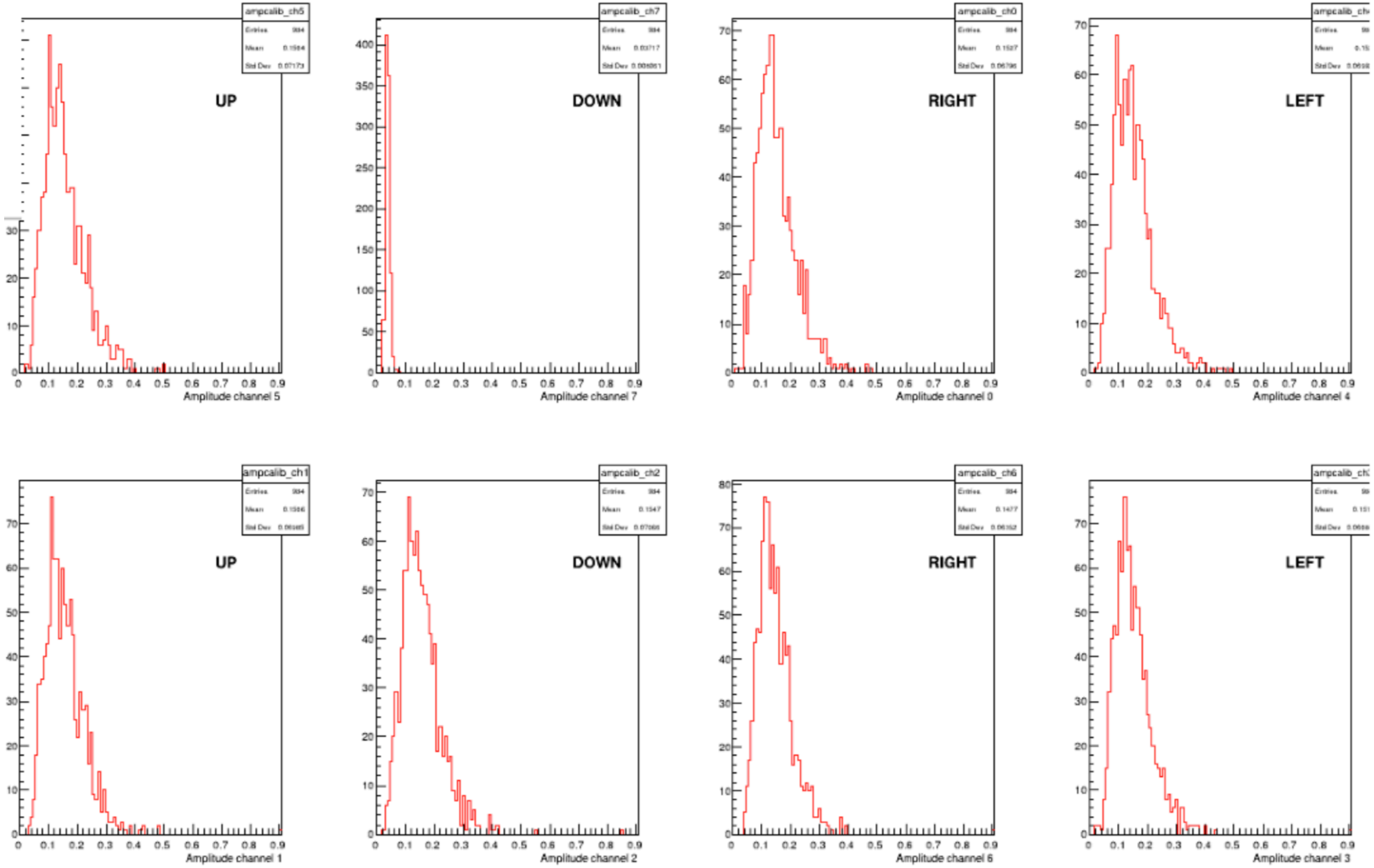
Range uncertainties in hadrontherapy

The error intrinsic in this conversion (due to $\mu(\rho_e,Z)$ dependency on atomic number and electron density) is the principal cause of proton range indetermination (3%, up to 10 mm in the head)
[Schneider U. (1994), Med Phys. 22, 353]

Source of range uncertainty in the patient	Range uncertainty without Monte Carlo	Range uncertainty with Monte Carlo
Independent of dose calculation		
Measurement uncertainty in water for commissioning	±0.3 mm	±0.3 mm
Compensator design	±0.2 mm	±0.2 mm
Beam reproducibility	±0.2 mm	±0.2 mm
Patient setup	±0.7 mm	±0.7 mm
Dose calculation		
Biology (always positive) ˆ	+~0.8%	+~0.8%
CT imaging and calibration	±0.5% [a]	±0.5% [a]
CT conversion to tissue (excluding I-values)	±0.5% [b]	±0.2% [g]
CT grid size	±0.3% [c]	±0.3% [c]
Mean excitation energy (I-values) in tissues	±1.5% [d]	±1.5% [d]
Range degradation; complex inhomogeneities	−0.7% [e]	±0.1%
Range degradation; local lateral inhomogeneities *	±2.5% [f]	±0.1%
Total (excluding *, ˆ)	2.7% + 1.2 mm	2.4% + 1.2 mm
Total (excluding ˆ)	4.6% + 1.2 mm	2.4% + 1.2 mm

Paganetti H. (2012), Phys. Med. Biol. 57, R99

T1 Start detector signal amplitude



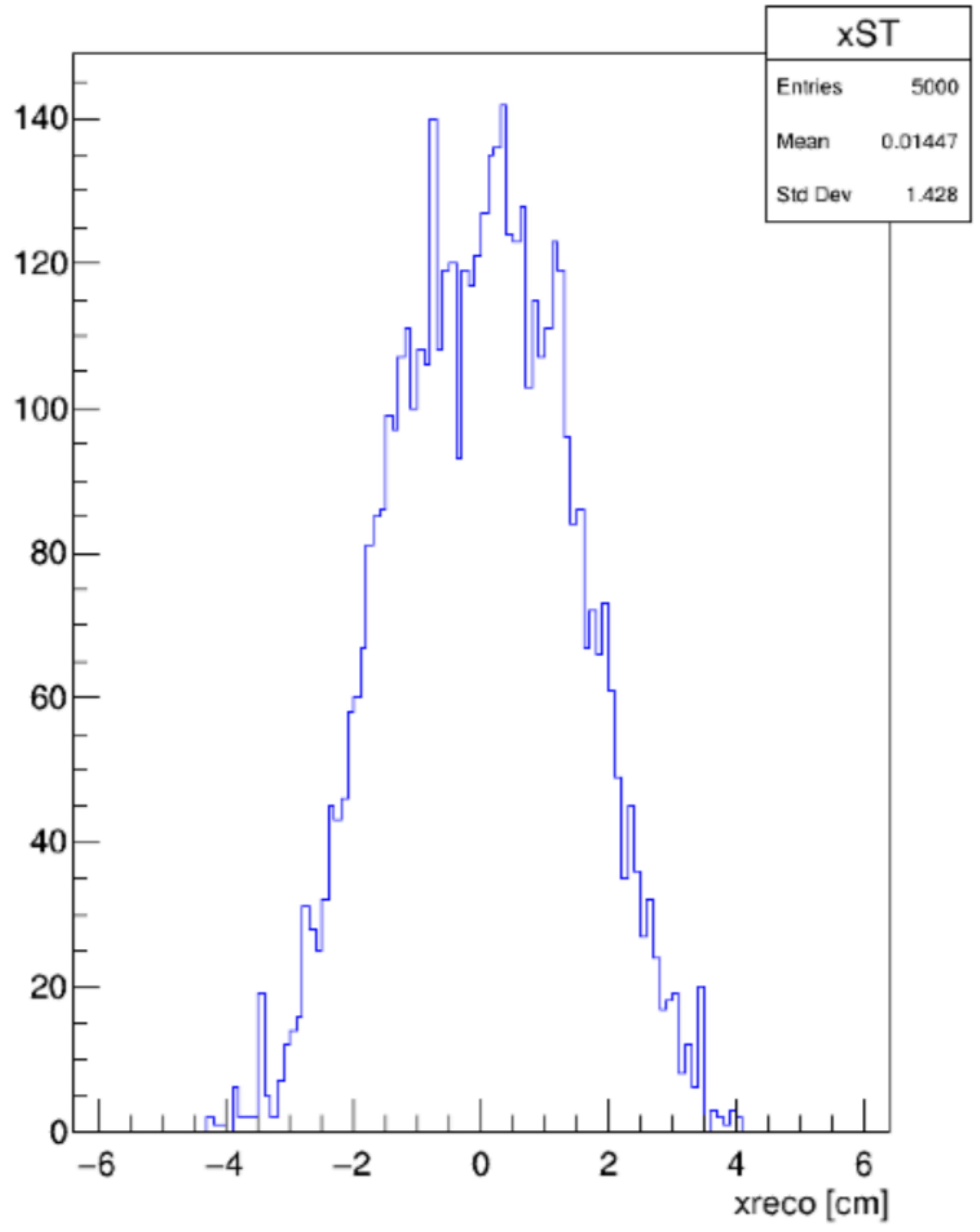
~ 30-35%

statistical

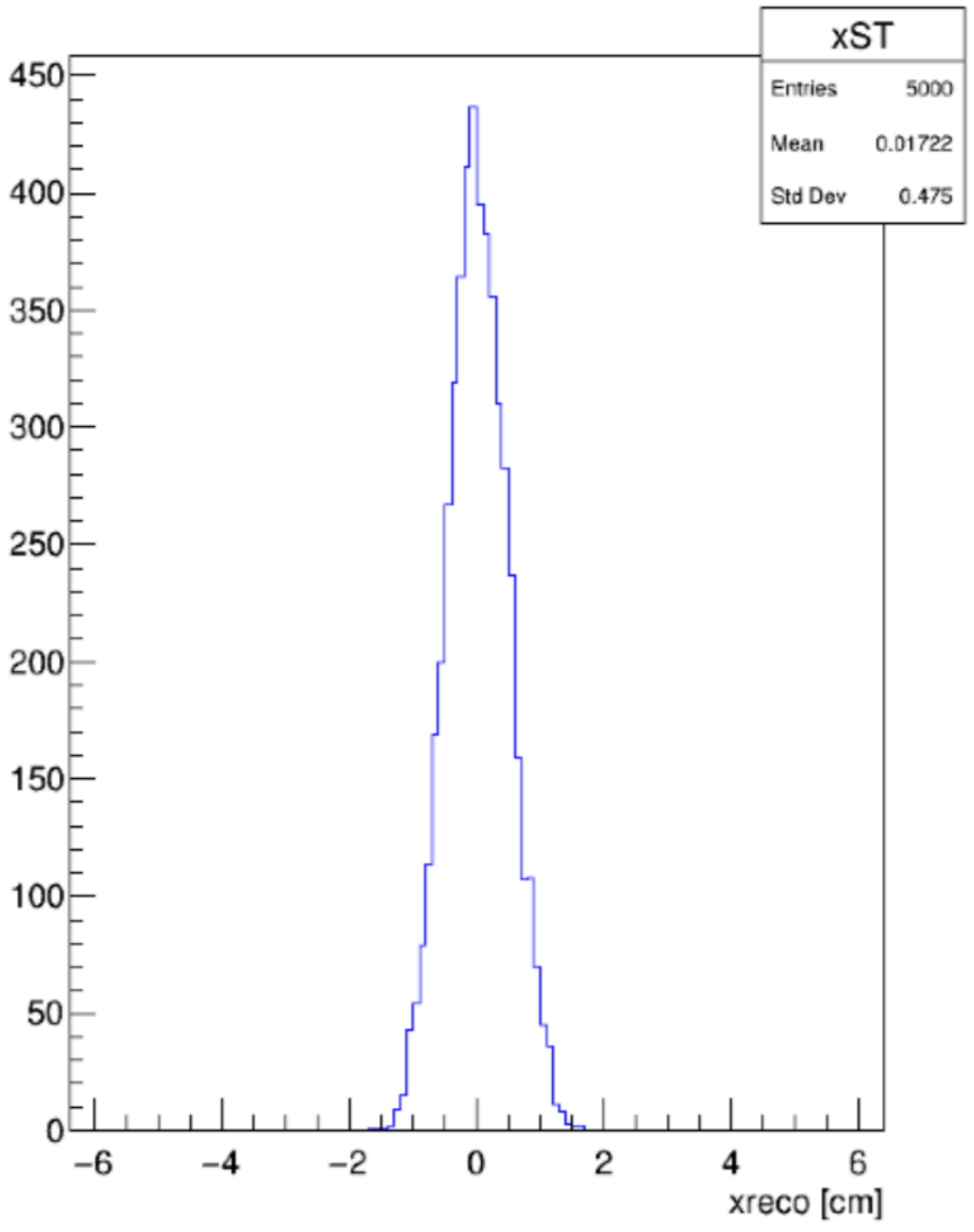
fluctuation

T1 Start detector MC studies

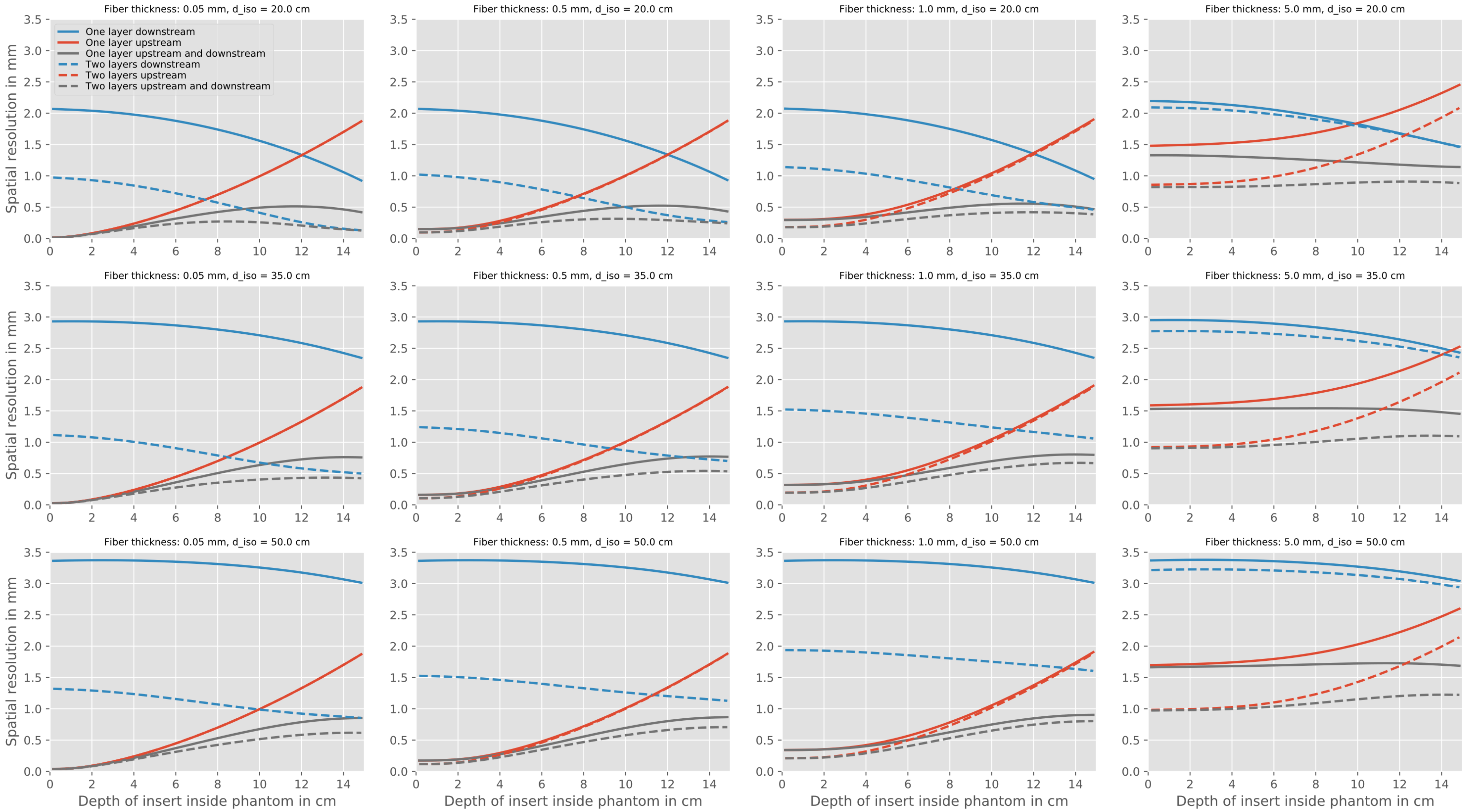
Data-like(35%reso)



7x7 cm2 with 10%reso



T1 Start detector MC studies



TOF resolution