Calorimeter prototyping for the iMPACT project pCT scanner

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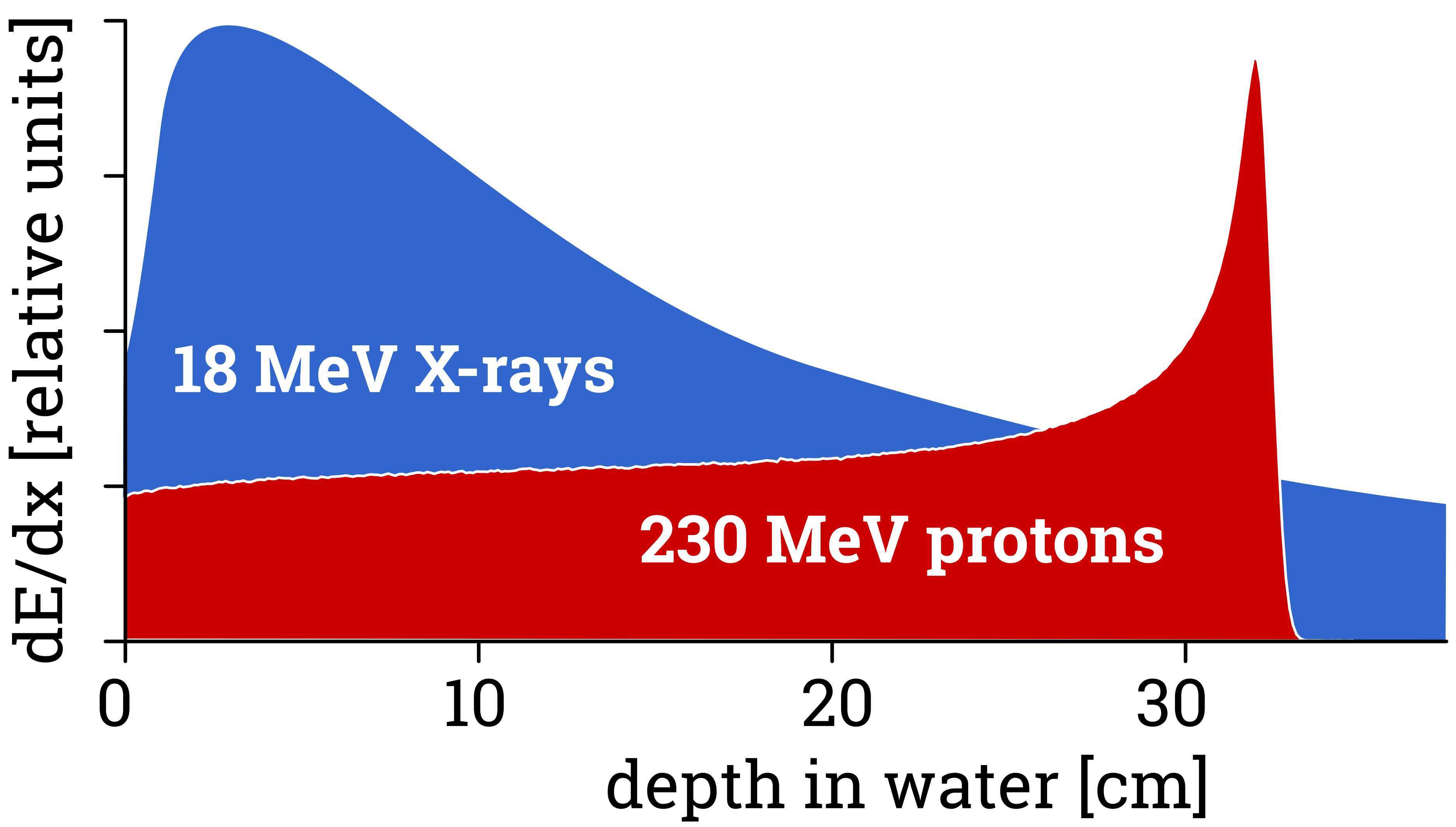
why proton Computed Tomography?

- **proton therapy is known to be more effective than traditional X-rays** in cancer treatment, with reduced collateral damage



- such benefits are **limited by the precise knowledge of the tissue density along proton path**, which is crucial for a better proton beam aiming depth

- major limit as of 2017: **5% to 10% error on proton beam energy, 10× the energy tuning** precision of modern proton therapy machines [1-3]

- such limitation can be overcome **if protons were also used as probes to map the tissue density**: same particle, same interaction with matter
  - plus: the proton-delivered dose for imaging purposes can be **as low as 1.5 mGy**, being 10-100 mGy the one of X-rays [4]

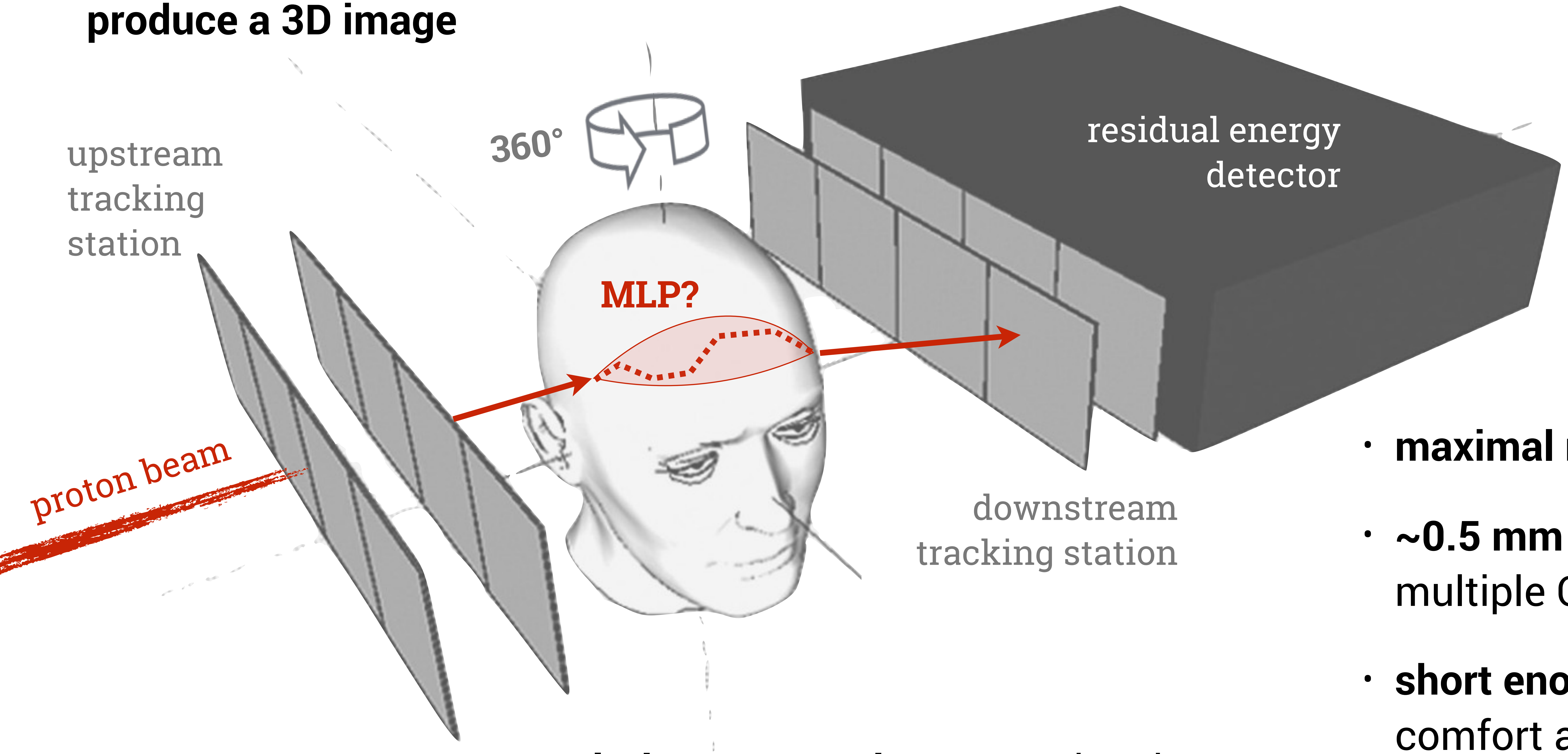
adapted from [5]

X-rays: better spatial resolution

protons: sensitivity to density

proton Computed Tomography: requirements …

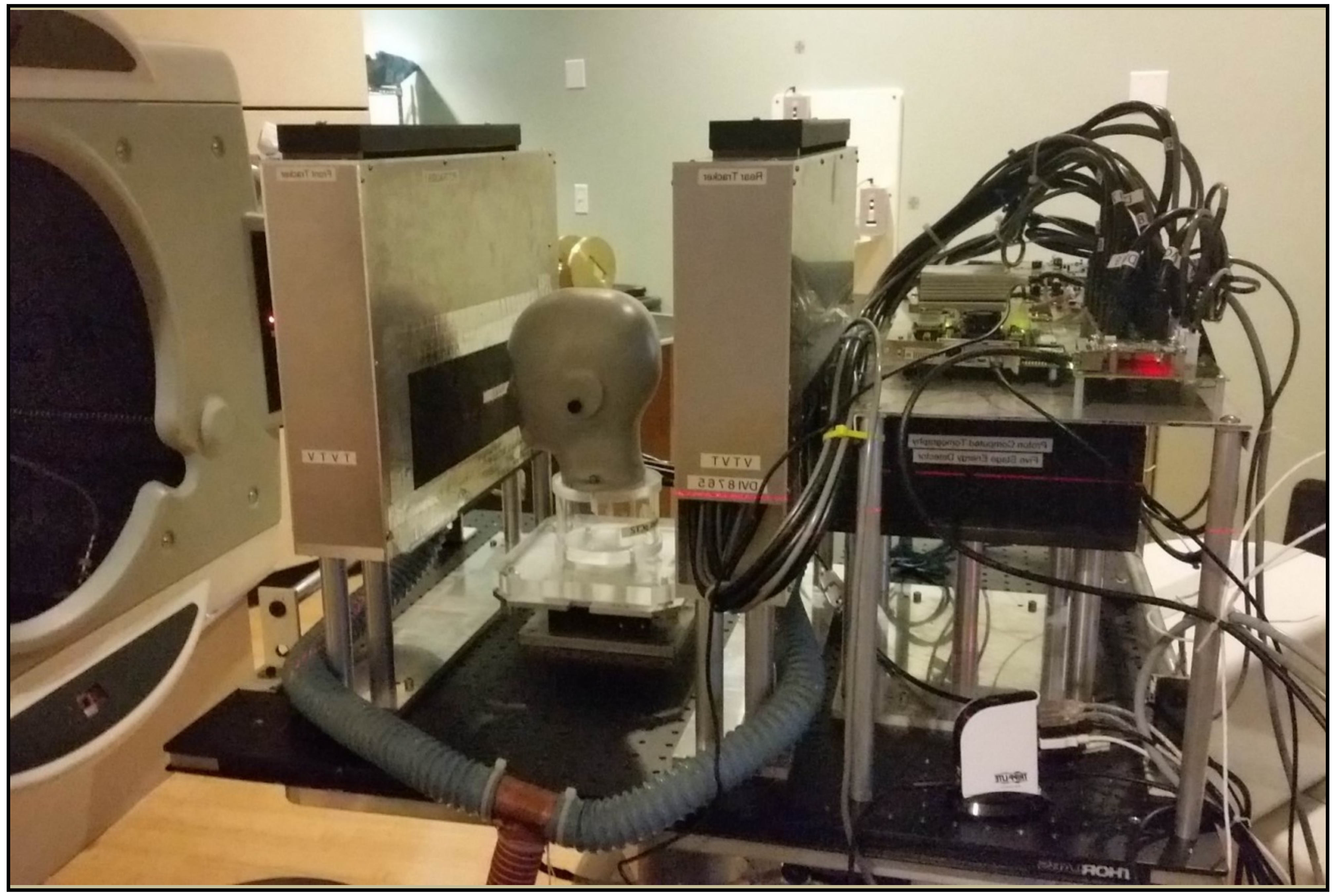
- **200 to 250 MeV protons** can be used to probe almost every section of human body from all directions **to produce a 3D image**
- **a detailed enough image is obtained with min 10^8 proton tracks**: entry/exit point and direction, as well as lost energy [6]



- density map is the result of the **Most-Likely Path reconstruction** for each track [7]
- **maximal recording efficiency** → low dose
- **~0.5 mm position resolution** → only limit: multiple Coulomb scattering
- **short enough exposure time** for patient comfort and stability
- [mounted on the proton gantry rotating around the patient]
- **1% resolution on stopping power**, i.e. tissue density → e.g. 3 mm error on 200 MeV proton range, **main limit: proton straggling**

… and state of the art as of 2017

see [0] for an extensive review



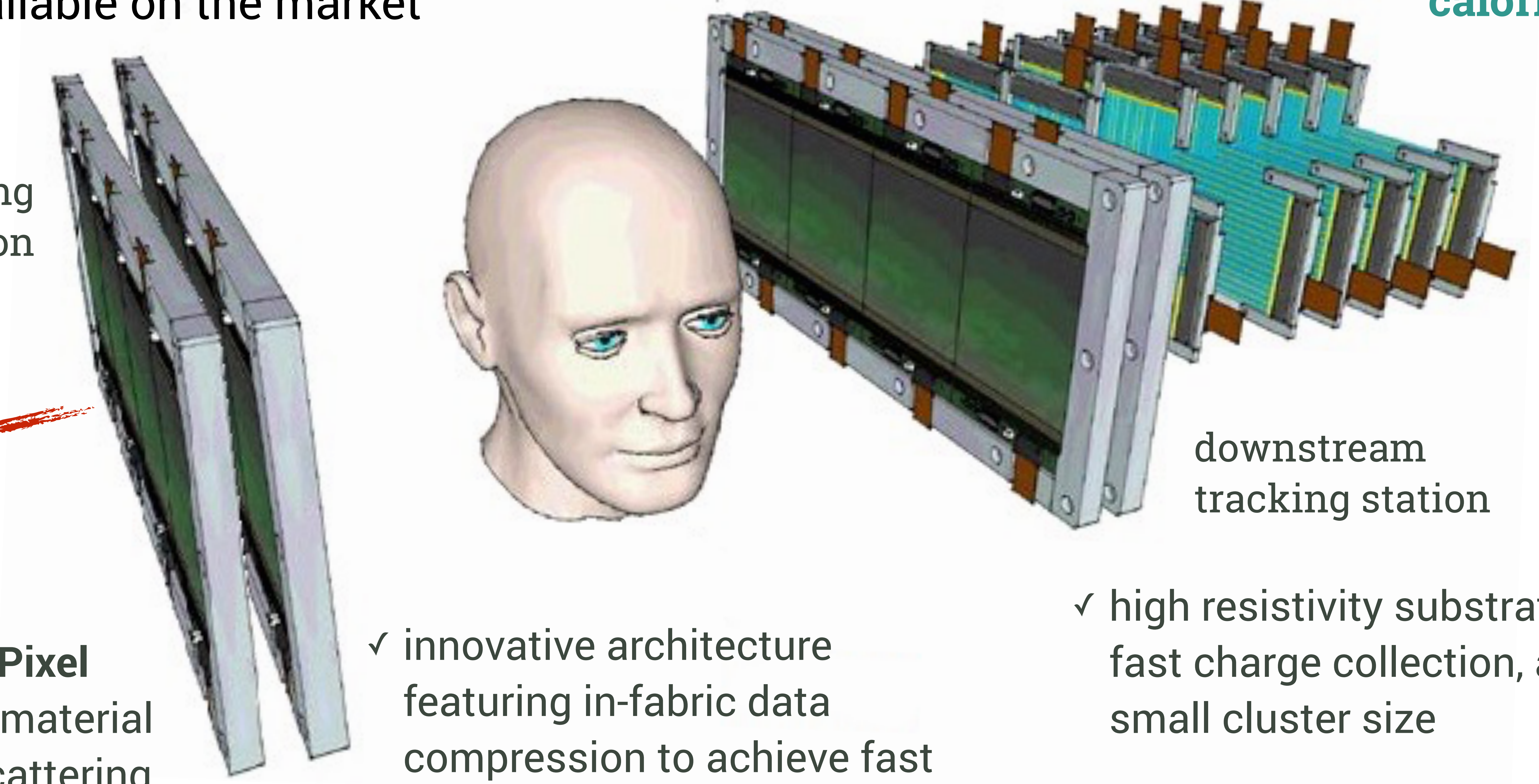
- R&D projects mainly designed around Si strip detectors and range calorimeters, LLU/UCSC Phase-II prototype marked the best exposure time so far: 6 min with continuously rotating phantom [8]
- **main limiting factors: pulse shape digitisation, proton pile-up in the detector**
  - Si strips require several layers per tracking station to disambiguate multiple hits per frame: increased amount of material
  - the measured residual energy must be correctly associated to each proton
    - **increase granularity, go digital, and be capable of seeing >MHz proton rate**
- goal of the iMPACT project: **squeeze the exposure time to O(10) s**, thus making the gantry rotation time the irreducible although affordable limit to a clinically viable pCT apparatus

no detector/technology today meets such requirements

the iMPACT project pCT scanner

more about iMPACT, its tracker, and related earlier projects: [10—15]

- **innovative Medical Proton Achromatic Calorimeter and Tracker**
- target: sustain >10 MHz proton rate using off-the-shelf technologies already available on the market



tracking stations design features

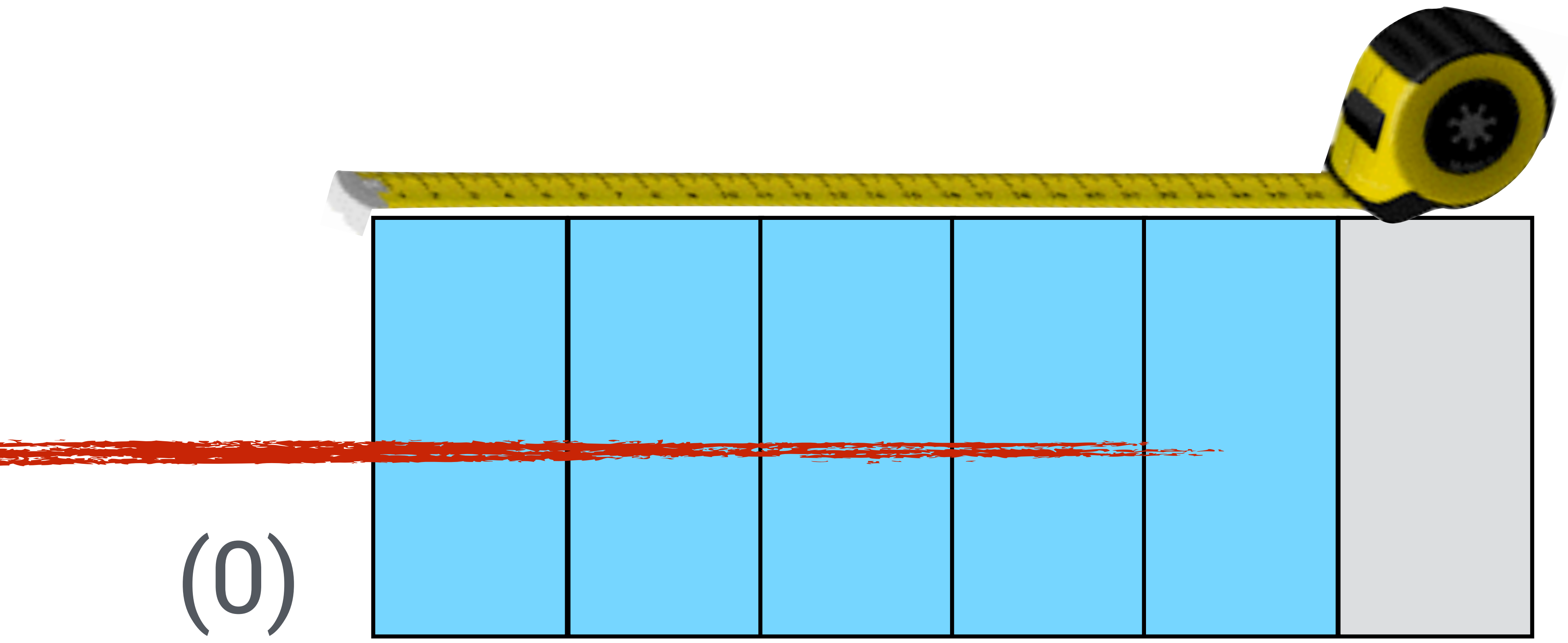
- ✓ ~100 μm thin **CMOS Monolithic Arrays of Pixel Sensors** to minimize material budget and proton scattering
- ✓ approximately 50 μm pixel size featuring digital readout
- ✓ innovative architecture featuring in-fabric data compression to achieve fast tracking up to 100 kHz/cm^2 a 10×10 cm^2 surface and a ~10 mW/cm^2 low power
- ✓ high resistivity substrate for fast charge collection, and small cluster size
- ✓ large area sensors that can be stitched and tiled to cover a larger area, **free of support**

the hybrid energy-range calorimeter concept

- the **proton MLP** inside the patient can be inferred **only after measuring its residual energy**

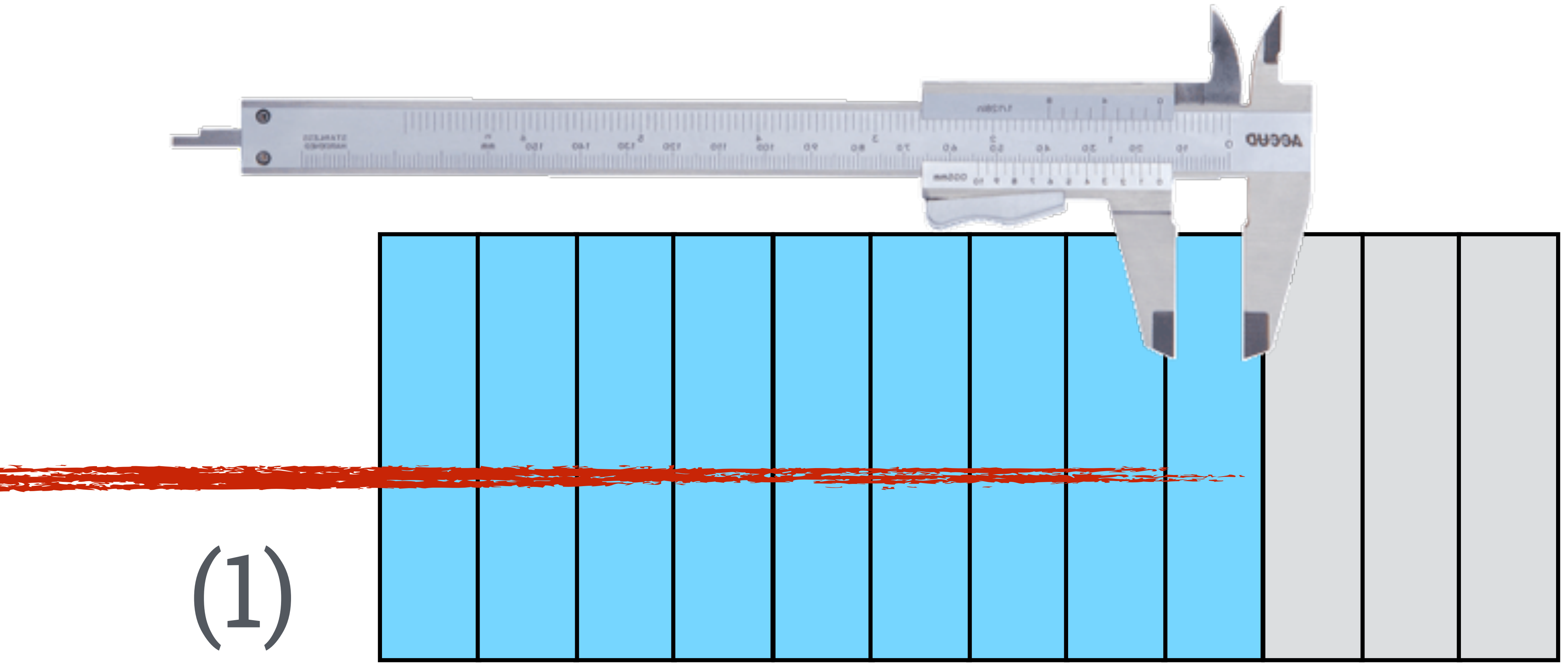
- this can be done via range measurement, i.e. where the the distance traveled inside the sensitive volume

$$R(E) = \int_0^E dE' \langle dE'/dx \rangle^{-1}$$



(0)

- step 0: **find ho deep the proton went**, e.g. with scintillators segmented in the direction of proton path

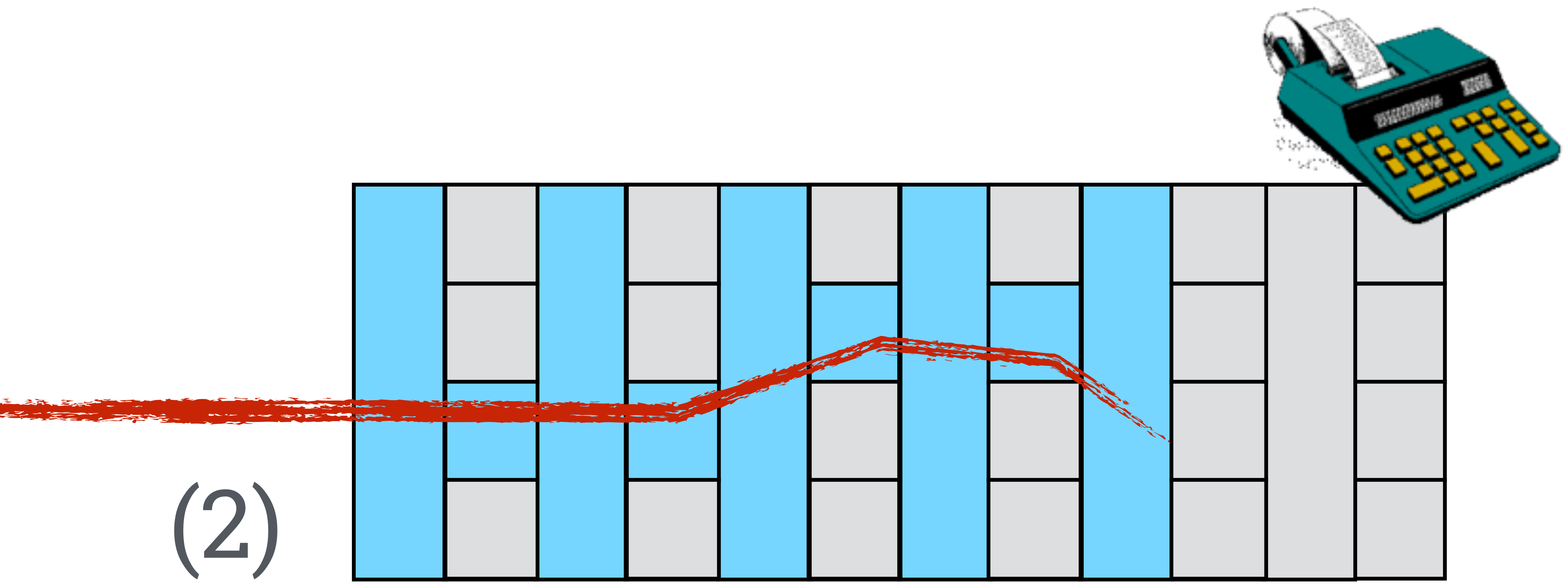


(1)

- step 1: **adopt a finer segmentation along proton path** to improve the range estimate
  - 5 mm thick layers contribute with an error of ~1.4 mm

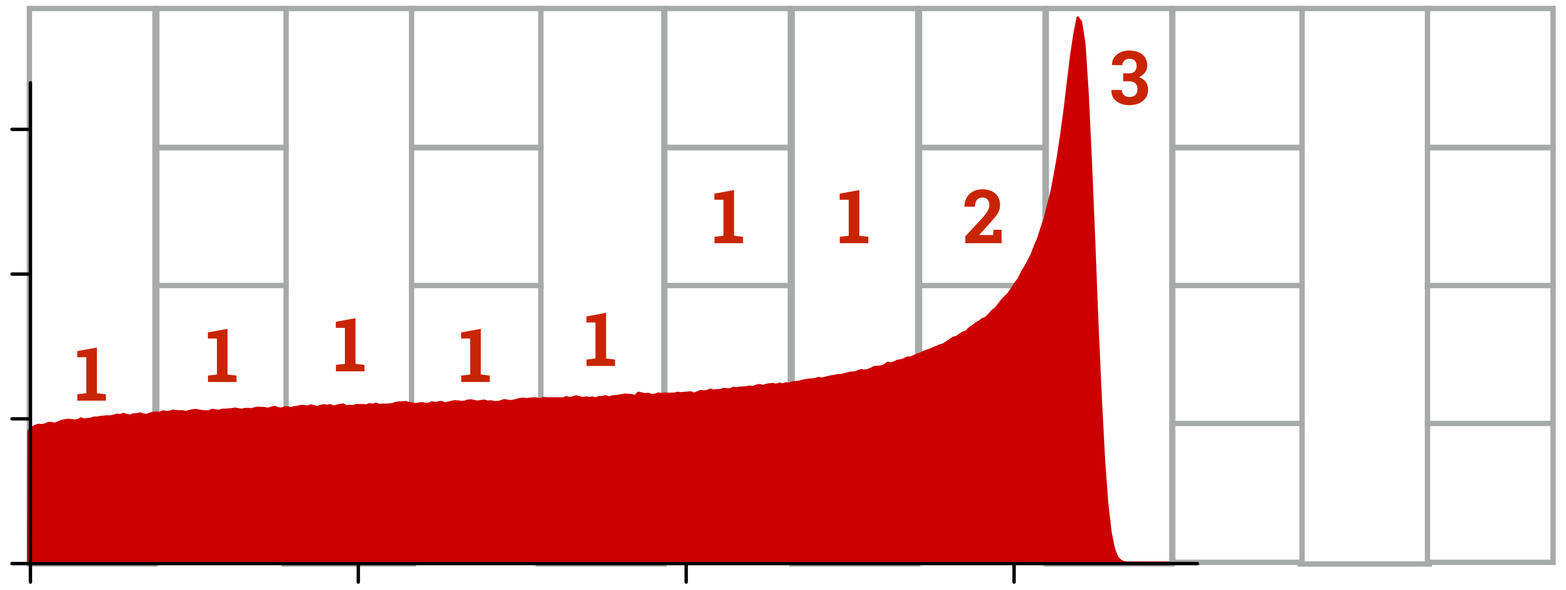
the hybrid energy-range calorimeter concept

- **multiple Coulomb scattering may cause lateral deviation from the straight line** and irreducible fluctuations result in a lower limit on range resolution of **few mm: range straggling**, same order of magnitude as error with 5 mm thick elements



(2)

- step 2: **segment the calorimeter also in the transverse projection** to account for lateral deviations of proton tracks
  - multiple protons measurable

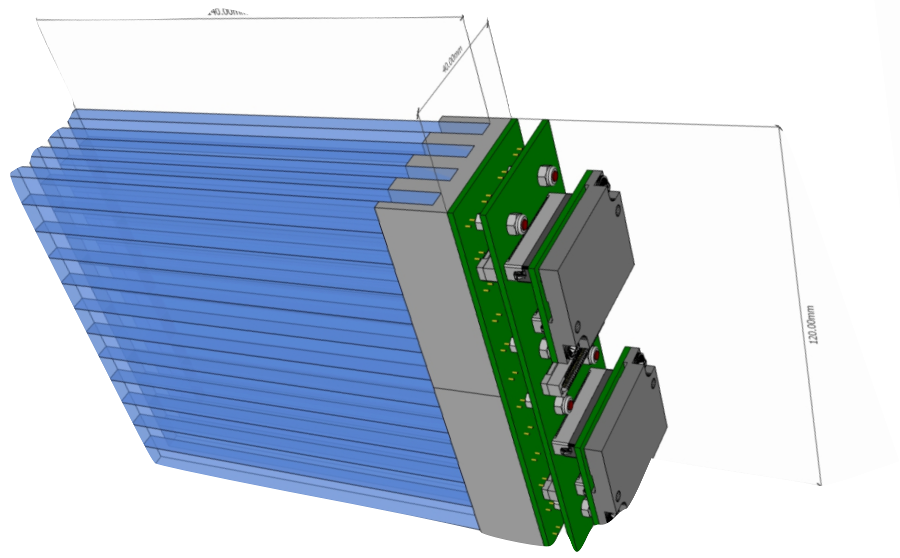


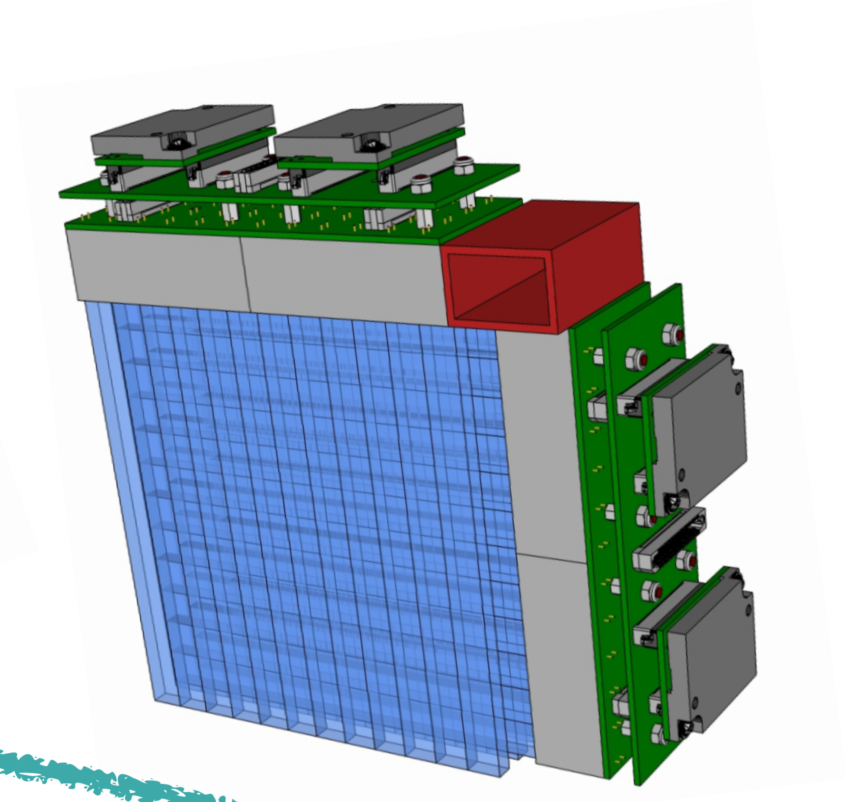
(3)

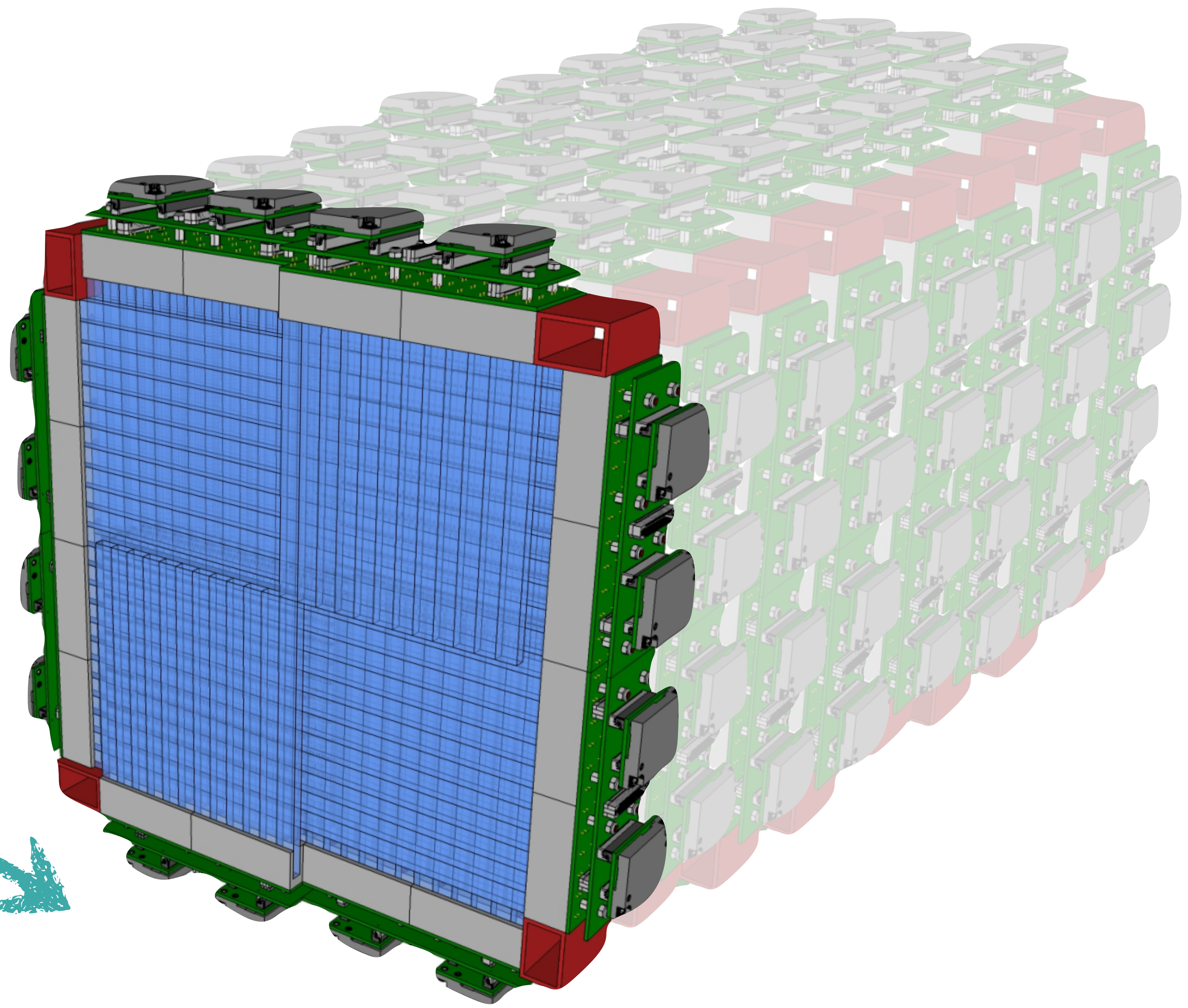
- step 3: **exploit the collected signal amplitudes** to enhance the estimate of Bragg peak location and reduce poor resolution effects at short ranges [9]
  - ⟨no. detected photons⟩ scales as ⟨lost energy⟩

the iMPACT hybrid energy-range calorimeter

- **also the iMPACT calorimeter must sustain the 100 kHz/cm^2 proton rate** while using intrinsically slower sensors than any silicon-based tracker
- the chosen technology is **fast plastic PVT scintillators** equipped with **SiPM**-based read-out: **⟨read-out signal⟩ ~ ⟨lost energy⟩**, 20 ns response time after signal shaping → **it must be highly segmented**
  - sensitive elements are **200 × 10 × 5 mm^3 PVT fingers**, allowing for an **average hit interval of O(1) μs,** total amount: 5120 channels







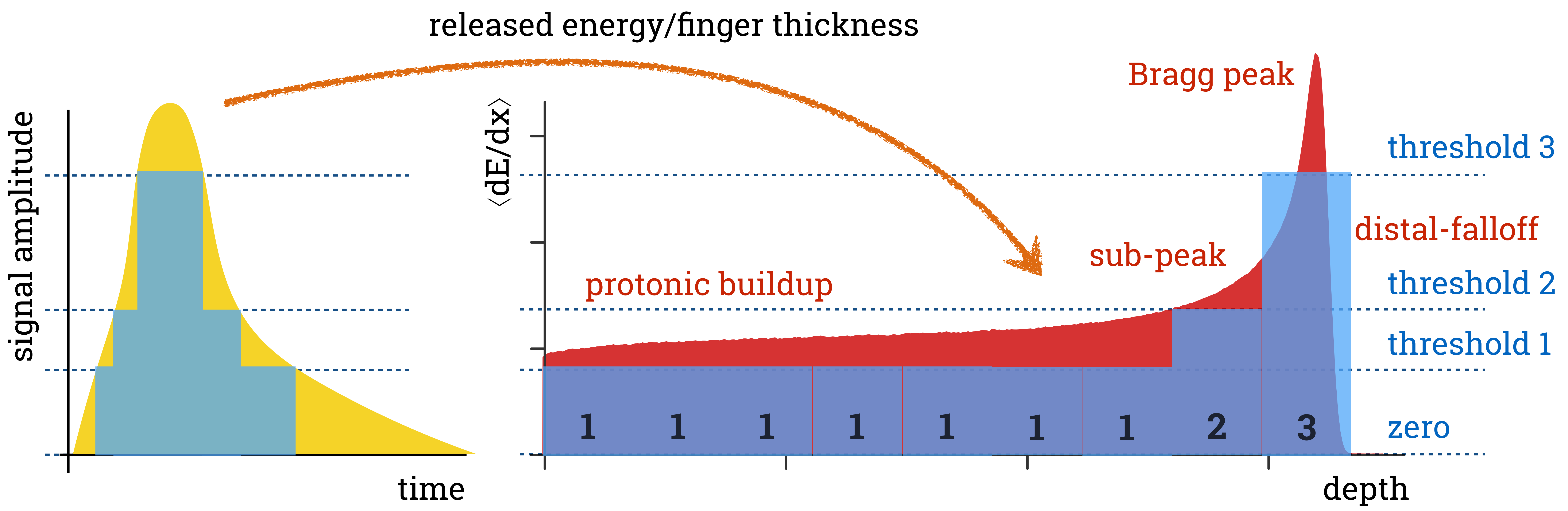
modular design:
2 modules = 1 corner
4 corners = 1 full layer
8 full layers = complete calorimeter

the iMPACT hybrid energy-range calorimeter

- evaluated technologies:
  - **St.Gobain BC-408** and BC-420 PVT scintillators and **Eljen Technology EJ-200** equivalent
  - Hamamatsu SiPM (MPPC) **S12572-025c 3 × 3 mm^2 featuring 25 × 25 µm^2 APD cells** and S12571-015c 1 × 1 mm^2 with 15 × 15 µm^2 APD cells
  - custom read-out electronics based on commercial products
- **early stage** characterisation of **sub-module prototypes**
  - **single-photon response** SiPM + front-end characterisation
  - **bench measurements** with cosmic muons and fast pulsed lasers 
  - **5 MeV proton beam** measurements at INFN-Legnaro laboratories
  - **70-228 MeV proton beam** measurements at the TIFPA beam line hosted at the APSS-Trento proton therapy centre 
  - **GATE simulation** toolkit based on the **Geant4** libraries

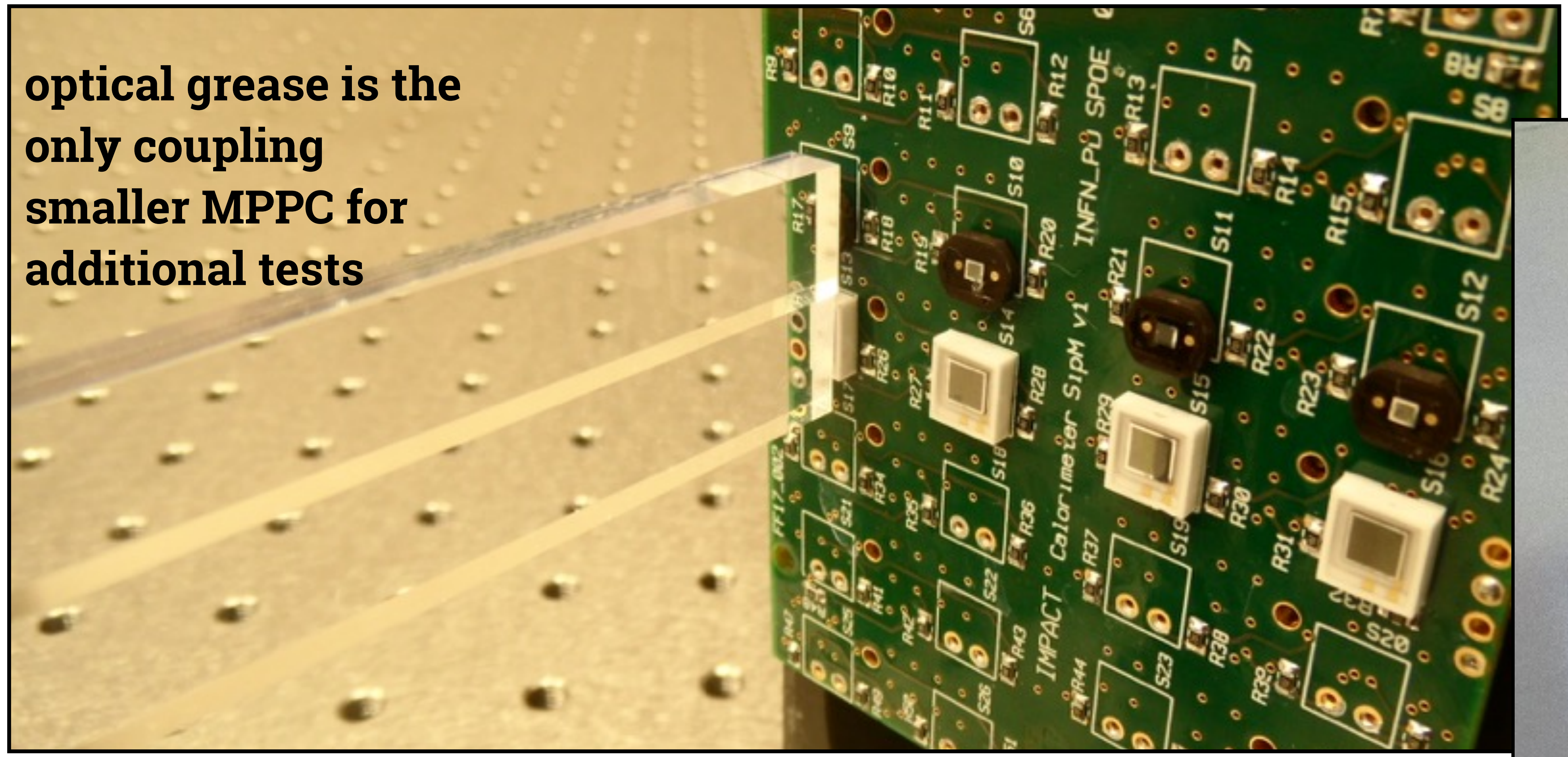
the data volume problem

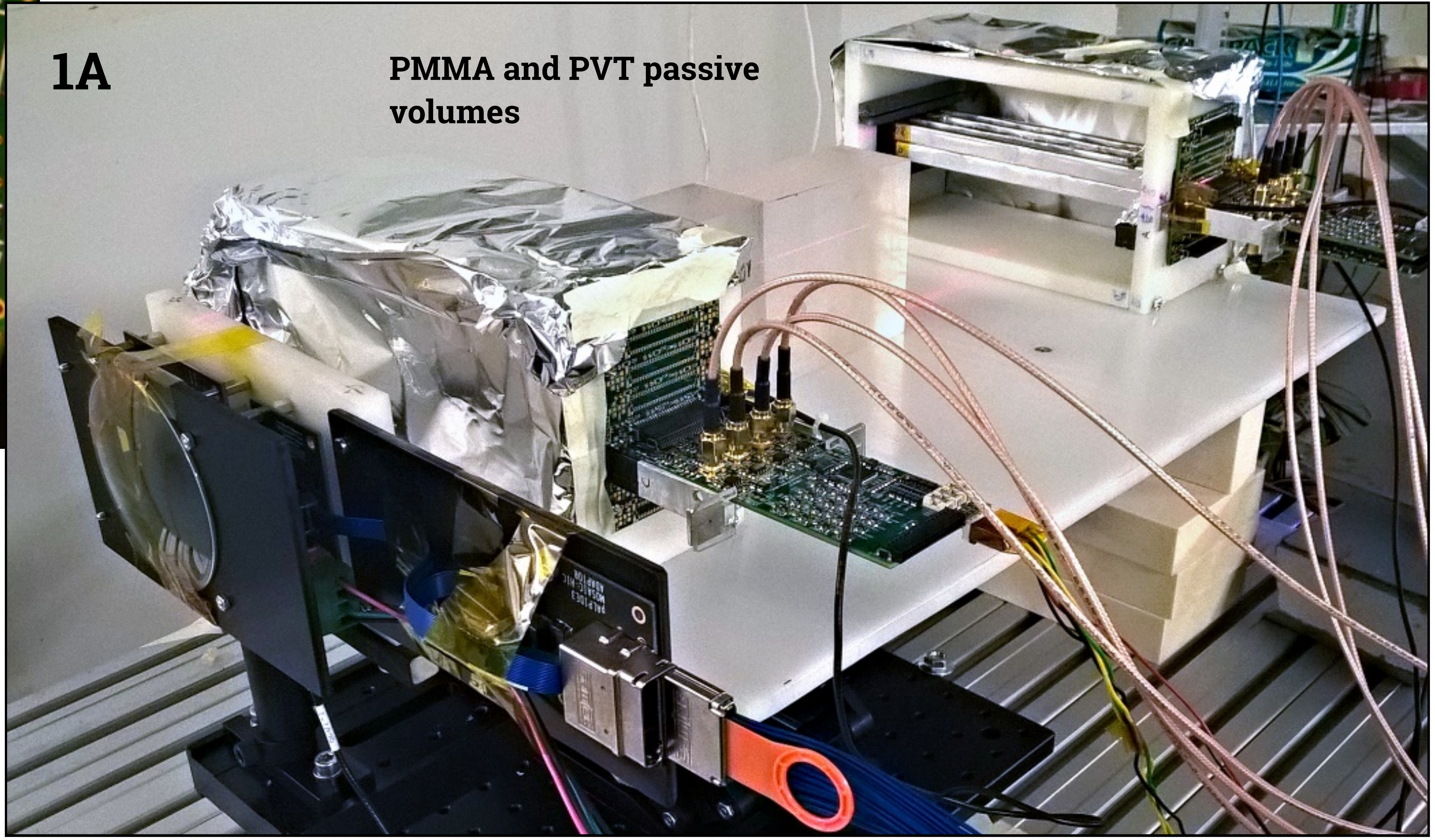
- a 230 MeV proton range in PVT is ~32 cm, resulting in ~60 crossed PVT fingers:
  up to ~60 excited channels per proton track
  - the footprint of a finely sampled, i.e. **analog-like, waveform** can be reduced down to **~25 kb**, resulting in an **overall non-sustainable load of O(1-10) Tbps**



can a clever digitisation of the signal based on few thresholds bring the needed band down to O(1) Gbps while retaining enough information for the purpose of pCT?

a sub-module prototype experimental setup

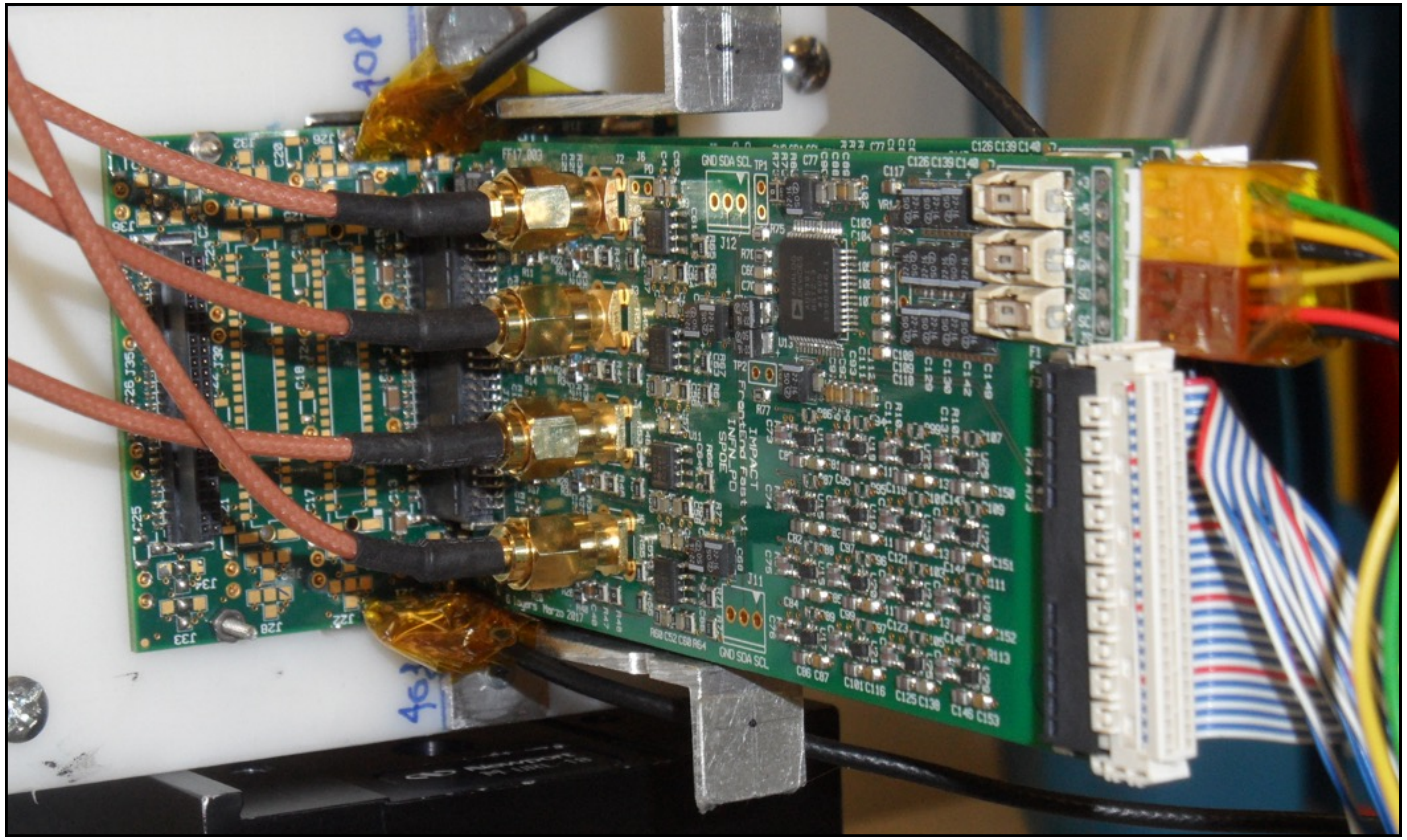




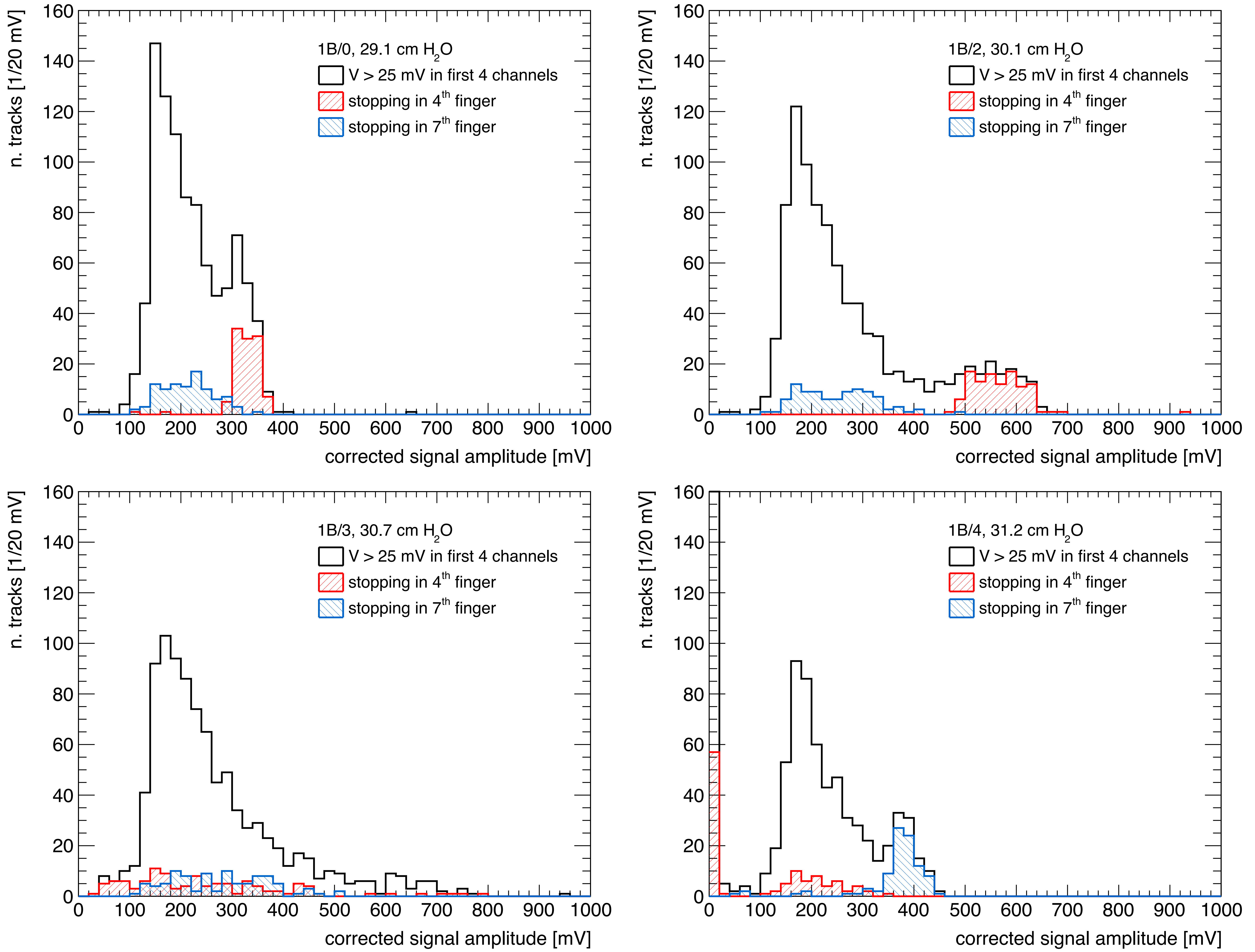
- several arrangements of active and passive volumes to sample the energy loss curve, e.g. “1A”: 4 fingers […] 4 fingers

a sub-module prototype experimental setup

- **expected collected signal: 1500–2000 photons** at Bragg Peak
  - 10 ns long photon burst
  - **primary signal from the SiPM lasts up to 100 ns** (SiPM quenching)
    - **derivative shaping stage** added to keep it below 20 ns
      - hit rate up to ~10 MHz /finger
- 3 comparators with programmable thresholds per channel
- SMA connectors let the analogue signal be available for debugging purpose
  - PSI DRS4 evaluation board for DAQ



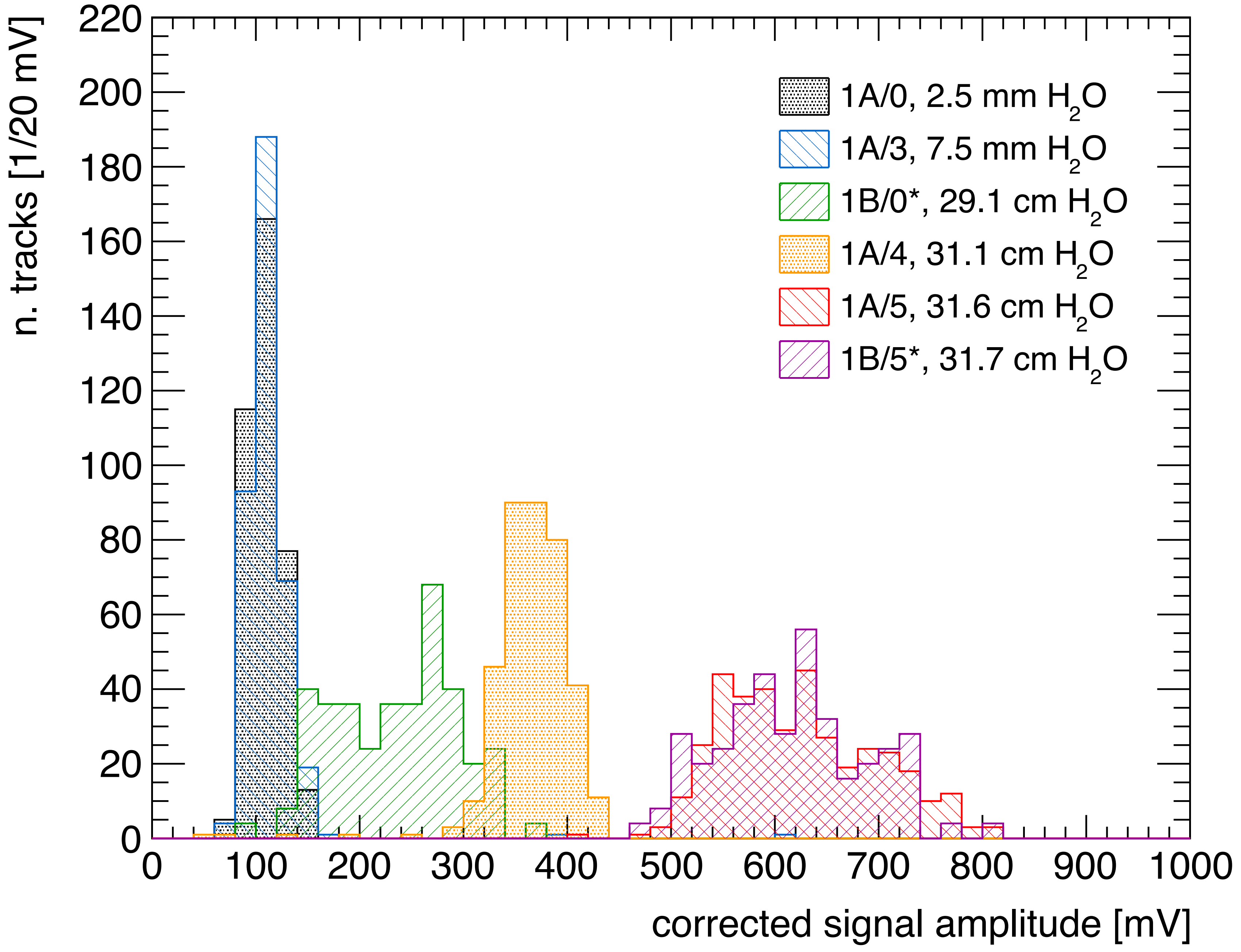
characterisation with medical energy proton beam

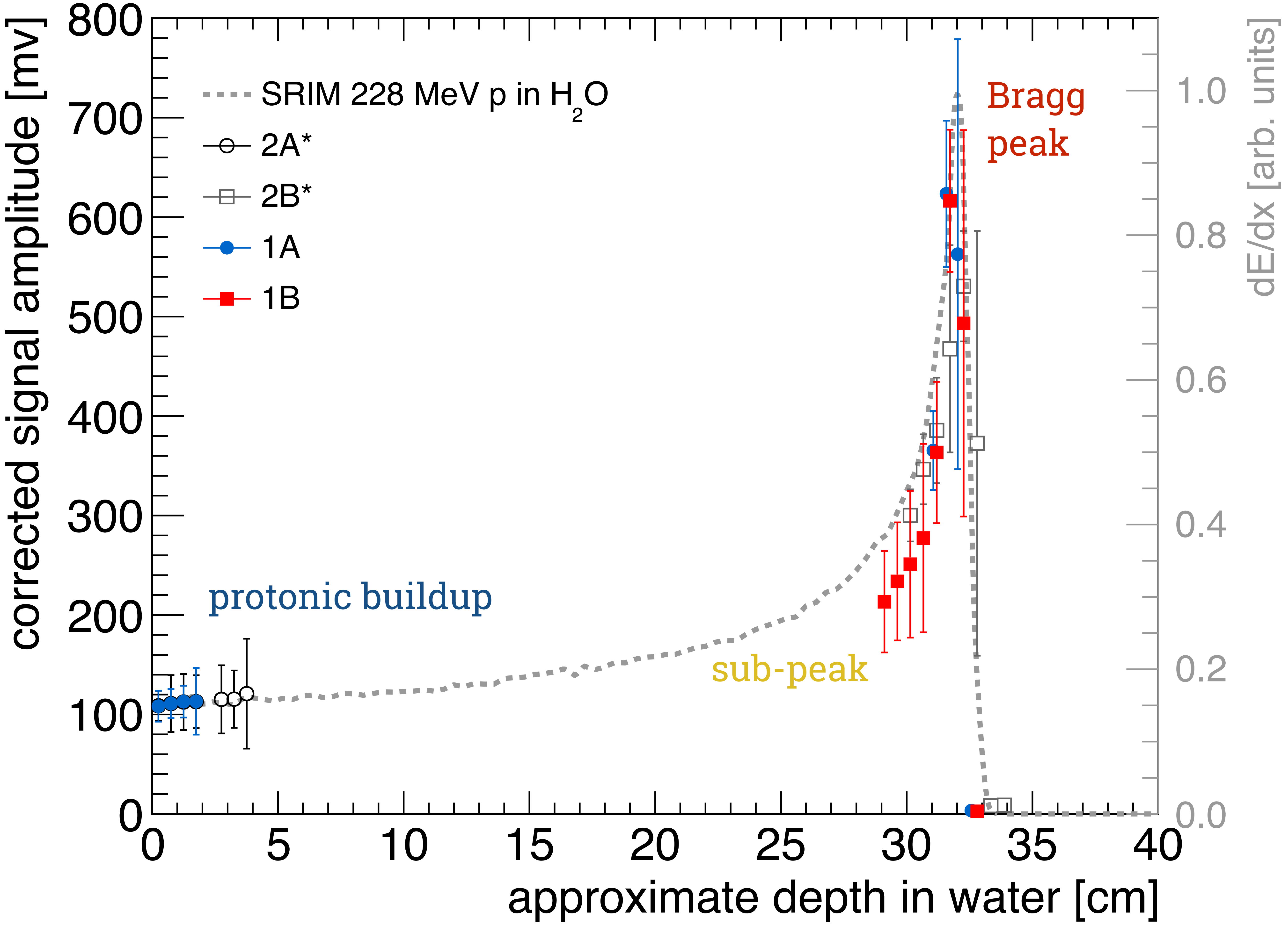


- MAPS sensor under test: additional material crossed by protons
- the prototype can see protons stopping at different depths

characterisation with medical energy proton beam

- different sampling depths along proton path: distinct signal spectra



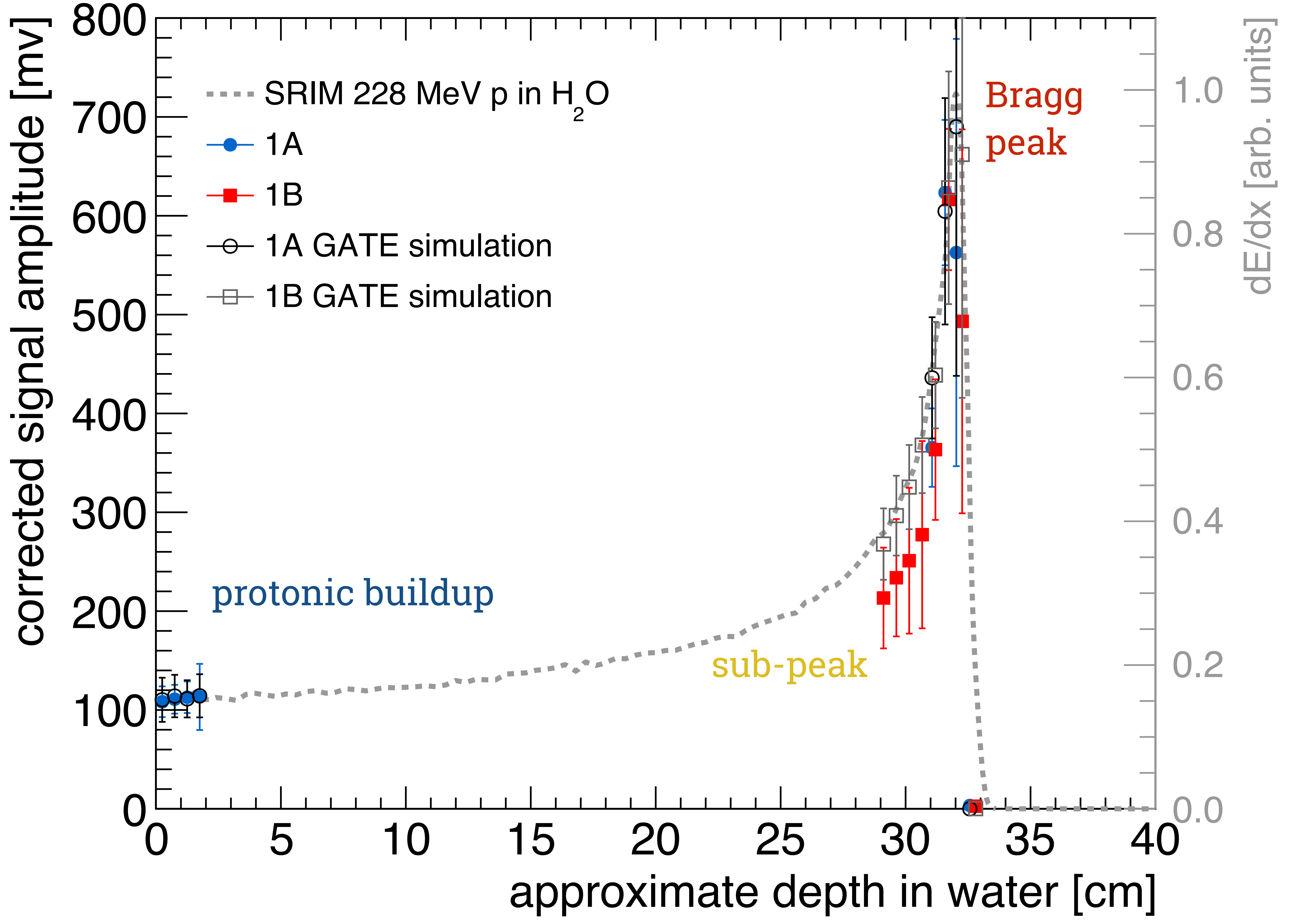


- **the energy loss curve can actually be reconstructed even with few 100's efficiently collected protons**

- shown: only protons coming at rest at a depth corresponding to 6th/7th active PVT finger in 1A/1B

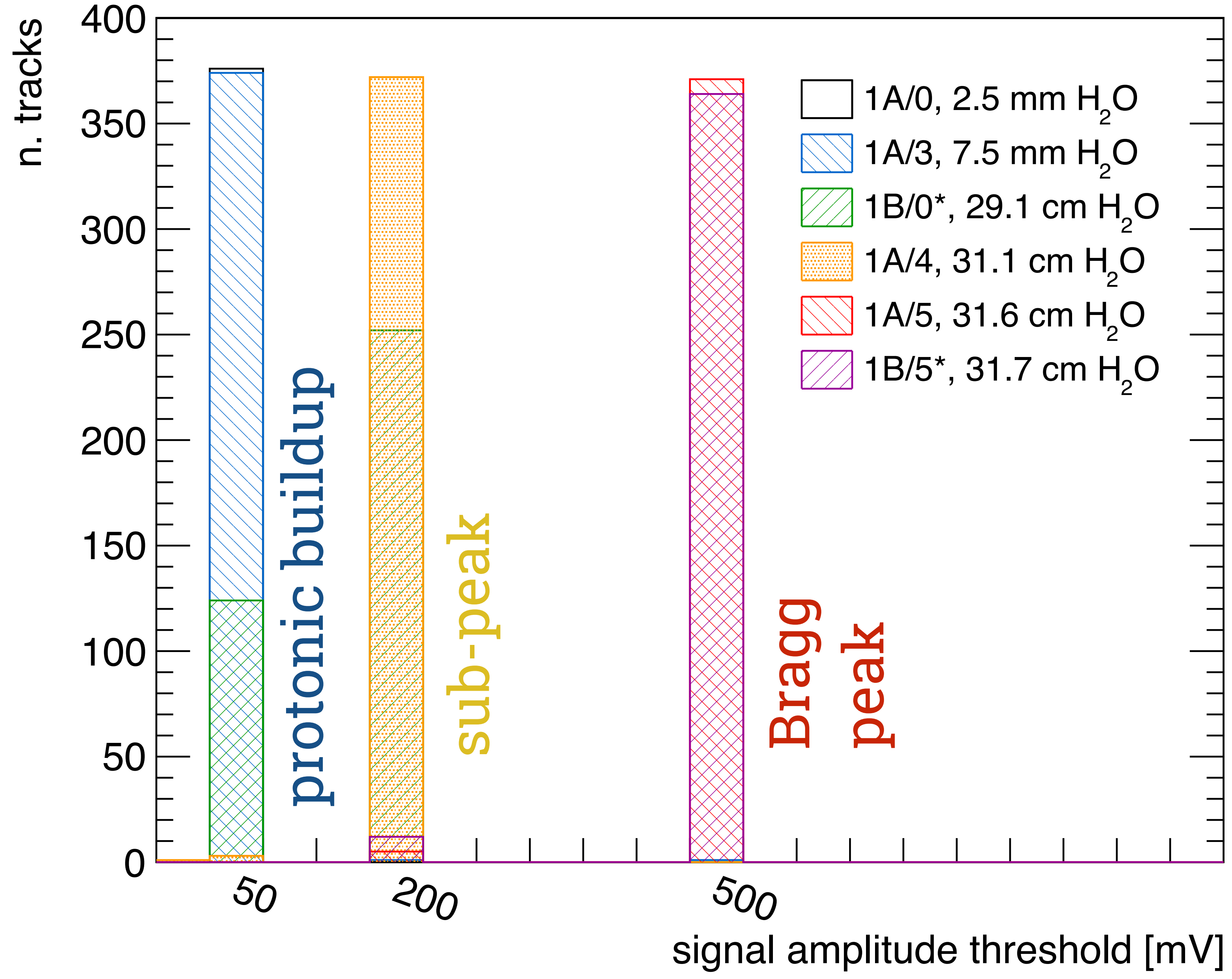
characterisation with medical energy proton beam

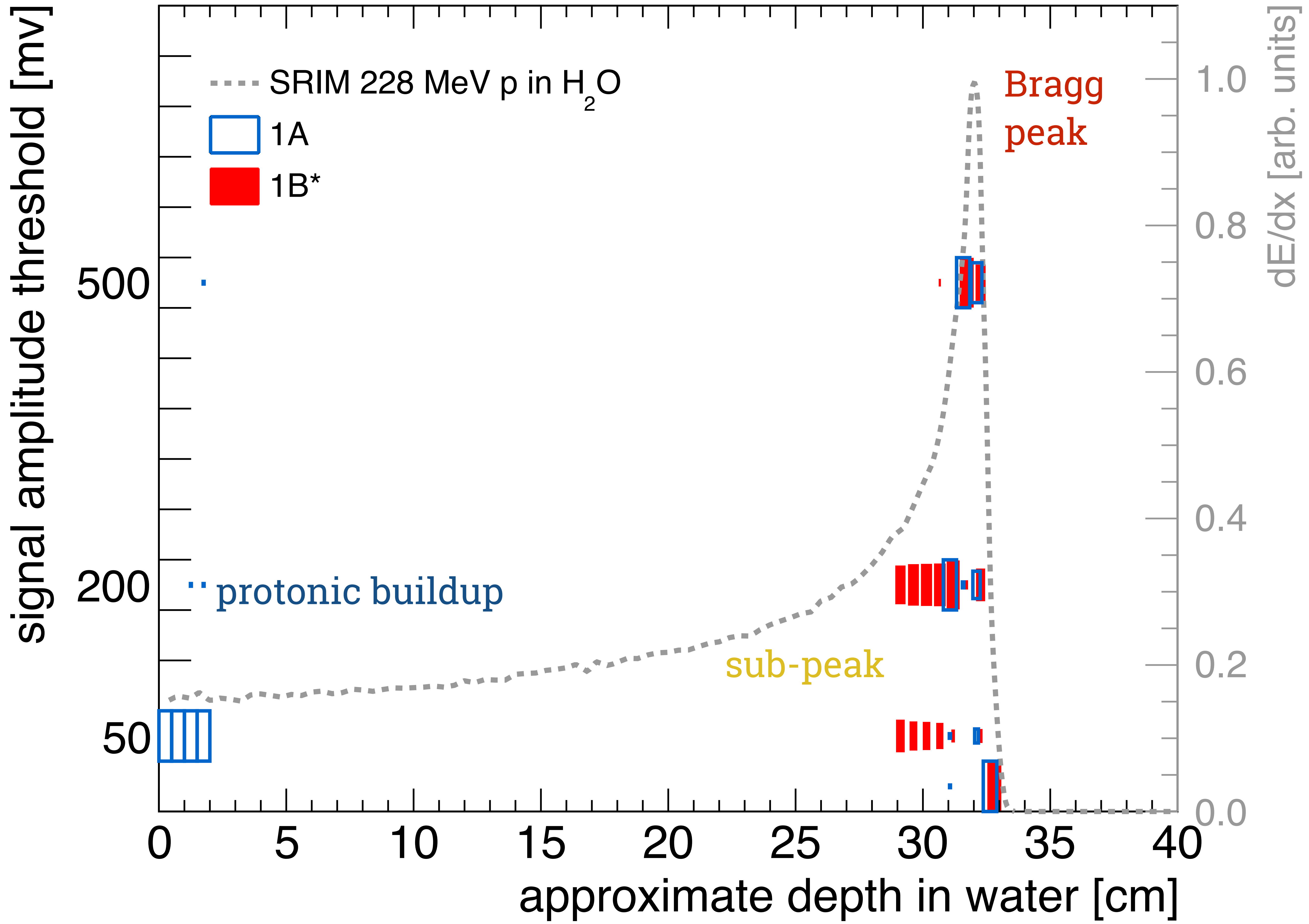
- GATE simulation is under control, despite being still tuned w.r.t. an earlier version of the readout electronics
- signal amplitudes are systematically affected by trigger anomalies currently being addressed



2-bits digitisation of the expected signal

- what does the energy loss curve look like when digitally sampled at the relevant depths?



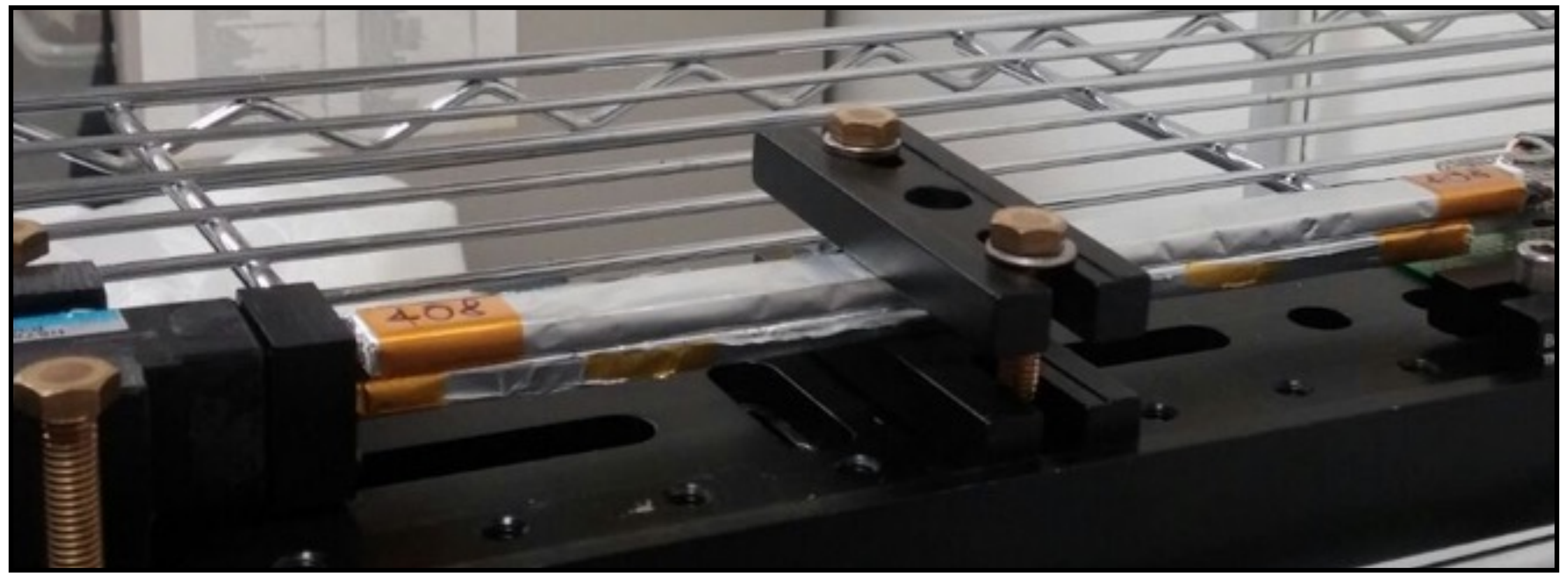


- box area is proportional to the number of tracks resulting in a signal larger than each threshold
- wide spectrum at the sub-peak results in both first and second level digital signals, being the second population larger

the 3-threshold-based digitiser can be a viable solution

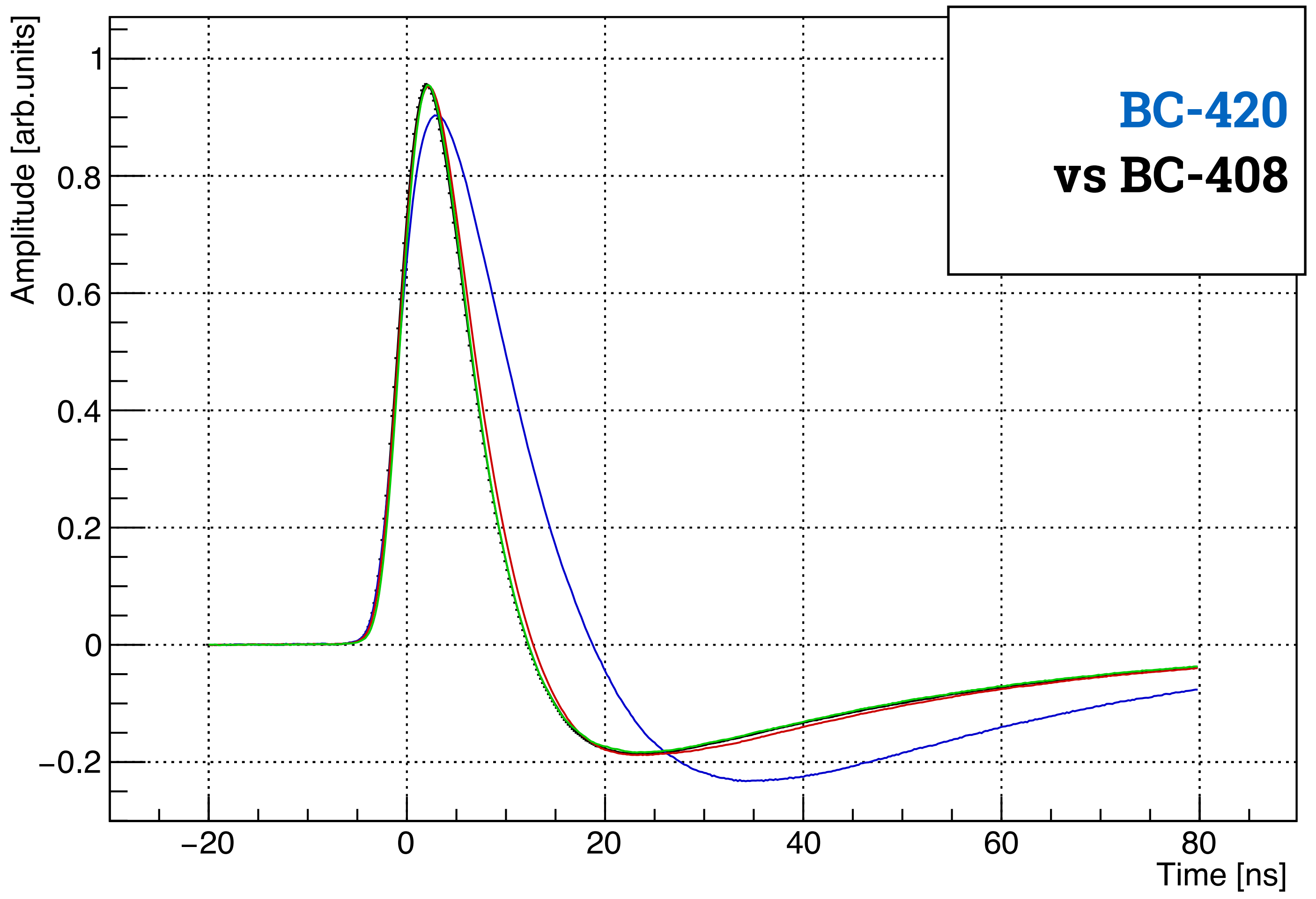
comparative studies with cosmic MIP muon

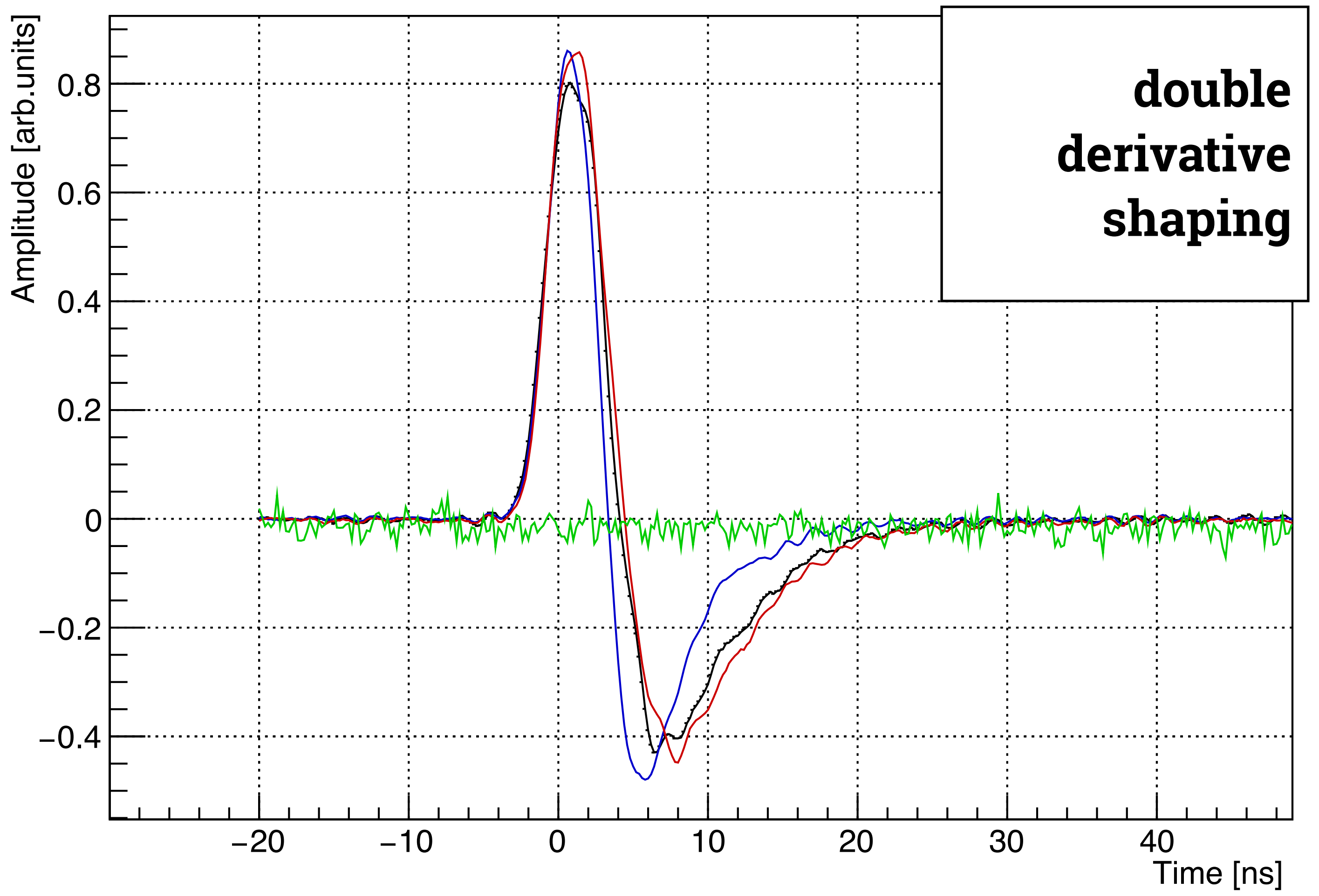
- arrays of PVT fingers in coincidence with oscilloscope and LabView interface



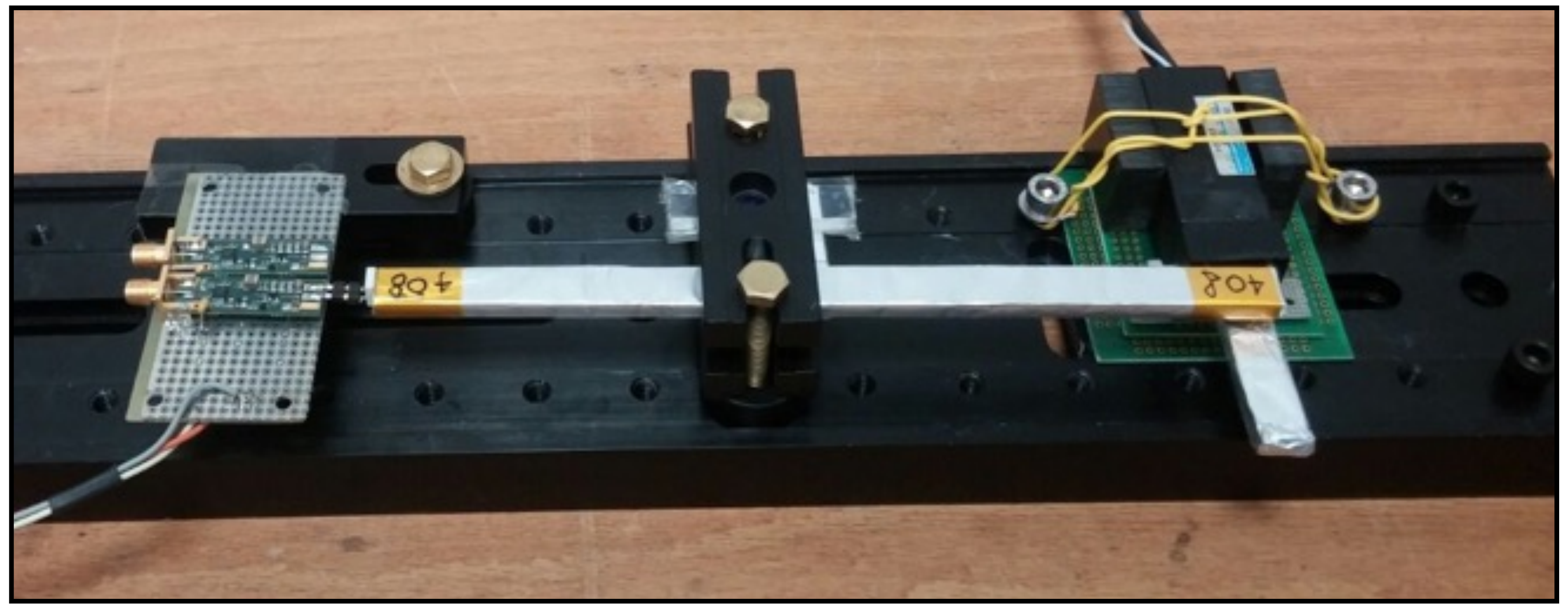
- **EJ-200** equivalent to BC-408, both faster than BC-420
- **additional derivative** stage in pulse shaping shortens the signal
- **SiPM quenching time** estimated **~100-120 ns** → 10 MHz/finger

- finger length /2 and /4 resulting in 2 ns shorter signals, no relevant difference if PMT in place of SiPM: **scintillation process still dominating signal length**



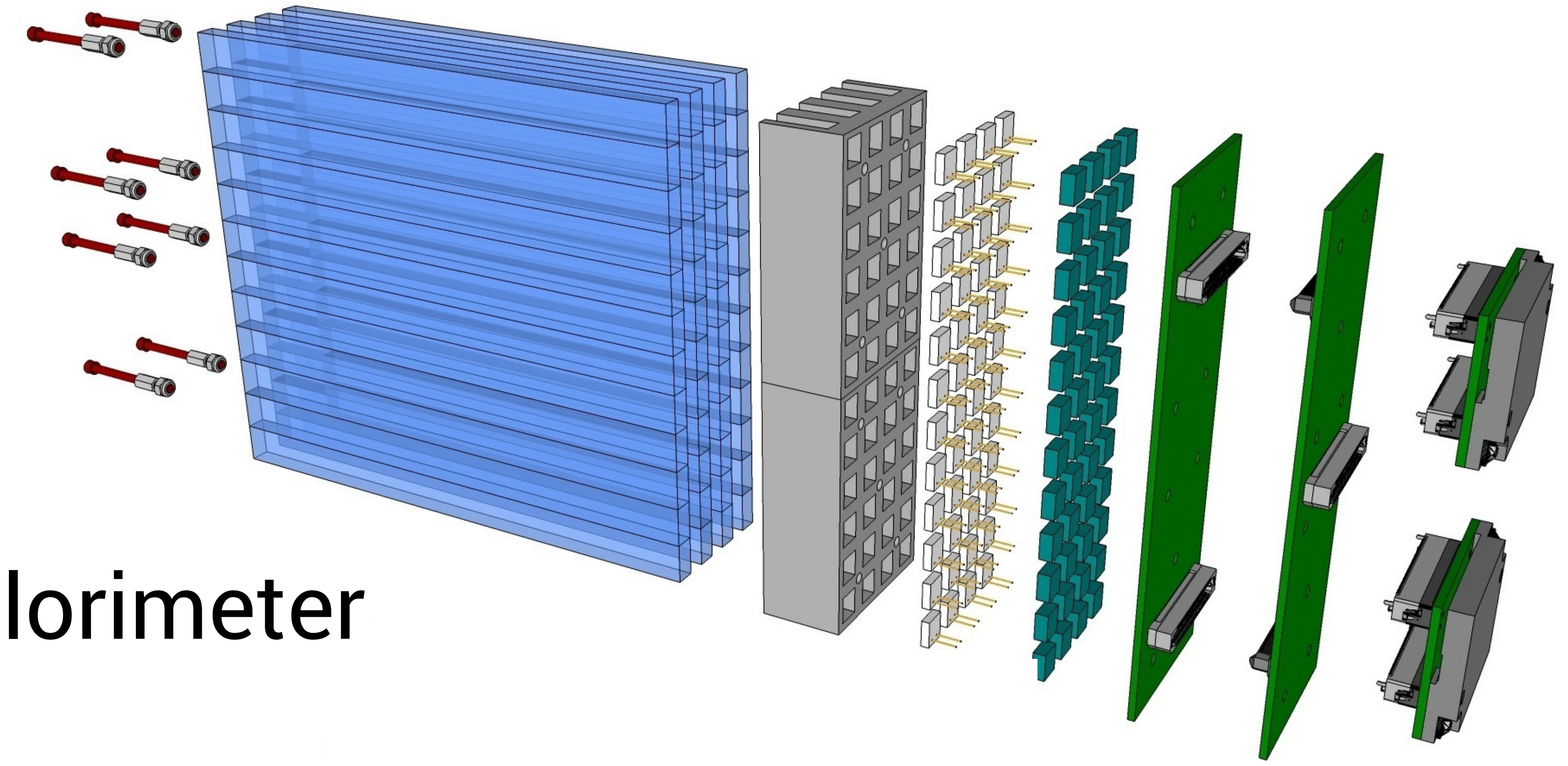


- crossed scintillators to evaluate the effect of particle impact position …

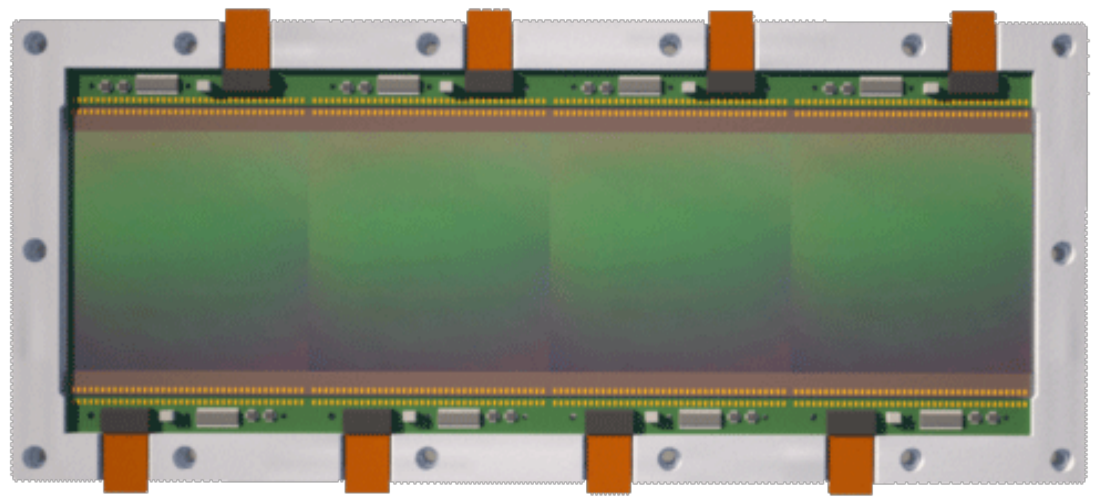


future developments

- new tests with proton beam data at the end of this year
  - consolidation of calorimeter simulations
  - DAQ development
  - construction and characterisation of **one full module** of the calorimeter



- construction of one tracker station
- development of a new tracker sensor with a faster architecture



the iMPACT project has received funding from the European Research Council under the European Union's Horizon 2020 research and innovation programme

references

[0] *Rep. Prog. Phys.* **81** (2018) 016701 — the most recent review on pCT

[1] *J. Rad. Oncol. Biol. Phys.* **5** (1979) 1809
[2] *Br. J. Radiol.* **58** (1985) 542
[3] *Phys. Med. Biol.* **43** (1998) 1579
[4] arXiv:1707.01580, *JINST* **12** (2017) C01034
[5] *Phys. Med. Biol.* **53** (2008) 5461
[6] *IEEE Trans. Nucl. Sci.* **26** (1979) 1635
[7] see, for example, *Med. Phys.* **40** (2013) 031103
[8] *IEEE Trans. Nucl. Sci.* **63** (2016) 52
[9] *Med. Phys.* **43** (2016) 664

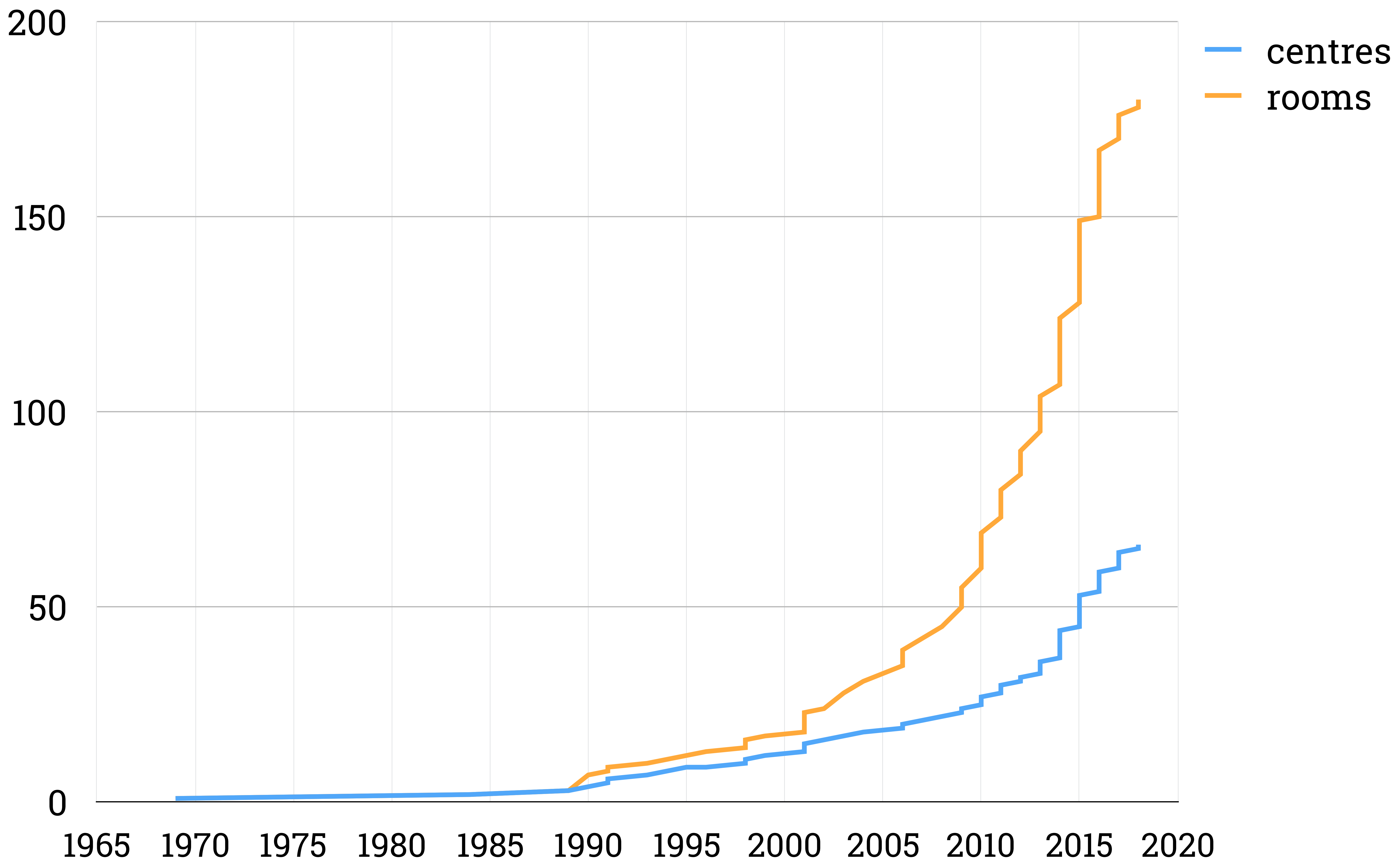
more about iMPACT and related projects

[10] *Nucl. Instrum. Meth. A* **845** (2017) 664
[11] F. Baruffaldi — accepted by *Il Nuovo Cimento* (SIF 2017)
[12] S. Mattiazzo et al. – acc. by *IEEE Trans. Rad. Plasma Med. Sci.* (IEEE NSS/MIC 2017)
[13] P. Giubilato in IEEE NSS/MIC 2016
[14] *JINST* **10** (2015) C05004
[15] *Radiat. Prot. Dosimetry* **166** (2015) 388

backup material

proton therapy growth

- source: ptcog.ch particle therapy co-operative group



pCT: state of the art as of 2017

- NIU, FNAL: sci-fi + ~3 mm thick planes scintillator calorimeter, large aperture

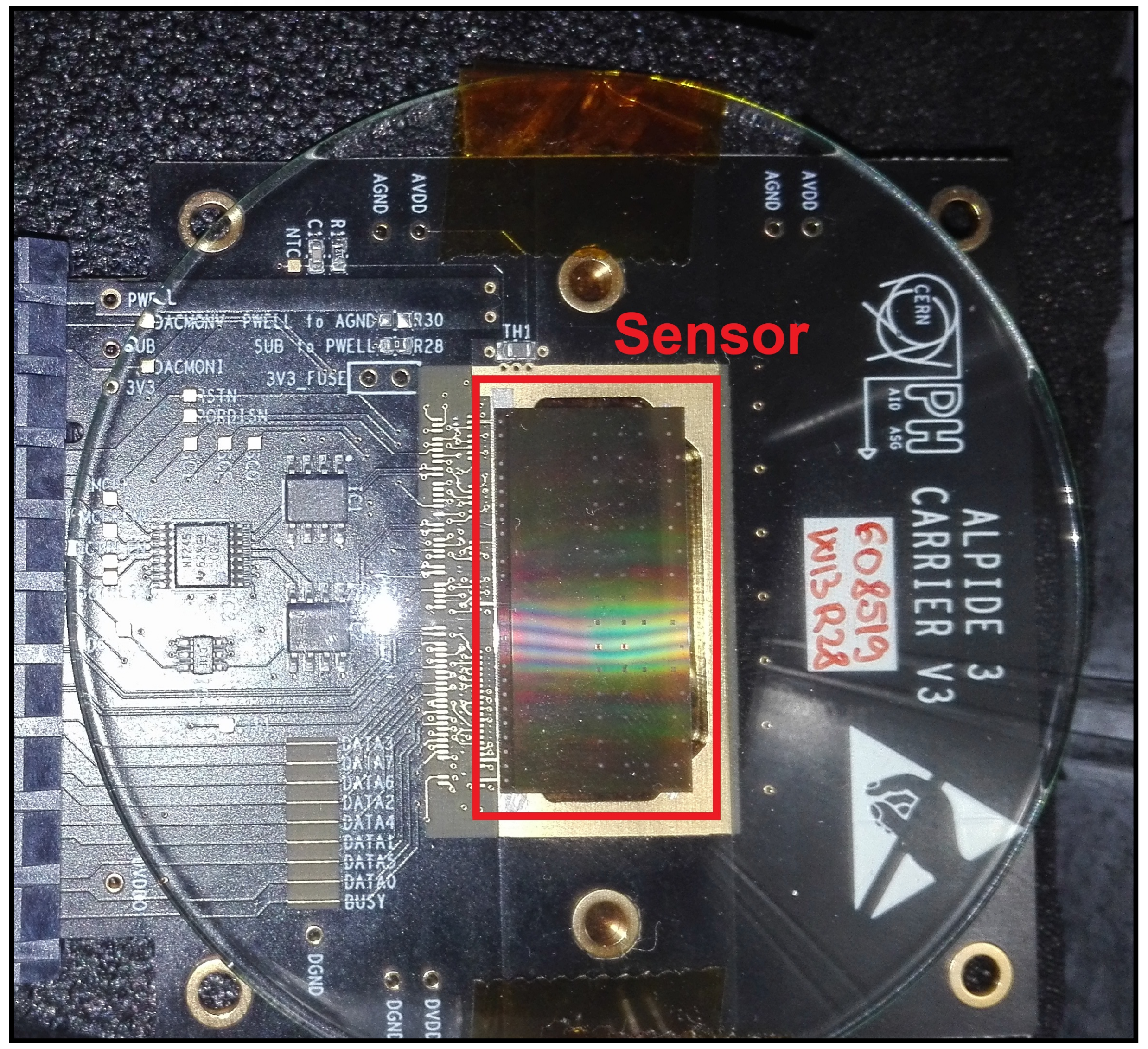
- PRIMA: 8 layers of Si strip + cerium-activated yttrium aluminum garnet crystals (YAG:Ce, fast decay scintillator)

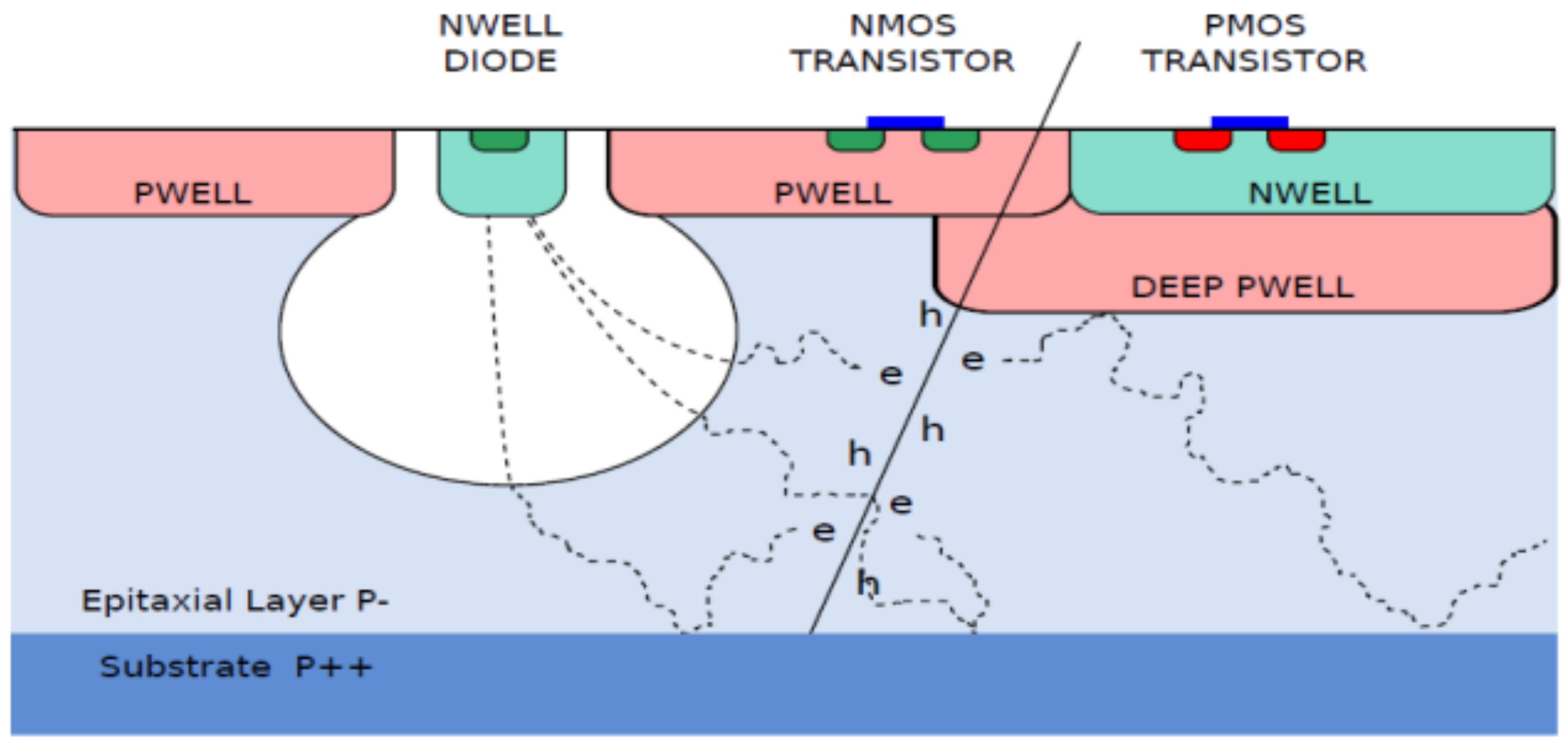
- LLU/UCSC Phase-II: the most advanced prototype so far, 1.2 MHz proton rate,
  8 layers of Si strip derived from gamma astrophysics experiments + hybrid 5-stage energy-range calorimeter
    - same tracker sensors used in Niigata: early-stage small-aperture prototype

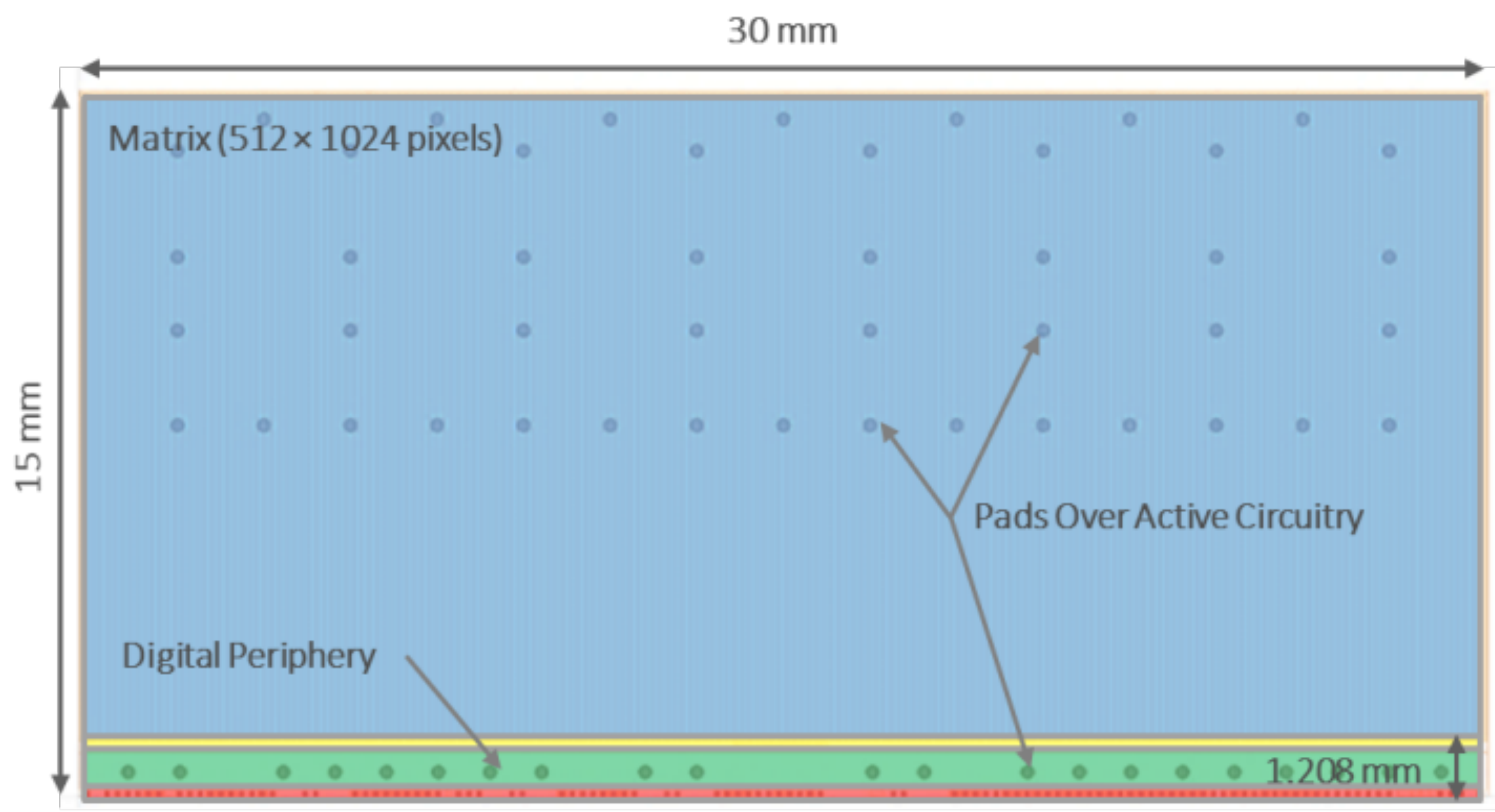
- PRaVDA: all-Si based pCT scanner

preliminary tracker prototype: the ALPIDE sensor

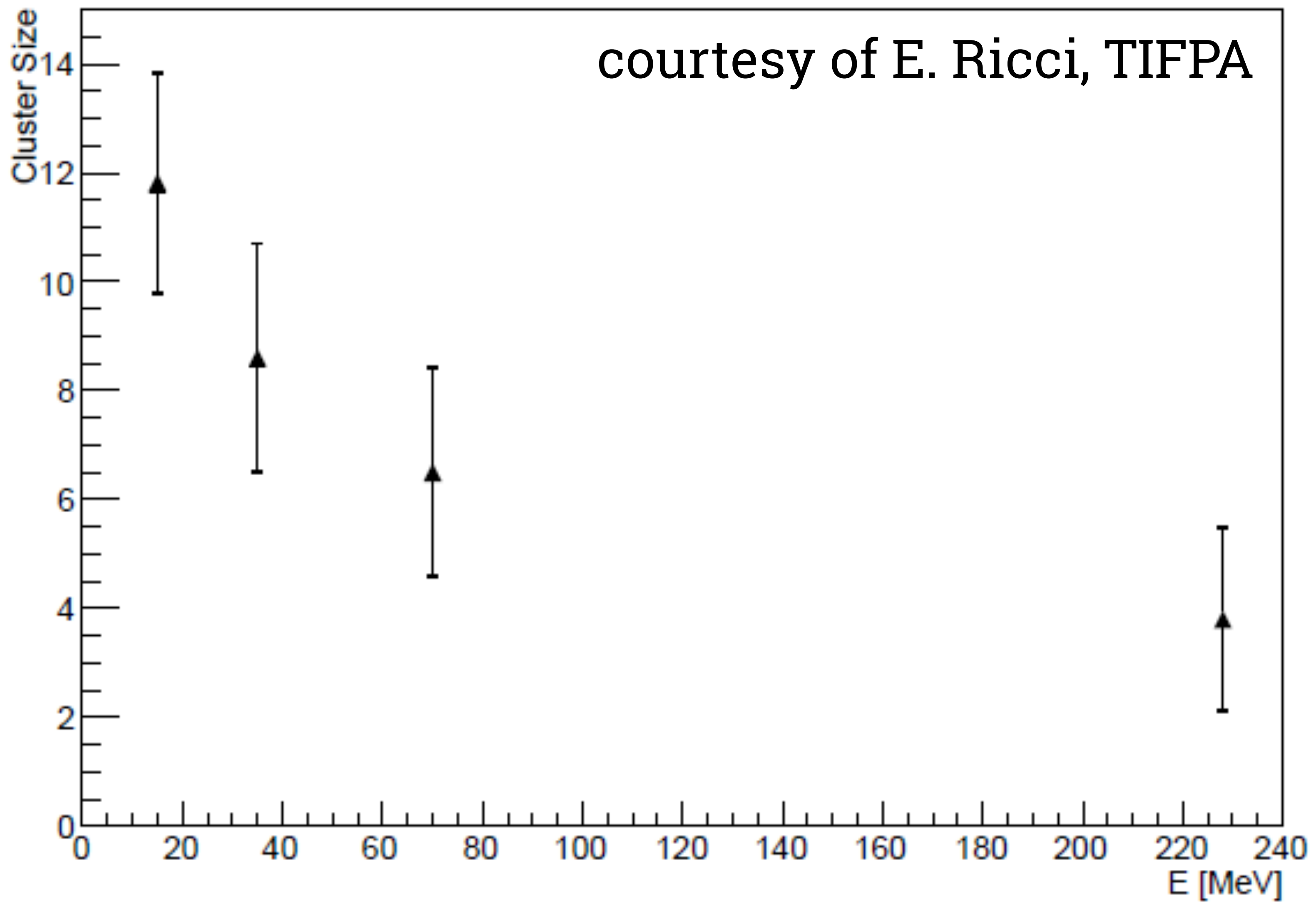
- developed for the upgrade of the ALICE Inner Tracking System
- ALPIDE chip is a MAPS of 30 × 15 mm^2 active area, 1024 × 512 matrix of 28 × 28 μm^2 large pixels
- 180 nm Tower Jazz process on a high resistivity epitaxial layer, backthinned to 100 μm
- sustainable particle rate up to 100 kHz/cm^2
- digital output with priority encoder-based zero suppression logic on-chip



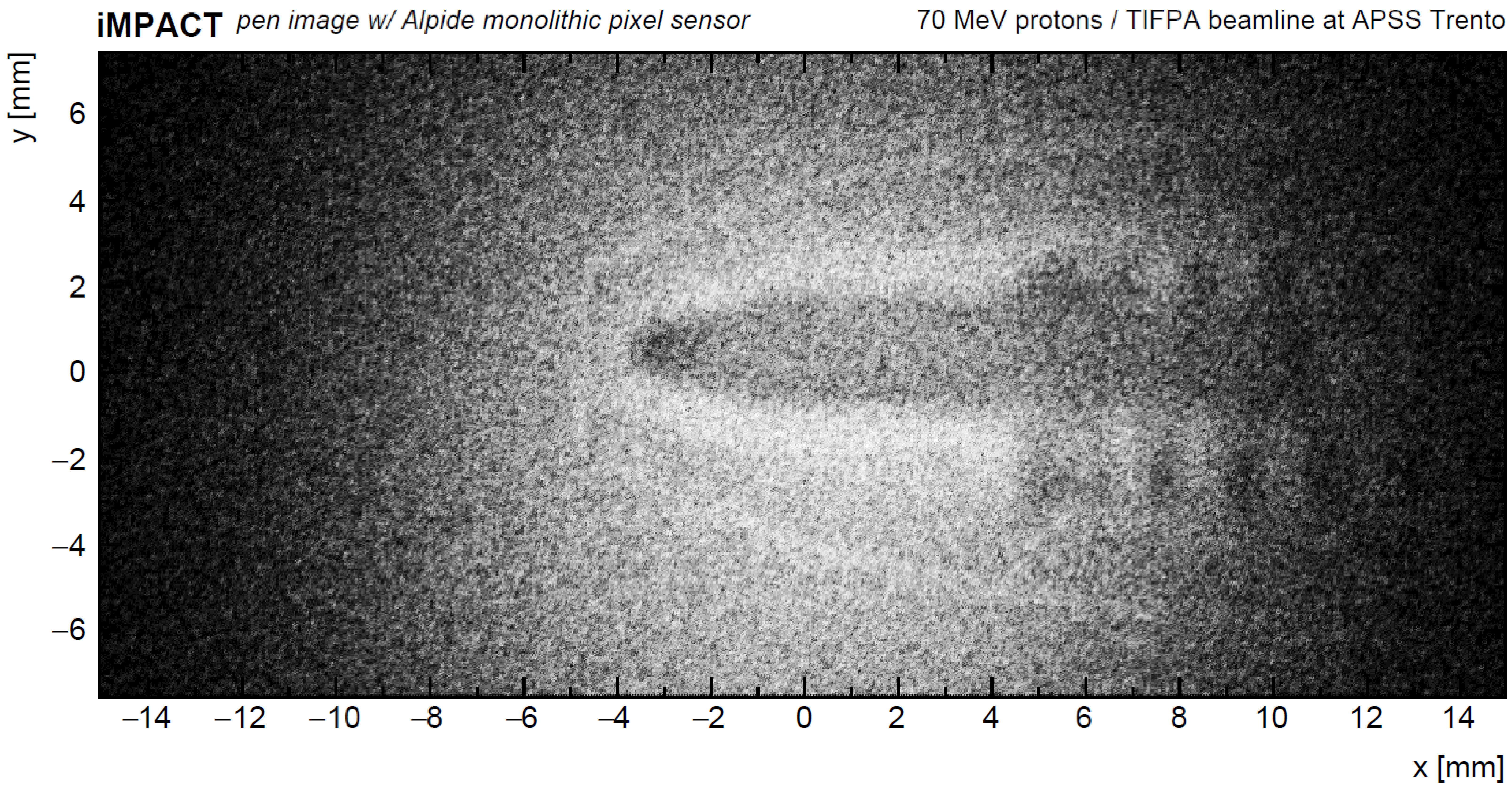




preliminary tracker prototype: the ALPIDE sensor

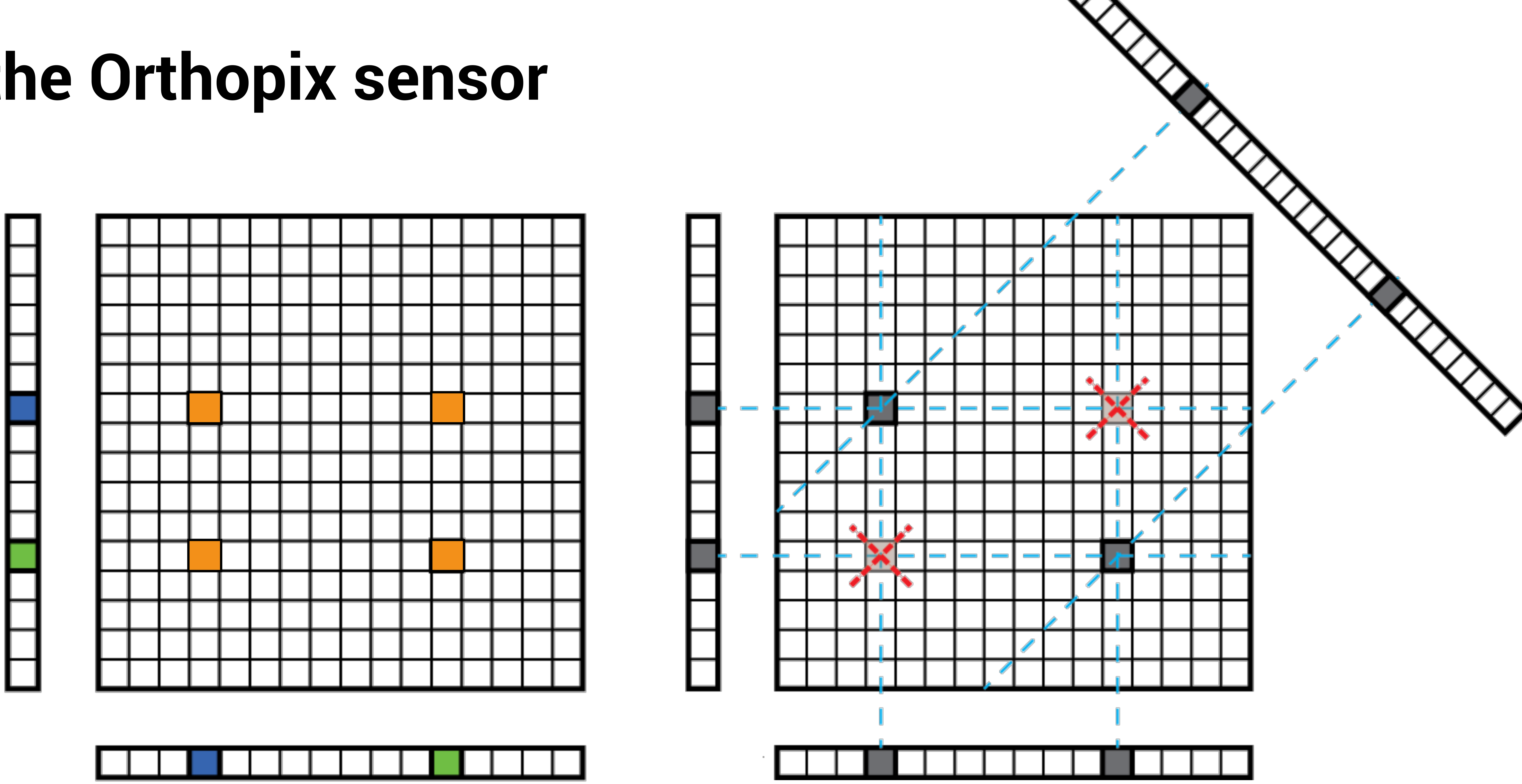


- cluster size evaluated with different proton beam energies and backside voltage
- demonstration of proton radiography capabilities



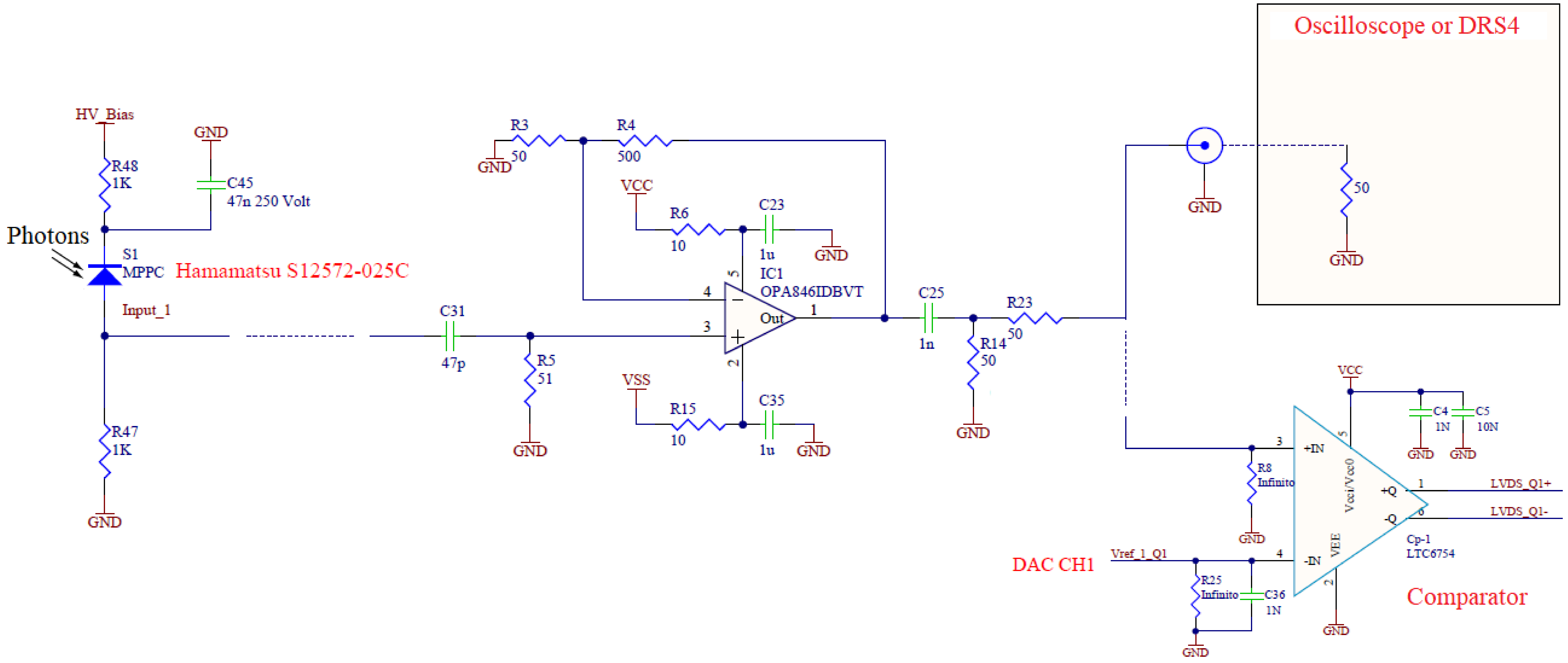
parallel tracker R&D: the Orthopix sensor

- projective readout as in Si strips is affected by ambiguous assignments of measured hits
- ambiguities can be solved by a general projection system that can be implemented by metal lines in modern deep sub-micron microelectronic processes



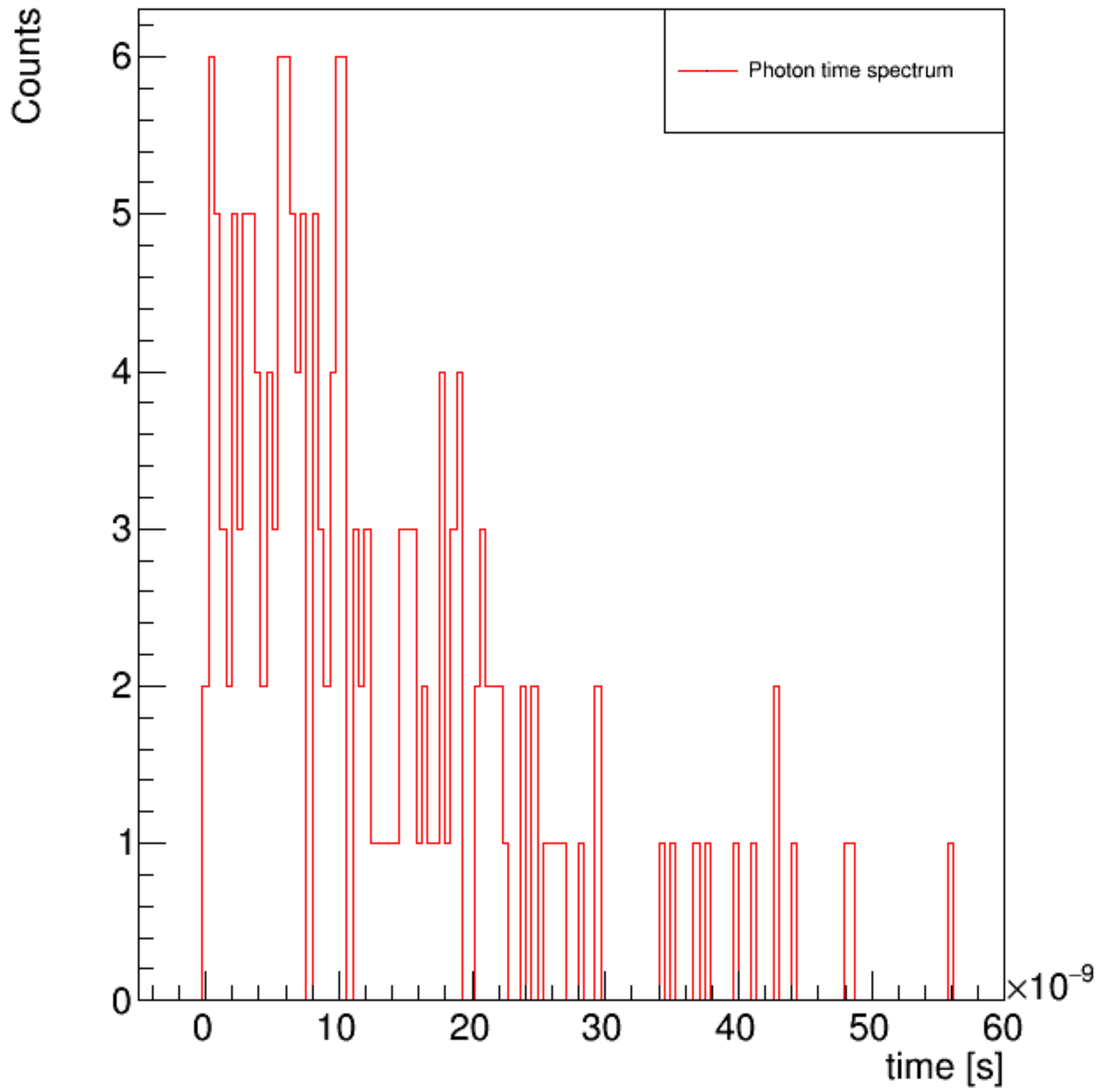
"Method and system for compressing a data array"
P. Giubilato and W. Snoeys – Patent – C31652PCT

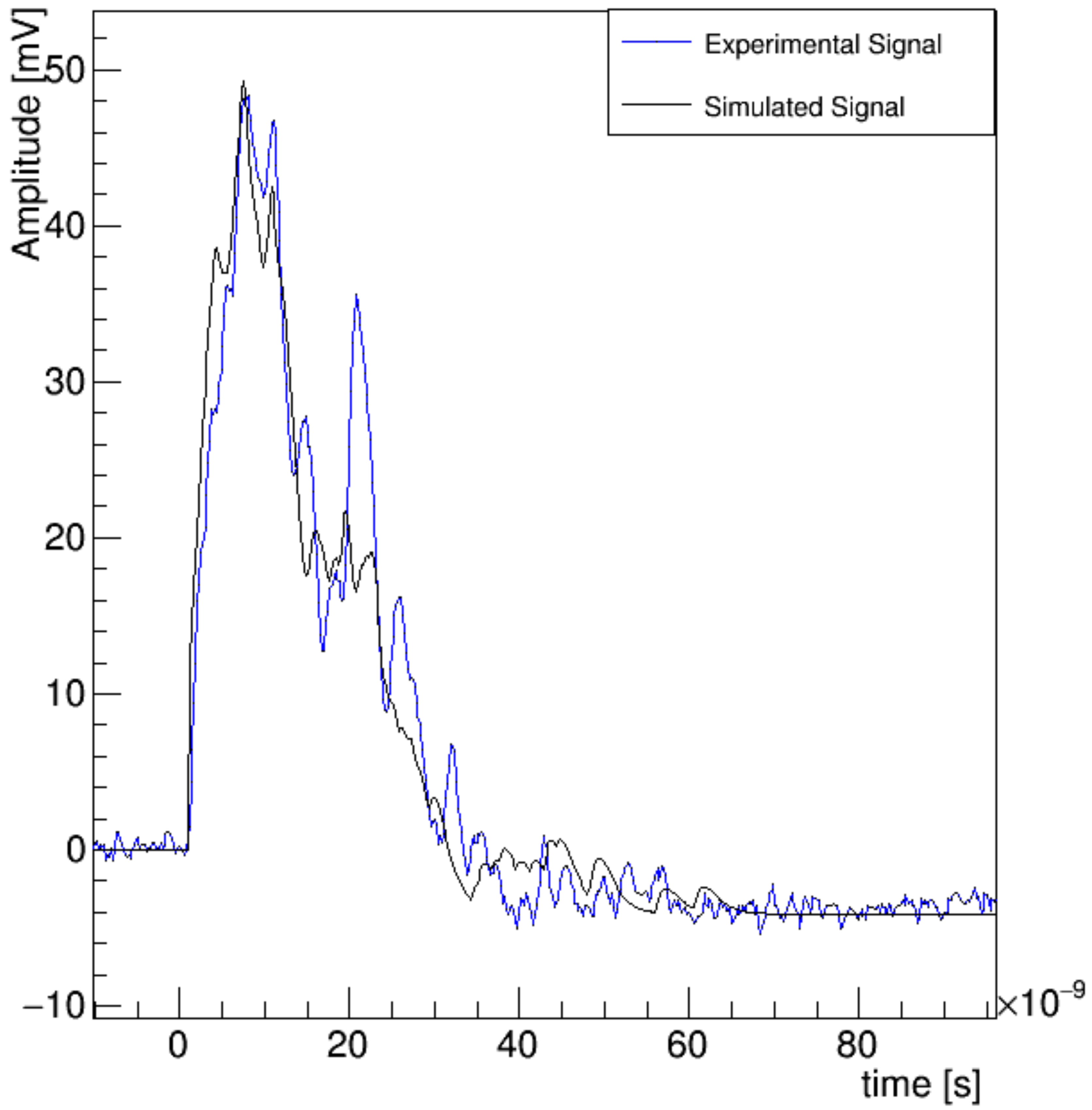
custom front-end electronics



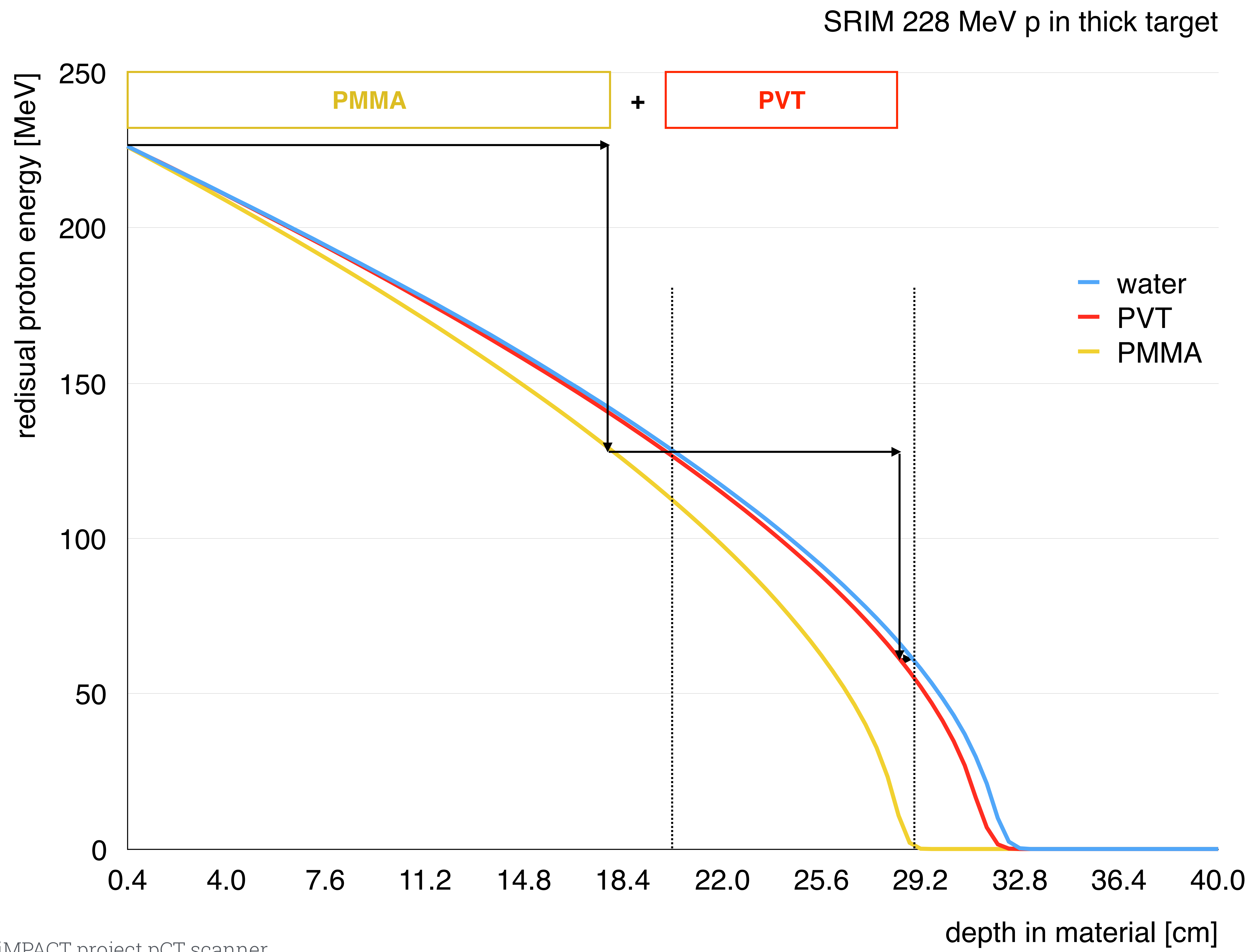
data-driven signal simulation

- photon time distribution convoluted with single photon signal pulse
- full chain tested with laser, cosmic rays and 3.5-5 MeV proton beam at the CN accelerator in INFN-Legnaro laboratories

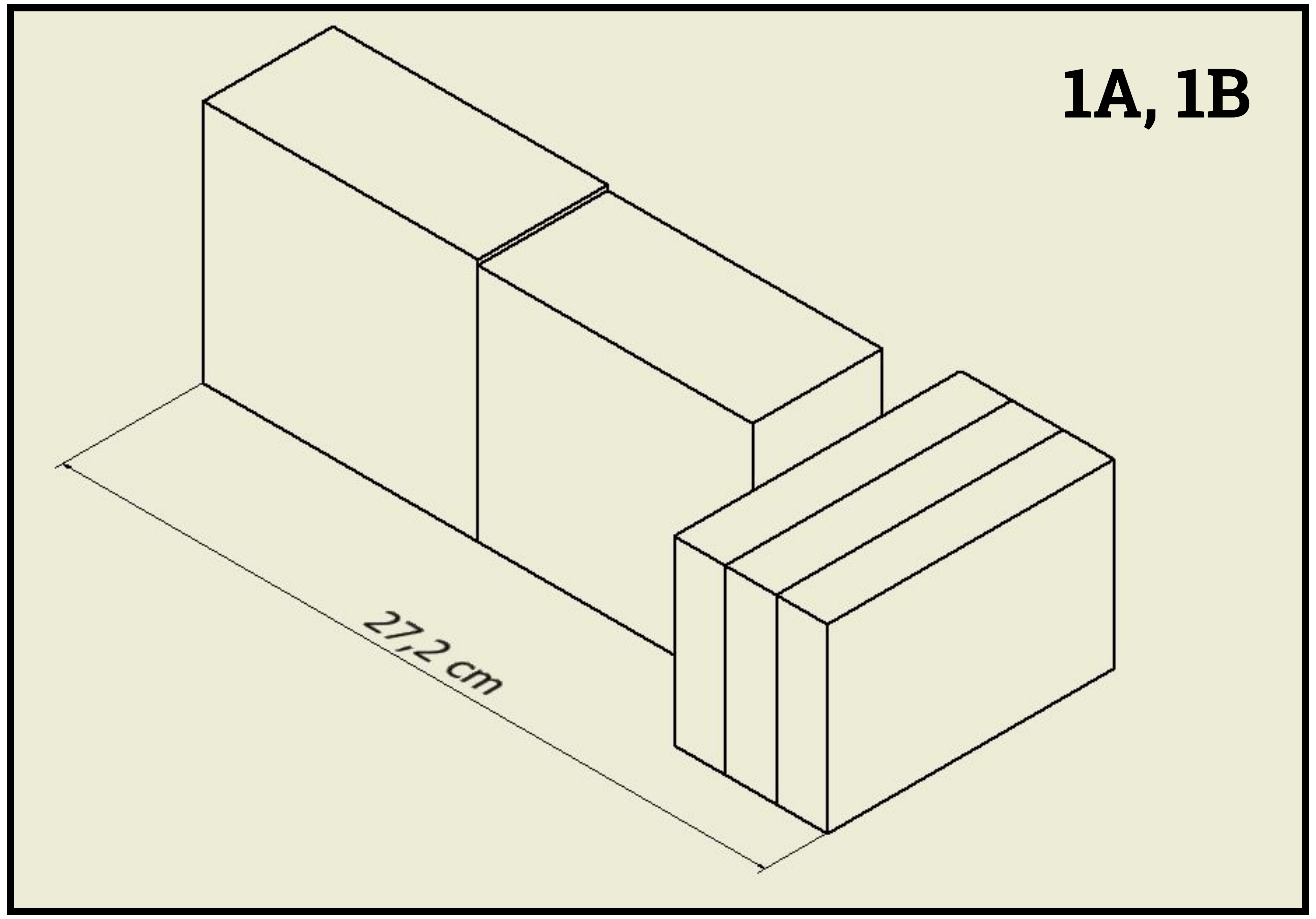


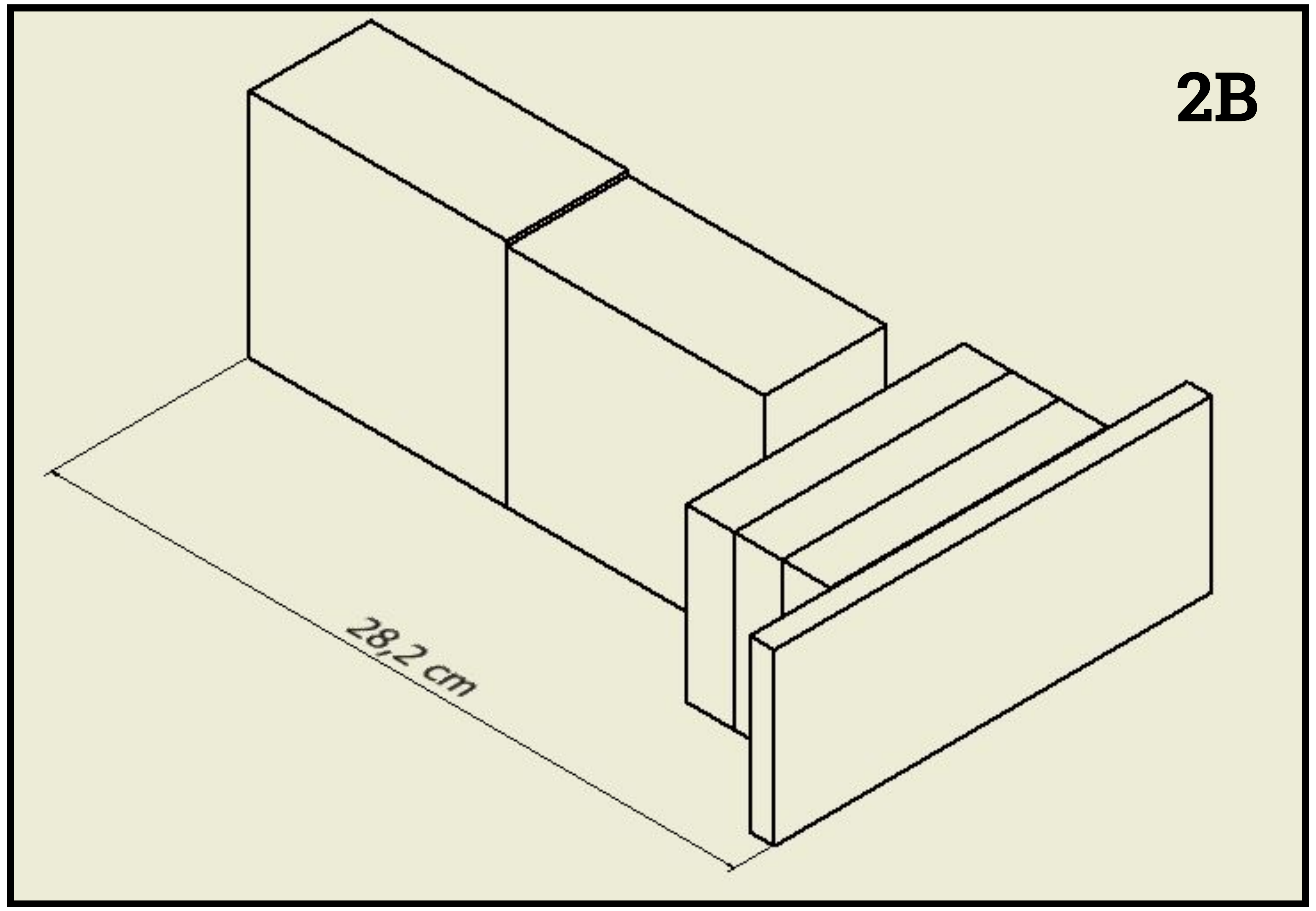


approximate equivalent depth in water



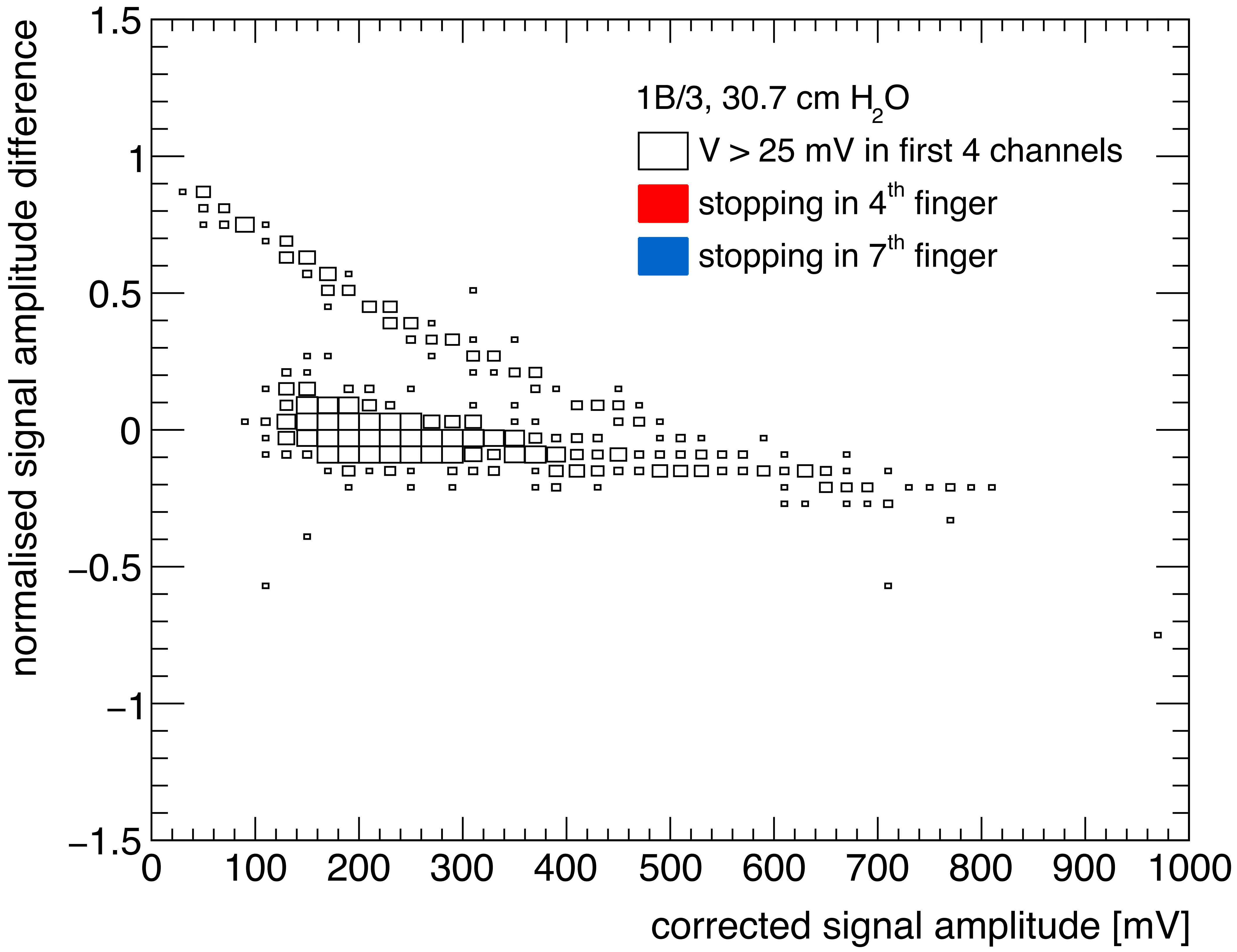
layout of passive PMMA and PVT volumes

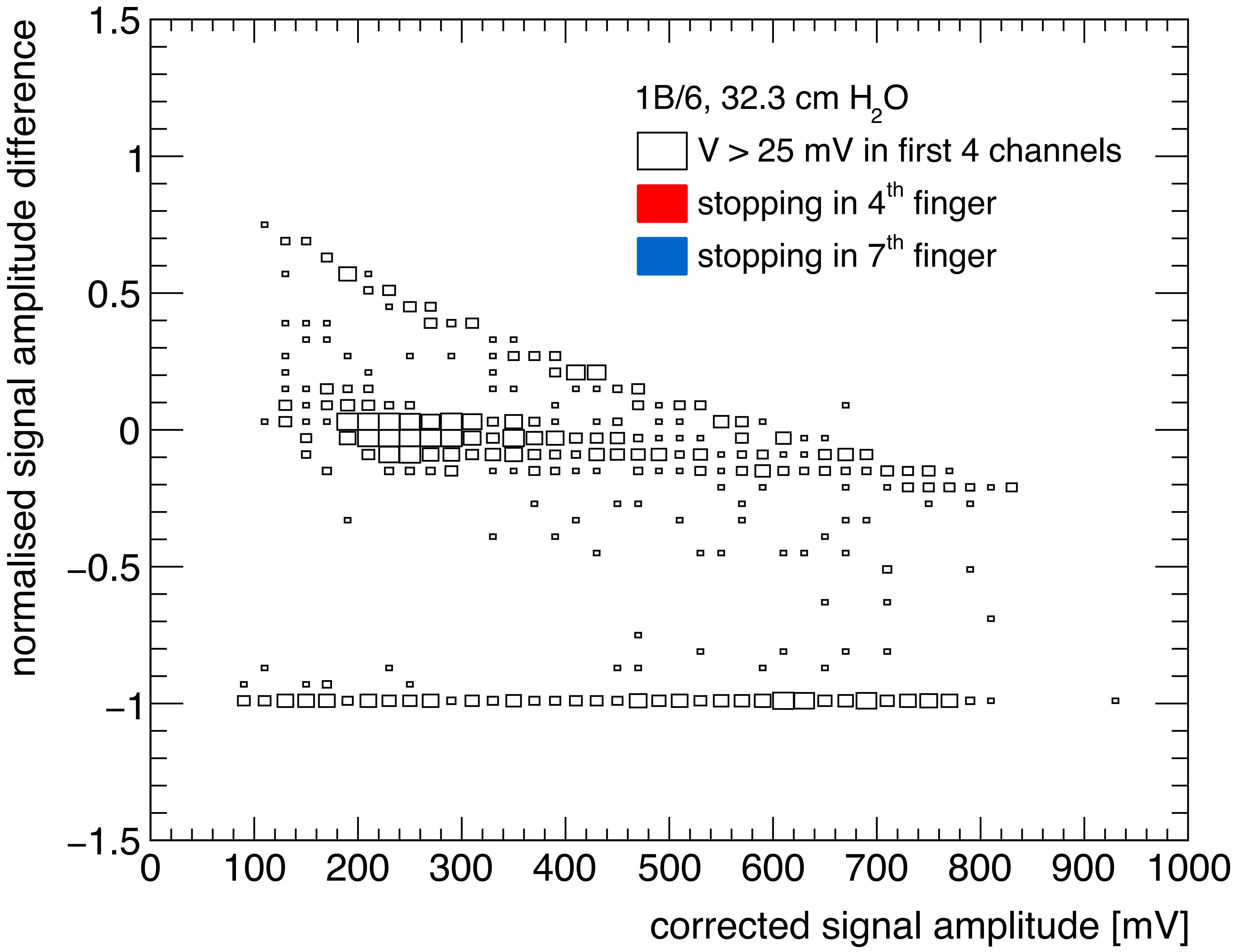




selection of protons stopping in the sensitive volume

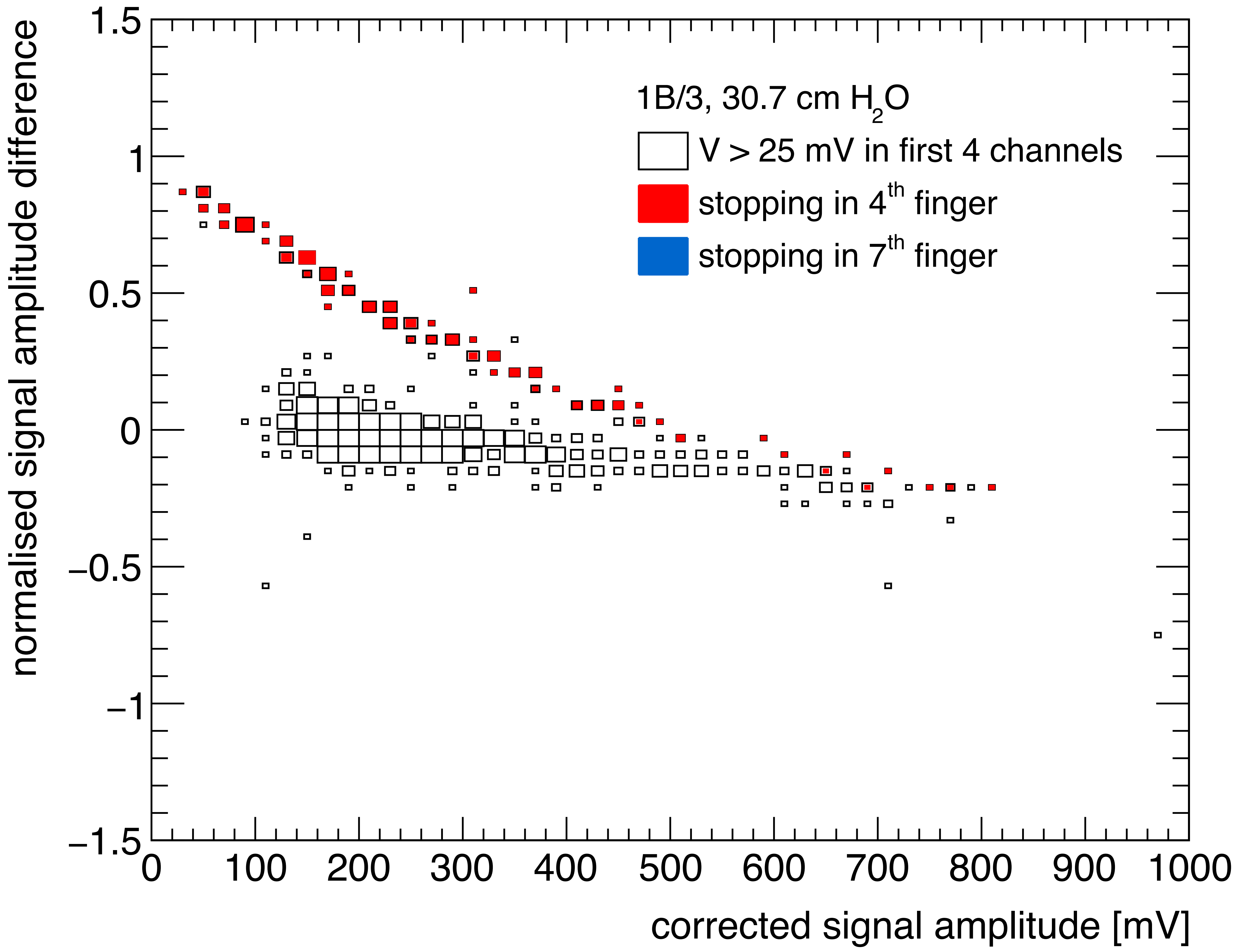
- non-null signal in first 4 fingers
  - anomalies in the trigger result in random coincidences

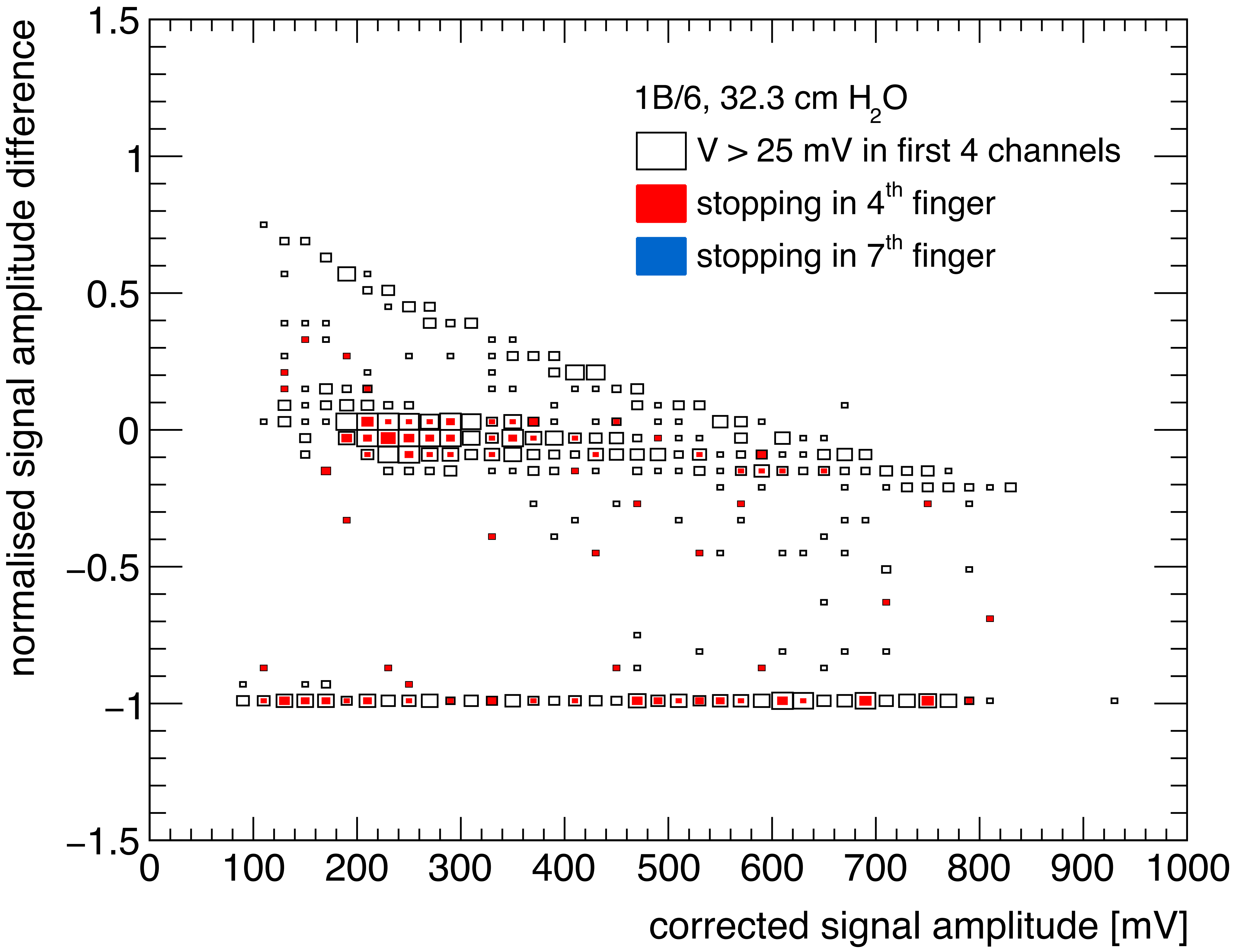




selection of protons stopping in the sensitive volume

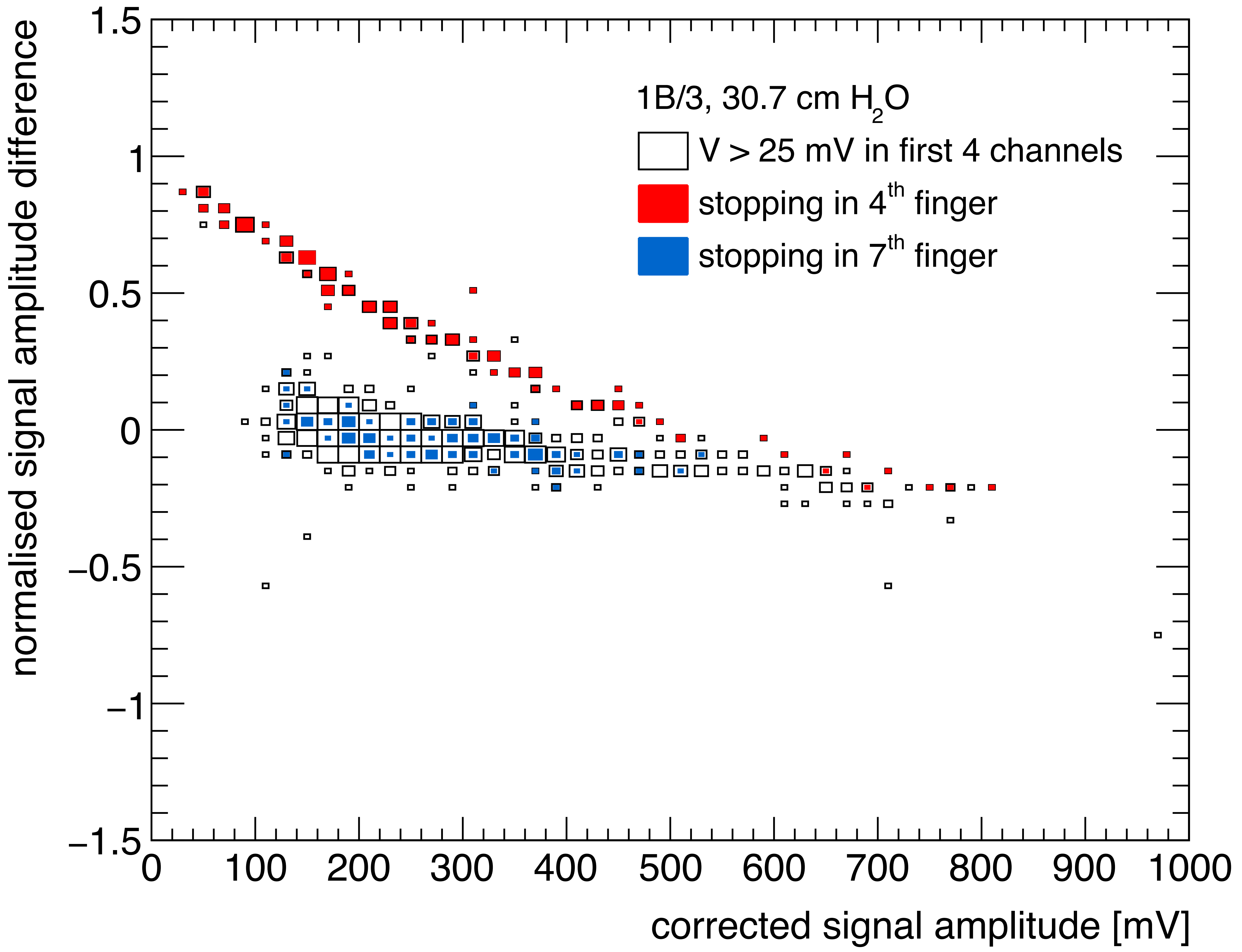
- random coincidences are equivalent to protons exiting from the sensitive volume

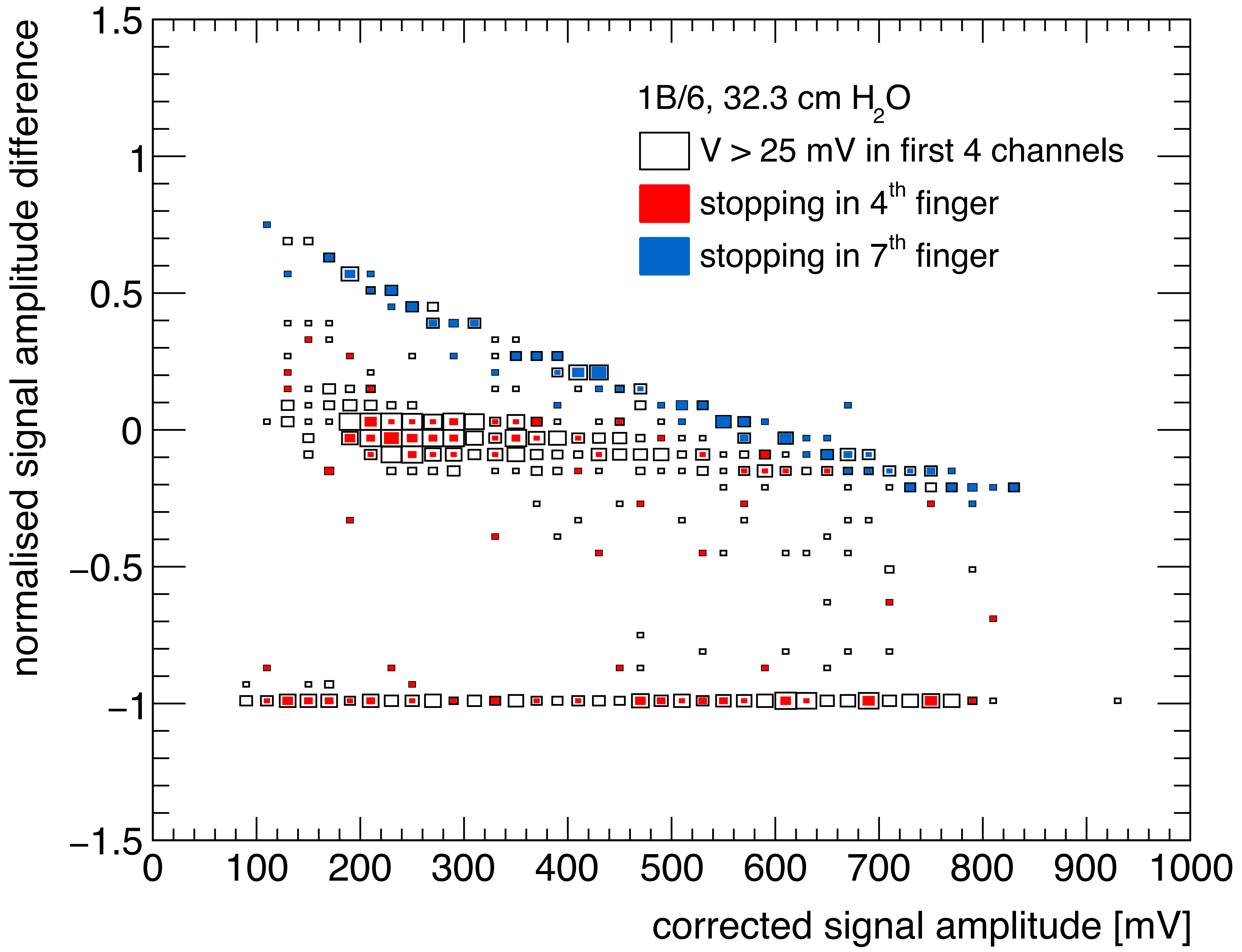




selection of protons stopping in the sensitive volume

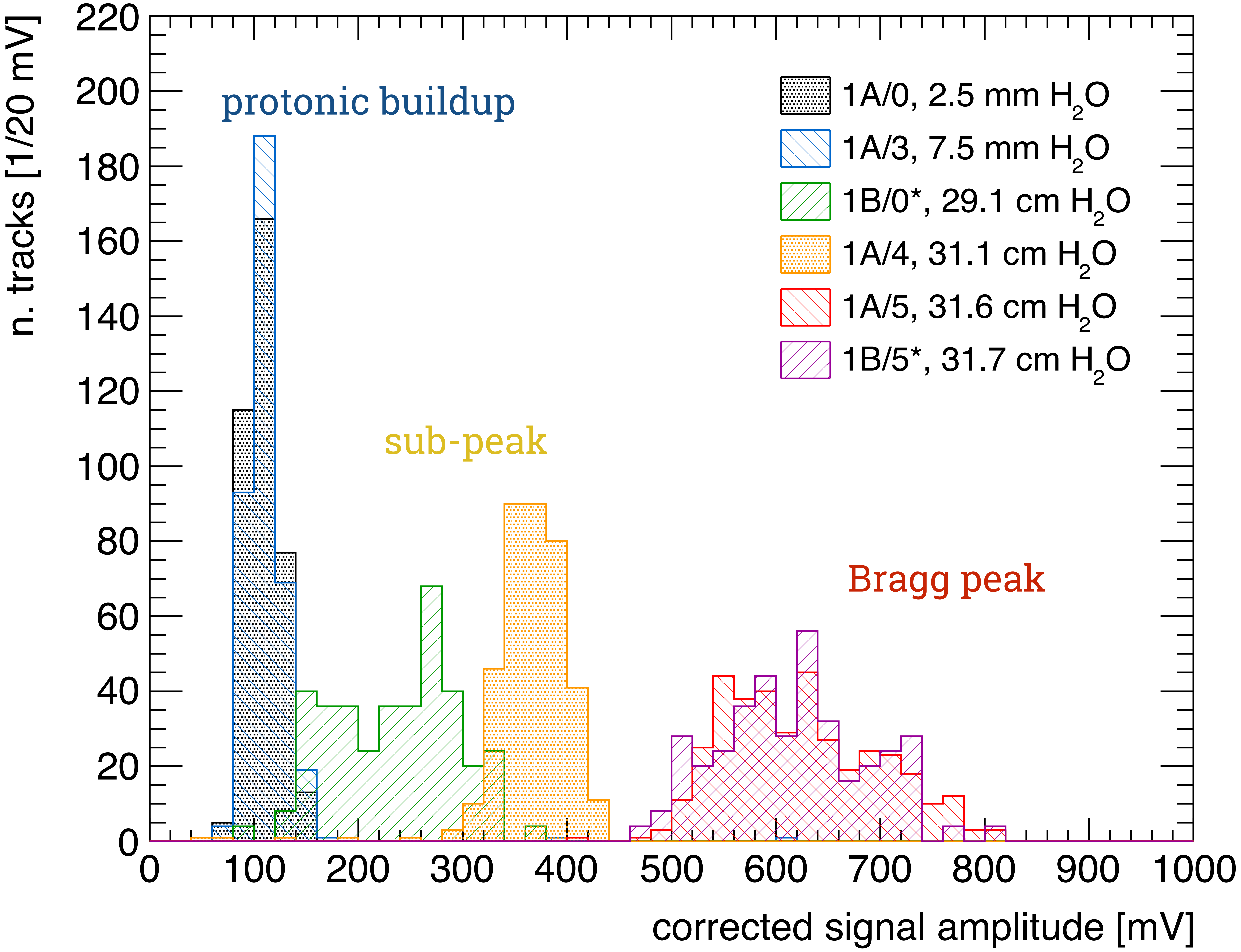
- stopping proton: high asymmetry of energy deposition





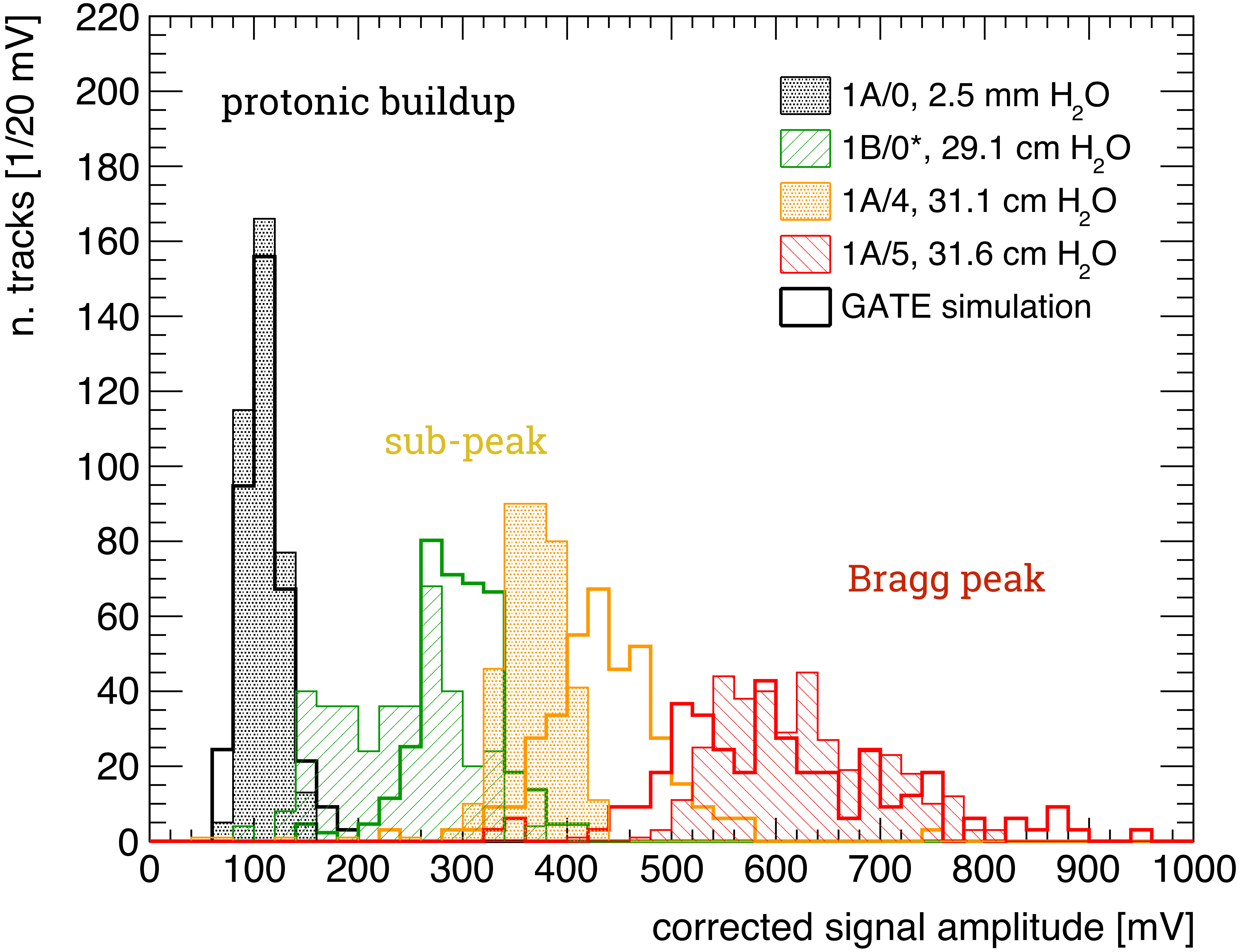
characterisation with medical energy proton beam

- different sampling depths along proton path result in distinguishable signal spectra
- shown: only protons coming at rest in the 6th active PVT finger



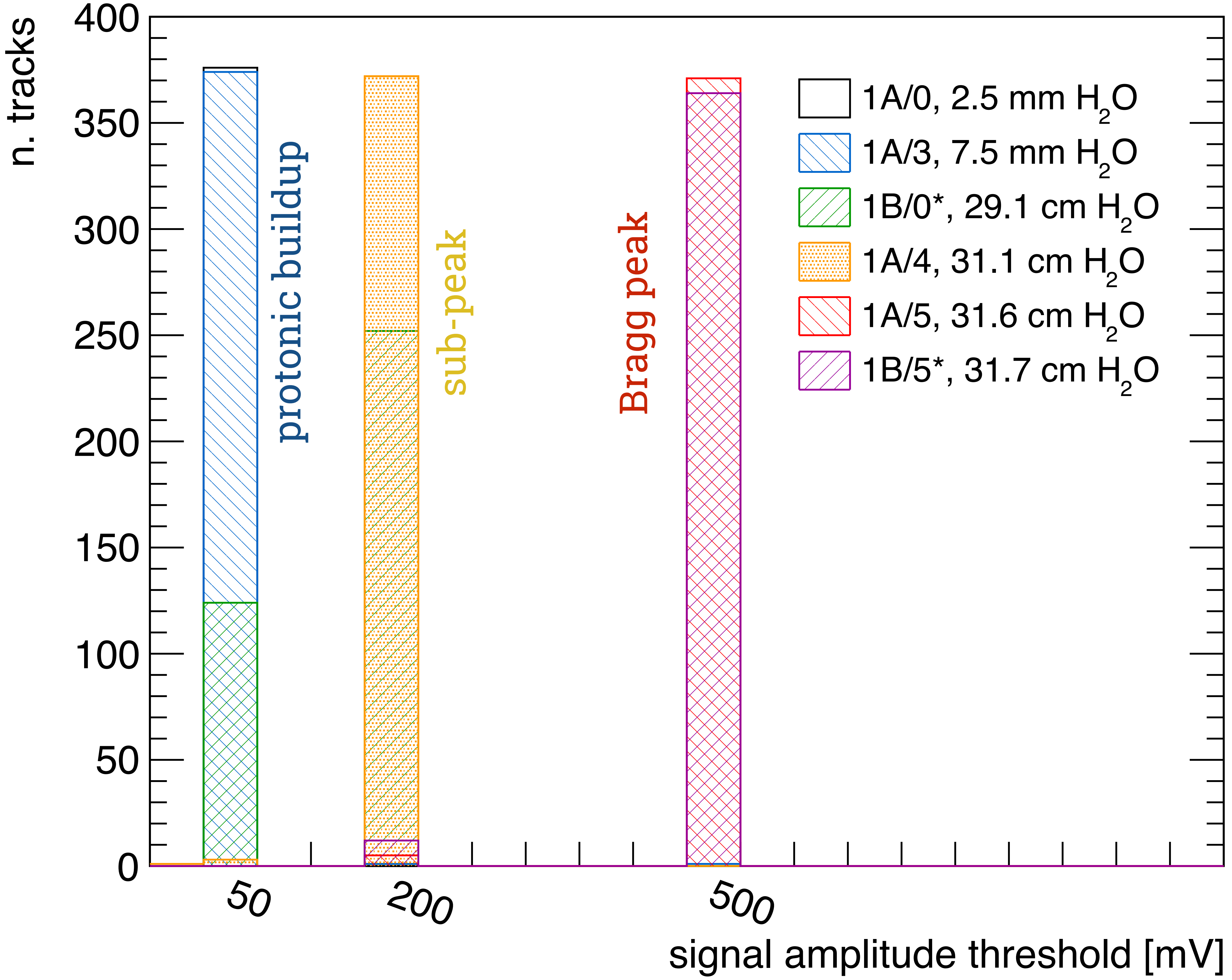
characterisation with medical energy proton beam

- simulation under control
  - read-out response to be updated

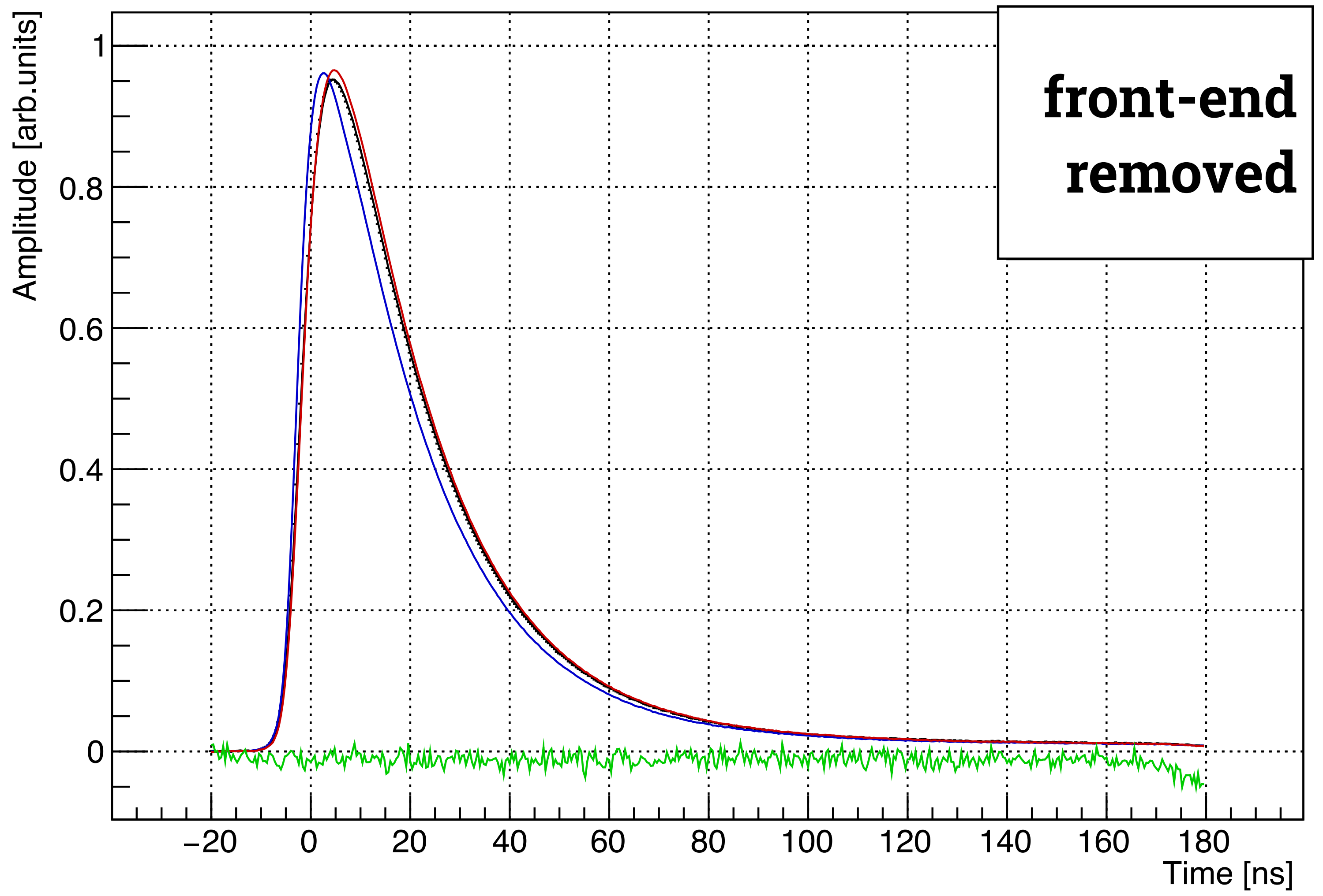


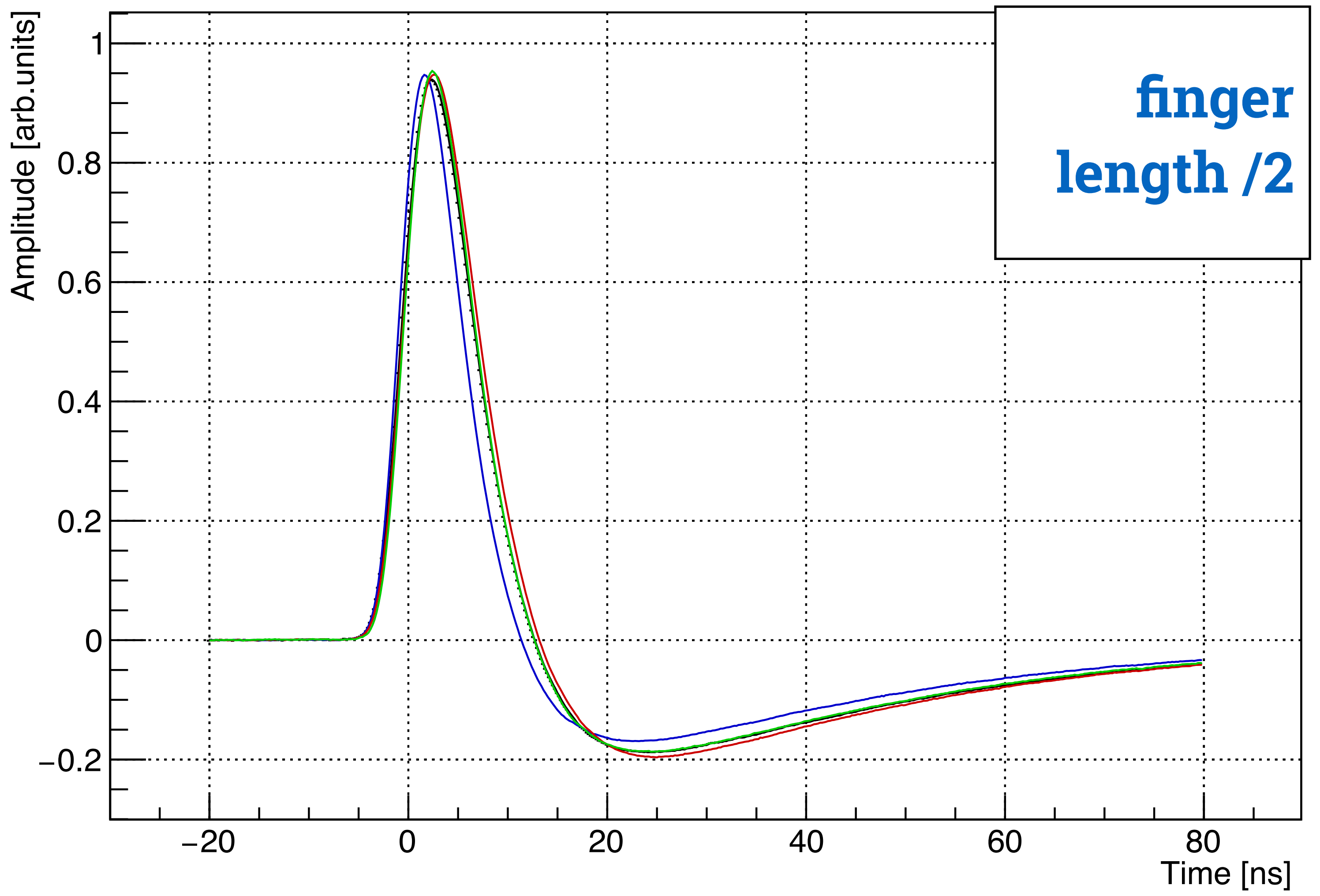
2-bits digitisation of the expected signal

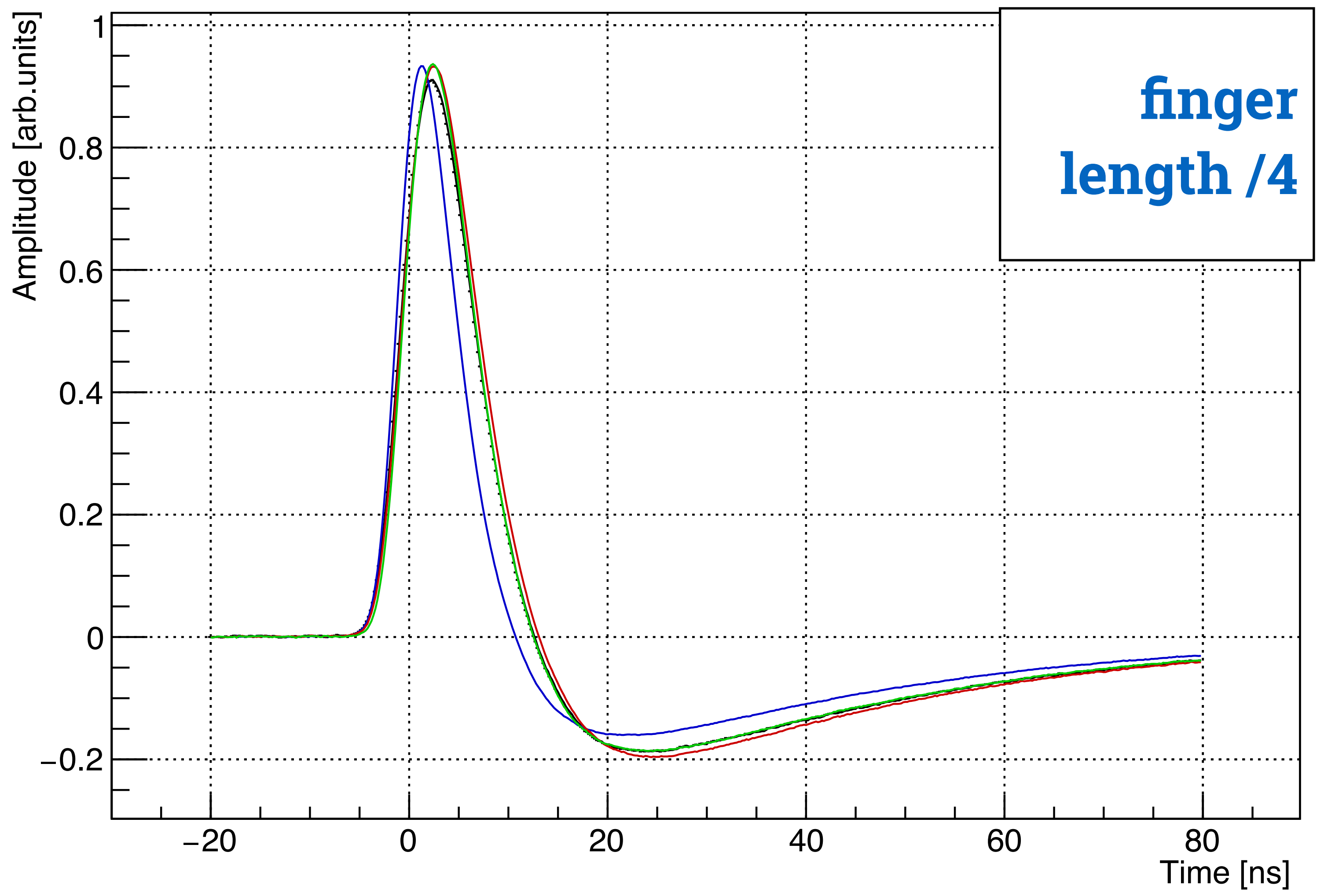
- what does the energy loss curve look like when digitally sampled at the protonic buildup, at the sub-peak, and at the Bragg peak?

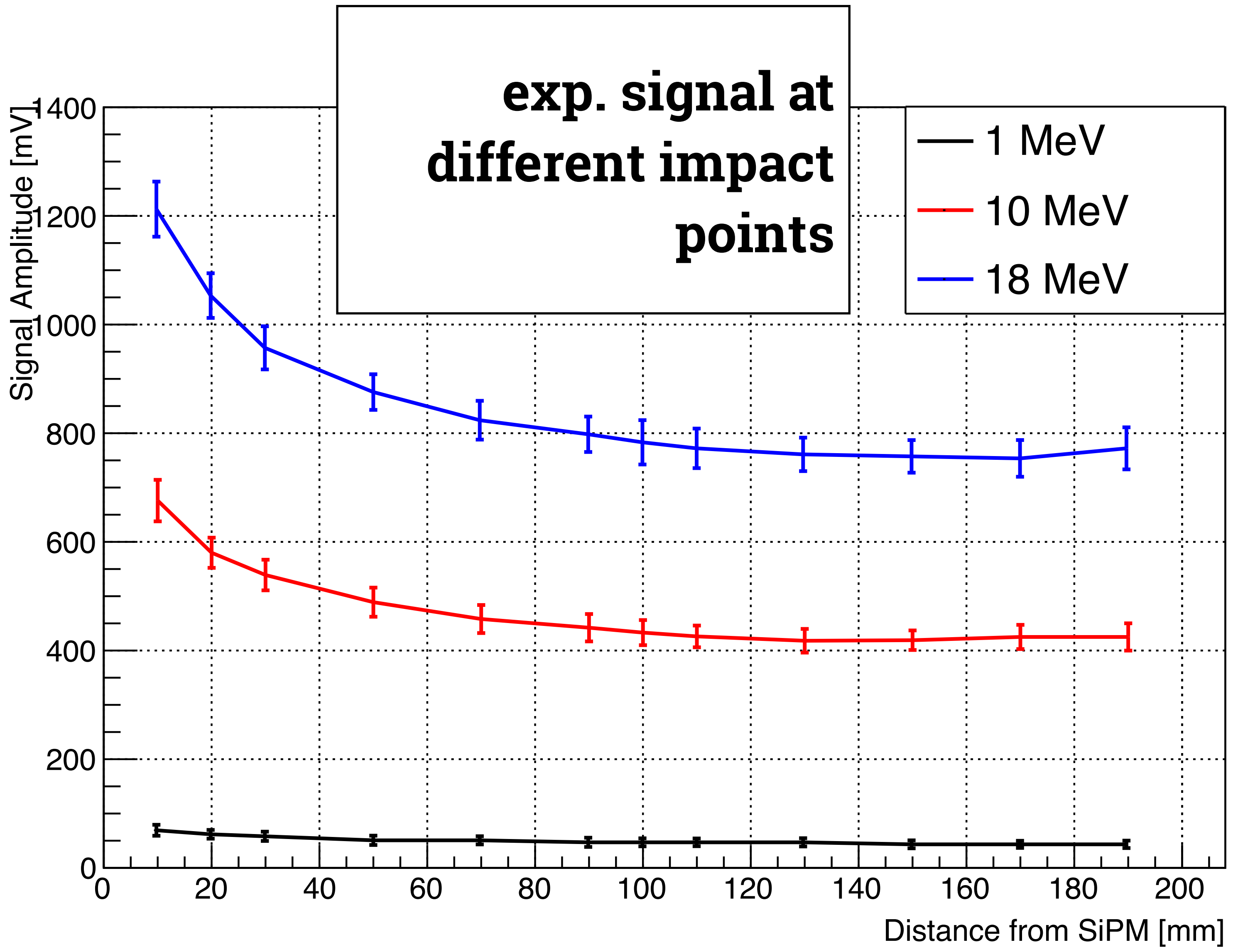


comparative studies with cosmic MIP muon









linearity of the SiPM response