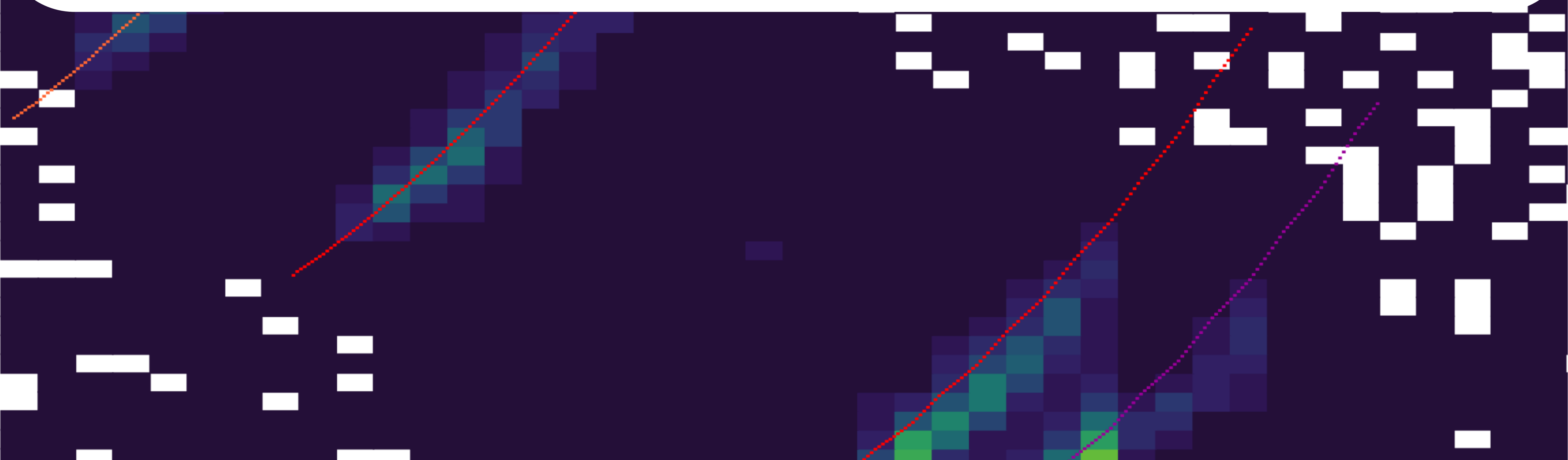
TORCH time-of-flight detector for LHCb Upgrade II

16th Pisa Meeting on Advanced Detectors

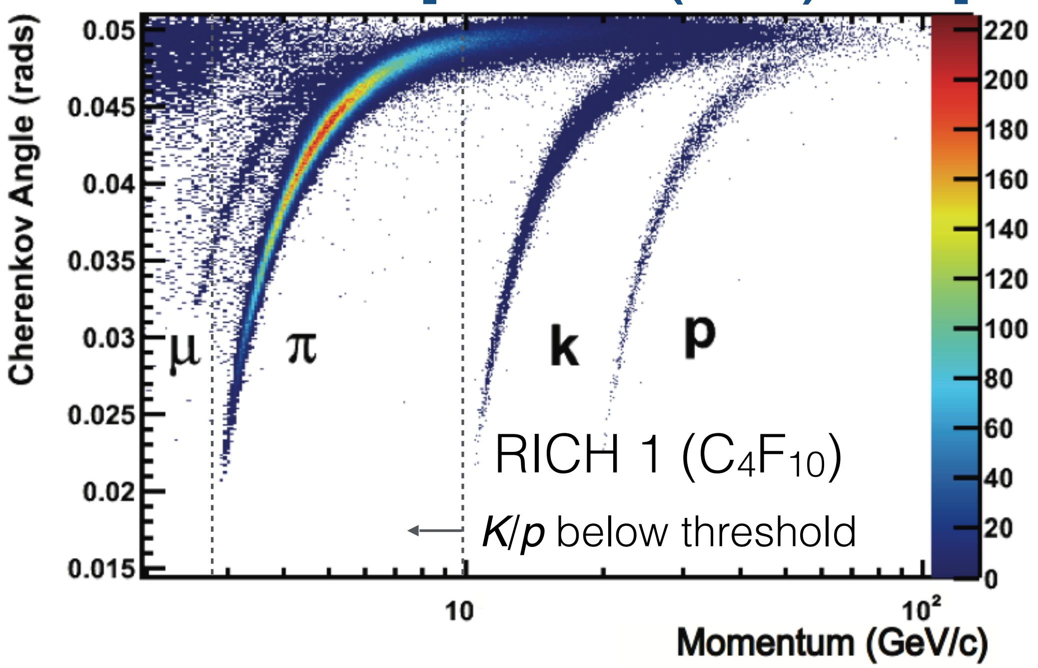
27th of May 2024

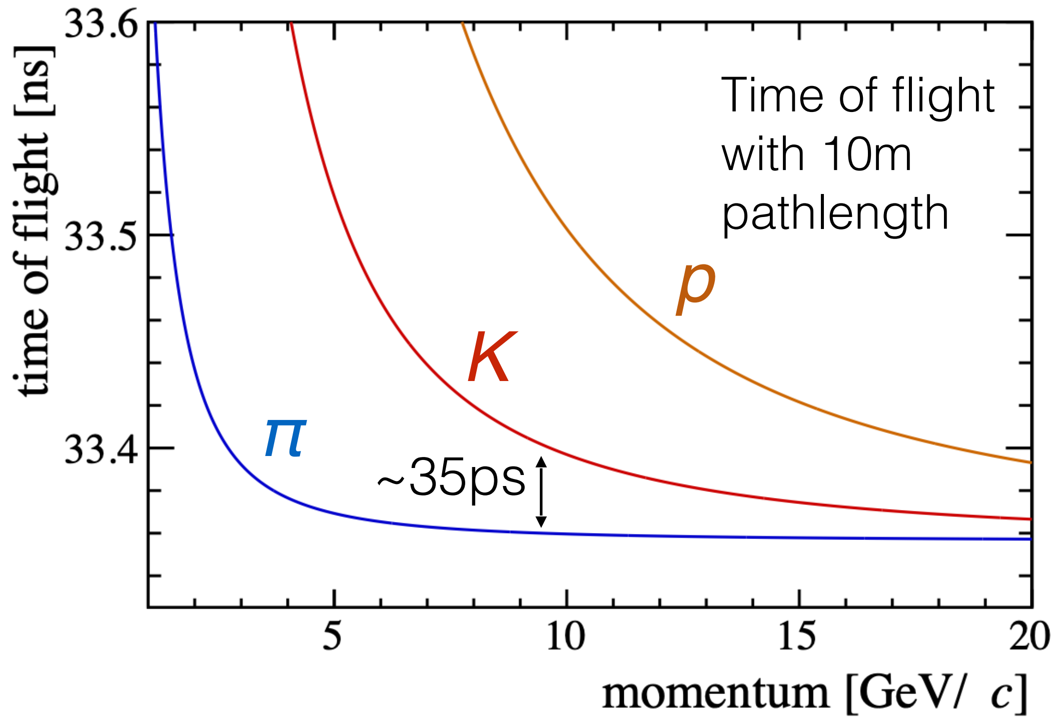


Detector concept

- Large area time-of-flight detector designed to provide PID in the 2–15 GeV/*c* momentum range.
- Aim to supplement PID performance in momentum region where *K*/p are below threshold in LHCb RICH detectors.
- For K/π separation over 10m, aim for a resolution of 15 ps per track (requires 70 ps per photon).
- Developed for Upgrade II of LHCb (for installation in LS4) to run during the HL-LHC era at instantaneous luminosities of 1–1.5x10^{34} $cm^{-2}s^{-1}$.

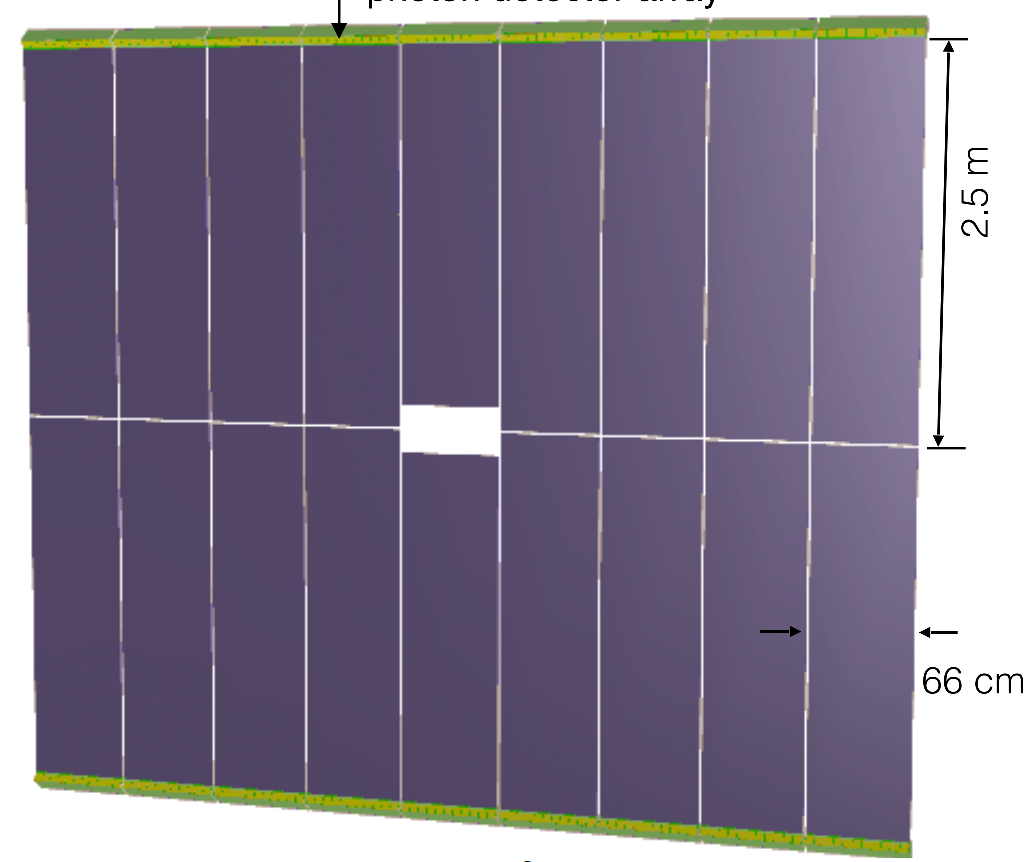
LHCb [EPJC 73 (2013) 2431]

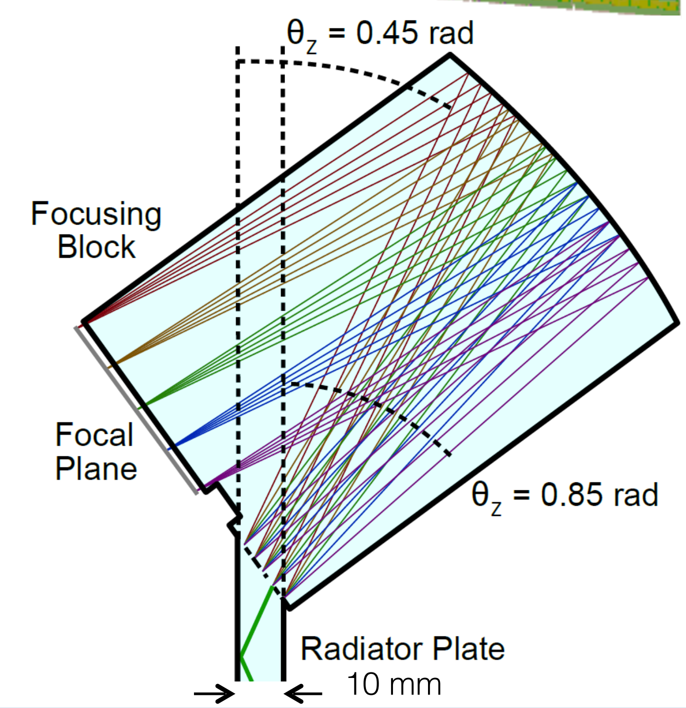




Detector concept

- Exploit prompt production of Cherenkov light in an array of fused-silica bars to provide timing.
- Cherenkov photons are propagated to detector plane via total internal reflection from the quartz surfaces.
- Cylindrical focussing block, focusses the image onto a detector plane with highly segmented photon detectors.
  - Used to correct for chromatic dispersion.
- Large area detector required to cover the full LHCb acceptance (5x6m^2).

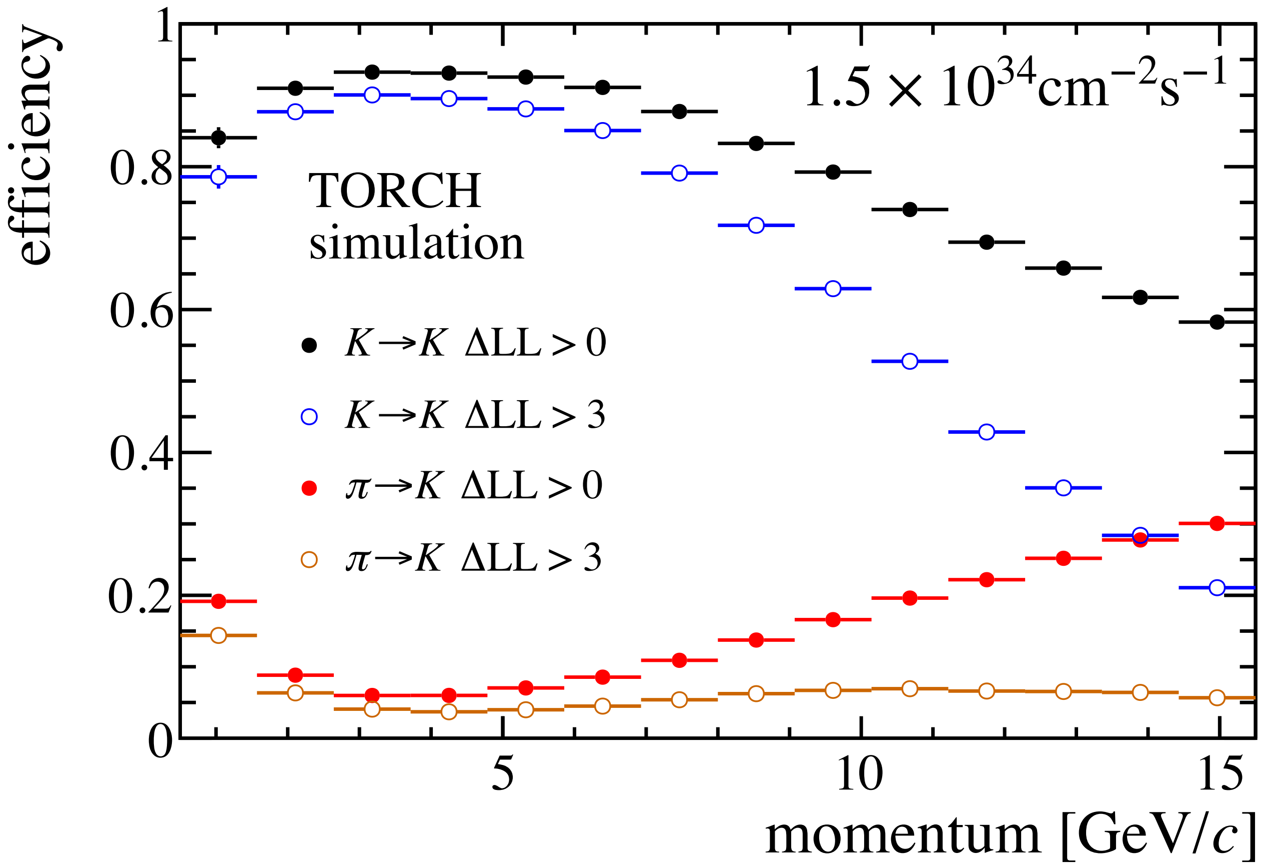


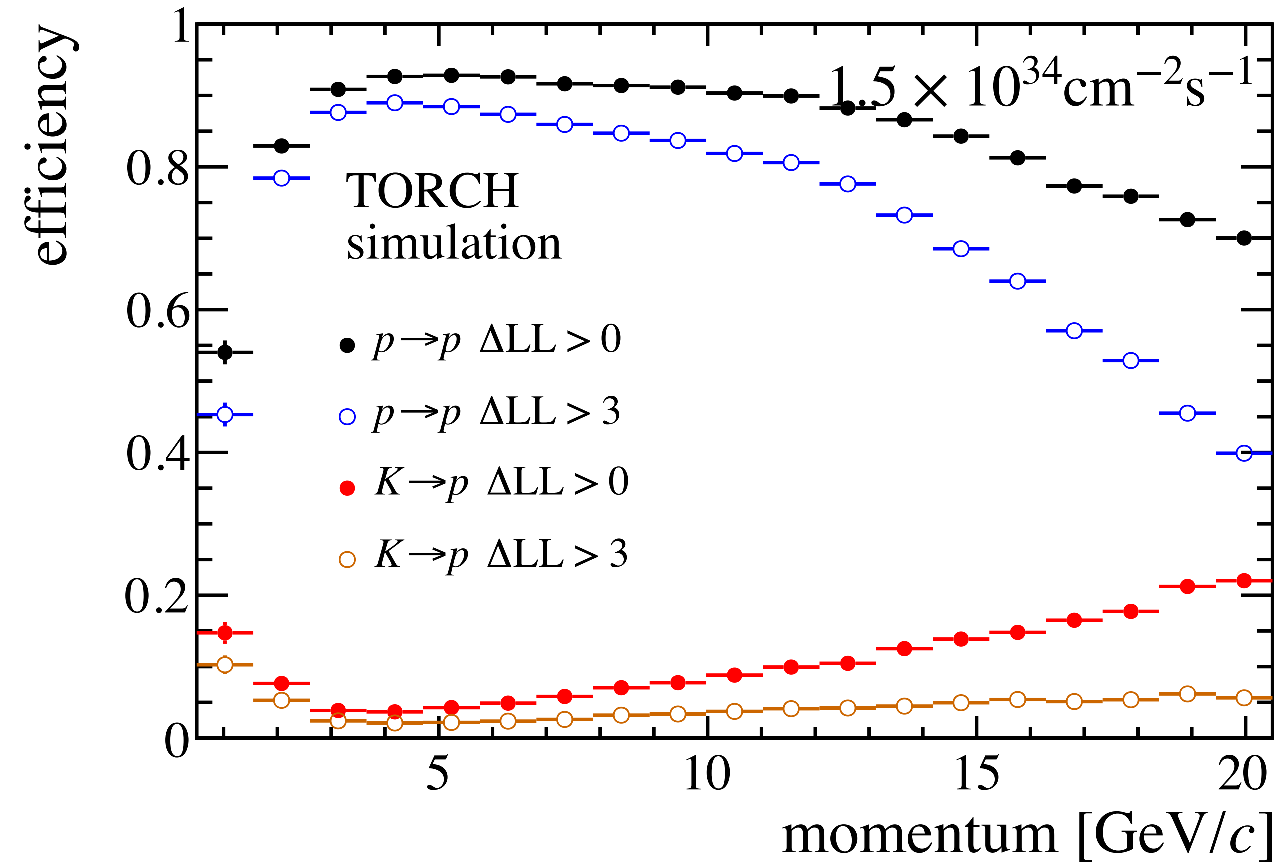


For more details on the TORCH concept see **[NIM A 639 (1) (2011) 173]**

Expected performance

- Provides π/K (p/K) separation in the 2–10 (2–15) GeV/c range:
  - Improves phase space coverage of many analyses and improves effective flavour tagging power [LHCb-PUB-2020-006].





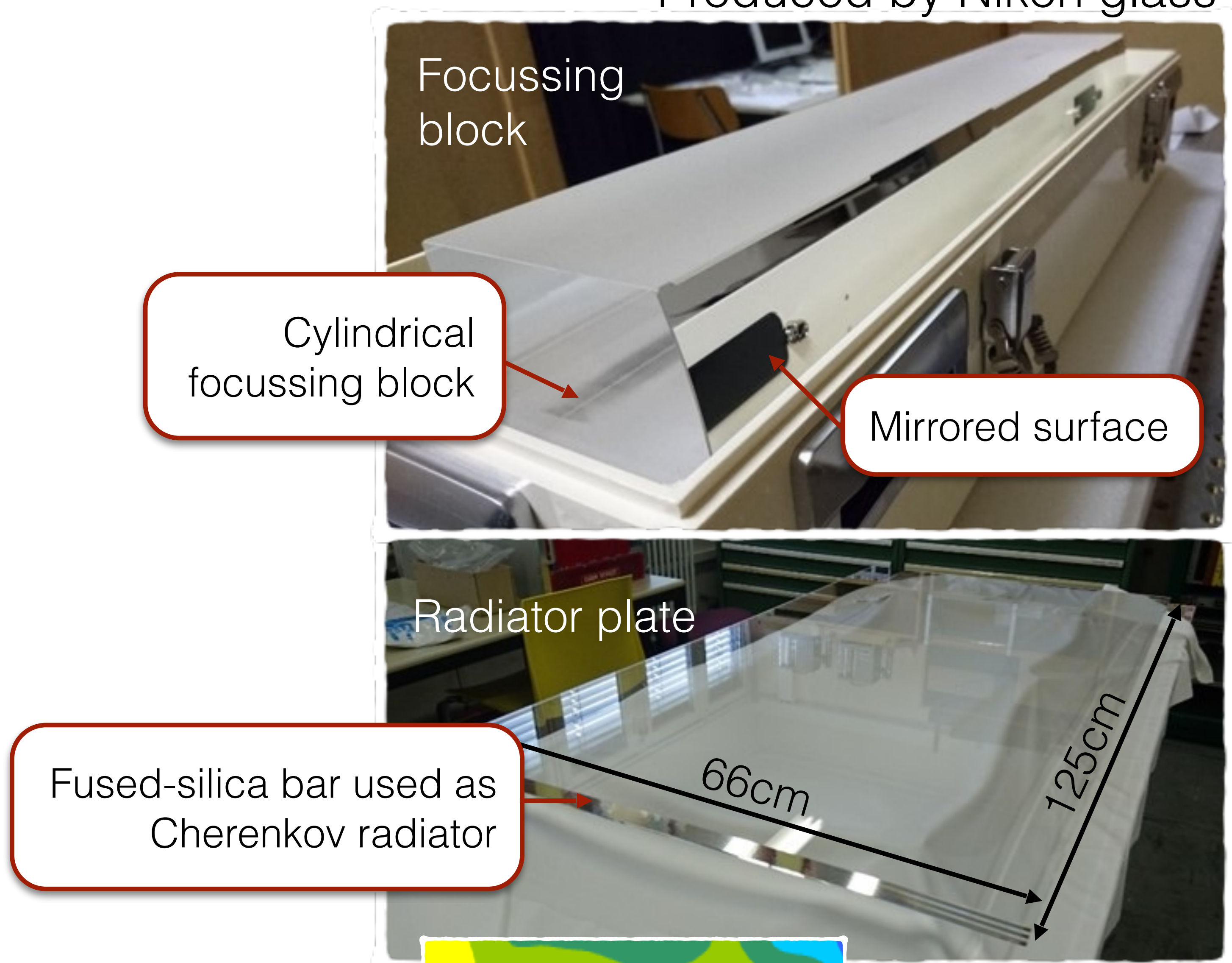
Fused-silica pieces

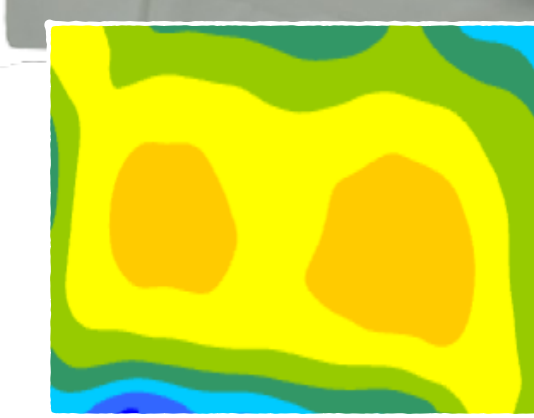
- Optics formed from multiple pieces of synthetic fused-silica that are bonded.
  - Pactan 8030 used with existing prototype but a structural epoxy will be used for final detector.

- Require high-quality surface on front and rear faces (flatness variation $\leq 3\mu\text{m}$ and surface roughness 5Å).

- Two 66x62.5x1cm^3 radiator plates have recently been acquired to equip a full-sized module.

Produced by Nikon glass

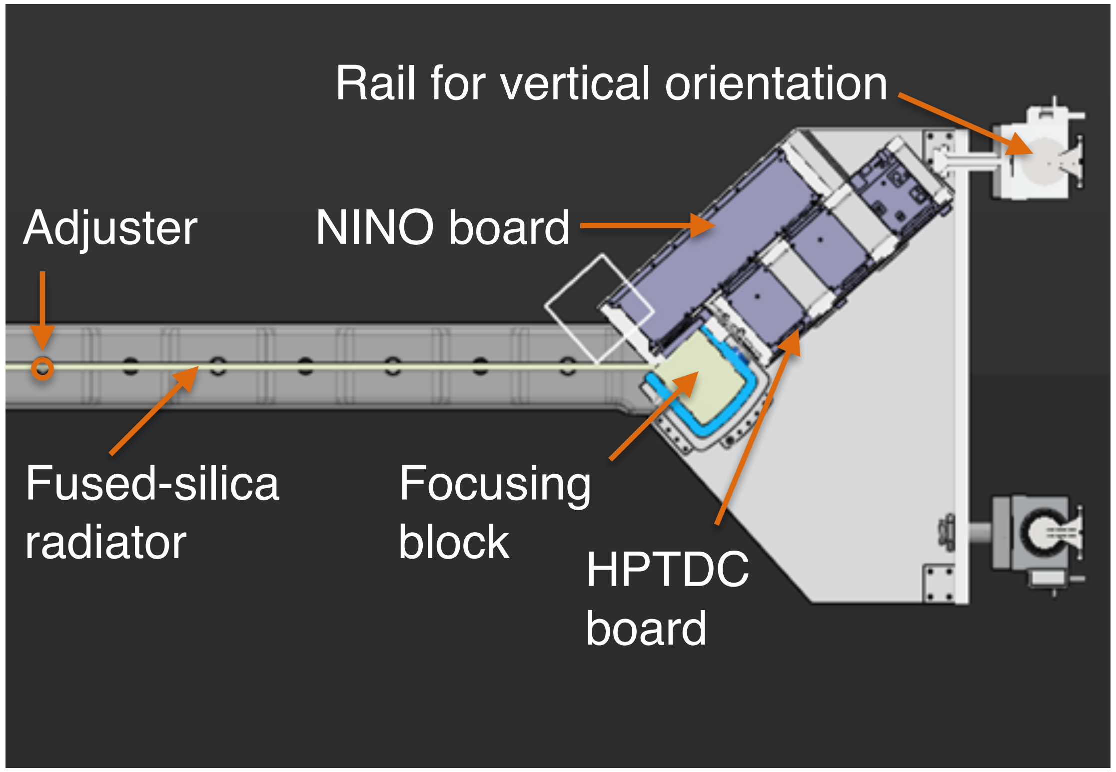


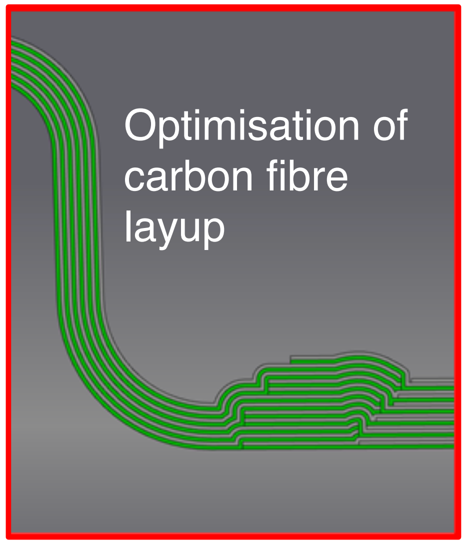


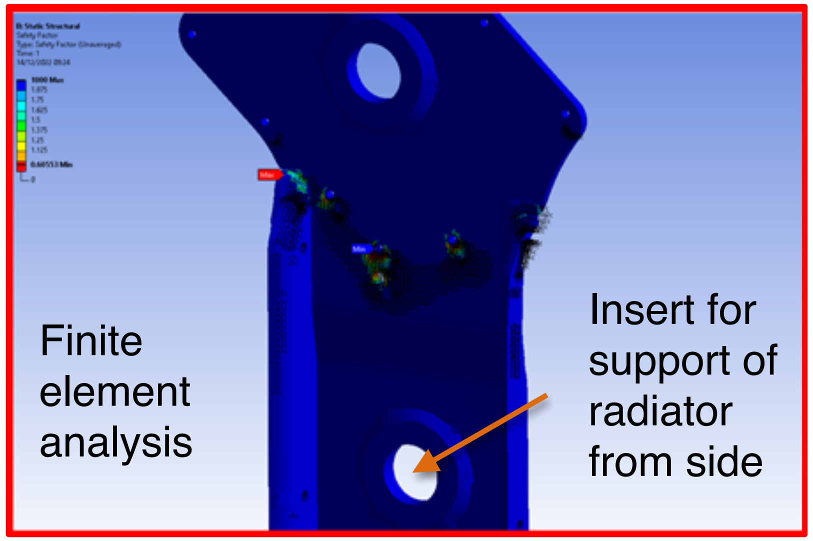
Measured flatness variation in 1 μm contours

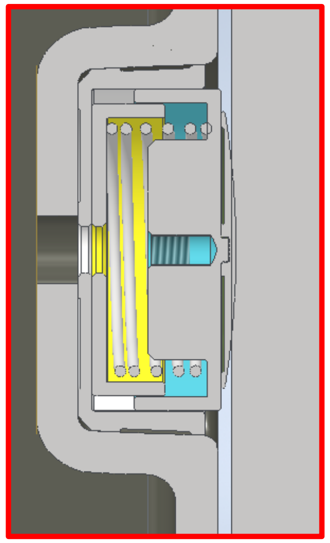
Support structure

- Aim for light-weight carbon fibre support structure inside detector acceptance to minimise X_0.
- Prototype of the support structure has been designed and is currently being produced.
  - Designed to accommodate the existing photon detectors and electronics.
- Plan to assemble a full-scale module in the summer and test the assembly in a beam test in 2025.









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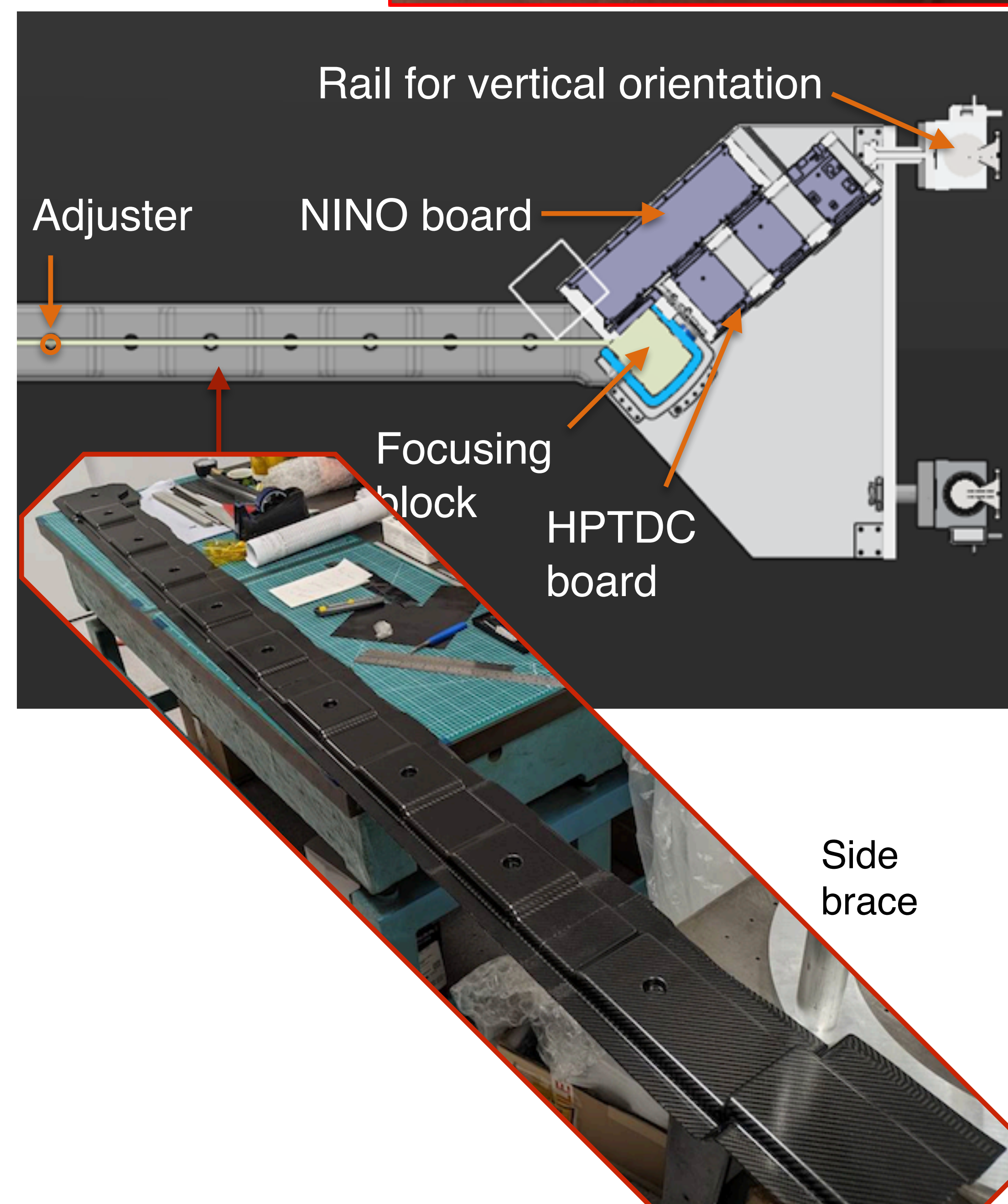
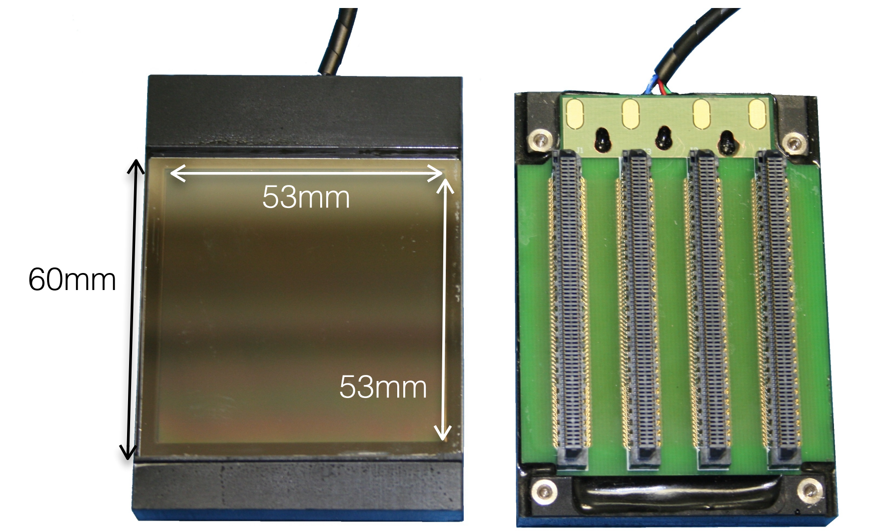
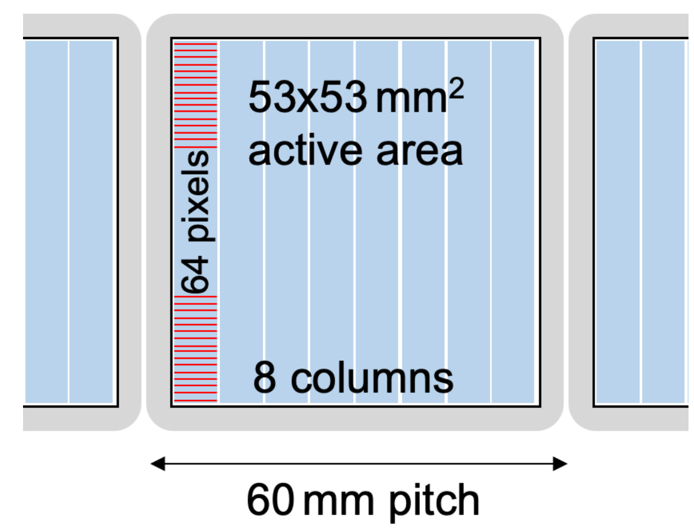
Bottom brace

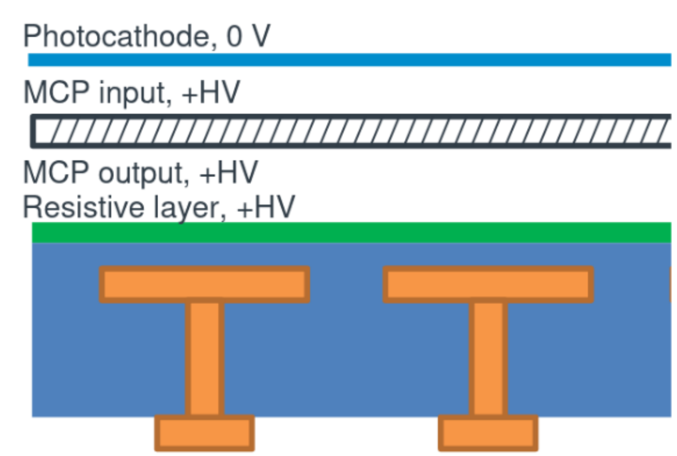


Photon detectors

- Current TORCH prototype uses custom 53-by-53mm MCP-PMTs with 64-by-64 pads **[JINST 10 (2015) C05003]**.
    - Offer excellent intrinsic time resolution (< 30 ps).
- Pads are electronically ganged to form a 8-by-64 pixel arrangement.
- Readout connectors are mounted on an external PCB and connected via anisotropic conductive film.
    - Anode is capacitatively coupled.
- MCP is ALD coated for a lifetime > 5 Ccm^{-2}.



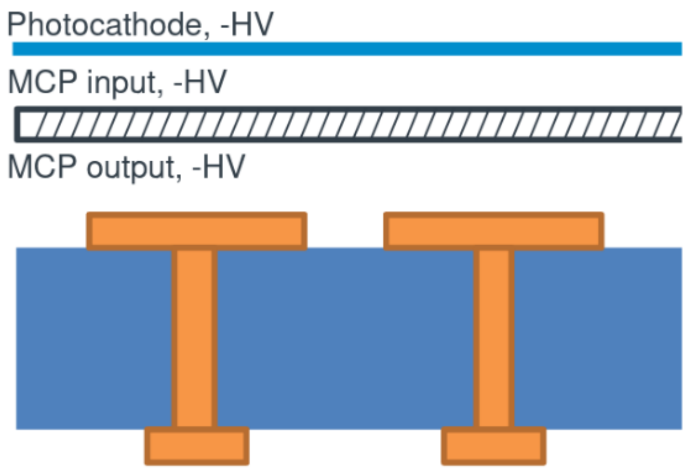


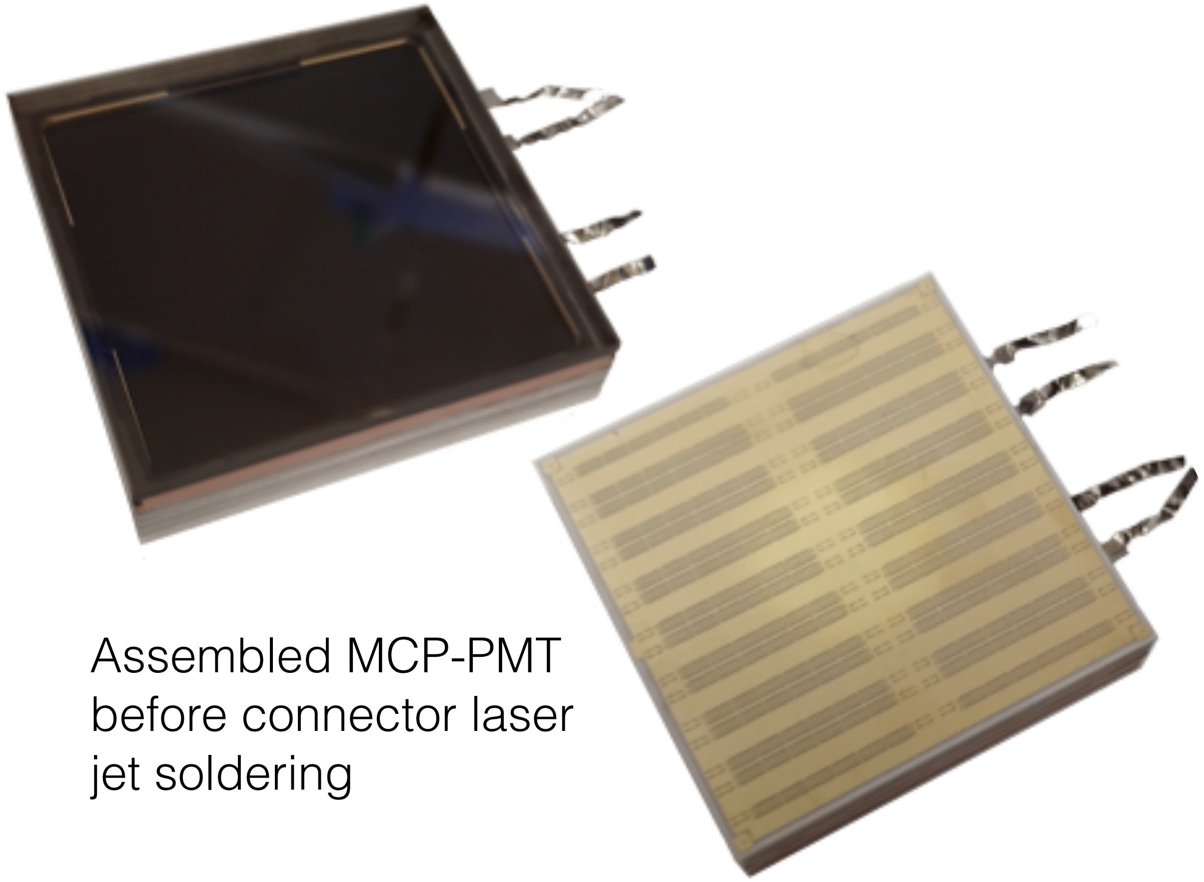


Photon detectors

PHOTEK
ENVISAGE THE FUTURE

- Recent R&D effort to produce a 16-by-96 pixel MCP-PMT using direct rather than capacitive coupling.
    - New tube is currently under test at Photek.
- Aim to reduce charge-sharing and per-pixel occupancies.
    - 8-by-64 prototype exploits charge-sharing to achieve 8-by-128 effective resolution.
- Work ongoing in context of DRD4 to improve rate capability and lifetime (ideally well beyond $10C/cm^2$).



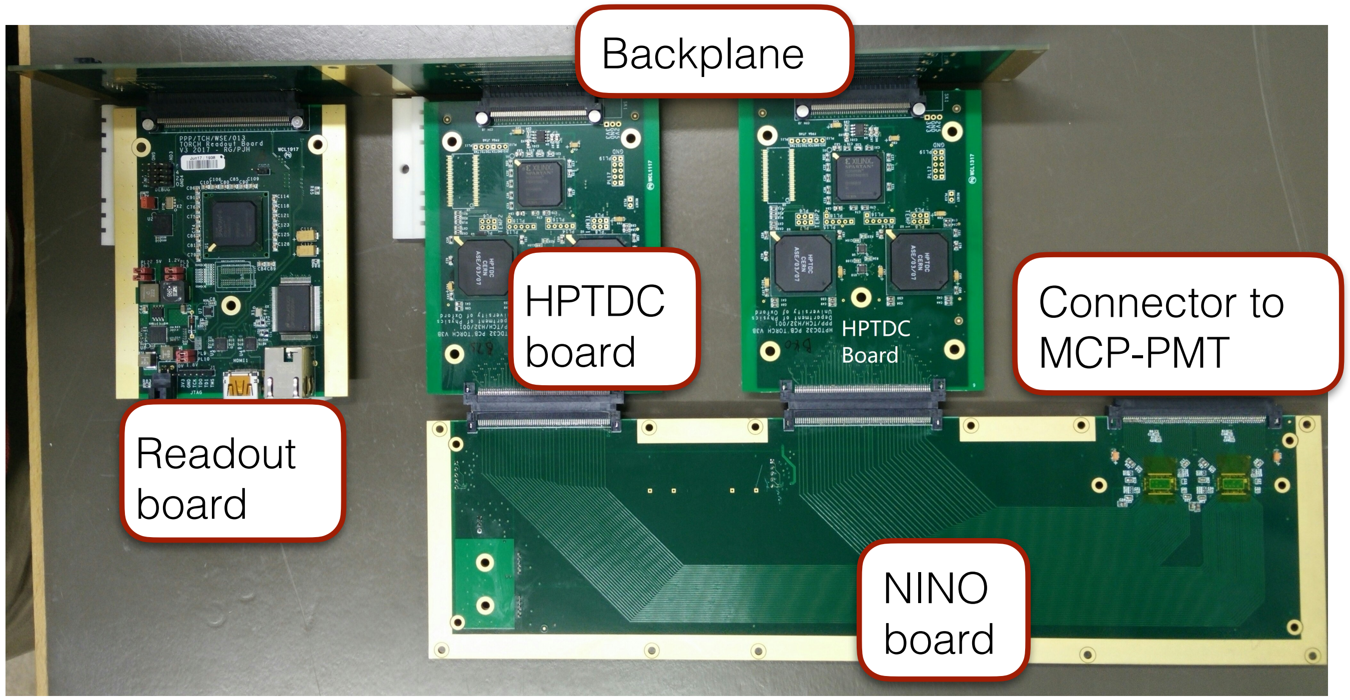


Assembled MCP-PMT before connector laser jet soldering

Electronics

- Existing electronics are based on NINO and HPTDC (with100ps TDC binning) ASICs developed for the ALICE TPC.
[JINST 11 (2016) 04 C04012]

- Adaptors are being designed to read the DC-coupled MCP-PMT with existing electronics.

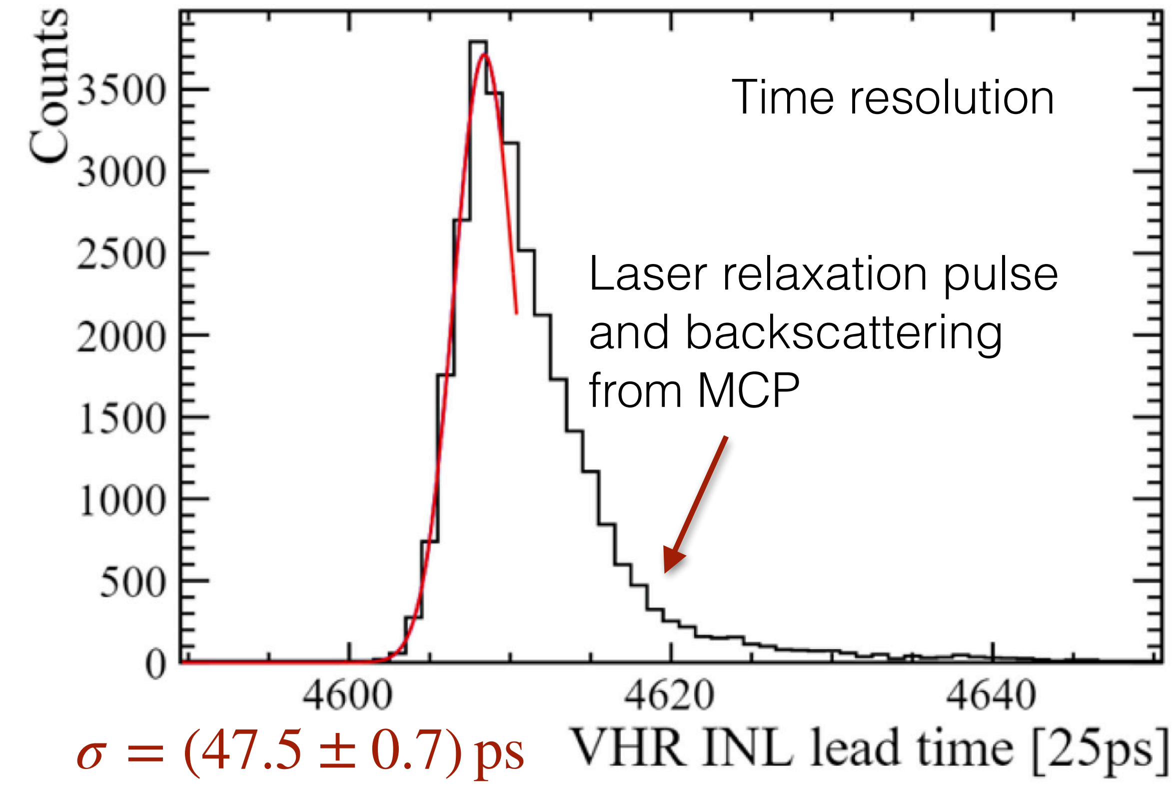


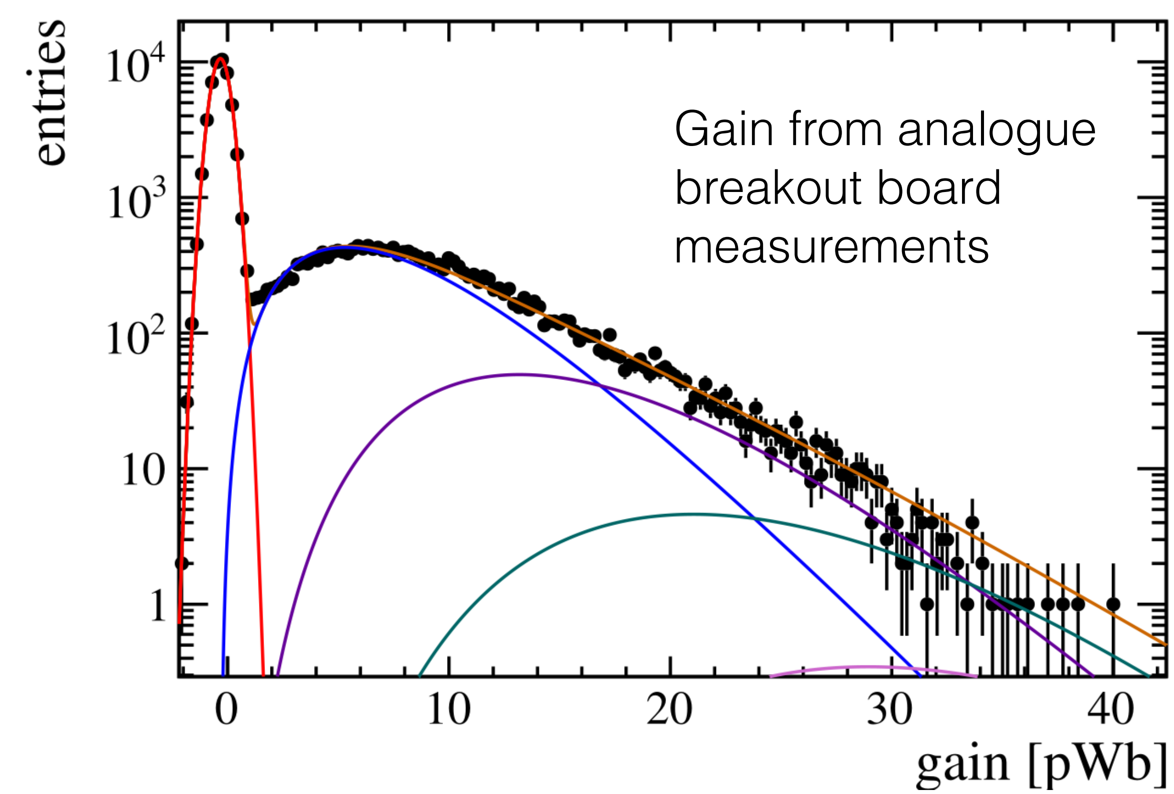
- For upgrade II plan to use the FastRICH (with 25ps TDC binning) ASIC developed by CERN-ESE and University of Barcelona.
[https://fastrich.docs.cern.ch/]
  - Constant fraction discriminator reduces need to transmit time-over-threshold information, otherwise needed to correct time-walk.

Detector performance

[NIMA 1038 (2022) 166950]

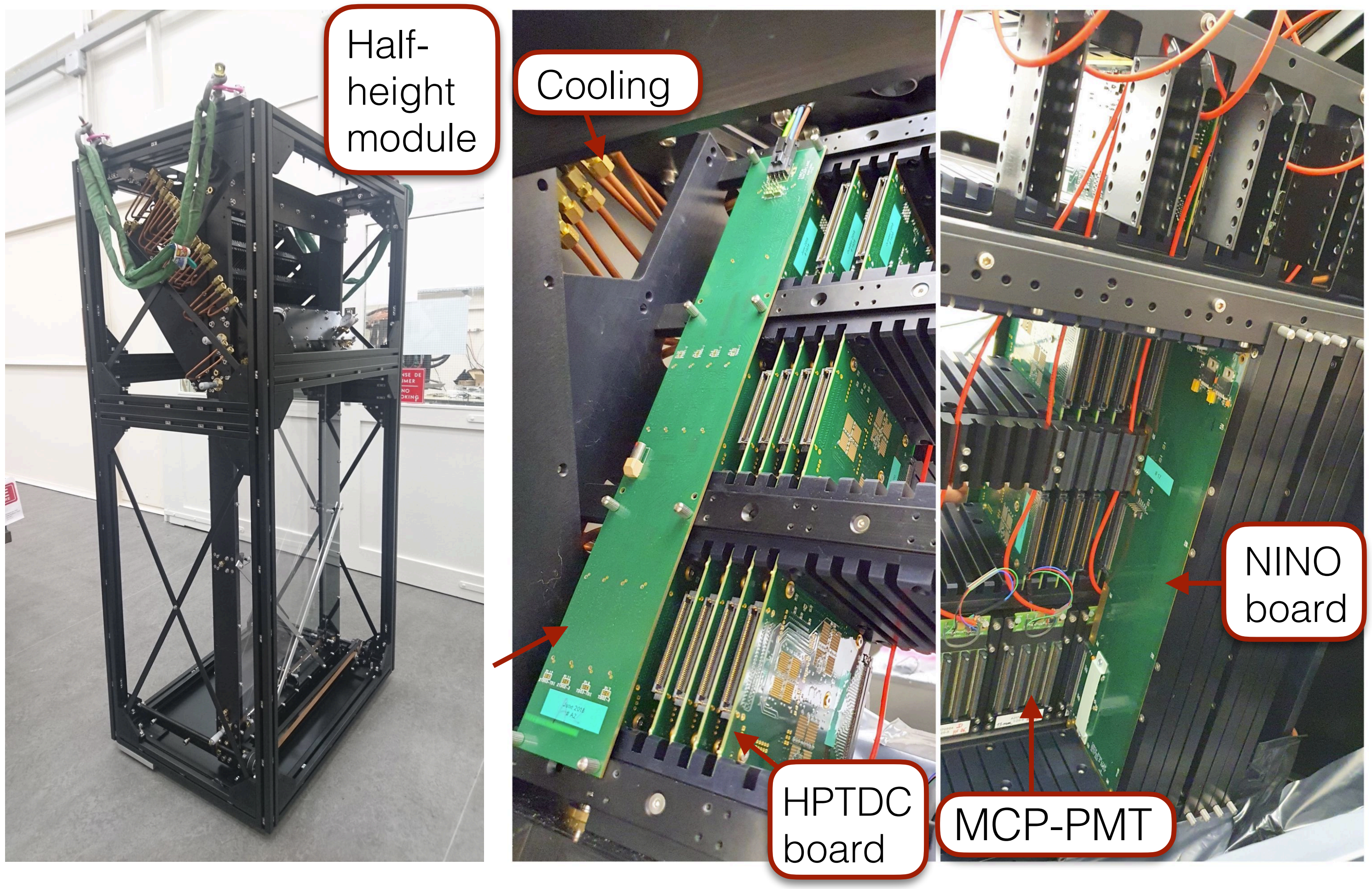
- MCP-PMT and electronics performance studied extensively in laboratory measurements with pulsed 405nm picosecond laser.
    - Intrinsic time resolution of MCP-PMT and readout electronics (after INL correction) is around 50ps.
- Dedicated calibration system developed to improve time-walk and INL corrections for 2022 beam test.





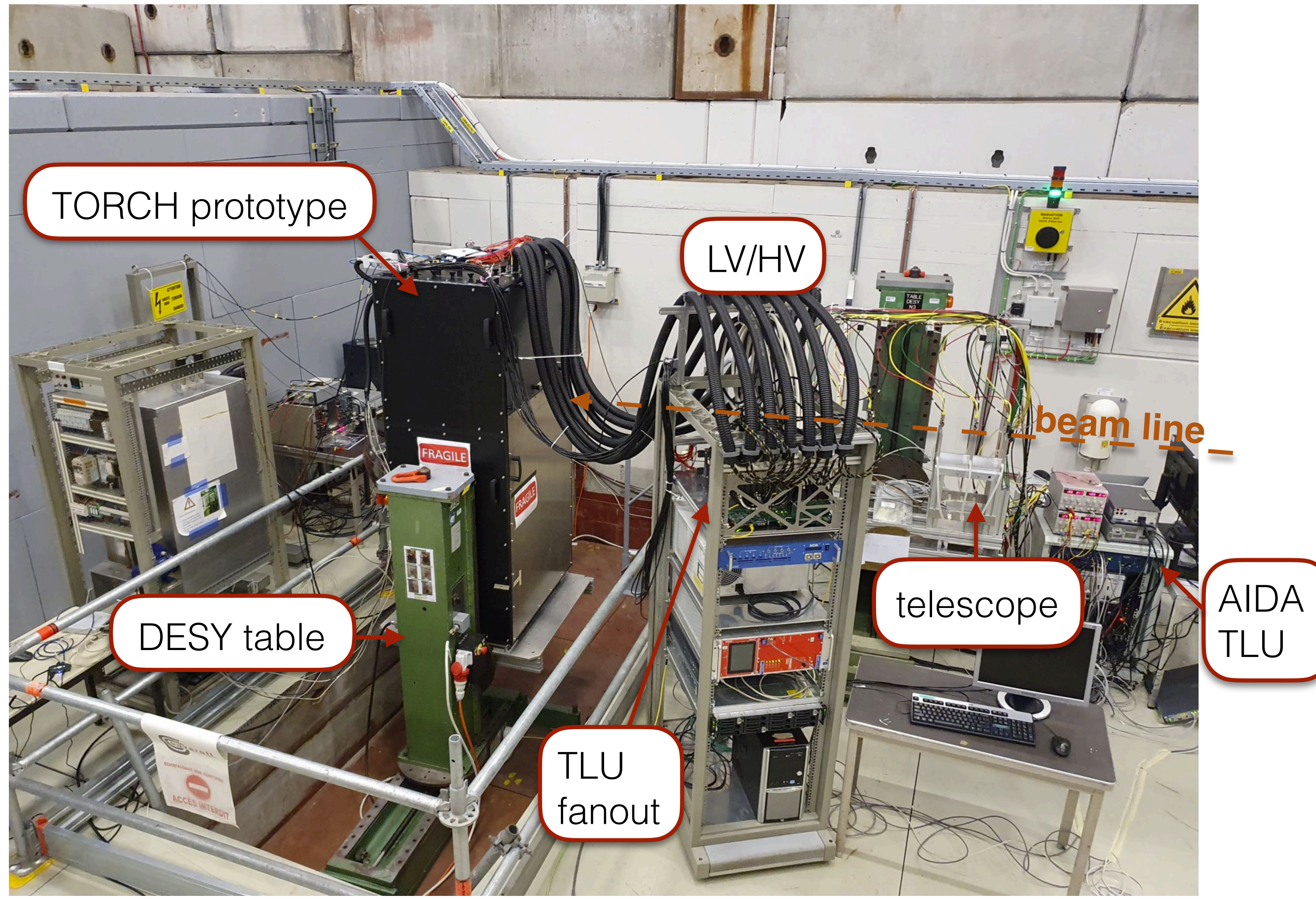
Detector performance

- Detector performance has also been studied in a mixed proton/pion beam at the CERN PS in 2018 and 2022.
  - Prototype equipped with two (in 2018) and six (in 2022) MCP-PMTs and half-height radiator.
- Analysis of 2022 data is ongoing. Results from 2018 published in **NIMA 1050 (2023) 168181]**.

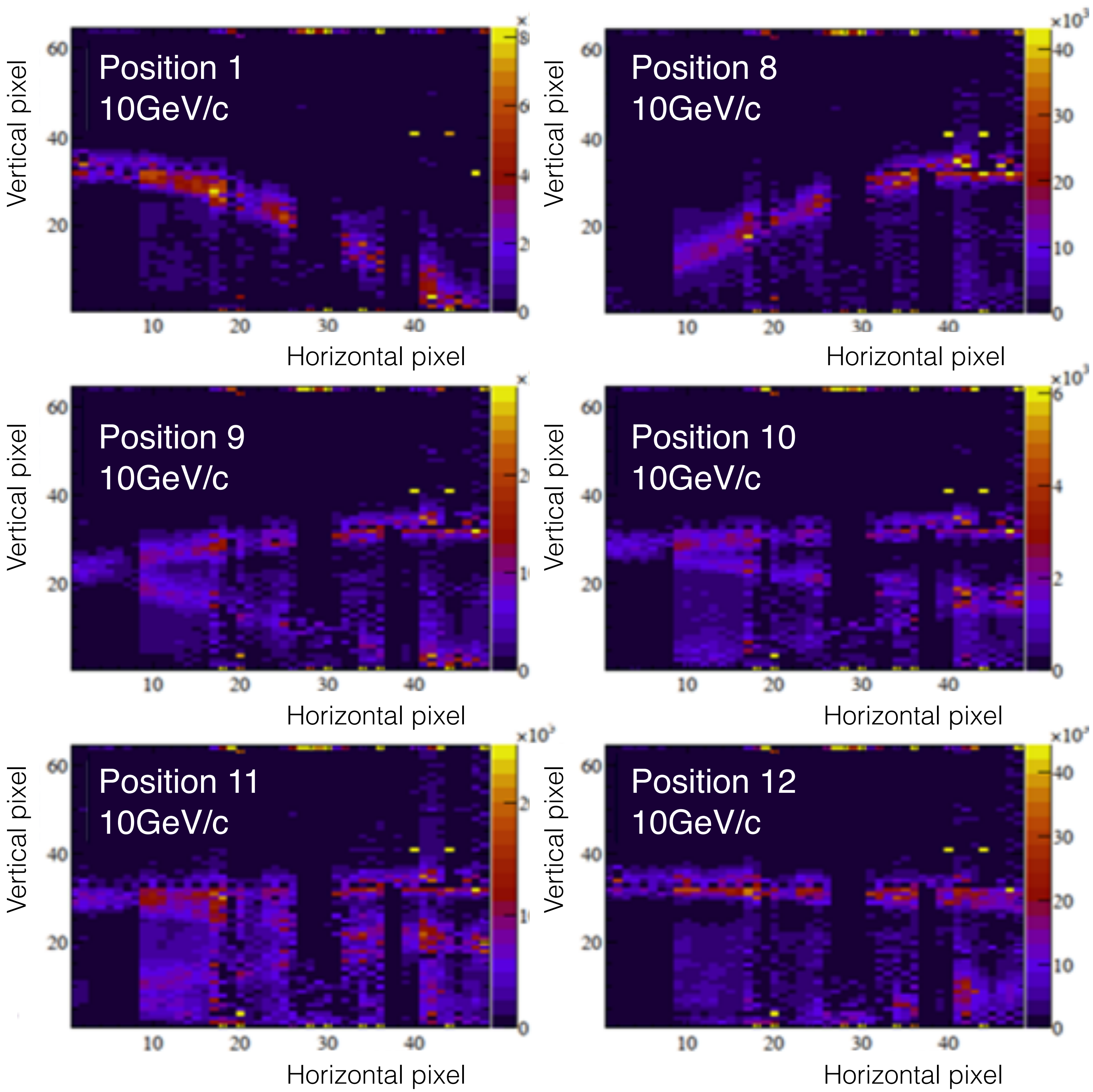


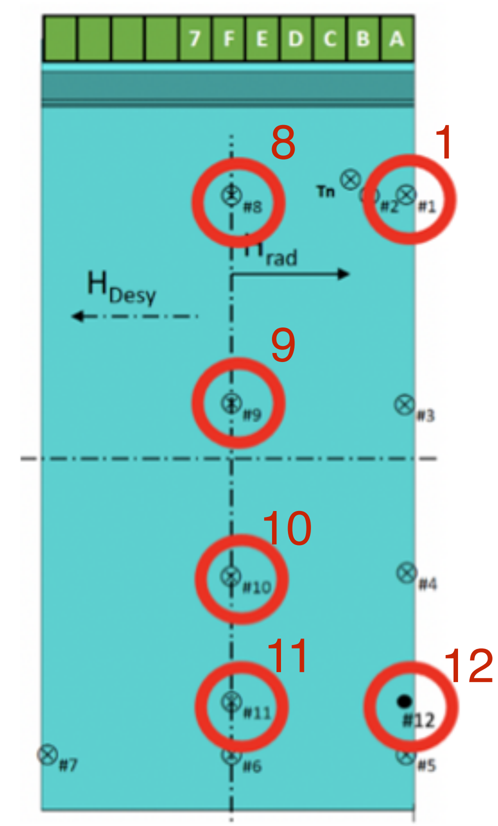
Beam test experimental area

- Already a large scale prototype requiring significant infrastructure.
  - We are equipping 3072 channels with 6 MCP-PMTs.



TORCH image with 6 MCP-PMTs

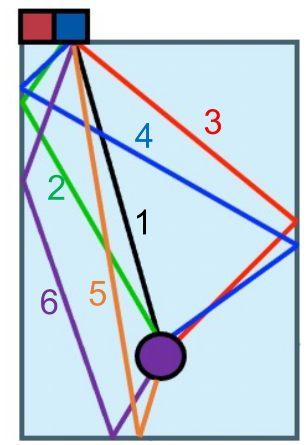


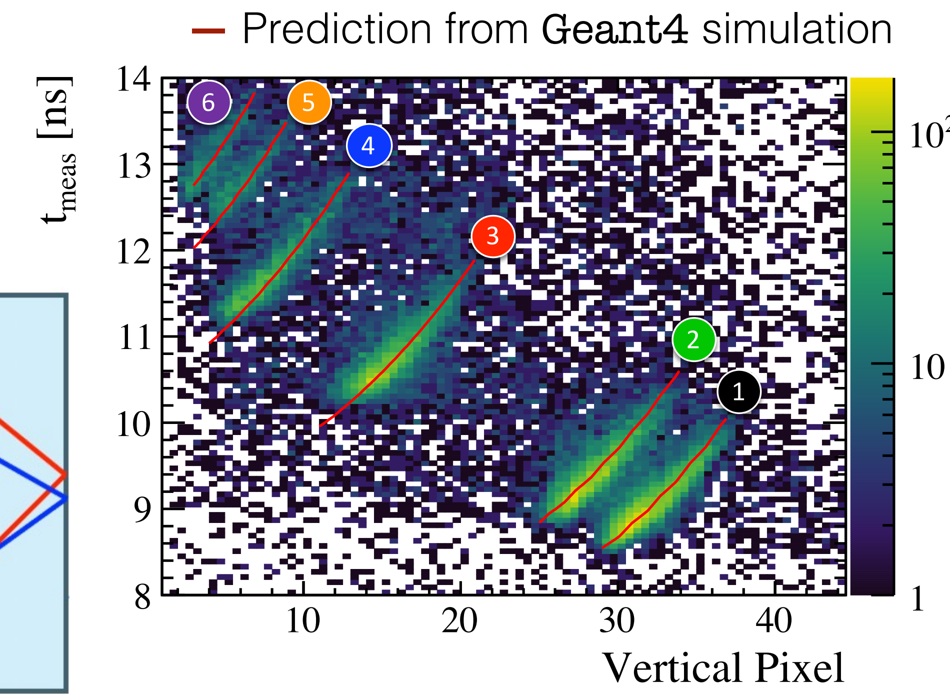


Data taken at six beam positions on the radiator bar at 3, 5, 8 and 10 GeV/*c*.

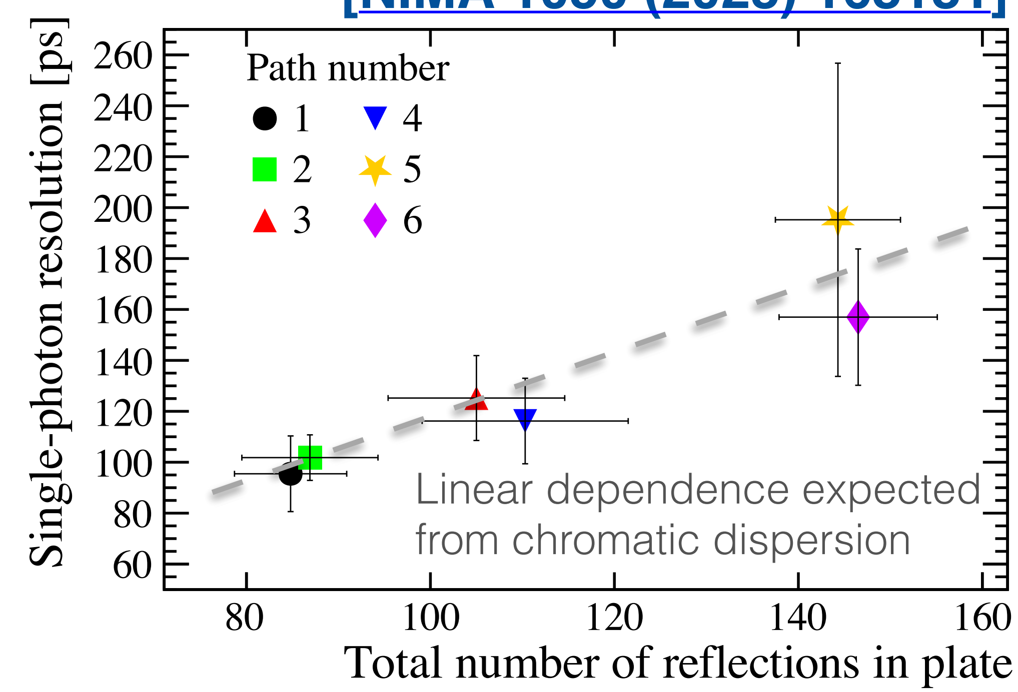
Performance in 2018 beam test

- Observed pattern is consistent with `Geant4` simulations of the prototype.
  - Form image in space time that is folded by reflections from the sides of the radiator.
- Studies indicate that time resolution can meet the needs of TORCH.





[NIMA 1050 (2023) 168181]



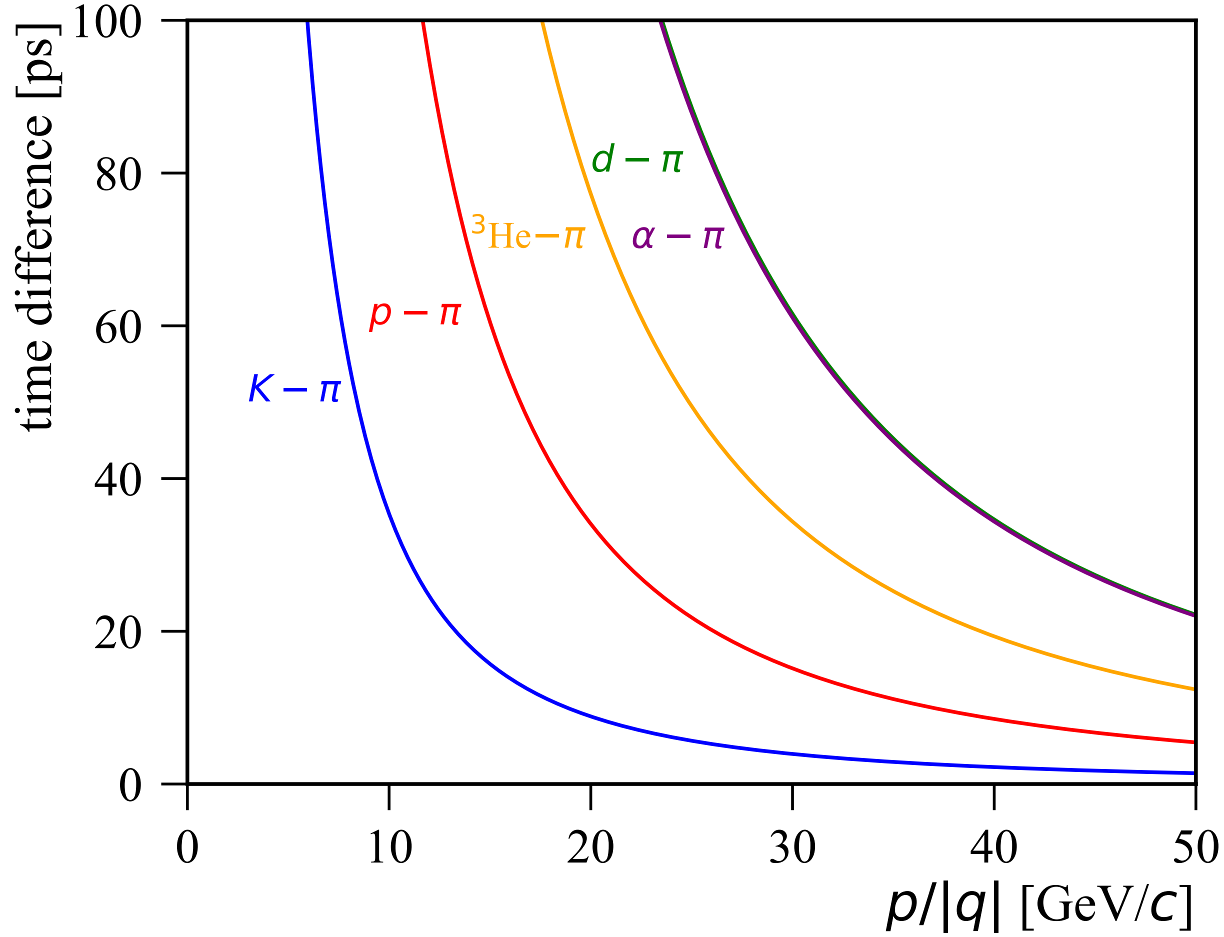
Summary

- TORCH is a large-area time-of-flight detector designed to improve the particle identification capability of the LHCb experiment for particles with $2 < p < 15\,\mathrm{GeV}/c$.
- Significant progress in several areas since the last Pisa Meeting.
  - Beam tests indicate that desired time precision can be obtained.
  - Aim to assemble a full scale prototype with light-weight support this summer to be tested in particle beams at the CERN PS next year.
- R&D ongoing as part of DRD4 to develop:
  - MCP-PMTs with increased lifetime; lightweight mechanics; systems to qualify the surface finish of the large area fused-silica radiators.

New collaborators are welcome. Please get in contact with us if you would like to contribute to the project.

Physics case

- Time-of-flight information from TORCH can also be used to identify heavier particles e.g. deuteron, ^{3}He and ^{4}He.
  - Limited deuteron-^{4}He separation based time-of-flight alone but photon yield scales with q^2.
- TORCH is also able to provide general purpose timing information that could aid in event reconstruction, e.g. providing timing after the LHCb magnet to reduce track ghost rates.

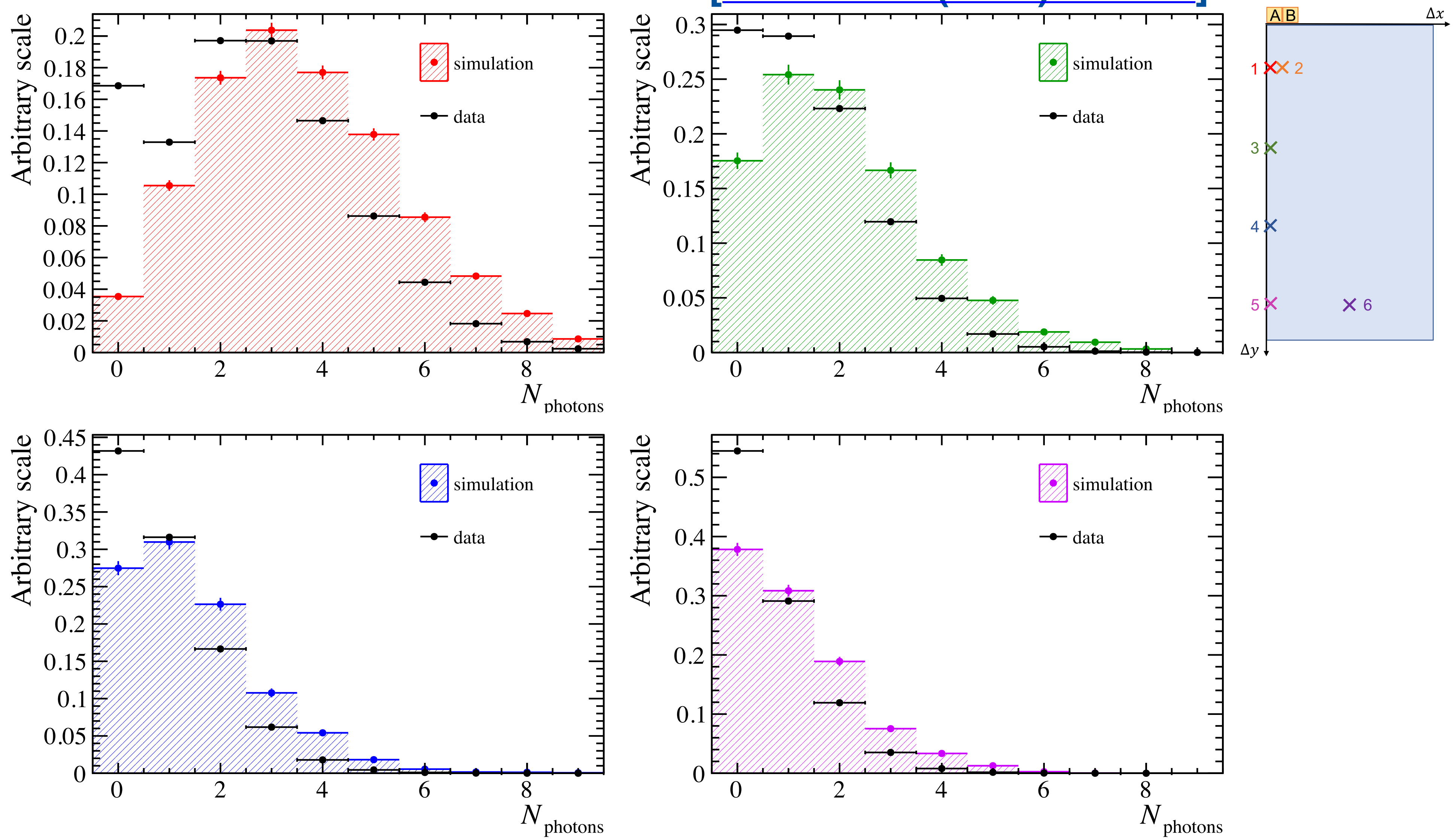


Photon yield in 2018 beam test

Compare the test beam data to a `Geant4` simulation taking into account surface effects in the radiator bar and our understanding of the MCP-PMT response (QE, gain and charge-sharing).

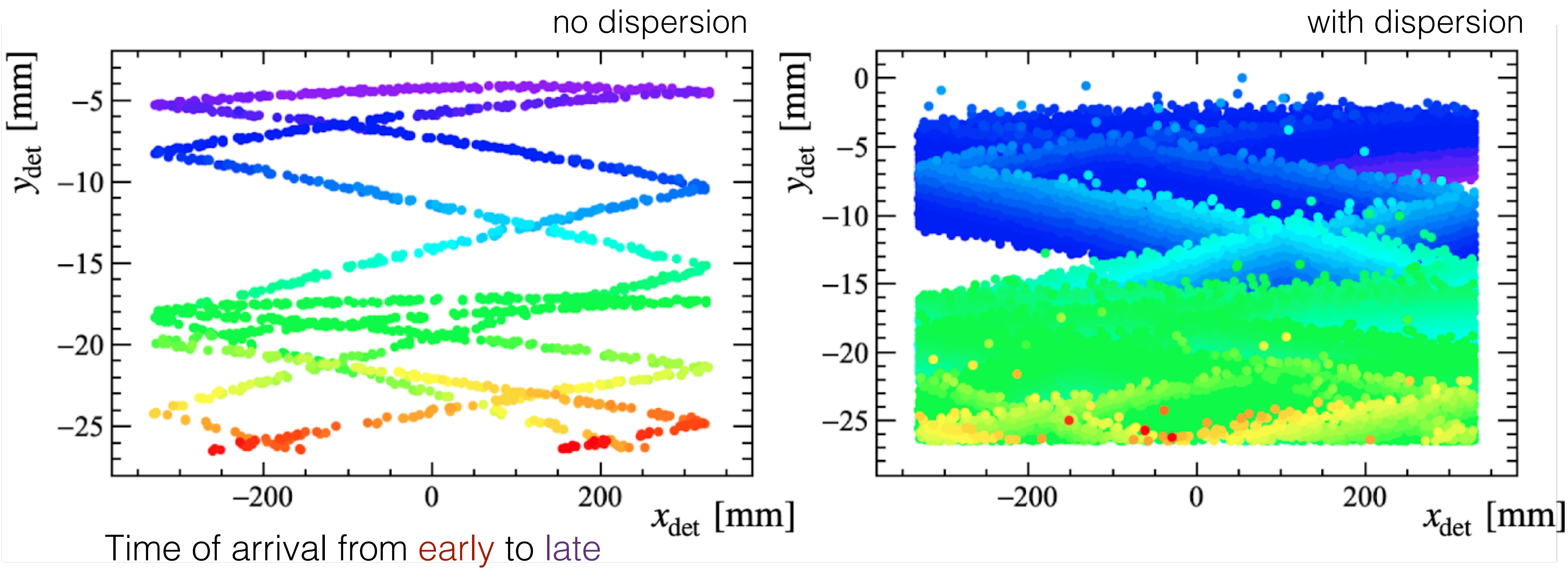
Photon yield in data/simulation is 82–85%.

[NIMA 1050 (2023) 168181]



TORCH image

- TORCH image forms bands in space/time:



- Use granularity of photon detector in y_{det} to account for chromatic dispersion.

TORCH reconstruction

- Likelihood for given hypothesis combination calculated from

$$L = \prod_{\text{hit } i} \left[\left(\frac{N_{\text{bkg}}}{N} \right) P_{\text{bkg}}(x_i) + \sum_{\text{particle } j} \left(\frac{N_j}{N} \right) P_j(x_i \,|\, h_j) \right]$$

Contribution from reconstructed tracks

- Iterate to find best combination of particle hypotheses, h_j.

- Probability for a hit comes from summing over allowed paths (reflections from sides or bottom of the radiator)

$$P(x \,|\, h) = \sum_{\text{path } k} |J_k| \, P(E_k, \phi_k, t_k \,|\, h)$$

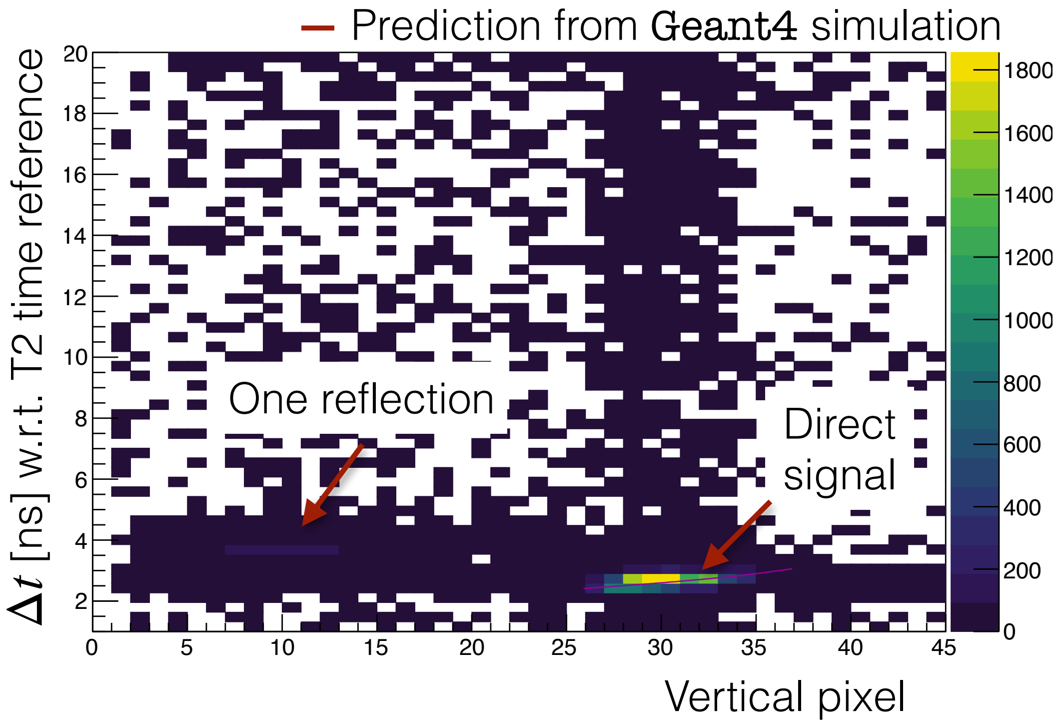
Probability in emission space

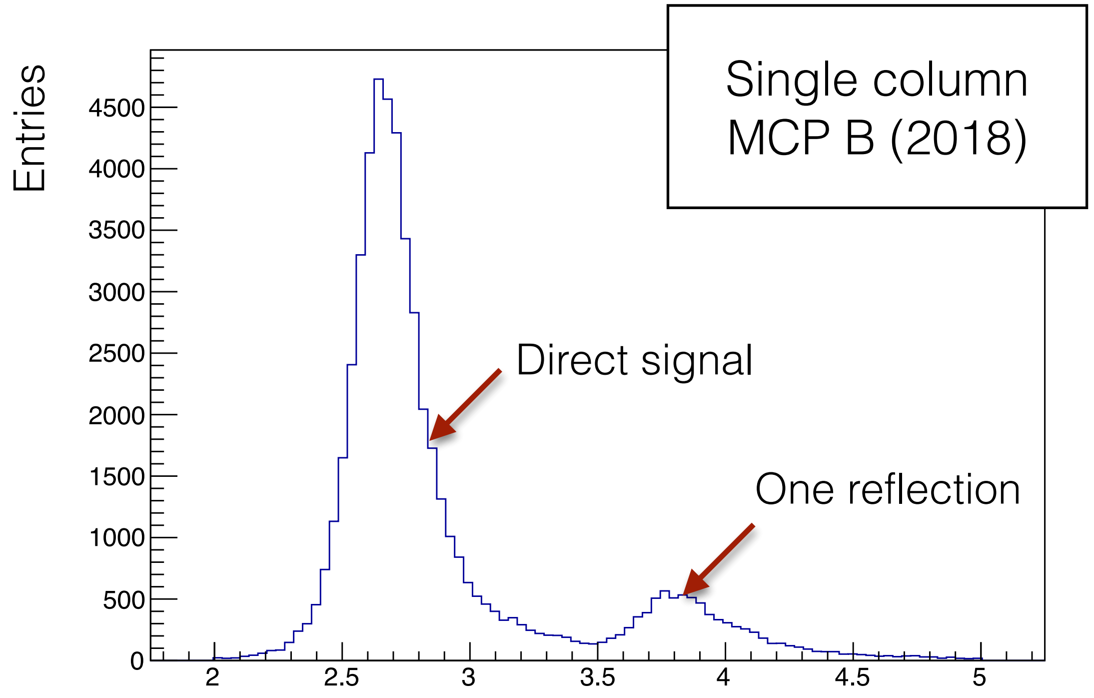
Jacobian for transformation from emission to detection space

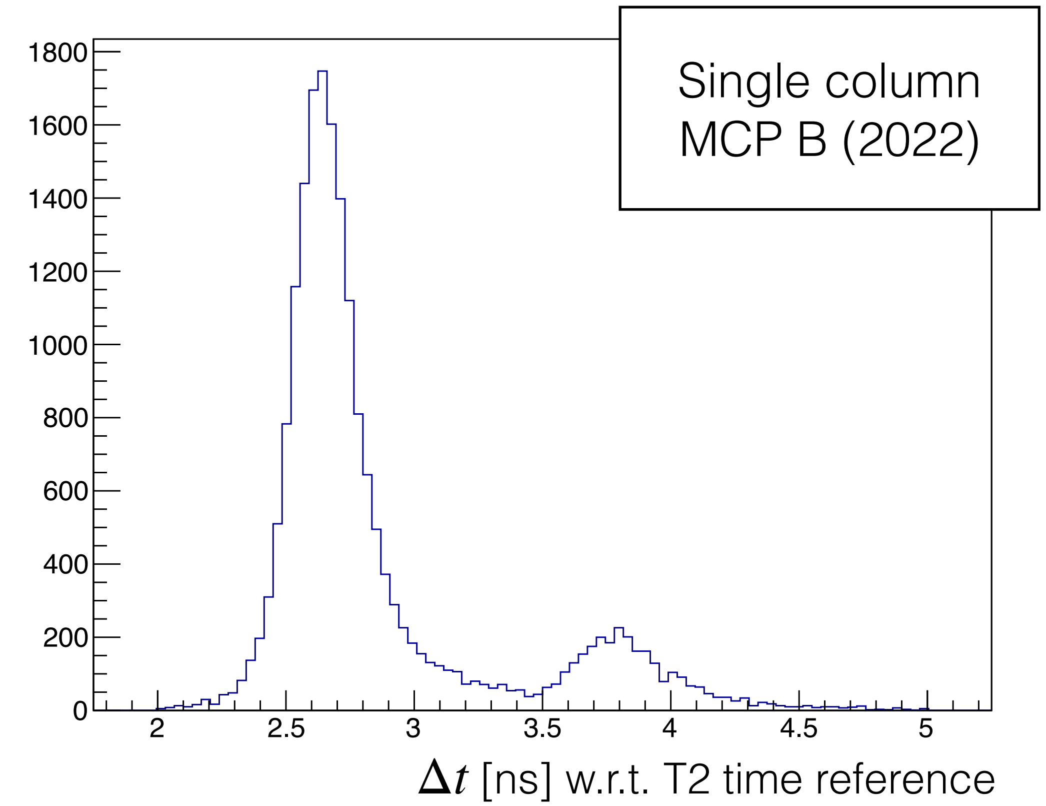
- Determine PDF normalisation, Jacobian and expected photon yields numerically. Assume photon emitted at centre of radiator.

Time resolution in 2022 test beam

- Analysis of the 2022 data is ongoing.
- Comparisons indicate a similar time resolution is seen in 2018 and 2022.
- Data are corrected for integral non-linearities in the HPTDC and NINO time-walk using data-driven approaches.







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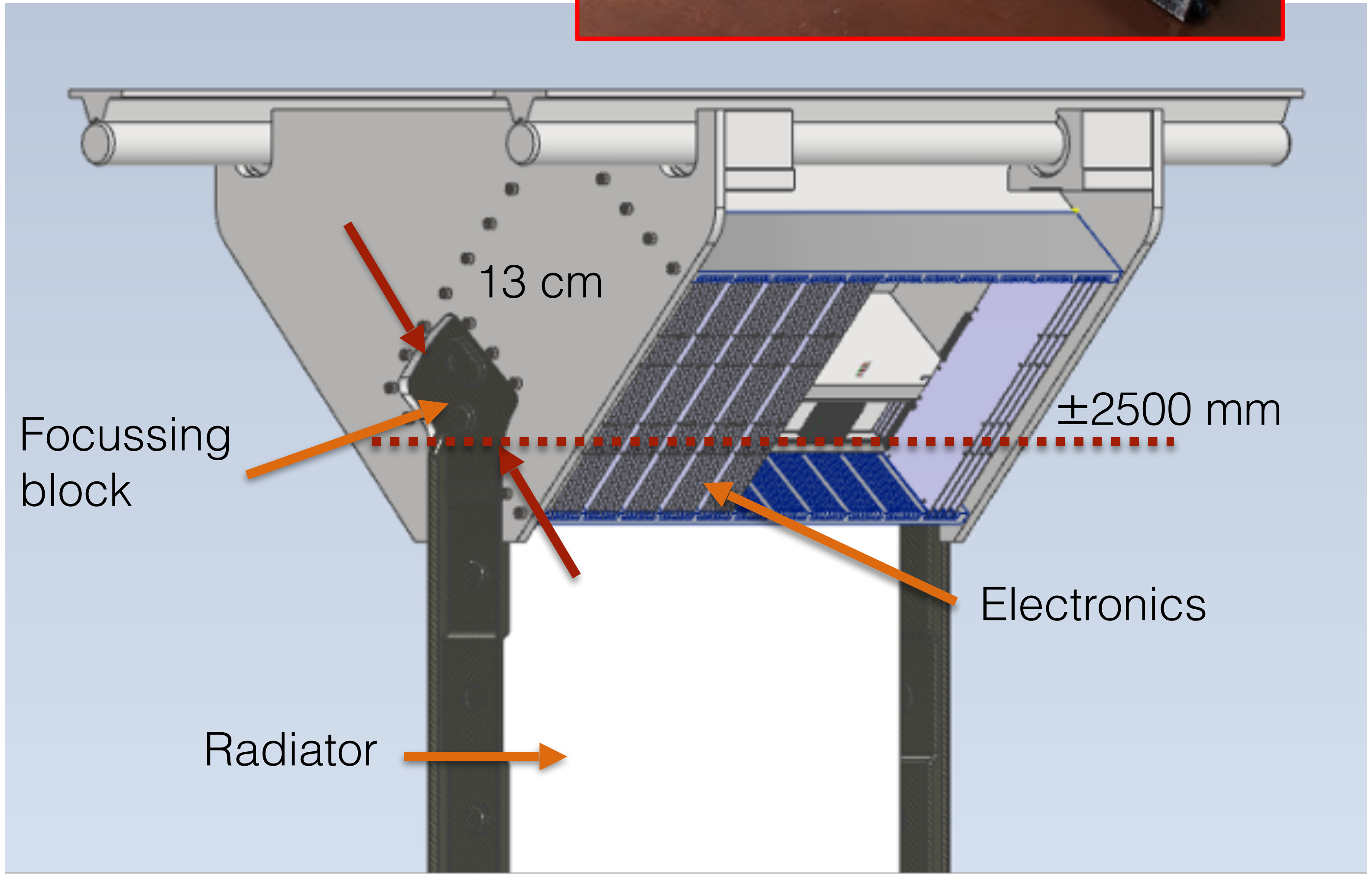

Support structure

- Design is already in an advanced state.
- Plan to assemble a full-scale module in the summer and test the assembly in a beam test in 2025.