TORCH: extending LHCb's particle ID capabilities in Upgrade II

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University of BRISTOL
UNIVERSITY OF OXFORD
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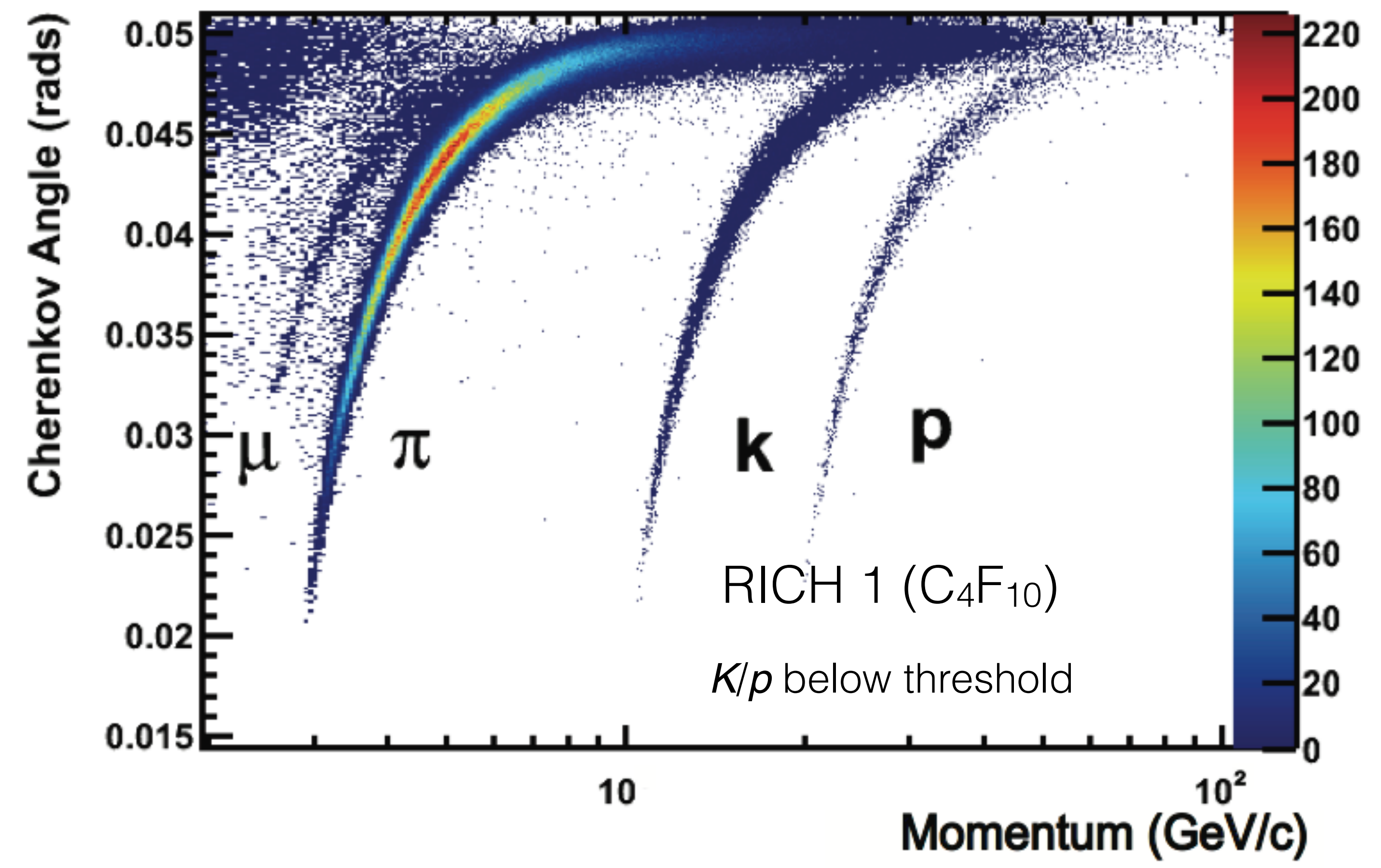
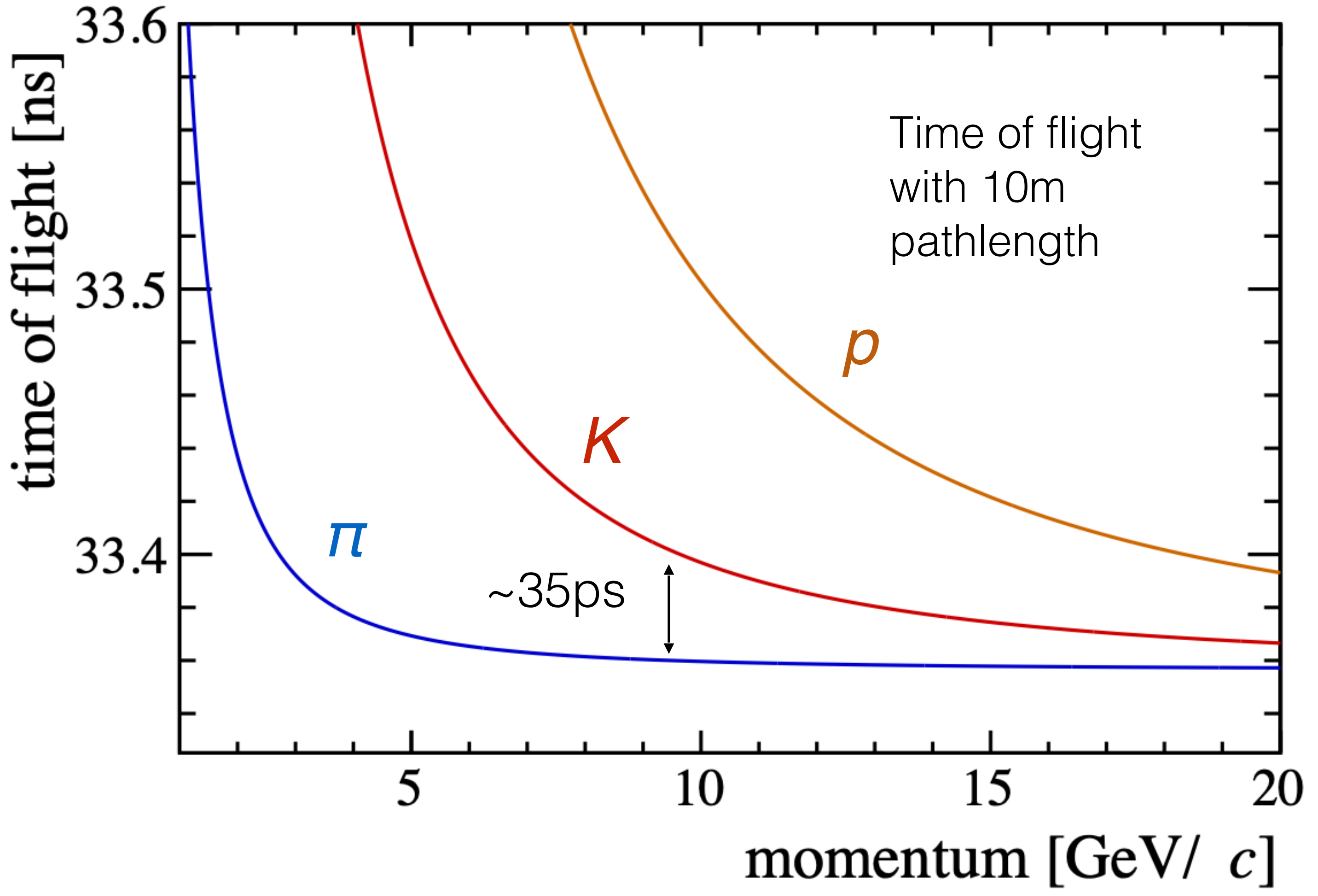
Detector concept

- ➡ 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 separation over 10 m, 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 at instantaneous luminosities of 1–1.5x10^{34} $cm^{-2}s^{-1}$

LHCb [EPJC 73 (2013) 2431]





Detector concept

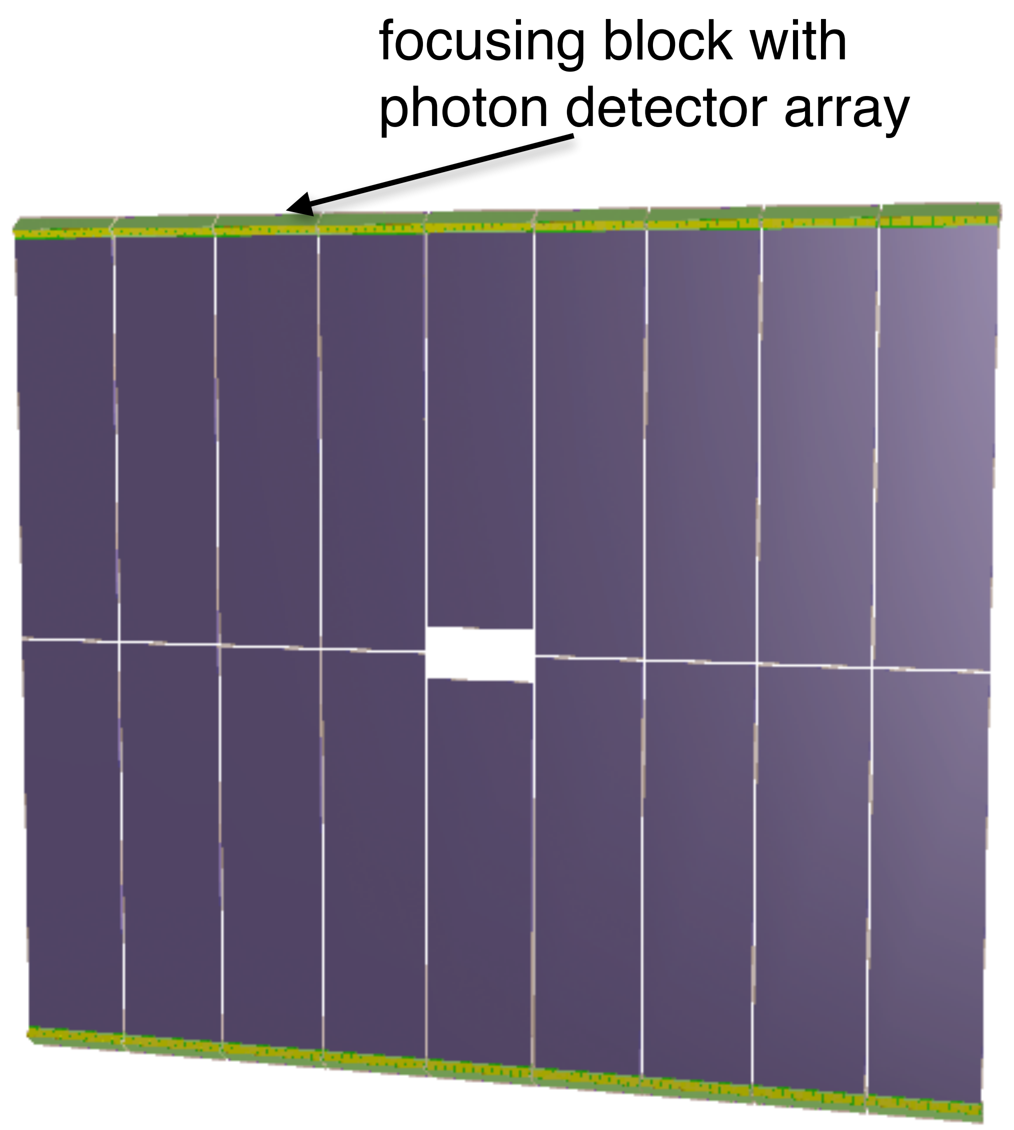
➡ Exploit prompt production of Cherenkov light in an array of fused-silica bars to provide timing

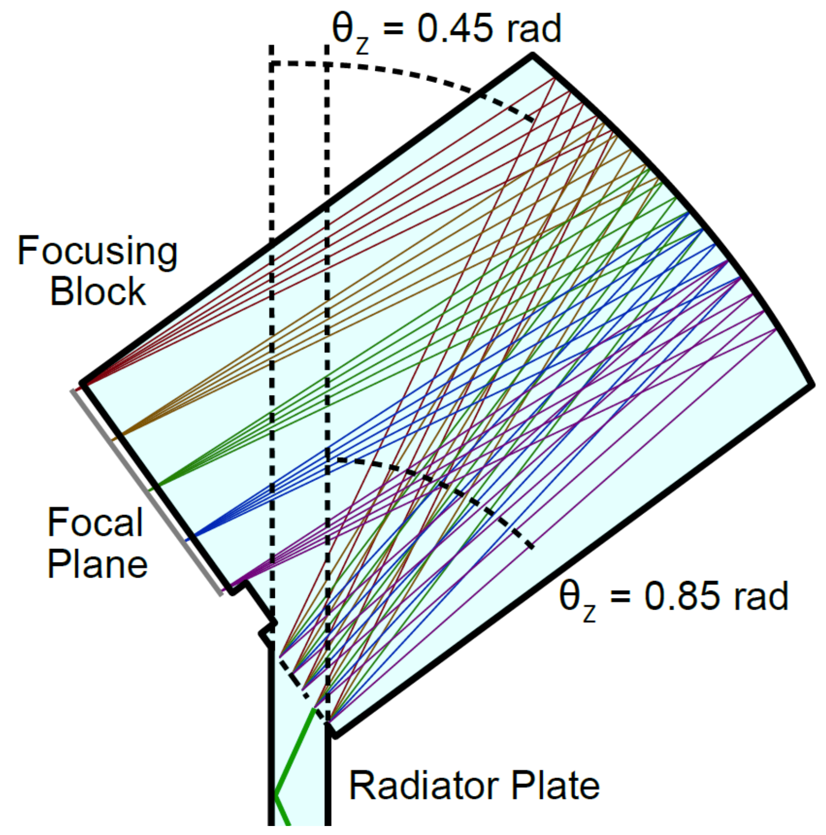
➡ Cherenkov photons are propagated to detector plane via total internal reflection from the quartz surfaces

➡ 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 (5x6 m^2) comprised of 18 modules (2500x66x1 mm^3)





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

Expected PID performance

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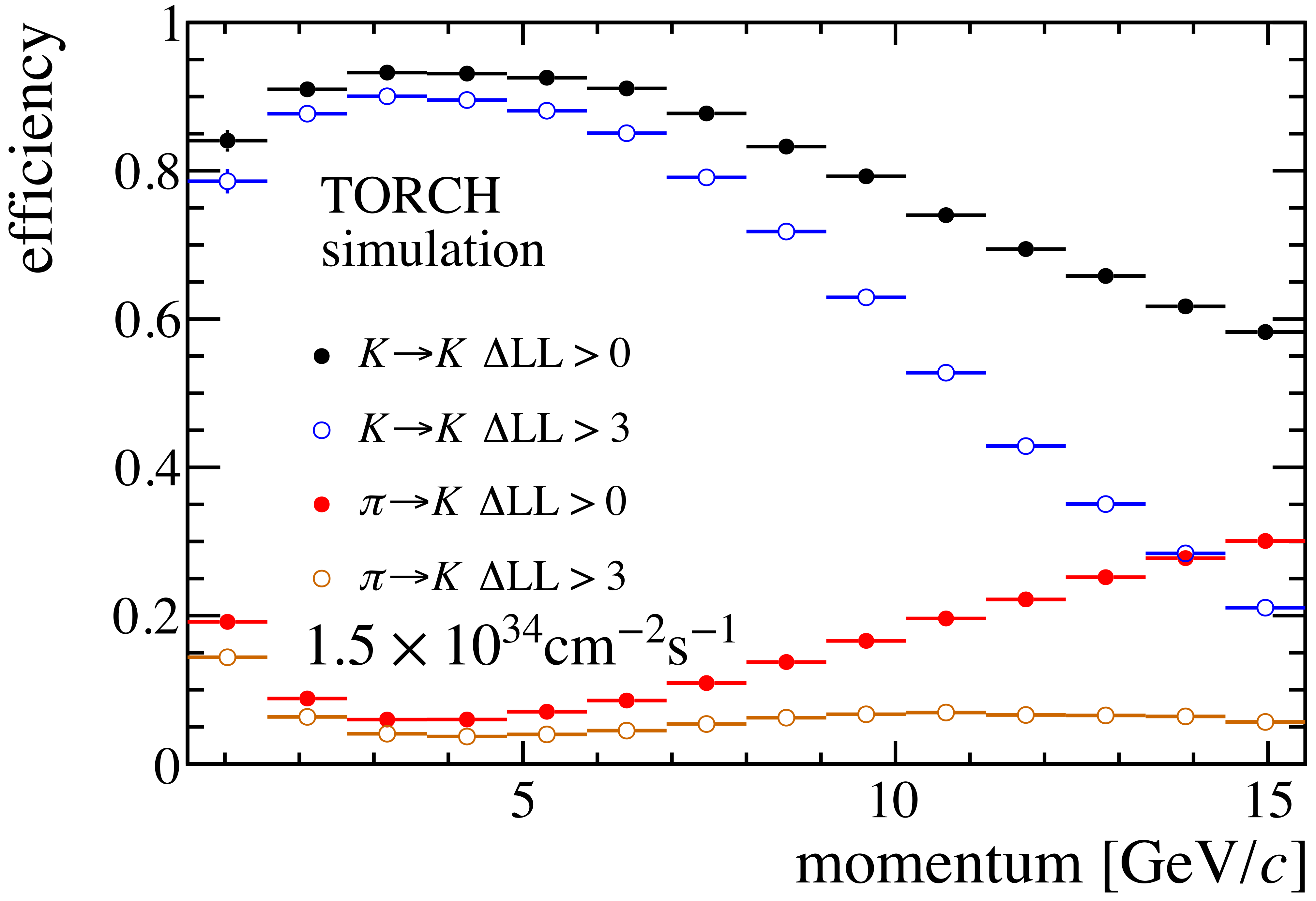
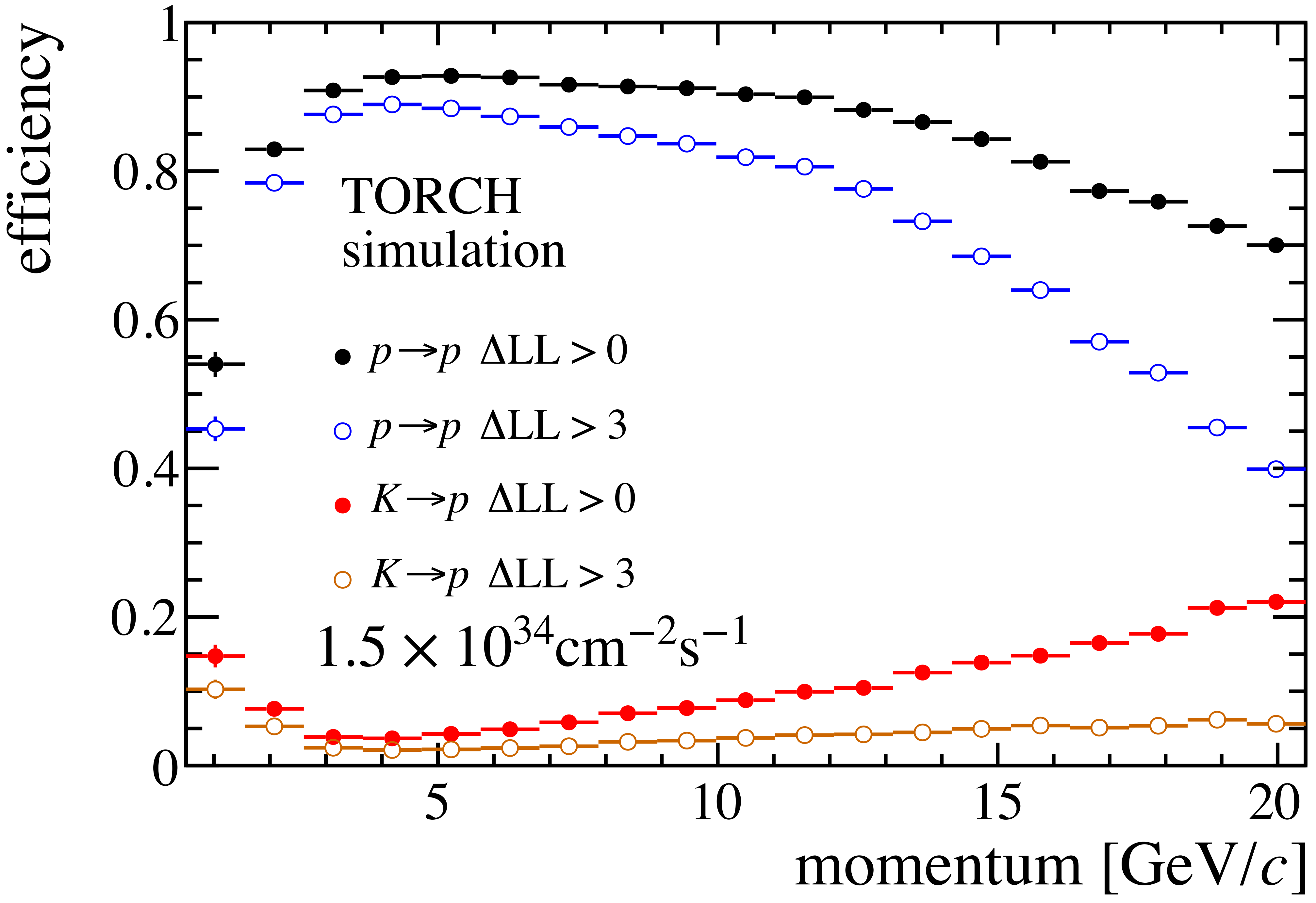
- ➡ Provides *π*/*K* (*p*/*K*) separation in the 2–10 (2–15) GeV/*c* range:
  - ❖ Improves phase space coverage of many analyses and effective flavour tagging power [LHCb-PUB-2020-006]

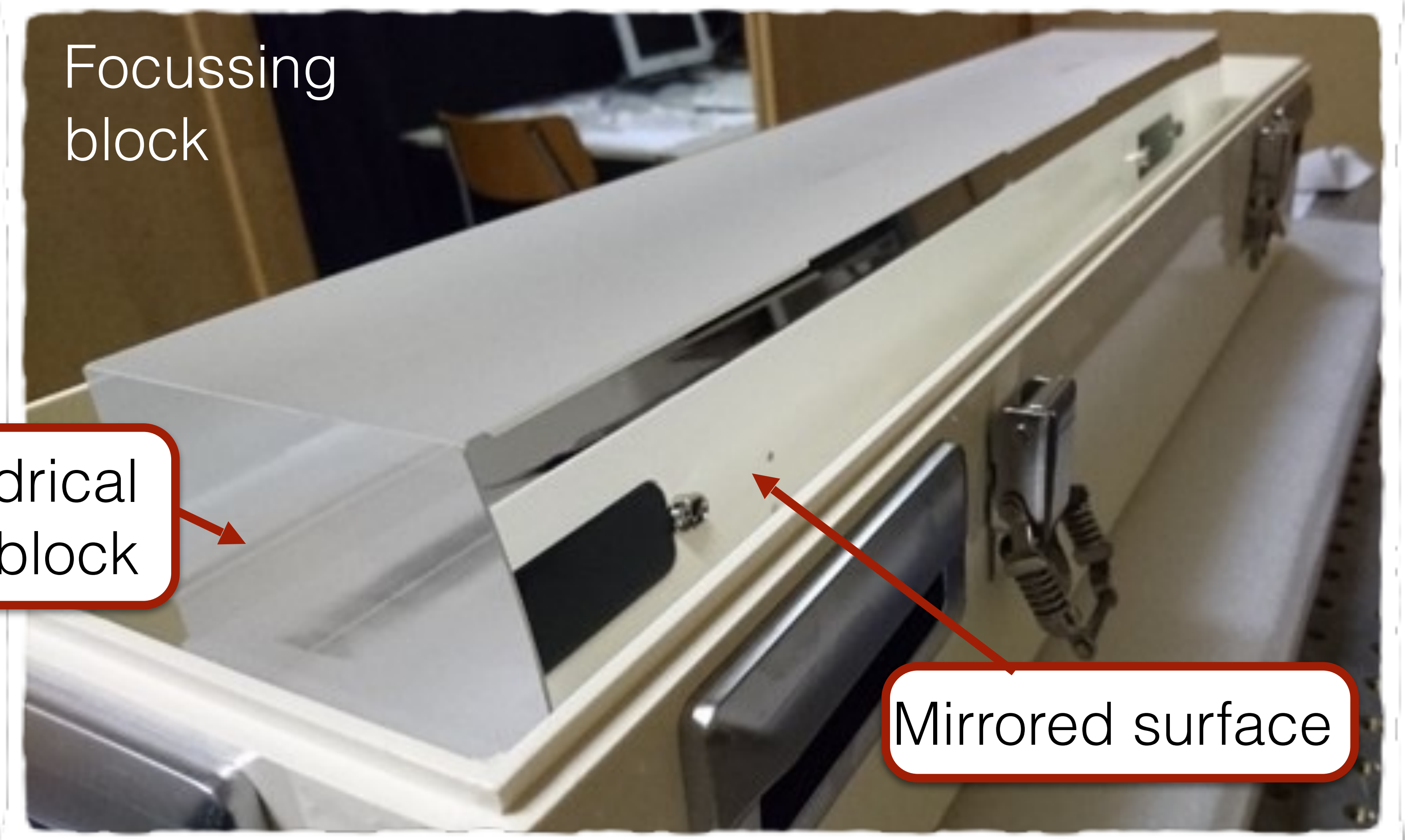


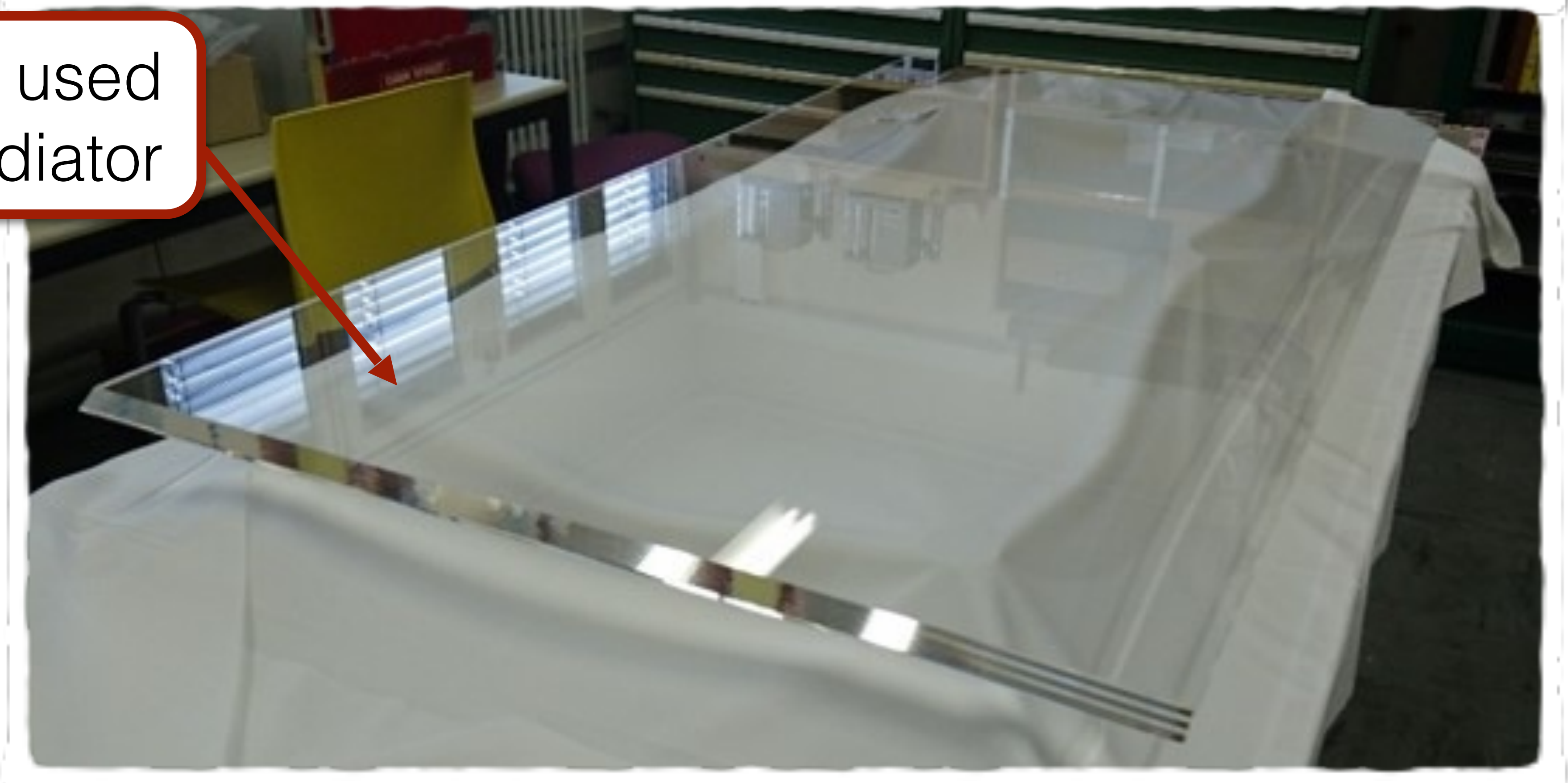


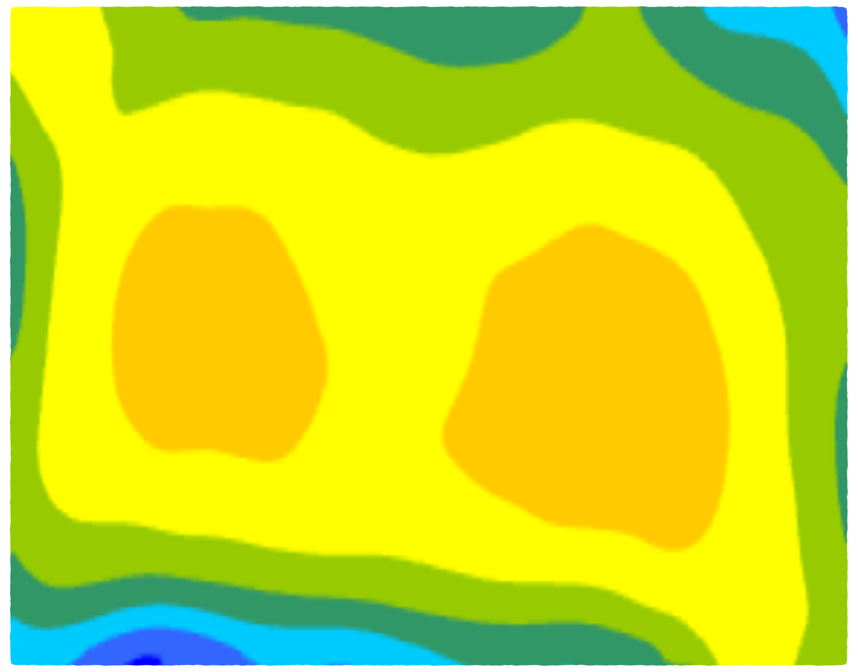
Fused-silica pieces

- ➡ Optics formed from multiple pieces of synthetic fused-silica
- ➡ Require high-quality surface on front and rear faces (flatness variation ≤3 μm and surface roughness 5Å)
- ➡ Two 66x62.5x1cm^3 radiator plates acquired to complete a full-sized module

Produced by
Nikon glass



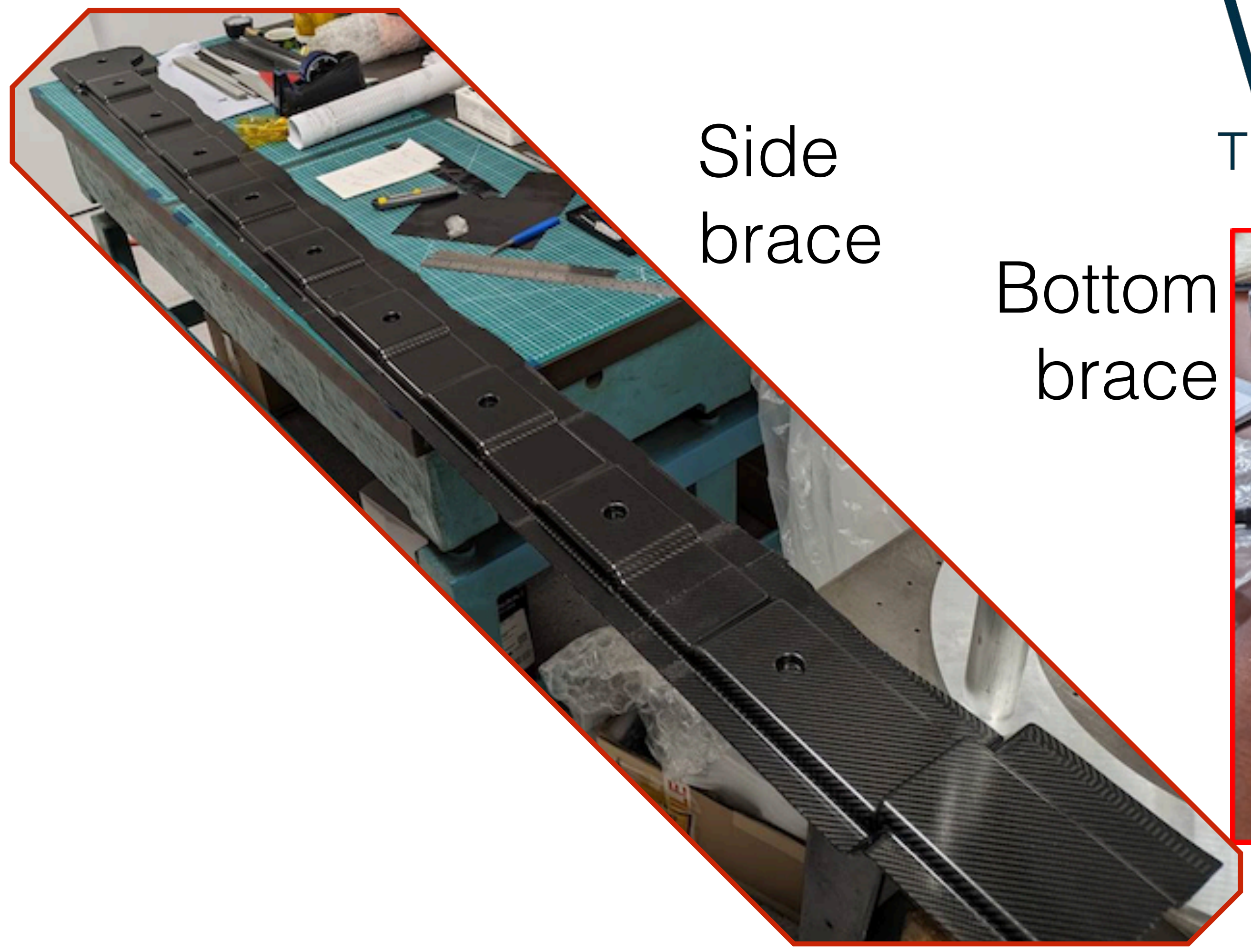




Measured flatness variation in 1 μm contours

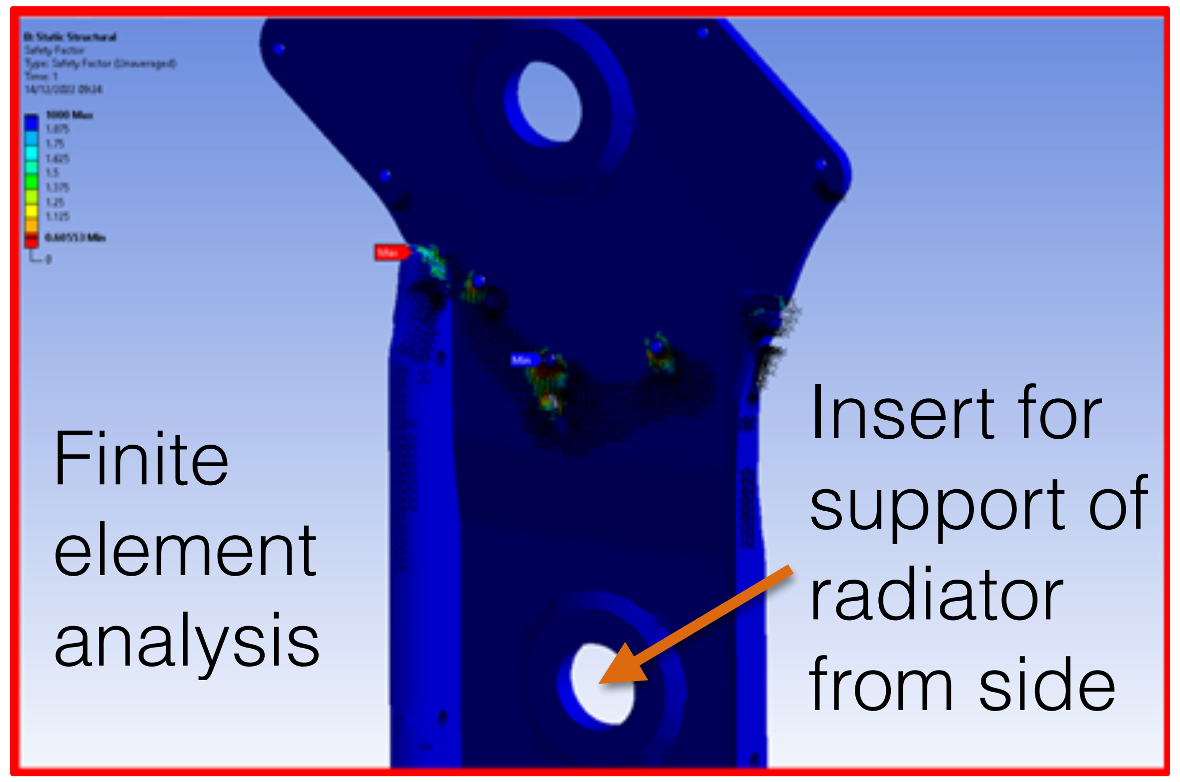
Mechanical support

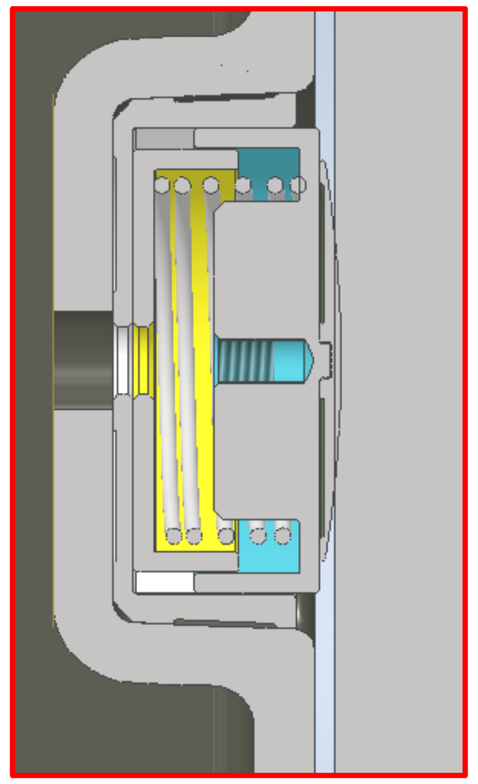
- ➡ Need lightweight structure to minimise material in front of other subdetectors
  - ❖ Carbon fibre structure
- ➡ Prototype of the support structure is designed and being produced
- ➡ Plan to assemble full scale module for use in a beam test in 2025

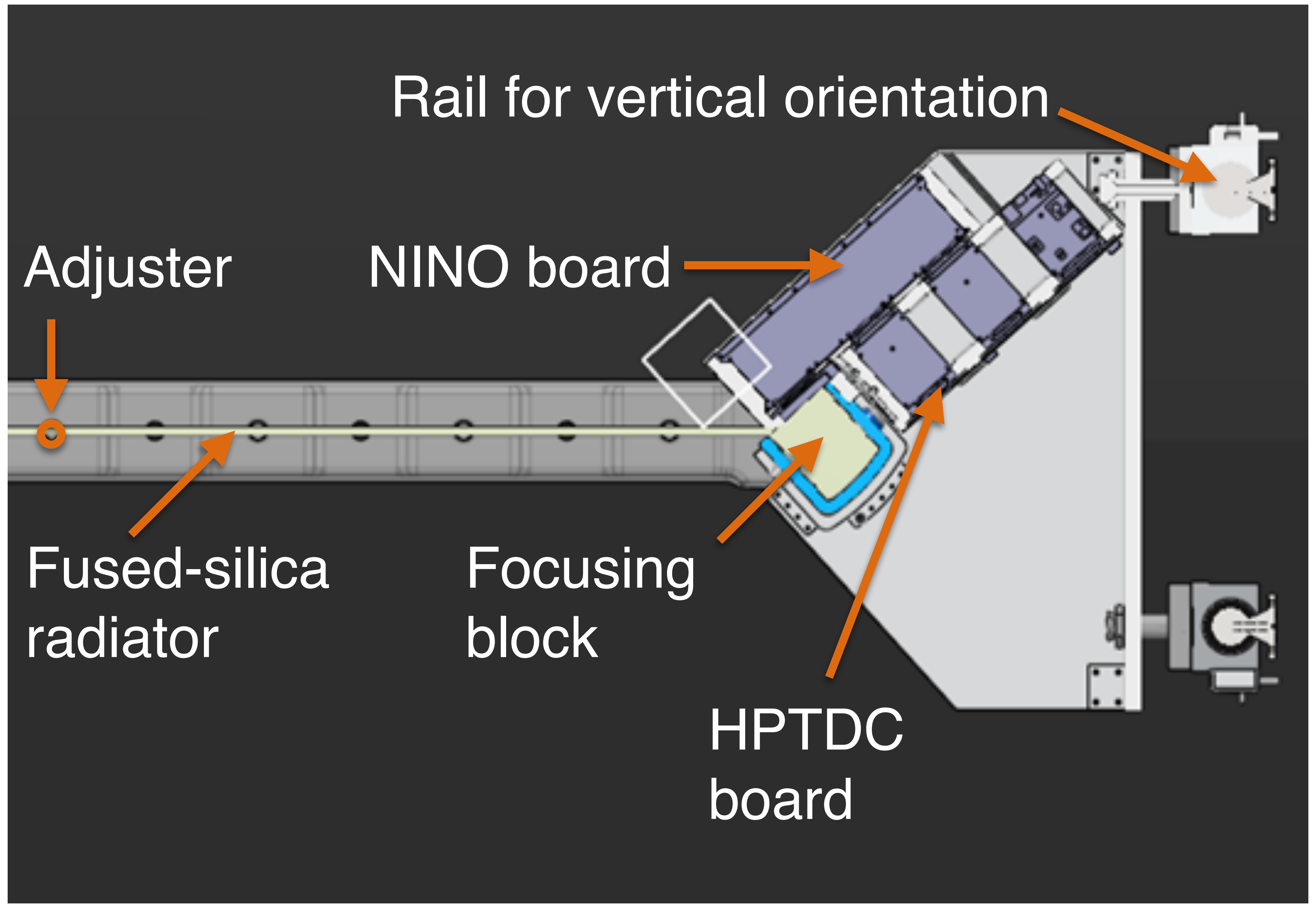


Side brace

Bottom brace

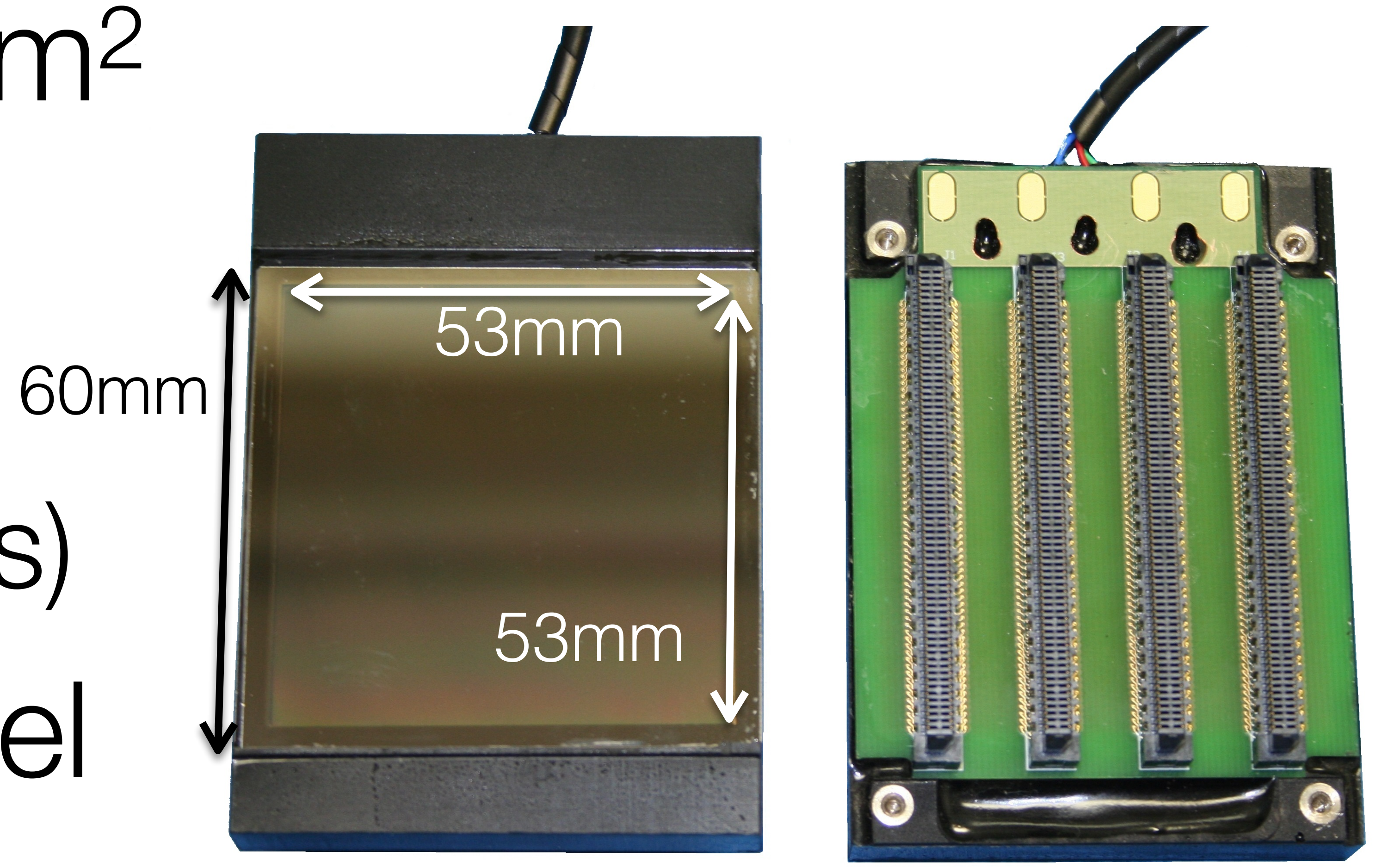


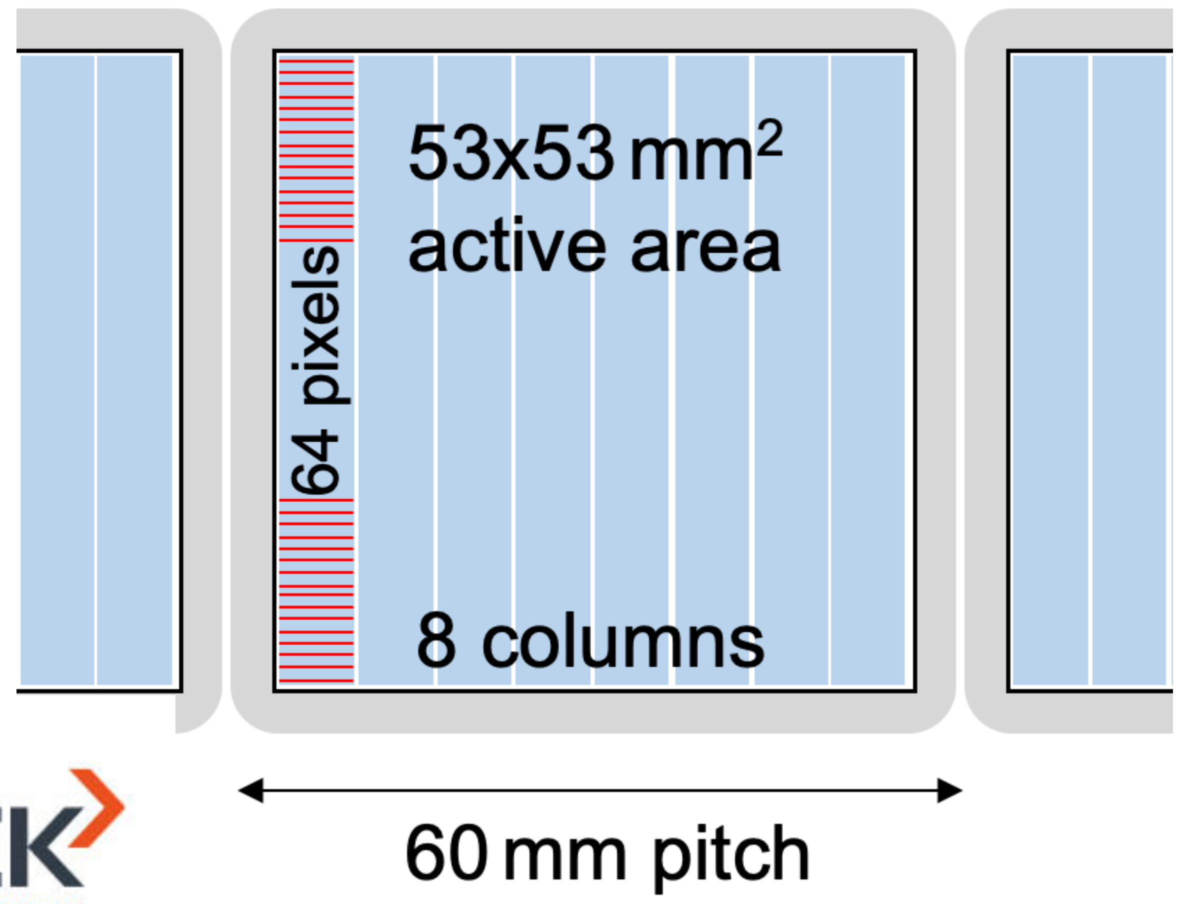




Photon detectors

- ➡ Current TORCH prototype uses custom 53-by-53 mm^2 MCP-PMTs with 64-by-64 pads [JINST 10 (2015) C05003]
  - ❖ MCP-PMTs 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 C/cm^2





Photon detectors

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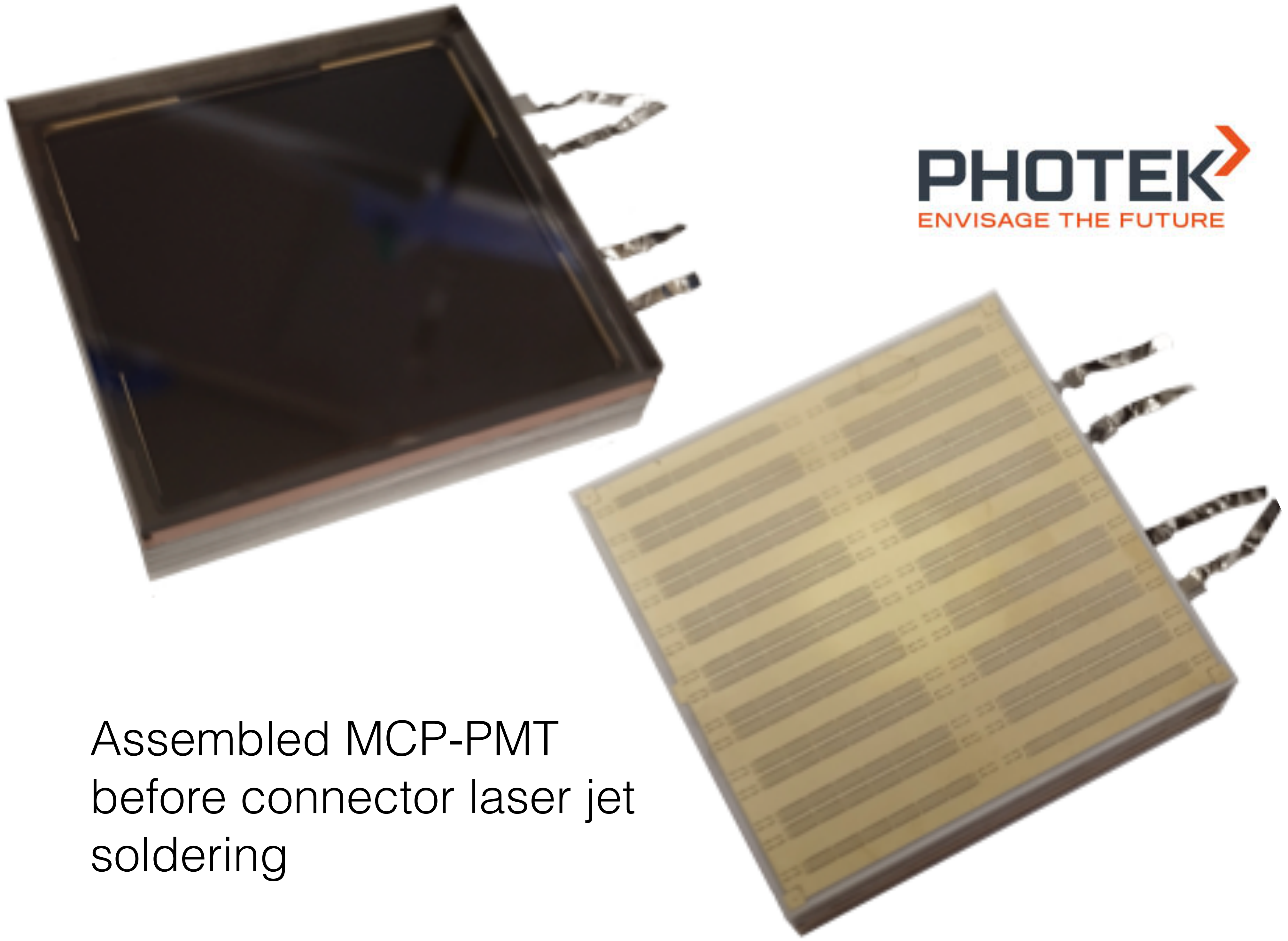
- Existing devices are not suitable for the HL-LHC environment
- R&D effort to produce a 16-by-96 pixel MCP-PMT with direct coupling
  - Smaller pixels and reduced charge-sharing between pixels to reduce per-pixel occupancy
  - Non-trivial task due connectors and space for electronics
- Work ongoing in context of DRD4 to improve rate capability and lifetime (ideally well beyond 10 C/cm^2)

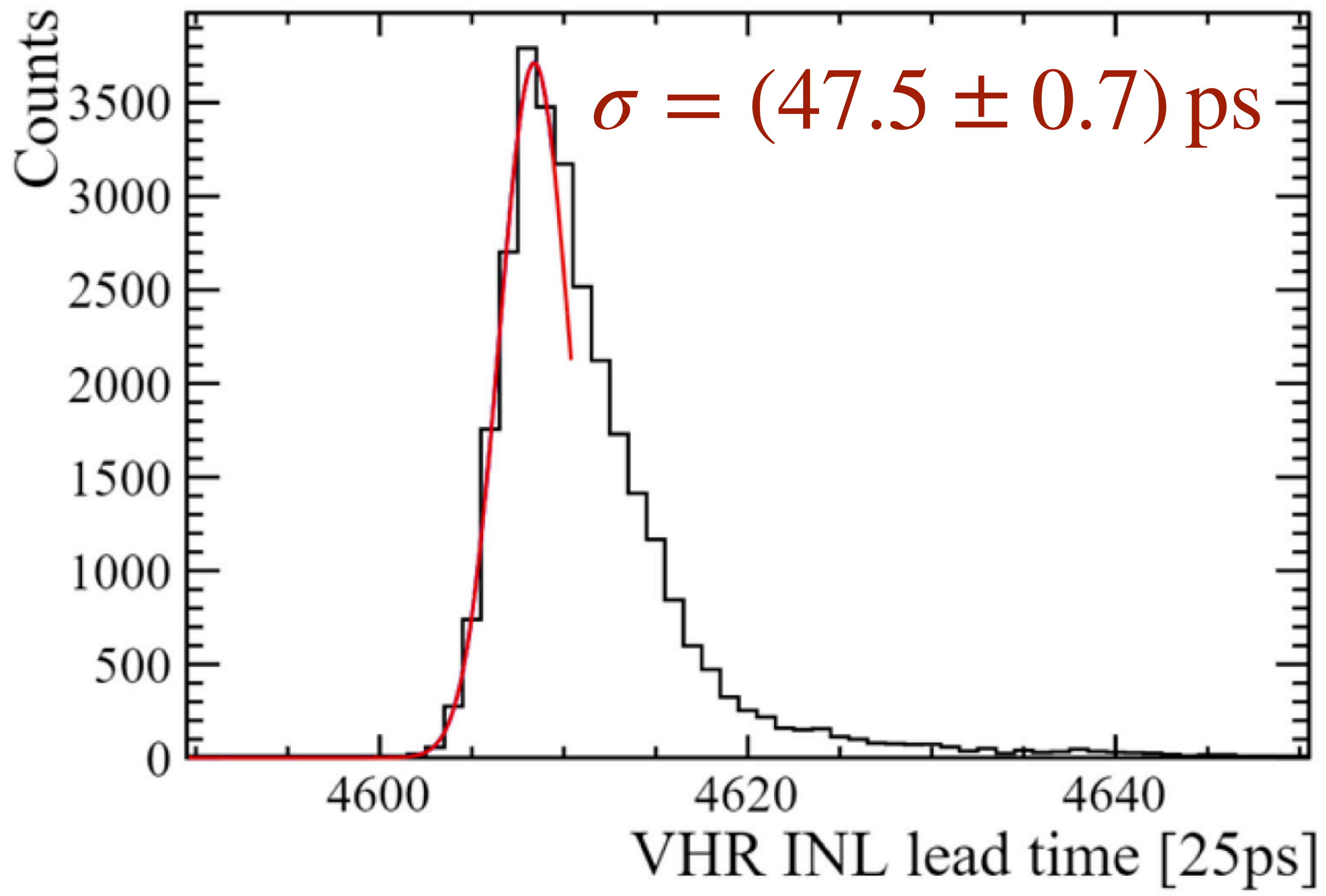


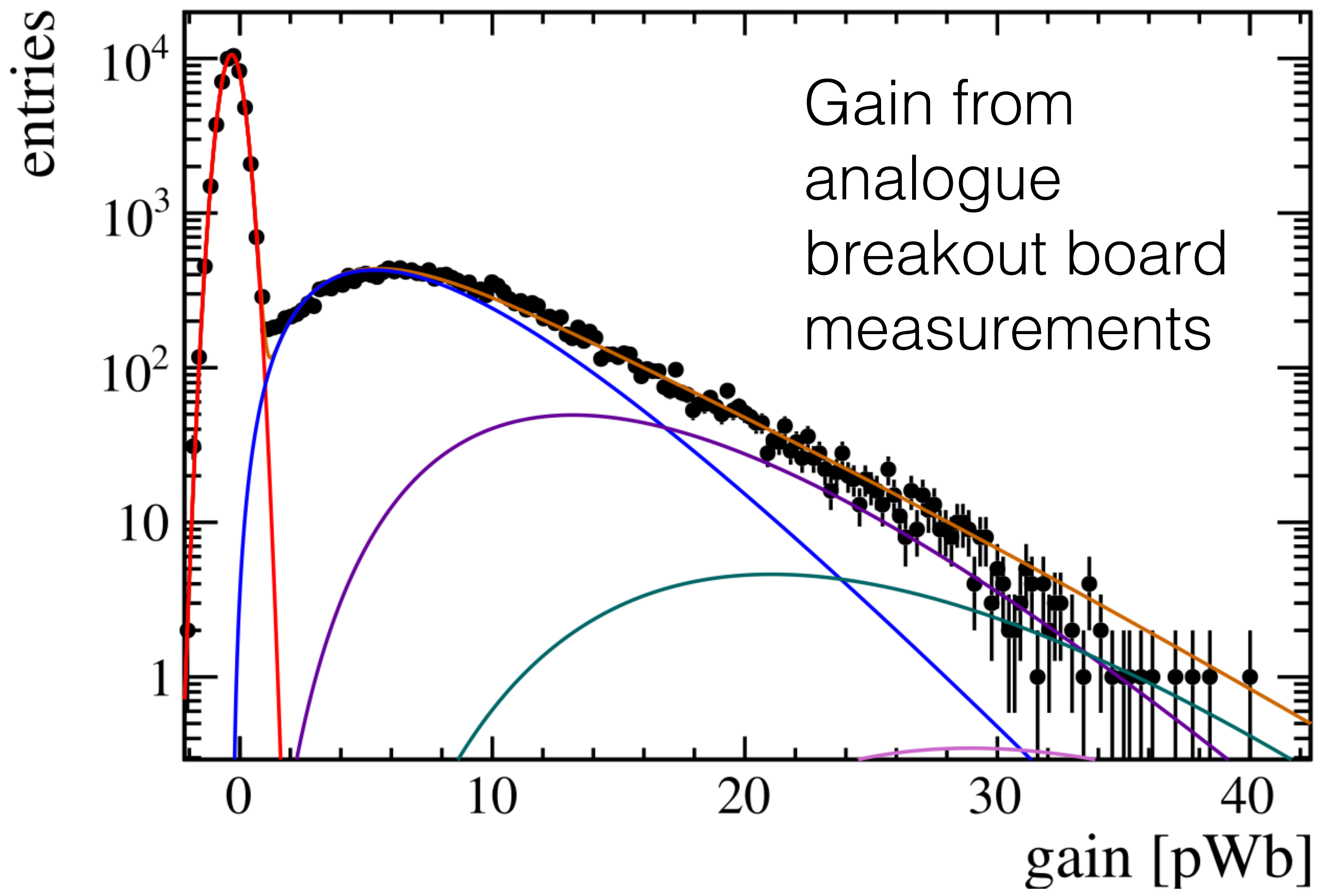
PHOTEK
ENVISAGE THE FUTURE

Assembled MCP-PMT before connector laser jet soldering

Detector performance

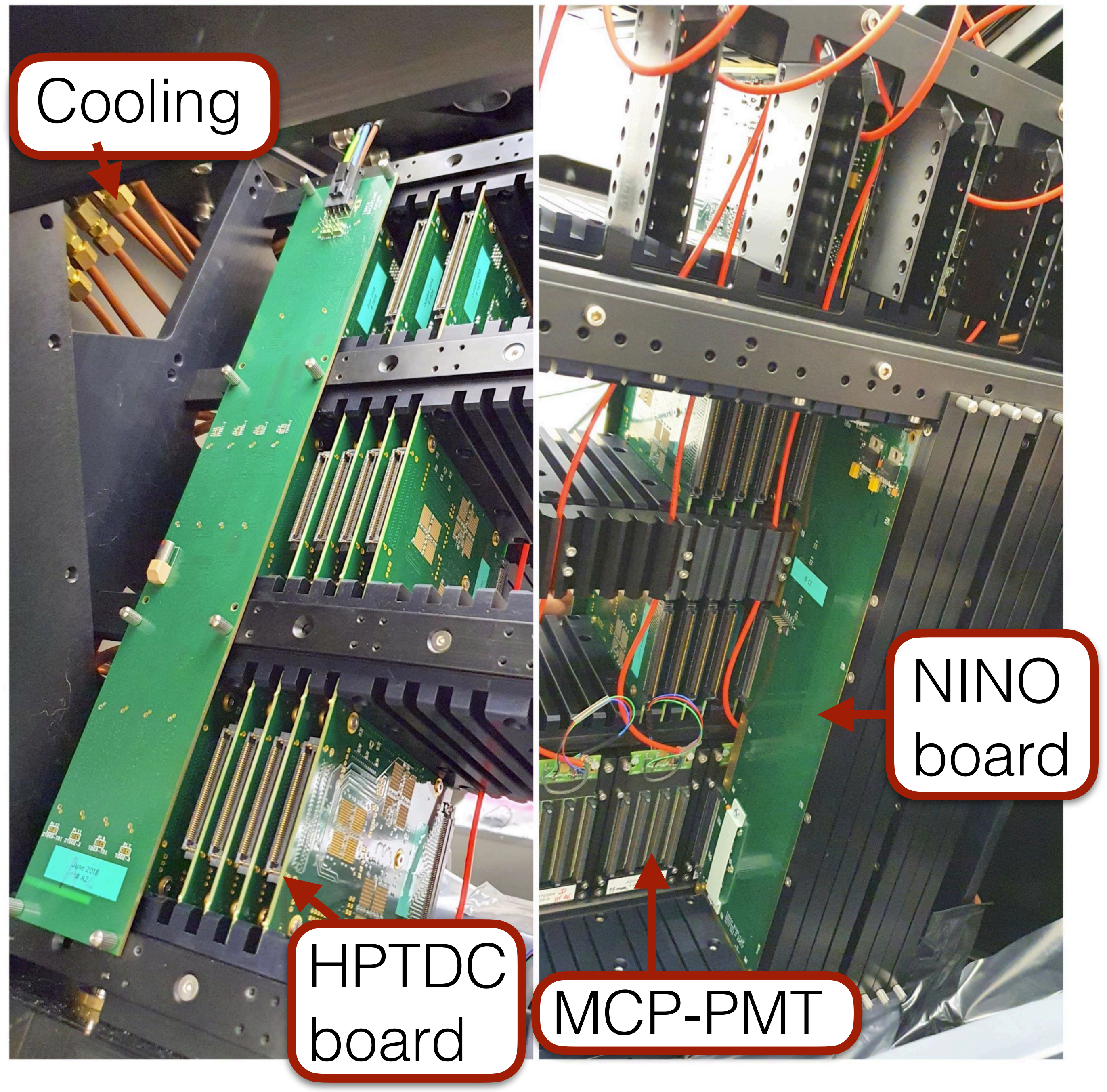
- ➡ Electronics based on NINO+HPTDC ASICs [JINST 11 (2016) 04 C04012]
- ➡ MCP-PMT and electronics performance studied extensively in laboratory measurements with pulsed 405 nm picosecond laser
  - ❖ Intrinsic time resolution of MCP-PMT and readout electronics (after INL correction) is around 50 ps
- ➡ Dedicated calibration system developed to improve time-walk and INL corrections for 2022 beam test
  - ❖ Injection of defined charges directly into electronics



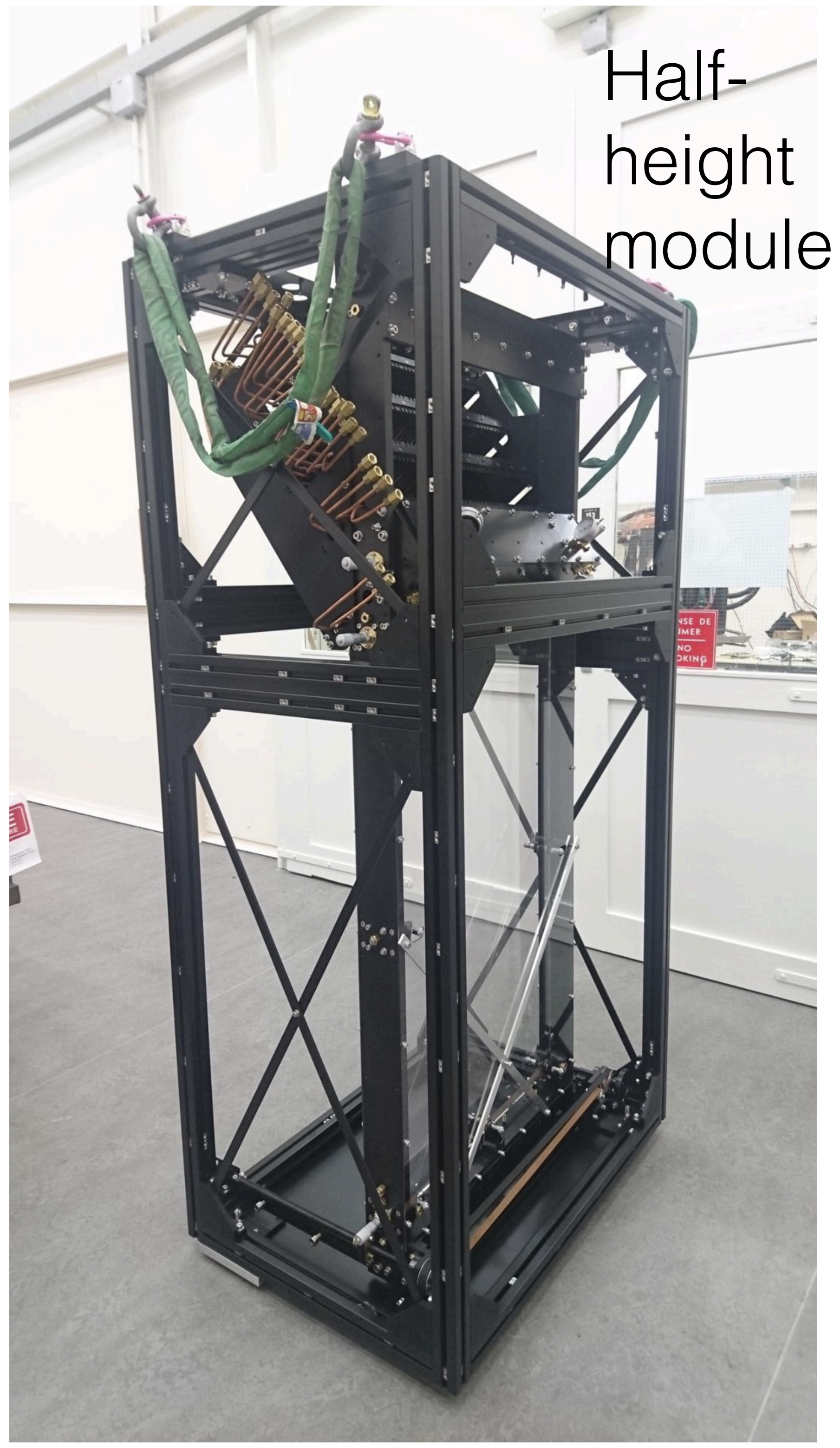


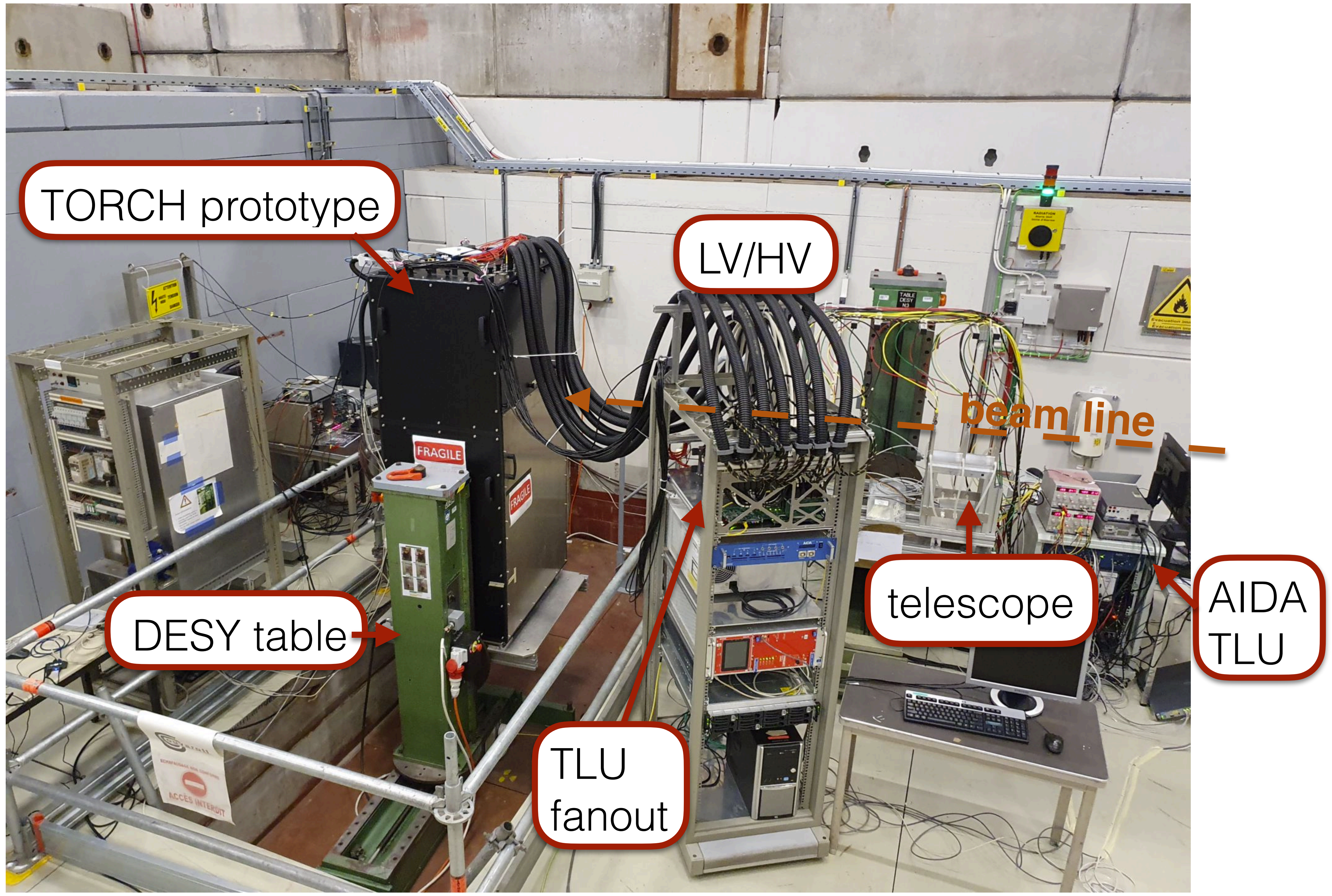
[NIMA 1038 (2022) 166950]

Beam test setup



- 2 MCP-PMTs (1024 channels) in 2018
- 6 MCP-PMTs (3076 channels) in 2022





Performance in 2018 beam test

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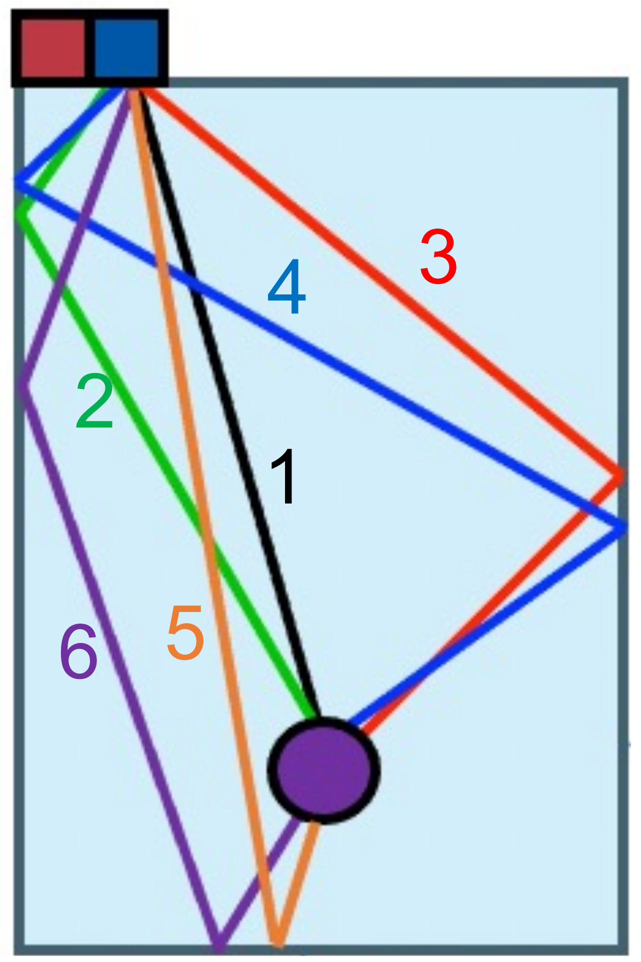
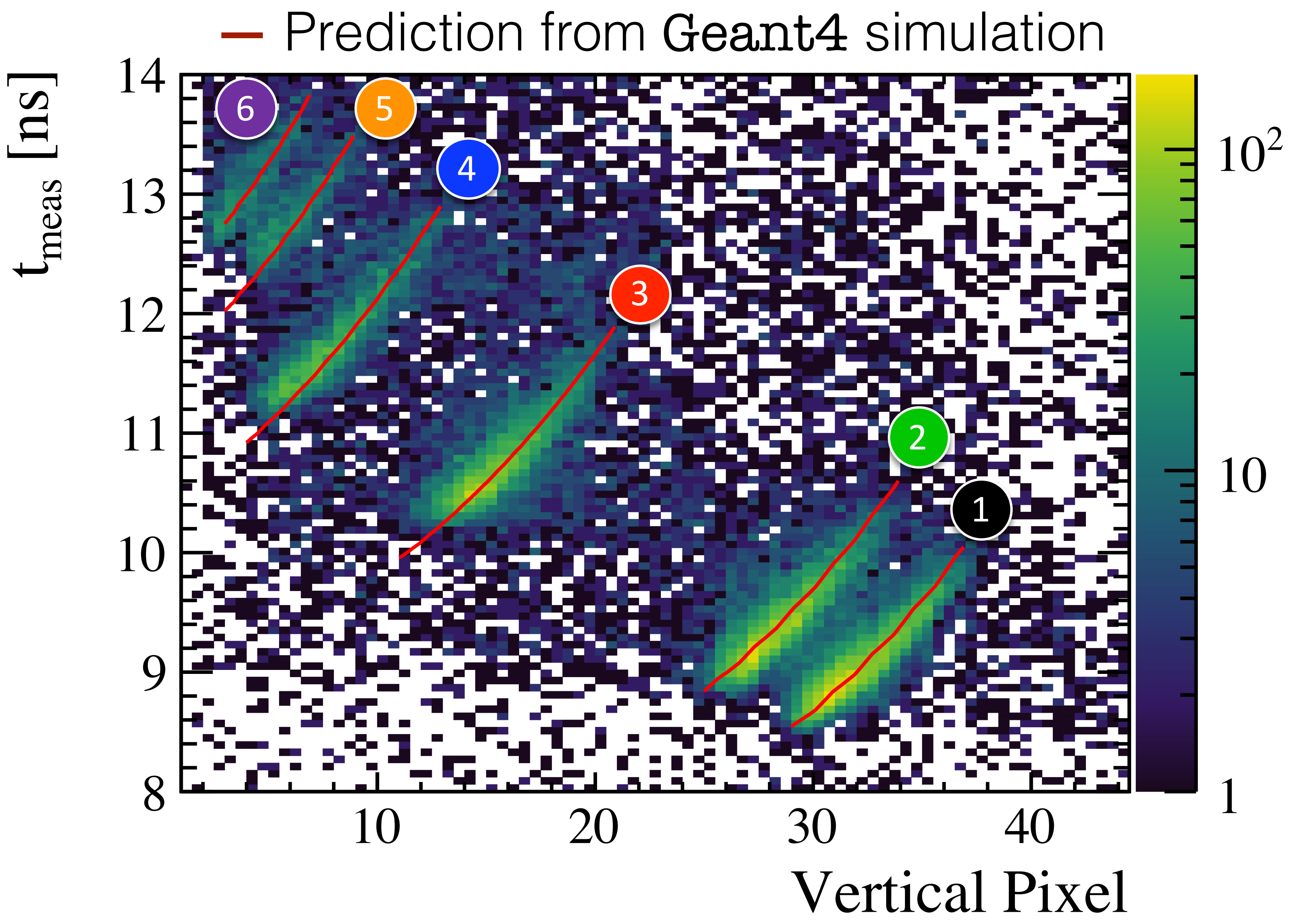
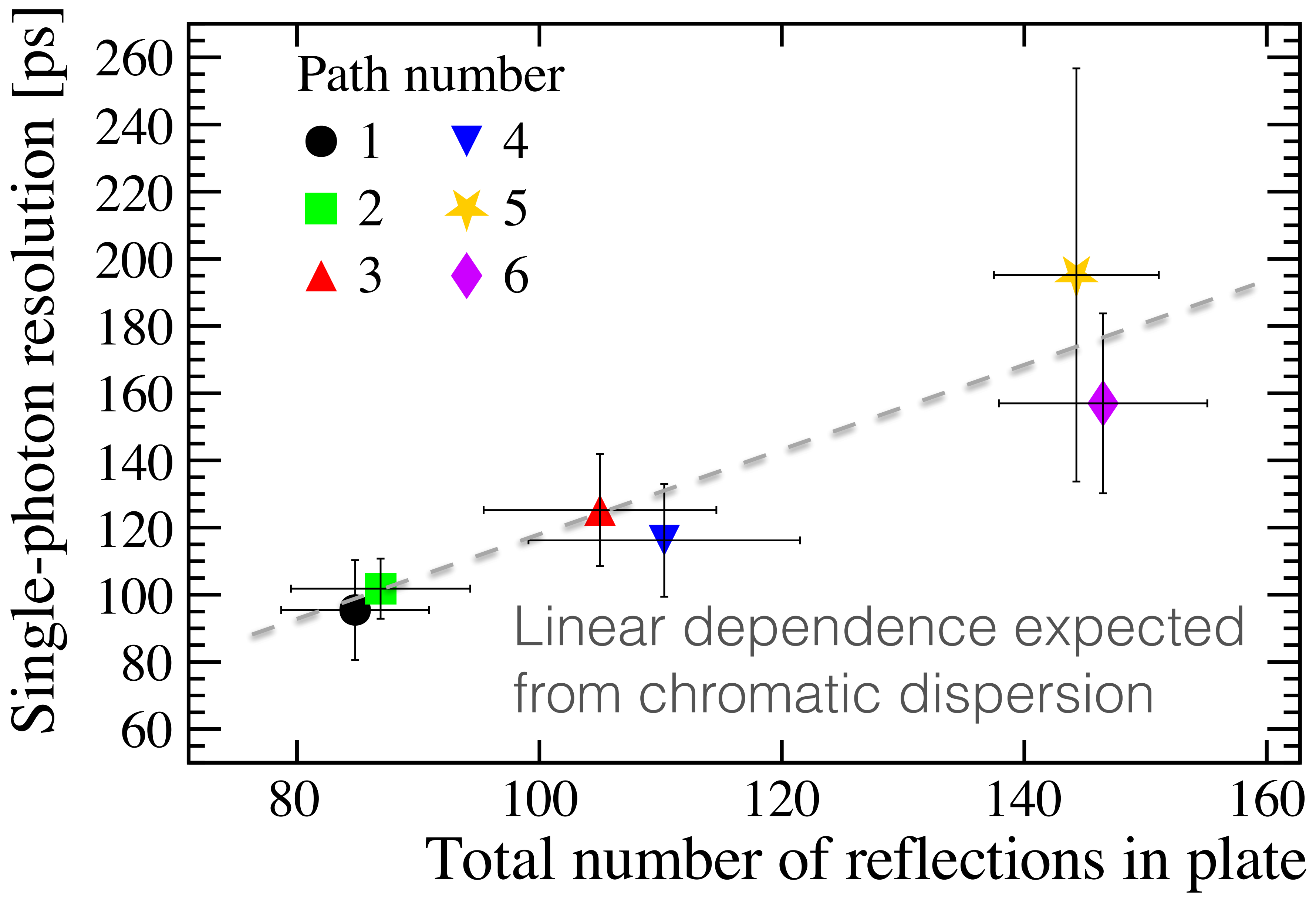
- ➡ Pattern consistent with Geant4 simulation of the prototype
- ➡ Time resolutions close to the needs of TORCH
  - ❖ Expect improvement with better electronics calibration







[NIMA 1050 (2023) 168181]

Beam test with 6 MCP-PMTs

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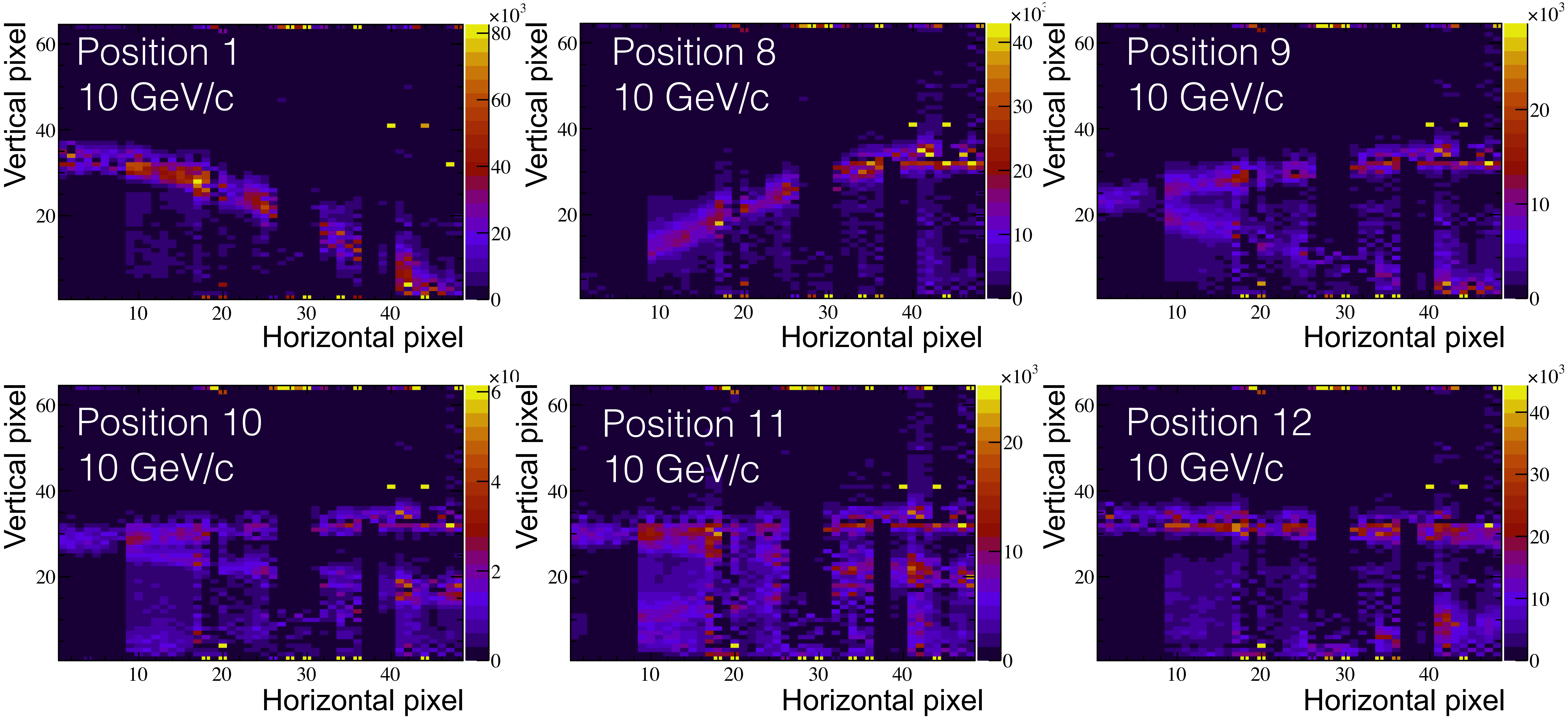

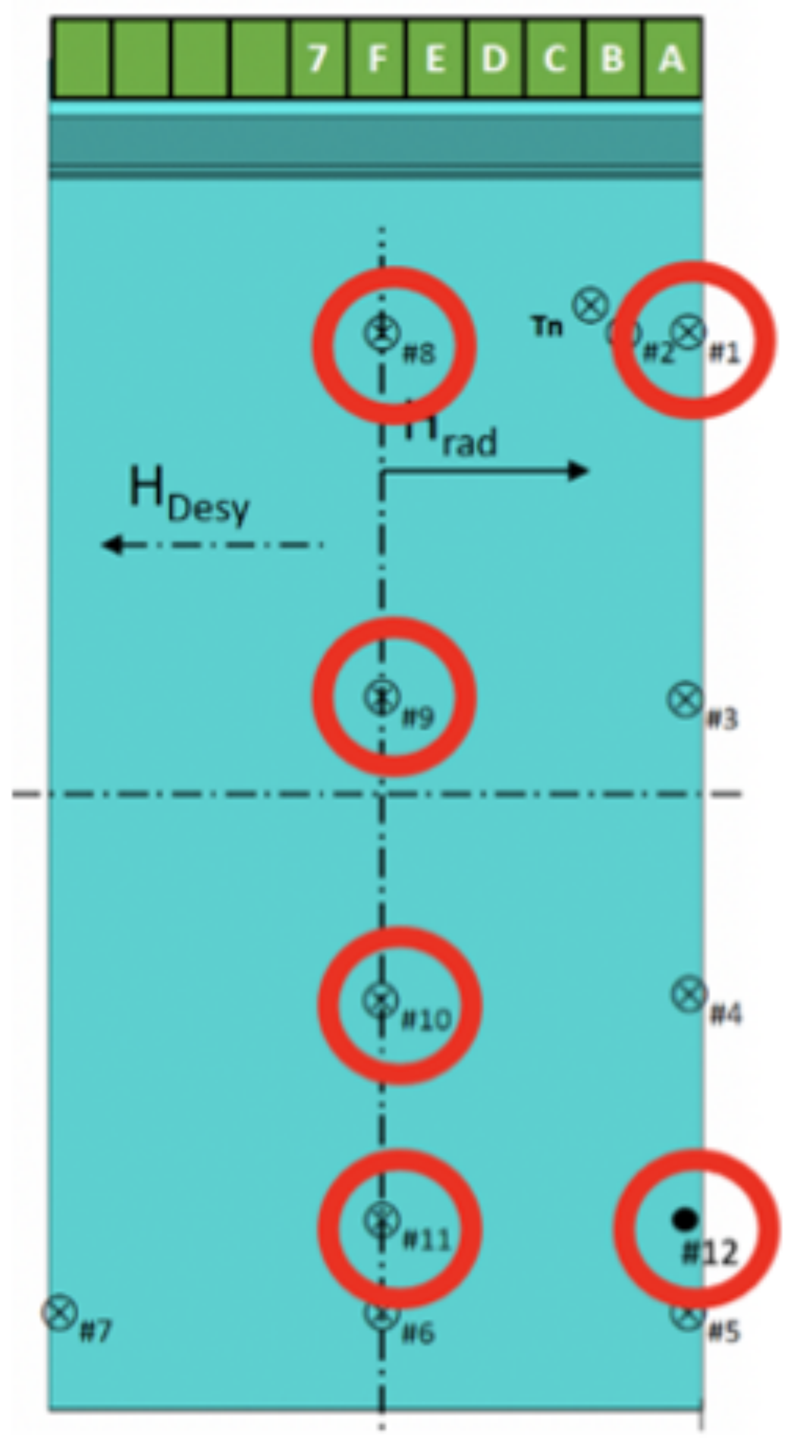

Data taken at six beam positions on the radiator bar at 3, 5, 8 and 10 GeV/*c*

2022 beam test data analysis ongoing

Summary

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- TORCH is a large-area time-of-flight detector designed to improve the particle identification capability of the LHCb experiment for particles with $2<p<15$ GeV/c
- Significant progress in last few years
  - Beam tests indicate that desired time precision can be obtained
  - Light-weight support mechanics designed and under construction
  - Aim for beam test in 2025 with full scale prototype and new mechanics
- R&D ongoing as part of DRD4 to improve relevant aspects needed for TORCH
- New collaborators welcome

Electronics

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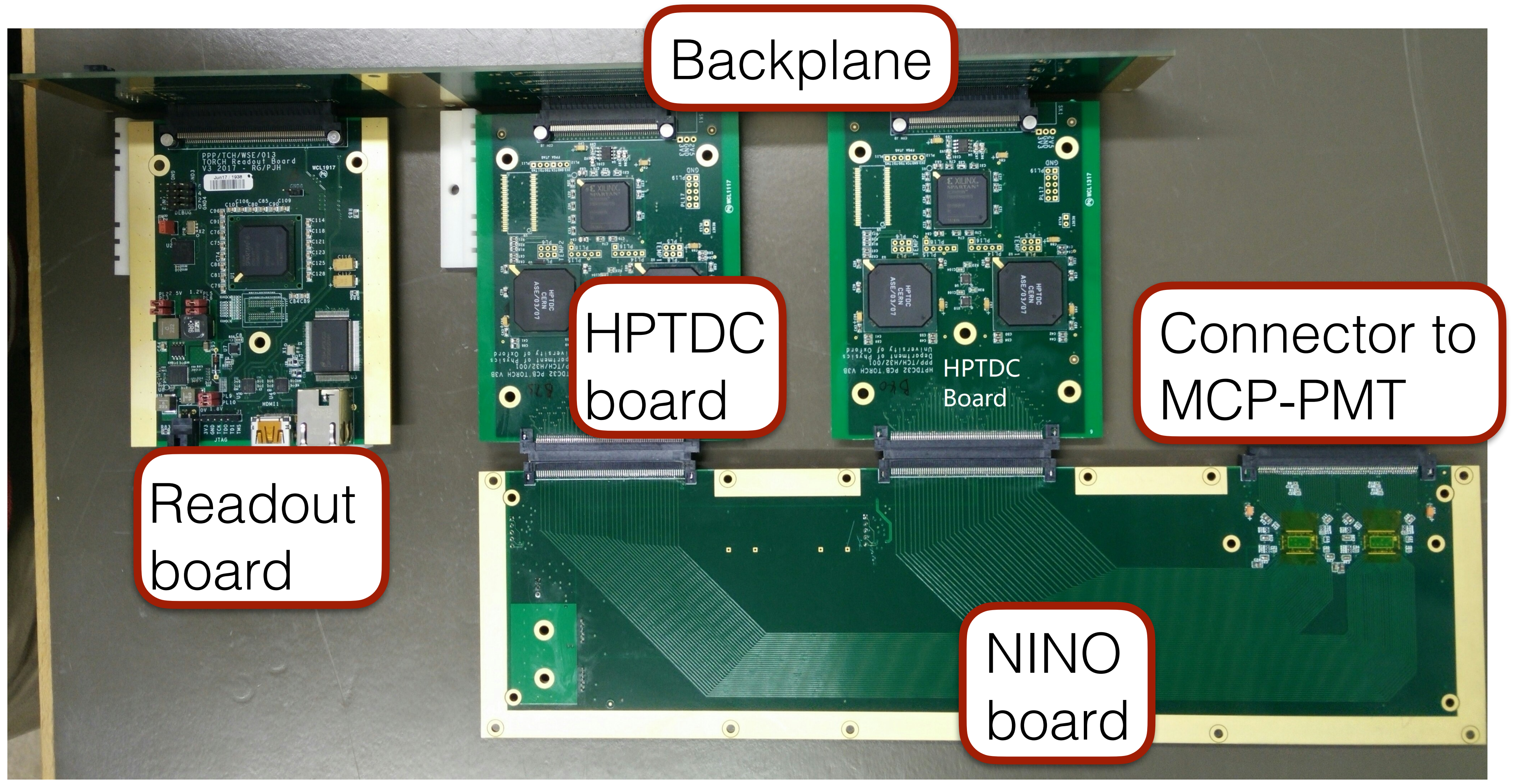
- ➡ Existing electronics are based on NINO and HPTDC ASICs developed for the ALICE TPC [JINST 11 (2016) 04 C04012]
- ➡ Adaptors are being designed to read the DC-coupled MCP-PMT with existing electronics



- ➡ 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

PID reconstruction

➡ Photon arrival time

$$t_{\text{arrival}} = t_0 + \frac{d_{\text{track}}}{\beta c} + \frac{d_{\text{prop}}}{v_{\text{group}}}$$

PV time | track propagation | photon propagation

➡ Use likelihood to observe given pattern given tracks hypotheses

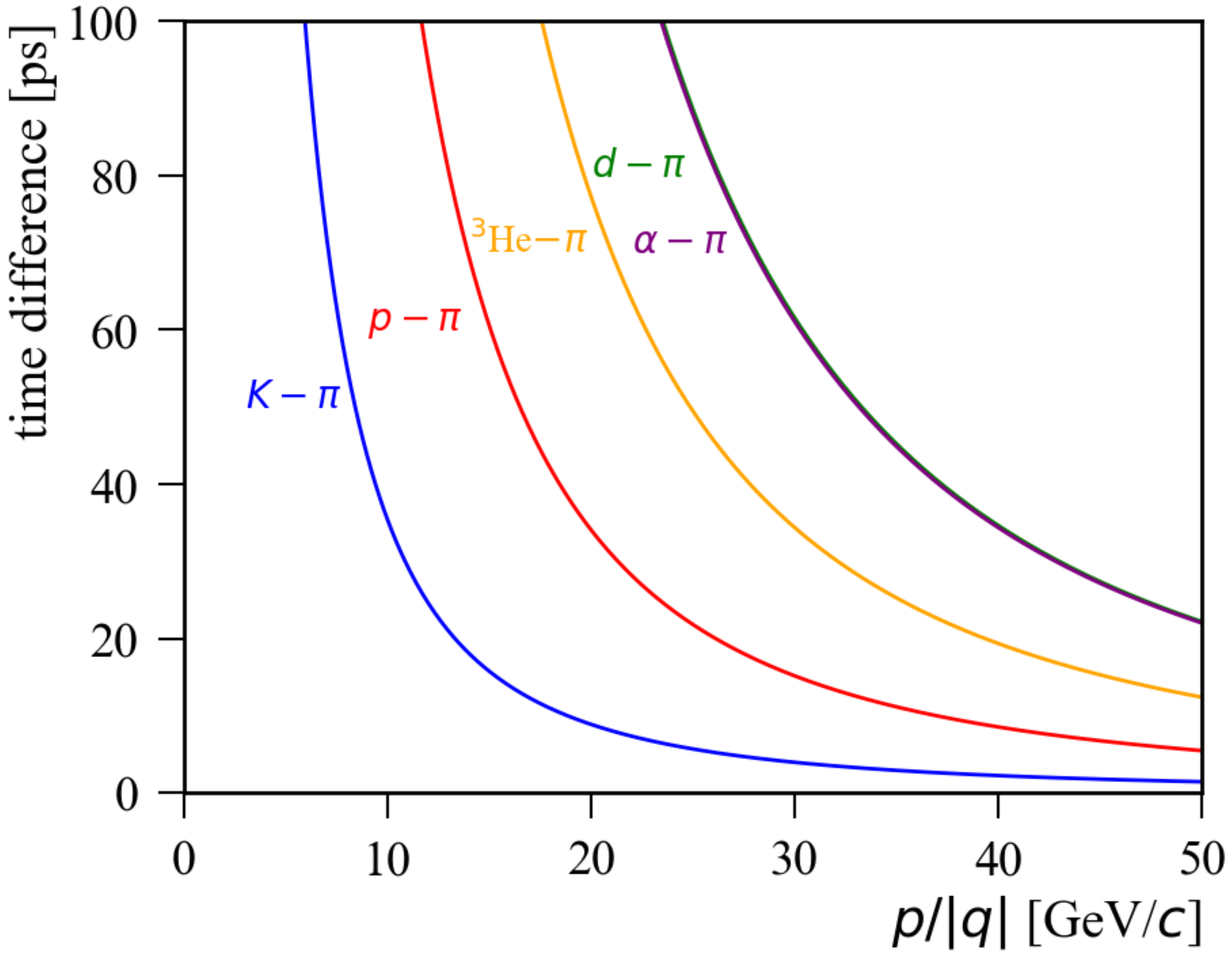
$$\log L = \sum_{\text{pixel } i} \log \left(\sum_{\substack{\text{track } j \\ j \neq t}} \frac{N_j}{N_{\text{tot}}} P_j(\vec{x}_i'' \mid h_j^{\text{best}}) + \frac{N_t}{N_{\text{tot}}} P_t(\vec{x}_i'' \mid h_t) + \frac{N_{\text{bkg}}}{N_{\text{tot}}} P_{\text{bkg}}(\vec{x}_i'') \right)$$

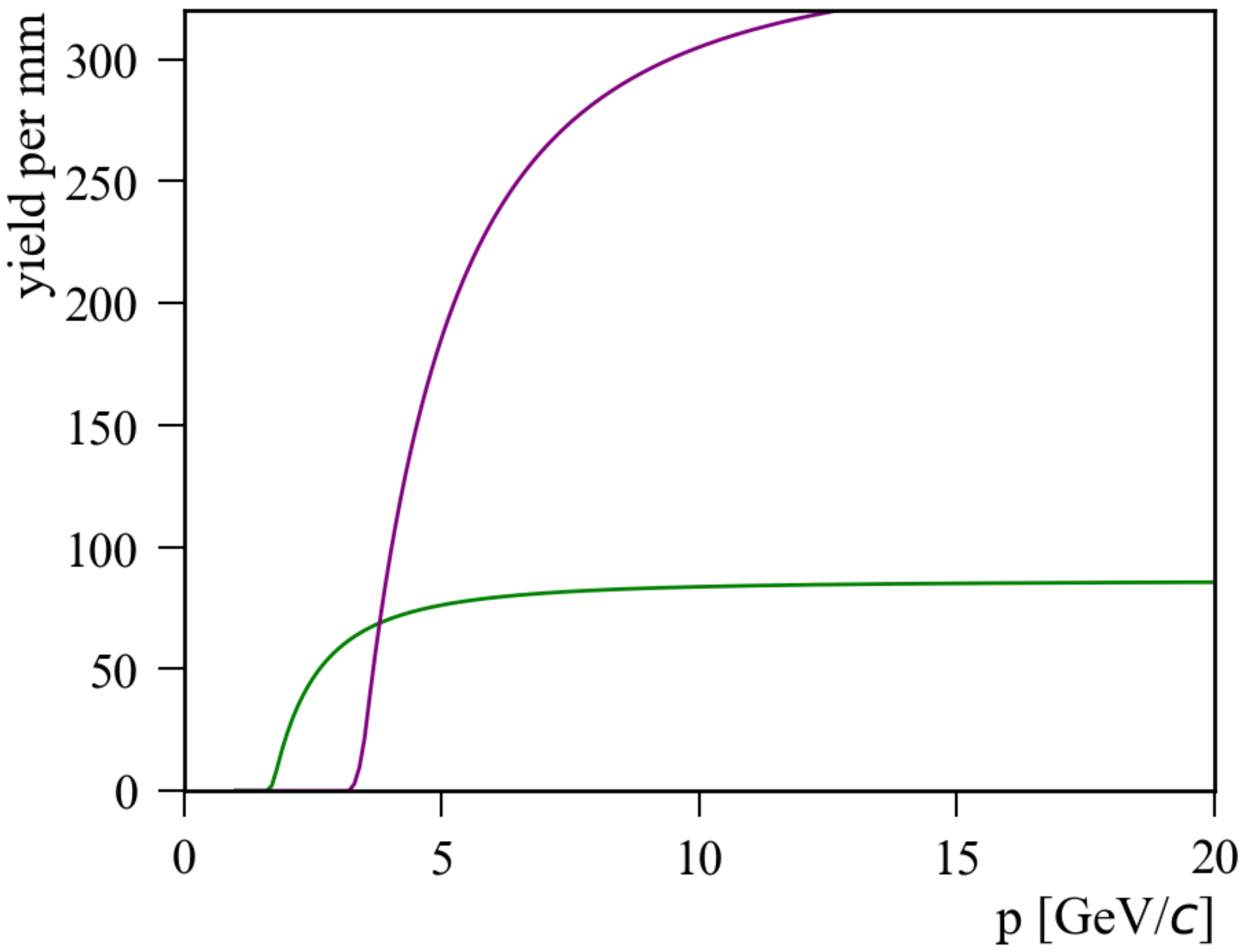
PDF for "best" hypothesis assignment for other tracks | PDF for considered track | Background contribution (assumed flat)

➡ Iterate over tracks hypotheses to find best solution

Physics case

- ➡ TORCH can provide new opportunities with light nuclei
  - ❖ Not only differences in time-of-flight but also in photon yield
- ➡ General purpose timing information to aid event reconstruction, e.g. reduce track ghost rates





Photon yield in 2018 beam test

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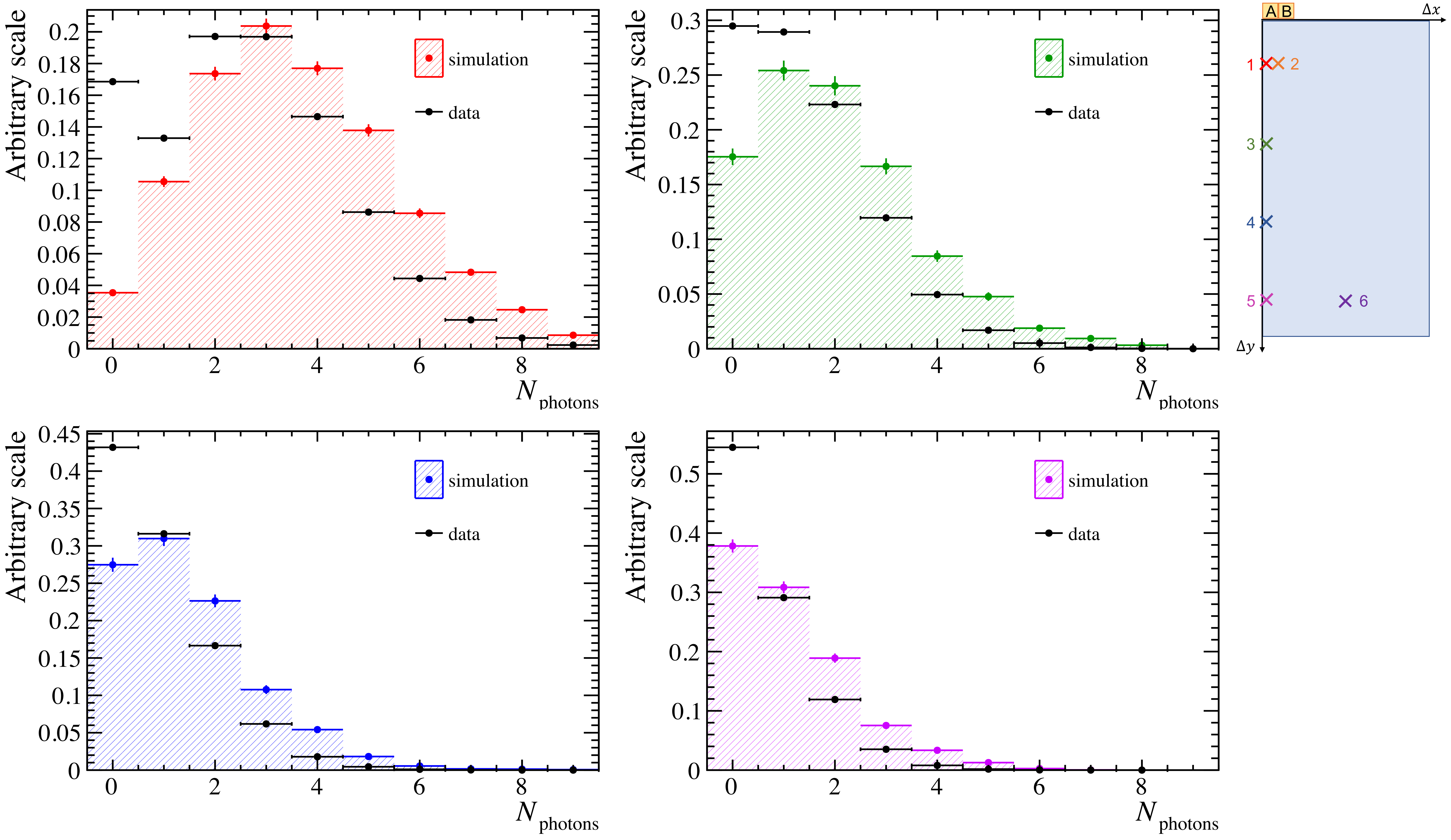
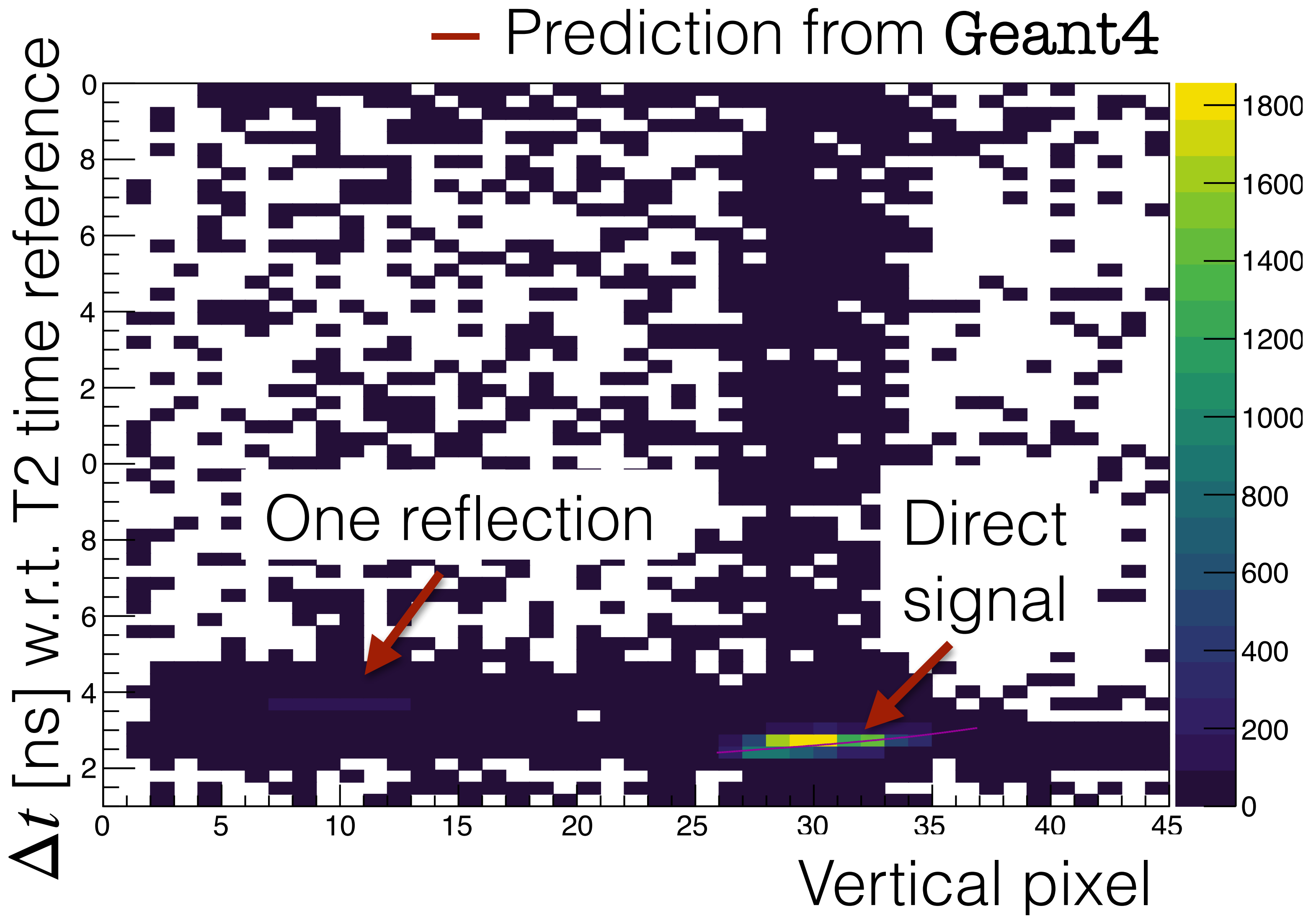
- ➡ Reasonable agreement with Geant4 based simulation of prototype
- ➡ Photon yield in data about 82-85% of expectation
- ➡ Work ongoing with 2022 beam test to further improve understanding

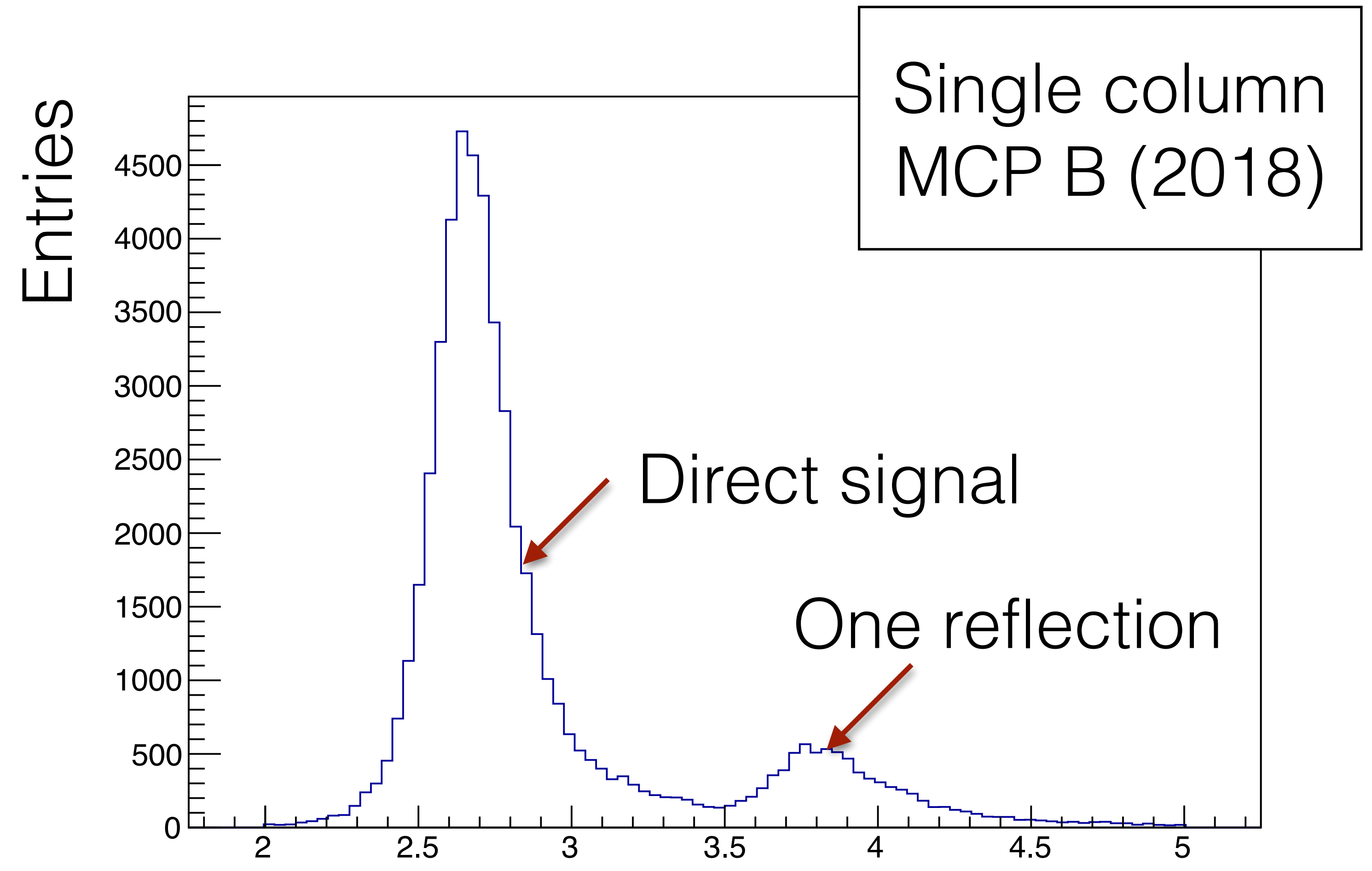
[NIMA 1050 (2023) 168181]

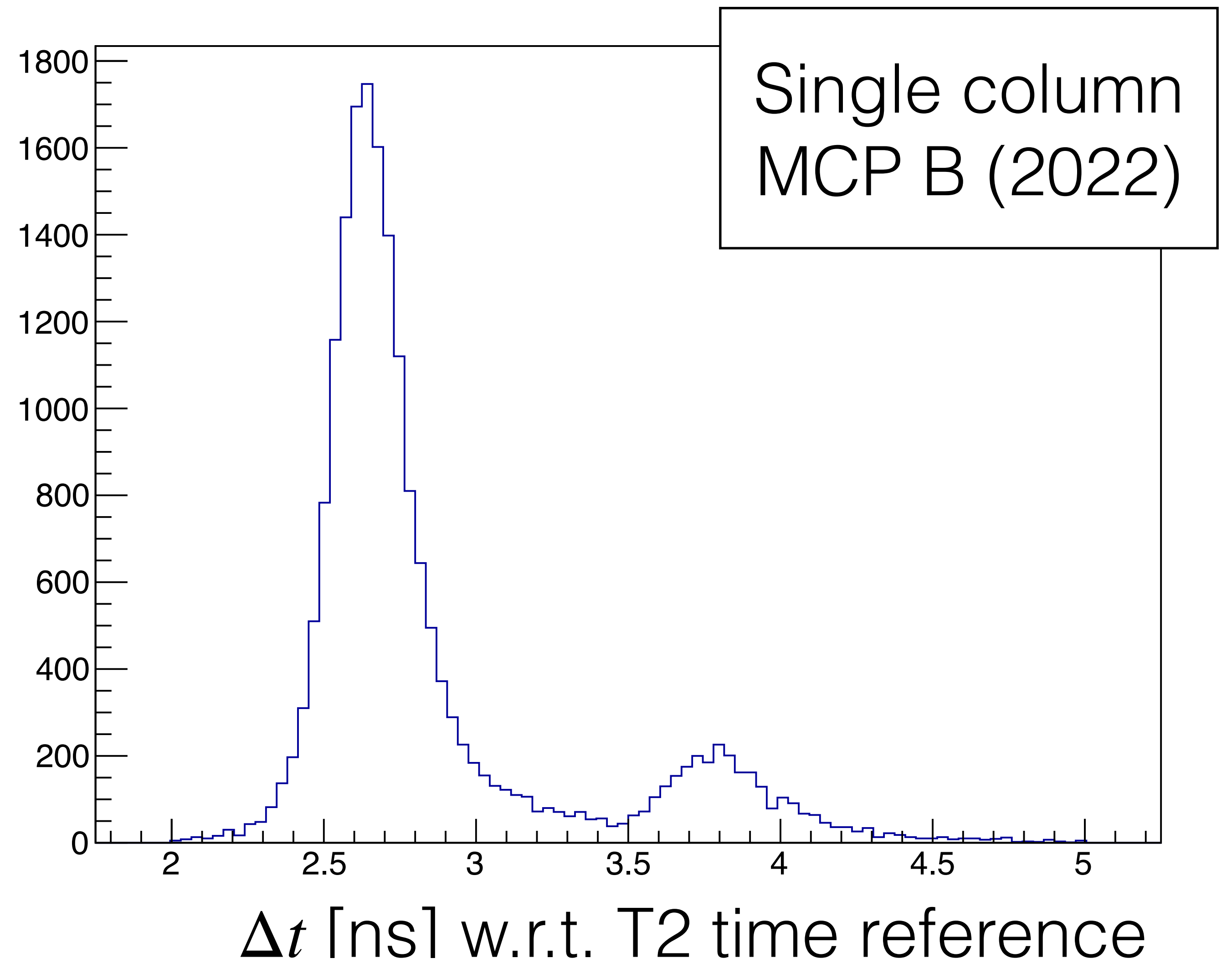


Time resolution in 2022 beam test

- ➡ 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

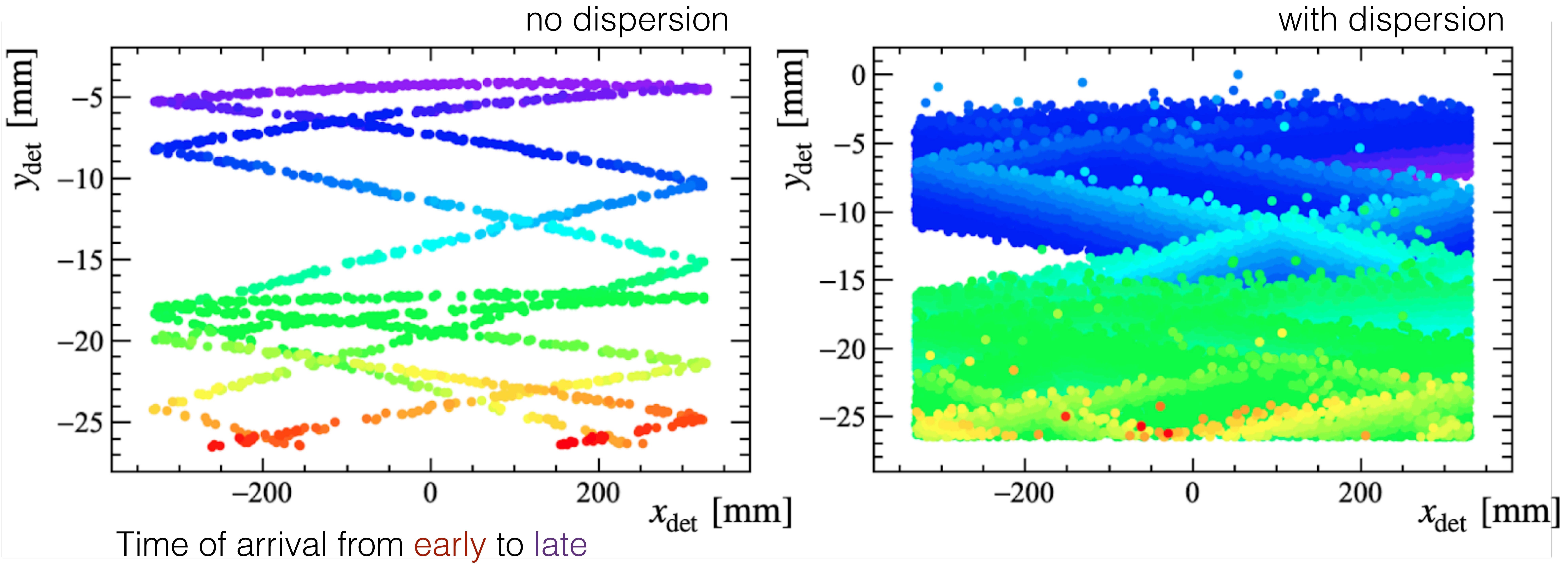






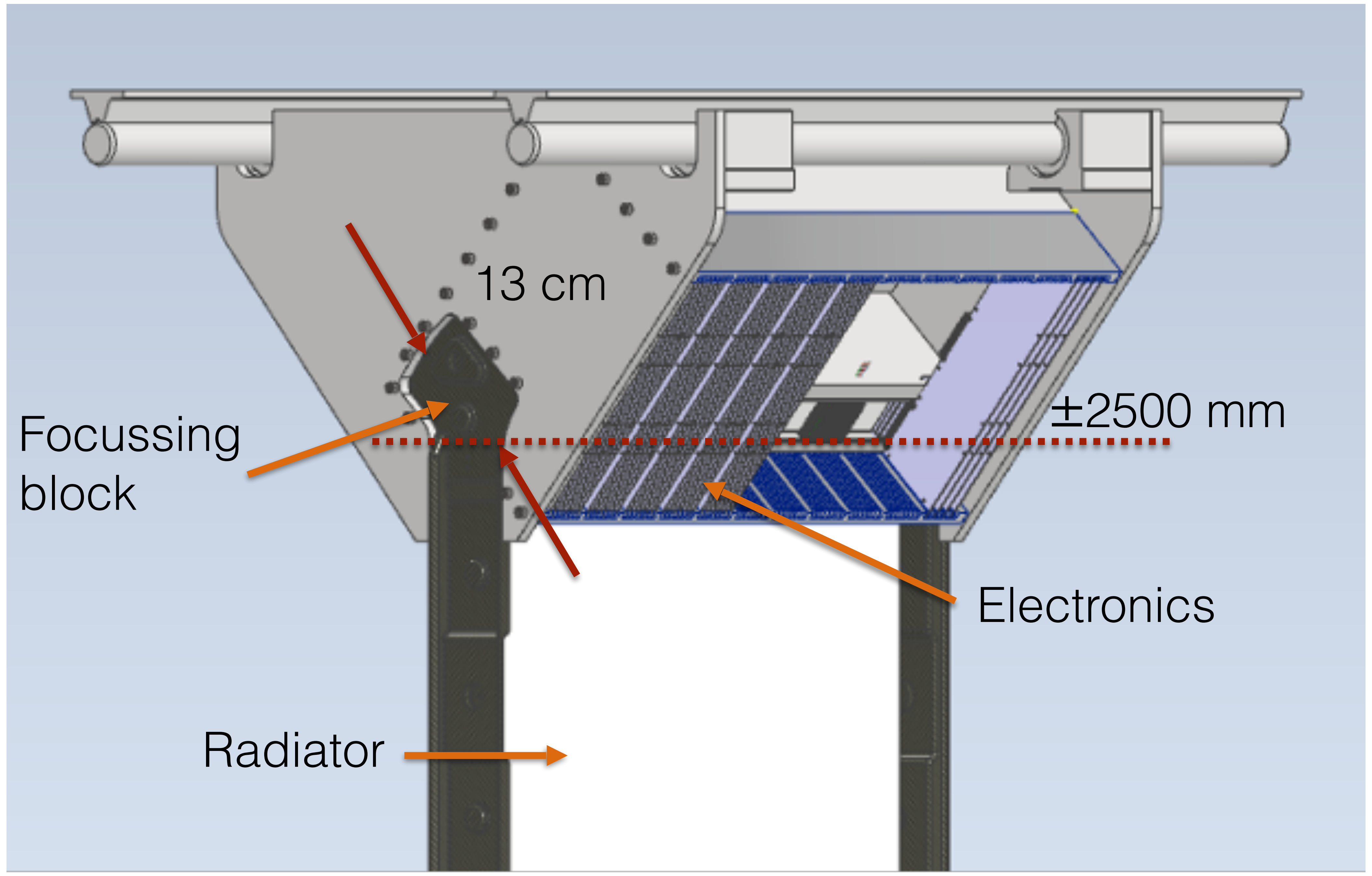
TORCH image

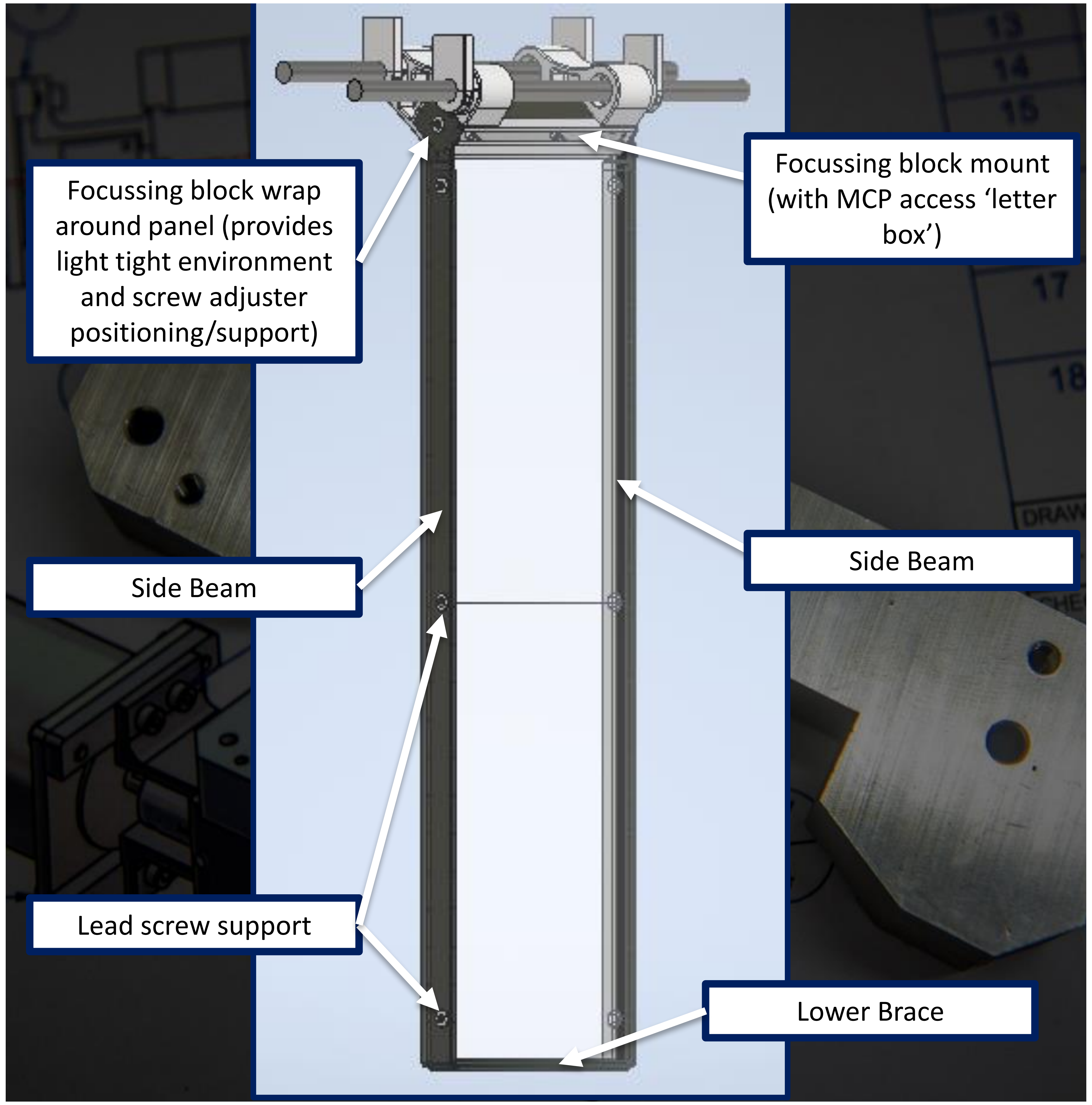
➡ TORCH image forms bands in space/time:



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

Support mechanics





➡ Prototype for current test module with existing electronics

INL correction

- ➡ HPTDC time bins do not have all same width in time
  - ❖ Manifests as non-uniform distribution of signals
- ➡ Correct using uniform sample over all HPTDC time bins
- ➡ Relative difference from the uniform population in each bin

$$DNL_i = \frac{N_i - P_{\exp}}{P_{\exp}}$$

- ➡ Change for each bin accumulates changes to previous bins

$$INL_i = \sum_{j=0}^{i} DNL_j$$