Status of the TORCH R&D project

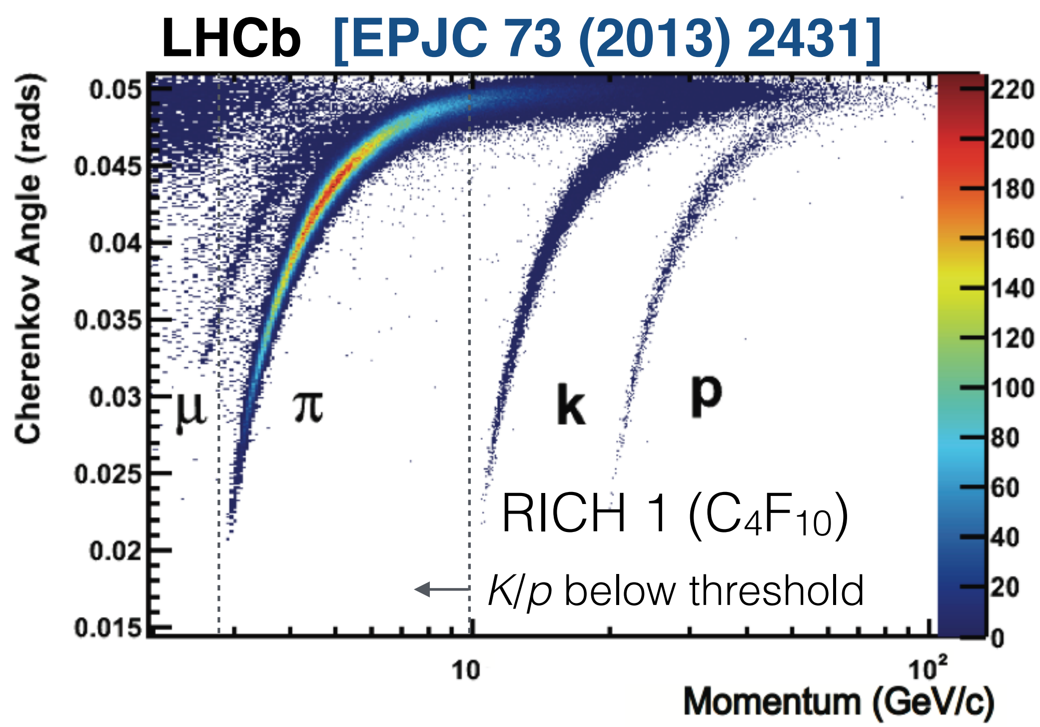
6th Workshop on LHCb Upgrade II

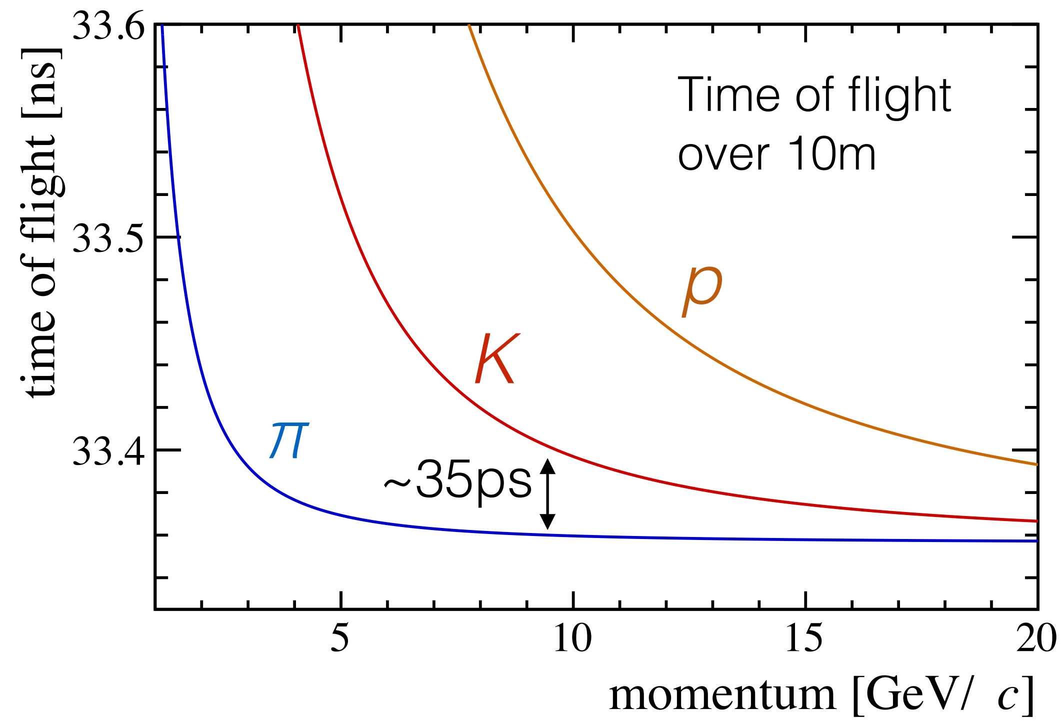
T. Blake on behalf of the TORCH collaboration

University of Oxford
University of Bristol
CERN
The University of Edinburgh
Jožef Stefan Institute
Warwick — The University of Warwick

TORCH concept

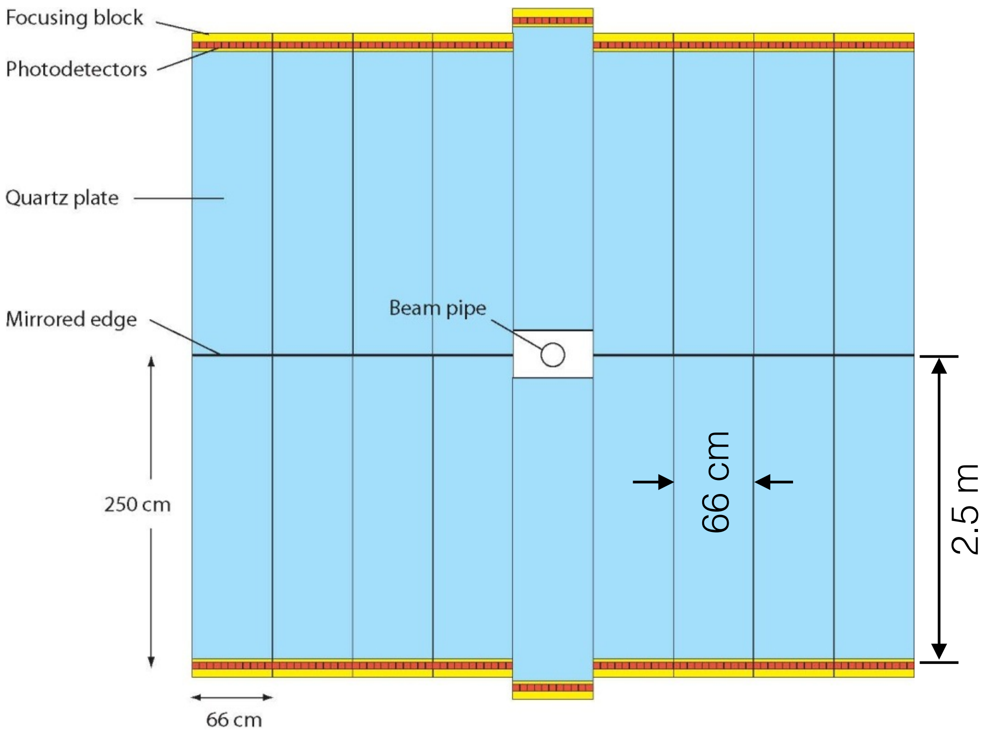
- Large area time of flight detector designed to provide PID in the 2–10 GeV/*c* momentum range.
- Exploits prompt production of Cherenkov light in a fused-silica radiator.
- For K/π separation over 9.5m, aim for a resolution of 10–15 ps per track (requires 70 ps per photon).

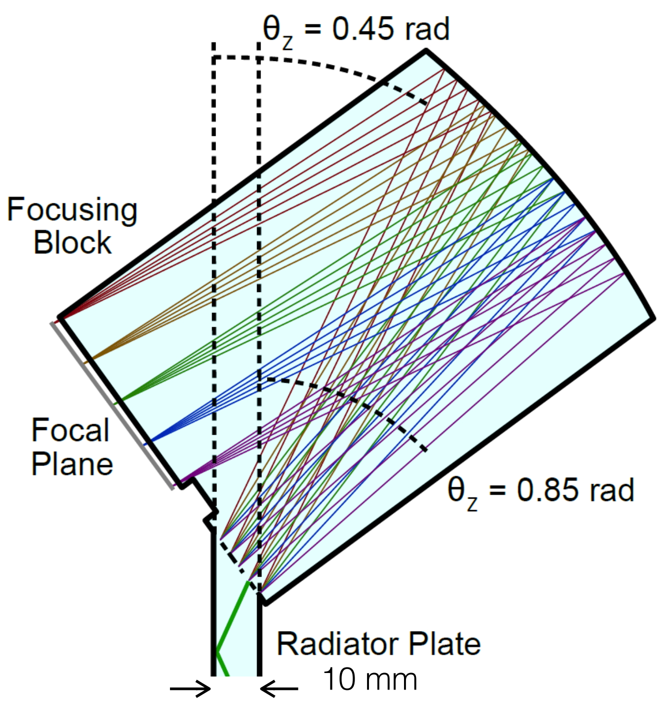




TORCH detector

- 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.
    - Used to correct for chromatic dispersion.
- Large area detector required to cover the LHCb acceptance (5x6m^2).

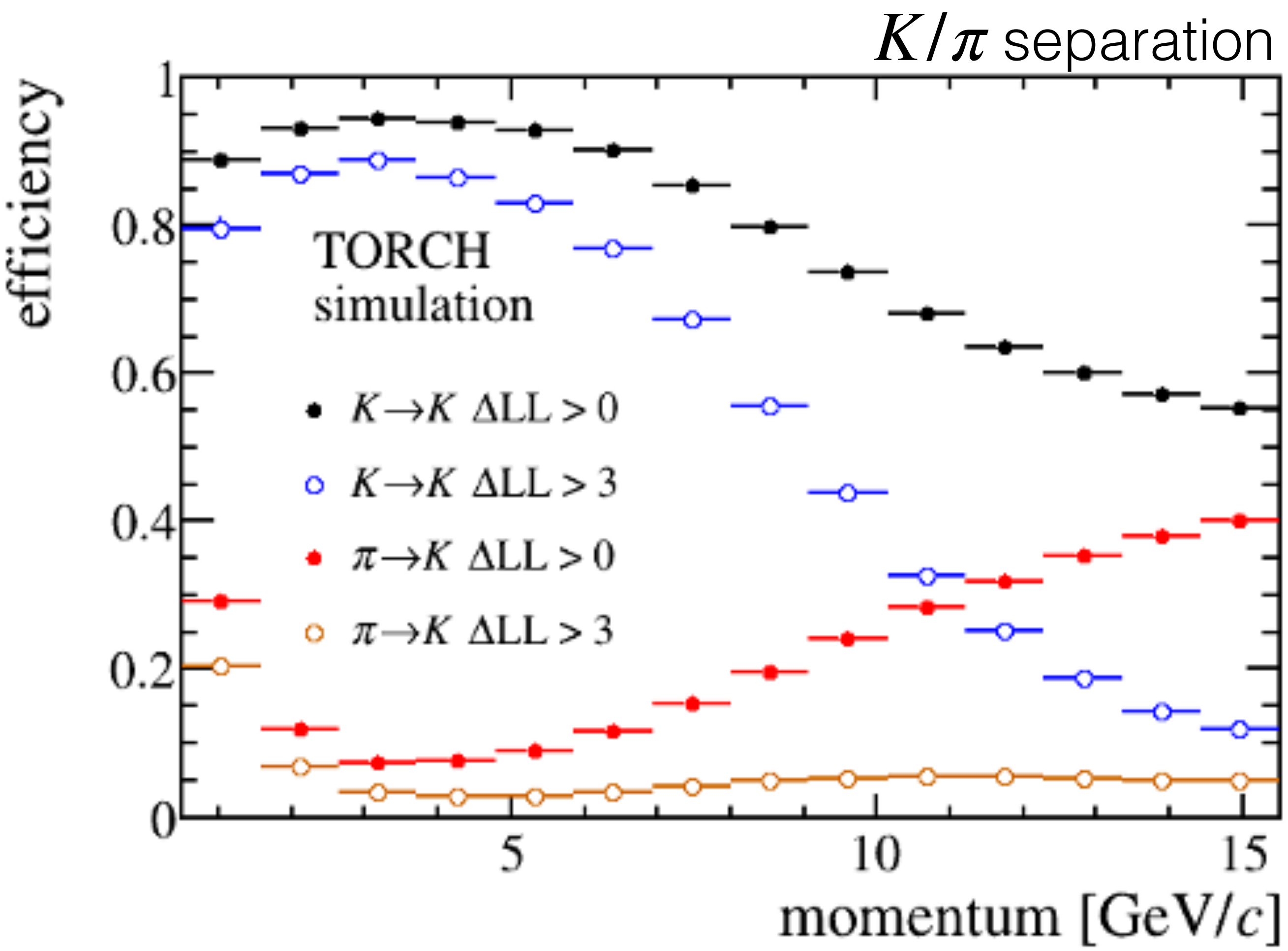


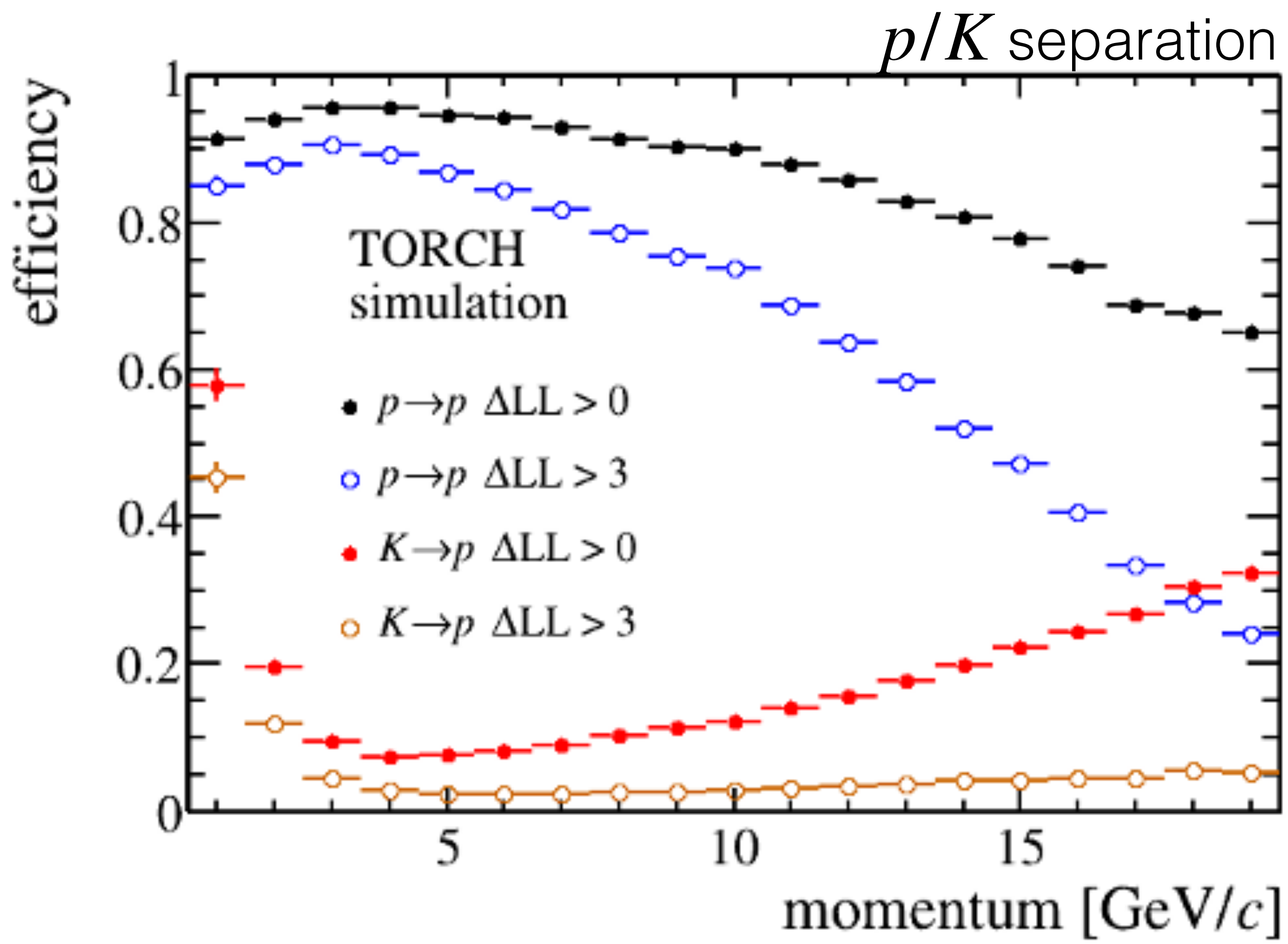


For more details on the TORCH concept see **[NIM A 639 (1) (2011) 173]**

PID performance

- Performance studied using a simplified `DetDesc` geometry and a standalone TORCH reconstruction:





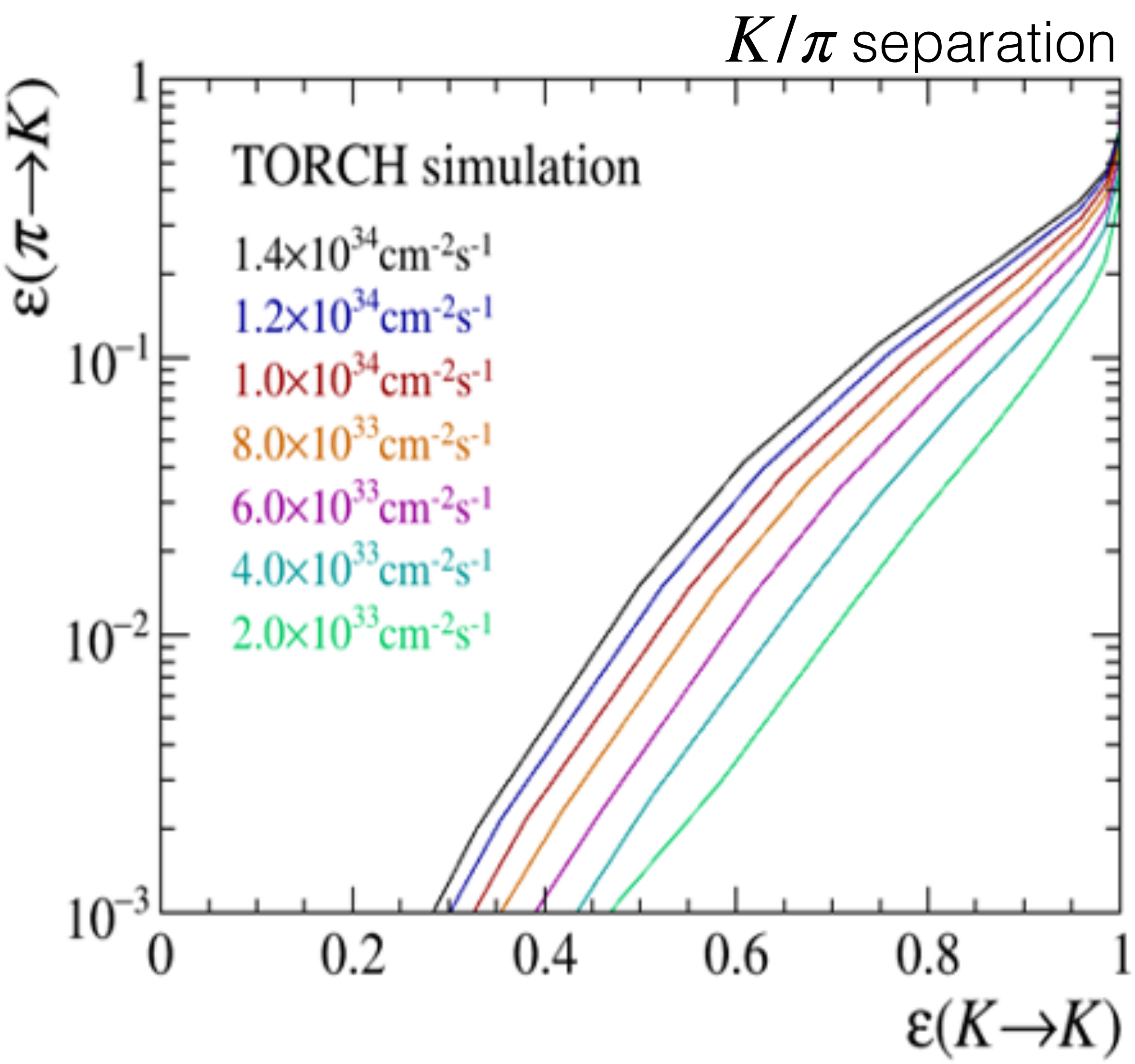
- Good separation is seen in the 2–10 (2–15) GeV/*c* momentum range.

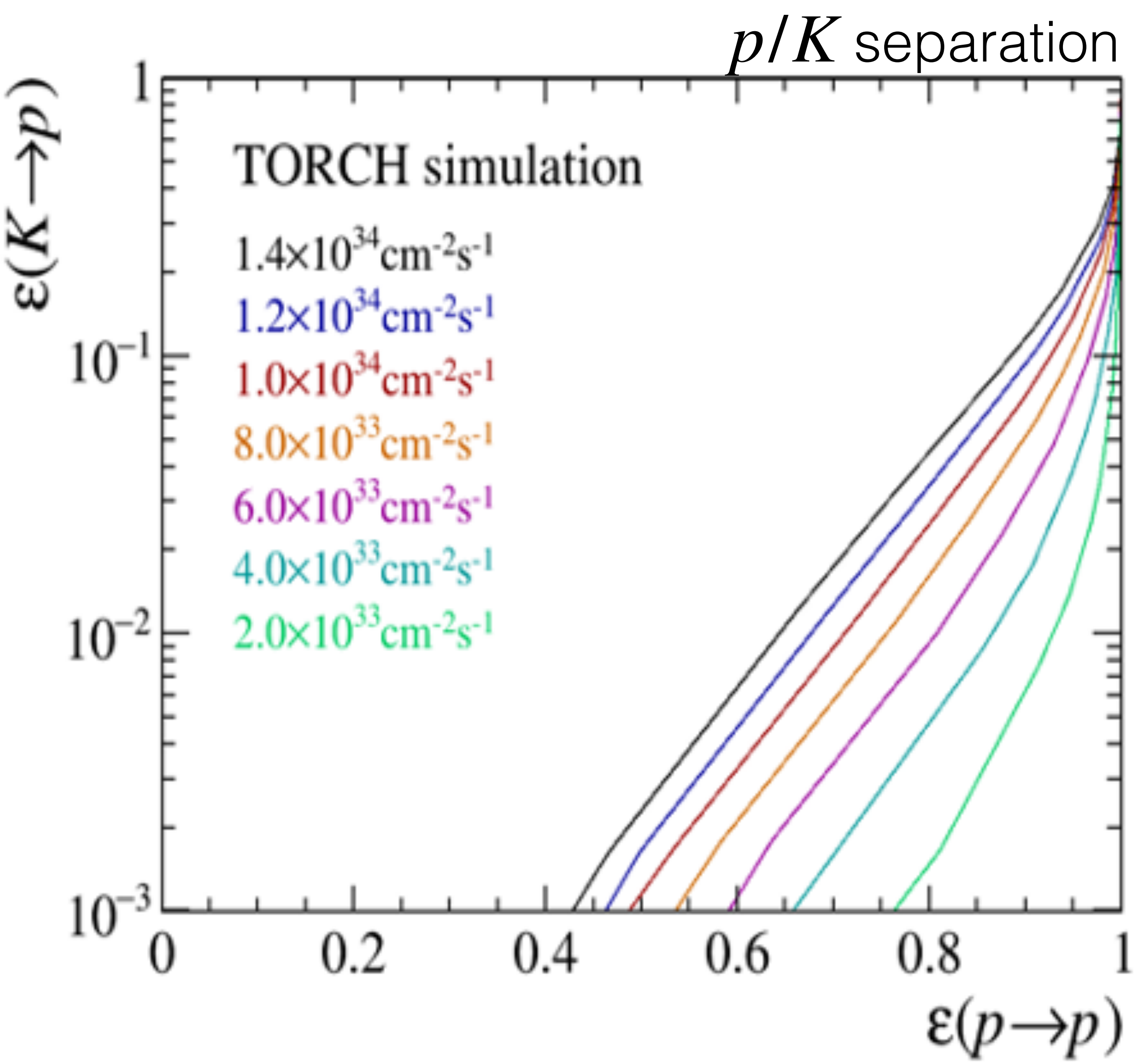
PID performance

- Simplified TORCH geometry produced in `DetDesc`.
  - Conversion to `DD4HEP` is currently being validated.
- Simulate `U1a` events and merge to achieve `UII` occupancies.
  - Samples are weighted to obtain representative luminosity profile.
- Run a standalone TORCH reconstruction:
  - Reconstruction and performance described in **[LHCb-PUB-2022-004]**, **[LHCb-PUB-2022-006]**, **[LHCb-PUB-2022-007]**.
- We assume that timing information with 20 picosecond precision is available from timing in UII VELO:
  - In principle we can reconstruct the PV time in TORCH likelihood calculation (by varying t_0 in the fit).
- Work is ongoing to obtain a combined TORCH/RICH PID performance.

Performance with occupancy

- Performance is strongly dependent on the detector occupancy (modules closer to beam line have worse performance).





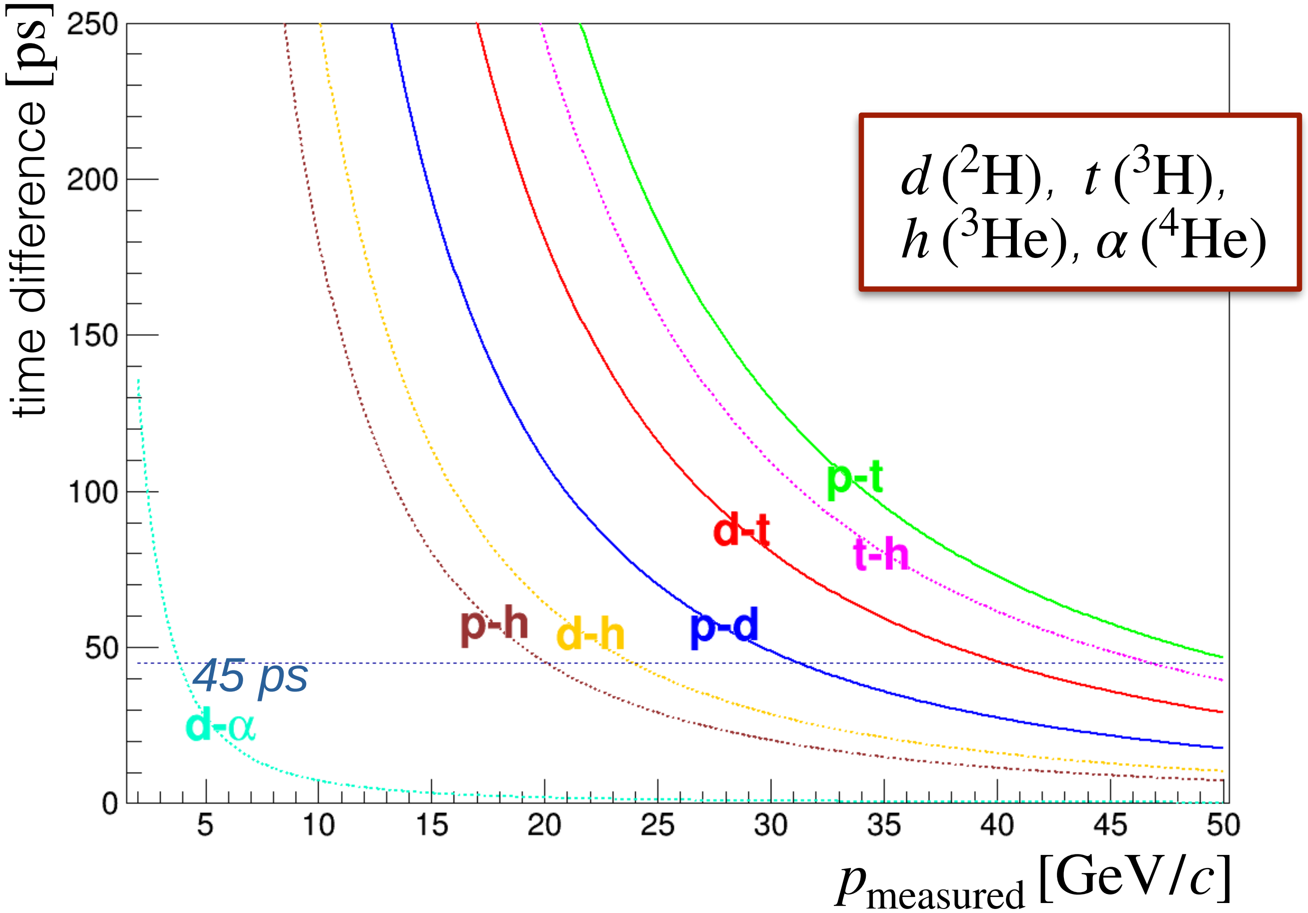
Physics case

TORCH physics performance: improving low-momentum PID performance during Upgrade IB and beyond

S. Bhasin[1], T. Blake[5], M. Flavia Cicala[5], R. Forty[2], C. Frei[2], E. P. M. Gabriel[3], S. Gambetta[3], R. Gao[4], T. Gershon[5], T. Gys[2], T. Hadavizadeh[4], T. H. Hancock[4], N. Harnew[4], M. Kreps[5], E. J. Millard[5], F. Muheim[3], D. Piedigrossi[2], J. Rademacker[1], M. Van Dijk[2], G. Wilkinson[4].

[LHCb-INT-2019-006]

- Provides particle identification at low momentum with benefits to:
  - Flavour tagging (cut based analysis shows gains of 25–50% in effective tagging power possible).
  - Uniformity of angular/Dalitz distributions.
  - Analyses requiring $p/K/\pi$ separation (e.g. analyses of Λ_b decays).
- Can provide deuteron and He separation (for e.g. searches for hyper-nuclei).
  - Note, *h*/α produces 4x the light-yield due to their charge and have a measured momentum that is 1/2 their true momentum from tracking.



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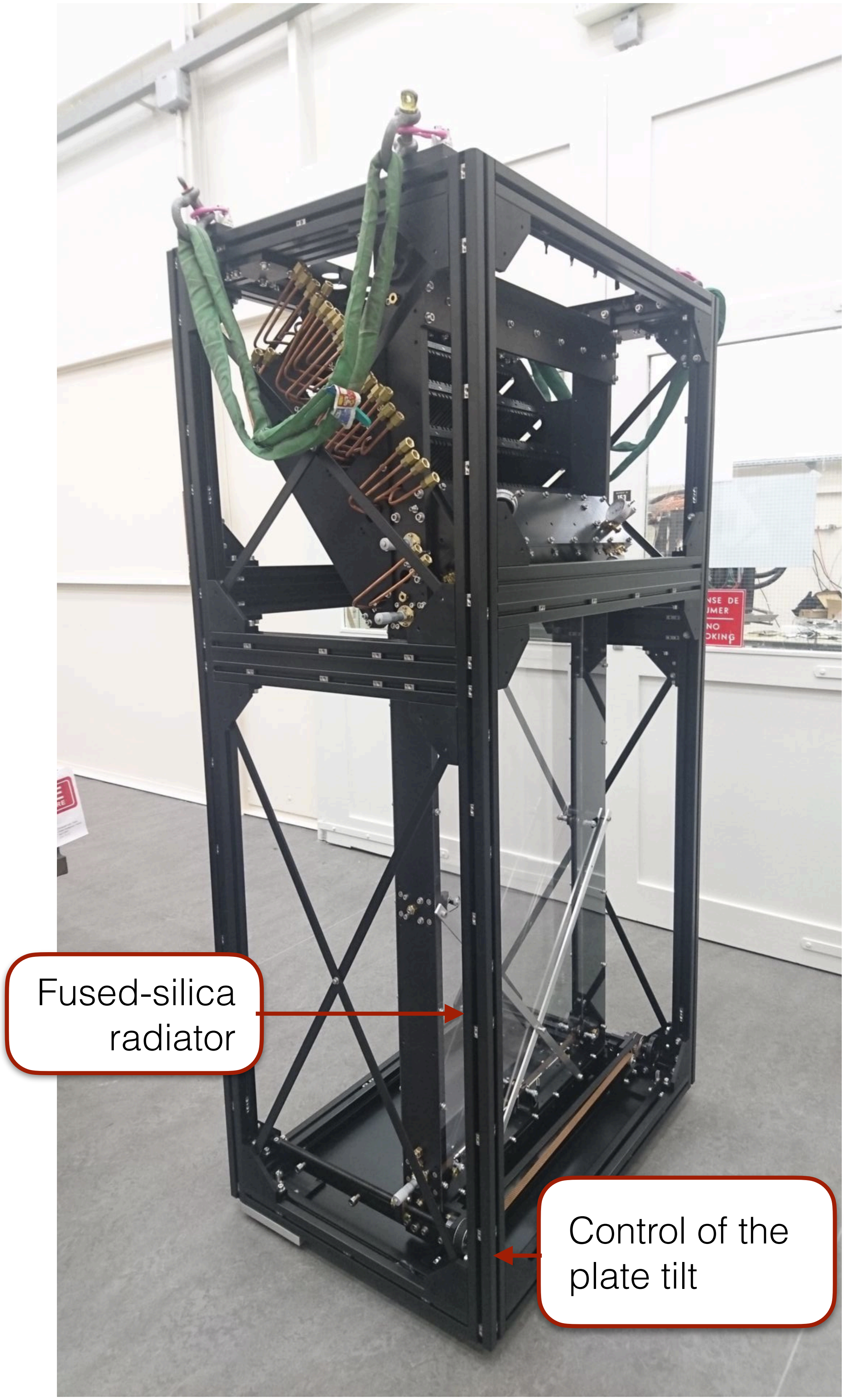
  - Note, *h*/α produces 4x the light-yield due to their charge but have a measured momentum that is 1/2 true momentum from tracking.

- In principle could also provide downstream timing for use in ghost rejection.
  - Main limitation is the speed of the reconstruction.

Current prototype

- Full-scale half-length module with 1250x660x10 mm^3 fused-silica radiator bar.
- Focussing block glued to the radiator bar with Pactan 8030 silicone-based adhesive.
- Can be equipped with 11 MCP-PMTs and associated electronics.



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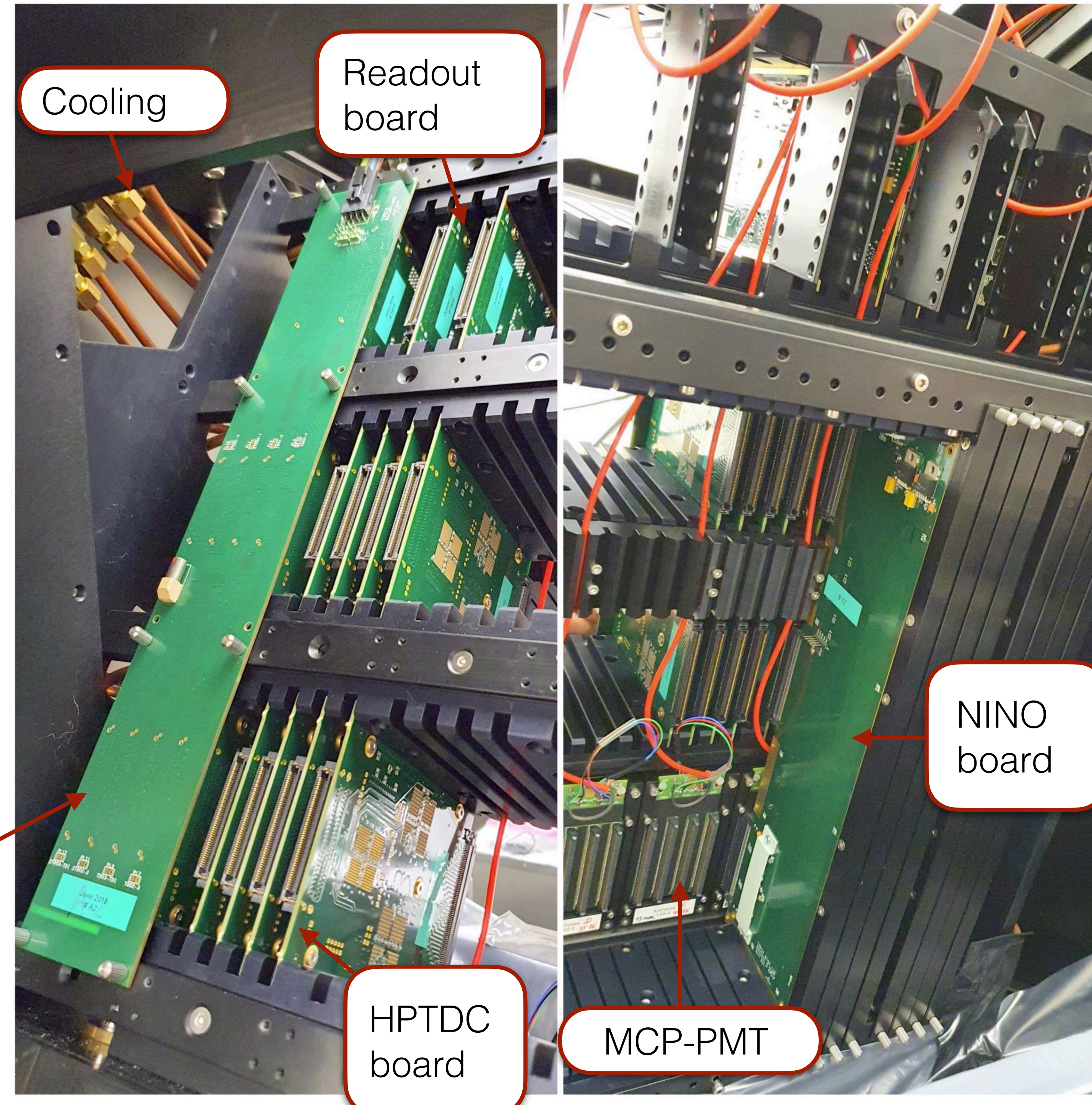

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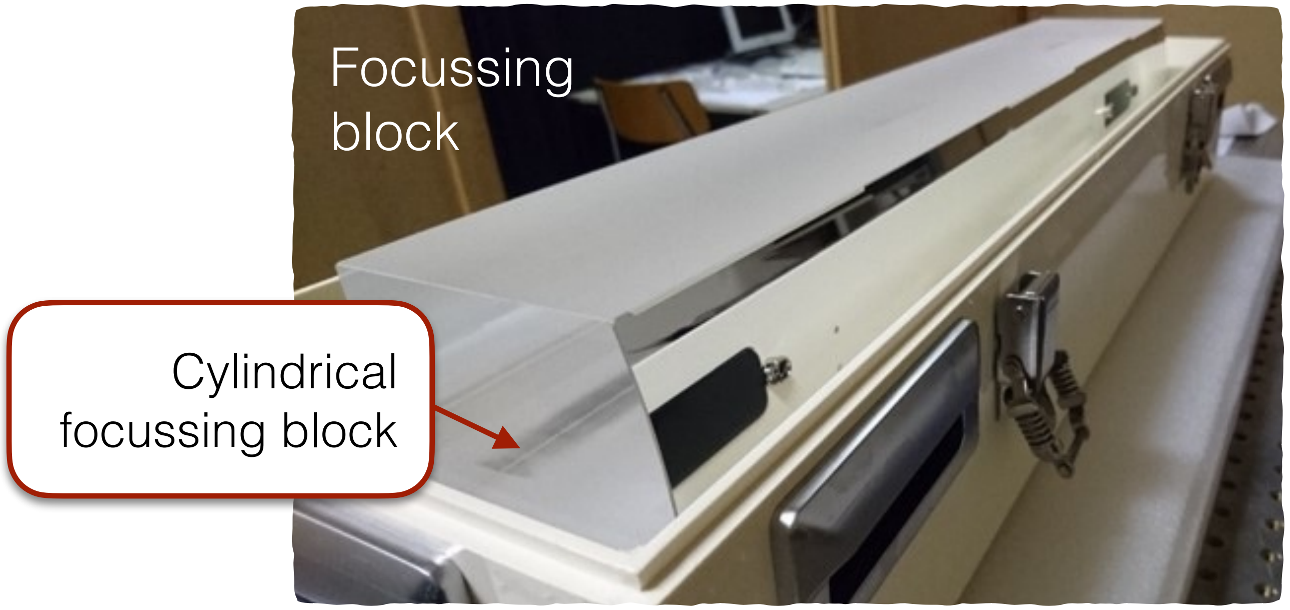
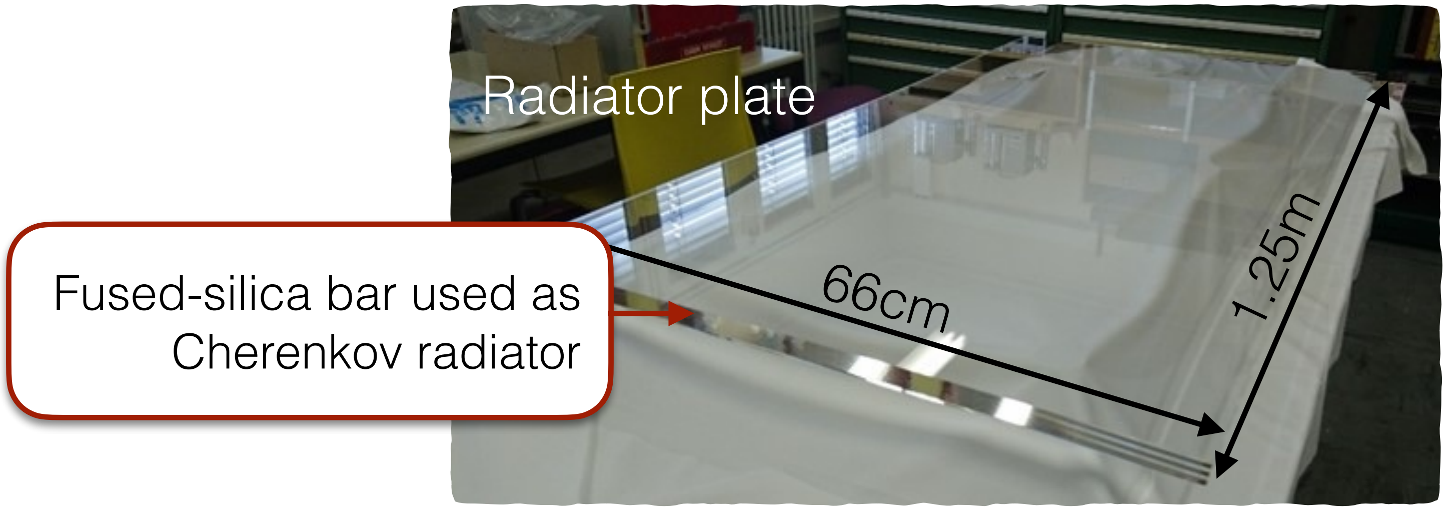
Produced by Nikon glass





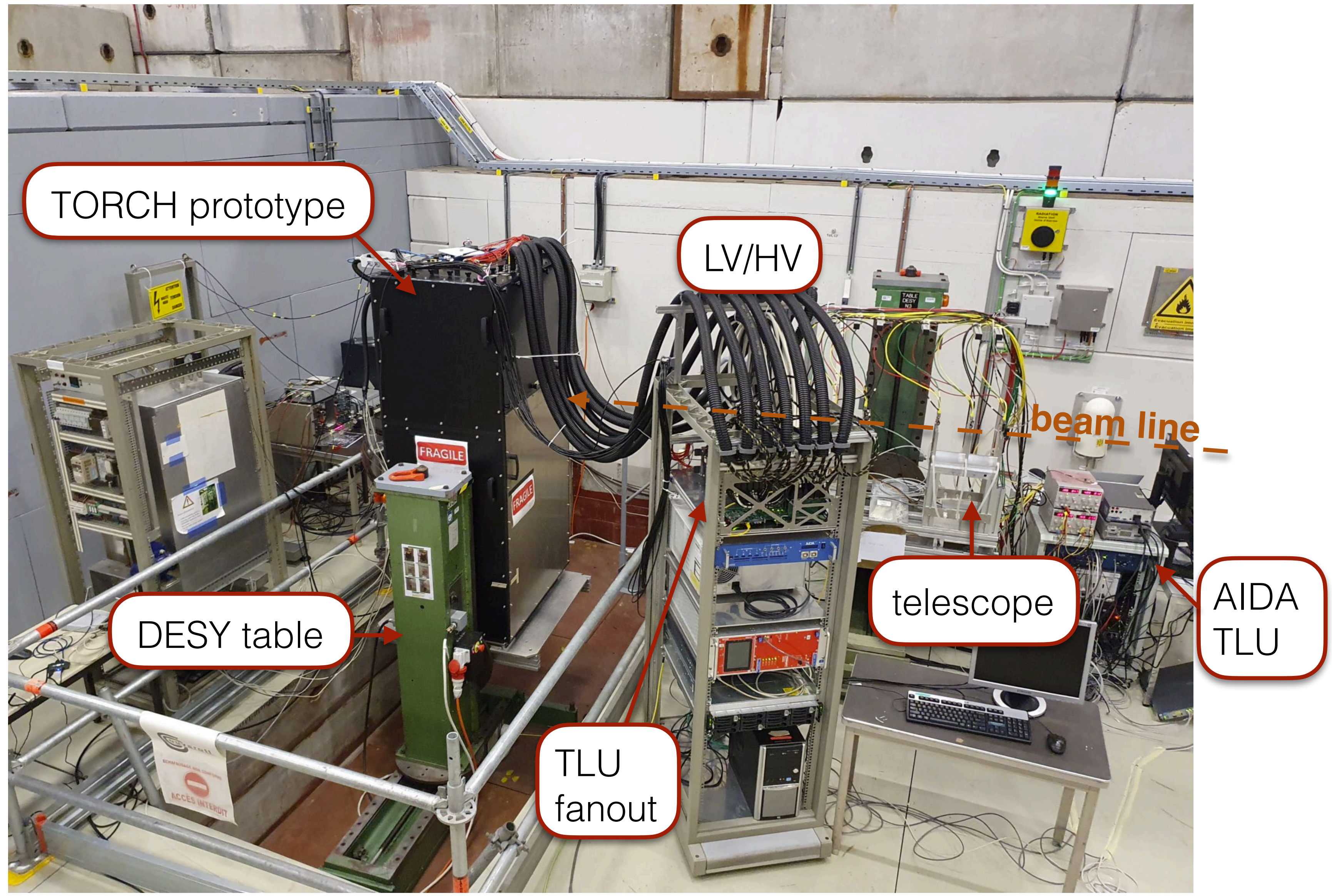
Thickness variation $\leq 3\mu m$ and surface roughness $0.5\mathring{A}$

Test beam campaigns

- Two test beam campaigns with the TORCH prototype in mixed π/p beams in T9:
  - 2018 test beam with two MCP-PMTs.
  - November 2022 test beam with six MCP-PMTs.

2022 test beam experimental area

- Prototype detector equipped with six MCP-PMTs and associated electronics.
- New DAQ, LV and HV supplies.

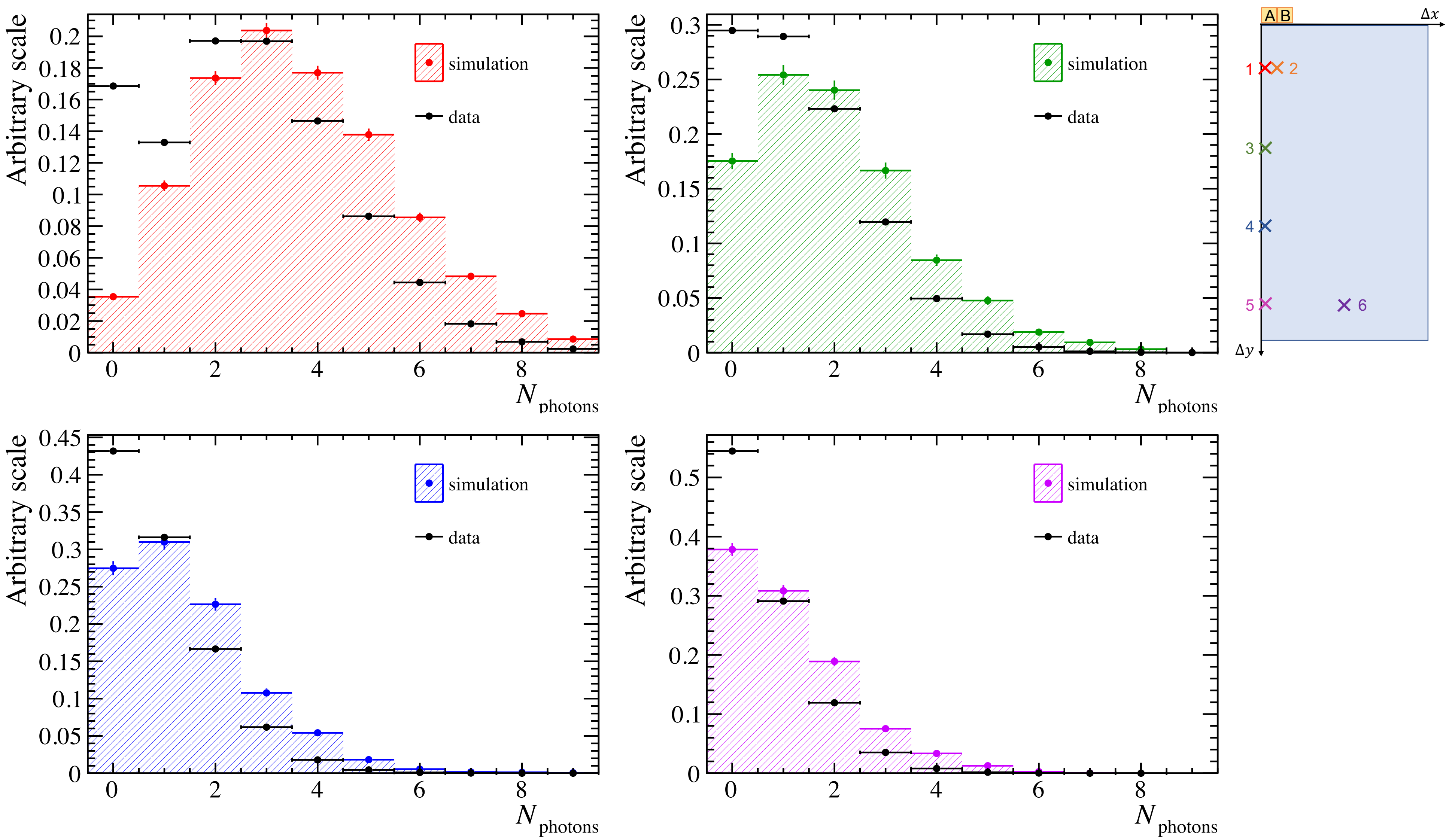


Photon yield in 2018 test beam

- Results from the 2018 beam test have recently published in [NIMA 1050 (2023) 168181].

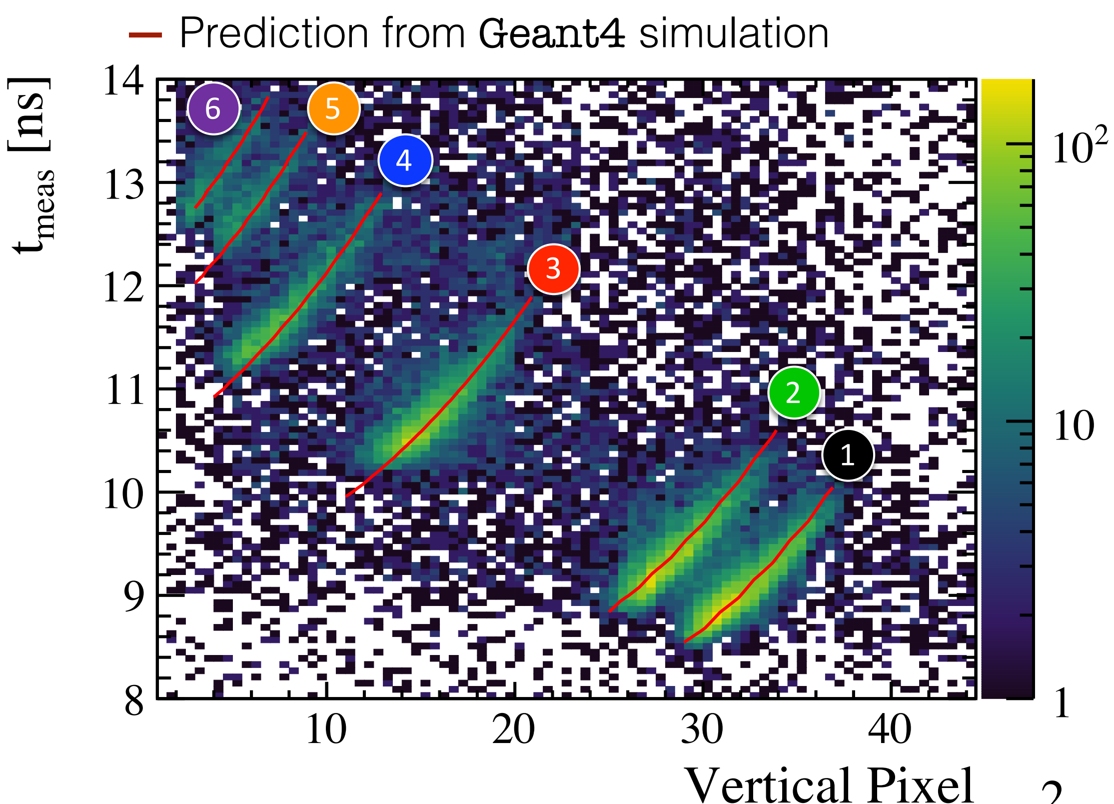
Compare the test beam data to a `Geant4` simulation taking into account surface effects in the radiator bar and our understanding of the MCP-PMT response (QE, gain and charge-sharing).

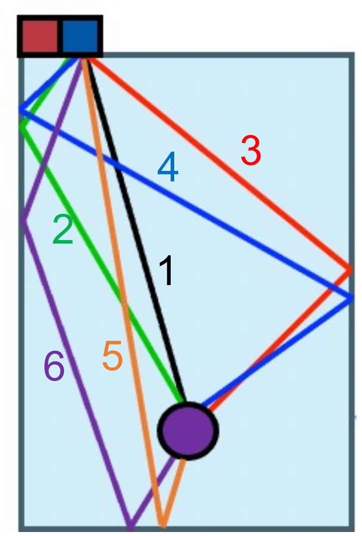
Photon yield data/simulation 82–85%.



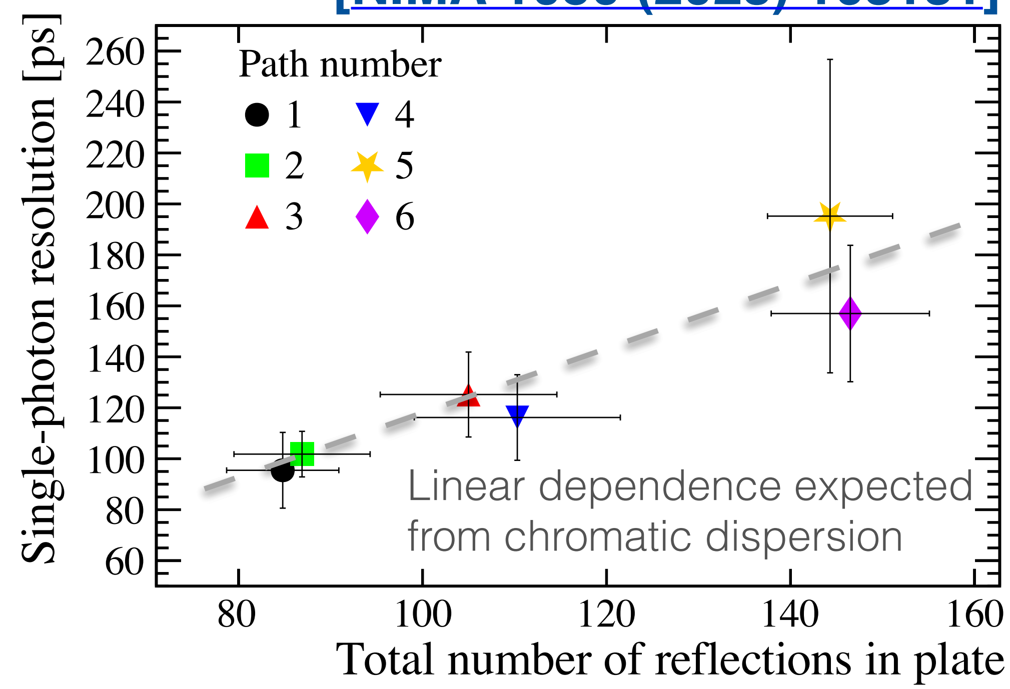
Time resolution in 2018 test beam

- Time response approaching TORCH requirement of 70ps per-track (reach 50ps for MCP and electronics in lab using the HPTDC in very-high resolution mode).
- Further improvements expected from improved detector calibration (e.g. improved charge-to-width calibration) and event-by-event tracking.





[NIMA 1050 (2023) 168181]



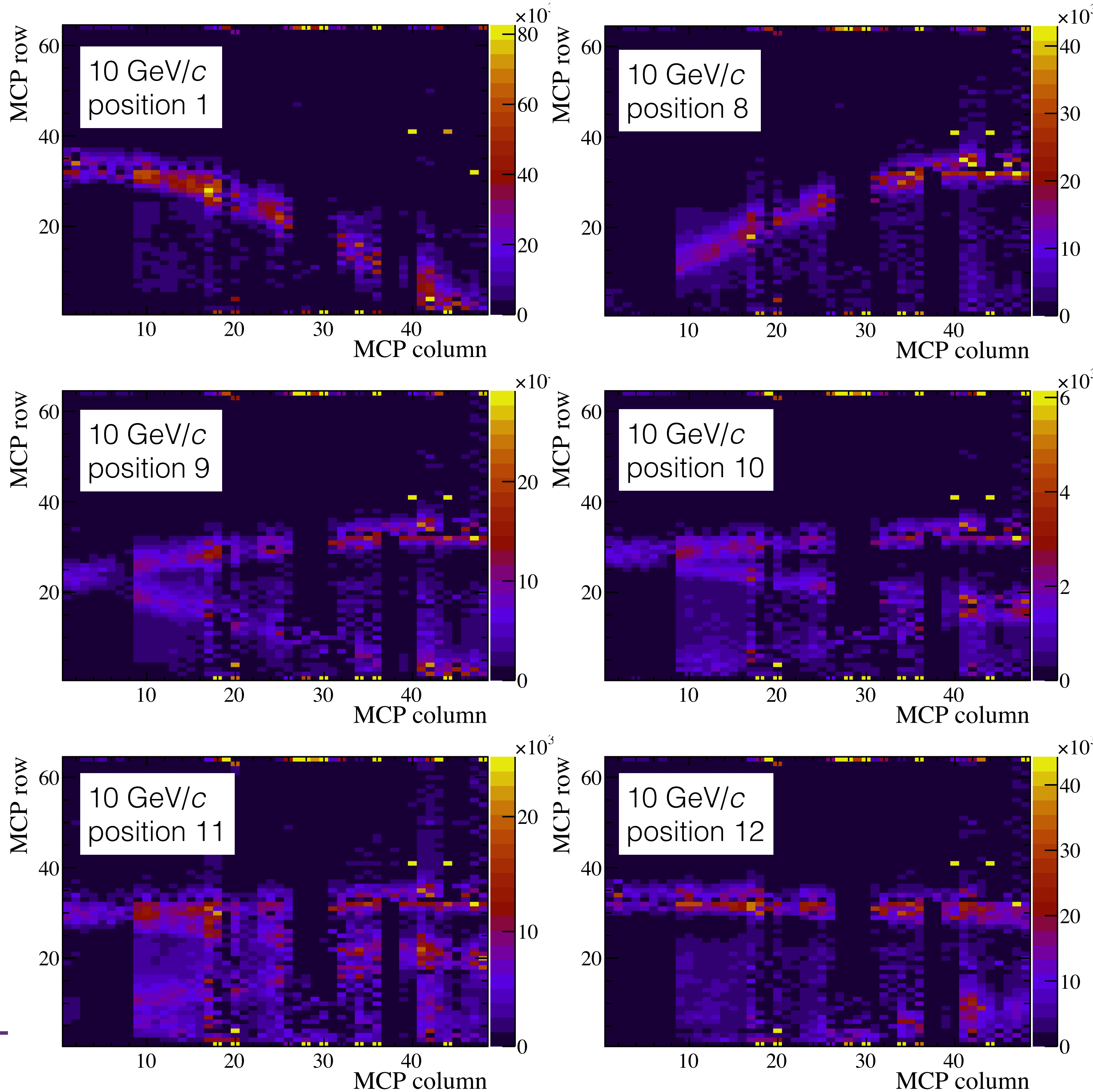
$$\sigma^2 = \sigma^2_{\mathrm{MCP}} + \sigma^2_{\mathrm{prop}}(t_{\mathrm{prop}}) + \sigma^2_{\mathrm{readout}}(N_{\mathrm{pixels}})$$

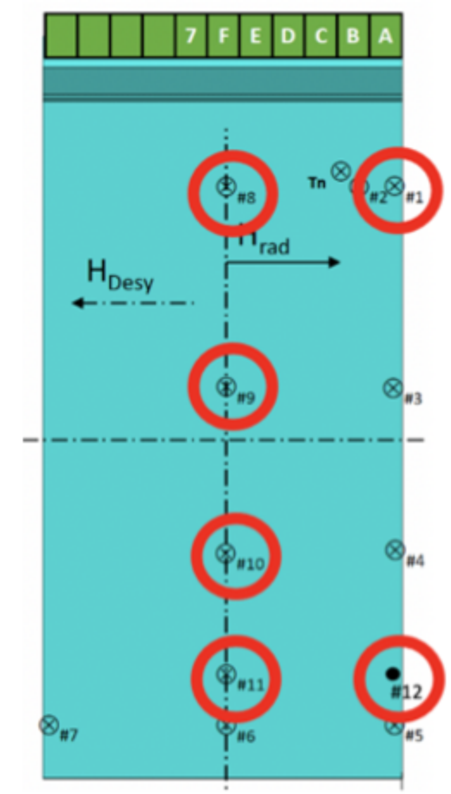
Intrinsic MCP-PMT resolution (~30ps)

Photon reconstruction and pixel size

Readout (with clustering)

Pattern in 2022 test beam

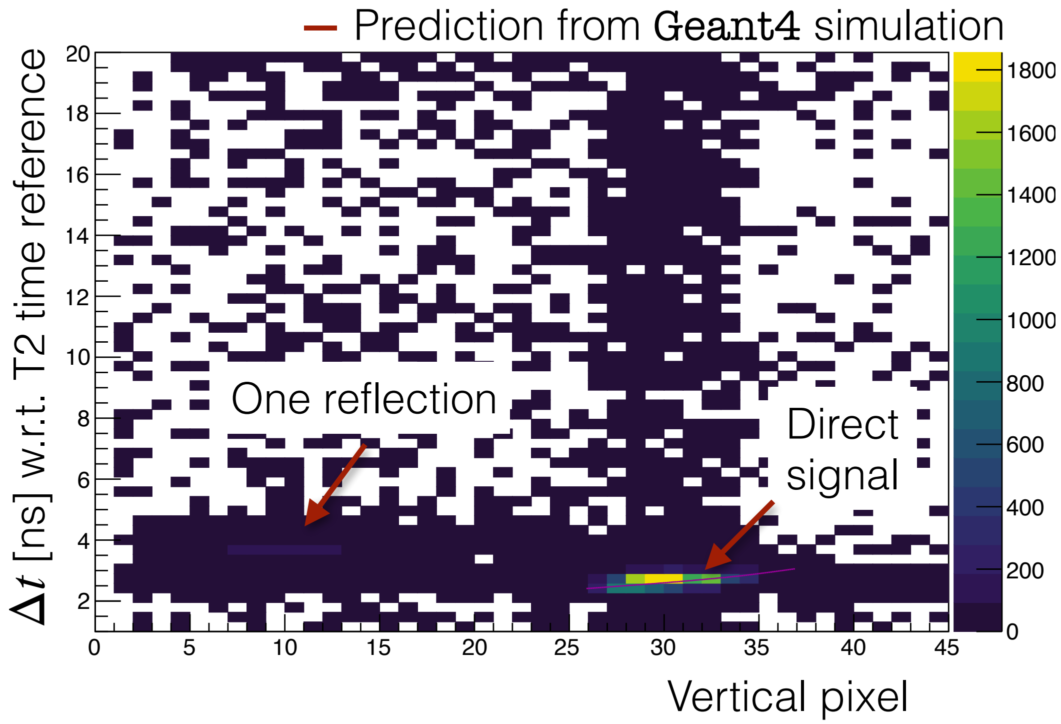


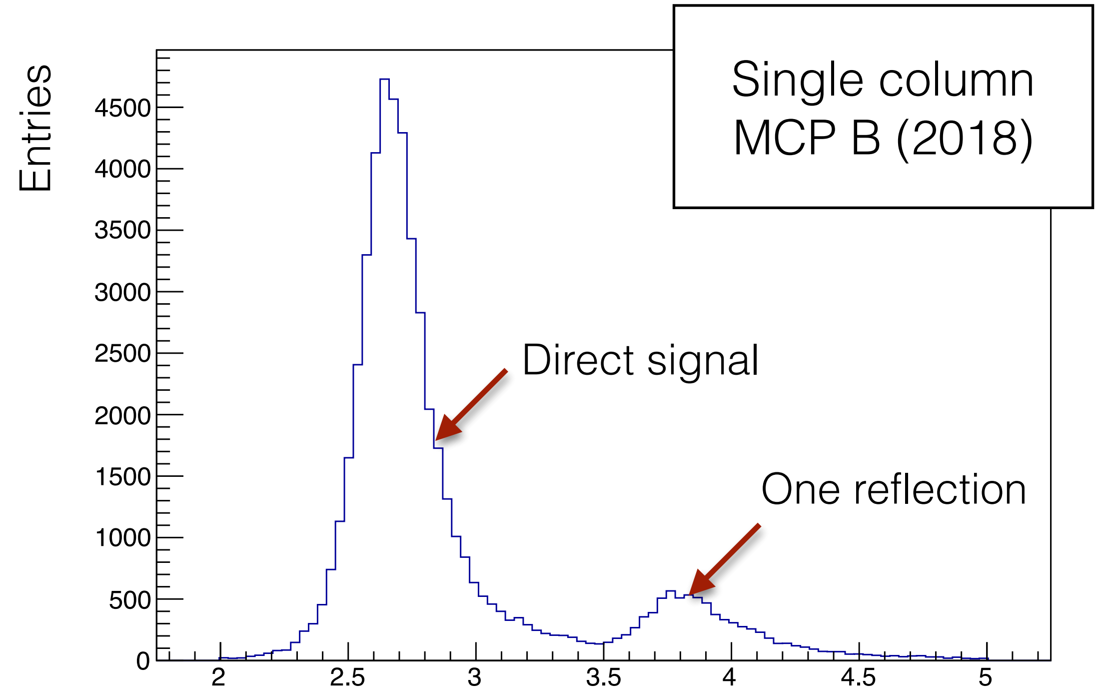


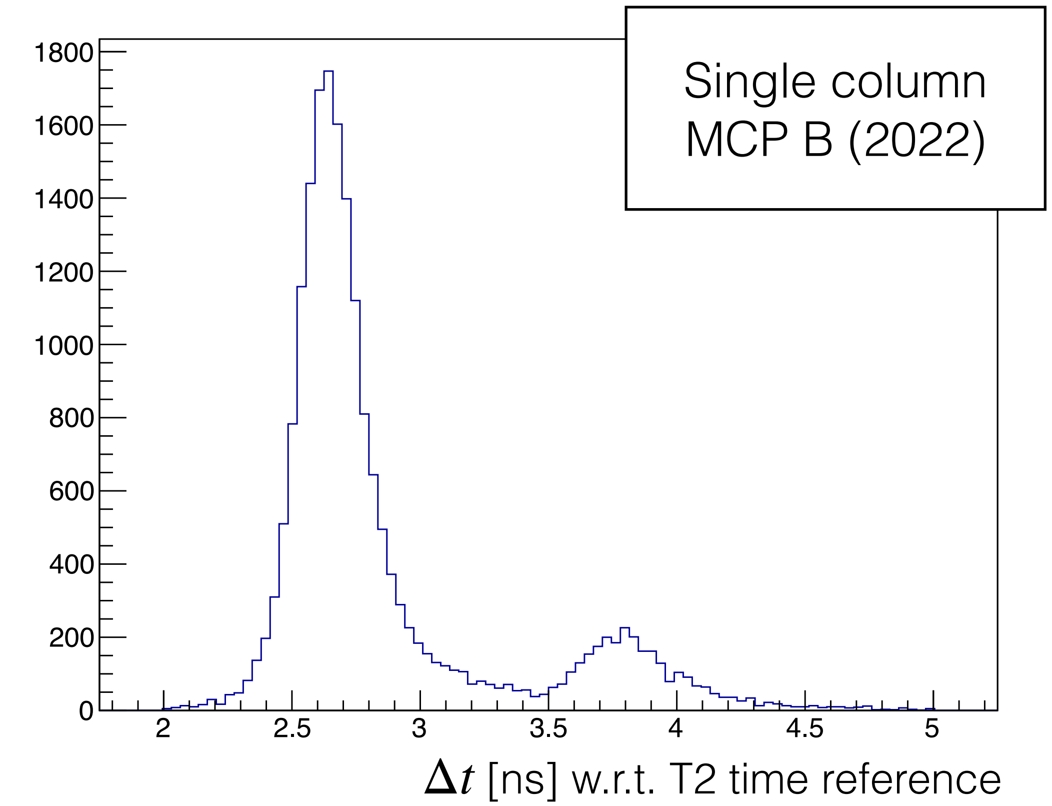
Data taken at six beam positions on the radiator bar at 3, 5, 8 and 10 GeV/*c* beam momentum.

Time resolution in 2022 test beam

- Analysis of the 2022 data is ongoing.
- Early 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.



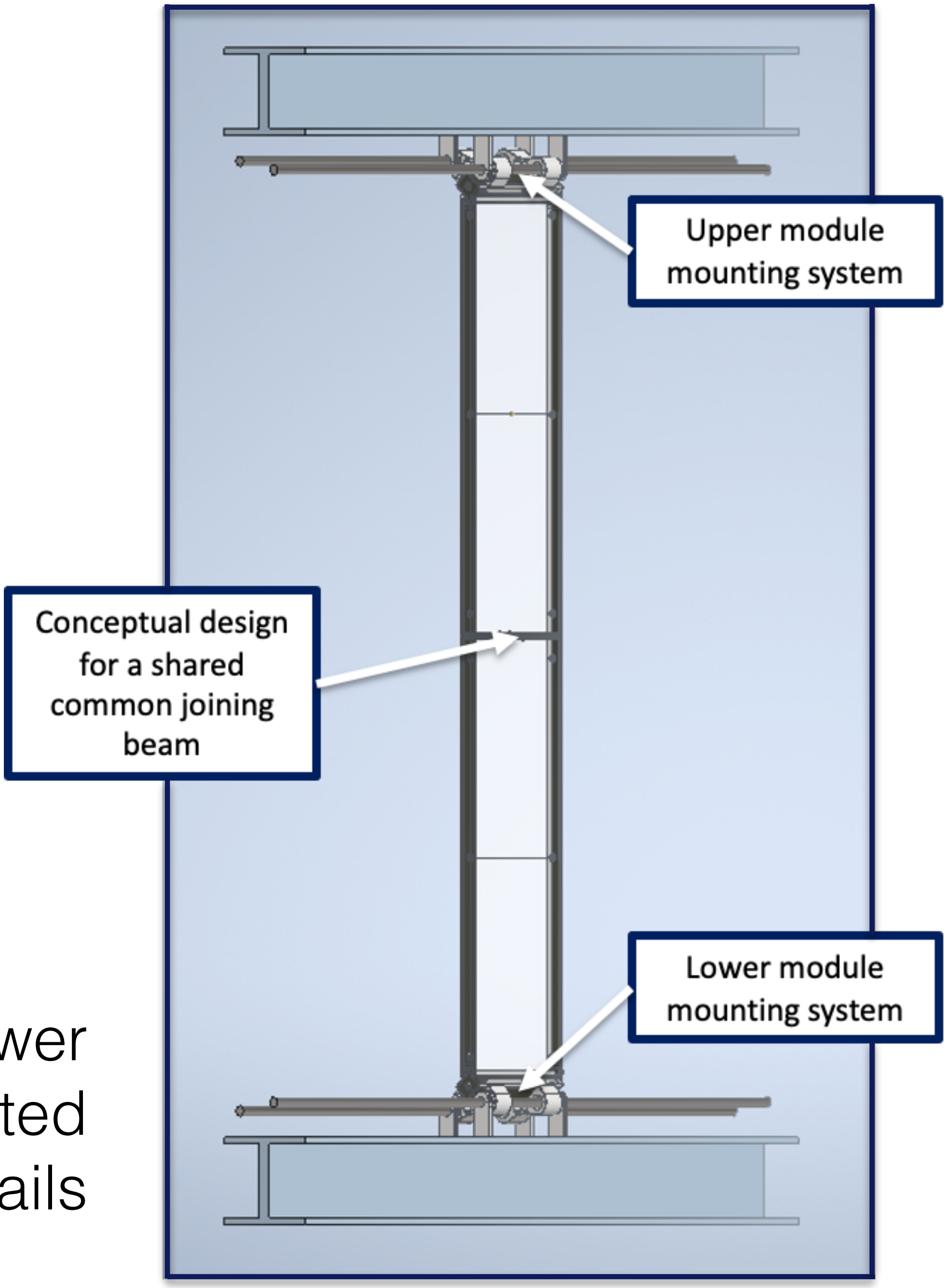




Holding mechanics

- Conceptual design for a light weight carbon-fibre holding frame for the TORCH modules produced and under internal review.
- Mechanics are designed to:
  - minimise material in the detector acceptance.
  - reduce optical contact with the radiator bar.
- Prototyping/finite element analysis is underway.

Upper and lower modules supported on rails



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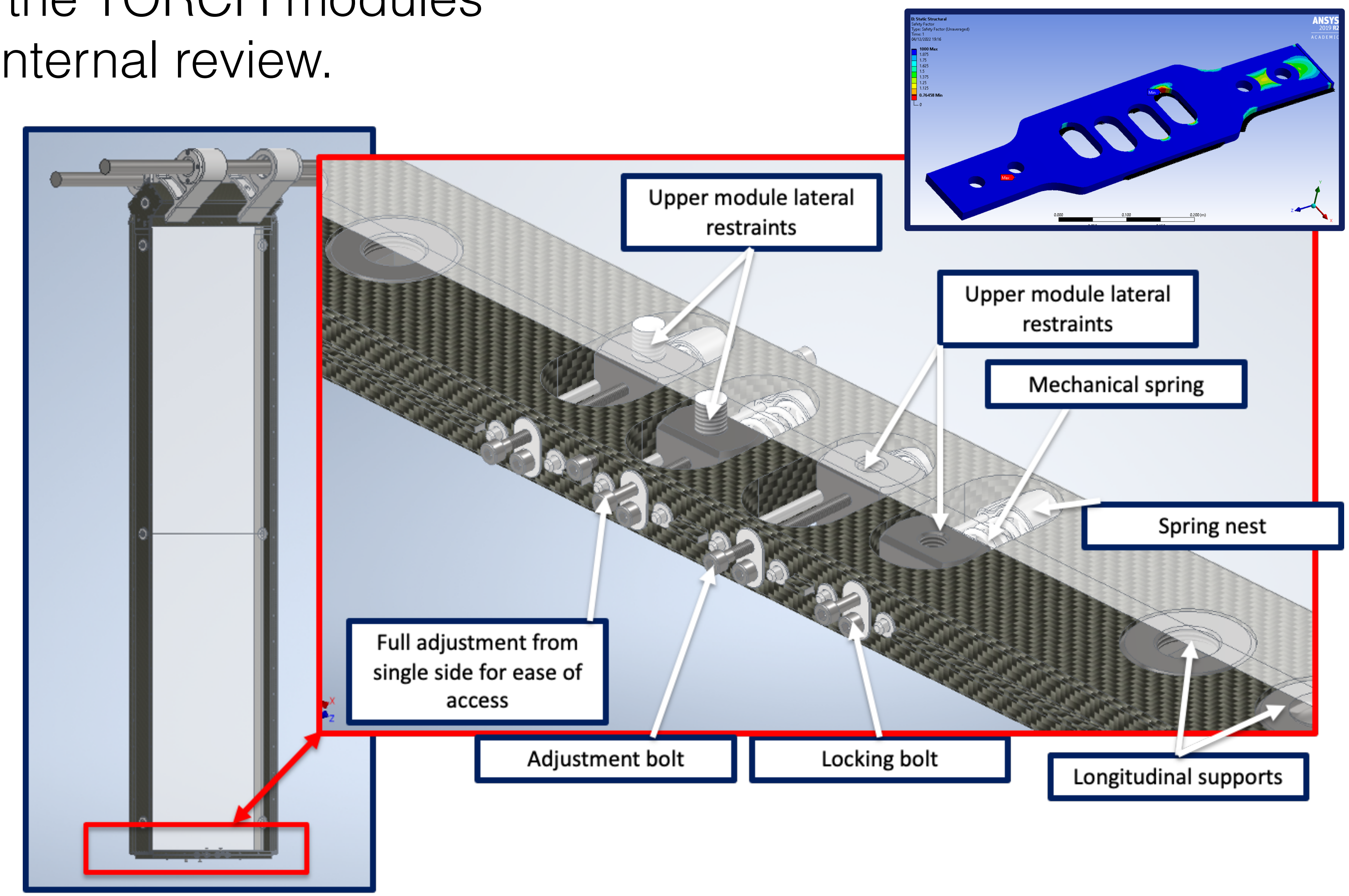

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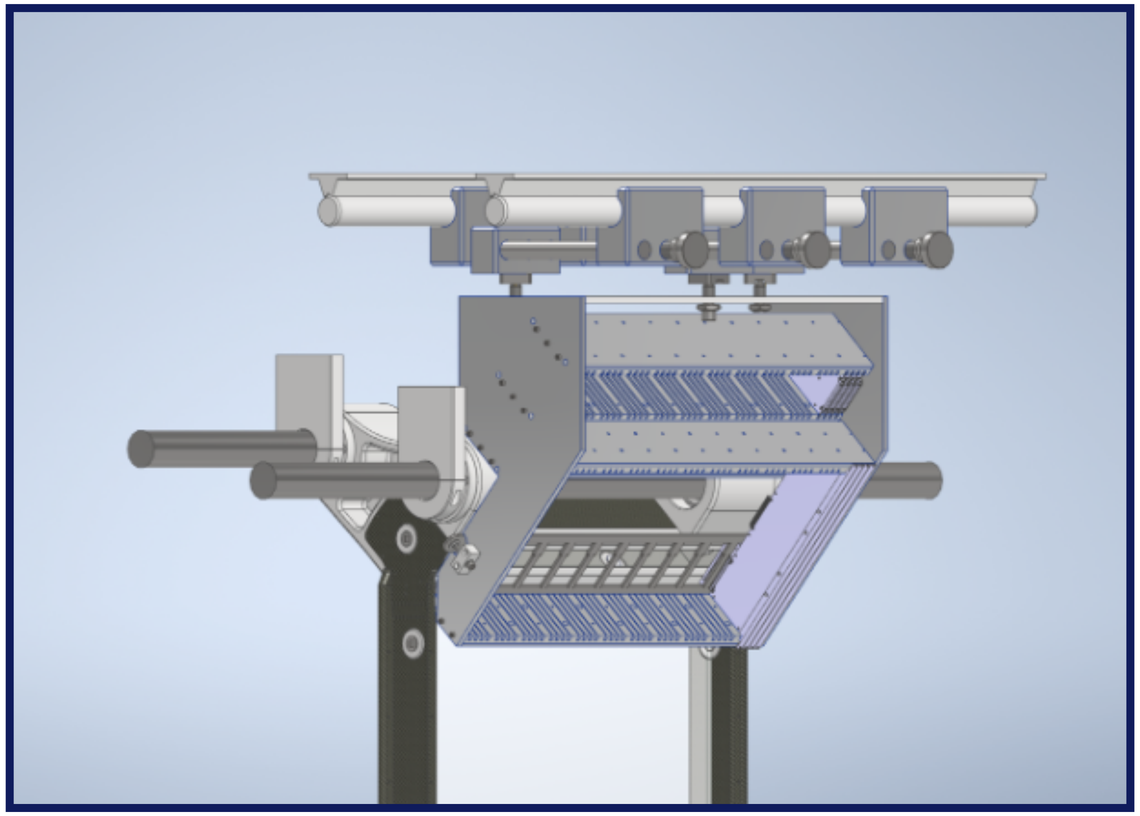
Electronics mounted separately to reduce weight during handling

Additional set of rails for the electronics assembly

Accurate position of the sensors achieved using push/pull screws



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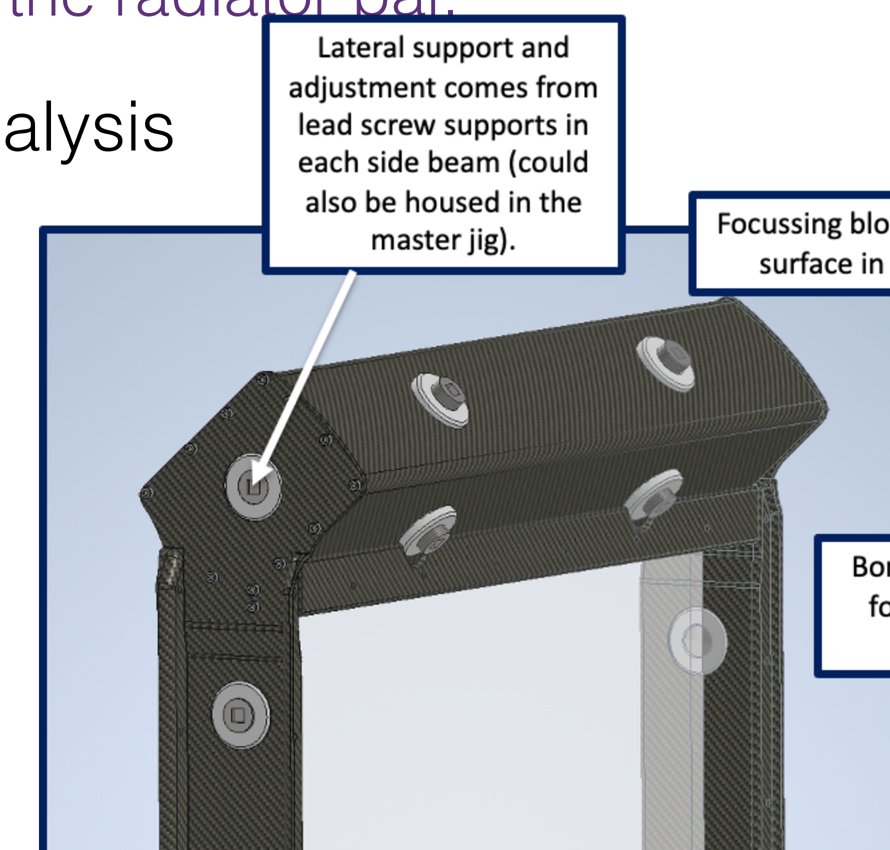
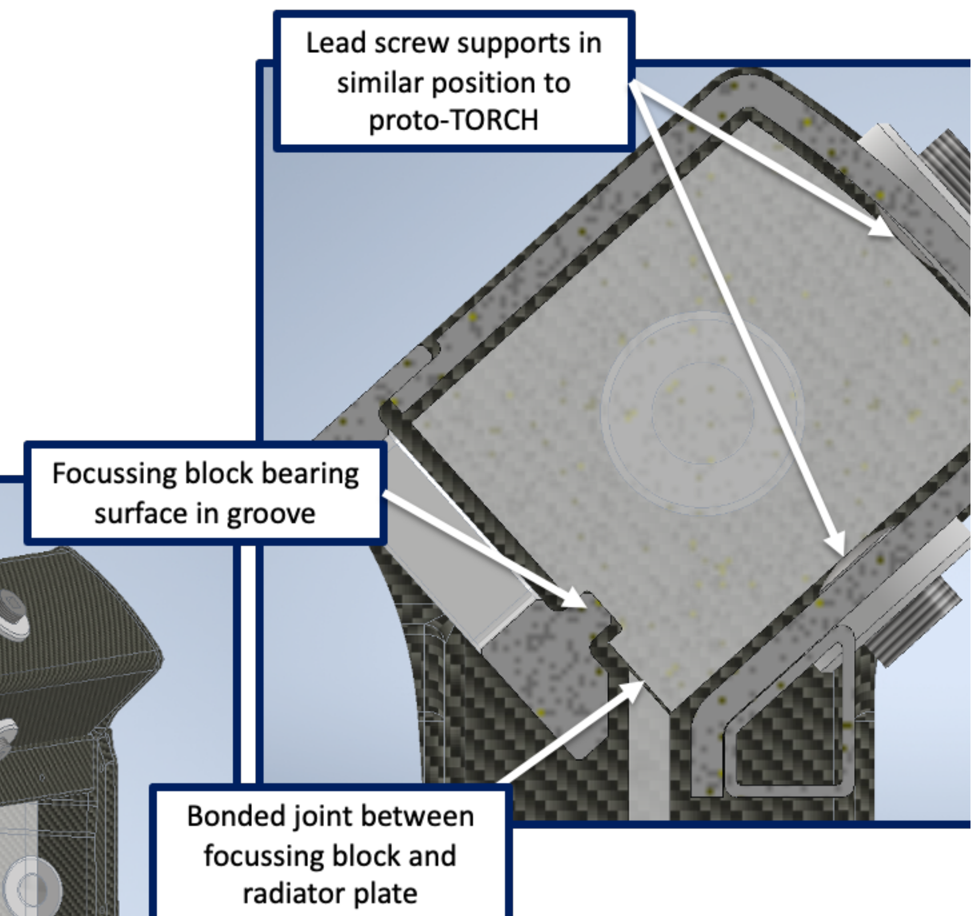


U-shaped side-beam



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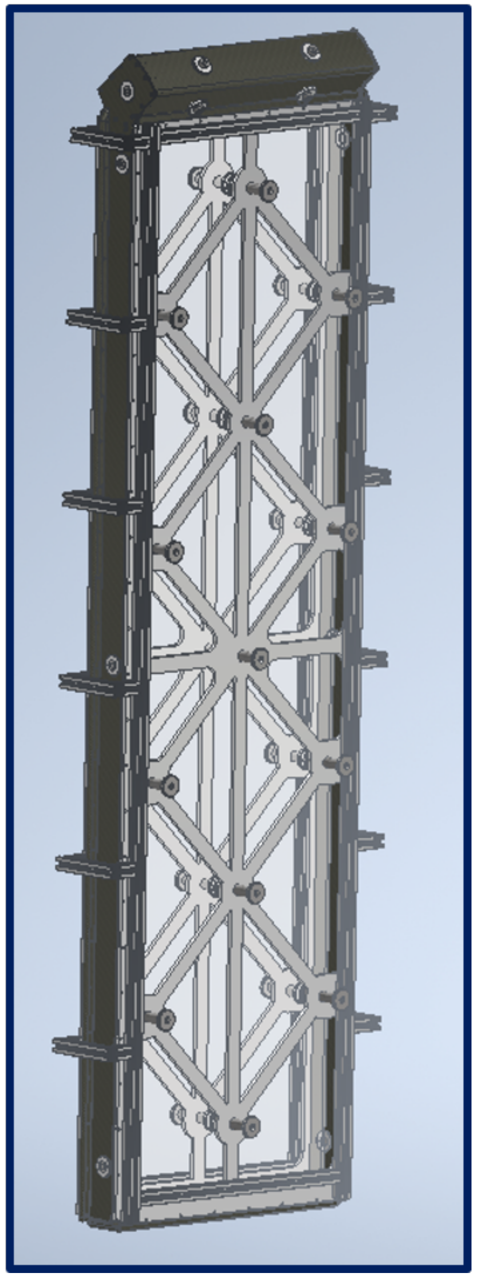
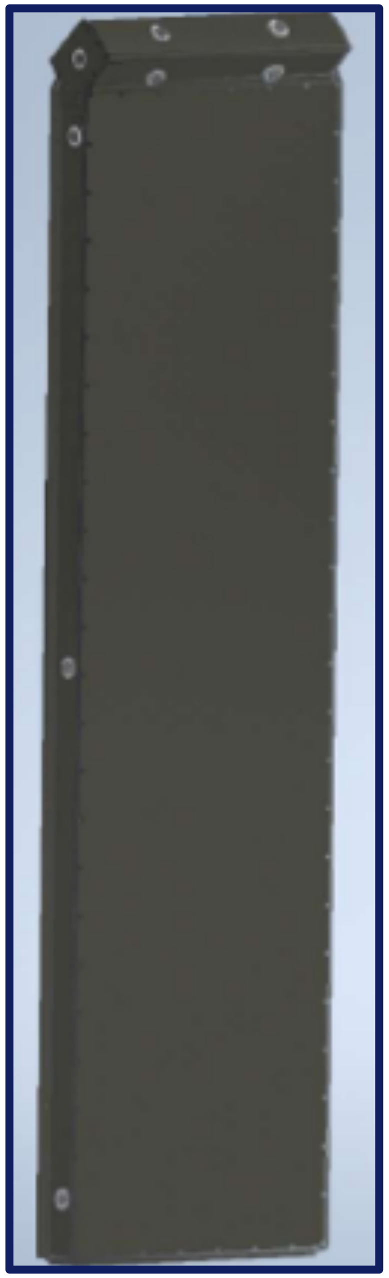
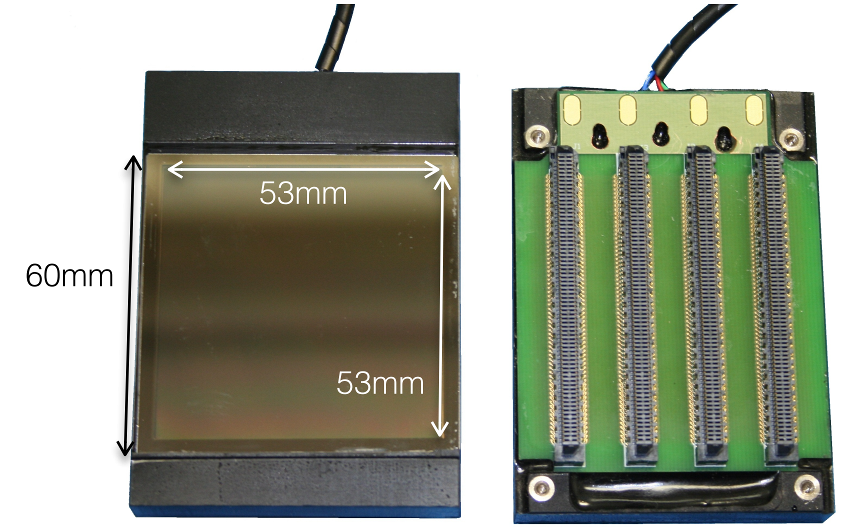
Exoskeleton used for quartz handling and jigging

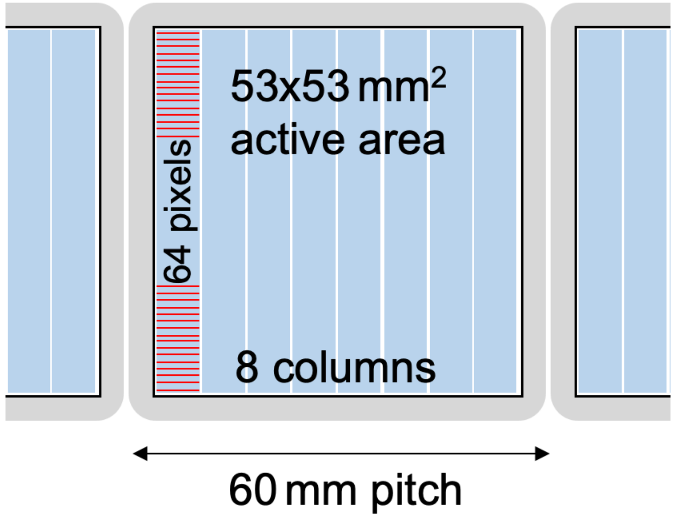


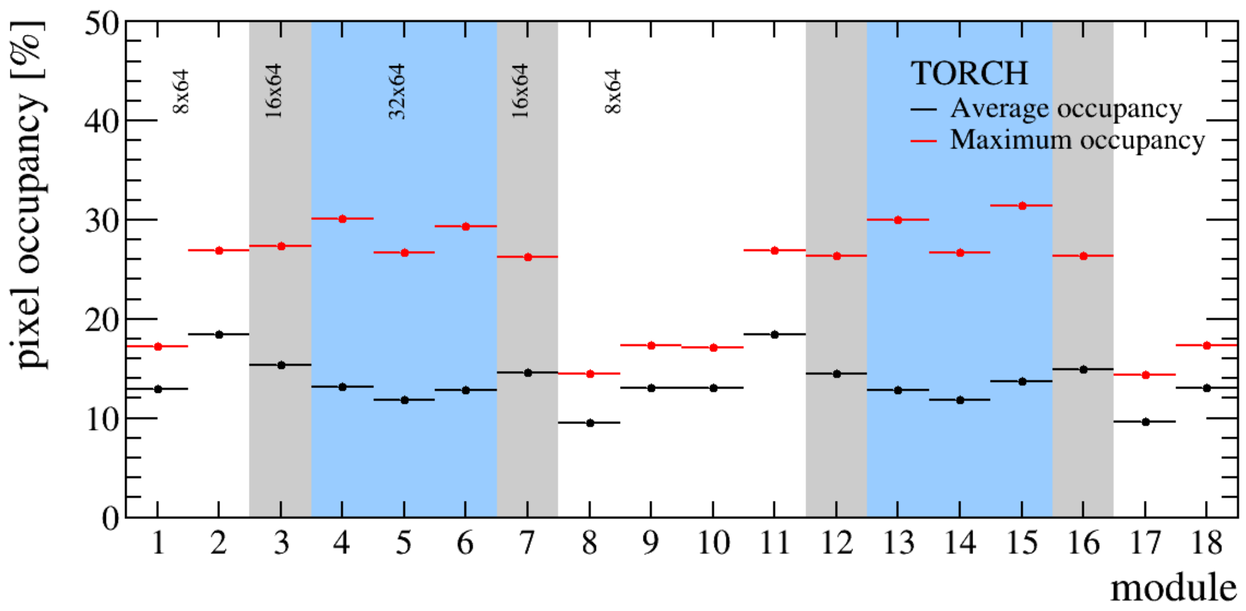


MCP-PMT development

- Currently use custom 64-by-64 pad Photek MCP-PMTs with 60mm pitch and 53-by-53mm active area **[JINST 10 (2015) C05003]**.
- Pads are electronically ganged into a 8-by-64 pixel arrangement.
- Readout connectors are mounted on an external PCB and connected via anisotropic conductive film.





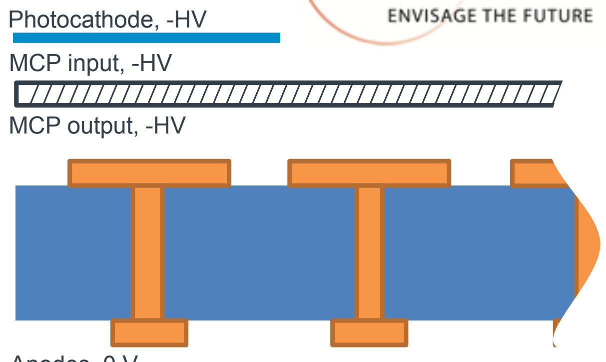


Need higher granularity devices to cope with occupancies in UII conditions

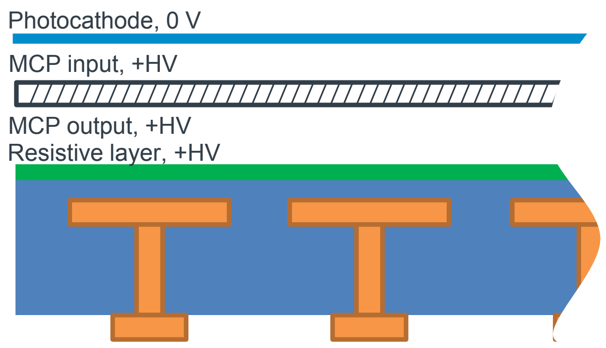
MCP-PMT development

- Move from capacitively coupled device to direct feed throughs.
  - Aim to reduce occupancy by reducing charge sharing.
- Increase granularity from 8-by-64 to 16-by-96 pixels to compensate for the loss of spatial resolution without clustering.
- Use 110 Hirose FX25-110s-0.4SV connectors with 96 connected channels and14 ground pins.
- Discussing specifications with Photek. Expect delivery of the new MCP-PMT at the end of the summer.

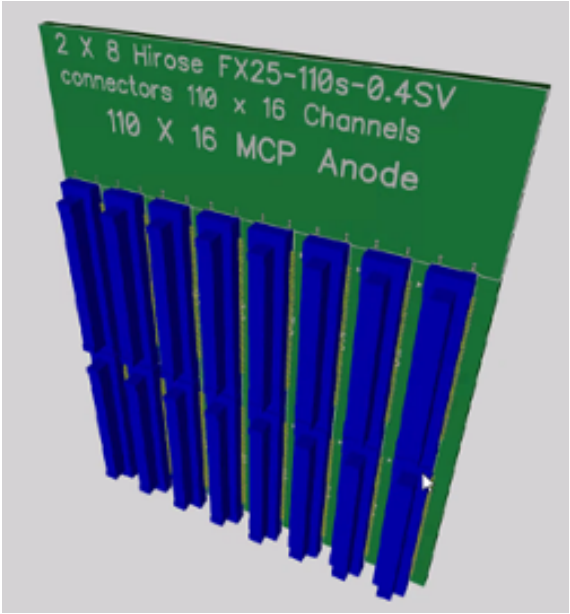
PHOTEK
ENVISAGE THE FUTURE



D.C. coupled anodes



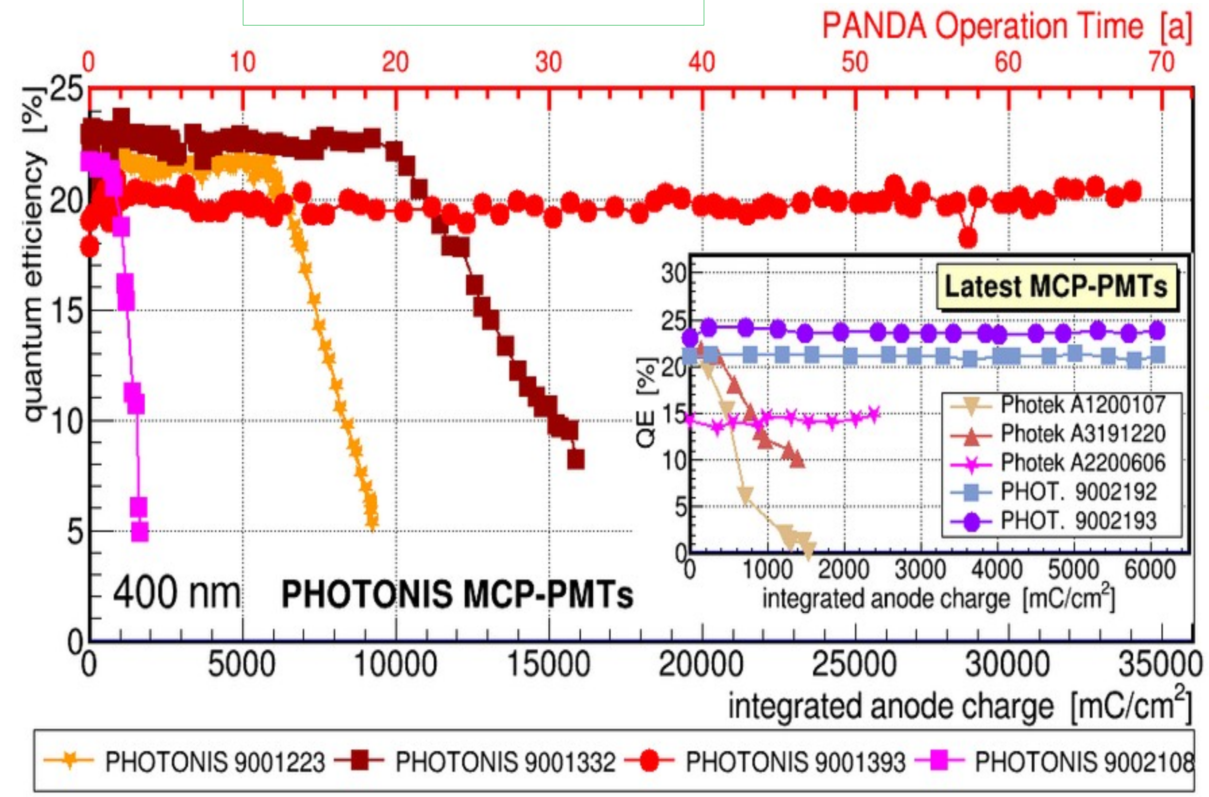
A.C. coupled anodes



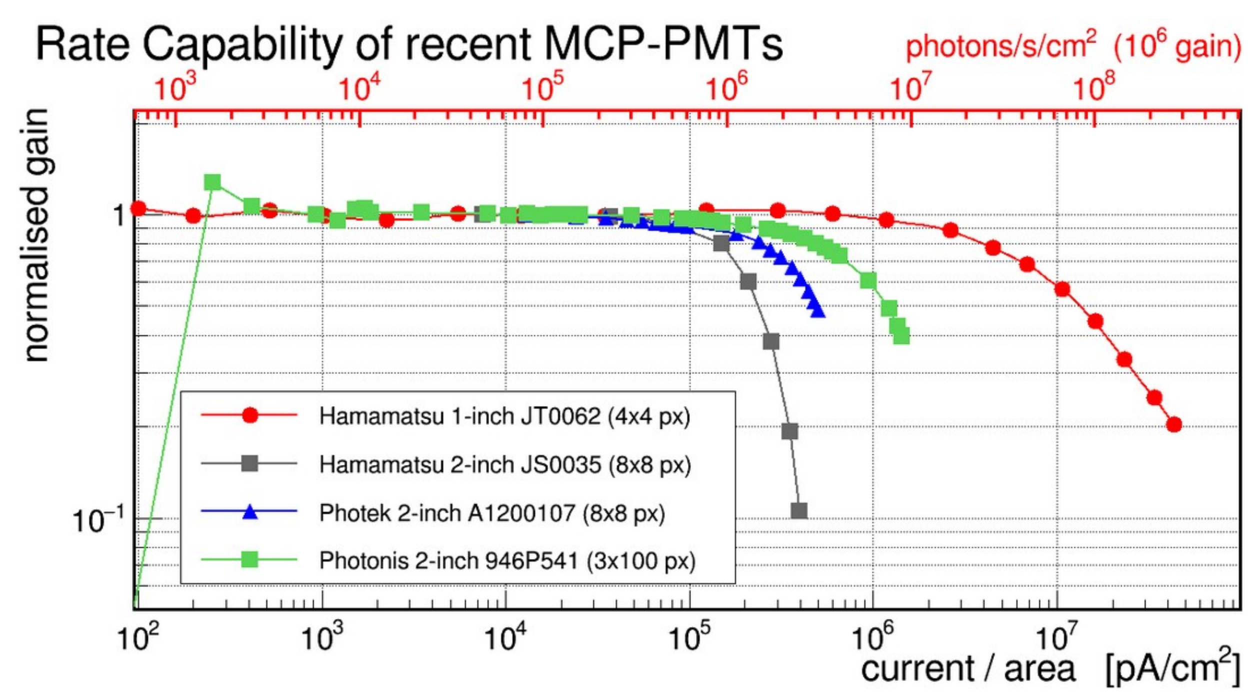
Future MCP-PMT developments

- It will also be necessary to increase the lifetime and rate capability of the MCP-PMTs for UII conditions.
- TORCH requirements are compatible with the requirements of the PANDA DIRC and proposed HIKE KTAG.
- Lifetime > 30 C cm^{-2} demonstrated by Photonis using ALD (c.f. > 5 C cm^{-2} in our current devices).
- Rate capability can be increased by reducing the MCP resistance & capacitance and operating at lower gain.

PANDA DIRC R&D



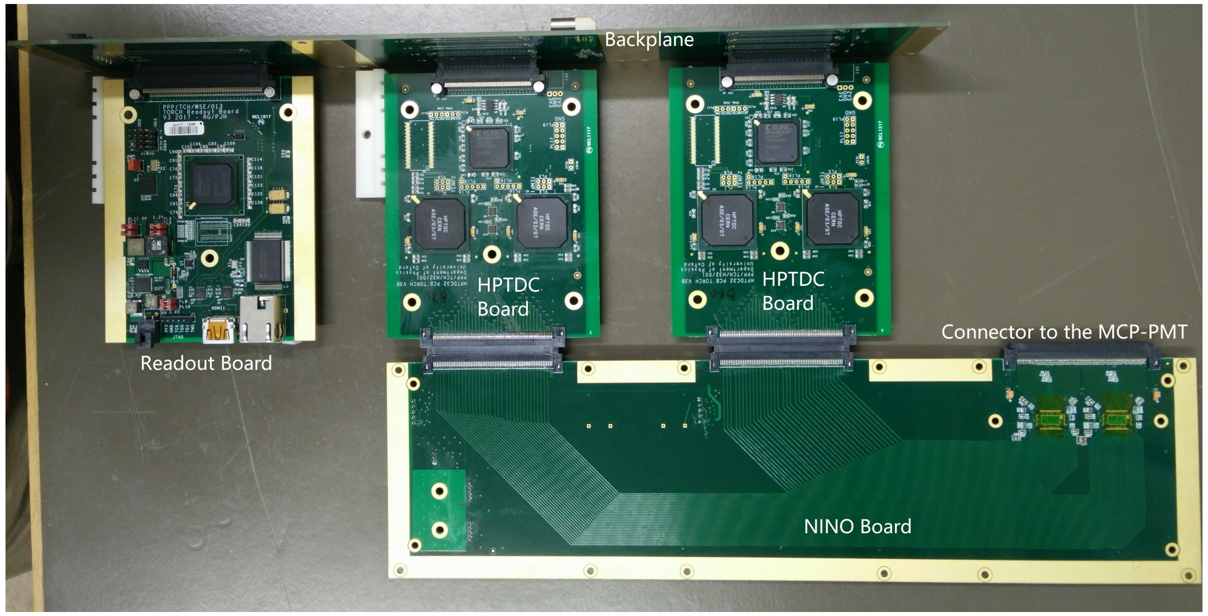
See [A. Lehmann RICH 22]

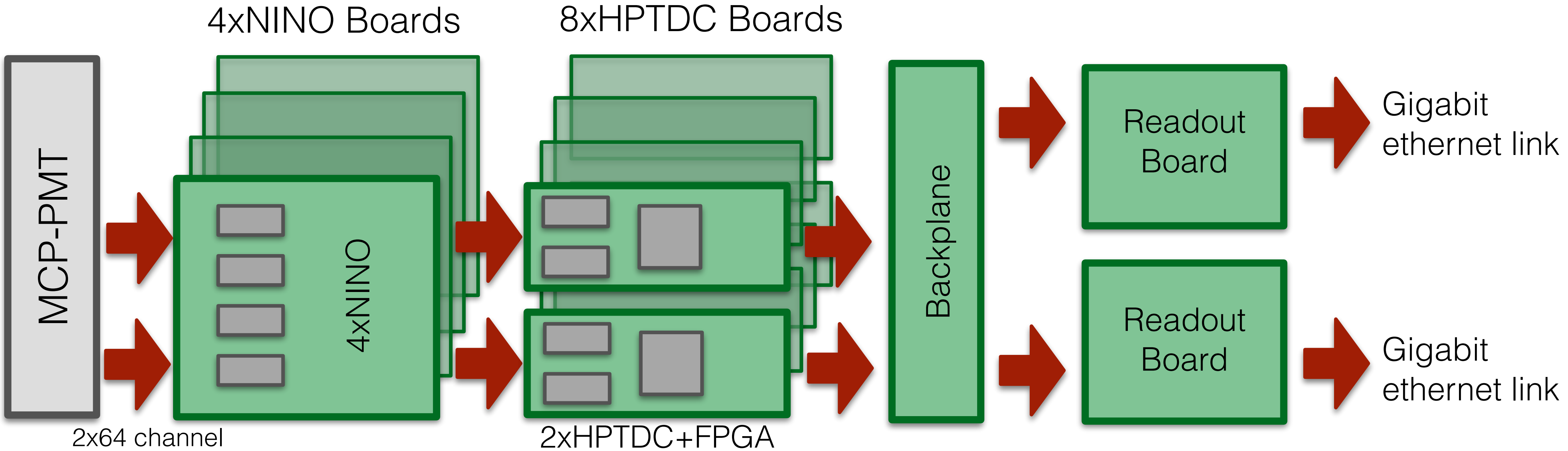


Electronics developments

- Current electronics are based on NINO/HPTDC chipsets. Originally developed for the ALICE TPC (i.e. designed for MRPC signals).

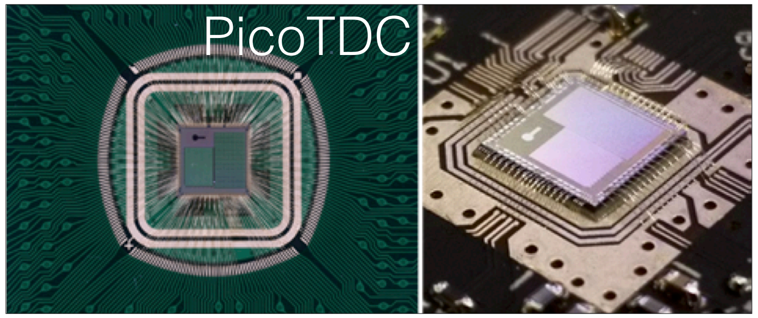
[JINST 11 (2016) 04 C04012]

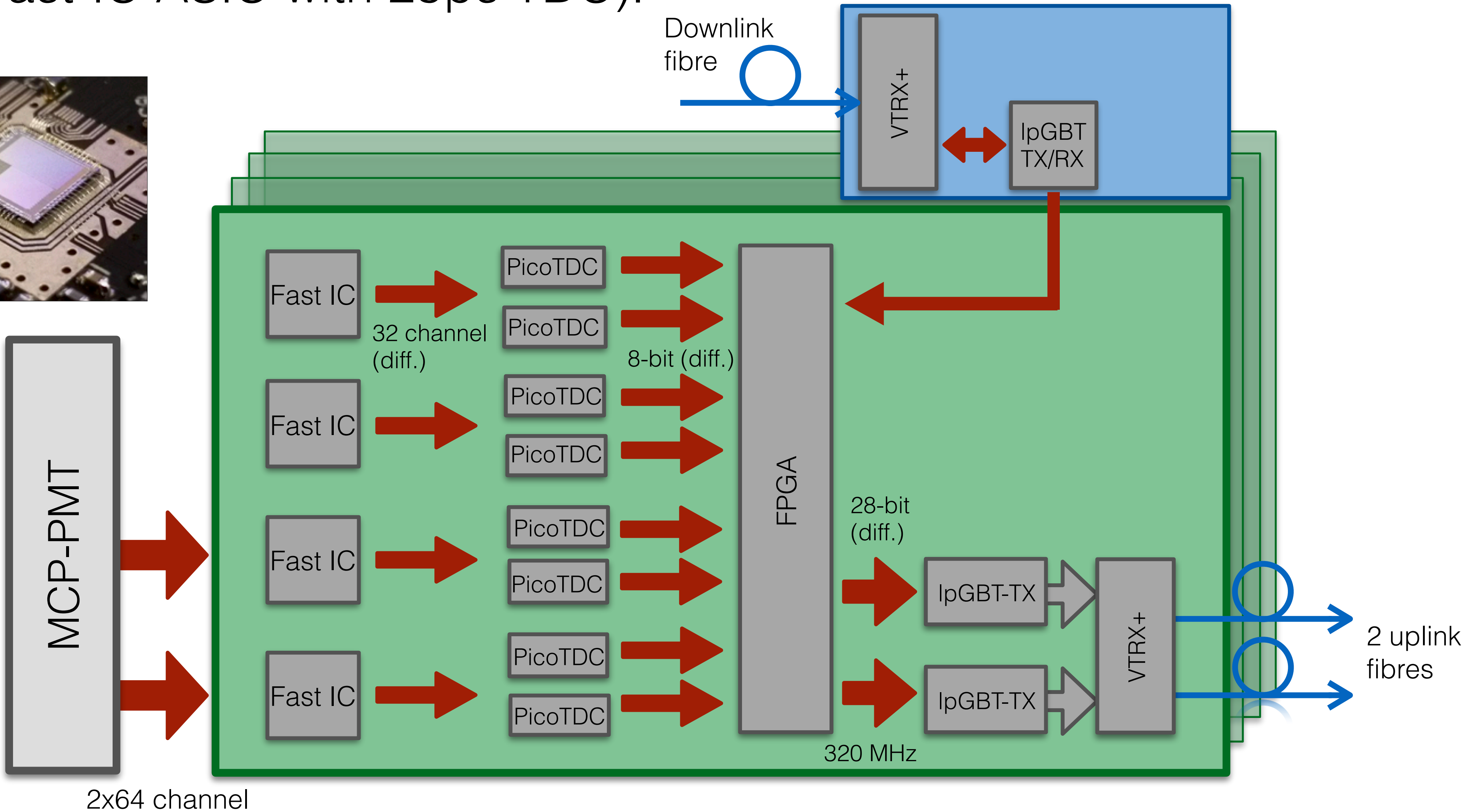




Electronics developments

- New electronics planned based on Fast-IC **[JINST 17 (2022) C05027]** and picoTDC **[users meeting]** (3 and 12ps binning). Design in progress.
- Possible synergy with RICH in Fast-RICH developments (integrated Fast-IC ASIC with 25ps TDC).





Preliminary cost estimate

Based on tender process for the TORCH prototype and PANDA DIRC.

MCP-PMT cost assumes 198 MCP-PMTs at 11.5 kCHF per device (need 220 with spares).

From the FTDR:

Item	Cost (kCHF)
Quartz radiator plates	2300
Quartz focussing block	1510
MCP-PMTs	2380
Mechanical superstructure	1000
On-detector electronics	1570
Off-detector electronics	1170
Total	9930

On-detector electronics cost assumes 1.5CHF/channel. Off-detector electronics cost based on 27Tb/s output rate and 91 PCIe40.

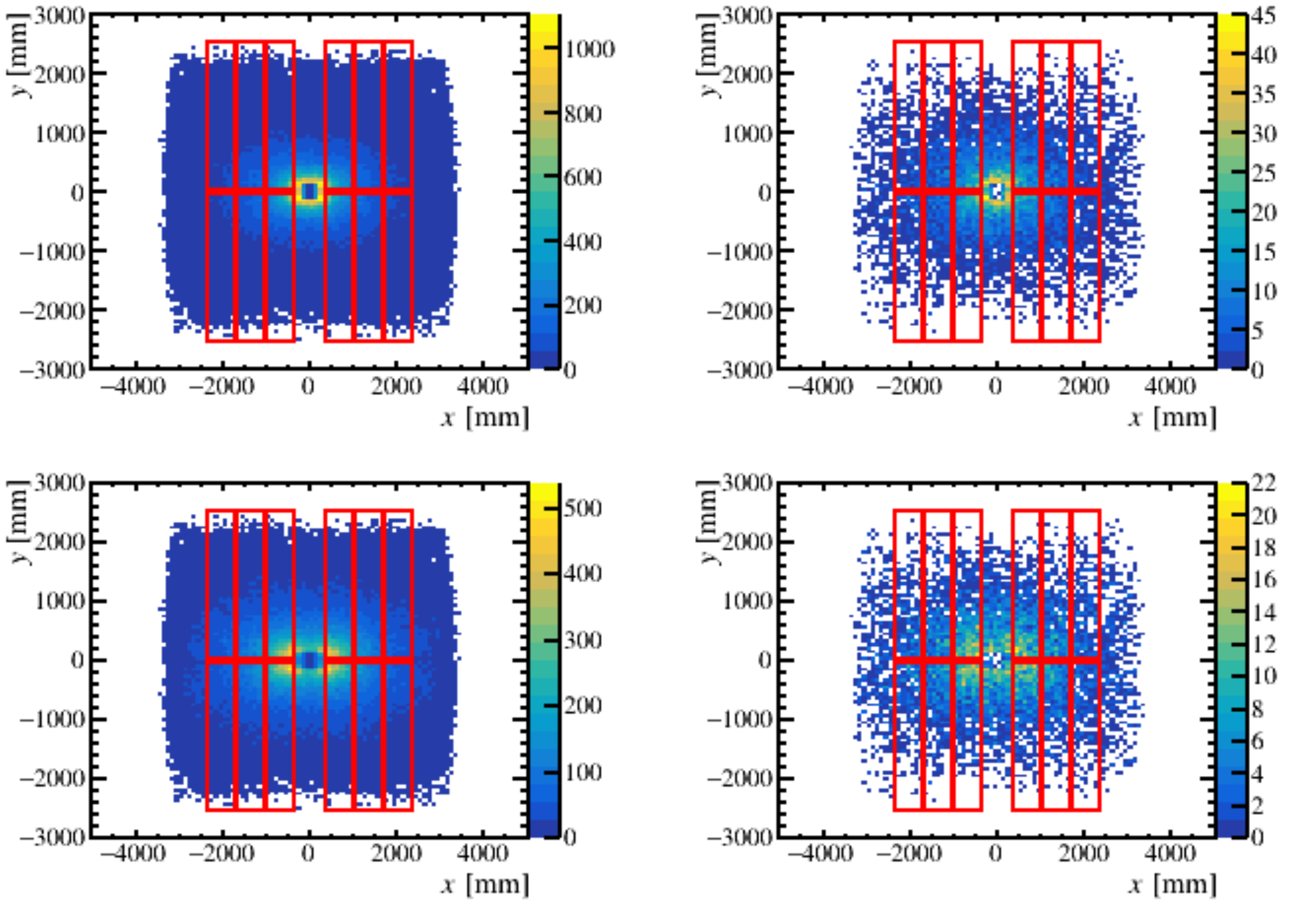
- A tender process is ongoing for a second 1250x660x10 mm^3 fused-silica plate. Costs have increased (driven by manufacturing costs).

  We are exploring cost savings from reducing tolerance requirements.

Scoping options

- Operating at lower luminosity only yields a modest cost saving:
    - Operating at $1.0 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ instead of $1.5 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ could save 800kCHF in electronics costs.
- We are exploring cost reductions from tolerances on radiator surfaces.
- Main cost driver is the area of the detector:
    - Reducing from 18 ↦ 12 modules reduces the cost of TORCH by ~1/3 and retains 76% coverage of low momentum particles.
    - We are preparing for an optimisation of scoping options over the summer.

All particles | From *b*-hadron



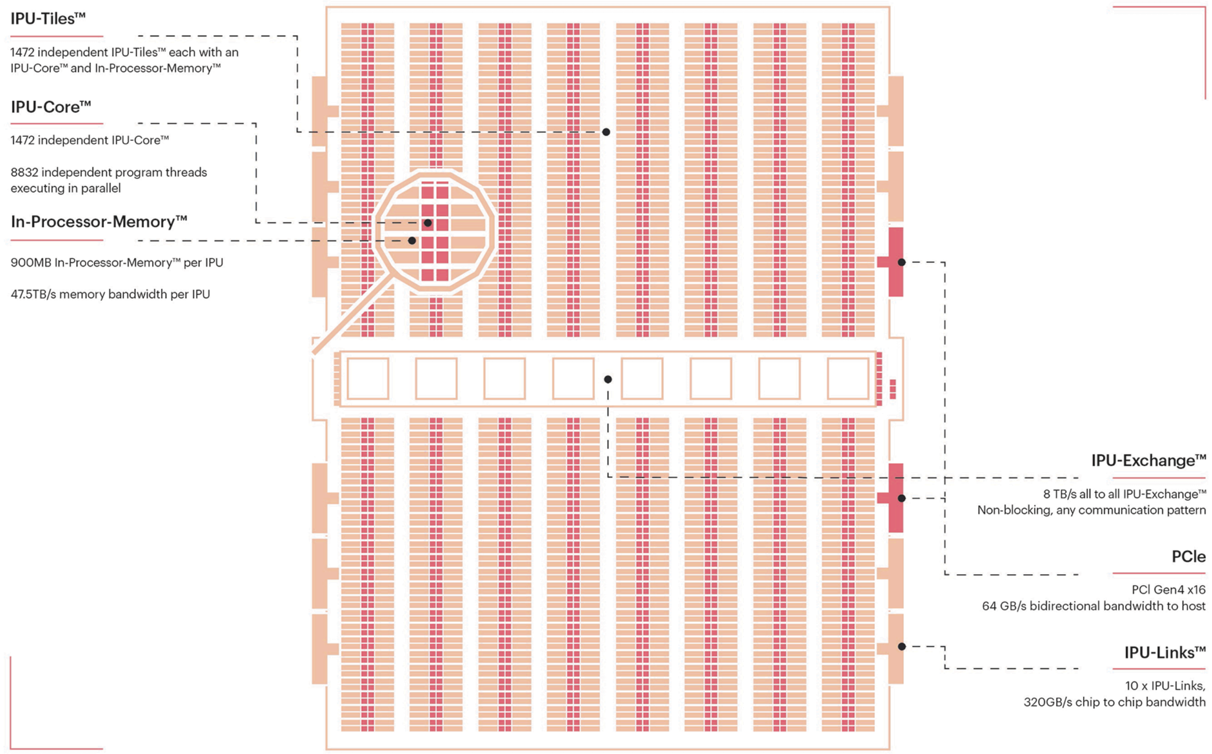
$p \leq 20\,\mathrm{GeV}/c$ | From *b*-hadron $p \leq 20\,\mathrm{GeV}/c$

Summary

- Several important developments since the last upgrade workshop:
  - Prototype with seven MCP-PMTs tested in beam test in T9.
  - Design of new generation of MCP-PMT with DC connected anode and improved granularity.
  - Design of carbon-fibre holding mechanics for TORCH.
  - Design work started for new readout electronics based on Fast-IC and picoTDC (aim for synergy with developments for the RICH).
- We aim to produce a full scale prototype module this year using the newly designed holding mechanics,
- We are investigating the possibility of using SiPMs as an alternative to MCP-PMTs in TORCH.
  - Potential solution for the highest occupancy modules that would have synergy with developments for the RICH.

Software developments

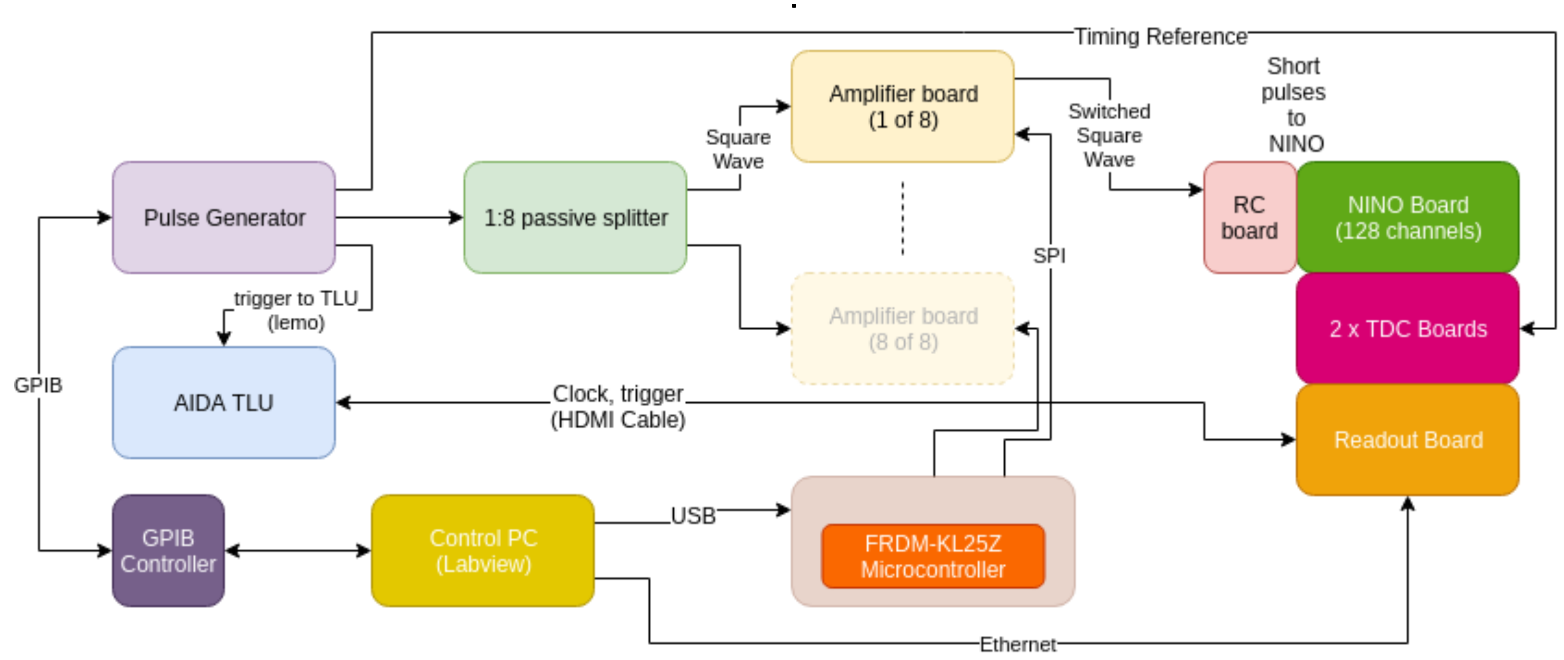
- A significant speed-up has been obtained in the reconstruction by implementing a semi-analytic calculation of the PDF (now 1s per event on CPU). Further improvements expected with code optimisation.
- TORCH reconstruction is well suited to parallelisation and hardware acceleration.
- A proof-of-principle implementation of the TORCH PID algorithm has been implemented on an IPU [graphcore.ai/products/ipu].
- Plan to also develop the reconstruction for GPUs.



[graphcore.ai/products/ipu]

Calibration system

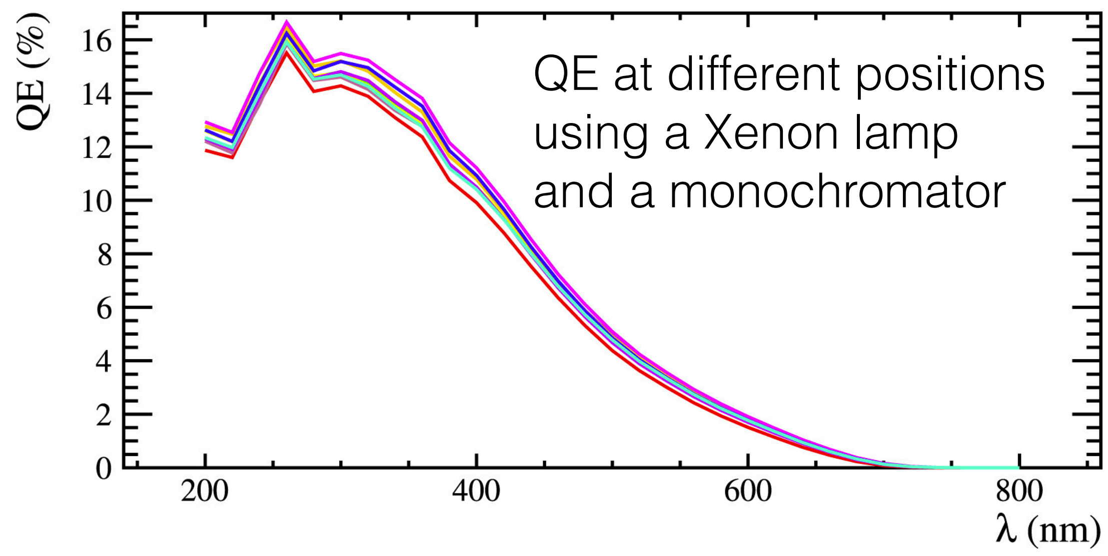
- We have developed a calibration system that can be used to inject a known charge into each channel of the NINO and HPTDC boards.

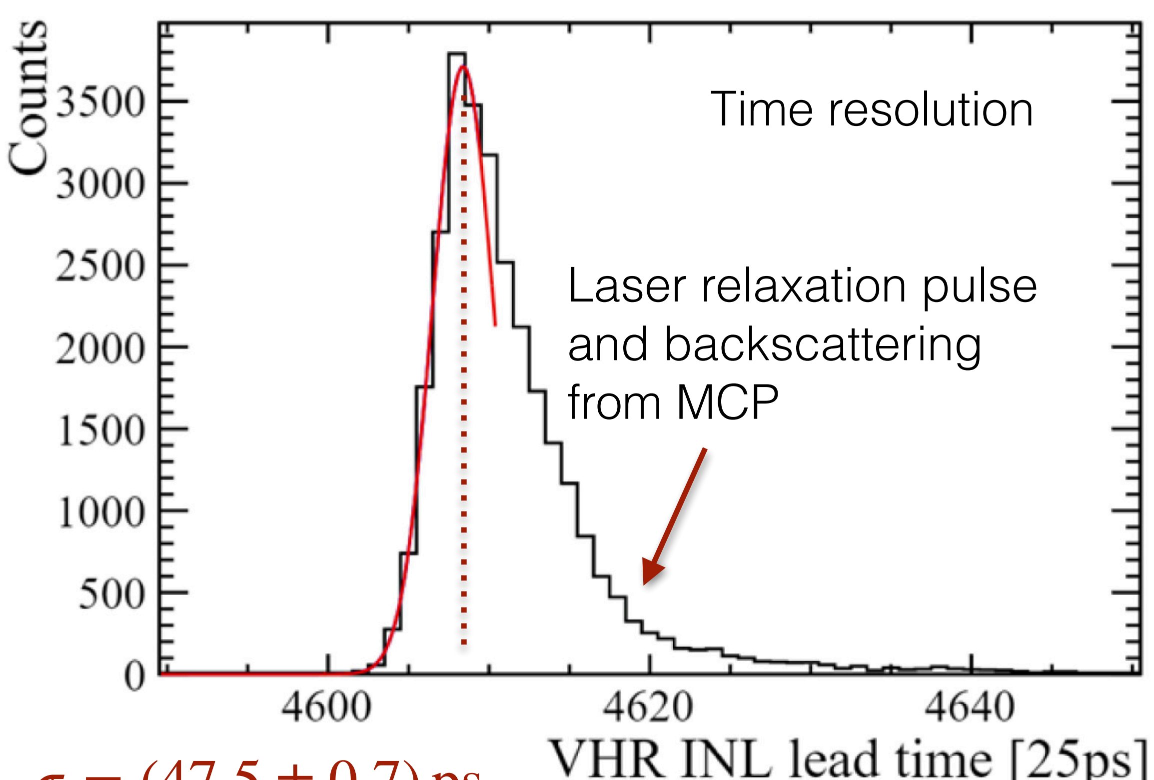


- The calibration system has been used to set the threshold of the NINO boards in the 2022 test beam.
- The calibration system will be used to improve the time-walk and integral non-linearity corrections of the lab and test beam data.

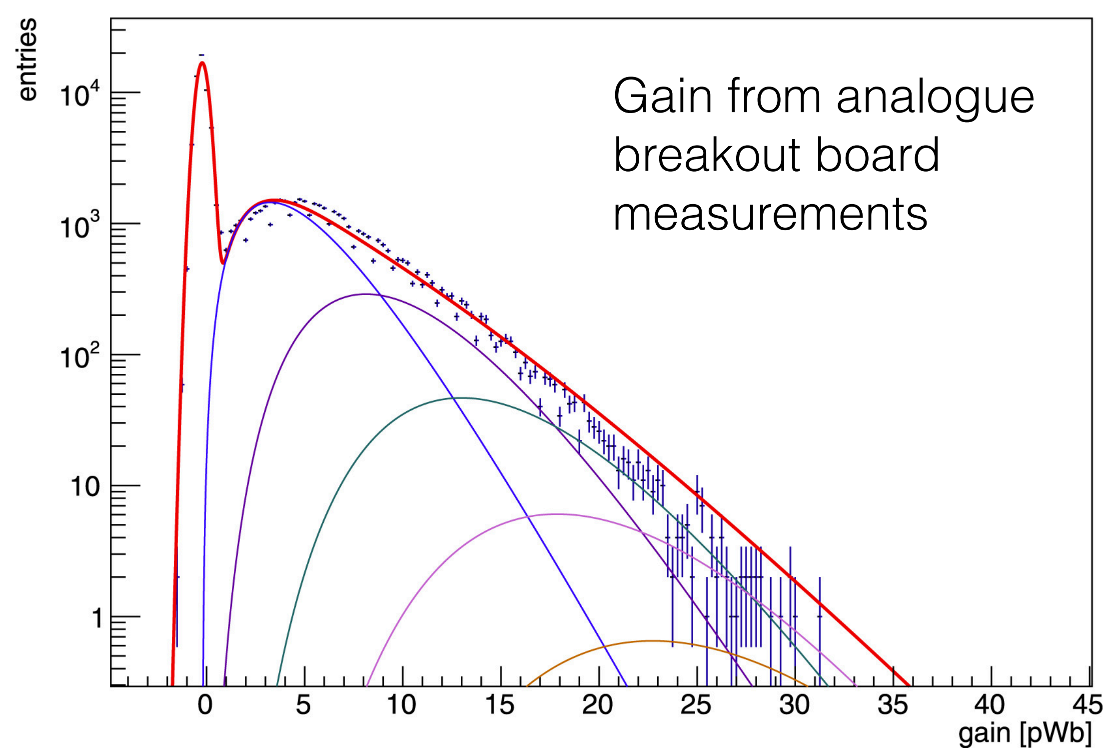
Results from the lab

- Extensive measurements performed at CERN to qualify the MCP-PMTs used in the TORCH prototype:
  - Measurements of QE and gain uniformity.
  - Intrinsic time response of the MCP and electronics using 405nm picosecond pulsed laser.

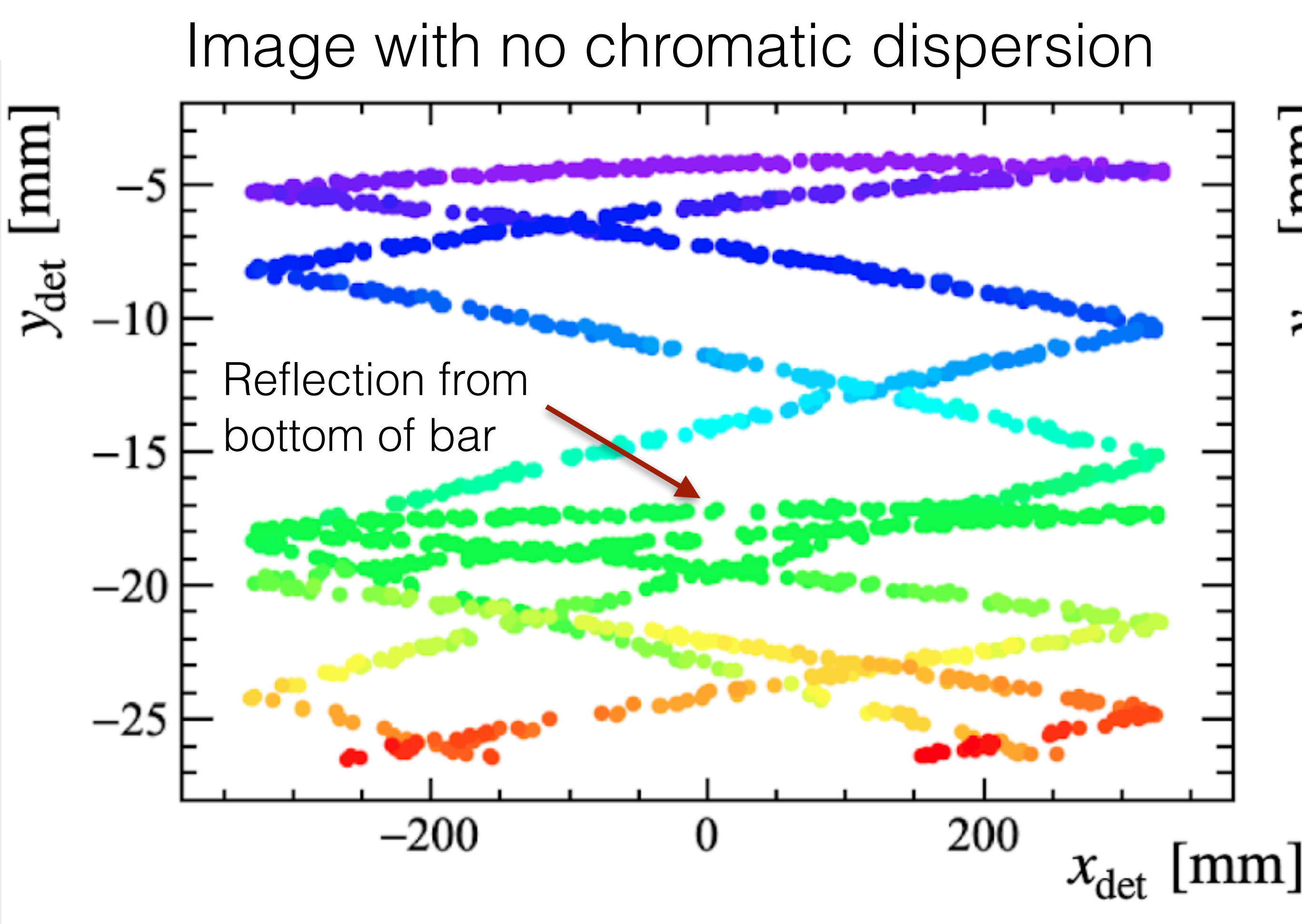


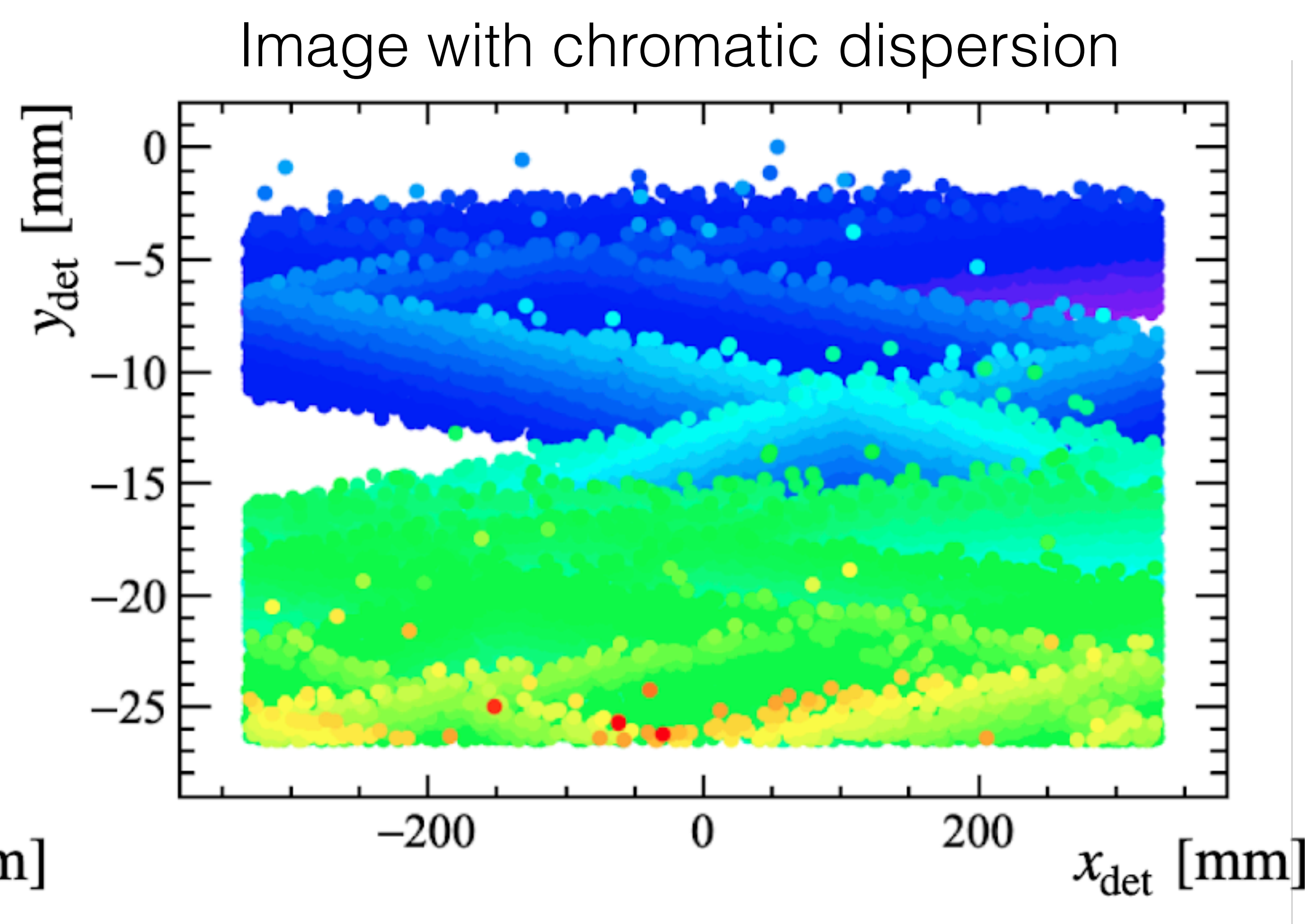


$\sigma = (47.5 \pm 0.7)\,\text{ps}$



TORCH image



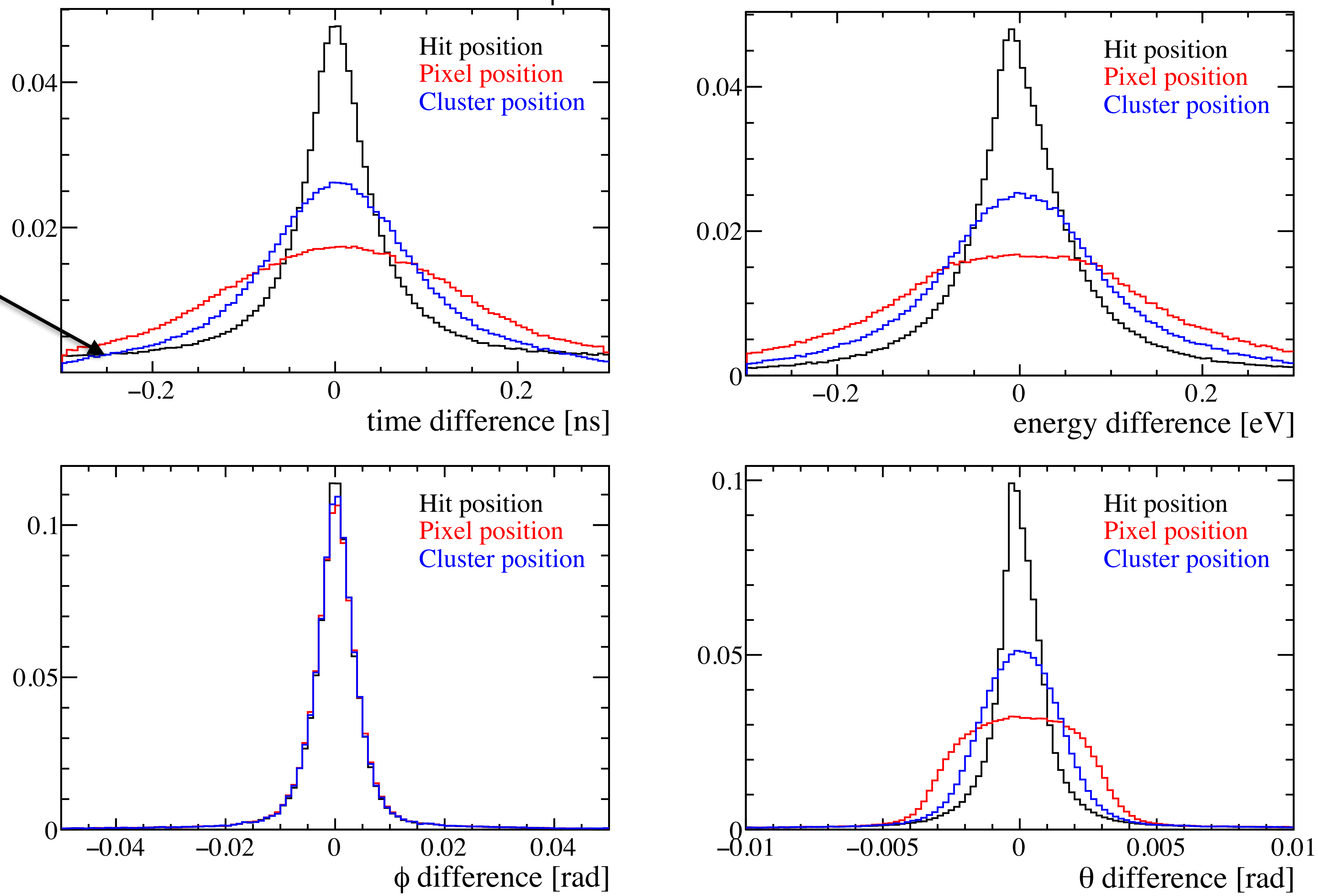


Colour indicates time of arrival (purple earliest/red latest)

Photon reconstruction

Resolution on reconstructed photon

Long tails due to incorrect assumption on the number of reflections



Photon reconstruction

- Linear dependence on path length due to chromatic dispersion and finite pixel size.
- Limited resolution is due to:
  - The unknown emission point and entrance point to the focusing block.
  - Resolution on the track slope and multiple scattering in the radiator.
- The combined 55ps resolution from the MCP-PMT and readout electronics is not included.