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

Marion LEHURAUX, on behalf of the TORCH project

The 6th International Workshop on Future Tau Charm Facilities, 18-21 November 2024, Guangzhou

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LHCb Upgrade II

Physics program & technical challenge

(Non-exhaustive) Physics program

- Constrain CKM model to increase sensitivity to CP-violating new physics
  - e.g. precise ($\mathcal{O}(0.35°)$) measurement of CKM angle γ
- Probing New physics model measuring the CP violating phase ϕ_s ($\mathcal{O}(0.17°)$)
- Exotic hadron spectroscopy
- More in [LHCB-TDR-023] & [CERN-LHCC-2017-003]

Technical challenges

- Running at high luminosity: $\sim 1.5 \times 10^{34}$ cm^{2}s^{-1}
- With high pile up: ~ 42

Can only be achieved with ***improved timing & PID*** *performances*

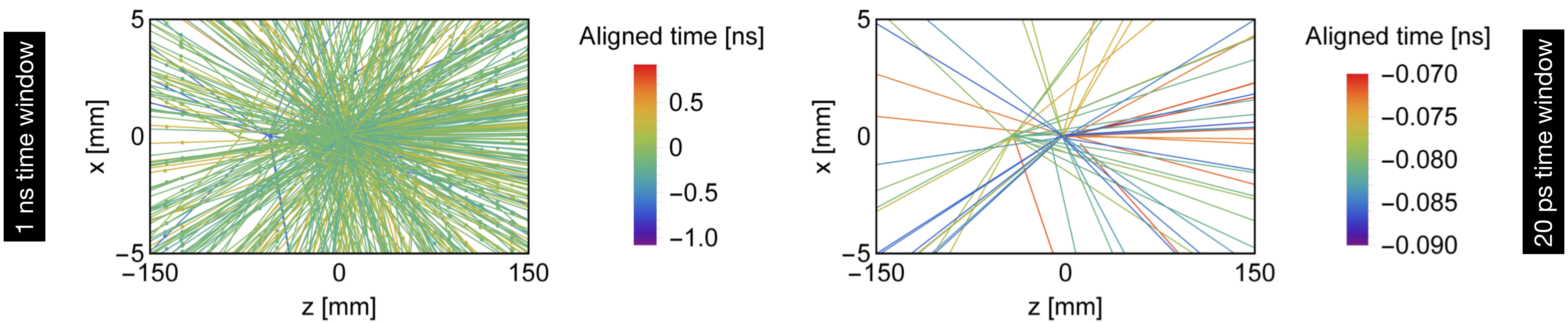


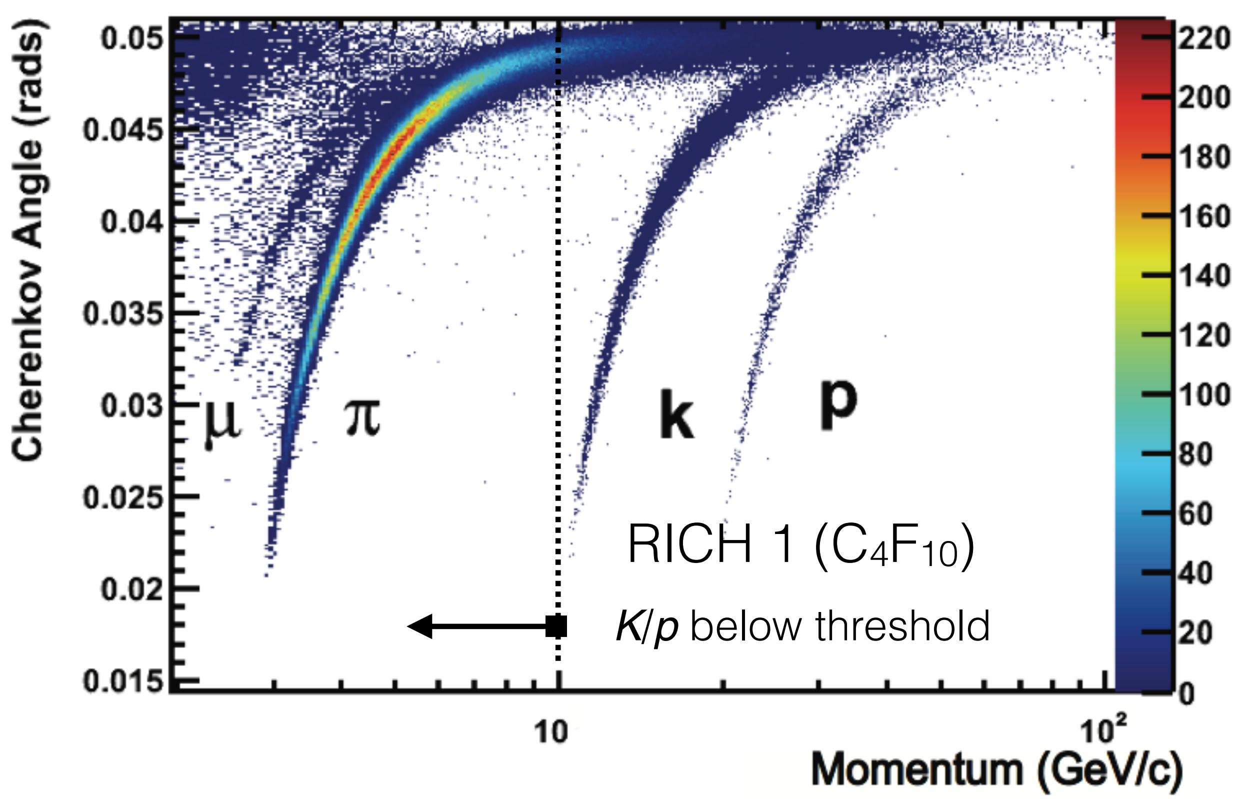
Illustration of the track density inside the VELO generated by 42 collisions spread over a bunch crossing

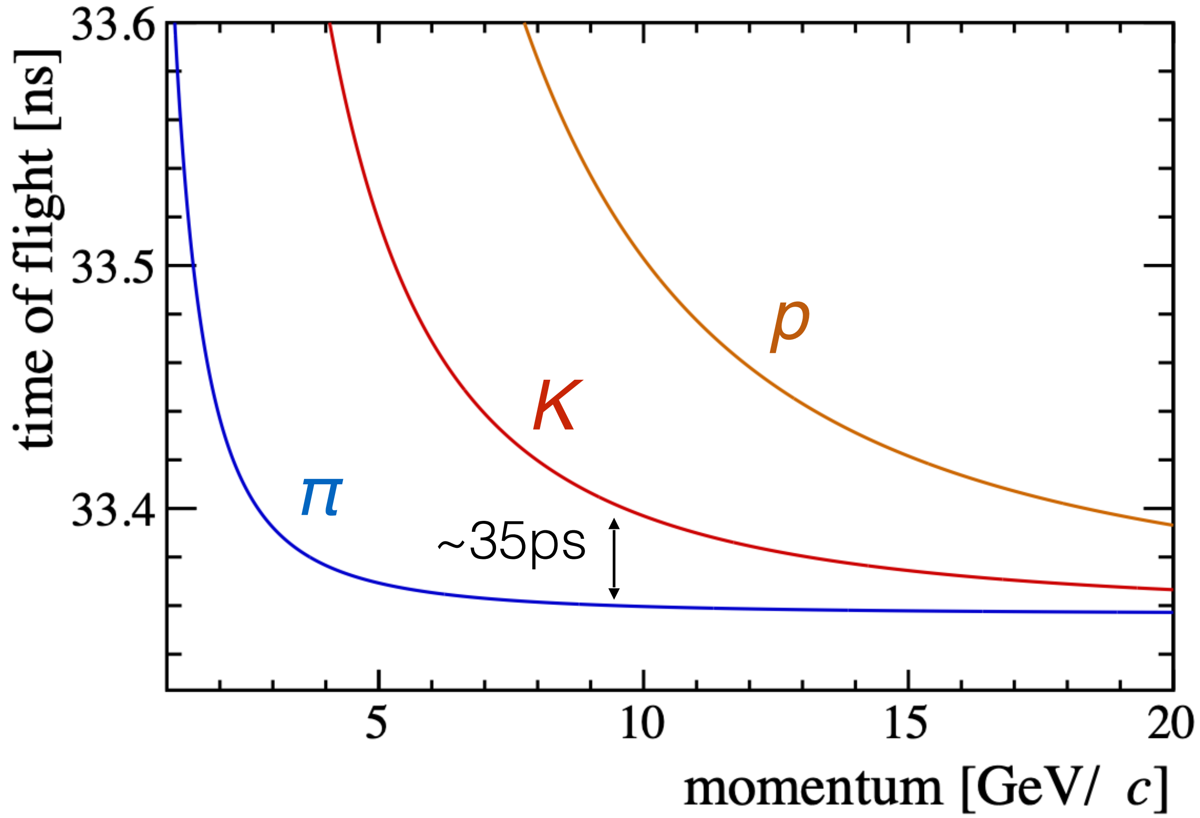
The TORCH detector

Detector concept

- Large area (6 x 5 m²) time of flight detector
- Designed to provide PID in 2-15 GeV/c momentum range
- Aims to supplement PID performance in momentum region where p and K are both below threshold in LHCb RICH detectors
- For *K/π* separation over 10m flight distance, aims for a 15 ps time resolution per track (i.e. ~ 70 ps time resolution per photon with 30 reconstructed photons)

LHCb [EPJC 73 (2013) 2431]



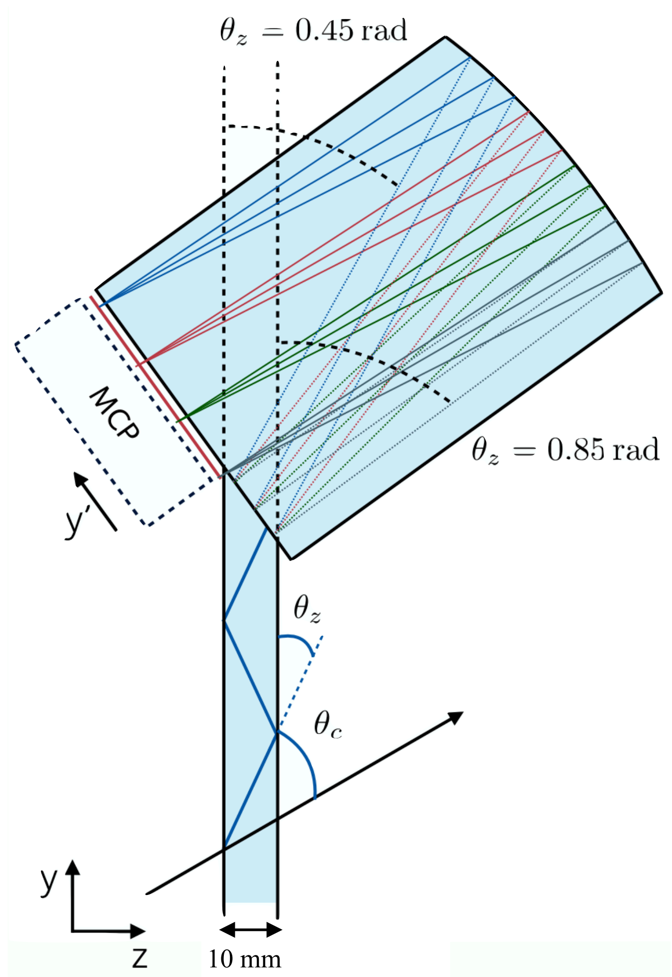


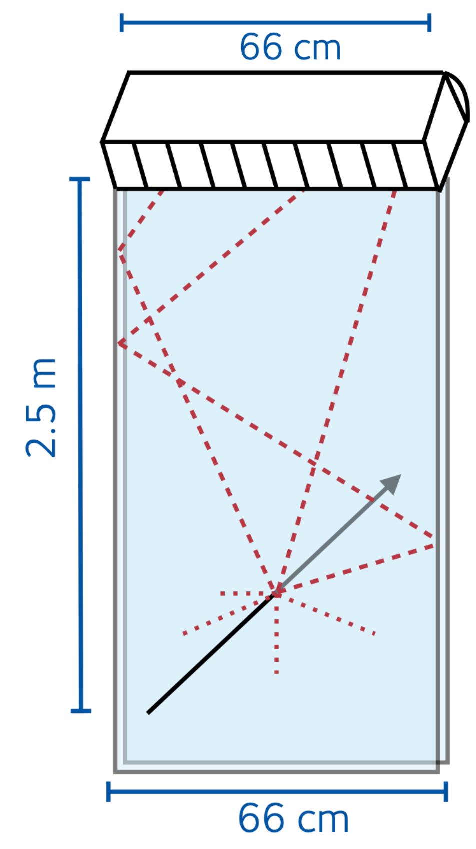
The TORCH detector

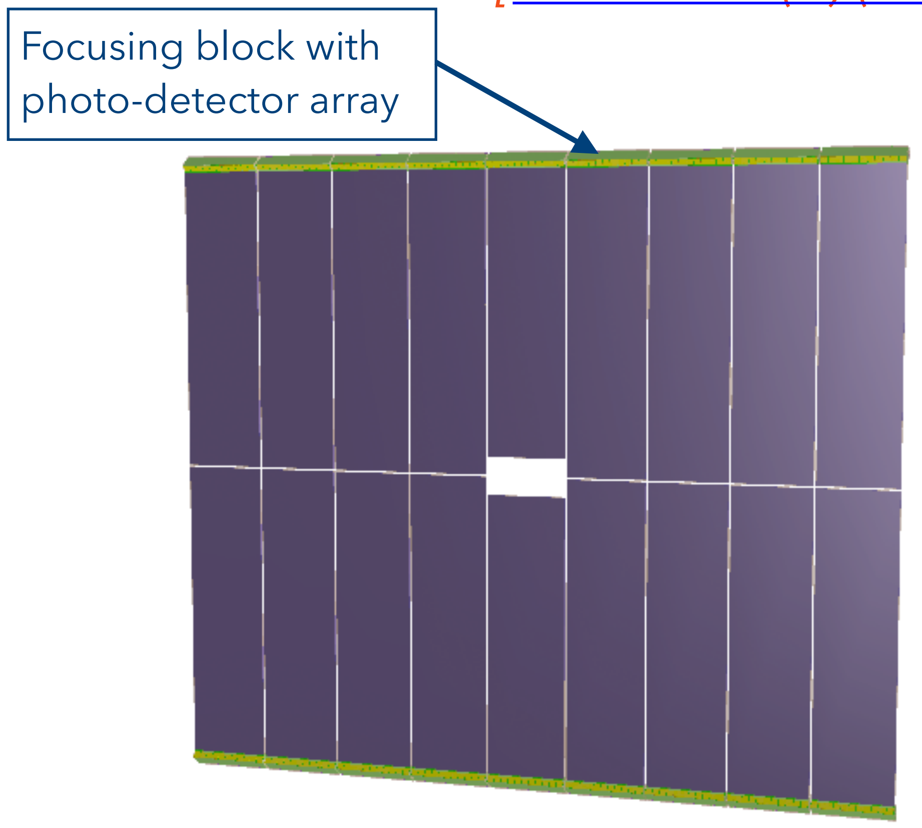
Detector design

- Large area to cover the full LHCb acceptance: 6x5 m^2 made out of 18 modules,
- Each module has 2500 x 66 x 1 cm^3 radiator
- Exploits prompt production of Cherenkov light in an array of fused-silica bars to provide timing
- Total internal reflection from quartz surfaces propagates the photons to the detector plane
- Cylindrical focussing block focusses the image onto a detector plane with highly segmented photo-detectors

Mode details on the TORCH design [NIM A 639 (1) (2011) 173]





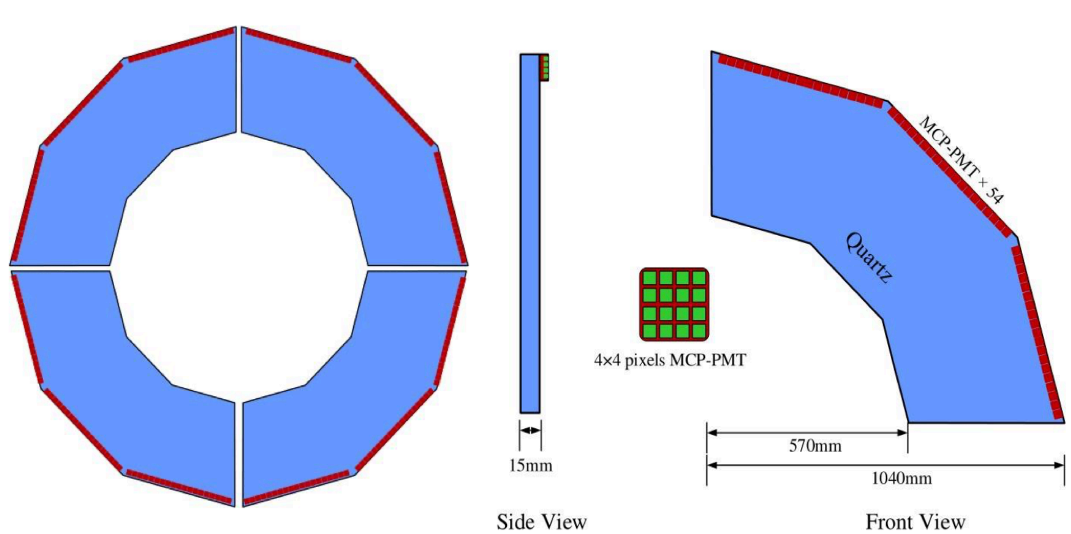


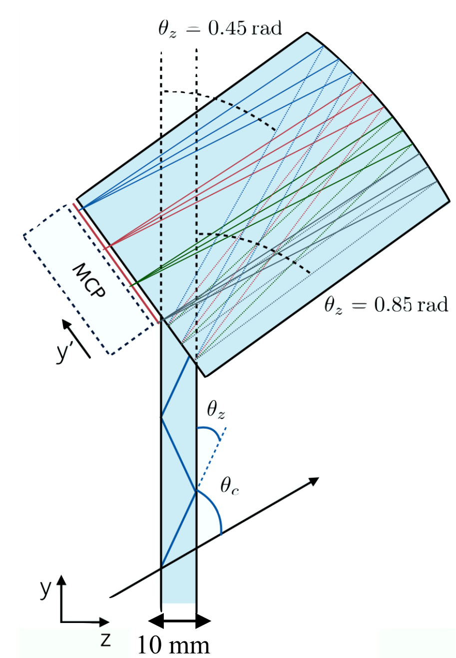
The TORCH detector

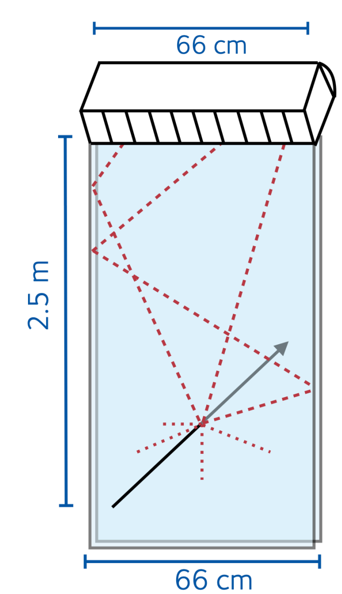
Comparison with STCF DTOF detector

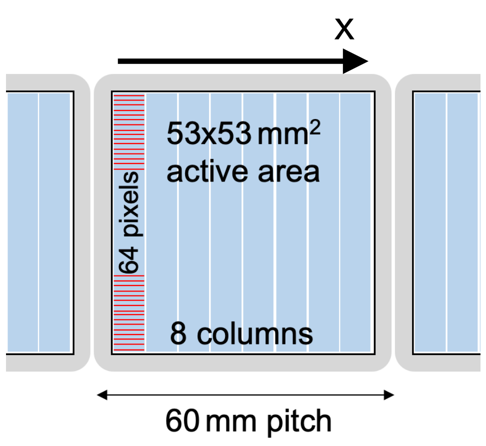
Similar concept, different detectors

- DIRC-like TOF detector concept
- High counting rate capabilities
- High radiation tolerance
- **Time resolution requirements:** $\sigma_{tot}^{\text{STCF}}$ < 50 ps while $\sigma_{tot}^{\text{TORCH}}$ < 15 / 70 ps *(per track / per photon)*
- **Momentum range:** < 2 GeV/*c* for STCF DTOF against [2-15] GeV/*c* for TORCH
- Different angles distributions
- **Radiator thickness:** 5 mm for STCF DTOF against 10 mm for TORCH
- **Number of readout channels:** 672 per sector x 4 sectors for STCF DTOF against 225k for TORCH
- **Overall dimensions:** 1.080 m diameter ring for STCF DTOF against 5 x 6 m^2 rectangle for TORCH
- **MCP dimensions & segmentation:** 23 x 23 mm^2 sensitive area in 4x4 pixels for STCF DTOF against 53 x 53 mm^2 sensitive area in 8x64* pixels for TORCH *(*varying granularity per module according to expected occupancy)*





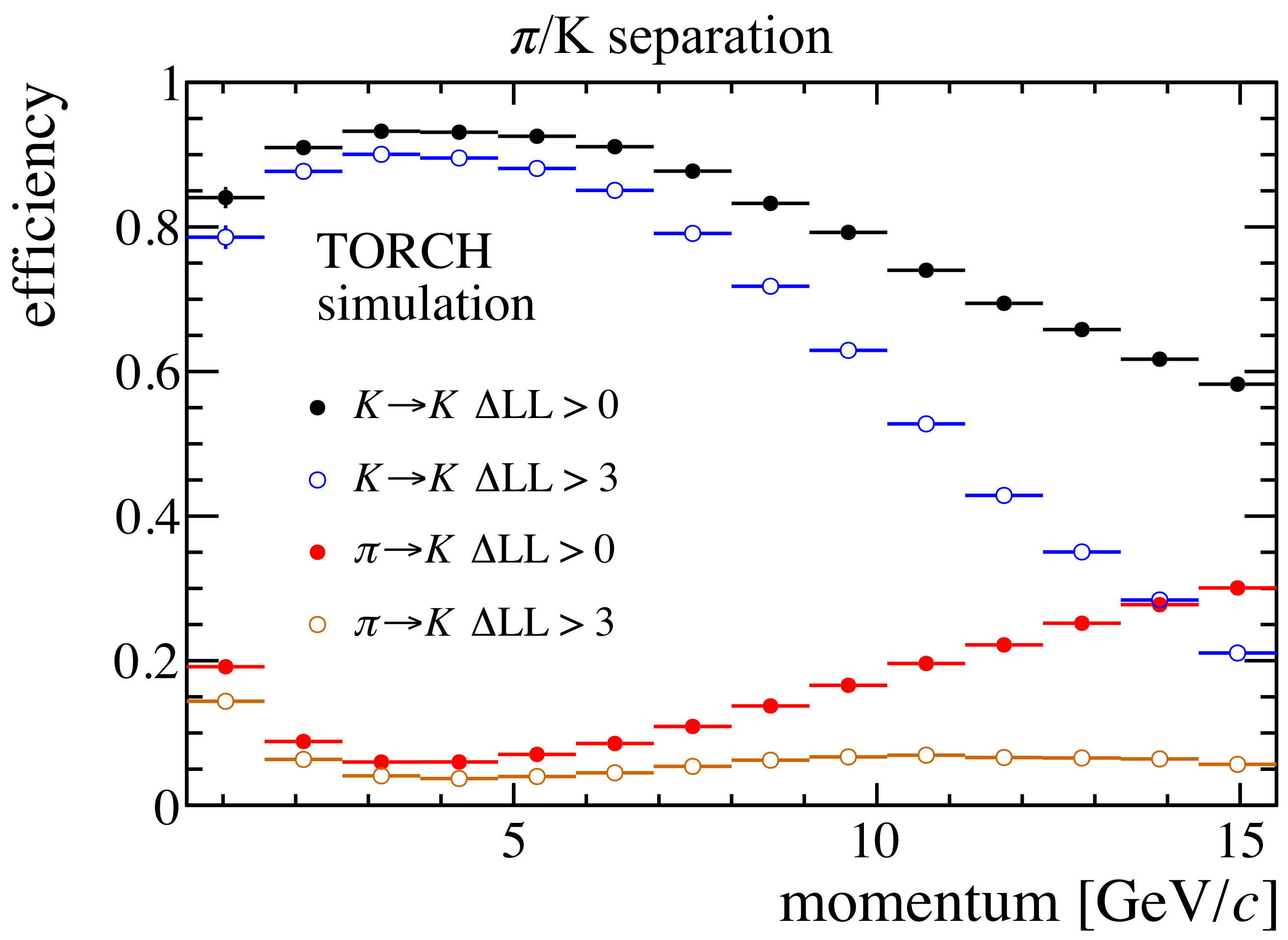


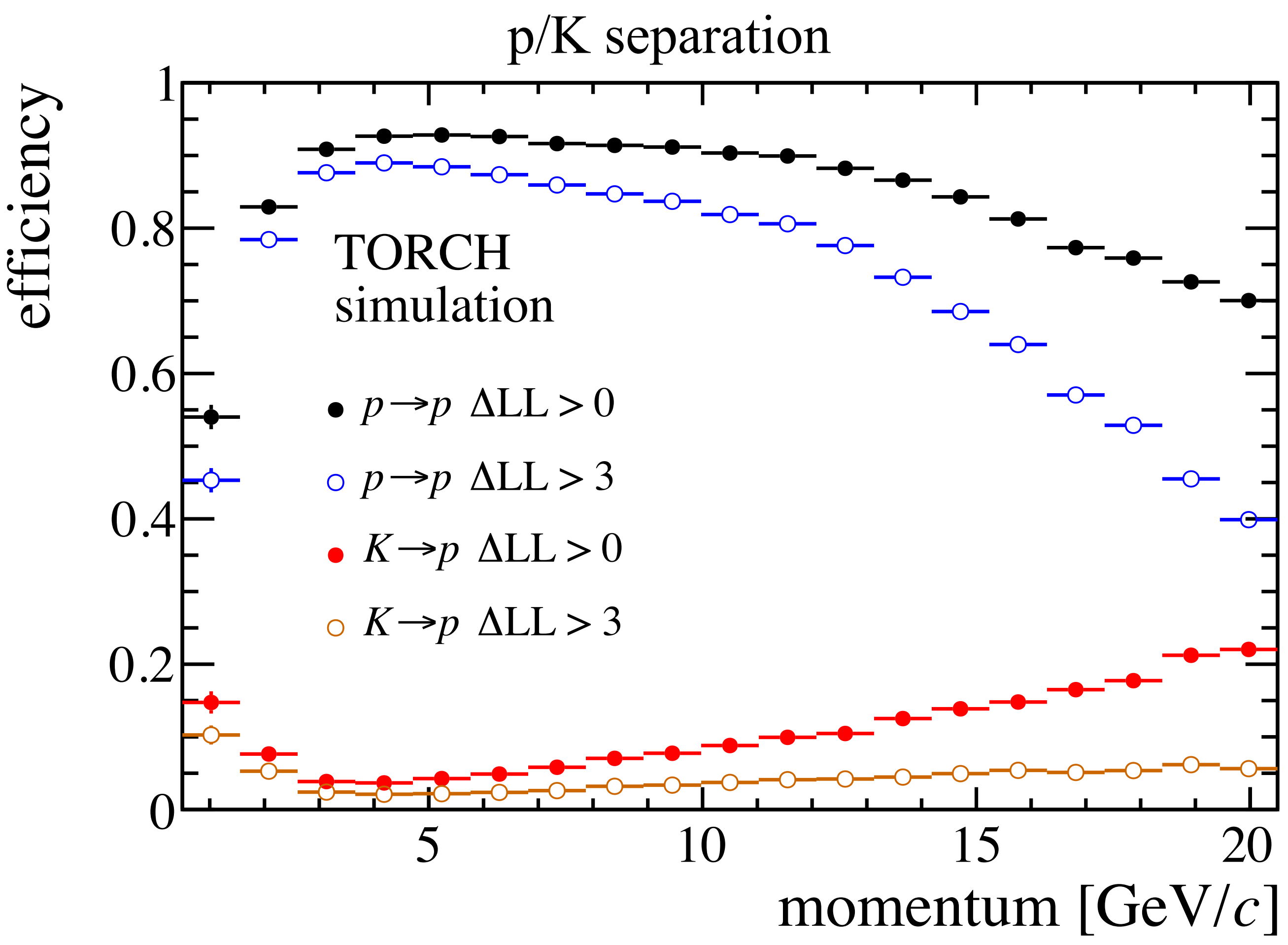


Expected PID performances

Impact on physics measurements

- Provides π/K (p/K) separation in the 2-10 (2-15) GeV/c momentum range



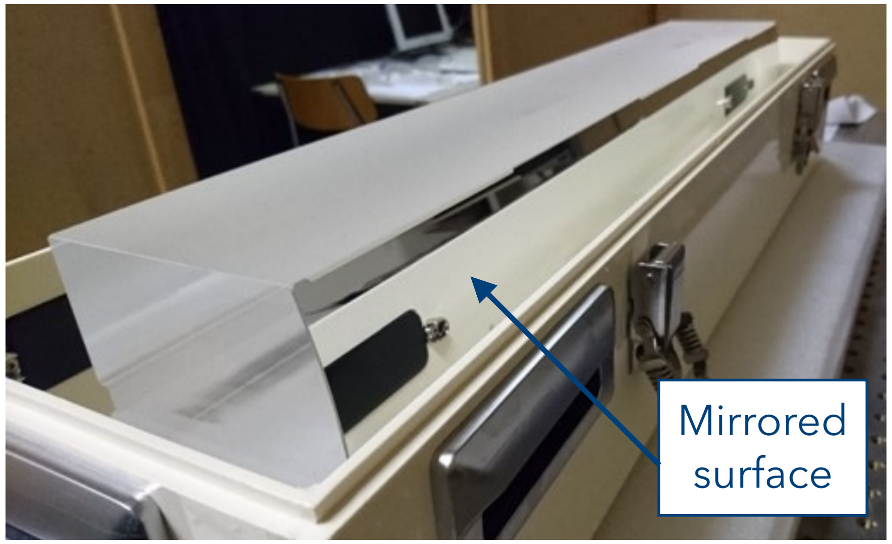


- Improves phase-space coverage of many analysis and improves effective flavour tagging power [LHCb-PUB-2020-006]
- Will complement RICH2 in providing timing for downstream tracks
  - e.g. reduce combinatorial when reconstructing K_S or Λ

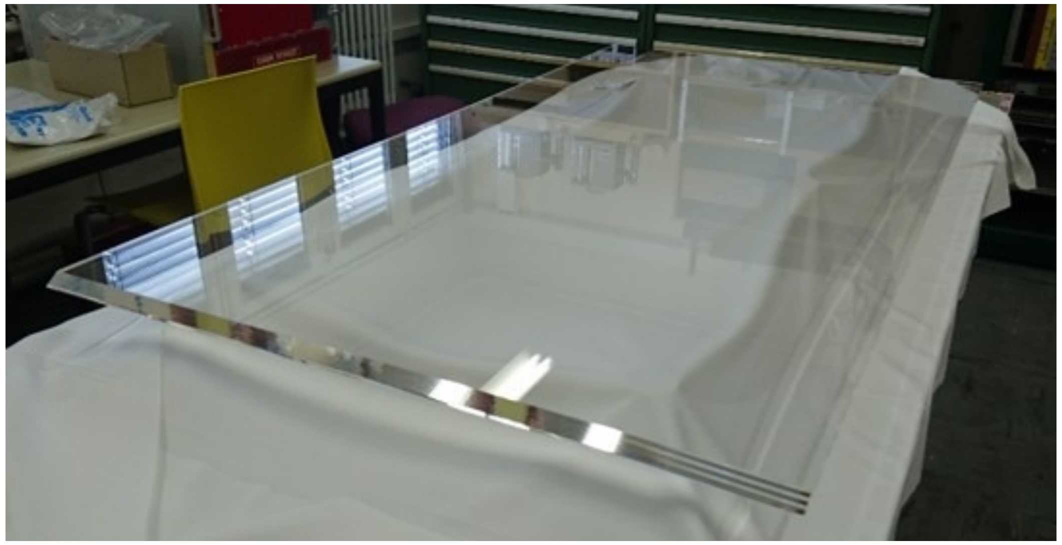
Fused-silica pieces

- Optics formed from multiple pieces of synthetic fused silica
- Requires high-quality surface on front and rear faces
  - Flatness variations ≲ 3 μm
  - Surface roughness ≲ 5 Å
- Two plates of $66 \times 62.5 \times 1 cm^3$ radiator are glued together to complete a full-sized module

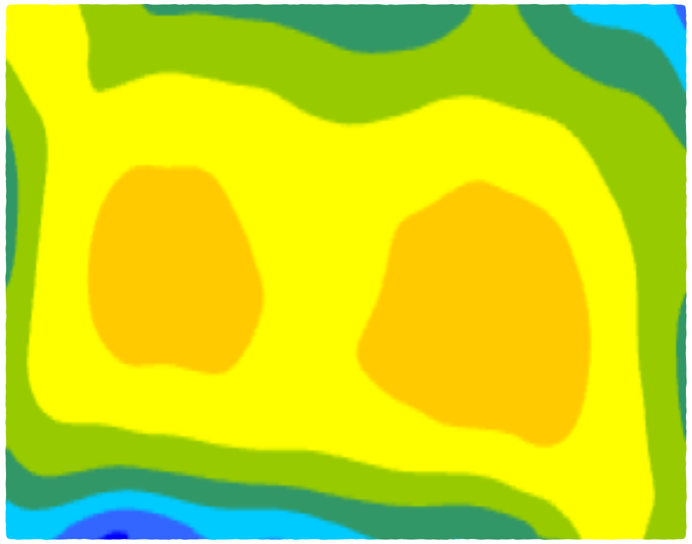
Produced by Nikon glass



Focusing block



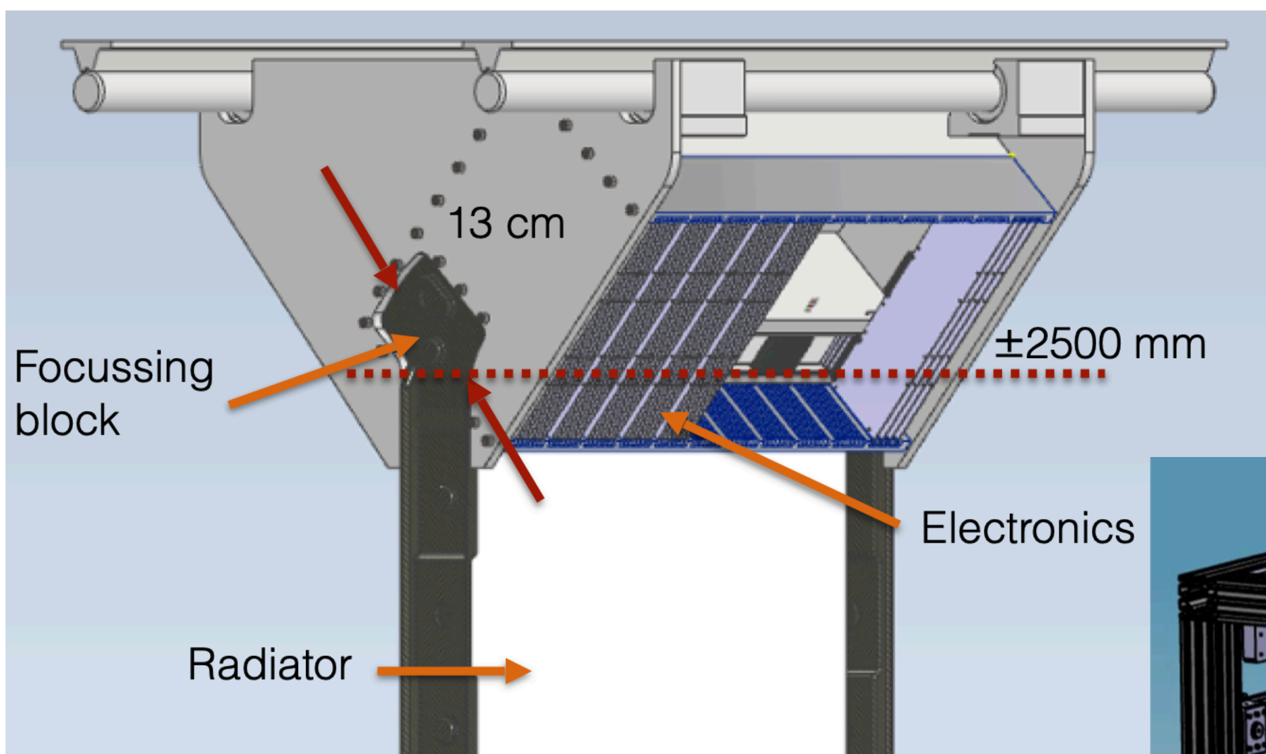
Fused silica bars used as Cherenkov radiator

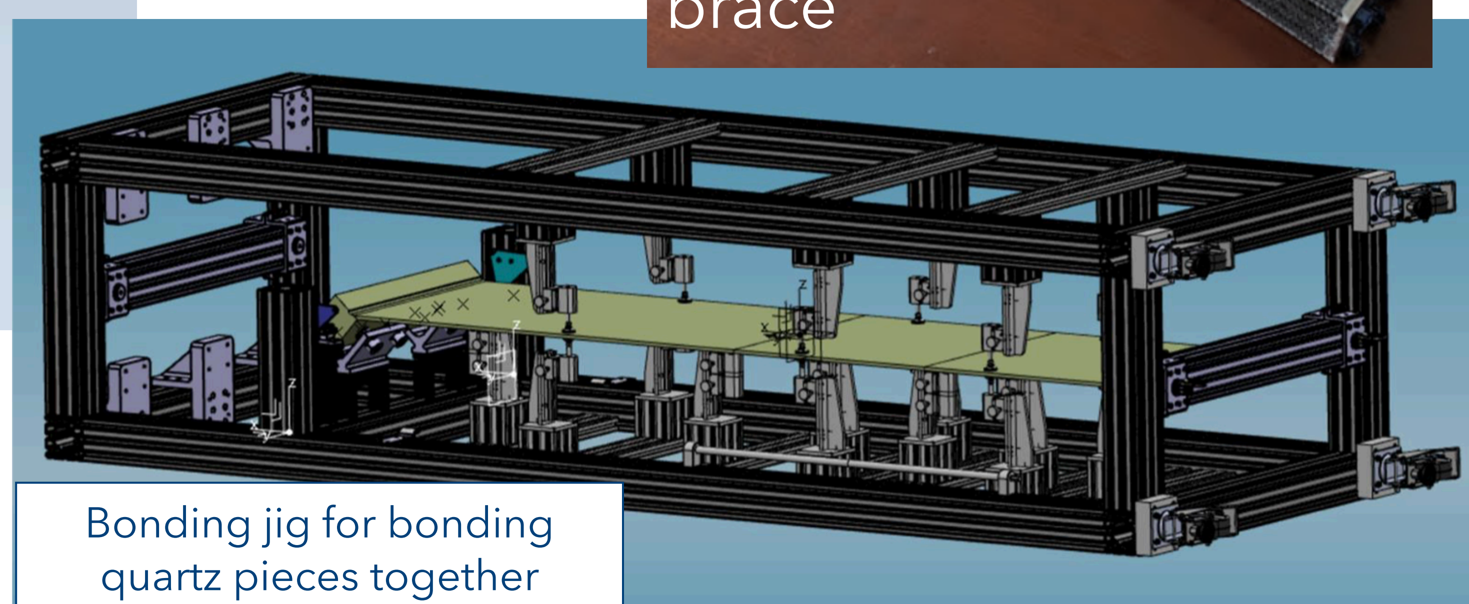


Measured flatness variations in 1 μm contours

Mechanical support

- Requires lightweight structure to minimise material inside acceptance → *carbon fibre*
- Prototype of the final support structure that accommodates existing photo-detectors and readout electronics has been designed
- Development of exoskeleton (self-standing structure to host single module) to take single full-size module to beam test also being produced



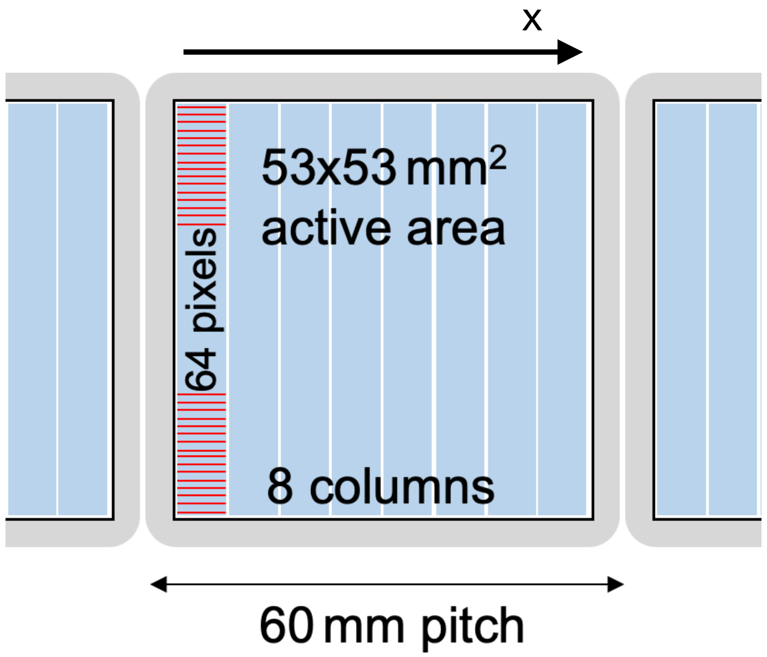


Bonding jig for bonding quartz pieces together

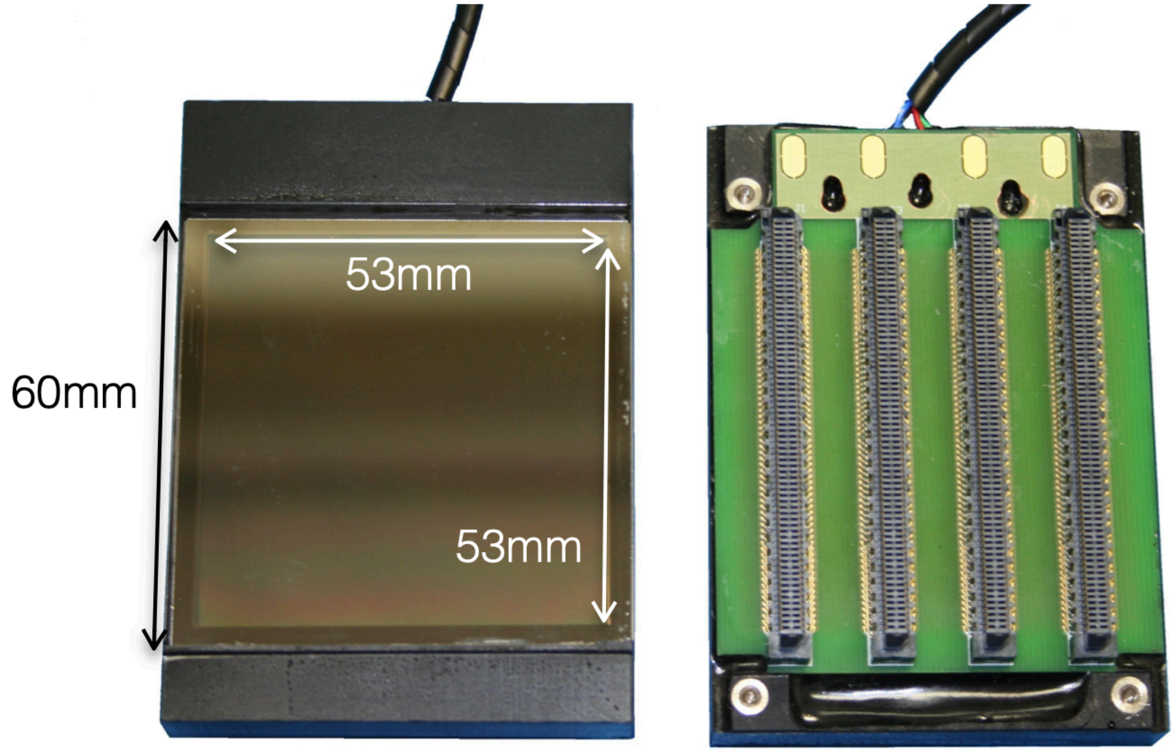
Photo-detectors

Current prototype

- Custom TORCH PMT: 53 x 53 mm² MCP-PMTs with 64 x 64 pads readout
  - Produced by Photek
  - Pixels grouped by 8 along x for effective anode segmentation of 8 x 64
- Excellent intrinsic time resolution < 30 ps
- Readout connectors are mounted on an external PCB and connected via anisotropic conductive film
- MCP is ALD coated to improve lifetime to ~ 5C/cm²



Not suitable for HL-LHC environment at this stage



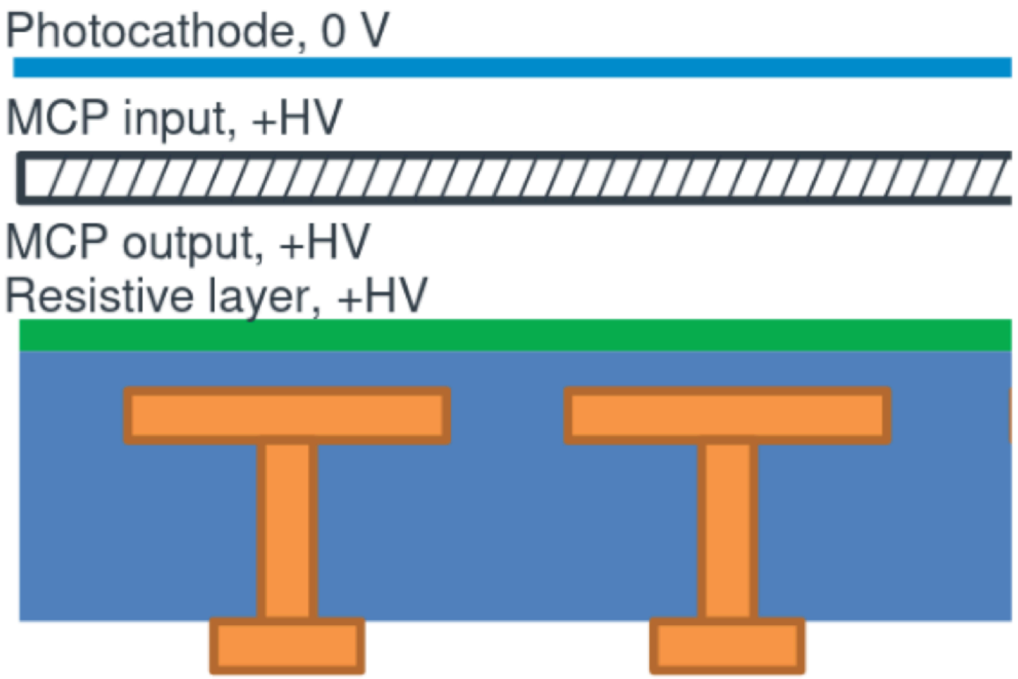
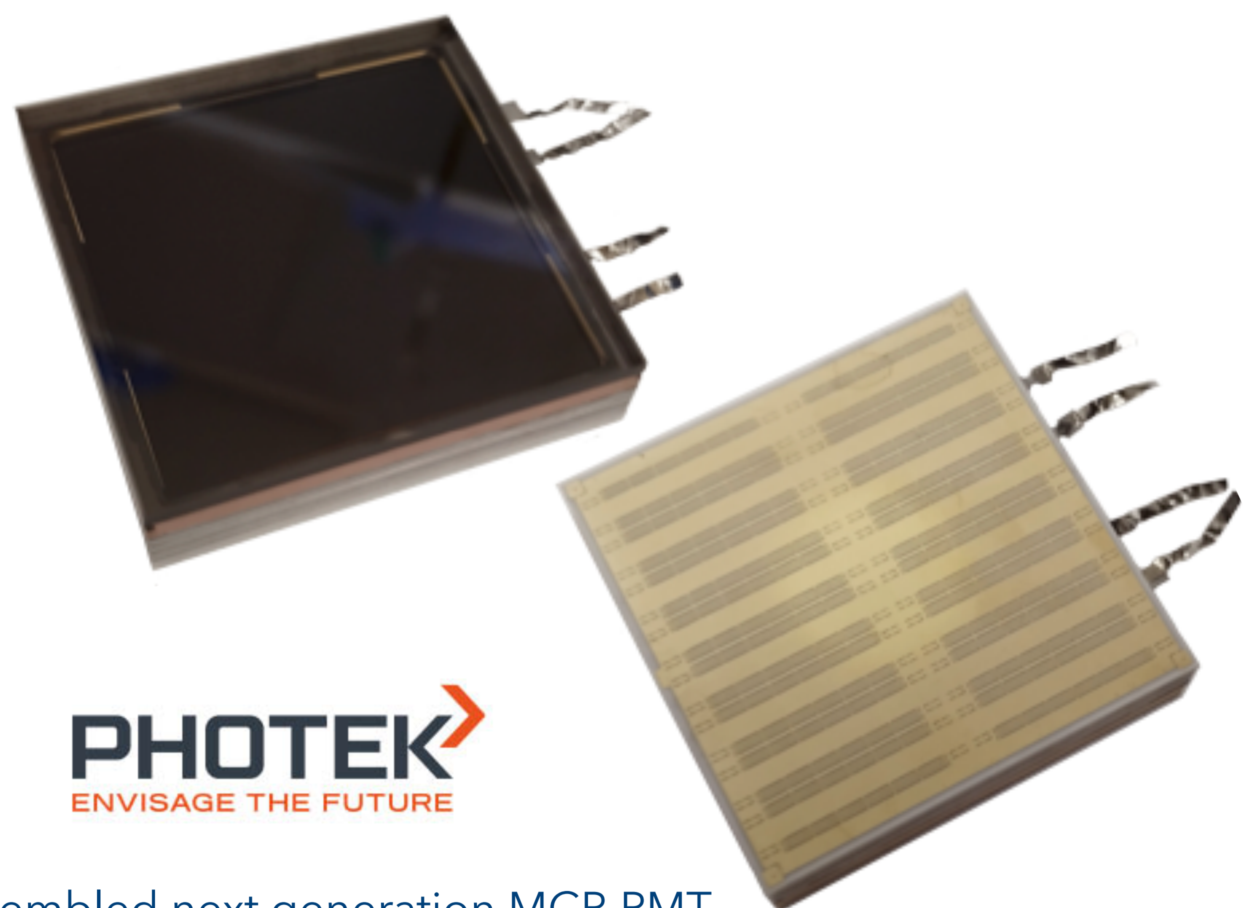


Photo-detectors

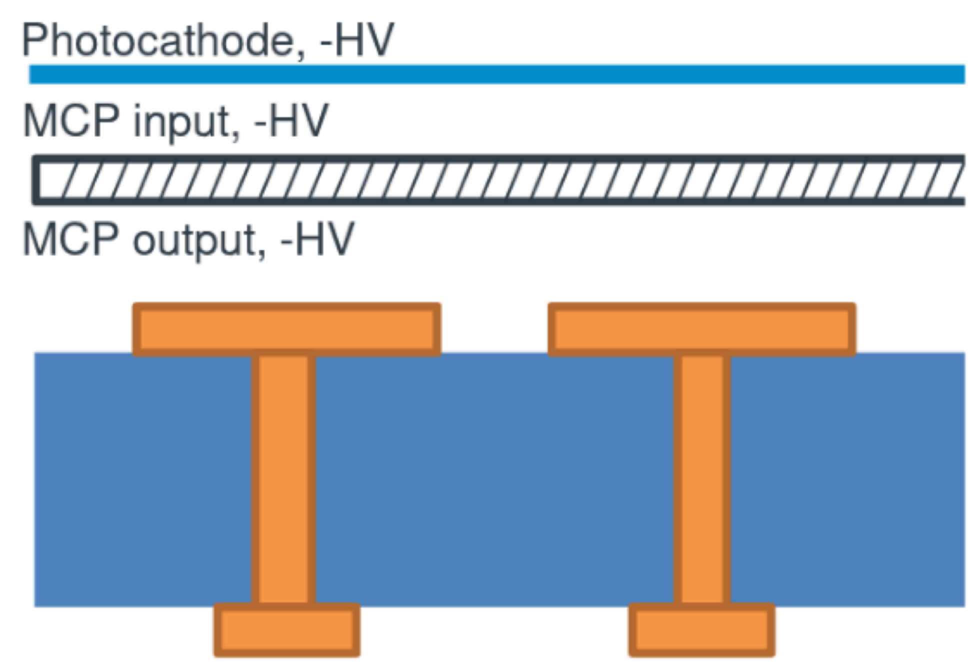
Next generation

- R&D efforts ongoing to find suitable solutions:
  - 16 x 96 pixels MCP directly coupled to reduce charge sharing & per-pixel occupancy
  - Efforts in the context of DRD4 to improve rate capability & lifetime
- Investigating other options such as SiPMs
  - Fill requirement of pixelised devices with time resolution < 50 ps ✓
  - Challenge to operate in radiation environment

    → would require cooling to keep dark count rate under control

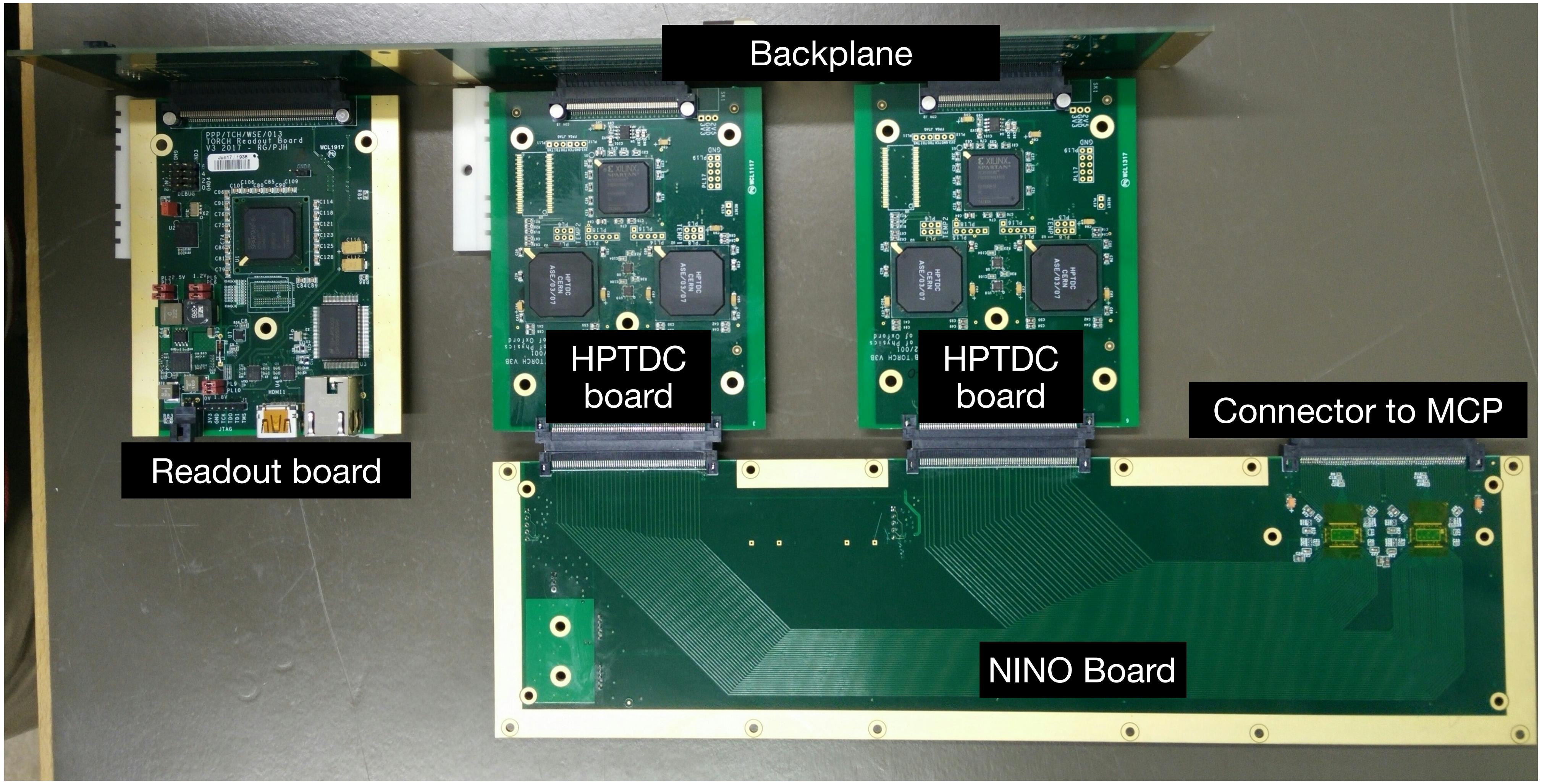


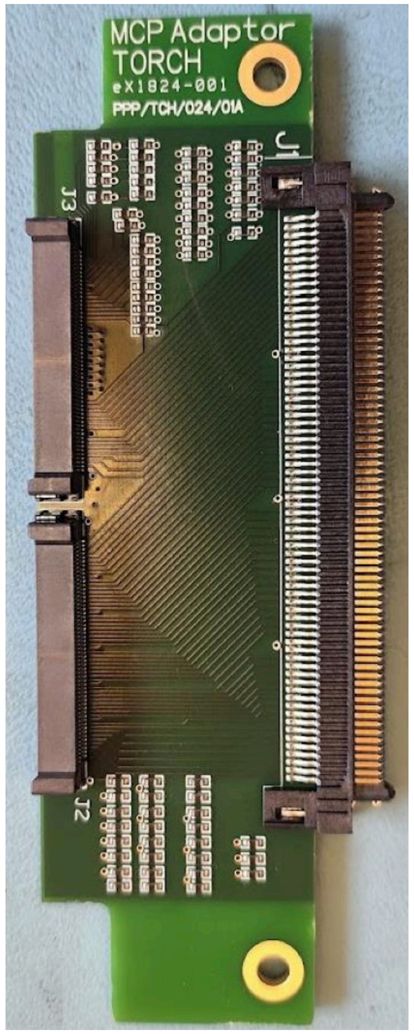
Assembled next generation MCP-PMT before connector laser jet soldering



Readout electronics

- Current electronics based on NINO & HPTDC (with 100 ps binning) ASICs
- Adaptator boards are being developed to read the new DC-coupled MCPs with existing readout
- For Upgrade II the plan is to use the FastRICH ASIC (25 ps binning)
  - Developed by CERN-ESE and University of Barcelona
  - Constant Fraction Discriminator → no need for time walk corrections & could avoid sending time over threshold information

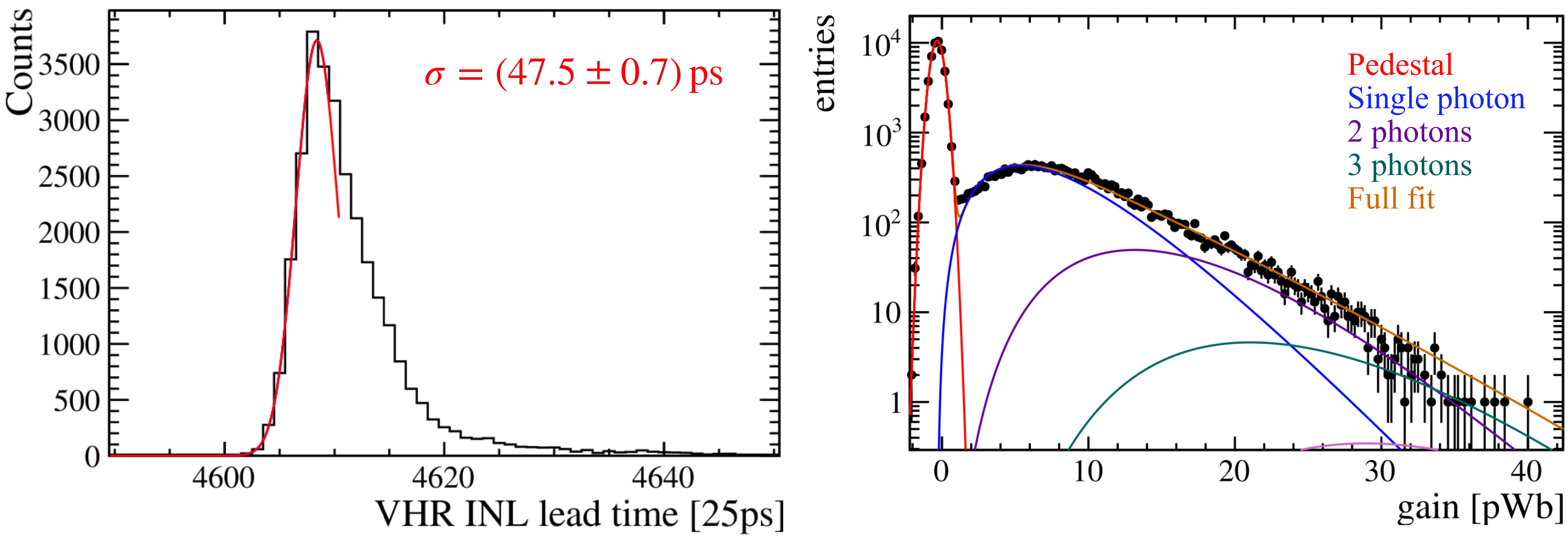




Detector performances

Some results

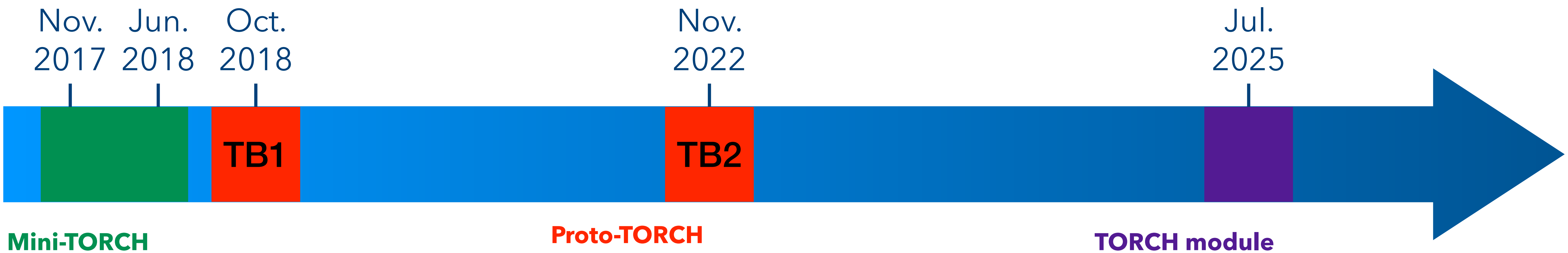
- MCP-PMT & readout electronics studied extensively in laboratory measurements with pulsed 405 nm picosecond LASER *(attenuated to reach single photon mode)*
  - MCP operated at 10^6 gain
  - Intrinsic time resolution of MCP-PMT + electronics is around 50 ps (after Integral Non-Linearity (INL) corrections) [NIMA 1038 (2022) 166950]



- Dedicated calibration system developed to improve the INL and charge-to-width calibration
  - Injection of known charge directly into electronics

Detector performances

Beam tests



Mini-TORCH

- Small scale module (120 x 350 x 10 mm^3)

Proto-TORCH

- Half-length module (660 x 1250 x 10 mm^3)
- TB1: 2 MCPs
- TB2: 6 MCPs

TORCH module

- Full size module (660 x 2500 x 10 mm^3)

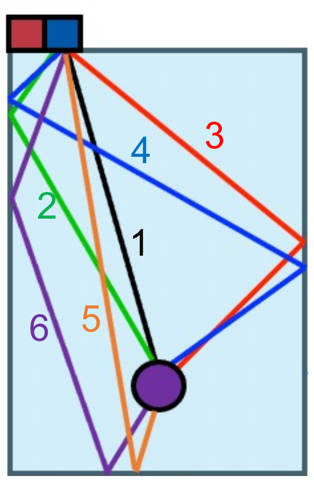

Setup at CERN T9 area for 2022 test beam

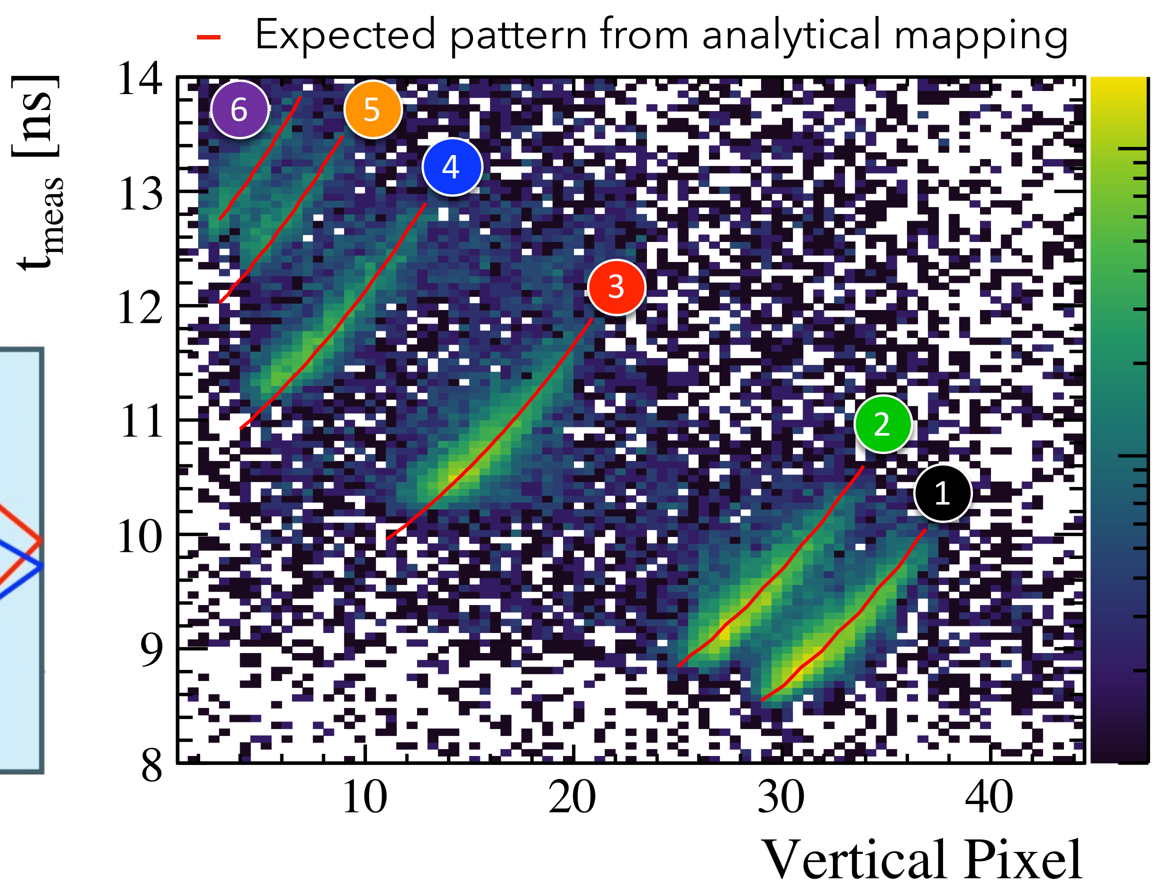

Proto-TORCH

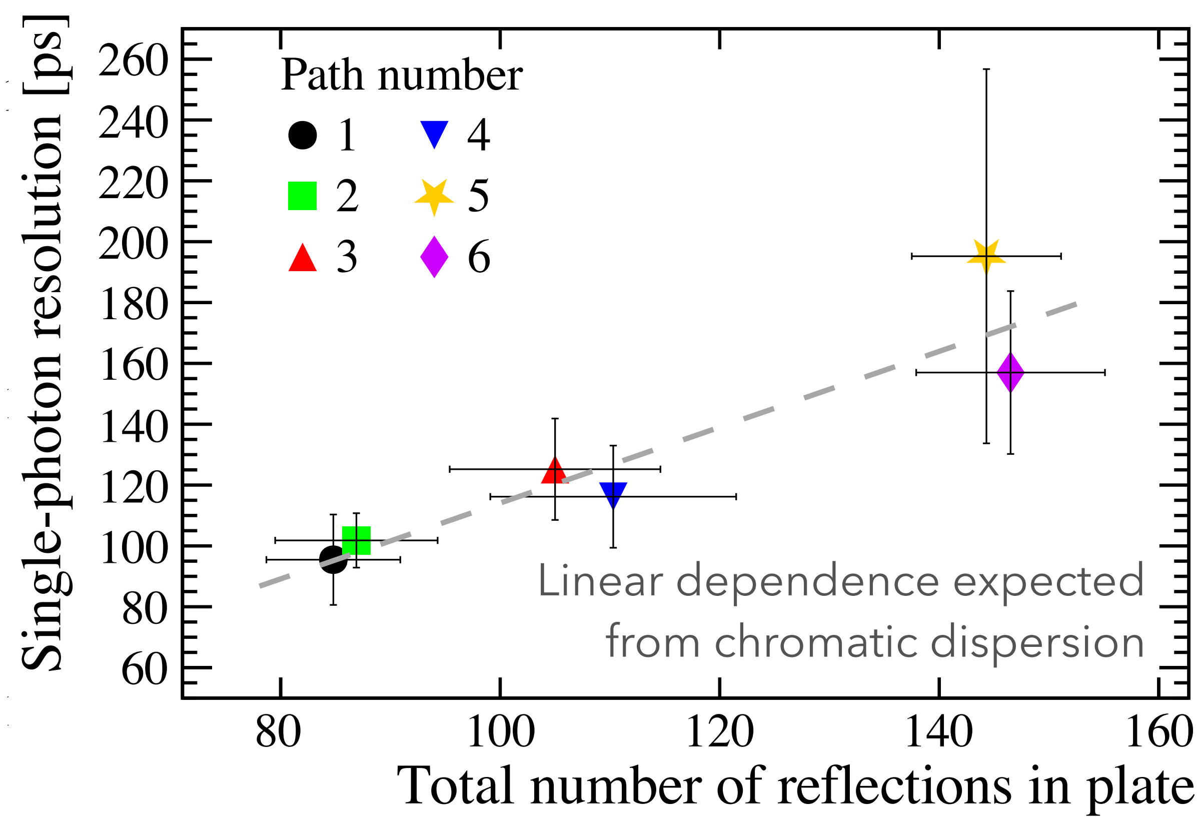
Detector performances

Results from 2018 beam test

- Observed pattern is consistent with GEANT4 simulation of the prototype
- Time resolutions close to the needs of TORCH
  - Expect to be improved with better electronics calibration
- Photon yield in data about 82-85% of expectations
  - Work ongoing with 2022 beam test data to further improve understanding
- More details in paper [NIMA 1050 (2023) 168181]



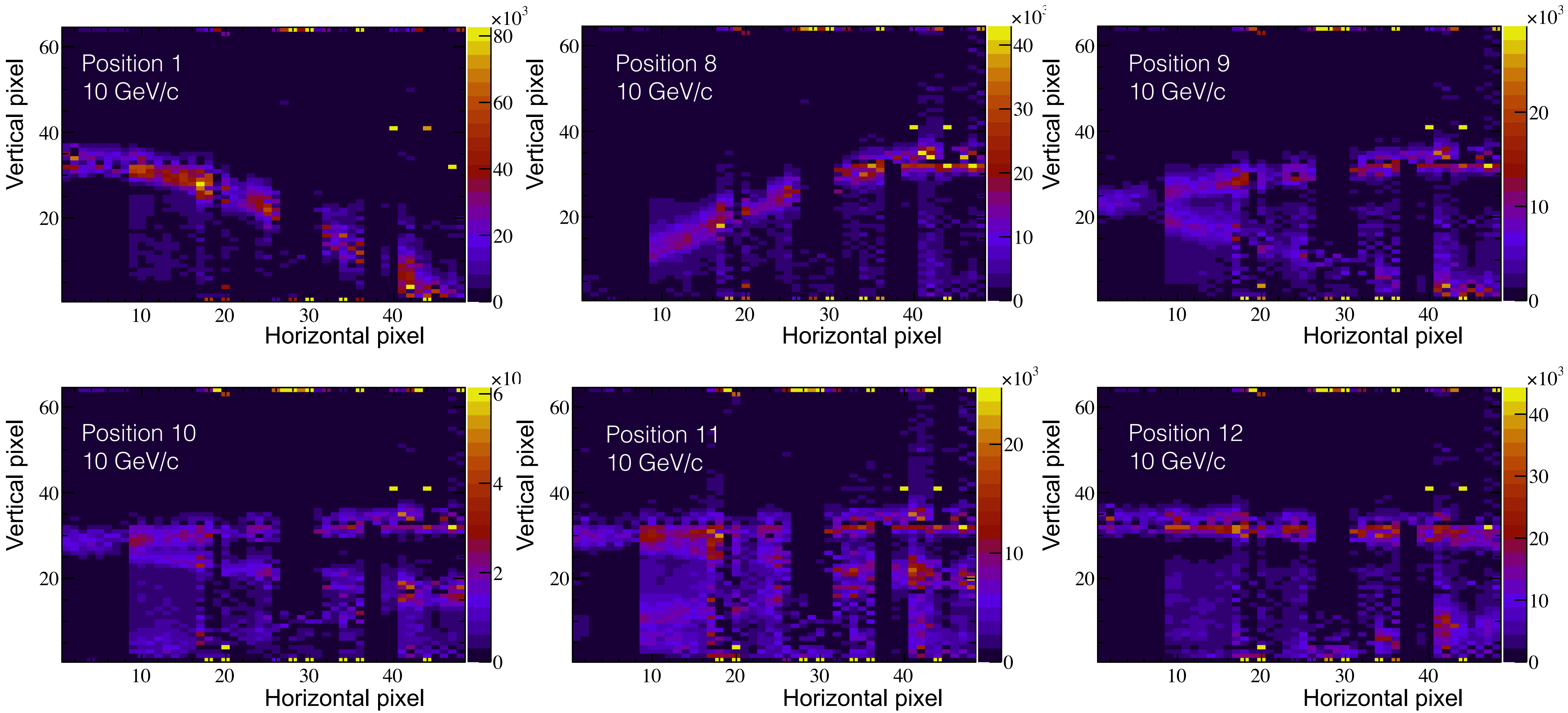




Detector performances

First look at 2022 test beam data

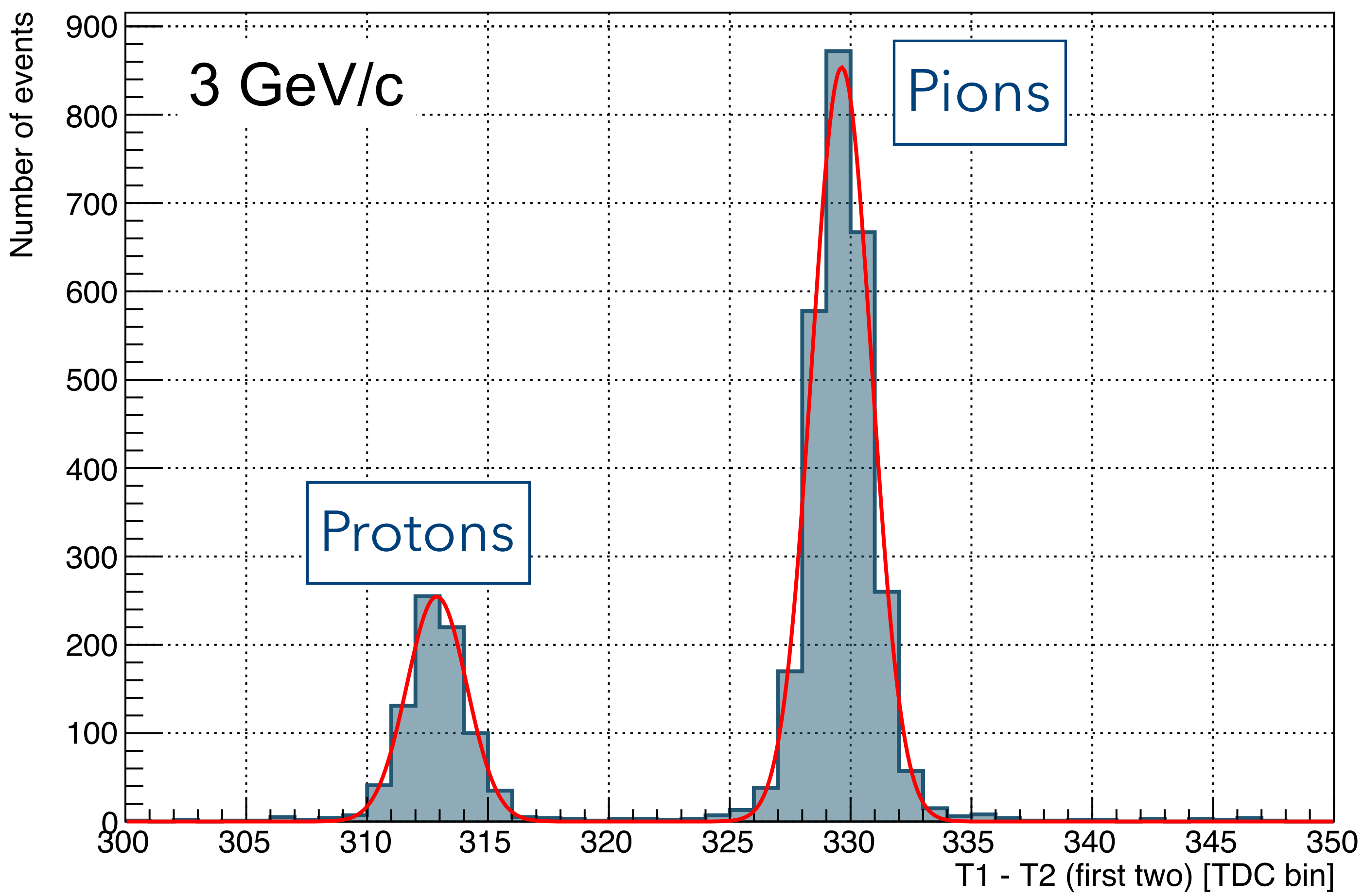
- 6 MCP-PMTs instrumented
- Data taken at multiple positions of the beam on the quartz radiator bar and for different beam momenta (3, 5, 8 and 10 GeV/c)

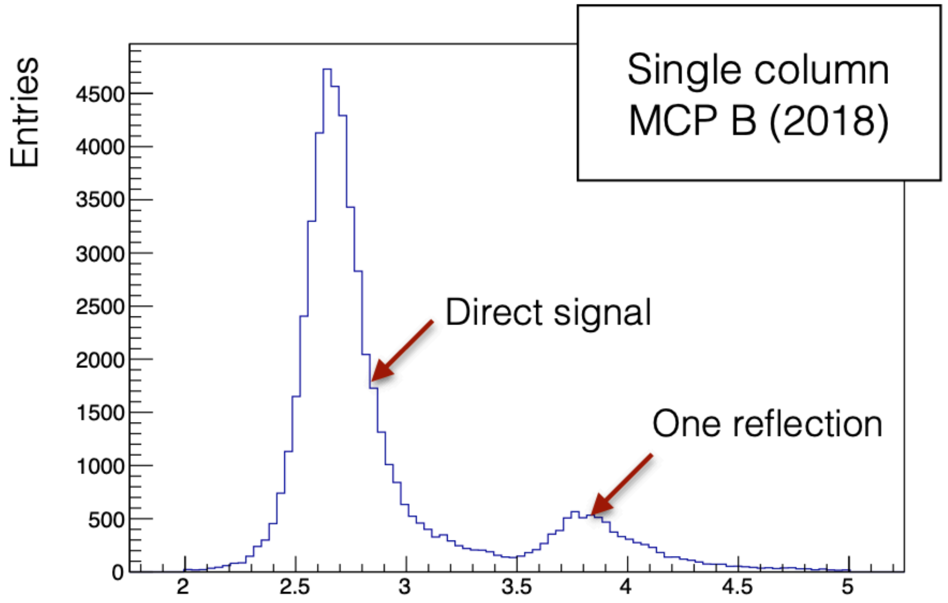


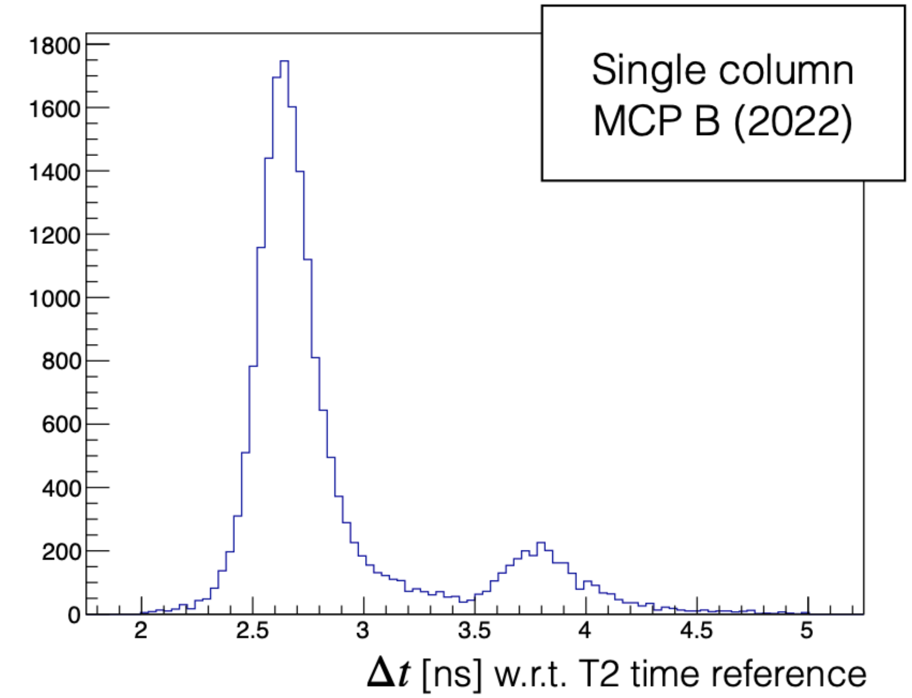
Detector performances

First look at 2022 test beam data

- Ongoing work
- Time difference between T1 and T2 consistent with time of flight difference
- Comparisons indicate a similar time resolution is seen in 2018 and 2022







Summary & next steps

- TORCH is a large area time-of-flight detector designed to improve LHCb PID performances for particles with $2 < p < 15$ GeV/c
- Developed for LHCb Upgrade II high luminosity running conditions & installation during LS4 (~2034)
- Significant progress has been made over the past few years :
  - Beam tests indicate that the desired time resolution can be achieved
  - Light-weight support mechanics designed and under construction
  - Aim for beam test in July 2025 with full scale prototype and new mechanics
- R&D is ongoing as part of DRD4 to improve the relevant aspects needed for TORCH (lifetime)
- New collaborators welcome !

BackUp slides

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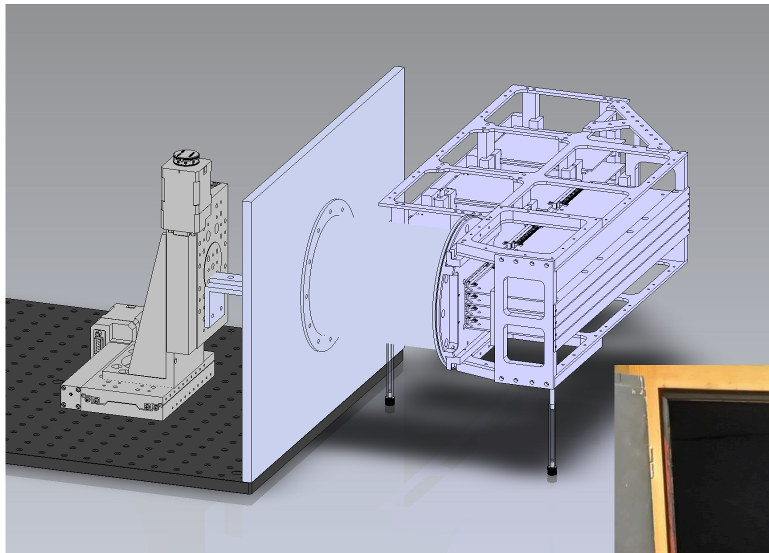
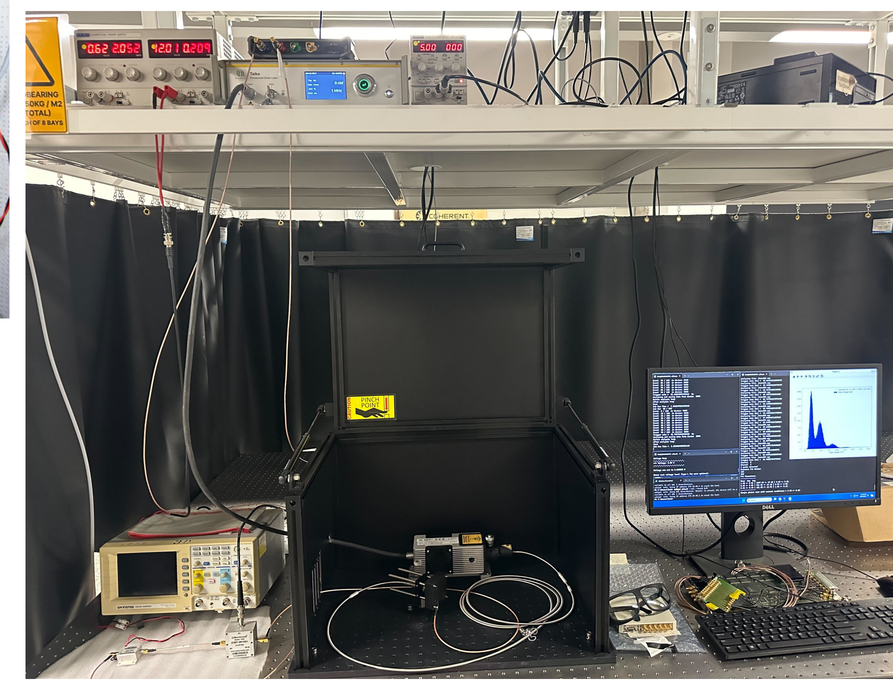
Detector performances

Characterisation of photo-detectors



@Warwick

@CERN

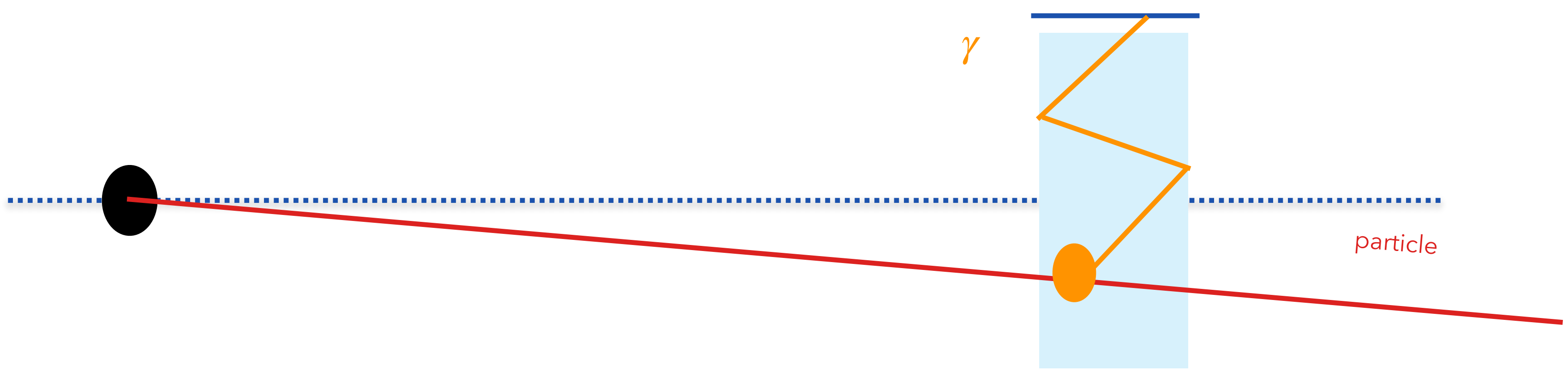


@Monash

- Multiple test benches are being developed to characterise MCP-PMTs & SiPMs
- Measurements of gain, quantum efficiency, lifetime

TORCH Reconstruction strategy

Approach inspired by RICH global PID algorithm



- **Ideally:** compare pattern on MCP to π/K/p hypothesis 'template'
  - Will be investigated in the future
- **In practice:** easier to compare information at emission point

For each mass hypothesis:

1. Each photon detected on the MCP is analytically back-propagated to its emission point and associated to a track
2. A log-likelihood is constructed for each given track/hypothesis combination

$$\log L = \sum_{\gamma} \log \left[\sum_{\text{track } j,\, j \neq t} \frac{N_j}{N_{\text{tot}}} P_j(\vec{x}_\gamma'' \mid h_j^{\text{best}}) + \frac{N_t}{N_{\text{tot}}} P_t(\vec{x}_\gamma'' \mid h_t) + \frac{N_{\text{bkg}}}{N_{\text{tot}}} P_{\text{bkg}}(\vec{x}_\gamma'') \right]$$

PDF for the best hypothesis assignment to each other tracks of the event

PDF for the considered track

PDF for the background contribution *(assumed flat)*

TORCH Reconstruction algorithm

Validation

Simulation pattern generated by forward-mapping ~ 10^6 photons for one track