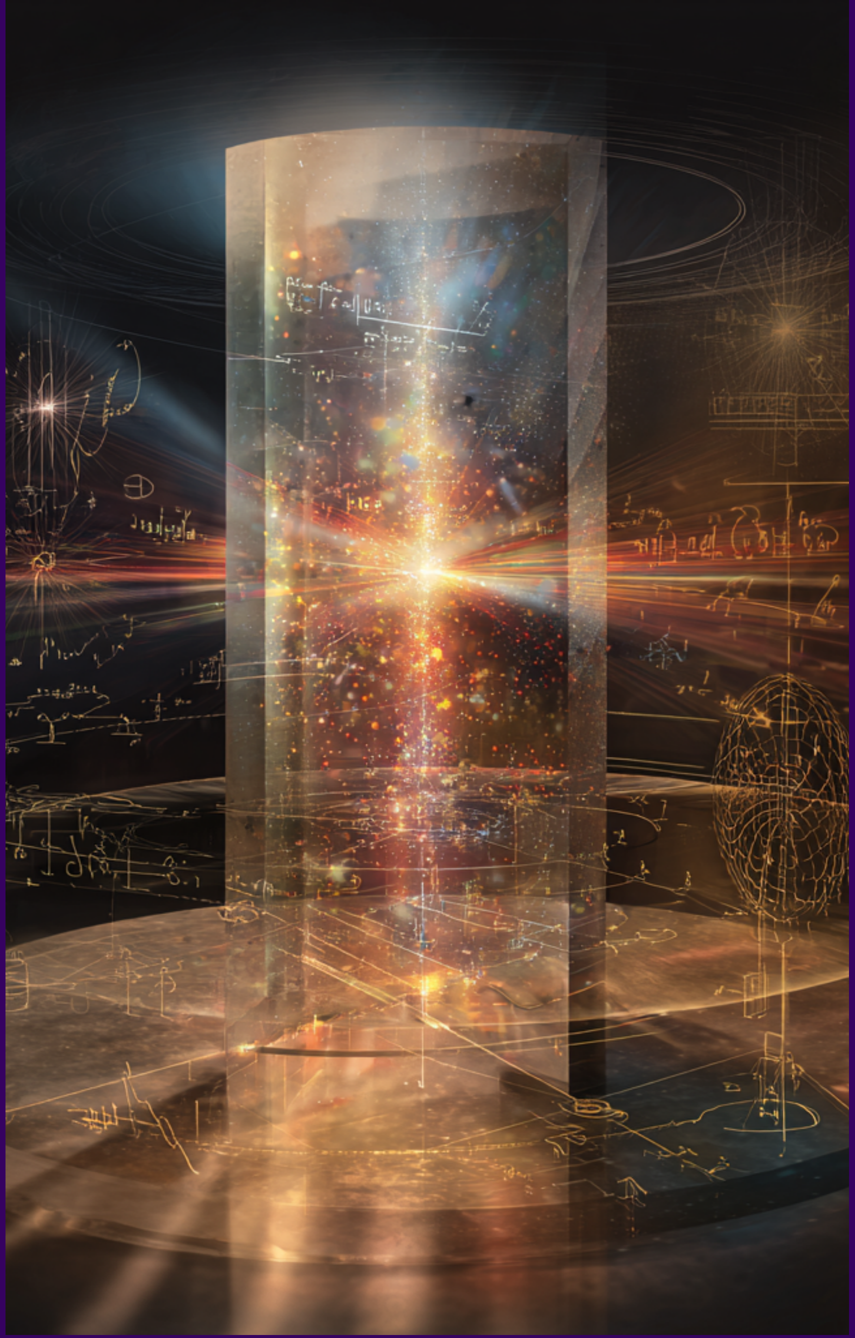
TORCH Detector Concept & Design

Marion Lehuraux, on behalf of the TORCH Collaboration,

XII International Workshop on Ring Imaging Cherenkov Detectors

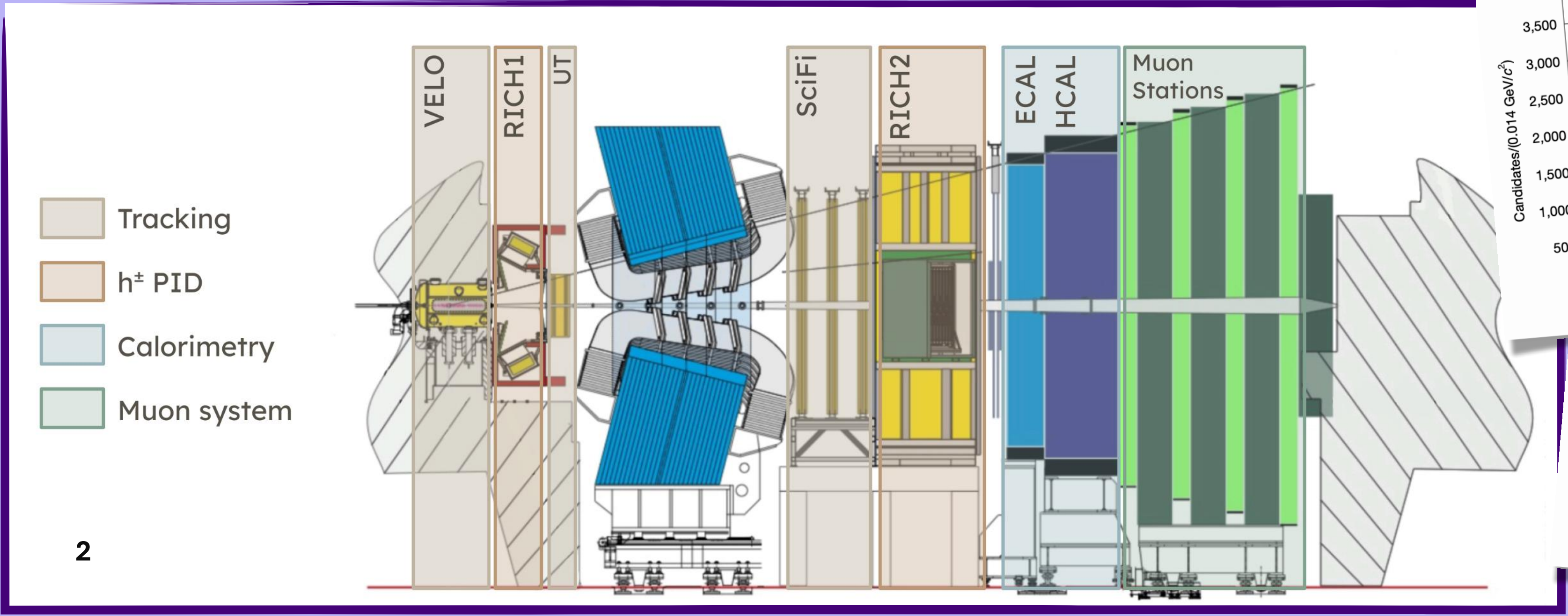
September 18th 2025 - RICH2025

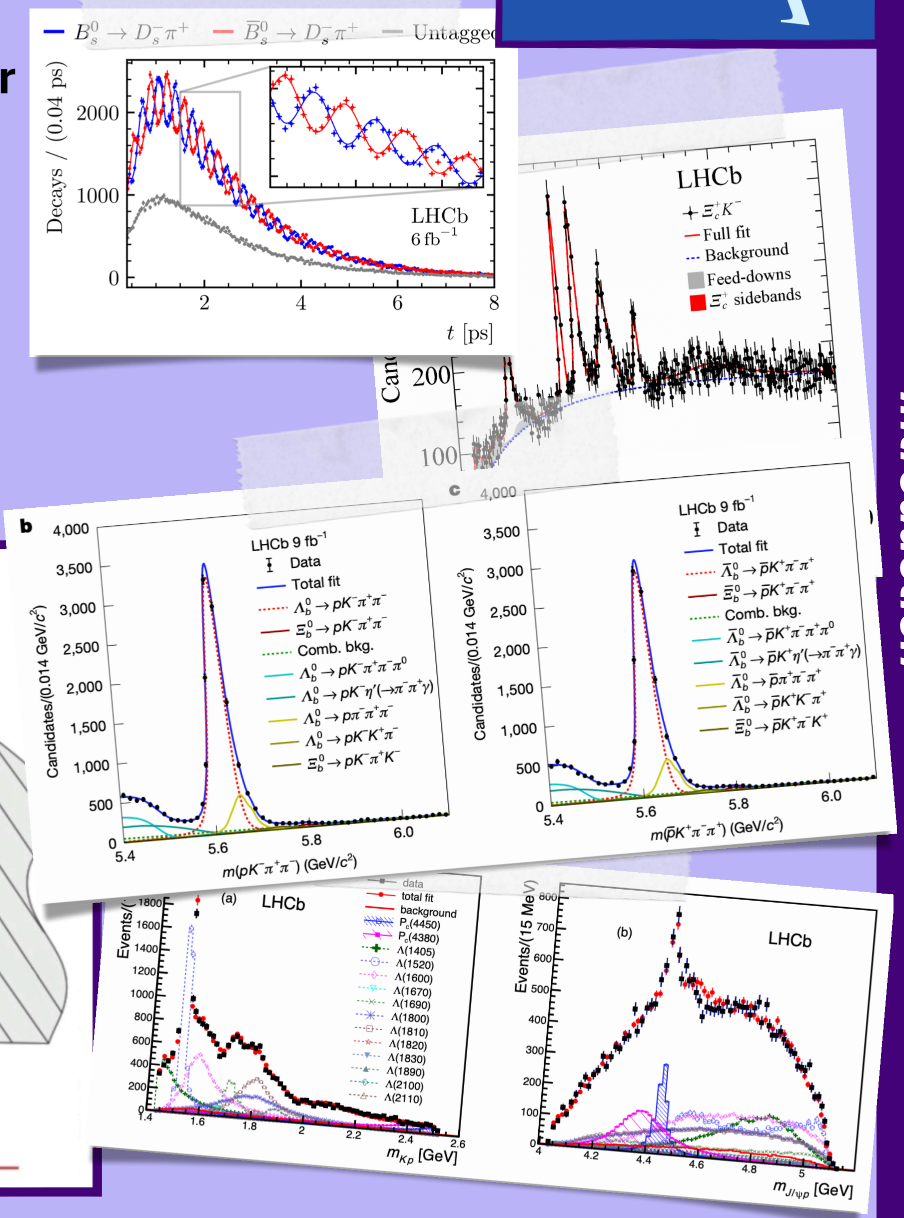


A Midjourney artistic rendering

The LHCb experiment

- Dedicated heavy **flavour experiment** @LHC → **forward spectrometer**
  - **Study CPV in the beauty sector** and rare heavy hadrons decay
- ...but also a **general purpose detector in the forward region**
  - QCD, heavy ions, electroweak, exotic spectroscopy etc.
- Published **more than 700 papers !**



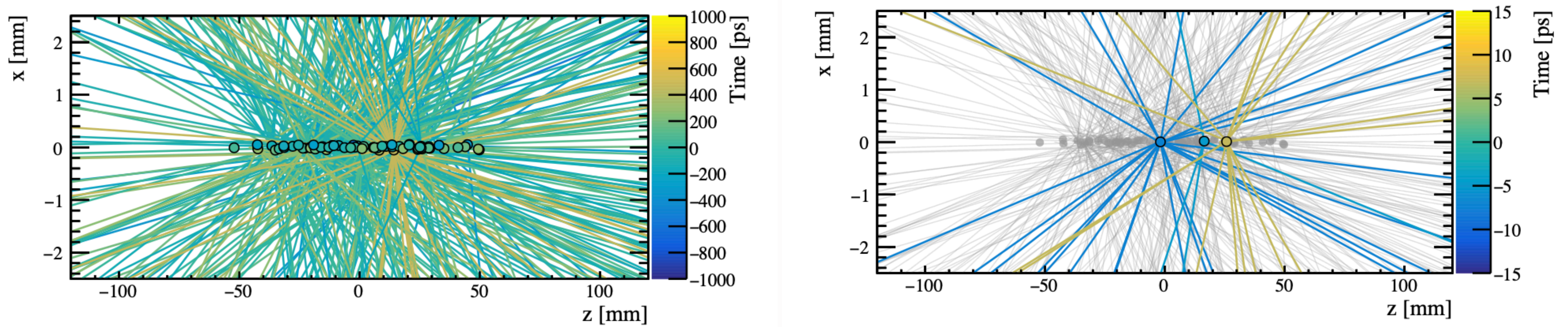


Introduction

LHCb Upgrade II - Experimental challenges

- Running at **high luminosity:** $\sim 1 \times 10^{34}$ $\mathrm{cm}^2\mathrm{s}^{-1}$
- High pile-up ~ 40 ie. **high track density** in the detector
- Excellent **spatial and time resolution…**
- …while withstanding **high rates and radiation damages**
- **Trigger and online computing** under unprecedented stress

Tracks in a typical bunch-crossing at LHCb in Upgrade-II

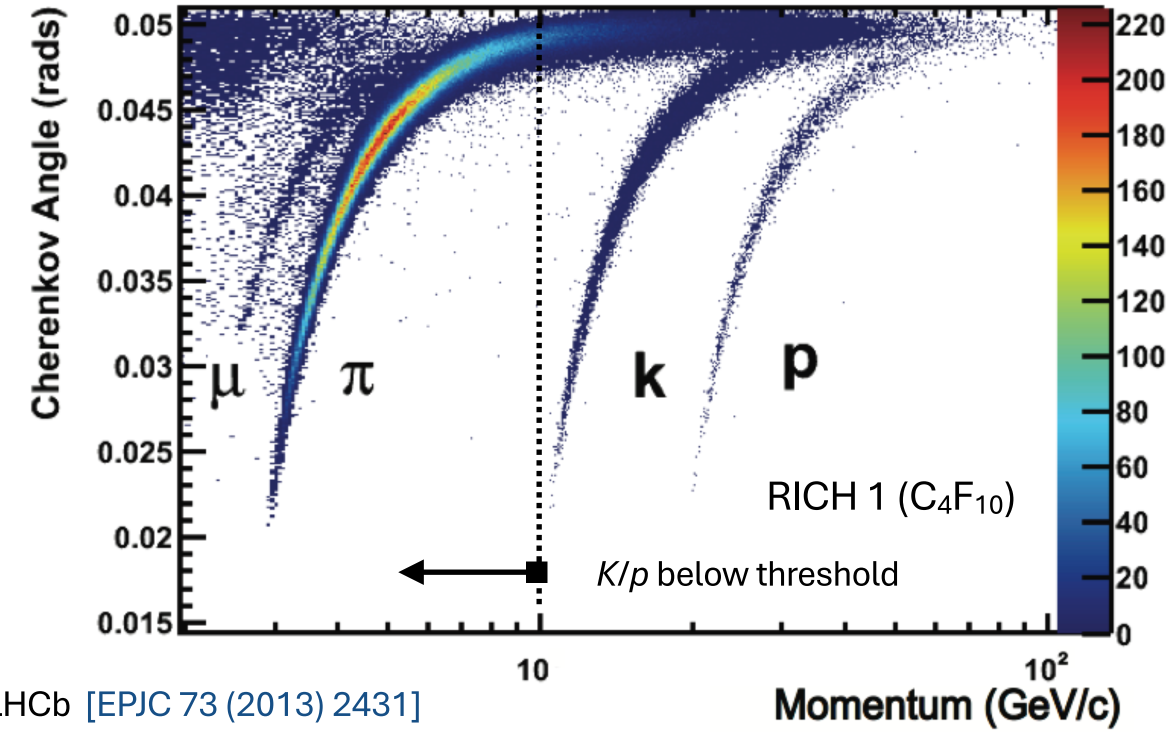


~ 1 ns time window

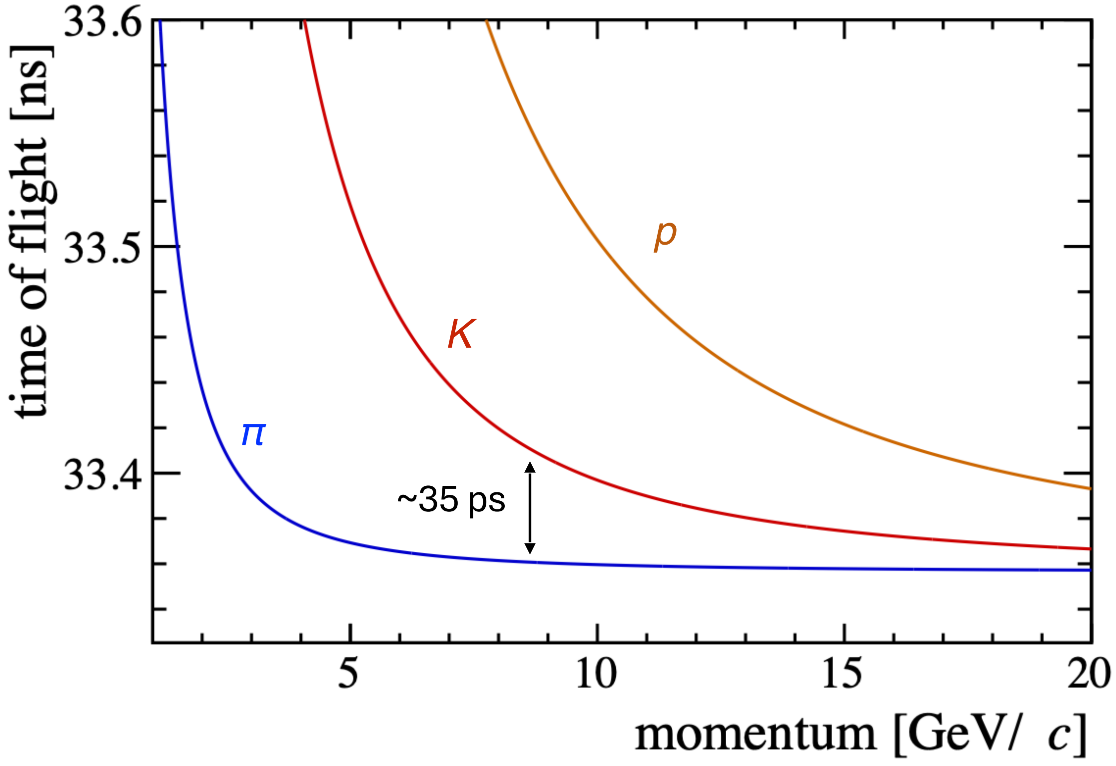
~ 15 ps time window

The TORCH detector - Motivations

- Hadron PID comes from RICH1 & RICH2 detectors
- Below 10 GeV/c both kaons and protons are below Cherenkov threshold → can't be separated
- TORCH aims to supplement PID performance in low momentum
- For K/π separation over 10m flight distance, aims for a 15 ps time resolution per track



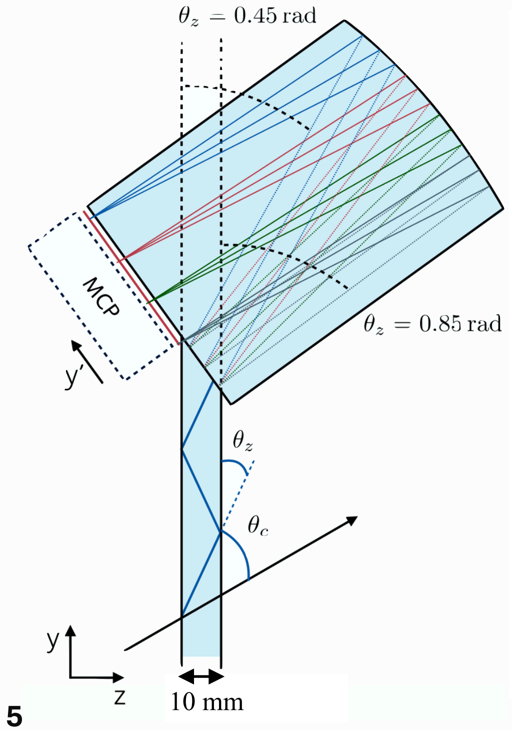
LHCb [EPJC 73 (2013) 2431]

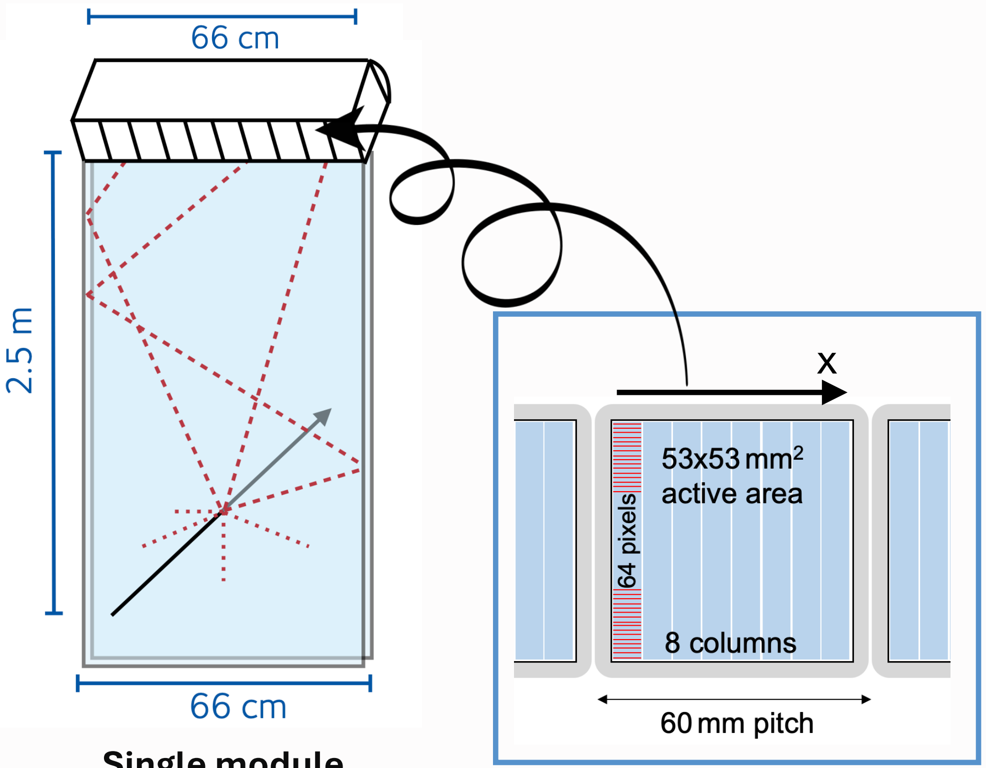


TORCH Concept

The TORCH detector - Concept & Design

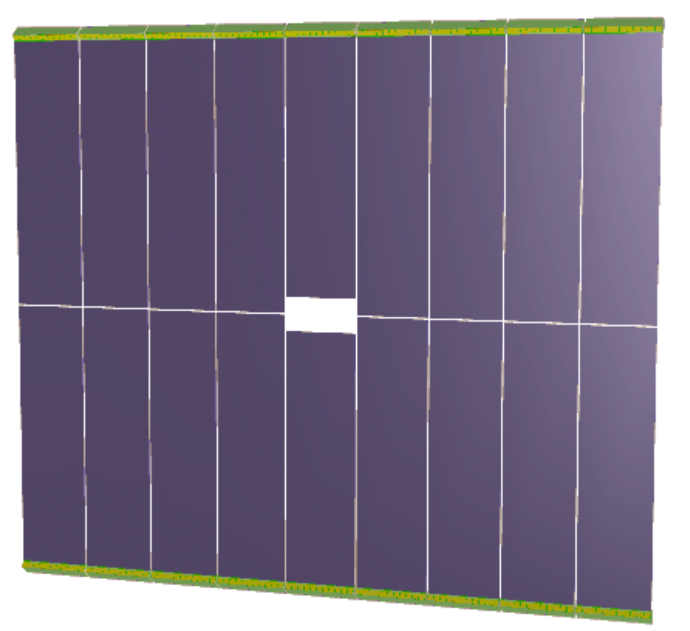
- Large area to cover the full (partial) LHCb acceptance 6x5 m2 made out of 18 (12) modules - depending on approved scenario
- Each module has 2500 x 66 x 1 cm^3 radiator
- Exploits prompt production of Cherenkov light in an array of fused-silica bars to provide timing
- Total internal reflection from quartz surfaces propagates the photons to the detector plane
- Cylindrical focussing block focusses the image onto a detector plane with highly segmented photo-detectors





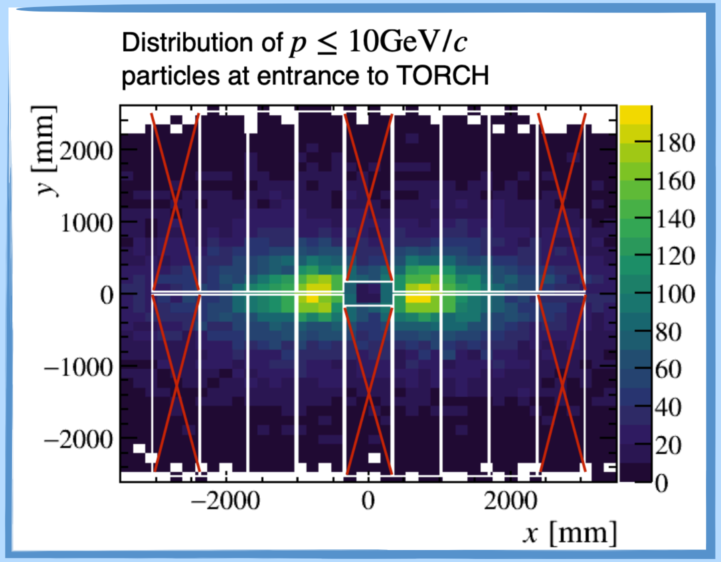
Single module

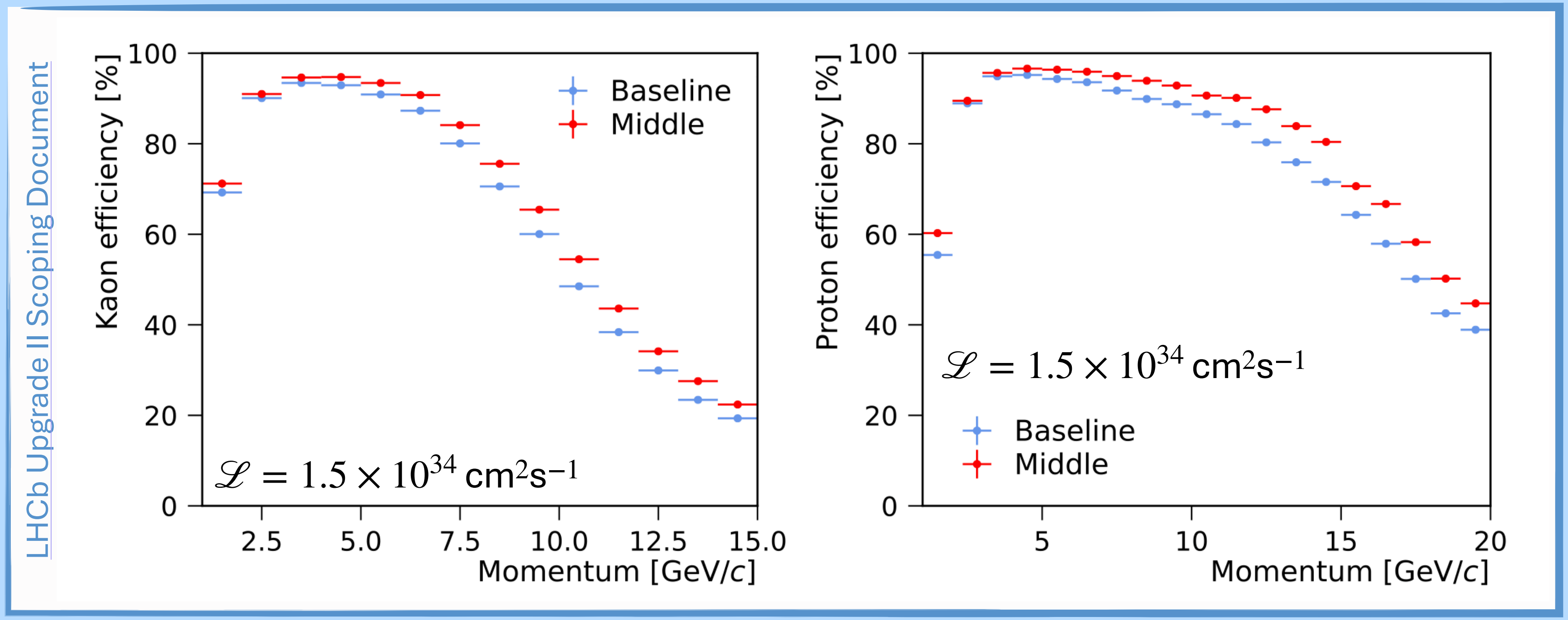
18 arranged modules



The TORCH detector - Expected performances

- Using simulation with Upgrade II luminosity conditions with luminosity $\mathscr{L} = 1.0 \times 10^{34}$ cm^{2}s^{-1}
- Reconstruction using tracking emulation
  - Tracking algorithm in Upgrade II conditions still under development
- TORCH “Middle scenario” geometry - 12 modules
  - Cuts out 1/3 of quartz area
  - Retains 75% detector acceptance for $p < 10$ GeV/c particles

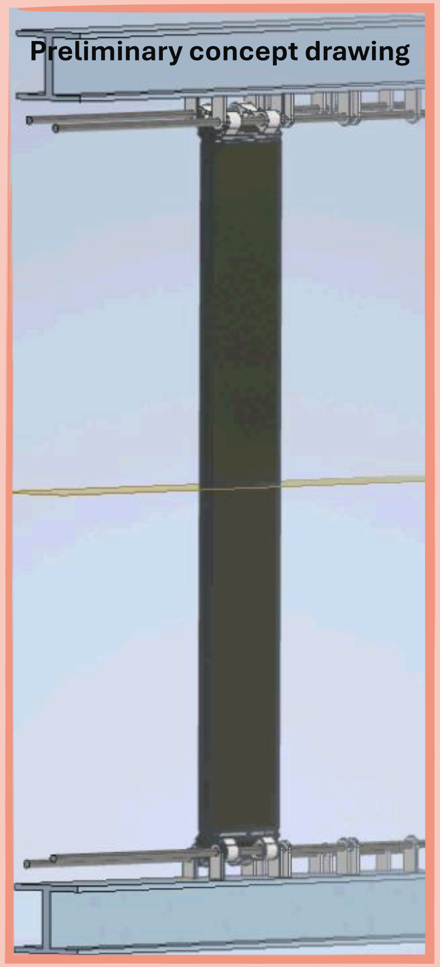


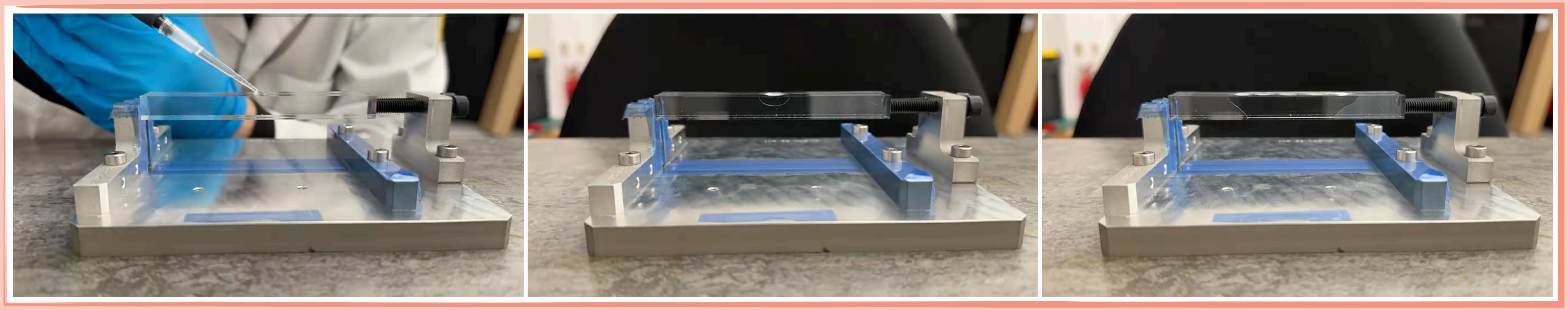


TORCH Concept

Mechanical design

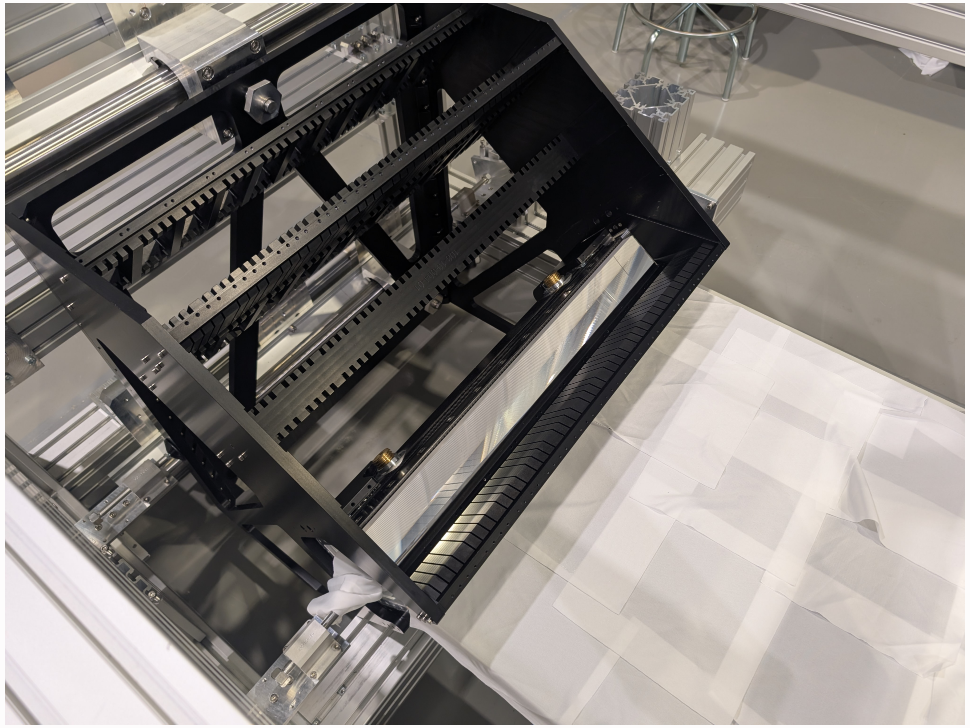
- **Mounted on rails** to minimise depth in LHCb acceptance and facilitate installation of each module in the cavern
- Support system has to **work in both orientations**
- **Light-weight carbon-fibre structure** to support modules
  - Minimise material introduced between tracking system and RICH2
  - Thermal expansion properties - minimal changes due to temperature cycling
- **Structural optical bonding** using **capillary action**
  - Bonding to reduce costs of large quartz sheets
  - Capillary action for **better bond uniformity** - minimise imperfections such as air bubbles
  - Real challenge on quartz sheets of 66 x 250 x 1 cm^3

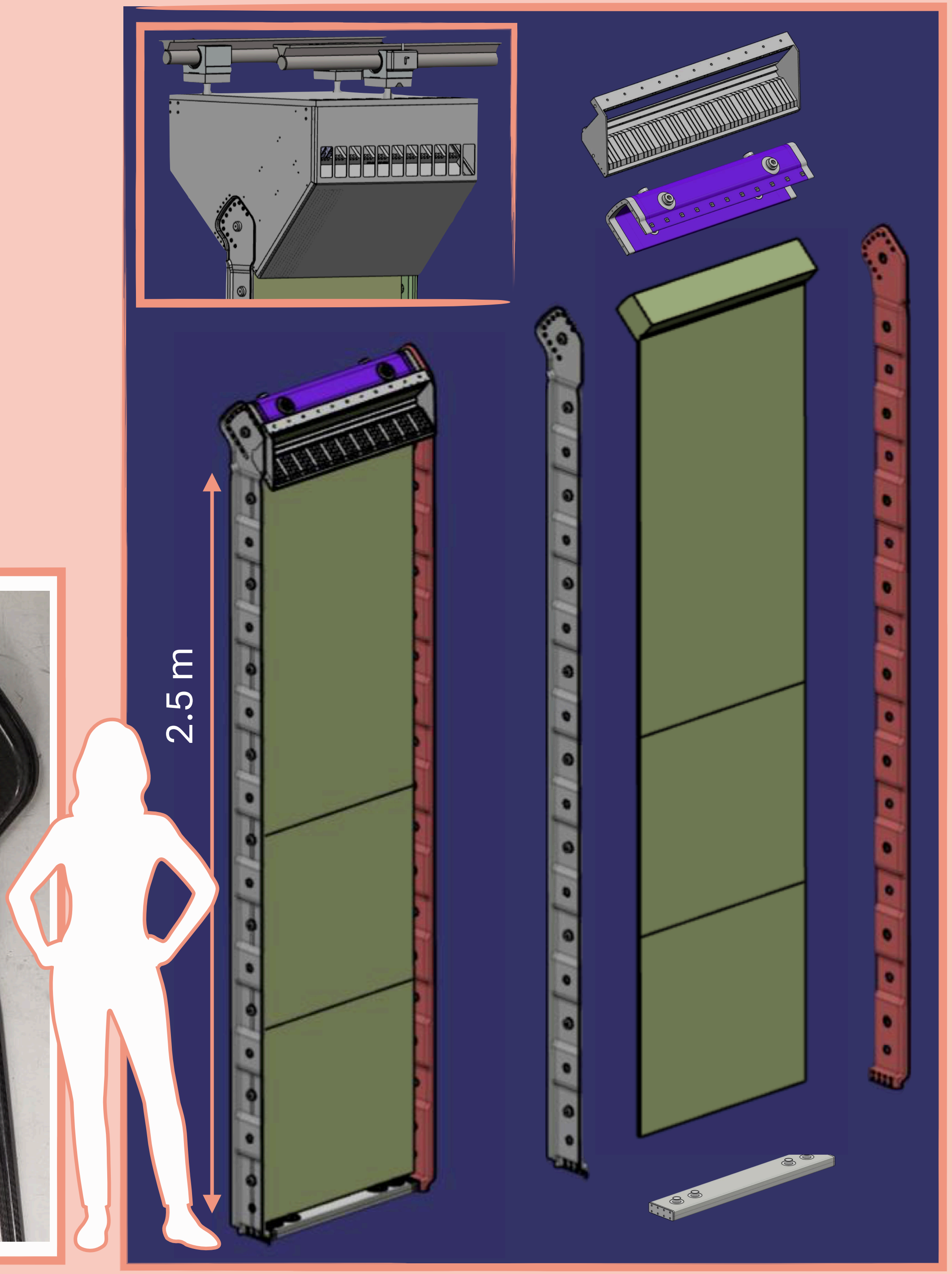




Building the first full size module

- As close as possible to final detector design
  - **Carbon fibre** sides and bottom braces with quartz support inserts
  - **Rail mounting**
- With some parts specific to beam test
  - Bonding jig used as exo-skeleton
  - Electronics housing





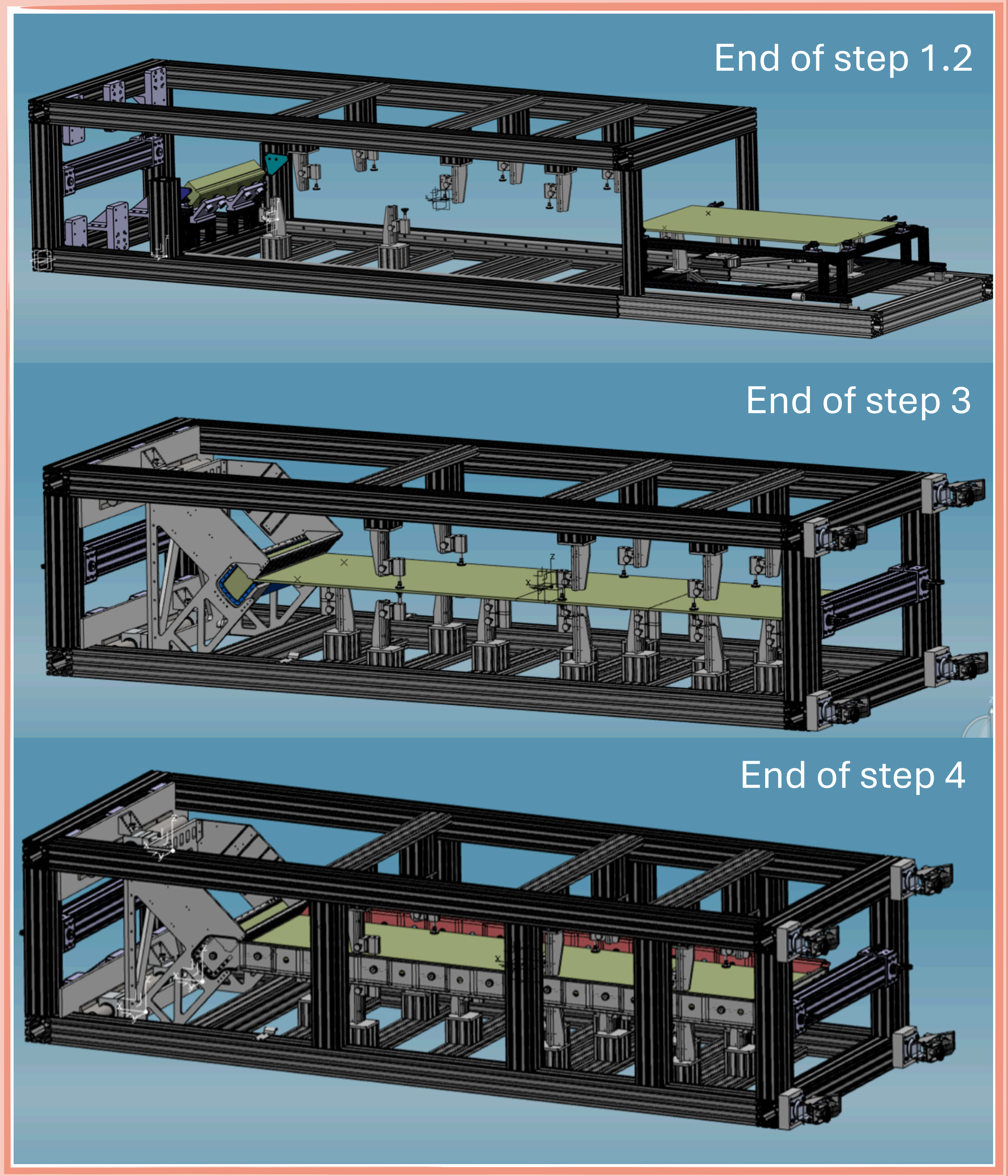
Building TORCH

From bonding jig to exo-skeleton

1. **Glue radiator plate R1 to focusing block FB**
    - 1.1. Position focusing block using adjuster screws
    - 1.2. Position radiator plate on sled
    - 1.3. Move sled to focusing block - within 10 cm
    - 1.4. Use screw for fine movement - up to 75 µm
    - 1.5. Use CMM arm for fine adjustments
    - 1.6. **Apply adhesive → capillary action**

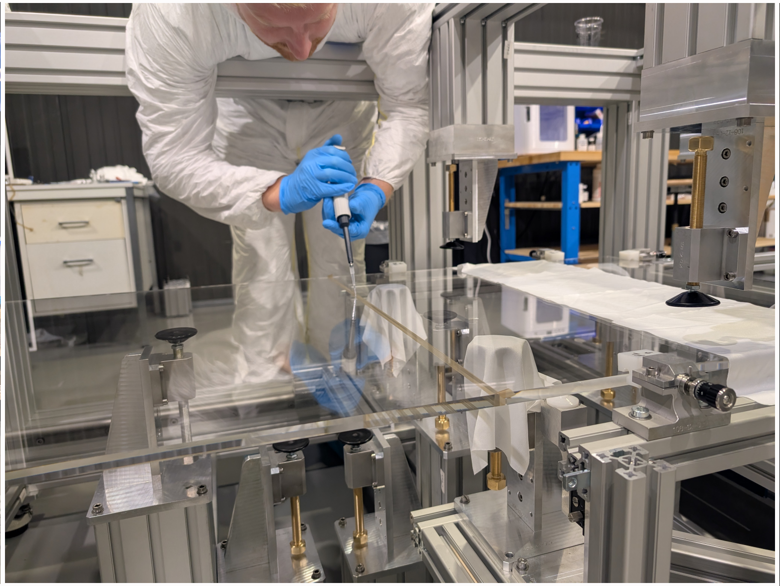
    (1.2–1.6: ∼ *a day*)

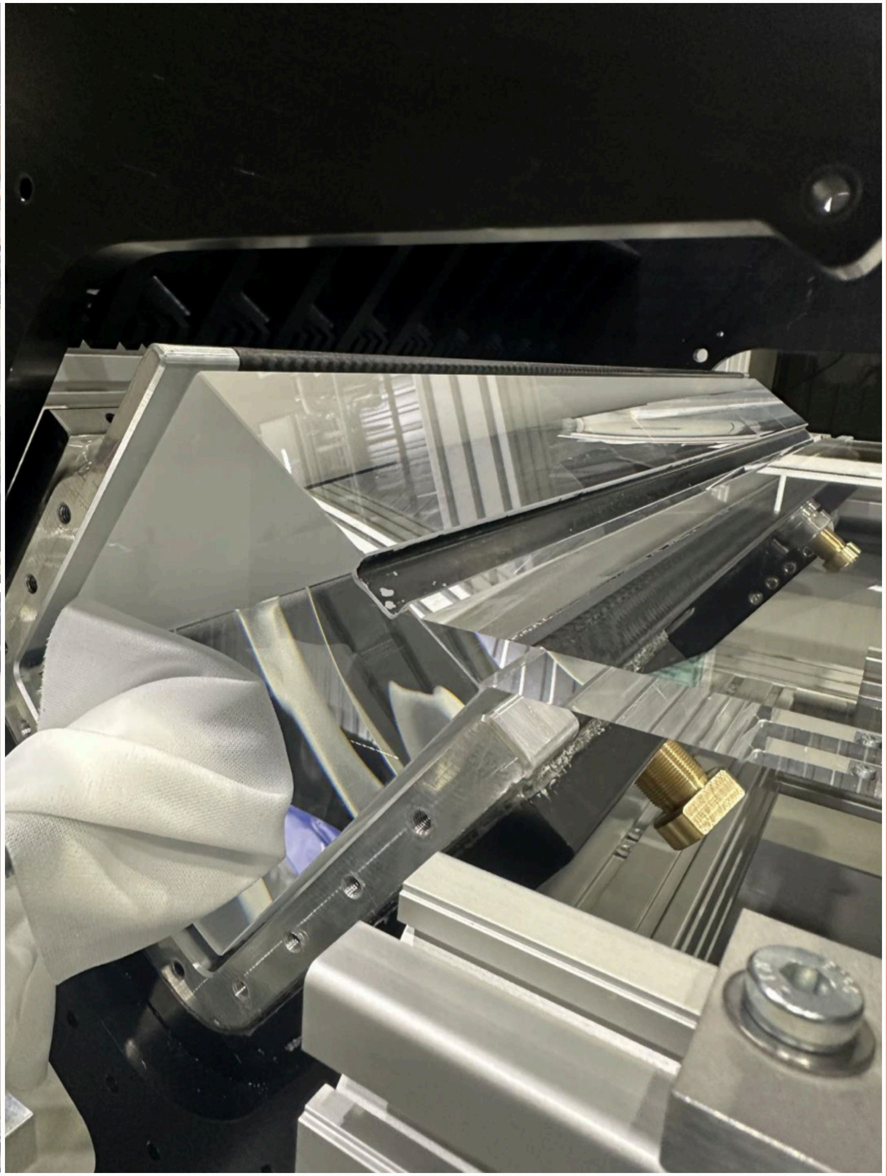
    - 1.7. Left to cure for ∼ 48h
    - 1.8. Set supports and remove sled
2. **Glue R2 to R1**
    - 2.1. Repeat steps 1.2 to 1.8
3. **Glue R3 to R2**
    - 3.1. Repeat steps 1.2 to 1.8
4. **Fit electronics housing and carbon fibre braces**

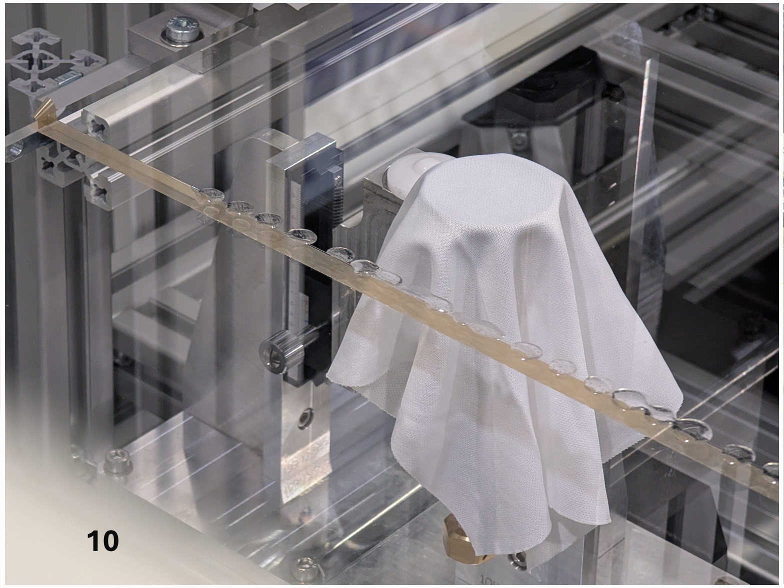


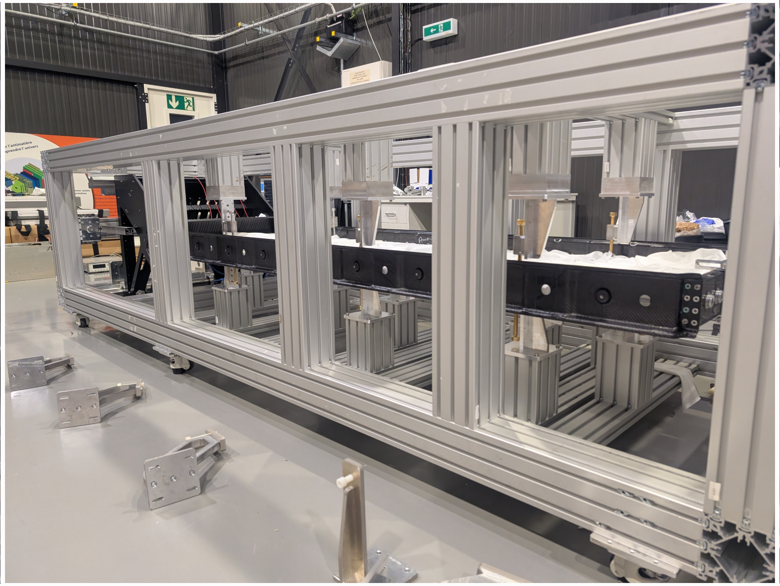
Building TORCH

3D model to actual prototype - Quartz bonding









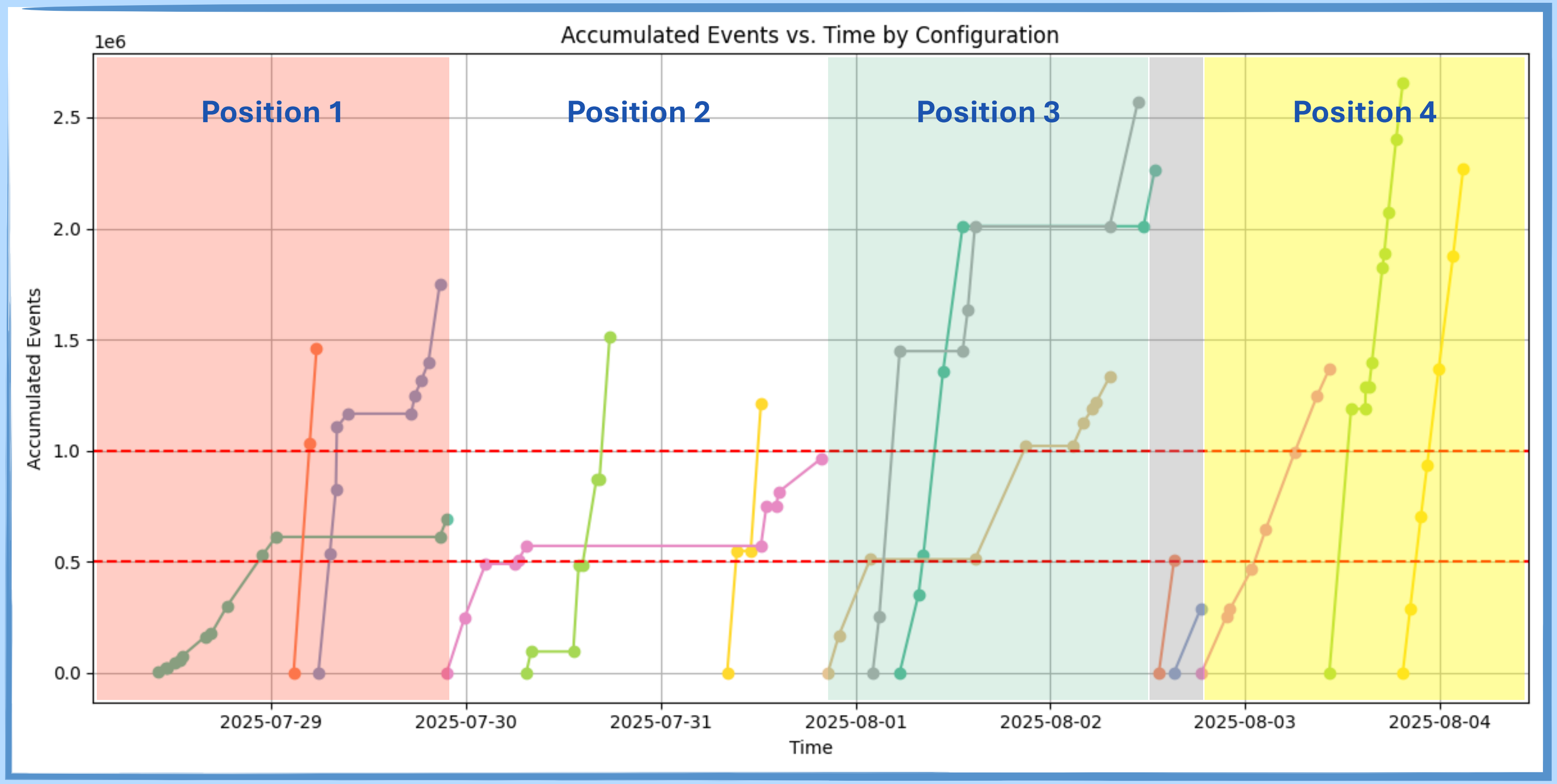
3D model to actual prototype - Transport and handling of assembled prototype

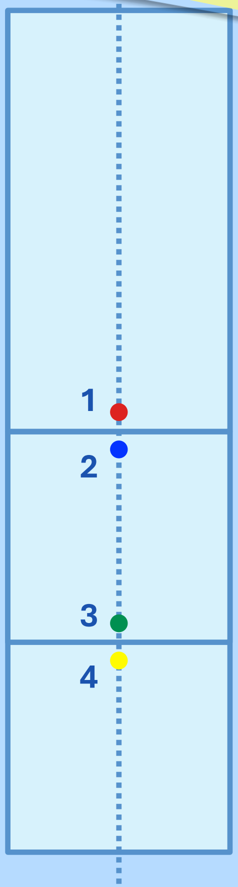
- Detector **assembled horizontally but operated vertically** → transition between different supports
  - Transport and rotation of the prototype absolutely critical
- Transported in a truck over 16 km
- Rotated twice and craned in position multiple times
- Would not have been possible without the **unwavering support of the CERN technical teams** !

TORCH 2025 beam test - The first test of a full-size module at CERN

- Validate **mechanical design of the hanging frame** and quartz support or a full-size module
- Validate the **bonding procedure** and optical properties of glue join
- Validate performances of a full-size module
- Data taken at 4 positions and 3 beam momenta (5, 8 and 10 GeV/c) using π^+/p beam

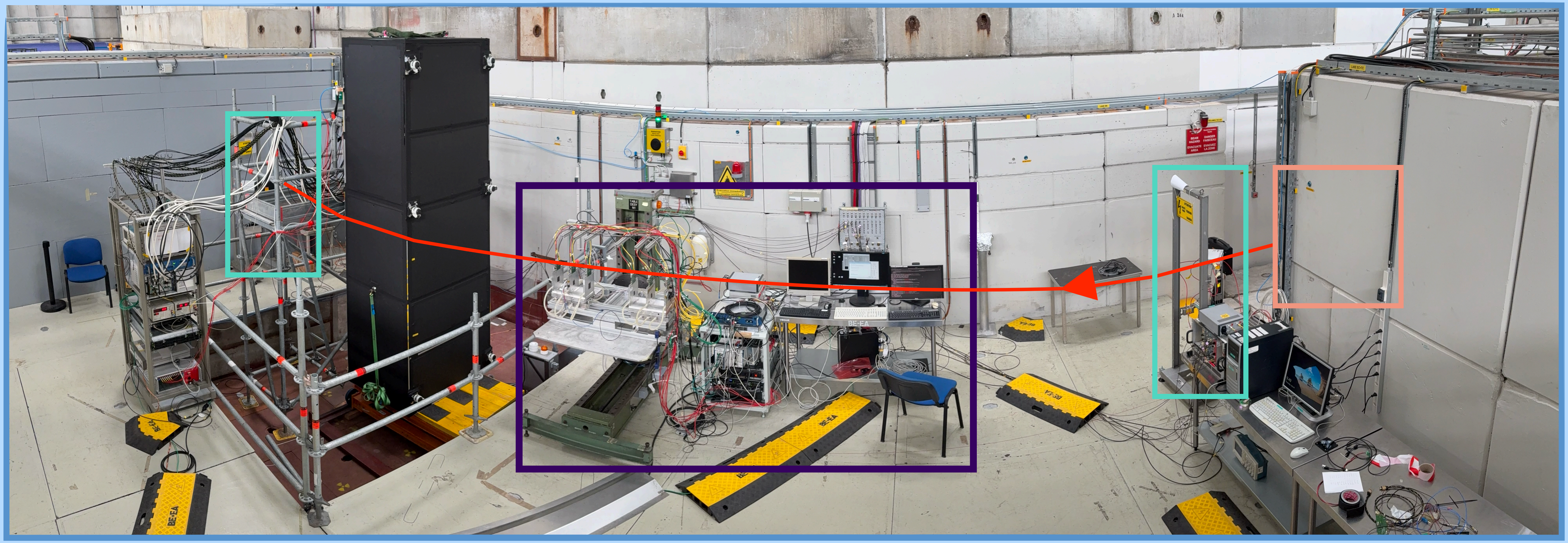
Checkout our poster for more info ! “First results from a full-scale TORCH prototype”

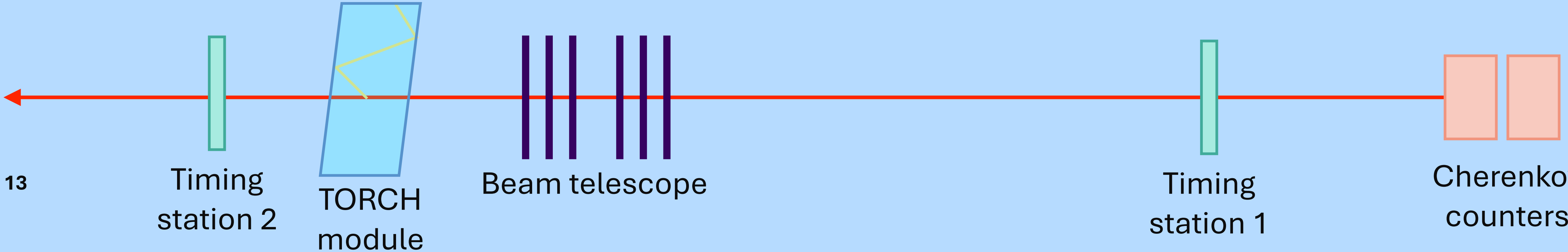




TORCH Beam test

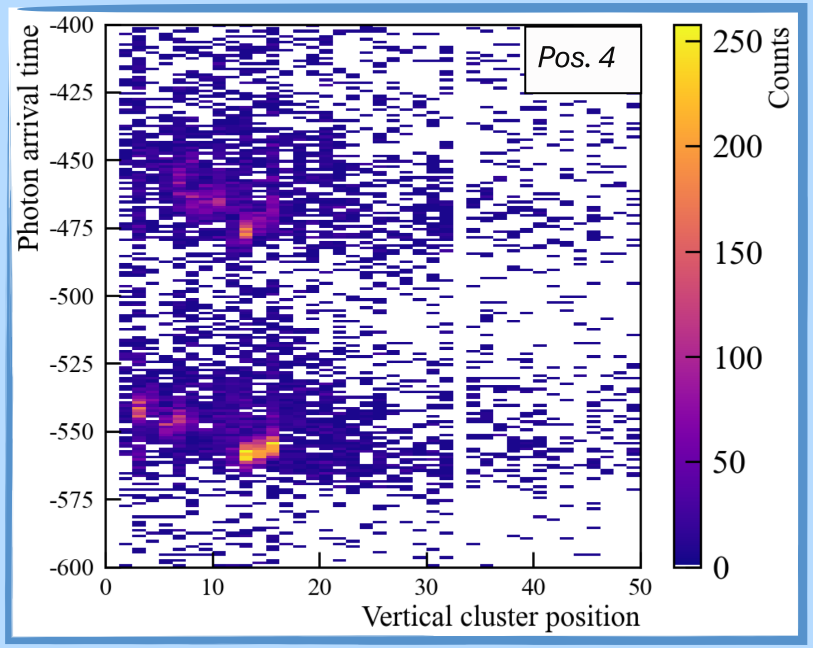
TORCH 2025 beam test - The first test of a full-size module

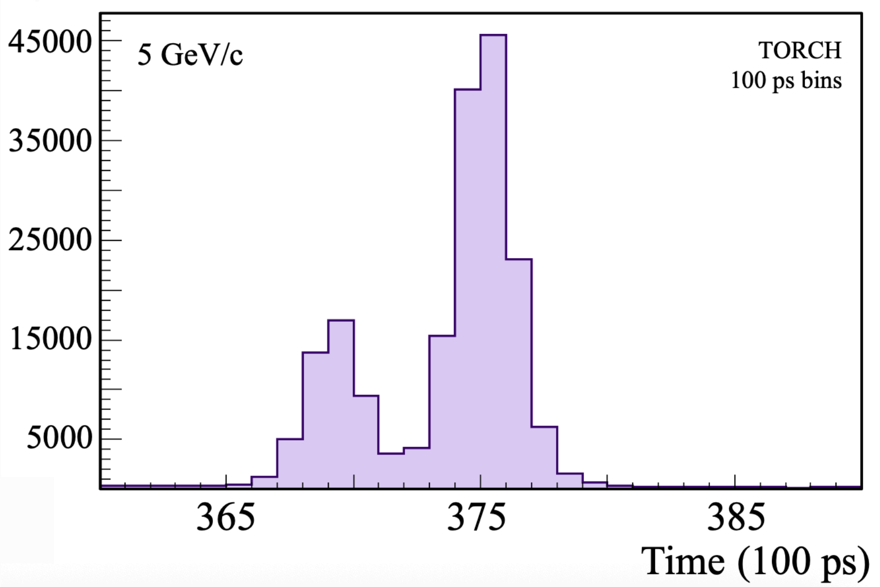


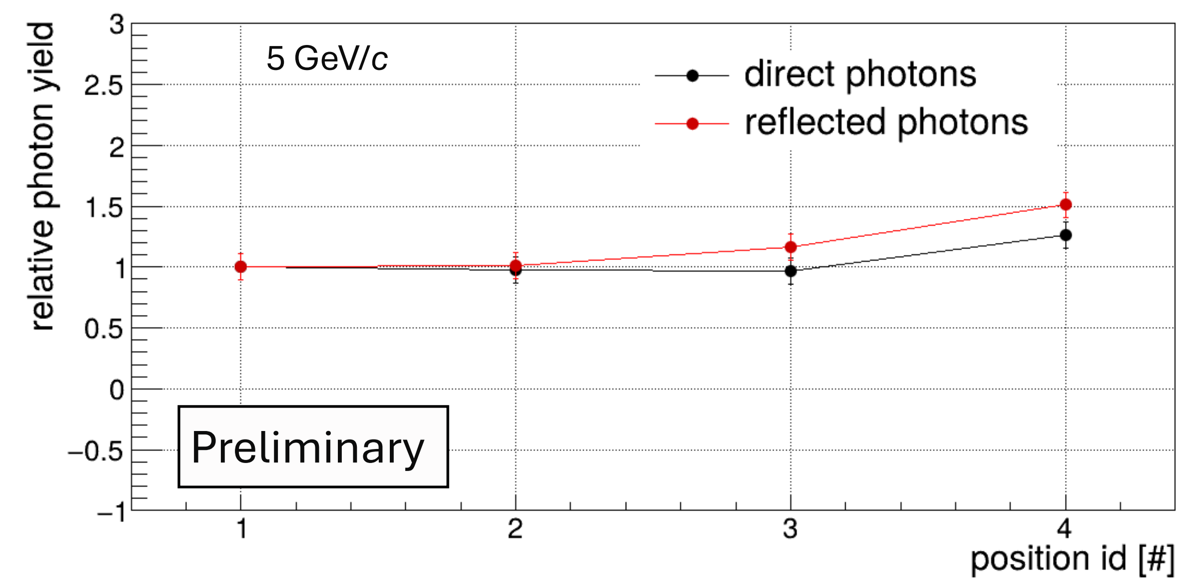


First look at 2025 test beam data

- See effects of MCP aging - QE and gain degradation
- Small cluster size, low number of clusters per event
- Expected p/π separation from the time reference system ✓
- Can see light in all 4 positions
  - **Very encouraging** for glue join optical quality !







Analysis still in preliminary stage but towards validation of mechanical design and bonding procedure

TORCH Beam test

From concept to reality, where challenges arise

Mechanical

- **Limited space in the LHCb cavern** to install TORCH
  - Integrated design with RICH2 necessary
  - New focusing block geometry ?

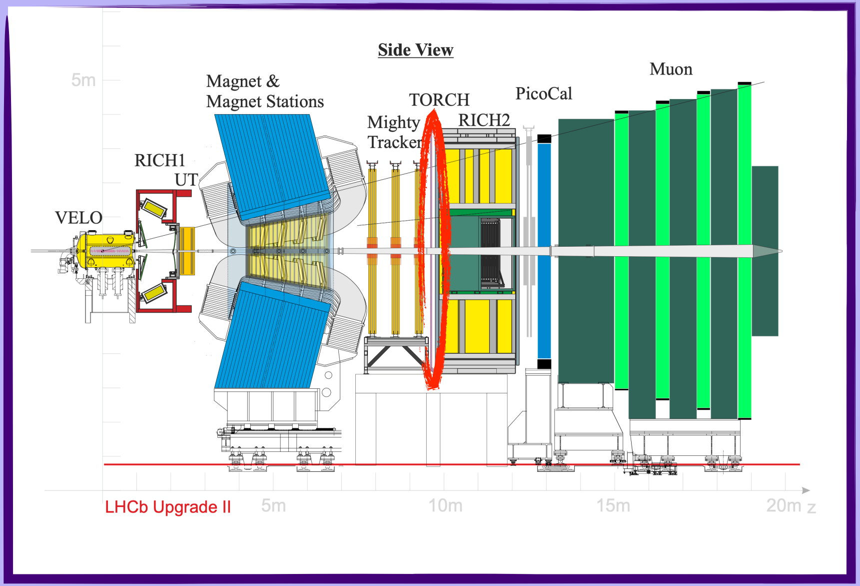


Photo-detectors

- High performances
  - 70 ps time resolution per photon
- Occupancy below 20% ie. **high granularity**
- **Radiation hard**
  - Neutron fluence up to $2 \times 10^{12}\ n/\text{cm}^2$
- High rate
  - 5 - 25 μA / cm^2 depending on the module

Main candidates

- MCP-PMTs but…
  - Too short lifetime
  - Limited rate capabilities
- SiPMs but…
  - Large dark count rates
  - Requires cooling

Mechanical challenges

- **Space constraints in the cavern → towards an TORCH + RICH2 integrated design**
  - TORCH radiator plate in front of RICH2 entrance window
  - Focusing block design to be reviewed to minimise impact on RICH2 active volume

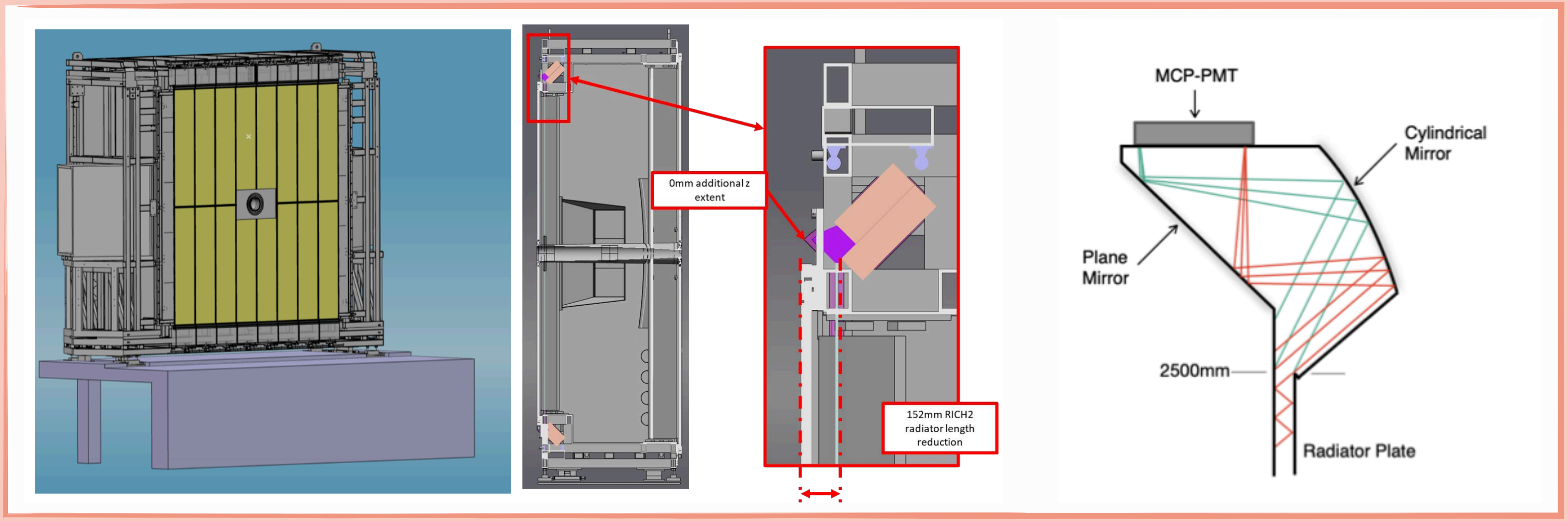


Photo-detector challenges

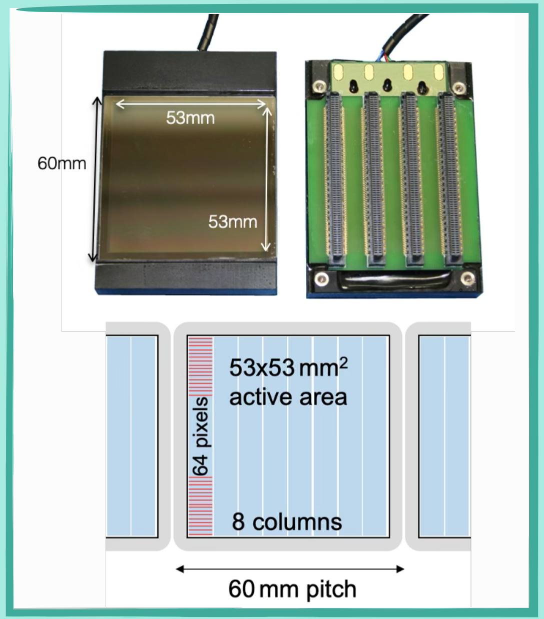
Micro-Channel Plate detectors R&D

- Multi-channel square MCP-PMT
- ALD coated pores
- Resistive coupling
- Granularity designed for TORCH: 8 x 64
- Used in beam tests

- Multi-channel square MCP-PMT
- ALD coated pores
- Direct coupling
- 16 x 96
- Characterised in the lab

Reduce pixel occupancy

Phase 3



Recent developments

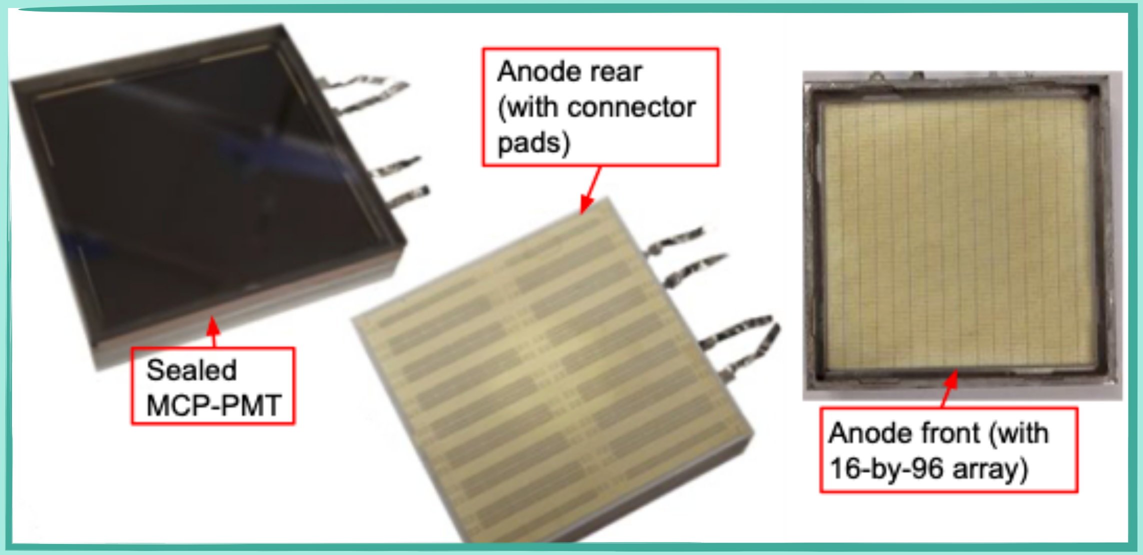


Photo-detector R&D - Multi-Channel-Plate detectors

Rate capabilities as a function of gain

- Measurements conducted at Photek on Phase 3 MCP
- Gain G is previously calibrated
- Uniformly illuminate area of known surface S_0 (cm²) and mask remaining MCP
- Vary the laser rate and measure the anode current I_{anode}

PHOTEK
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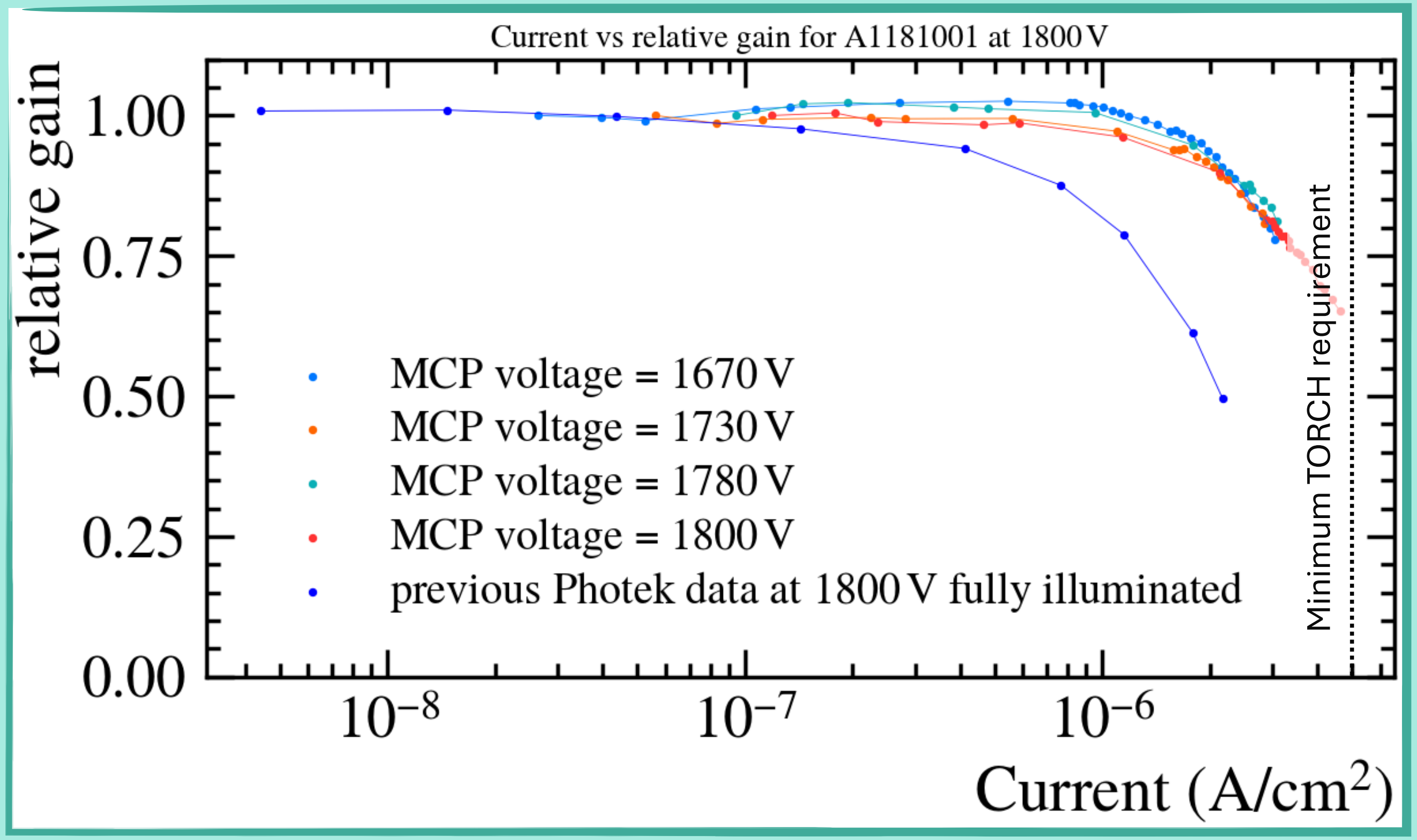
Checkout Amelia's poster for more info !
"Rate capability and transient gain drop of an single photon timing detector"

$$T_{\text{pe}} = \frac{I_{\text{anode}}}{S_0 \, . \, G \, . \, e}$$



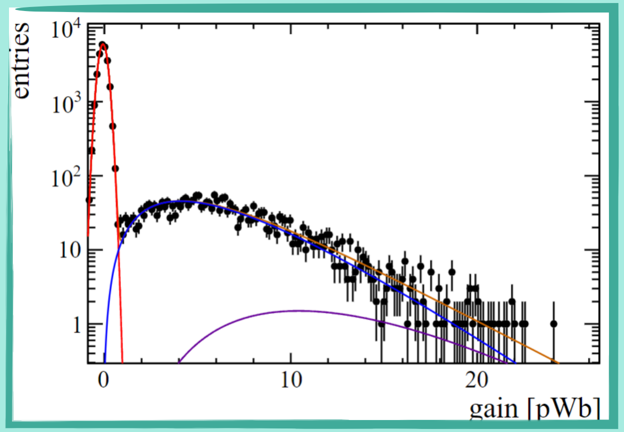
MCP voltage [V]	Calibrated gain
1670	4.93×10^5
1730	1.07×10^6
1780	1.76×10^6
1800	2.13×10^6

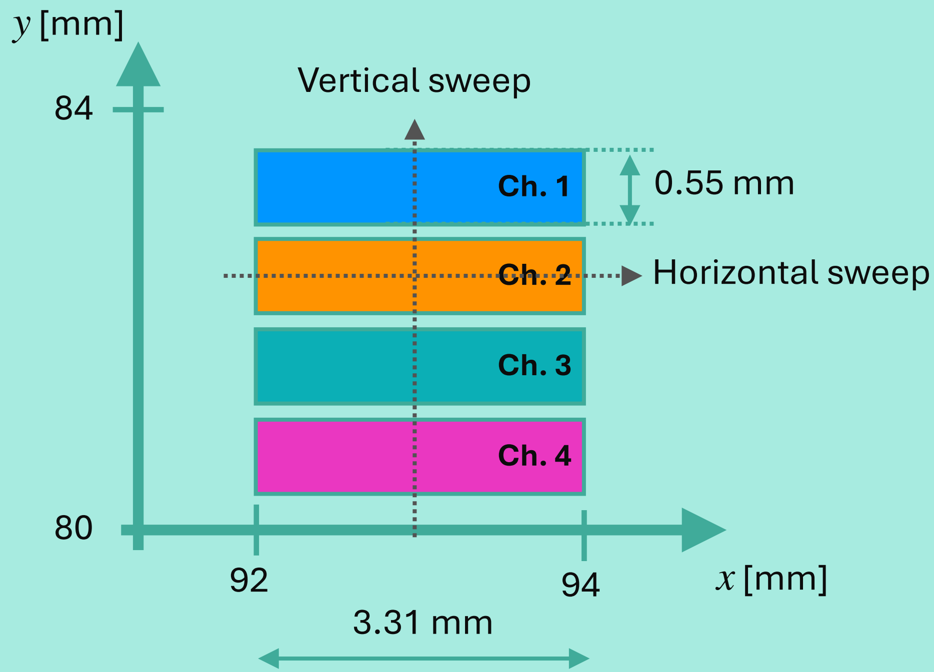
Photo-detectors

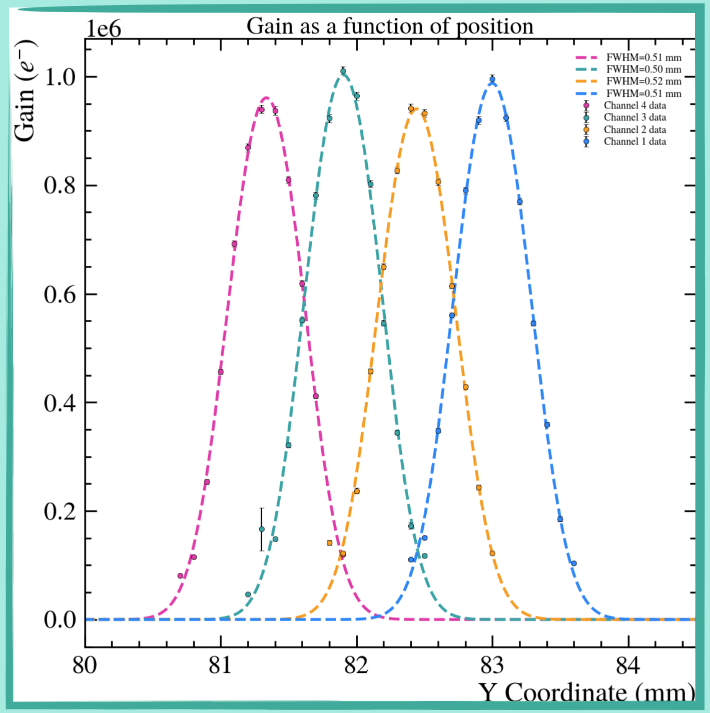
Photo-detector R&D - Multi-Channel-Plate detectors

Charge spread

- Difficulties with laser soldering → instrumented every other column for now
- Measurements conducted at Photek on 16 x 96 MCP
- Use Lecroy waveMaster 808zi-A (8 GHz, 40 GS/s) scope to read 4 neighbouring pixels
- Record the area under curve ∝ charge
- Fit gain distribution using a Polya-based model [Prescott, 39 (1966) 173-179]
- Shows point spread function smaller than fine pixel dimension ✓







Take away message

- LHCb Upgrade II: **extremely ambitious and challenging** !
- TORCH will **improve LHCb PID performances in low momentum region** and help face Upgrade II technical challenges
- TORCH detector concept already validated with simulation, but proves challenging to make happen
  - **Mechanically**: space constraints, light-tightness, low material budget…
  - **Photodetectors solution**: excellent performances required in hostile environment - rate & radiation
- **Incredible progress has been achieved** towards solving these issues
  - **First full-size scale module** has been assembled and successfully operated in beam test ✓
  - **Validate the module mechanical design** support structure ✓
  - **Validate the bonding** procedure ✓
  - **Ongoing R&D on photo-detectors** to find viable solution
- Looking forward to **promising results** coming out of 2025 beam test analysis !

Backup slides

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A Midjourney artistic rendering

University of Bristol
Jožef Stefan Institute
University of Warwick
University of Science and Technology of China
University of Chinese Academy of Sciences
University of Leicester
GSI Helmholtzzentrum für Schwerionenforschung
University of Oxford
Monash University
CERN

Photo-detector R&D - Multi-Channel-Plate detectors

Quantum Efficiency (QE)

- Measurements conducted at Photek on 16 x 96 MCP
- QE measured across full active area in steps of 0.25 mm
- First tube presents non-uniformities
  - Most likely due to poor vacuum seal
  - Dead area seems to be fixed in time
- Second tube is much better but does not have anode connectors yet

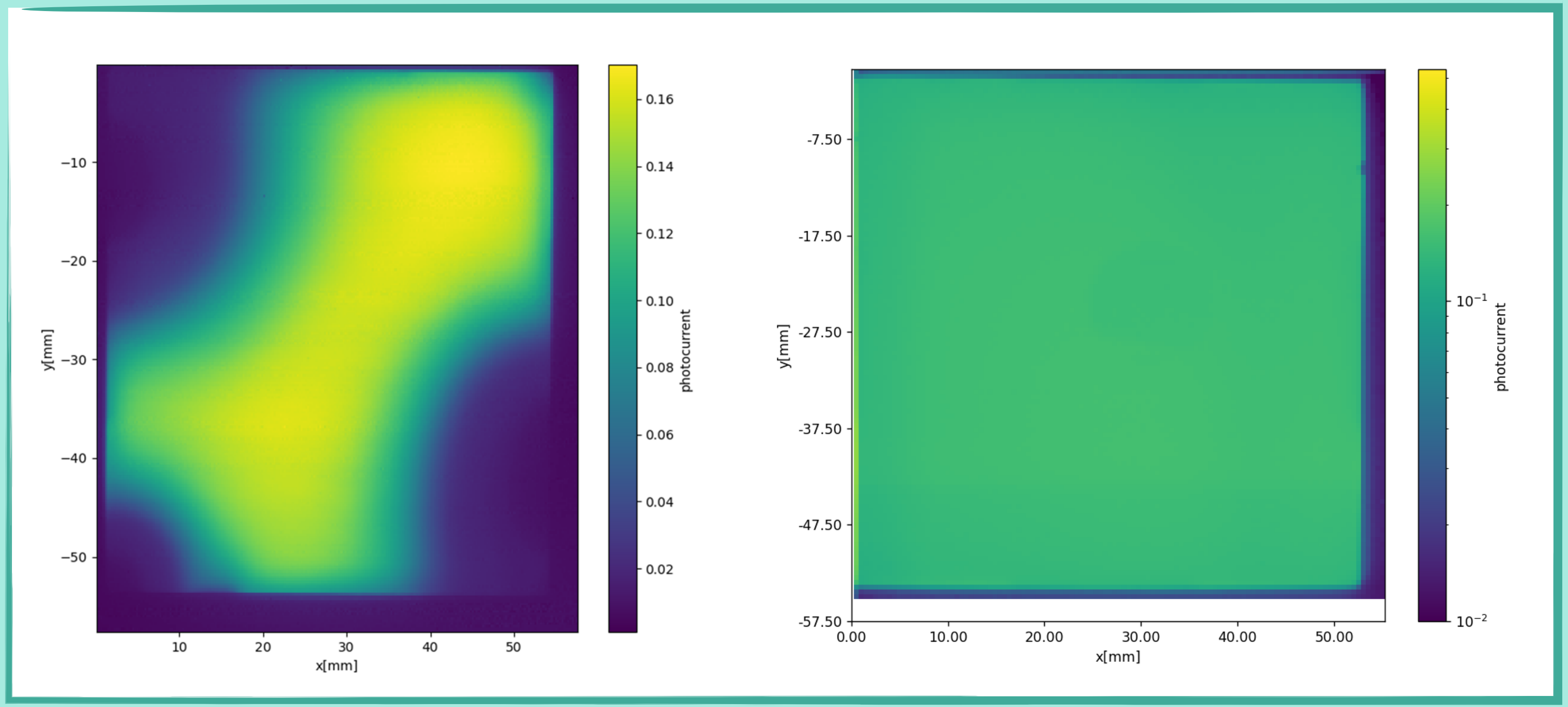

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Photo-detectors

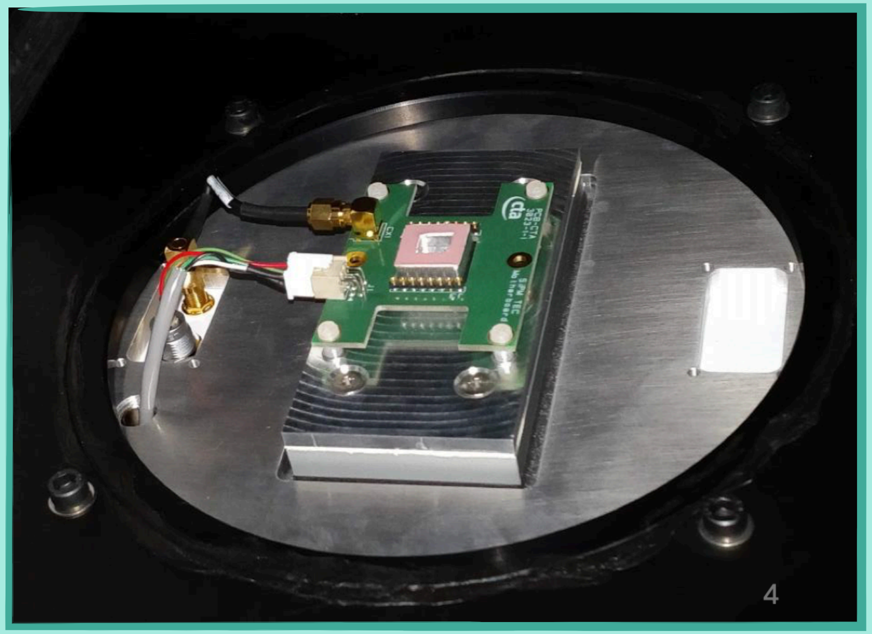
Photo-detector R&D - Silicon Photo-Multipliers

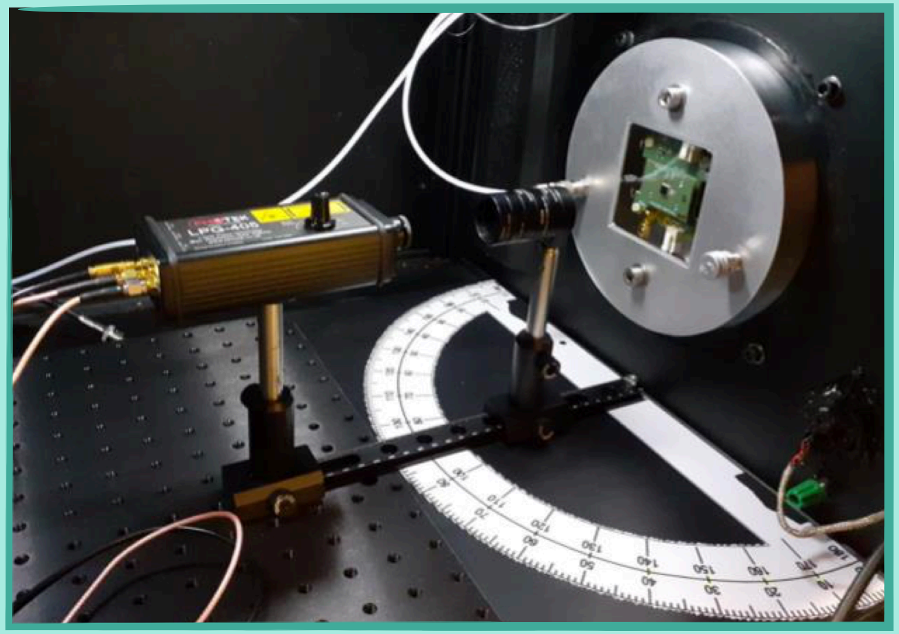
- Efforts ongoing at the University of Leicester, Monash and Warwick
- Can SiPMs be good candidates for TORCH ?
  - Time resolution, rate capabilities, dark noise levels
  - Lifetime, degradation after irradiation
  - Granularity required for TORCH
- Currently being tested using
  - 405 nm pulsed Photek laser
  - LeCroy 6 GSa/s scope - TORCH readout electronics adaptation in progress

UNIVERSITY OF LEICESTER

MONASH University

UNIVERSITY OF WARWICK





Precision of quartz plates positioning

First radiator plate (R1) w.r.t focusing block (FB)

- Top plane error 0.06°
- Side plane error 0.05°
- Lateral position error 0.016 mm

Second radiator plate (R2) w.r.t R1

- Top plane error (rotation around x and y axis) $\Delta\alpha$ = 0.05°
- Δz = 16 μm, Δy = 9 μm
- Rotation around z axis $\Delta\gamma$ = 0.01°

Third radiator plate (R3) w.r.t R2

- Top plane error (rotation around x and y axis) $\Delta\alpha$ = 0.0085°
- Δz = 3 μm, Δy = 28 μm
- Rotation around z axis $\Delta\gamma$ = 0.0068°