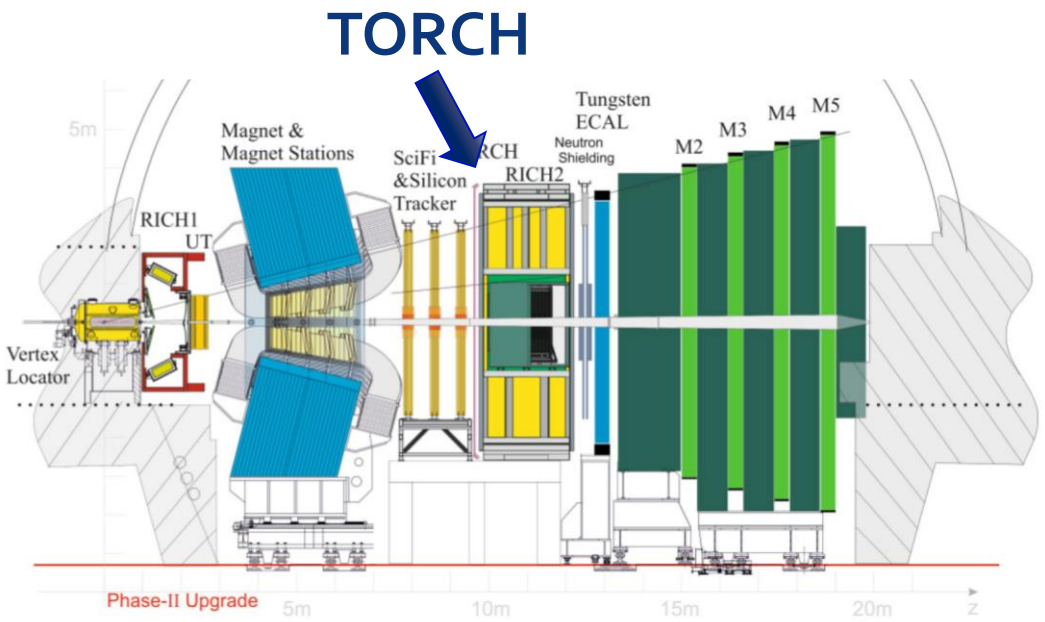
Performance studies of

THE TORCH DETECTOR

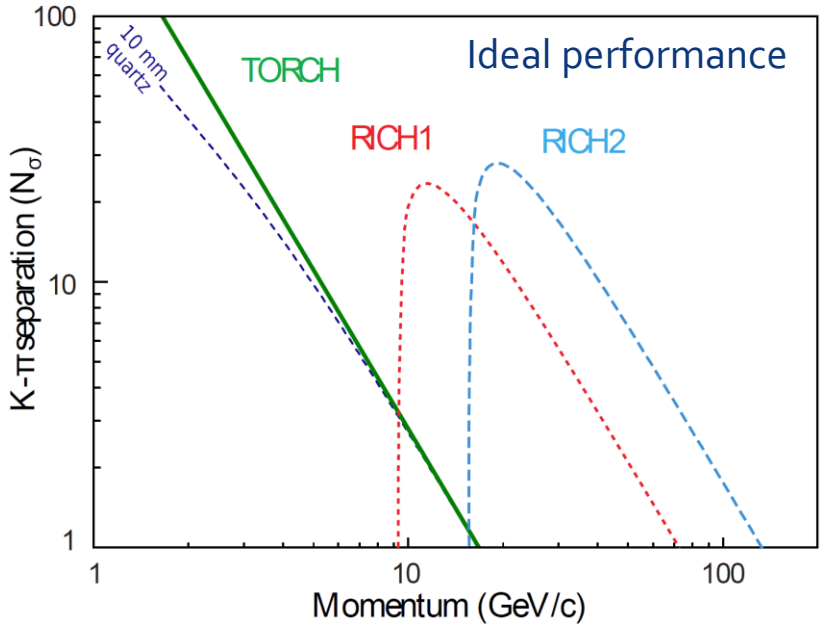
Maarten van Dijk on behalf of the TORCH collaboration

14-09-2022

The TORCH detector

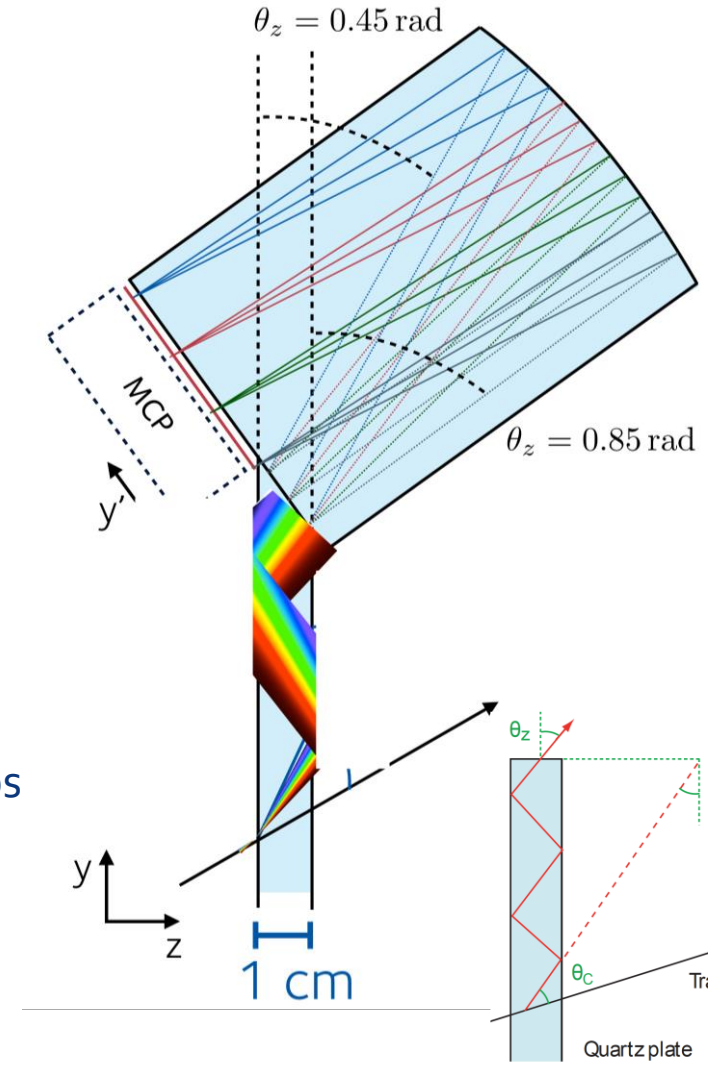


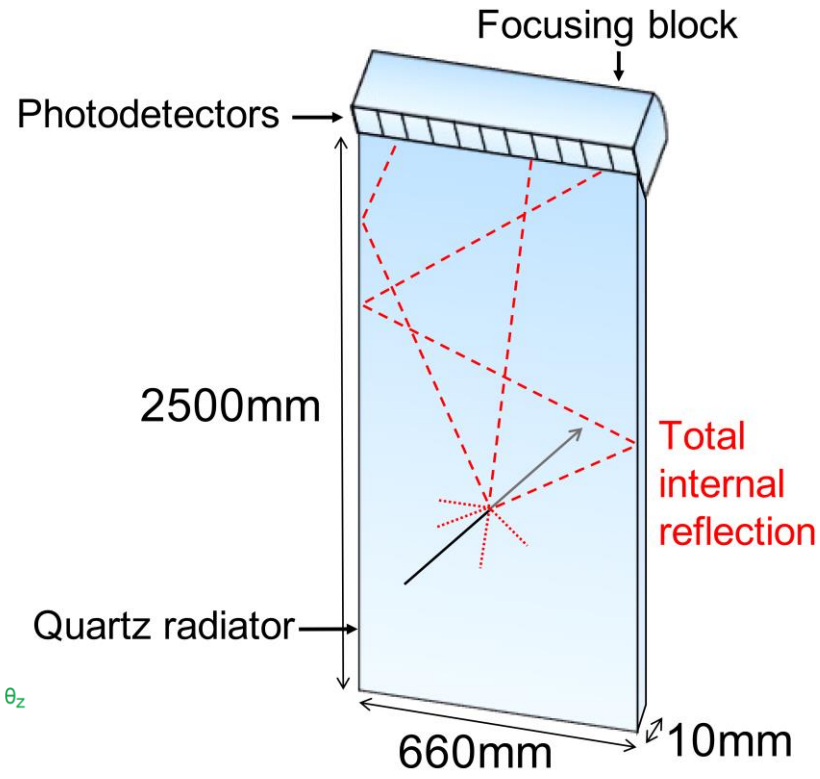
- TORCH: Time Of internally Reflected CHerenkov light
  - Also see talk of L.M. Garcia Martin (yesterday)
  - DIRC-like detector
  - Similar to RICH but with a solid quartz radiator
- Part of LHCb Upgrade II
  - Existing RICH has ~10 GeV/c threshold for kaons (~20 GeV/c for protons)
  - TORCH will complement the existing PID system (RICH1, RICH2) in the low momentum regime (2-10 GeV/c)
- Principle of operation
  - Required inputs are track angle, position and momentum
  - High precision timing of particle at known momentum provides PID
  - ΔTOF(π-K) = 37.5ps at 10 GeV/c
  - Target (three sigma separation) is ~15ps / track



Principle of the TORCH detector

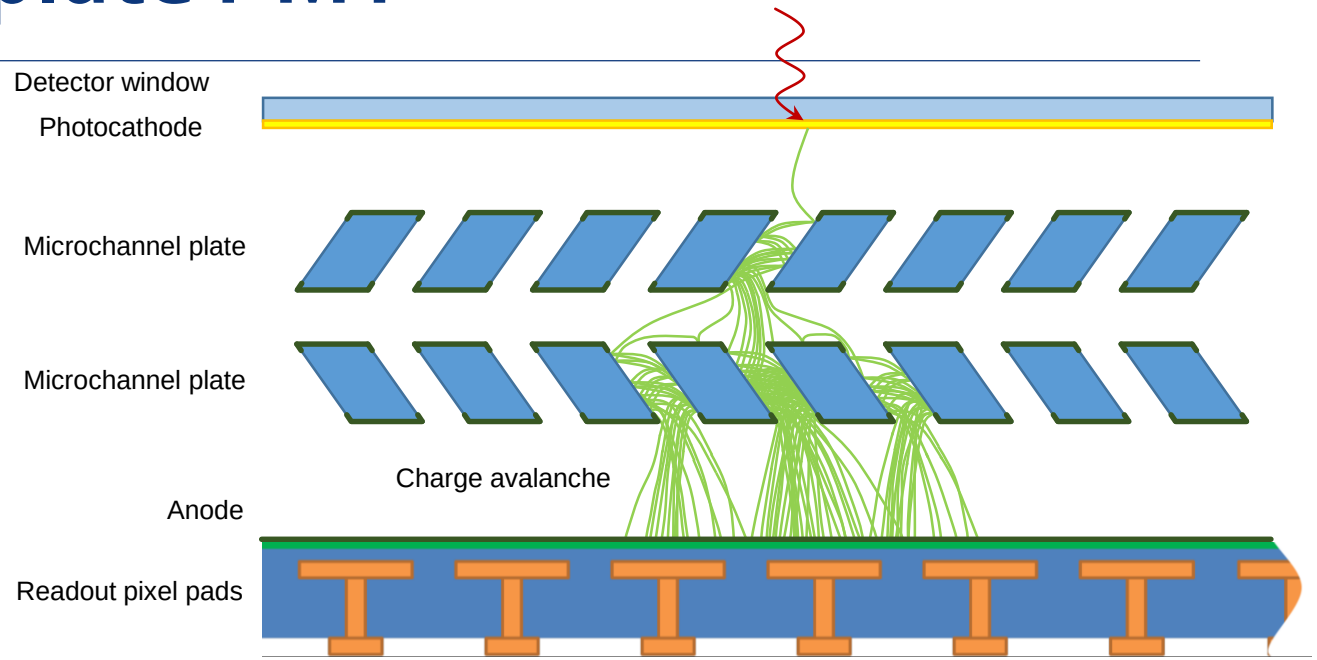
- Cherenkov light from radiator plate undergoes total internal reflection
  - Project light onto photodetector with focusing optics
  - Infer Cherenkov angle per photon to correct for chromaticity
  - Combine time of detected photons into track timestamp
- Single photon time resolution
  - Expect to detect ~30 photons / track
  - Required single-photon resolution is ~70ps
  - Budget
    - 50ps (electronics)
    - 50ps (photon reconstruction)

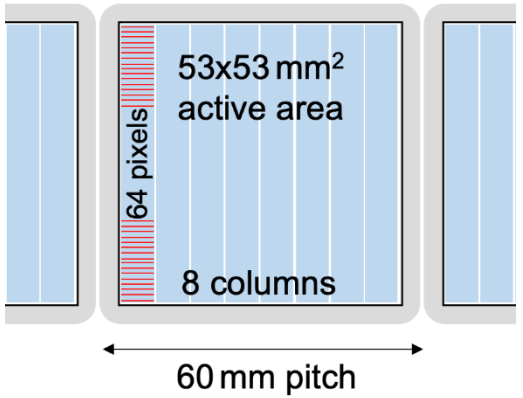


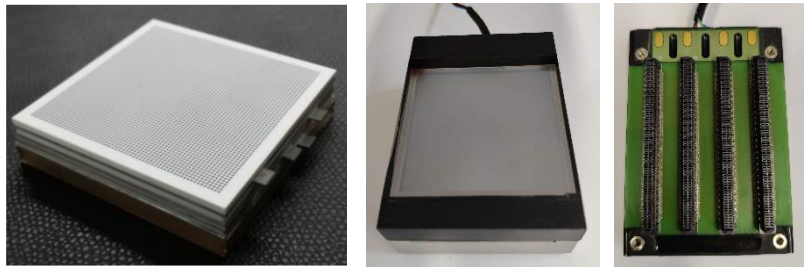


The TORCH microchannel plate PMT

- Requirement on angular resolution sets detector pixel size
  - Detectors with 53x53mm² active area
  - 1 mrad requirement on both angles translates to 128x8 pixels
- Charge spread over multiple pixels
  - Pixels grouped per 8 in horizontal direction
  - Required resolution achieved with 64x8 pixels
- MCP-PMT detector developed by Photek
  - 10 units have been delivered for use in prototype

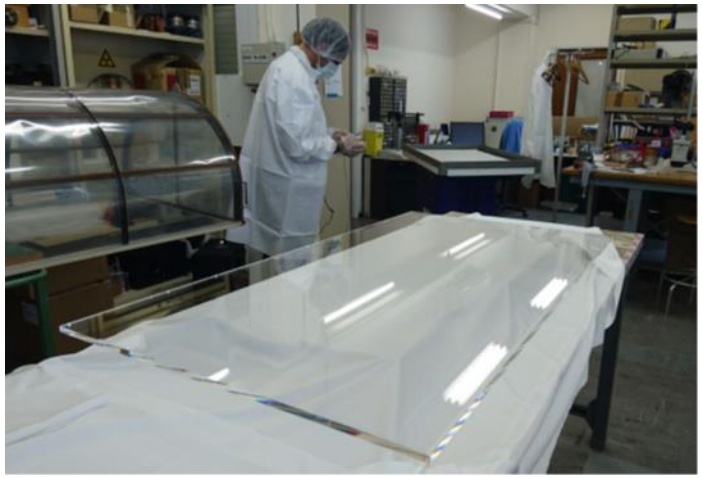


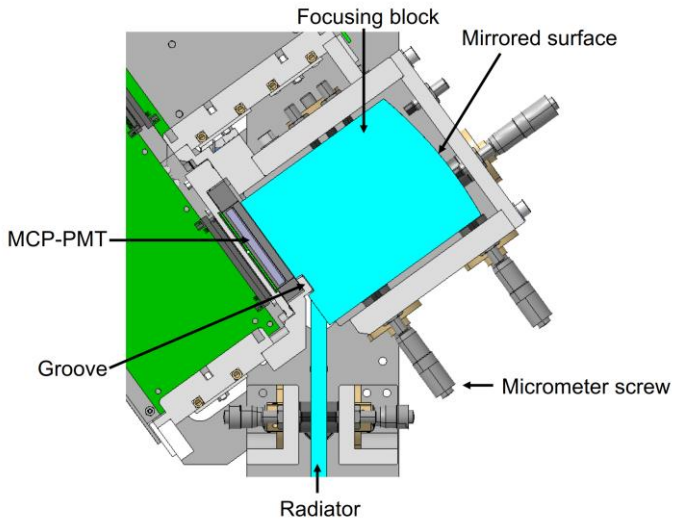


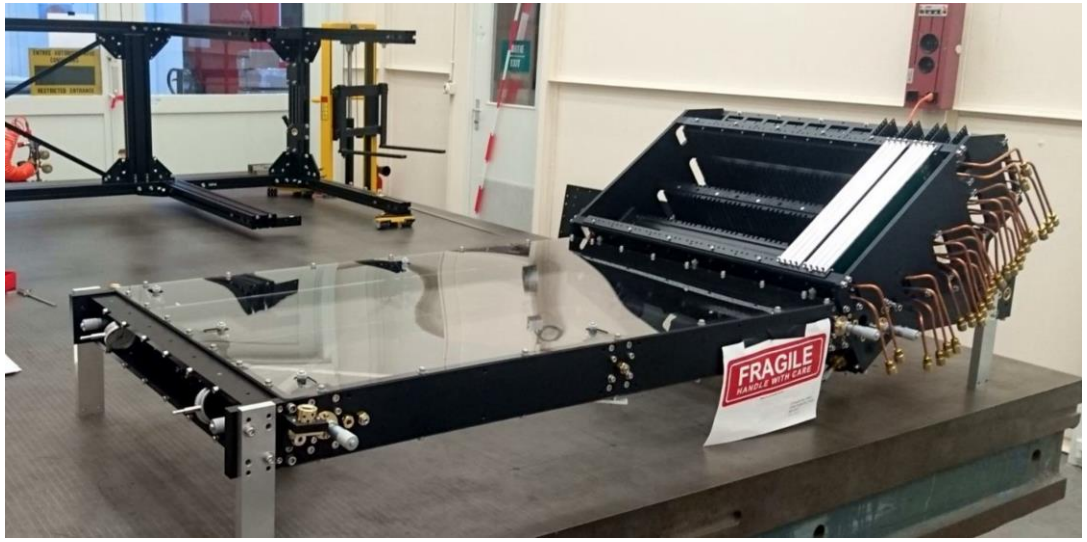


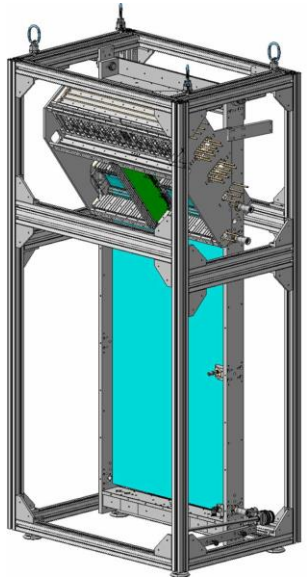
A prototype of the TORCH detector

- A prototype of the TORCH detector has been developed: ProtoTORCH
- Optics sourced from Nikon
  - Full-width, half-height radiator
  - Full-sized focusing optics
  - Glued with Pactan 8030



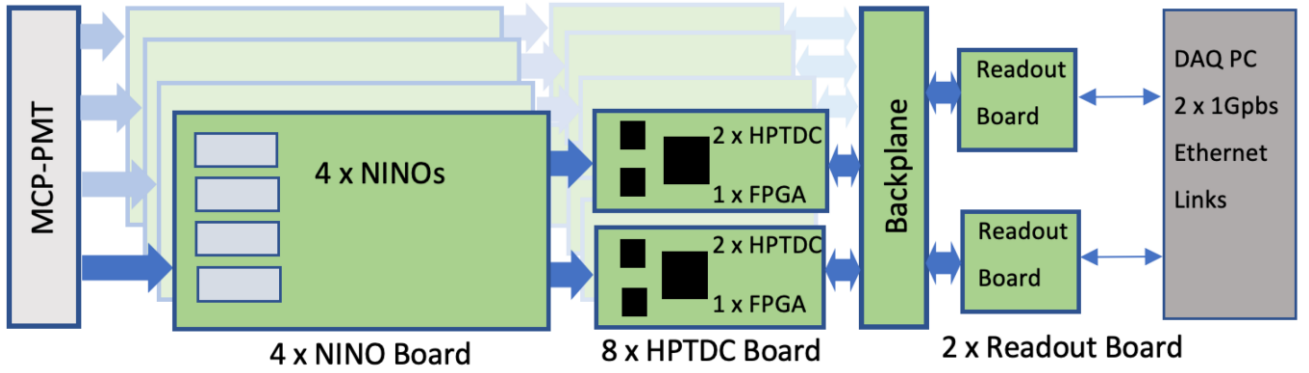


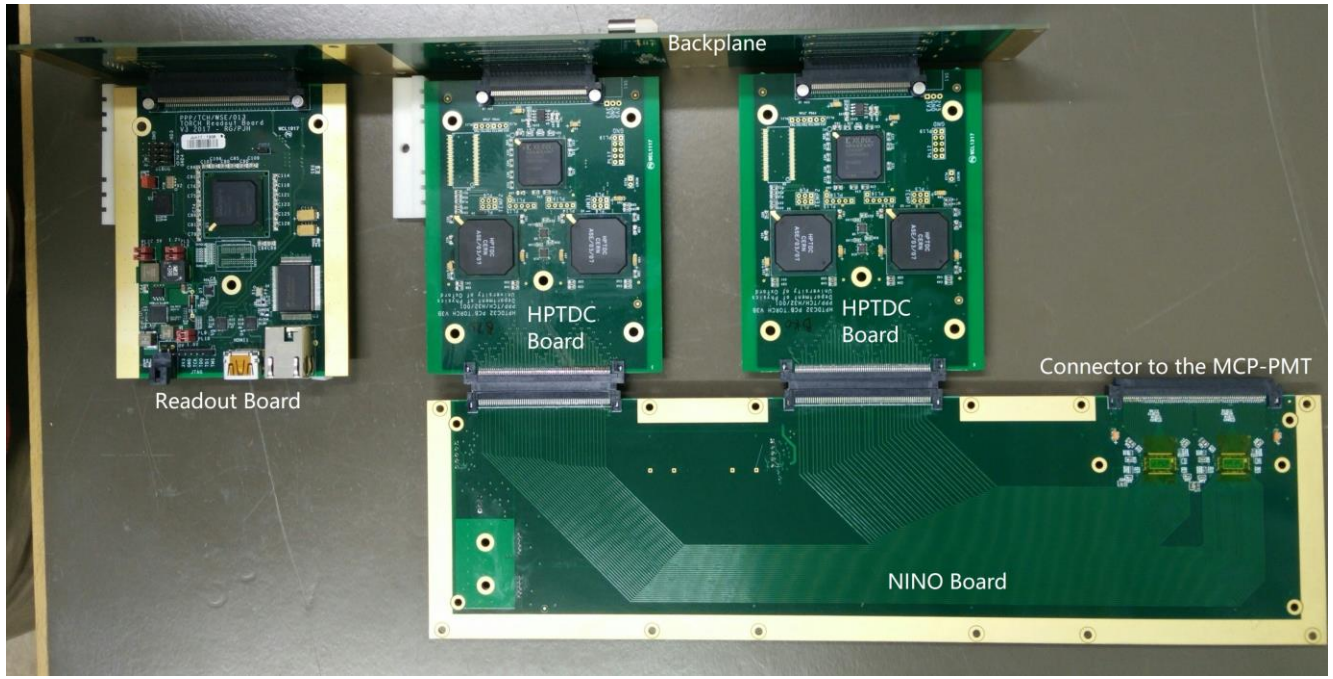




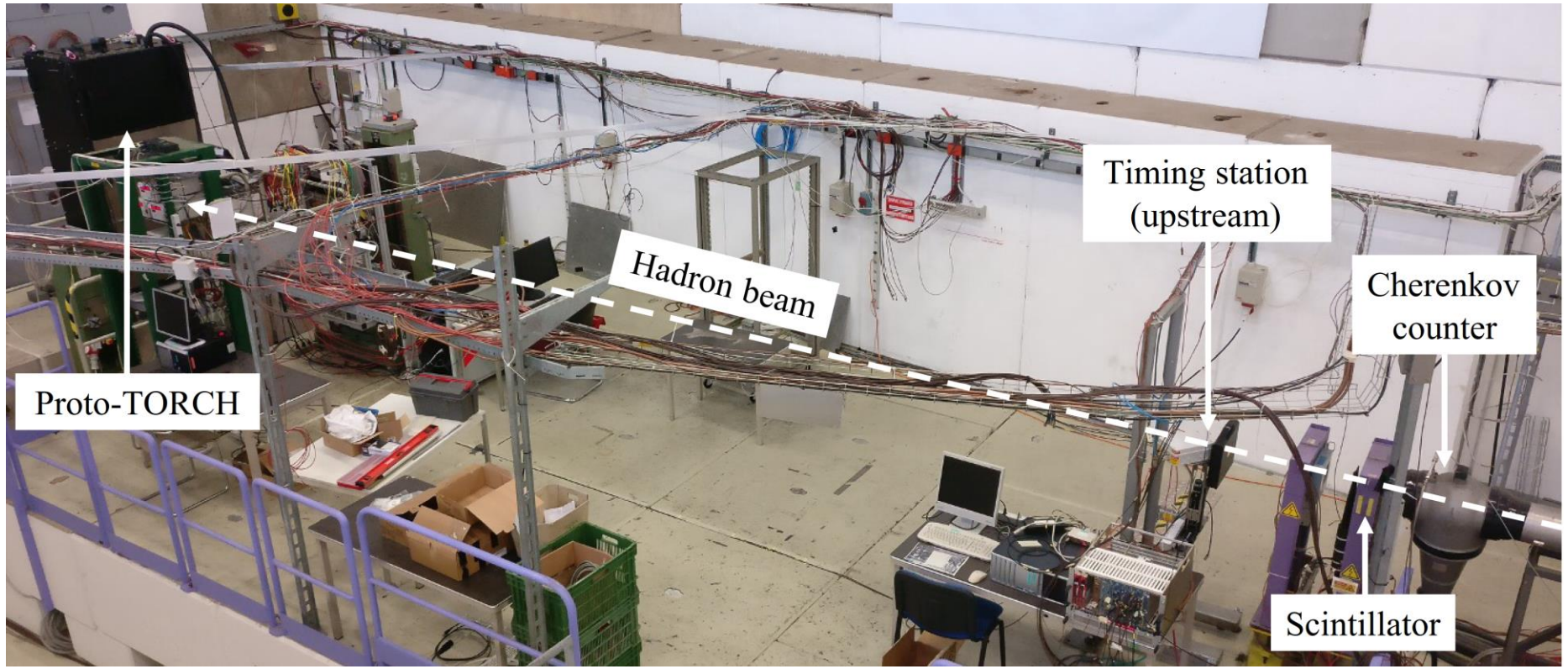
Detector readout for the TORCH prototype

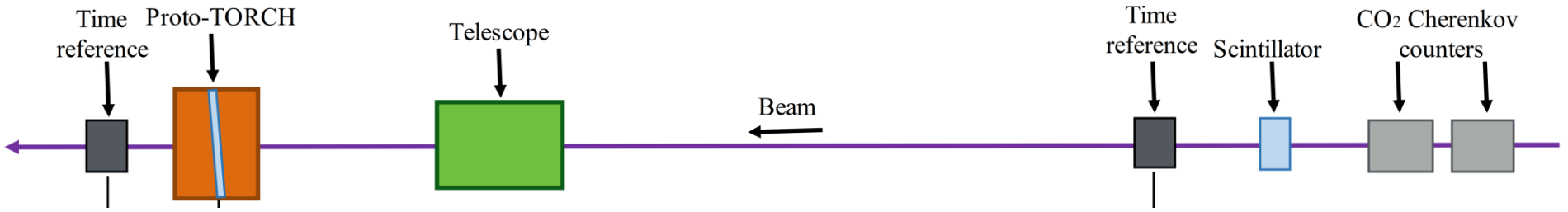
- Readout based on NINO and HPTDC chips
  - Originally developed for ALICE TOF
- Combination of NINO and HPTDC allows to time-tag leading edge and measure time over threshold
- Dedicated setup has been developed for board calibration
- Future versions based on picoTDC and fastIC under study





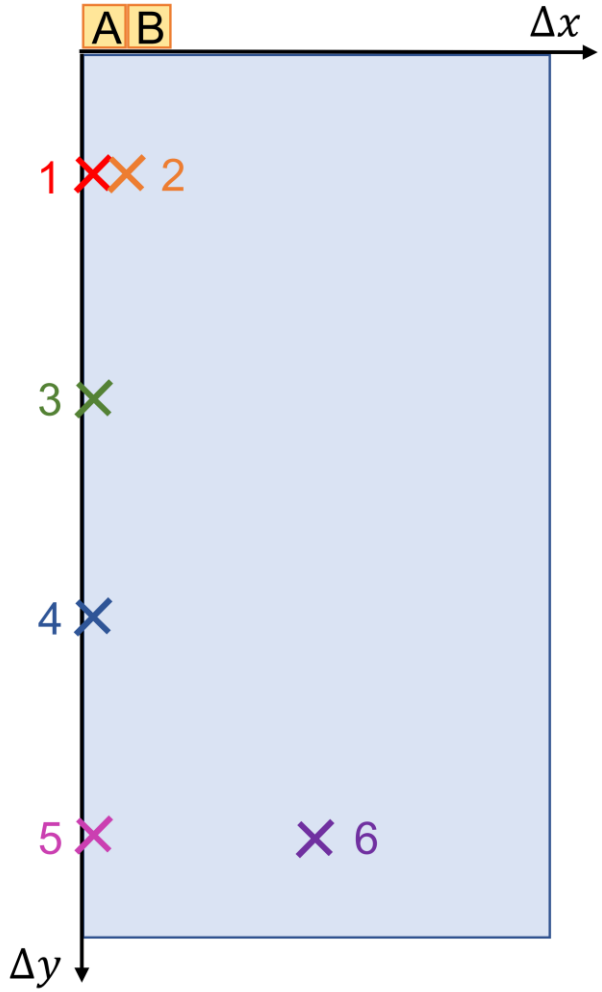
ProtoTORCH Testbeam @ T9 (November 2018)



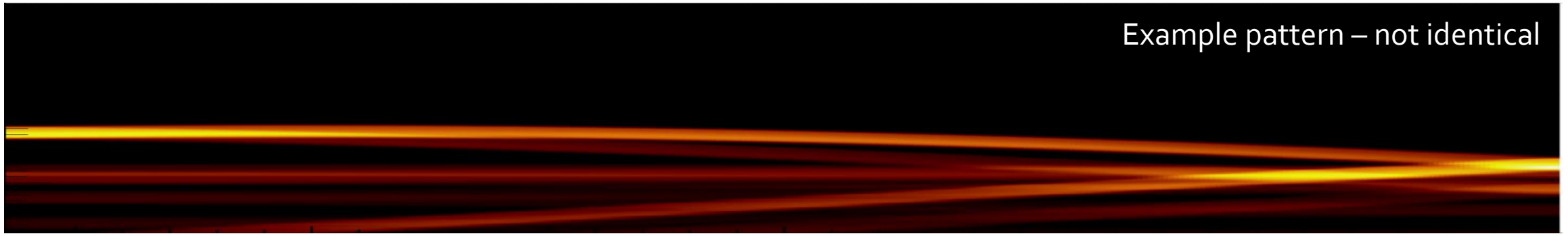


ProtoTORCH Testbeam @ T9

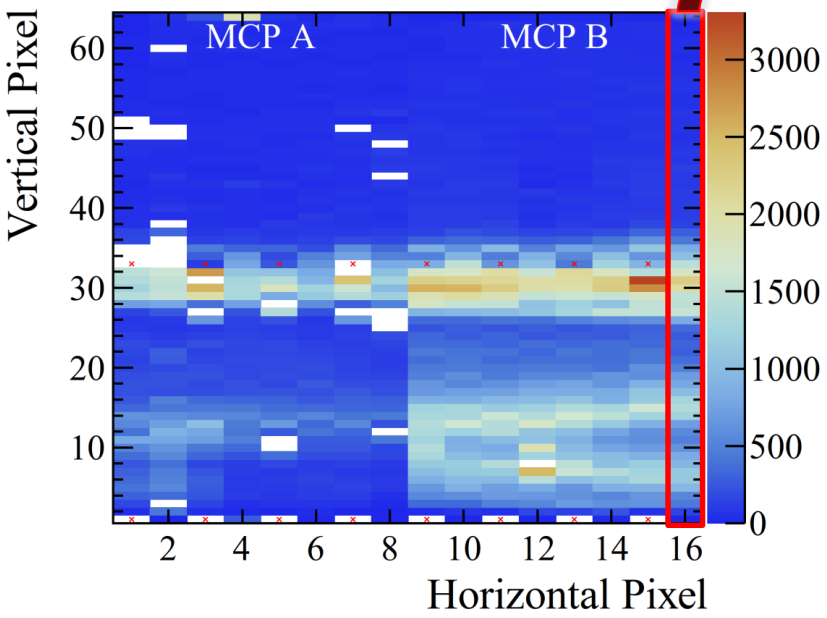
- ProtoTORCH was equipped with two MCP-PMTs for this testbeam
  - Time reference from timing stations inserted at HPTDC level
- 8 GeV/c beam
  - Combination of Time of Flight and Threshold Cherenkov counters used for PID
  - (47.3 ± 1.5)% pions and (52.7 ± 1.5)% protons
- Exposed to beam at six positions



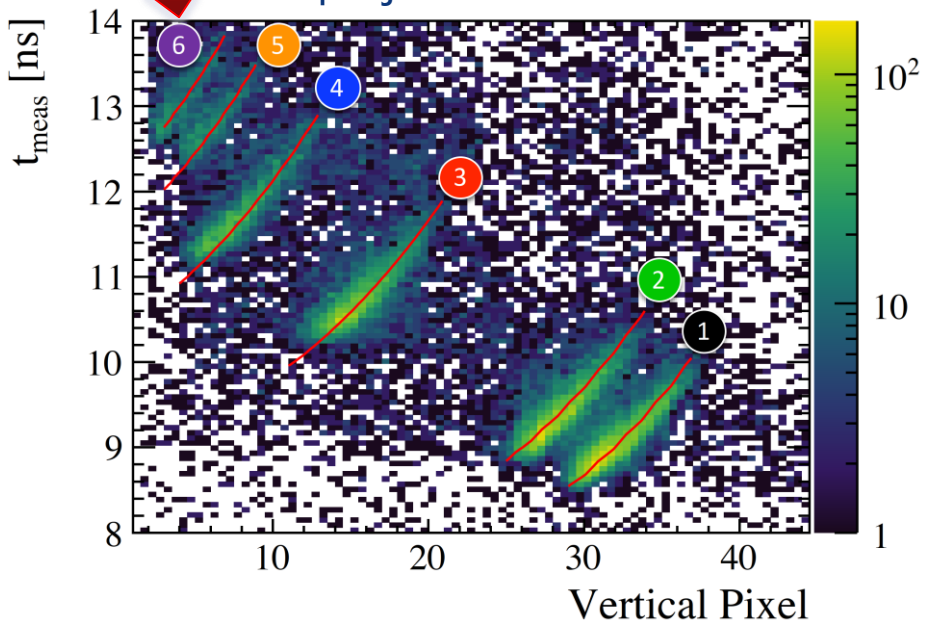
Collected data – Space & time

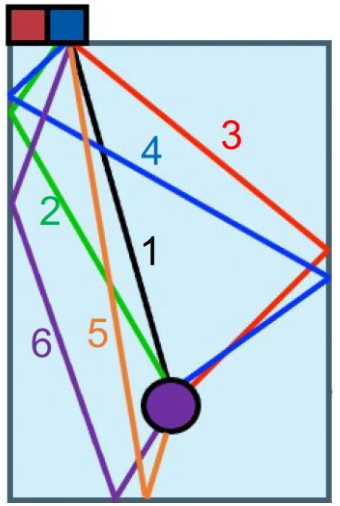


Data collected over area



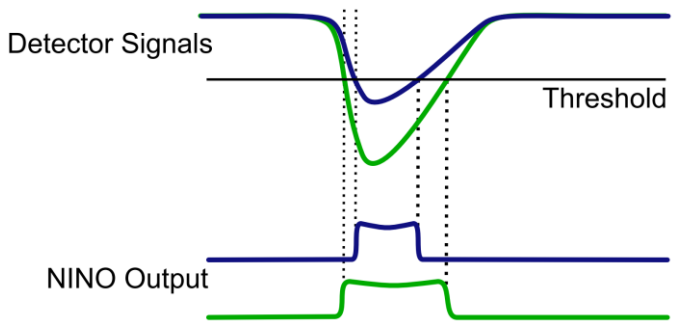
Time projection of column 16

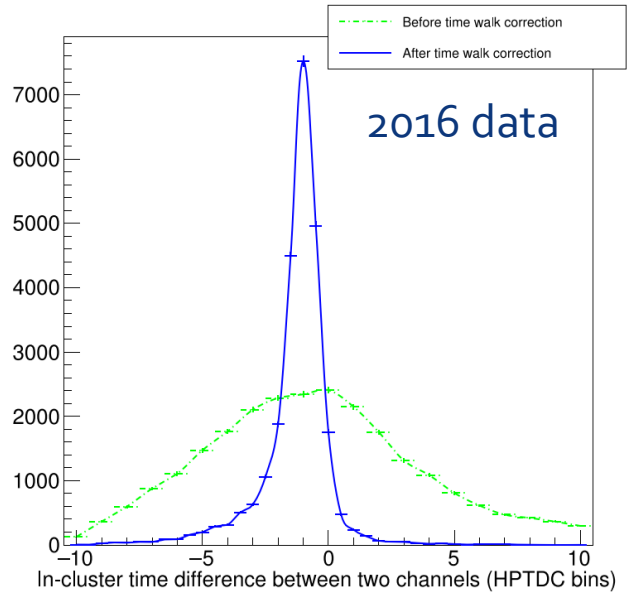




Testbeam data processing

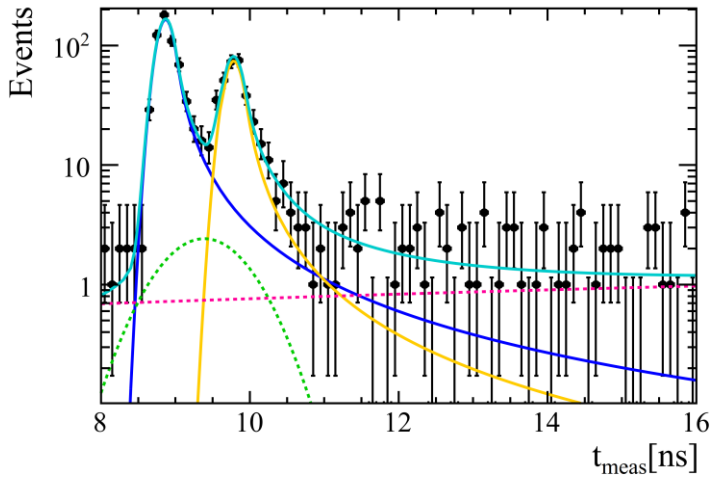
- Integral Non-Linearity
  - Not all time bins in HPTDC are equally sized
  - Can be mapped out from testbeam data as clock and data are not correlated
- Time walk is corrected for
  - Mapped out for electronics using data-driven method
- Clustering algorithm applied
  - Combine position and time information for neighboring pixels sufficiently close in time
- No charge to width calibration implemented yet
  - Expected to be operational for analysis of 2022 data

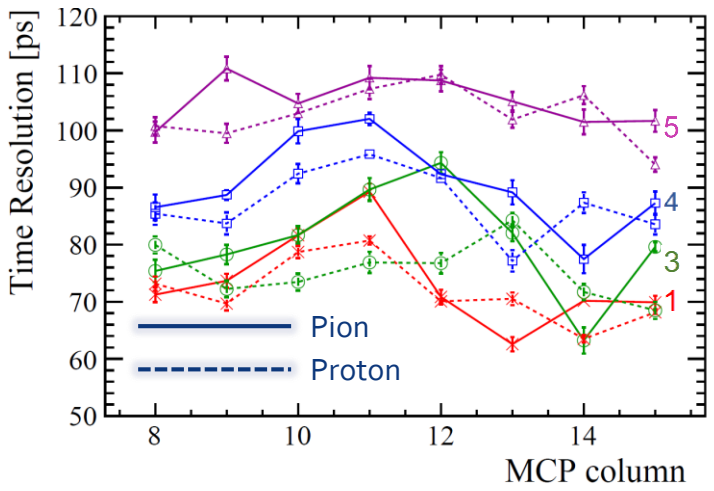


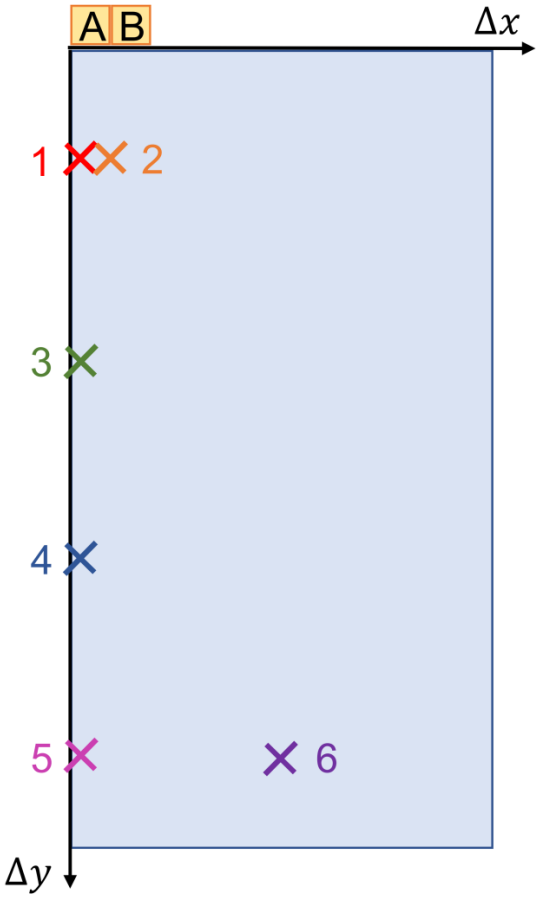


Testbeam – Time resolution

- Determine time resolution by fitting time distribution for observed peaks
  - Resolution derived from sigma of fitted Crystal Ball
- For beam position close to MCP-PMT, goal of 70ps time resolution is reached
  - Time resolution degrades as distance from MCP-PMT increases, indicating effect from reconstruction
  - Reconstruction strongly impacted by small readout effects: small errors in reconstruction of Cherenkov angle scale with photon path length
  - Improving calibrations further should significantly improve this issue

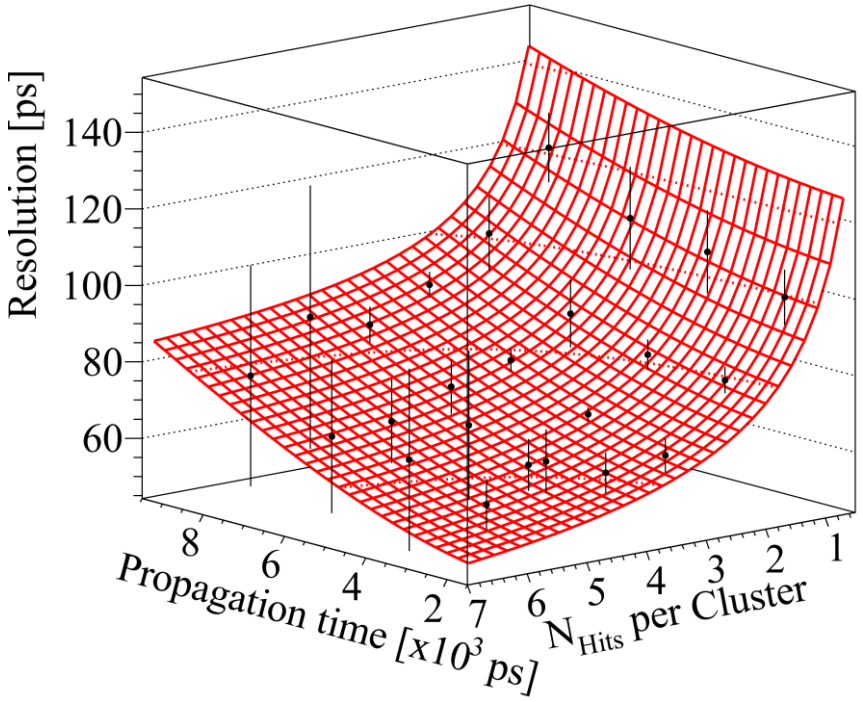






Time resolution – further analysis

- Time resolution can be broken down further
  - Analysed as a function of reconstructed propagation time per photon and number of hits per cluster
- Three factors contribute to time resolution
  - Propagation time in quartz (linear with path length)
  - MCP resolution (constant)
  - Number of hits in cluster ($\sqrt{N_{hits}}$)
- Further improvement expected
  - Better calibration will impact all parameters
  - Upcoming testbeam with full complement of PMTs

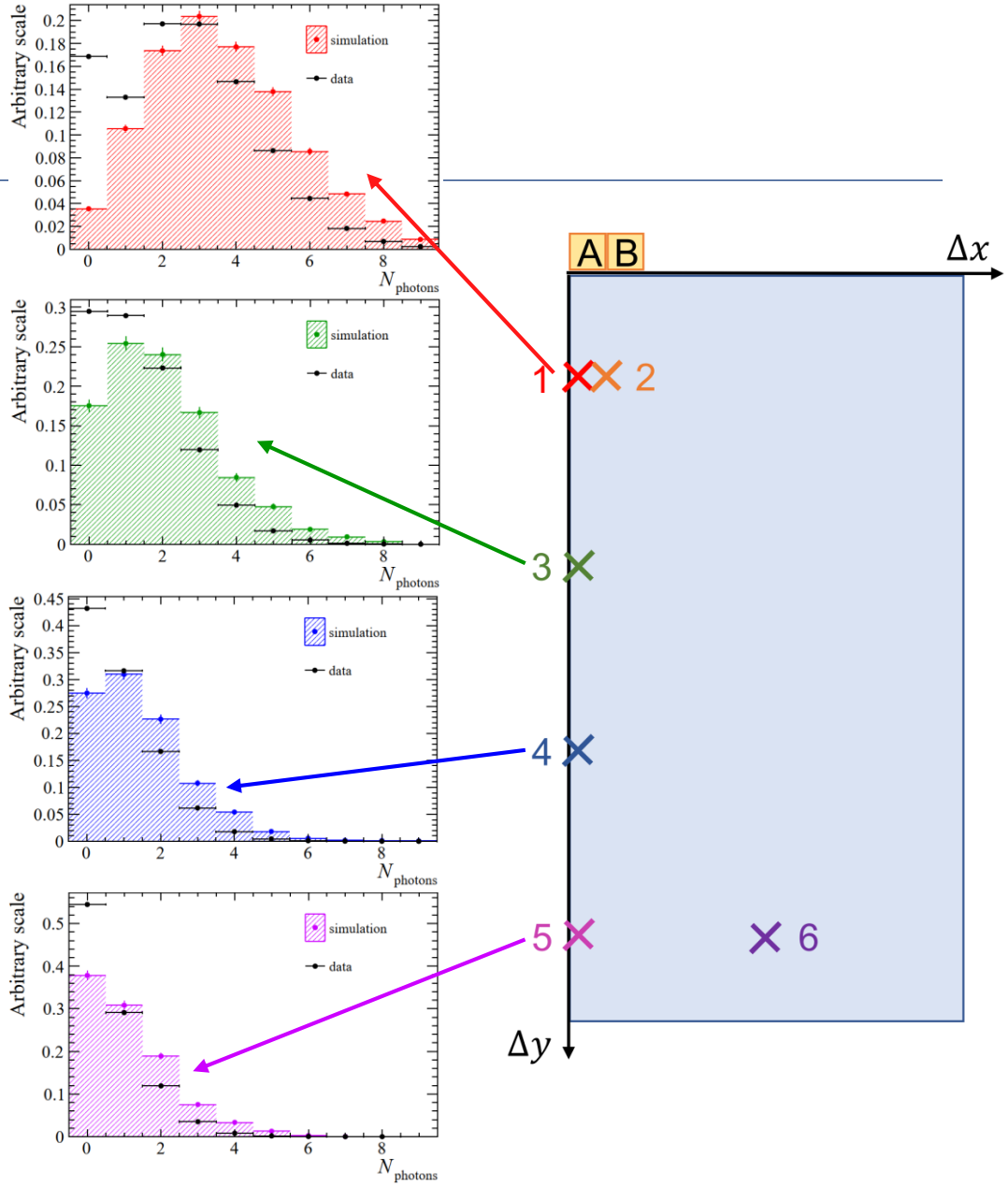


Contribution	Fitted values (ps)		Target values (ps)
	Pion	Proton	
$\sigma_{\text{prop}}(t_p)$	$(8.3 \pm 0.7) \times 10^{-3} \times t_p$	$(7.6 \pm 0.5) \times 10^{-3} \times t_p$	$(3.75 \pm 0.8) \times 10^{-3} \times t_p$
σ_{MCP}	34.5 ± 8.6	31.0 ± 7.6	33
$\sigma_{\text{RO}}(N_{\text{Hits}})$	$(96.2 \pm 6.7)/\sqrt{N_{\text{Hits}}}$	$(95.0 \pm 6.0)/\sqrt{N_{\text{Hits}}}$	$60/\sqrt{N_{\text{Hits}}}$

Testbeam – photon counting

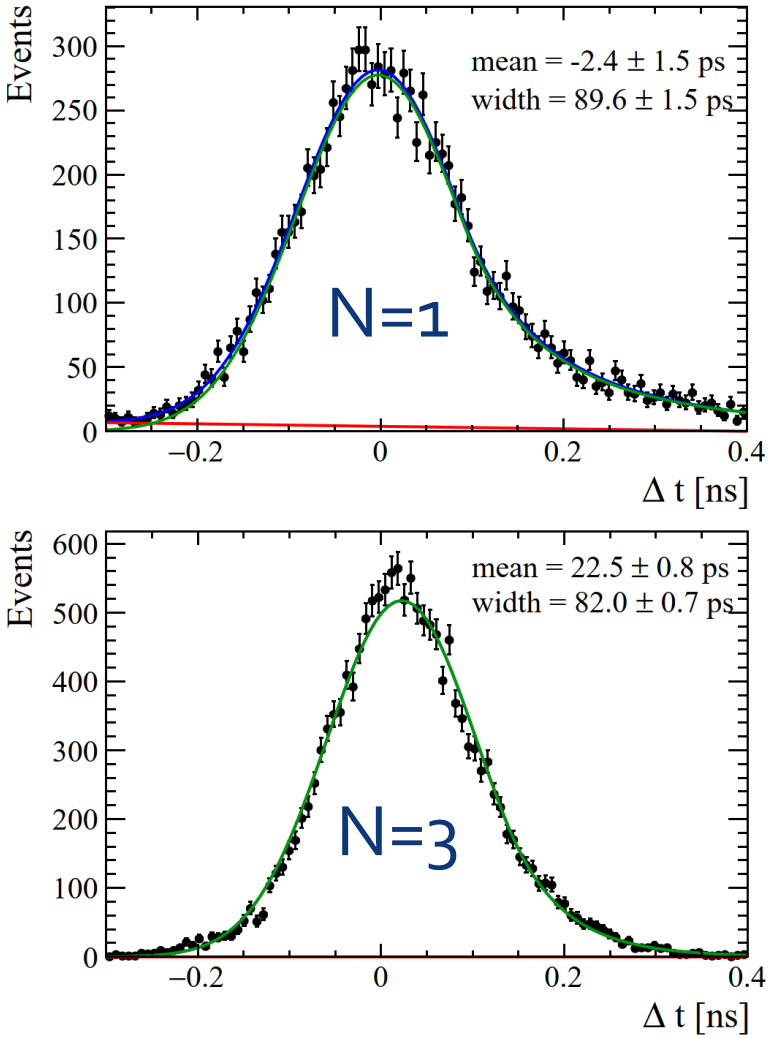
- Counting efficiency of incoming light is critical
  - Second figure of merit
  - Compare with Geant4 simulation to benchmark
- Light yield somewhat lower than expected
  - Information on no-light bin will improve with more PMTs
  - Expected to improve further with calibration

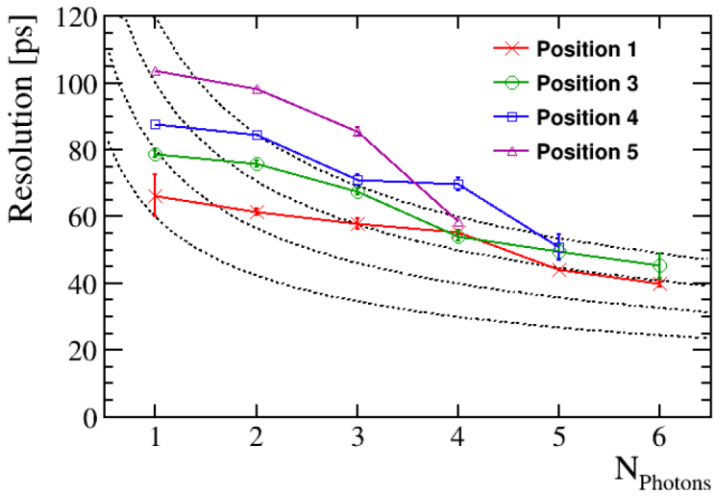
Position	Mean N_{photons}		Mean(Data)/Mean(Simulation)	
	Data	Simulation	All	Excluding N_{photons}=0
1	2.605 ± 0.007	3.586 ± 0.020	0.726 ± 0.004	0.843 ± 0.005
3	1.419 ± 0.005	2.016 ± 0.029	0.704 ± 0.010	0.824 ± 0.010
4	0.937 ± 0.004	1.454 ± 0.024	0.644 ± 0.011	0.823 ± 0.008
5	0.677 ± 0.002	1.127 ± 0.022	0.600 ± 0.012	0.820 ± 0.009



Testbeam – time resolution per track

- Time resolution per track has been studied
  - Only low statistics available (two photodetectors)
- Time resolution improves with more photons
  - But not as fast as expected
  - Calibration is key, as before





Upcoming testbeam

- Testbeam planned at T9 – CERN East Area
  - 31 October – 28 November
  - Area newly renovated
- Full instrumented detector
  - 10 MCP-PMTs with 8x64 channels
  - Fully equipped with NINO + HPTDC
  - Calibration of boards ongoing in dedicated test setup
- New DAQ for streamlined data taking, new and improved™ data analysis under preparation
- High expectations for fresh data: improved resolution and photon counts
  - Particle identification using TORCH should be within reach

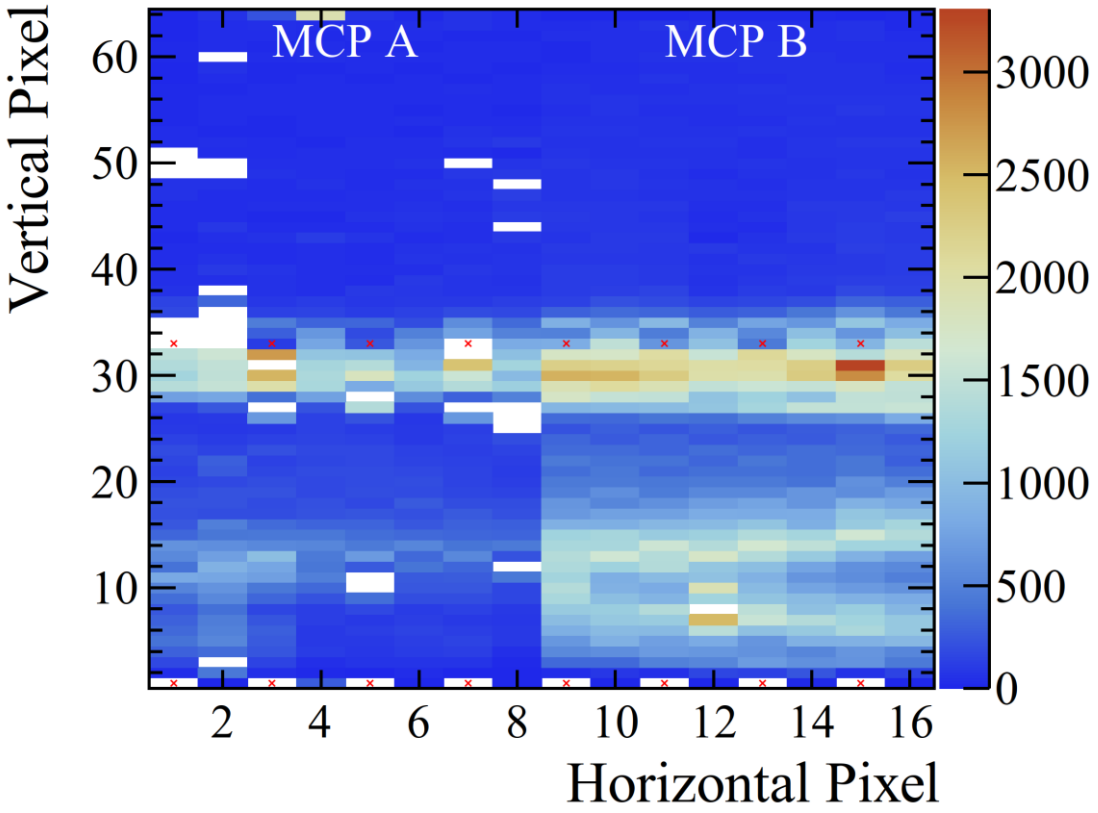
Conclusions

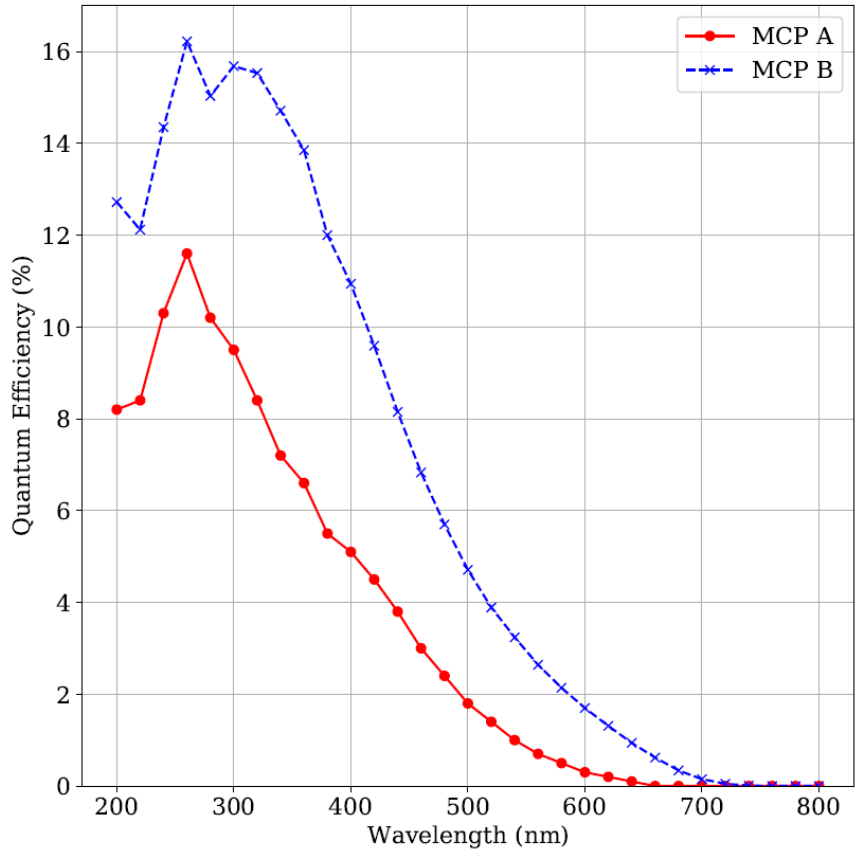
- TORCH is a solid Cherenkov-based PID detector designed to complement existing LHCb PID
  - Adds positive π-K separation (2-10 GeV/c) and p-K separation (2-20 GeV/c)
  - Part of the proposed Upgrade-II of LHCb
- Testbeam data analysis is nearly complete
  - Single photon time resolution 70-110ps, photon counting ~82% of expectation
  - Full paper nearing final collaboration review
- Testbeam preparation ongoing (November 2022)
  - Full complement of PMTs and readout >5k channels
  - Calibration of electronics ongoing, key feature for analysis
  - High expectations: TORCH-based particle-ID to show full scope of detector

Questions?

Quantum efficiency in testbeam

- Degraded performance of MCP A (left) relative to MCP B (right)
  - MCP A has ~half the efficiency of MCP B (integrated over the spectrum)





Propagation time reconstruction

- Large impact from length of path on reconstruction
  - Limits reconstruction
- The resolution in the Cherenkov angle is tied to the pixel size (fine direction) of the MCP-PMT
  - Uncertainty on Cherenkov angle dictates uncertainty on reconstruction of group refractive index
  - Path length functions as a lever arm
- As path length increases, the limited resolution on the Cherenkov angle factors linearly into the time resolution