Performance studies and future opportunities of THE TORCH DETECTOR

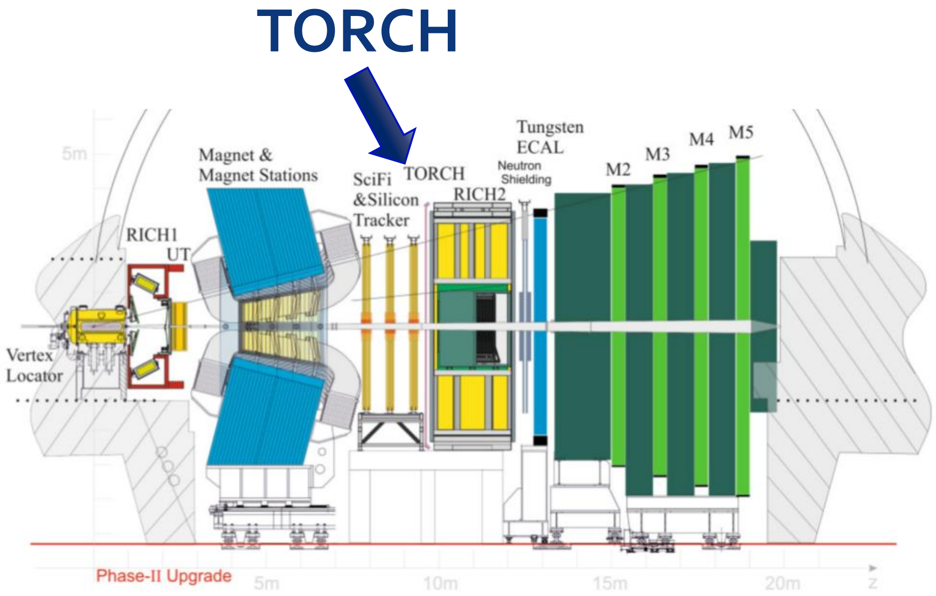
Maarten van Dijk on behalf of the TORCH collaboration

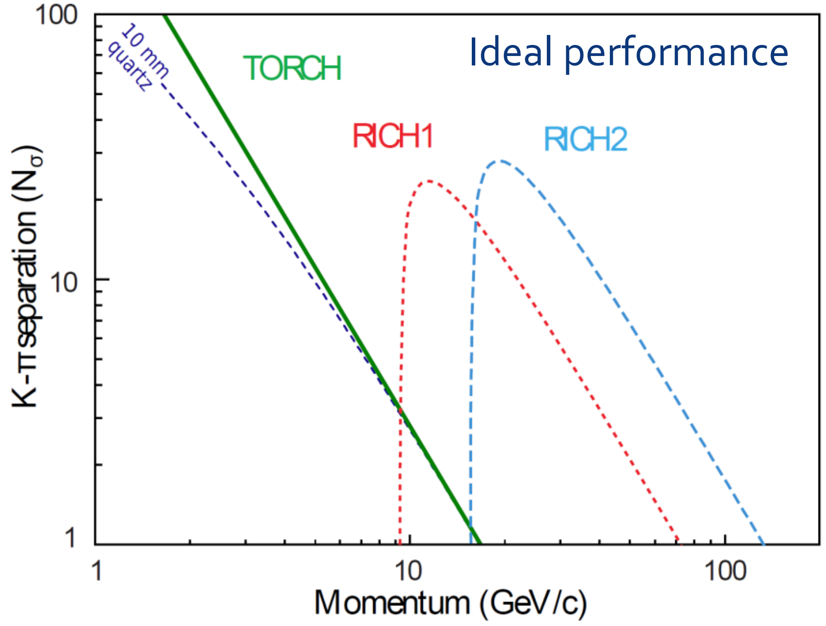
27-10-2022

PHOTEK ENVISAGE THE FUTURE
University of BRISTOL
UNIVERSITY OF OXFORD
CERN
THE UNIVERSITY OF EDINBURGH
WARWICK THE UNIVERSITY OF WARWICK
UNIVERSITY OF BATH
Jožef Stefan Institute

The TORCH detector

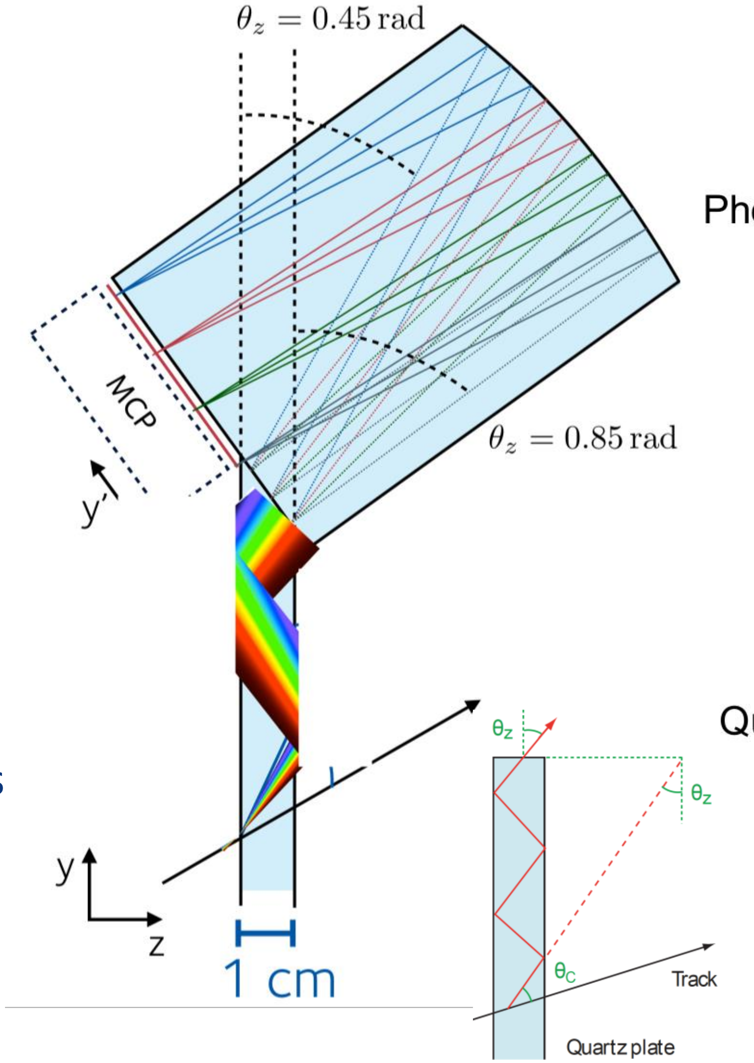
- TORCH: Time Of internally Reflected CHerenkov light
  - Also see this talk of L.M. Garcia Martin for details on reconstruction
  - DIRC-like detector
  - Similar to RICH but with a solid quartz radiator
- Part of LHCb Upgrade II
  - Existing RICH has ~10 GeV/c threshold for kaons (~20 GeV/c for protons)
  - 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

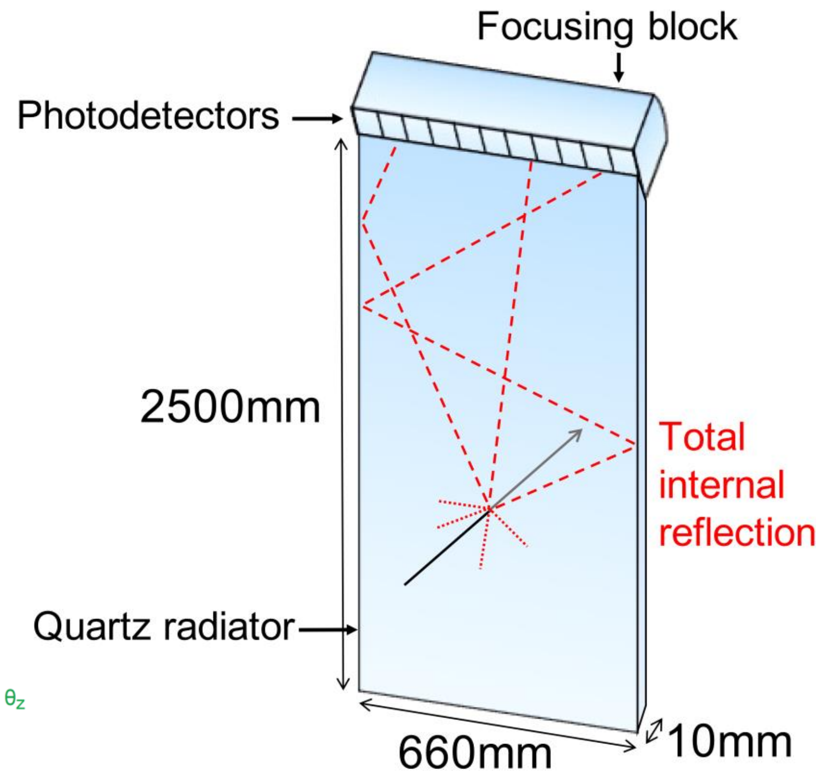




Principle of the TORCH detector

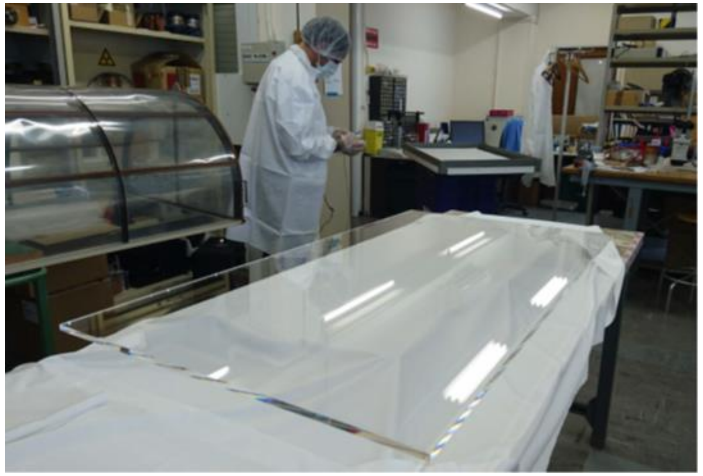
- Cherenkov light from radiator plate undergoes total internal reflection
  - Project light onto photodetector with focusing optics
  - Infer Cherenkov angle per photon to correct for chromaticity
  - Combine time of detected photons into track timestamp
- Single photon time resolution
  - Expect to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

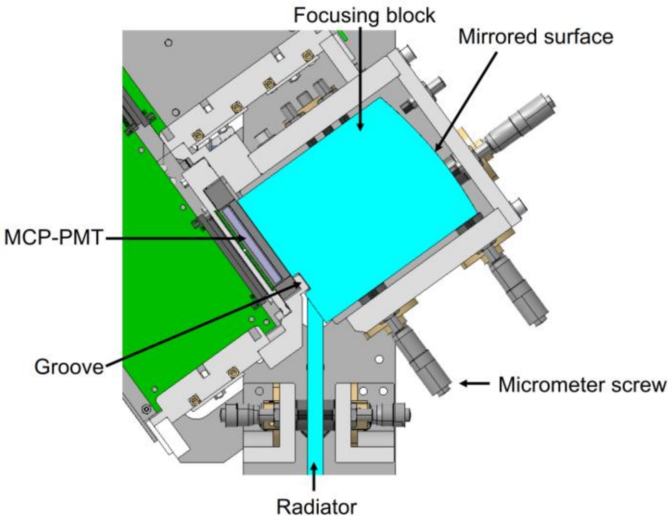


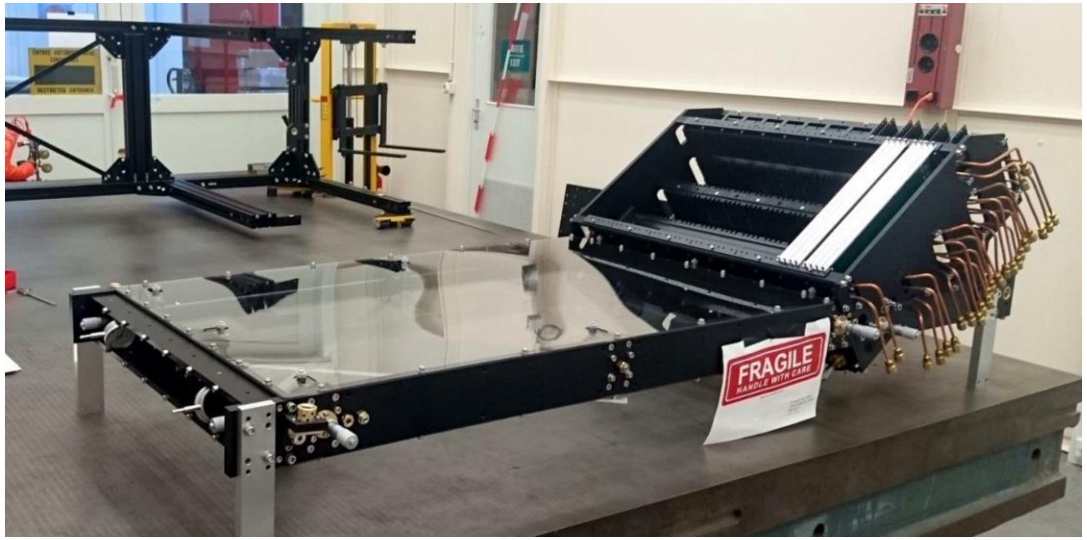


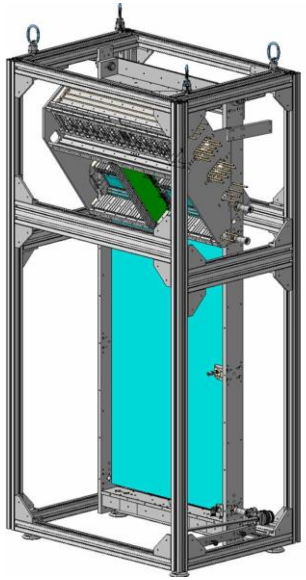
A prototype of the TORCH detector

- 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

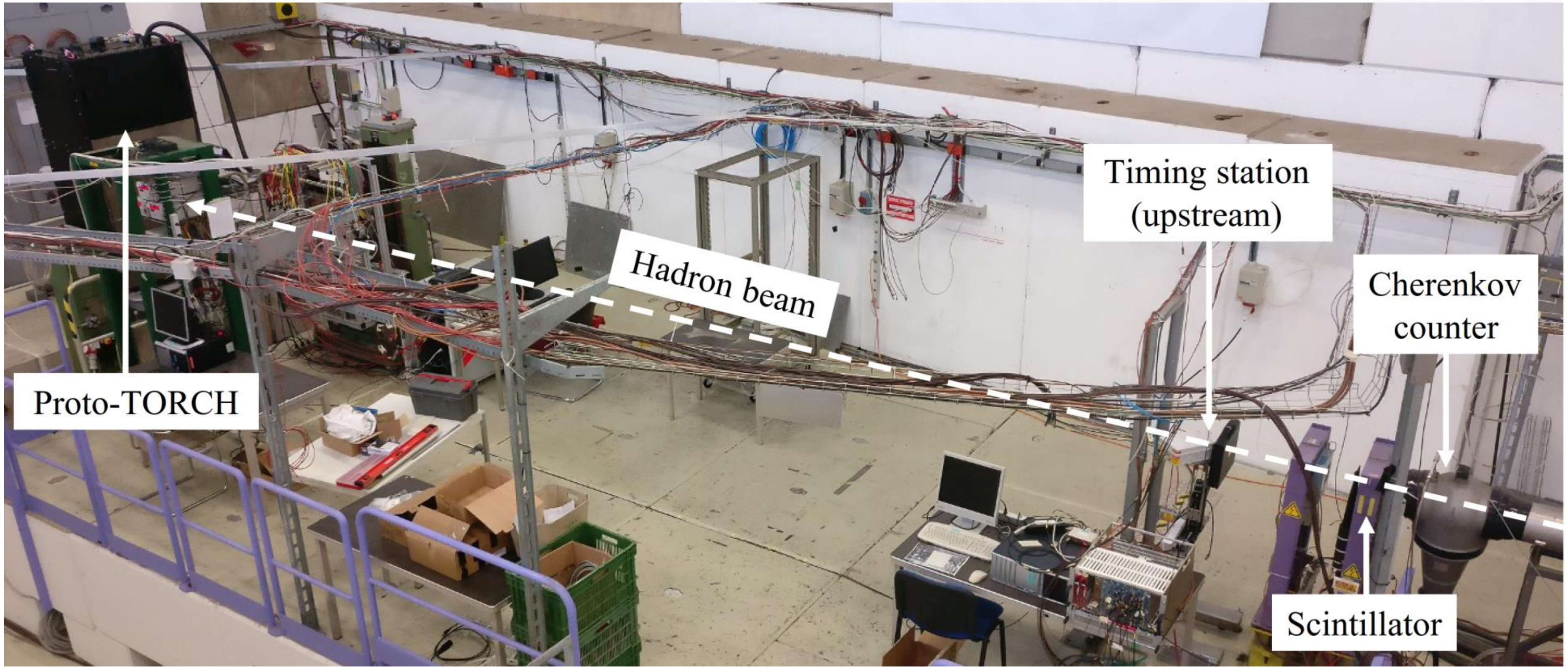


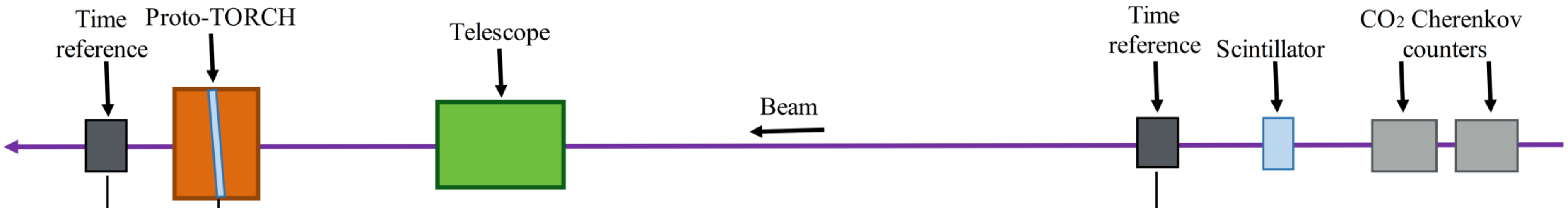






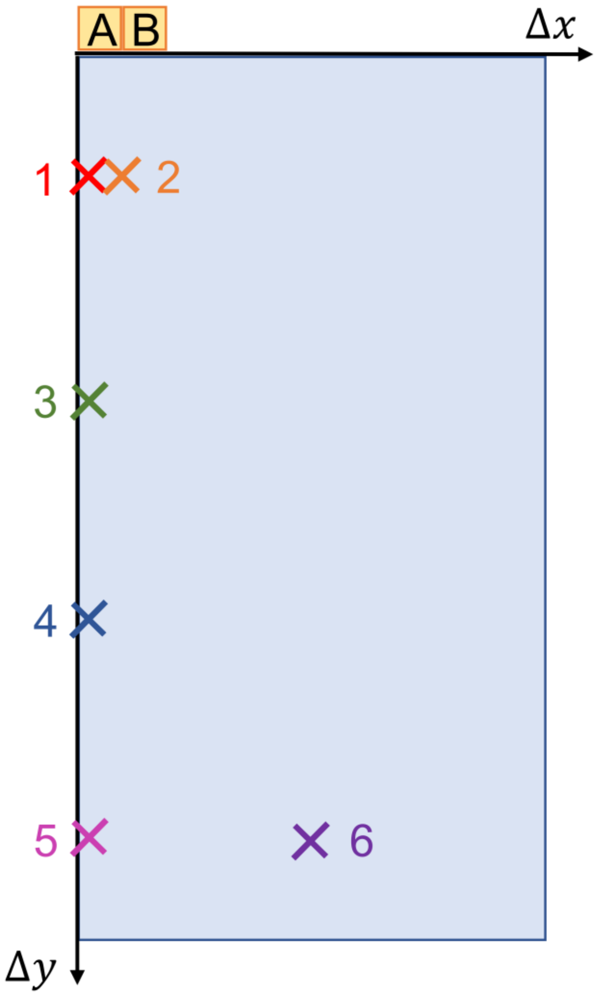
ProtoTORCH Testbeam @ T9 (November 2018)



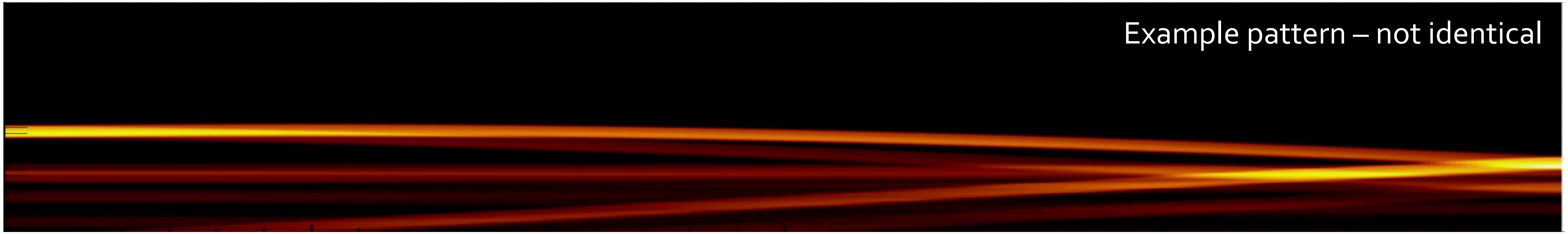


ProtoTORCH Testbeam @ T9

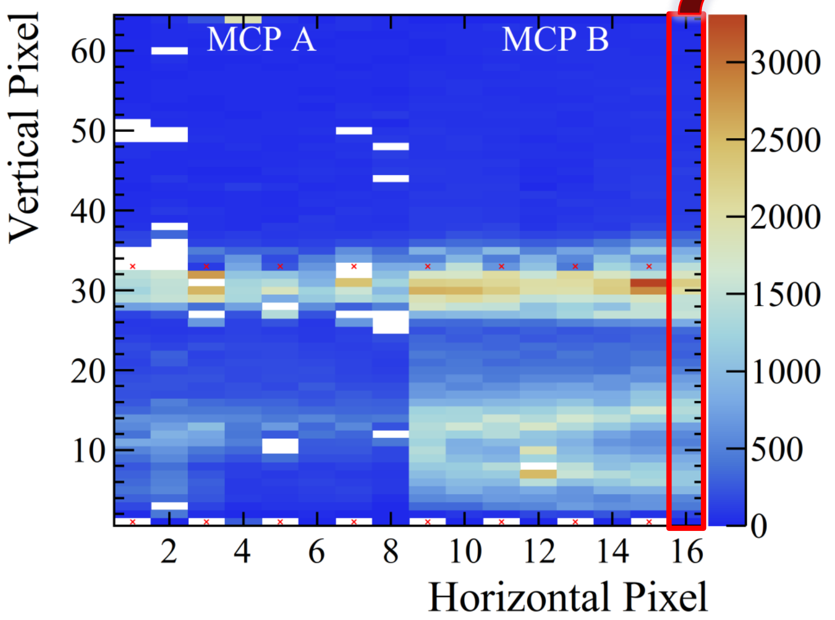
- ProtoTORCH was equipped with two MCP-PMTs for this testbeam
  - Time reference from timing stations inserted at HPTDC level
- 8 GeV/c beam
  - Combination of Time of Flight and Threshold Cherenkov counters used for PID
  - (47.3 ± 1.5)% pions and (52.7 ± 1.5)% protons
- Exposed to beam at six positions



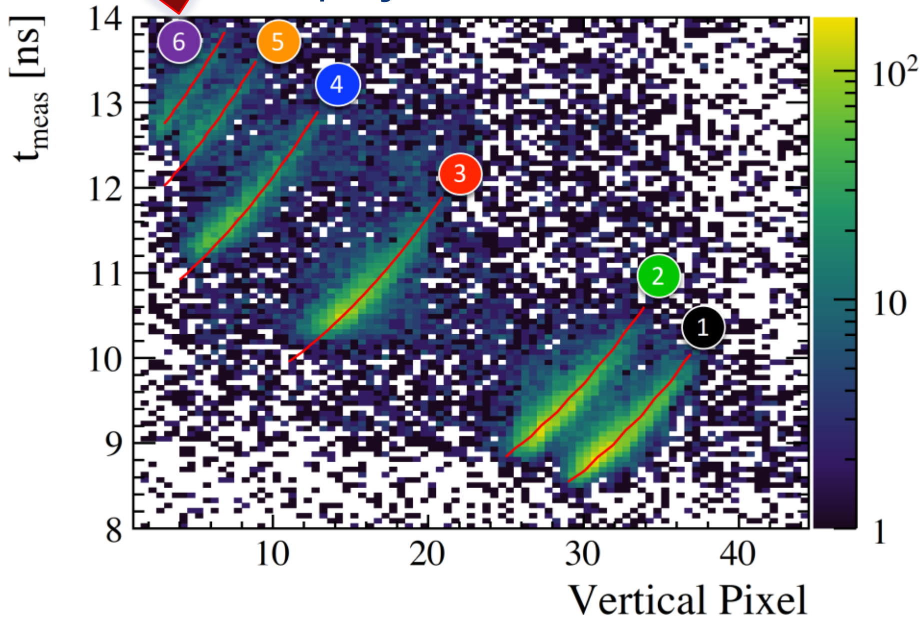
Collected data – Space & time

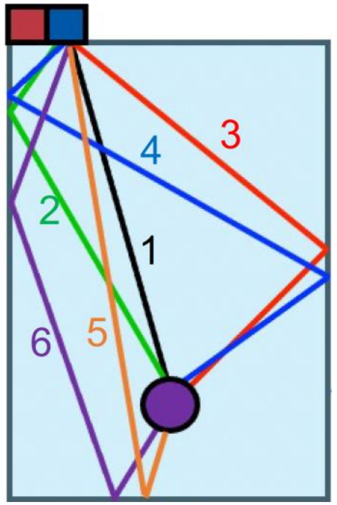


Data collected over area



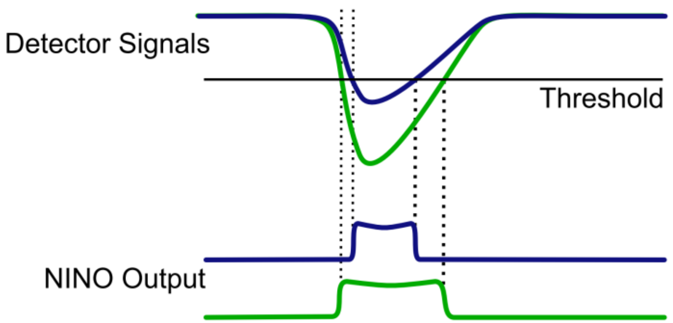
Time projection of column 16

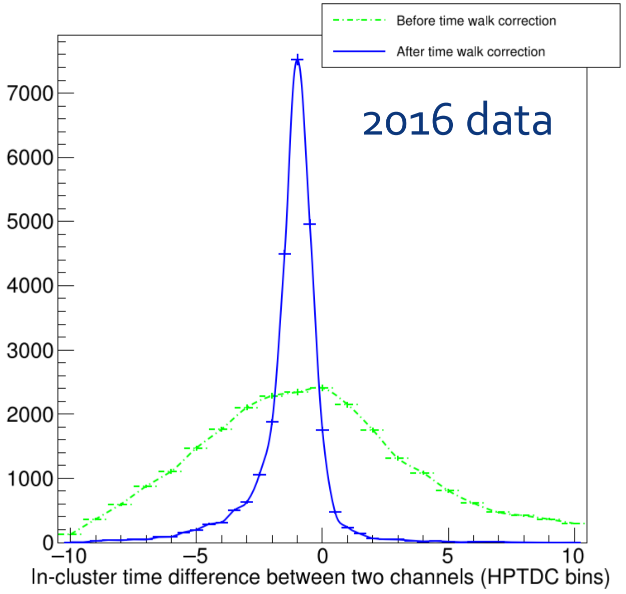




Testbeam data processing

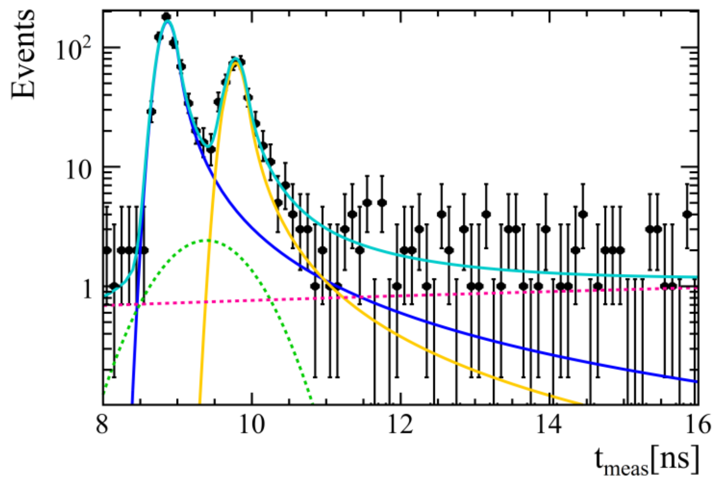
- Integral Non-Linearity
  - Not all time bins in HPTDC are equally sized
  - Can be mapped out from testbeam data as clock and data are not correlated
- Time walk is corrected for
  - Mapped out for electronics using data-driven method
- Clustering algorithm applied
  - Combine position and time information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

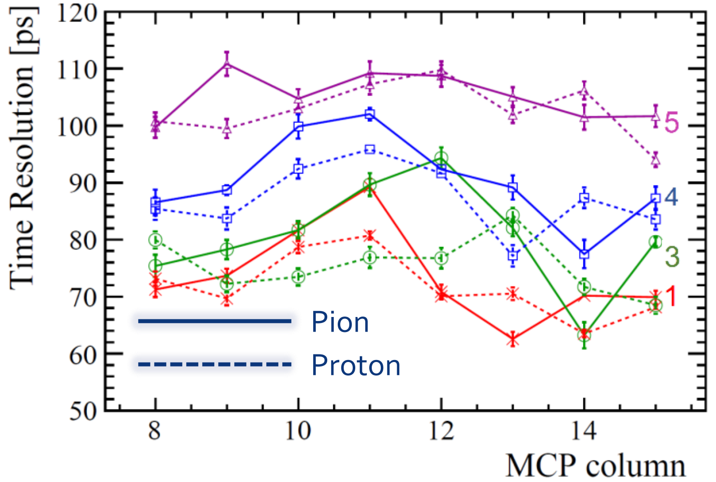


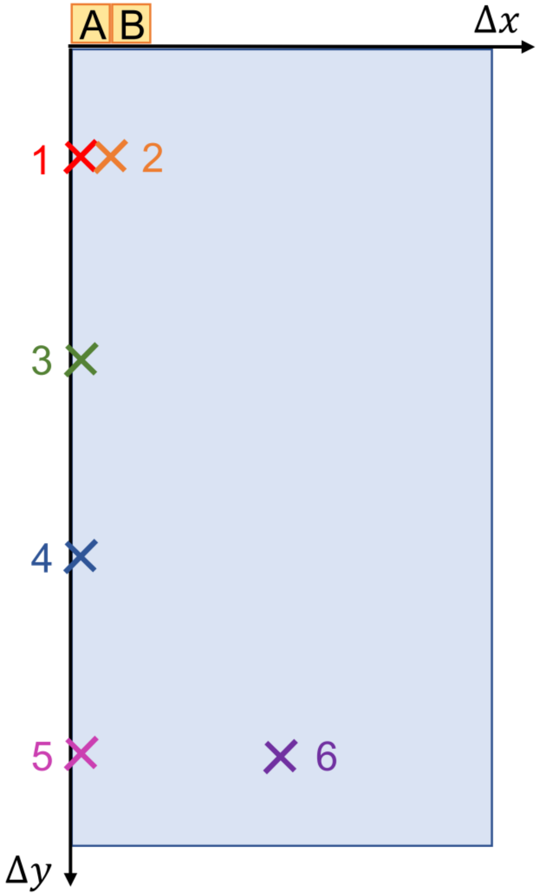


Testbeam – Time resolution

- 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

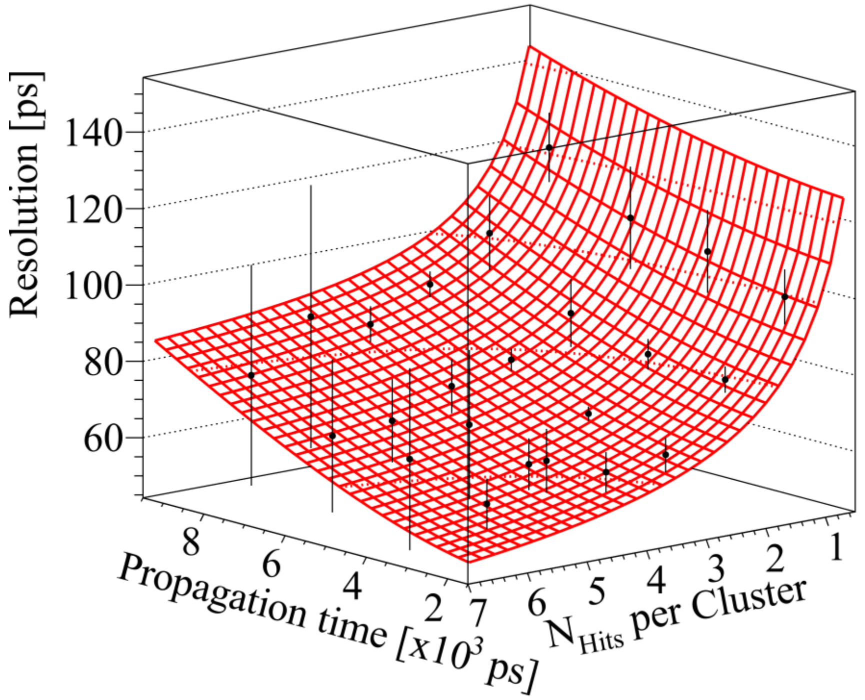






Time resolution – further analysis

- 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



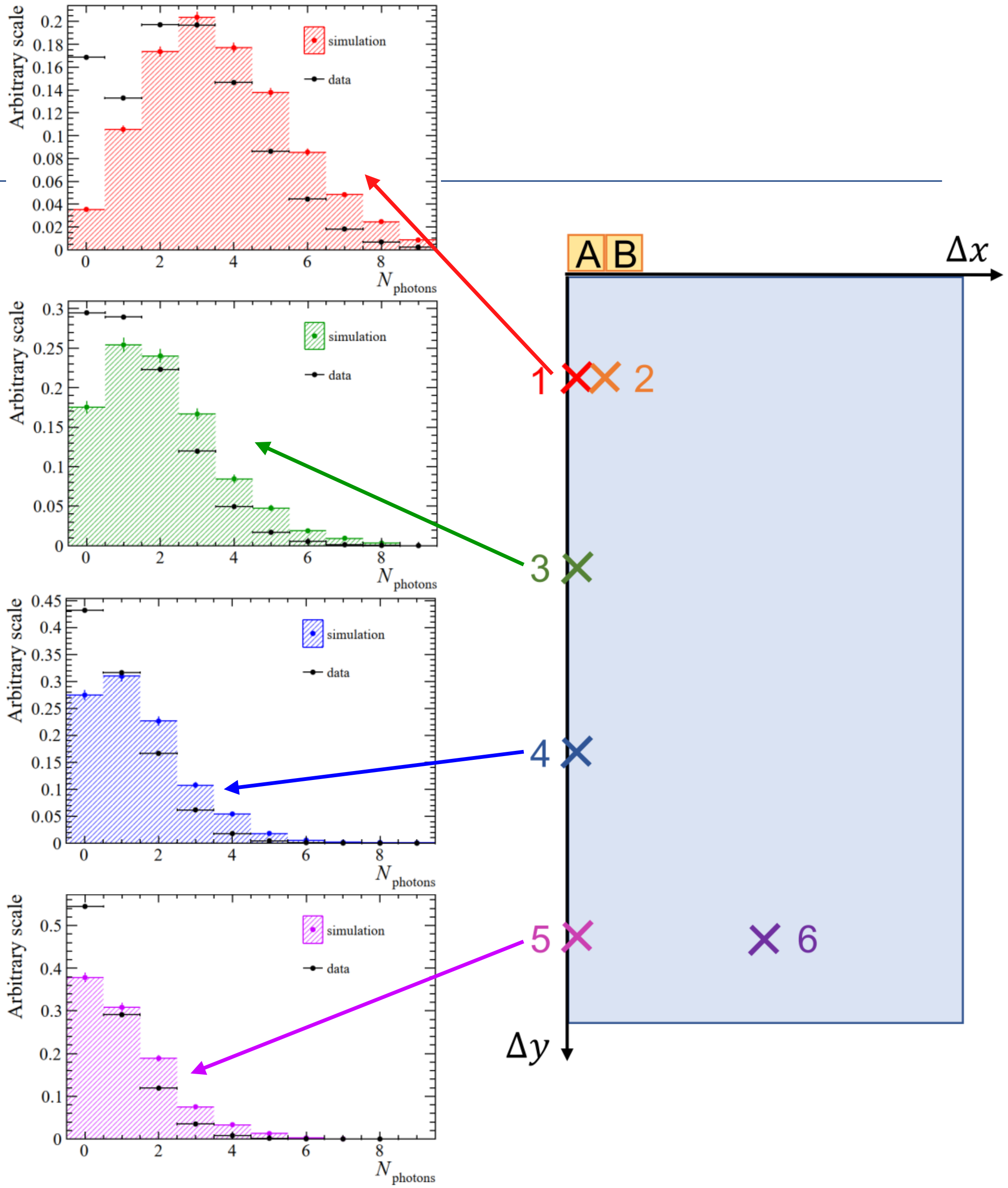
Contribution	Fitted values (ps)		Target values (ps)
	Pion	Proton	
$\sigma_{\mathrm{prop}}(t_p)$	$(8.3 \pm 0.7) \times 10^{-3} \times t_p$	$(7.6 \pm 0.5) \times 10^{-3} \times t_p$	$(3.75 \pm 0.8) \times 10^{-3} \times t_p$
σ_{MCP}	34.5 ± 8.6	31.0 ± 7.6	33
$\sigma_{\mathrm{RO}}(N_{\mathrm{Hits}})$	$(96.2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

Testbeam – photon counting

- Counting efficiency of incoming light is critical
  - Second figure of merit
  - Compare with Geant4 simulation to benchmark

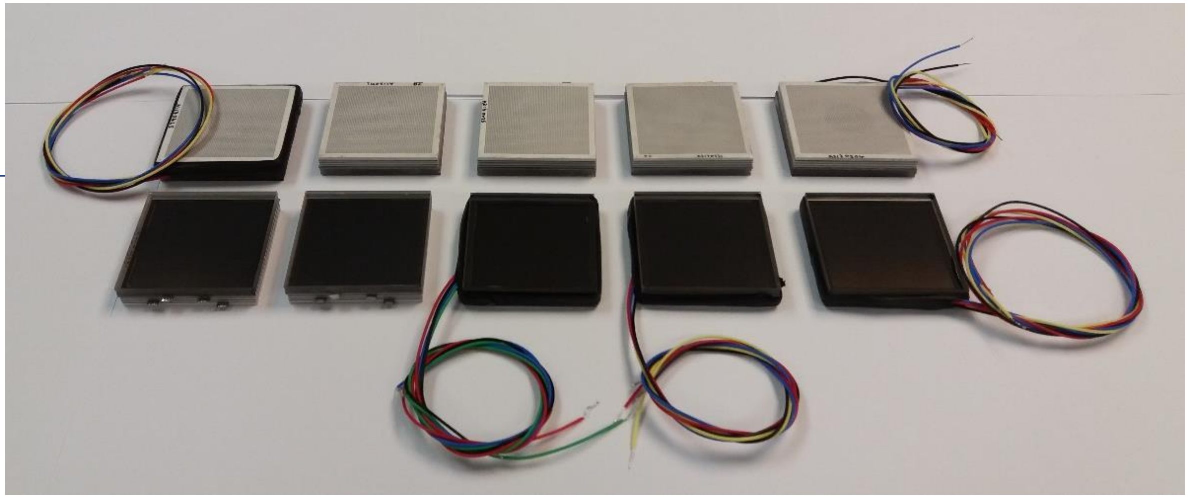
- Light yield somewhat lower than expected
  - Information on no-light bin will improve with more PMTs
  - Expected to improve further with calibration

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



Upcoming testbeam

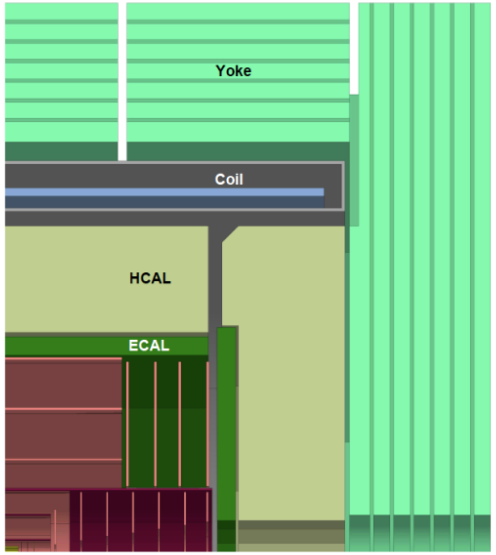
- Testbeam planned at T9 – CERN East Area
  - 31 October – 28 November
  - Area newly renovated
- Full instrumented detector
  - 10 MCP-PMTs with 8x64 channels
  - Fully equipped with NINO + HPTDC
  - Calibration of boards ongoing in dedicated test setup
- New DAQ for streamlined data taking, new and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



The future of TORCH?

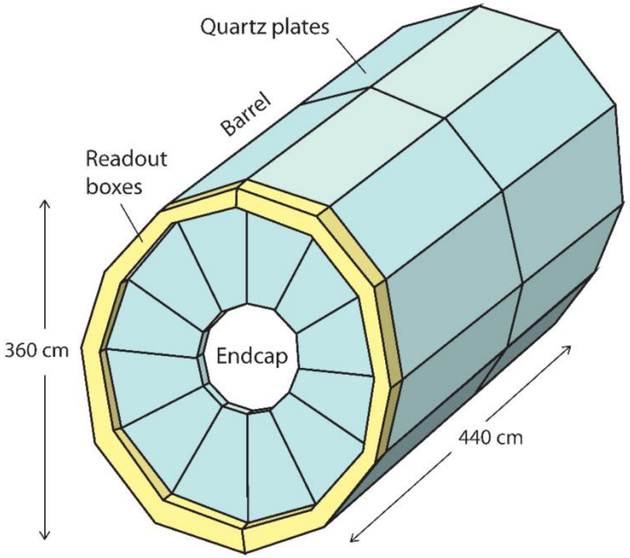
- Design explored in the context of FCC-ee

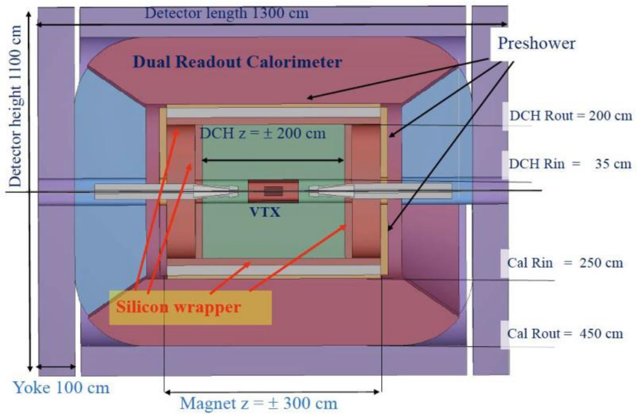
- Follow current TORCH design and find where it will need to deviate
  - 1cm thick quartz plates as radiator
  - Placement between tracker and ECAL
  - R=180cm, radiator length 220cm
    - R~2.1m (CLD), R<2m (IDEA)
  - Challenge is K/π separation, aim for 3σ
  - Momentum range as TORCH: up to 10 GeV/c
  - Track position, angles and momentum are assumed to be known



Concept	CLICdet	CLD
Vertex inner radius [mm]	31	17
Tracker half length [m]	2.2	
Tracker outer radius [m]	1.5	2.1
ECAL absorber	W	
ECAL X_0	22	
HCAL absorber	Fe	
HCAL λ_I	7.5	5.5
Solenoid field [T]	4	2
Overall height [m]	12.9	12.0
Overall length [m]	11.4	10.6

Tracker Material
11% X_0 Barrel
20% X_0 Forward





Particle separation in time – basics

- Time difference dictated by mass of relevant particles

$$\Delta t_{K-\pi} \approx \frac{x}{c}\frac{1}{2p^2}[m_K^2 - m_\pi^2]$$

  - *x* is the path over which the particles separate
  - *m* is relevant particle mass, *p* is momentum
  - Fill out constants, evaluate at p=10 GeV/c, x = 1.8m: $\Delta TOF_{K-\pi}$=6.7ps
- Additional separation from time of propagation of photons in quartz
  - Results from difference in Cherenkov angle due to mass difference, roughly 1 mrad
  - Separation factors in on per-photon basis: over 3.5m (typical here): $\Delta TOP_{K-\pi}$~7.3ps
  - Effects stack:$\Delta TOF_{K-\pi}$+$\Delta TOP_{K-\pi}$= 14.0ps
- Require 3σ separation (3.3ps), assume 30 photons: 25.6ps per photon
  - This can be split evenly between reconstruction and (detector + electronics): 18.1ps

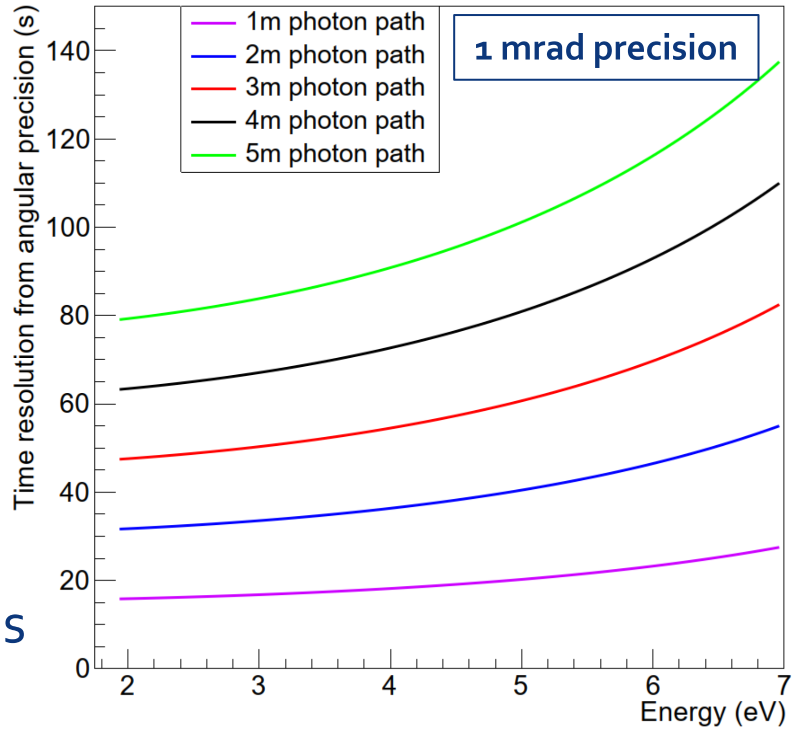
Particle separation in time – basics

- Errors accumulate along the calculation of the track timing
  - Basic structure of reconstruction, starting from known track position, angle and momentum
  1. Determine photon path through optics and derive path length
  2. Measure Cherenkov angle to correct chromaticity
  3. Combine individual photons into track time

- Emission point (along path in quartz) matters when aiming for 3.3ps time resolution
  - 1cm @ $c =$ 30ps: interpreted as flat smearing (scale with $\sqrt{12}$) gives an 8.7ps contribution
  - Reconstruction of emission point is required
  - **Note that this also means a new solution for the optics is required –focusing makes reconstructing the emission point impossible**

Angular precision

- Angular precision is the key factor driving this design
  - Granularity of photodetector determines angular precision
  - Angular uncertainty then sets limit on reconstruction of Cherenkov angle
  - 1 mrad error on θ_c gives ~20ps uncertainty per meter of path in quartz
    - Added TOP separation not enough to cancel this out
  - **Require ~0.1 mrad precision on angle**
    - Note this also includes the tracking input



- Coulomb scattering smears the angles of the detected photons
  - 1cm of quartz gives 0.5-1mrad of multiple Coulomb scattering
  - This would need to be corrected for in the reconstruction
    - Complicated problem to solve – assess first in simulation?

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

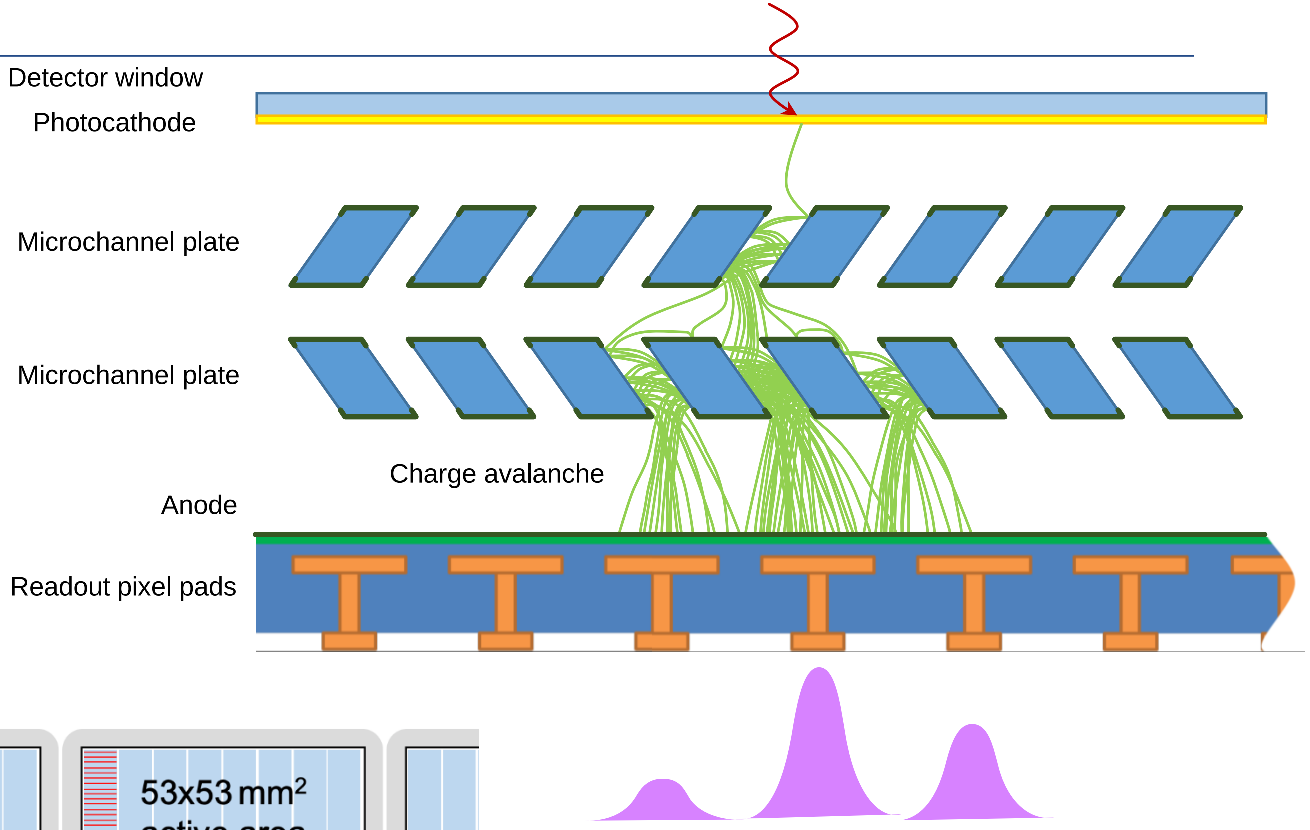
- Testbeam data analysis is nearly complete
  - Single photon time resolution 70-110ps, photon counting ~82% of expectation
  - Preparation for next testbeam preparation ongoing (November 2022)
    - High expectations: TORCH-based particle-ID to show full scope of detector

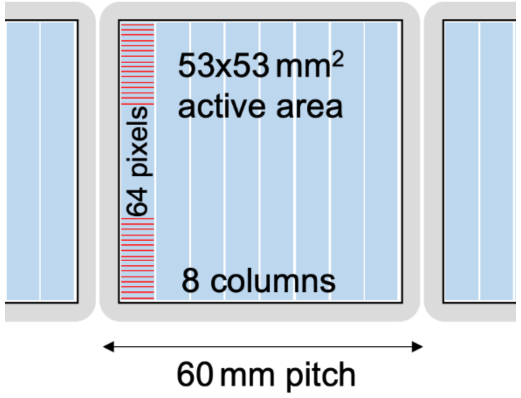
- Design for application of TORCH in barrel geometry explored
  - New solution for optics required (cannot reconstruct emission point with focusing optics)
  - Detector requirements: ~25.6ps single photon resolution, 0.1mrad reconstruction of photon angles

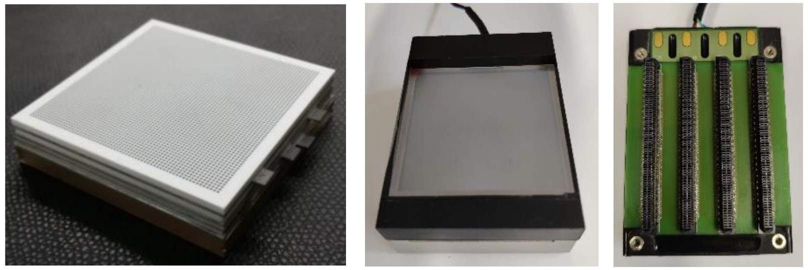
Questions?

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







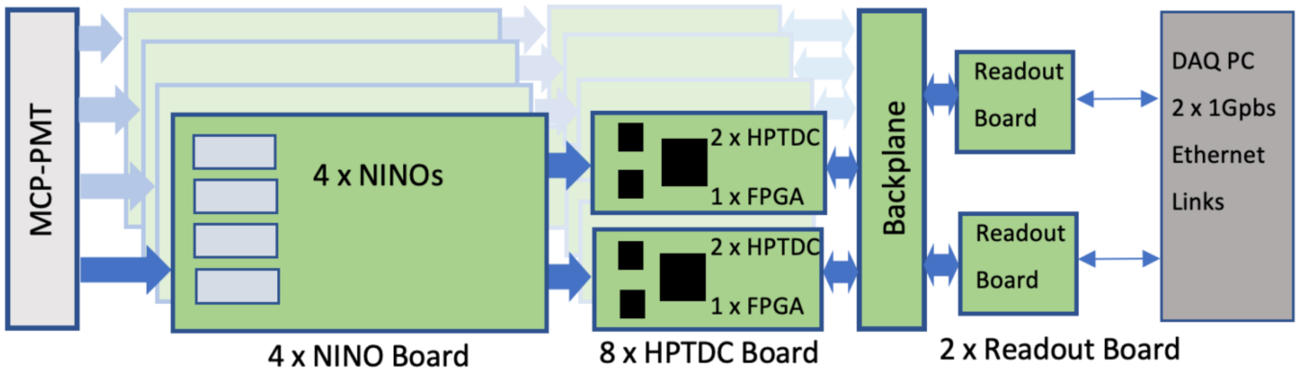
Detector readout for the TORCH prototype

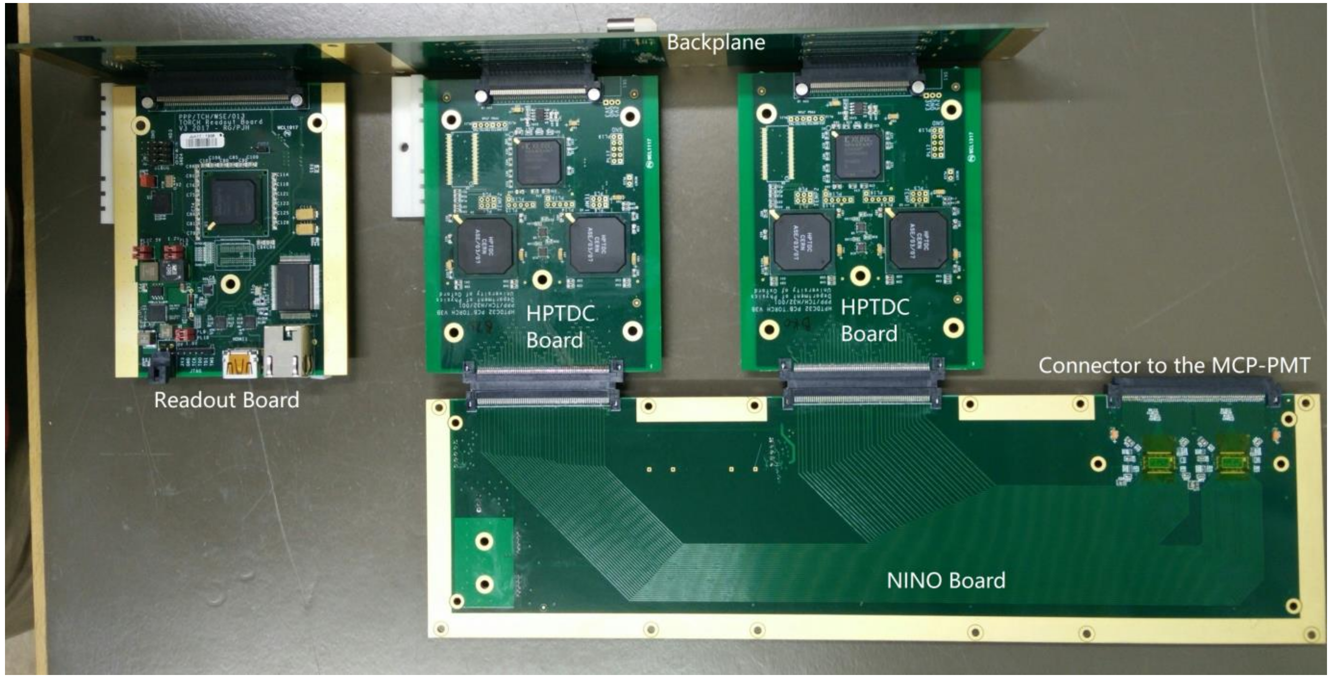
- Readout based on NINO and HPTDC chips
  - Originally developed for ALICE TOF

- 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

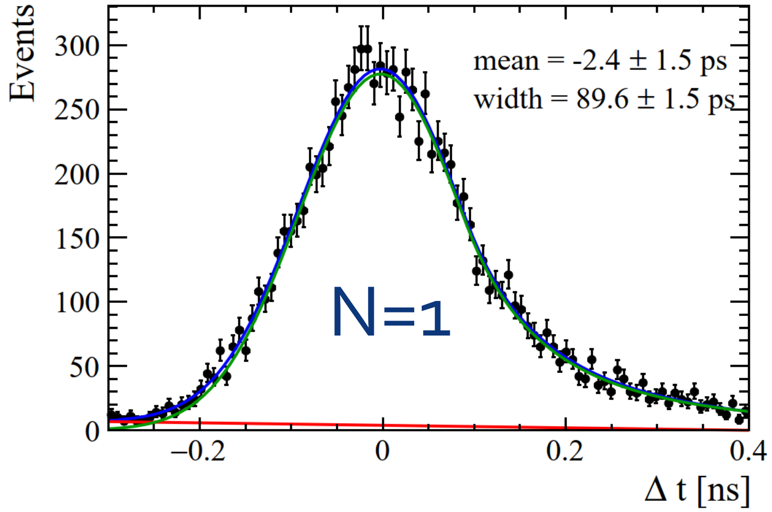


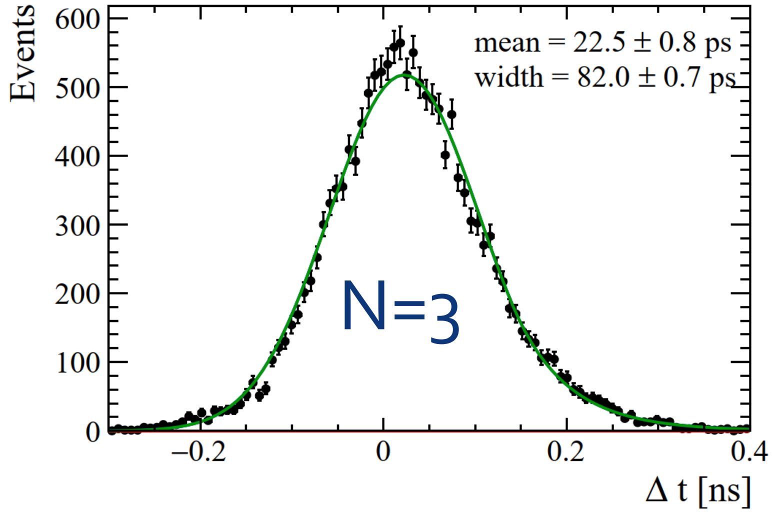


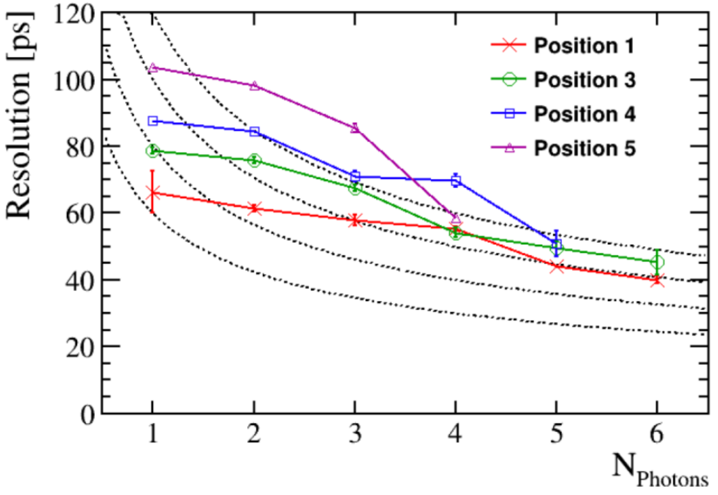
Testbeam – time resolution per track

- 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

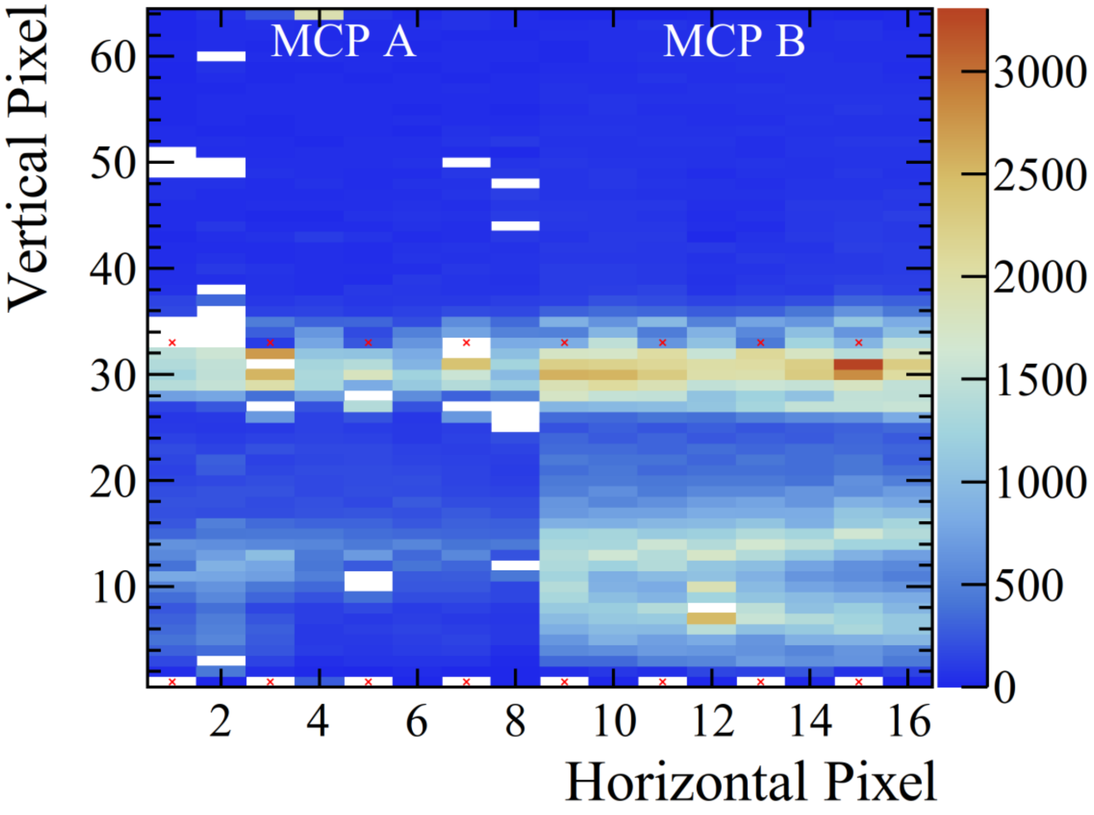


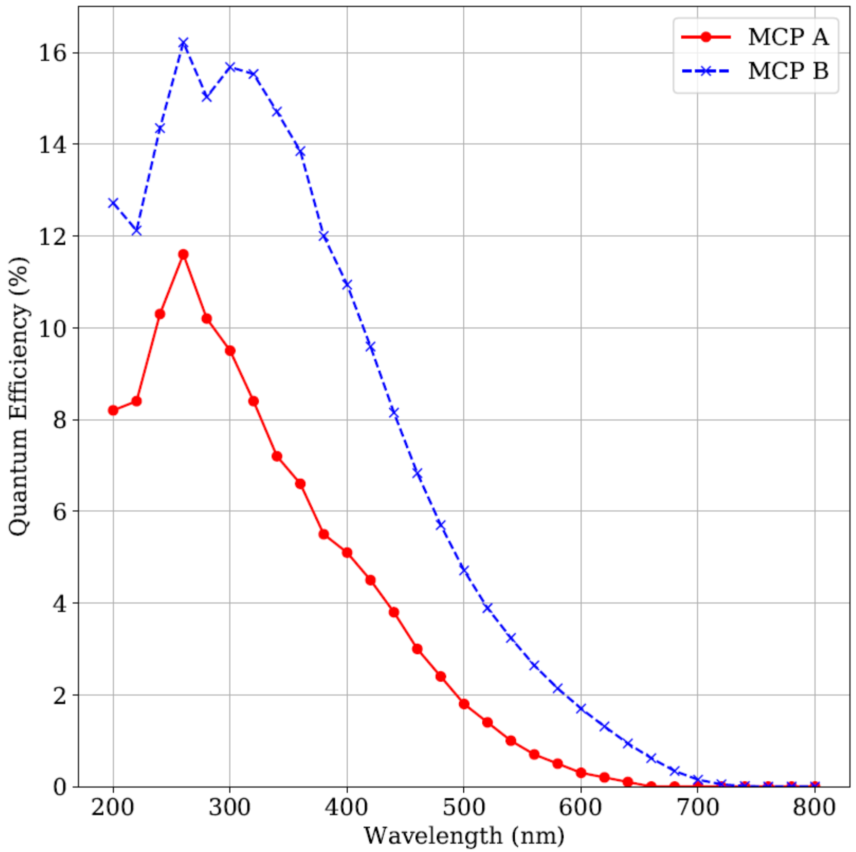




Quantum efficiency in testbeam

- 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