The TORCH Detector: Introduction and Status

@ Warwick:

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TORCH in Context

Diagrams of radiator and optics from “TORCH Concept”, T. Blake, https://indico.cern.ch/event/1385579/, presented 27/2/2024.

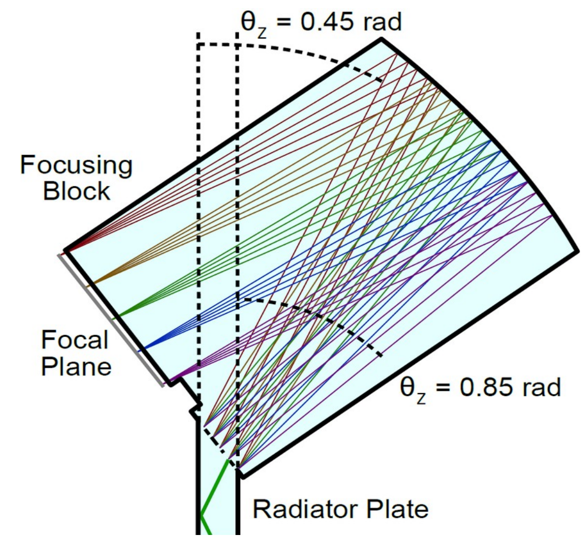
Time Of internally Reflected Čerenkov light (TORCH) proposed solution to low momentum PID.

Aim 2-10 GeV/c separation of K/π to compliment Ring Imaging Čerenkov (RICH) detectors.

Detector installation in 2033-2034 for Run 5 of the LHC

Expands the LHCb Detector’s flavour-physics capacity.

Related to iTOP of Belle II, DIRCs of PANDA and DTOF of STCF.



Upgrade II detector, Fig 2.2 from “Physics case for an LHCb Upgrade II ”, LHCb Collaboration, arXiv:1808.08865.

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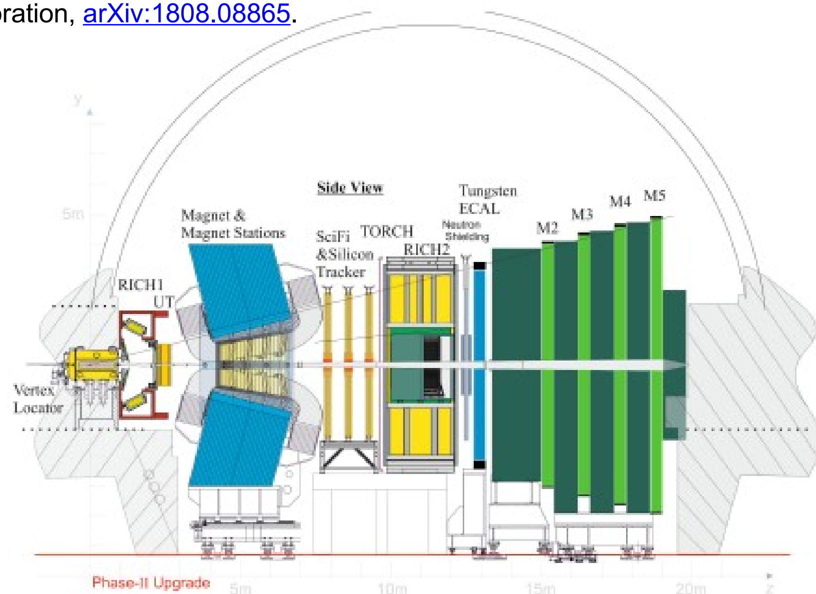
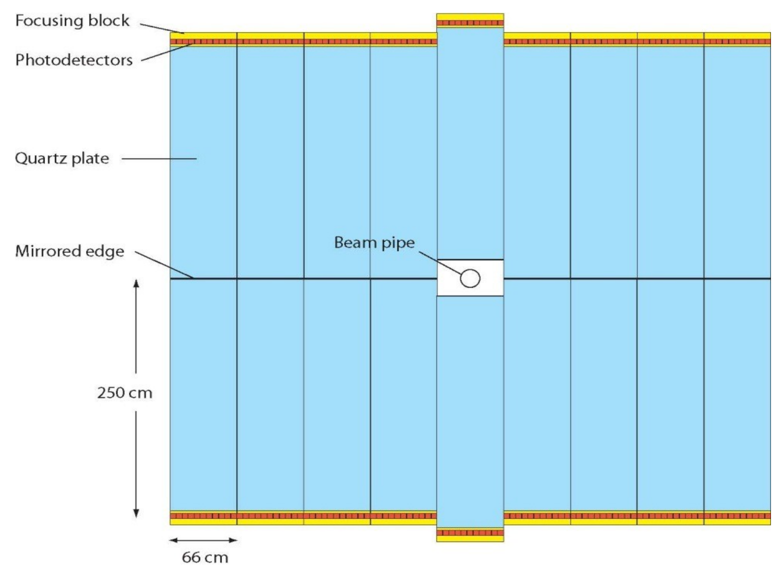




Details of Detector Concept

Plots from “TORCH Concept”, T. Blake, https://indico.cern.ch/event/1385579/, presented 27/2/2024.

Identification uses arrival time ***t*** of flight of particle of mass ***m*** with momentum ***p*** over distance ***x.*** Shown in eqn (1).

Taylor expand (1). to calculate the time resolution $\boldsymbol{\sigma_t}$ between K/π at 3σ. Given by eqn. (2).

With x = 10m, need: σ_t < 12.5ps per track.

Exploit prompt production of Čerenkov (Č) radiation..

From average Č-light yield, require time resolution of ≈70ps per photon.

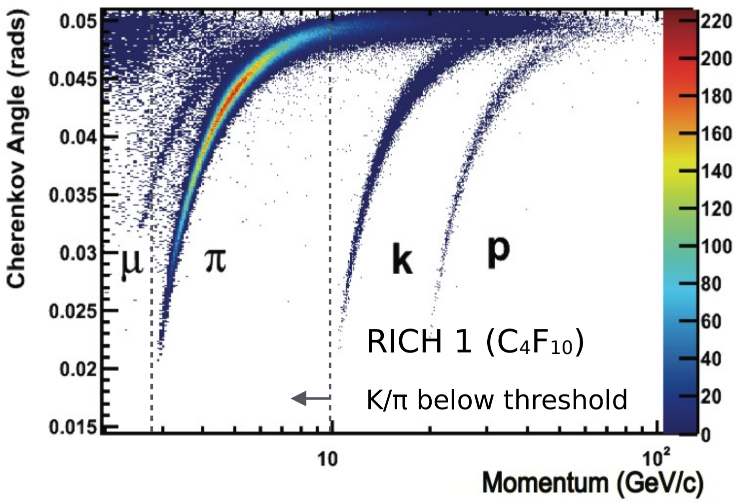
These timing constrains provide a significant R&D challenge.

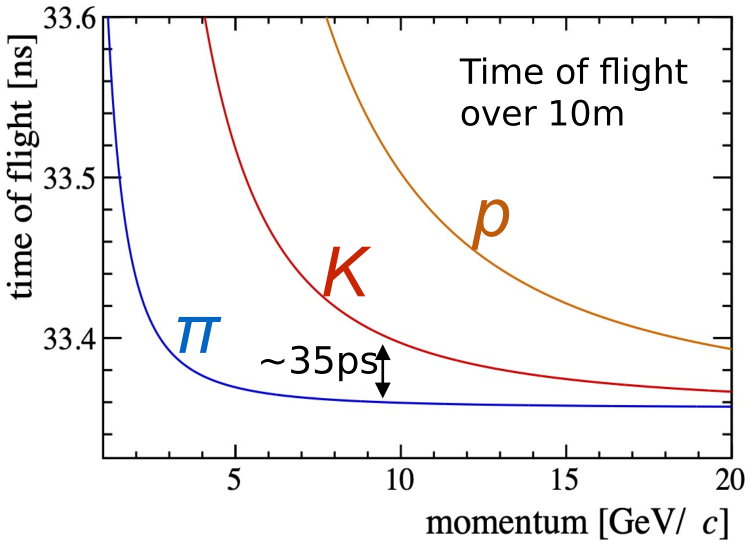
$$t_{TOF} = \left(\frac{x}{c} \sqrt{1 + \left(\frac{m_s}{p_i} \right)^2} \right) \quad (1).$$

$$\sigma_t < \left(\frac{1}{3} \frac{x}{c} \frac{1}{2p^2} \left[m_K^2 - m_\pi^2 \right] \right) \quad (2).$$

Details on TORCH concept [NIM A 639 (1) (2011) 173]

LHCb [EPJC 73 (2013) 2431]





TORCH Optics and Mechanics

Images and information from "TORCH Concept", T. Blake, https://indico.cern.ch/event/1385579/, presented 27/2/2024.

Optics formed from multiple pieces of synthetic fused-silica that are bonded with epoxy

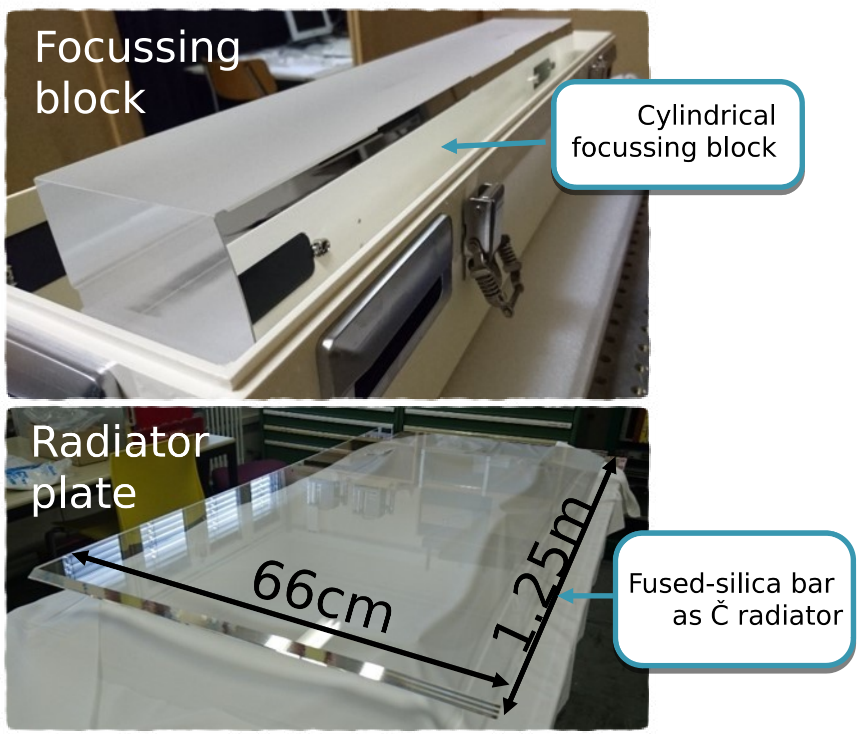
Require low thickness variation and surface roughness on faces of the radiator

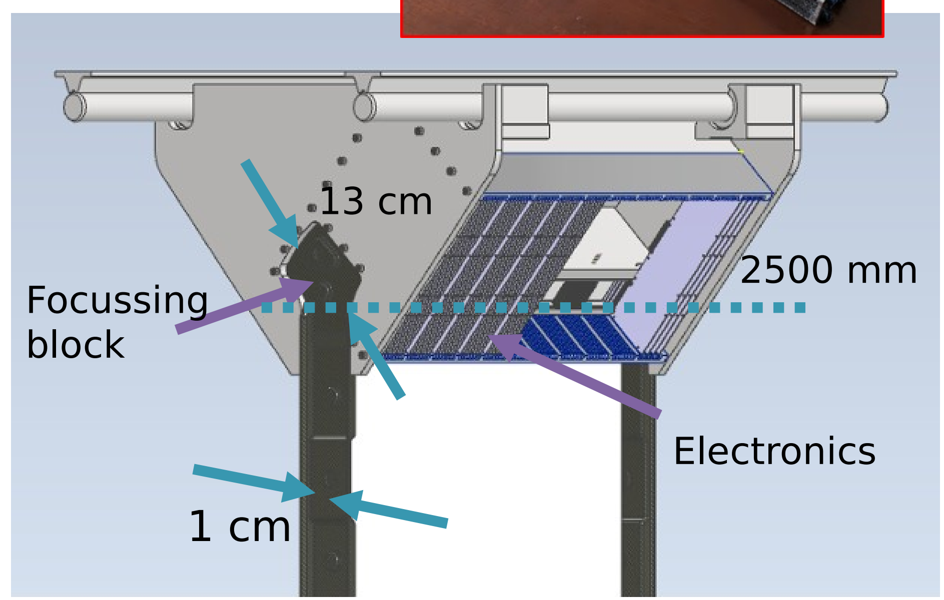
Further Information on "Mechanical design and assembly", A. Lowe and A. York, https://indico.cern.ch/event/1349839/, presented 12/2/2024.

Aiming for light-weight carbon fibre support structure inside LHCb acceptance.

Prototype development at Oxford; aim for full module by 2025.

Produced by Nikon glass





TORCH Electronics

Use segmented micro-channel plate (MCP) photo-detectors for localisation and fast timing of single photons.

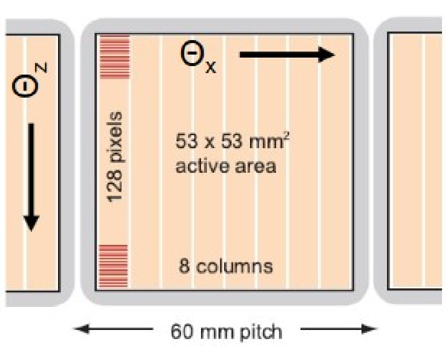
Current prototype uses 53-by-53mm MCP-PMTs whose pads are electronically ganged to 8-by-64 pixels (from Photek Ltd).

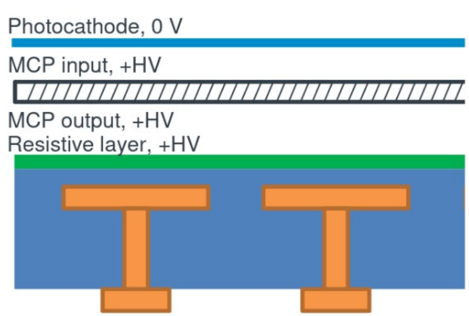
Pixel granularity to be increased to 16-by-64 and 32-by-64 for occupancy in central region.

Si-PMTs being investigated as alternative to these PMTs at Monash (see Sam's talk).

Text and MCP Image "An overview of TORCH photodetector developments", T. Gys, https://indico.cern.ch/event/1385579/, presented 27/2/2024.

Text and PMT Image "TORCH Concept", T. Blake, https://indico.cern.ch/event/1385579/, presented 27/2/2024.

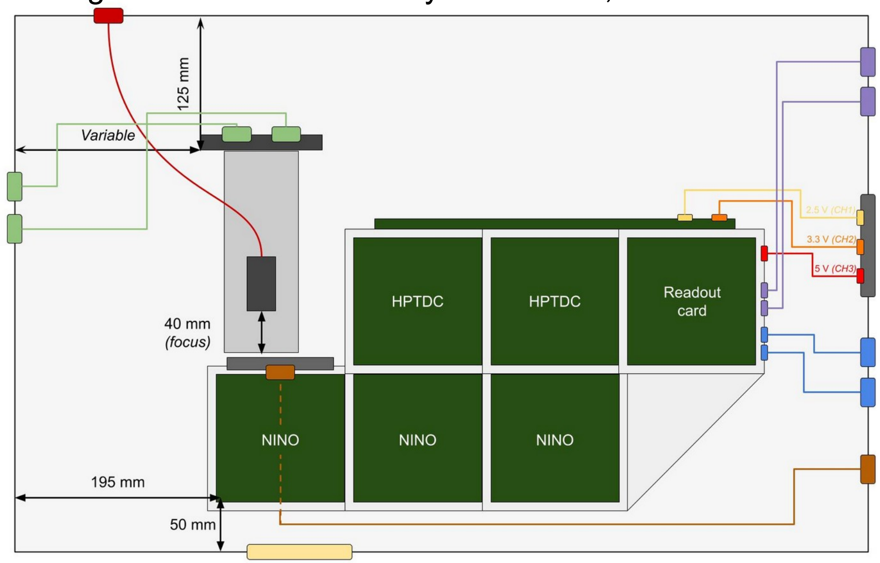


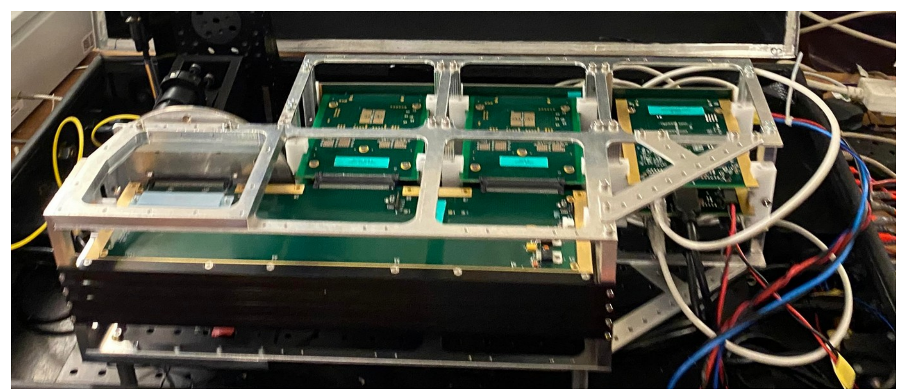


Electronics Diagram, M. Lehuraux *et al.*, https://codimd.web.cern.ch/NQHJbzSHTZSMBFvCNB2t6Q.

Readout electronics: NINO + HPTDC ASICs (originally developed for ALICE TOF)

Being tested in the laboratory at Warwick, Bristol and CERN.





TORCH Reconstruction

Many possible paths through the radiator

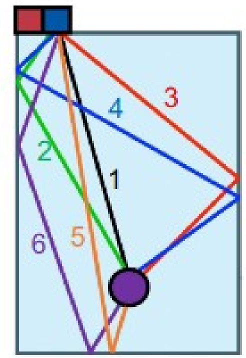
Use granularity in y to correct chromatic dispersion

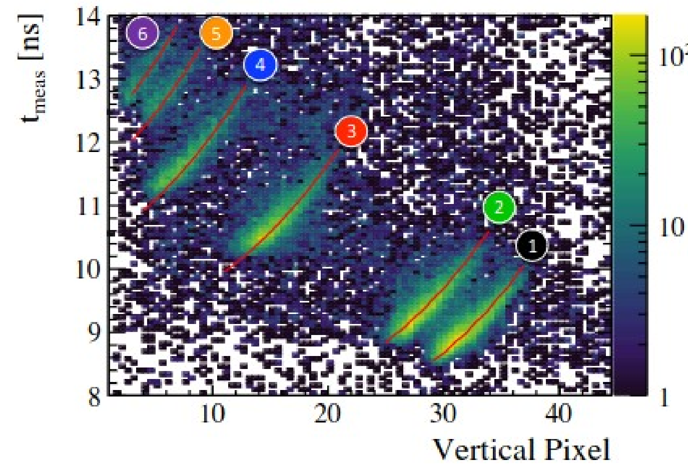
Measure a series of hyperbolic bands in time and space from Č photons.

Likelihood for a given hypothesis from eqn. (3).

Hit probability P_j from sum over all reflections: eqn. (4).

Minimise eqn. (3) for the best combination of hypotheses





Plots from [NIM A 1050 (5) (2023) 168181].

$$L = \prod_{hit\,i} \left[\left(\frac{N_{bkg}}{N} \right) P_{bkg}(x_i) + \sum_{particle\,j} \left(\frac{N_j}{N} \right) P_j (x_i \vee h_j) \right] \quad (3).$$

$$P(x \vee h) = \sum_{path\,k} \vee J_k \vee P(E_k, \phi_k, t_k \vee h) \quad (4).$$

Contribution from reconstructed tracks.

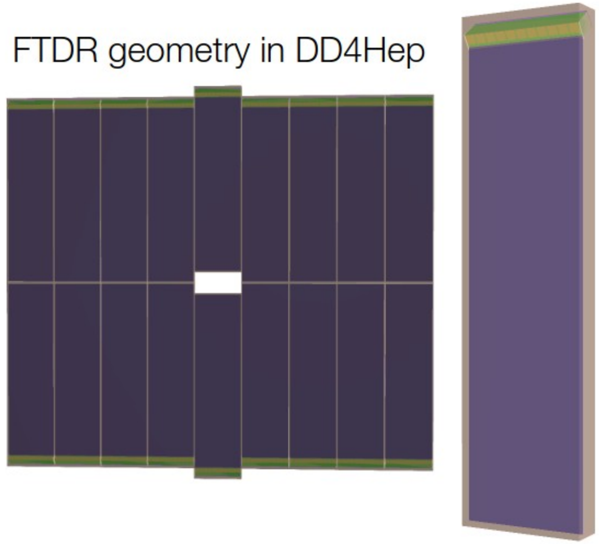
Jacobian of transformation from emission to detection space.

Probability of photon path in emission space

Eqn (3) and (4) from “TORCH Concept”, T. Blake, https://indico.cern.ch/event/1385579/, presented 27/2/2024.

TORCH Simulation

Diagrams from “TORCH SW in LHCb framework”, M. Kreps, https://indico.cern.ch/event/1349839/, presented 13/2/2024.



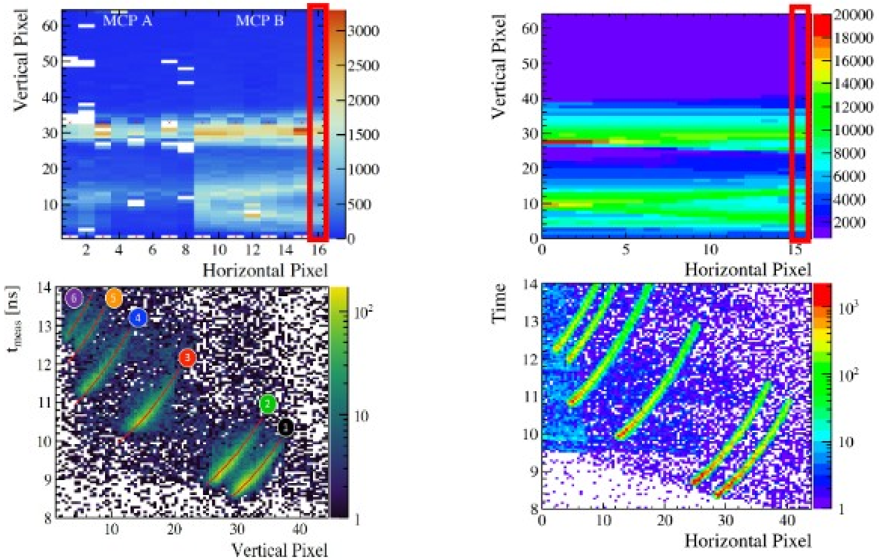
Require a stand-alone TORCH simulation and a simulation which is integrated into the Upgrade II detector.

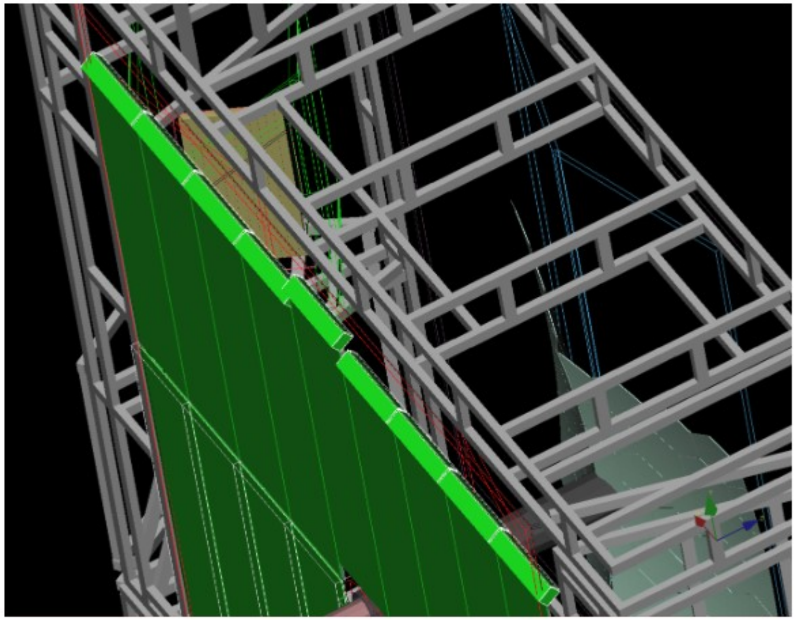
Need stand along simulation to compare to prototype modules.

Combine simulation to perform studies on physics prospects of U2 detector.

Want the combined PID performance of TORCH + RICH study effect of different scenarios for detector deployment.

Plots from “Standalone Simulation Development”, L. Zhu, https://indico.cern.ch/event/1349839/, presented 12/2/2024.





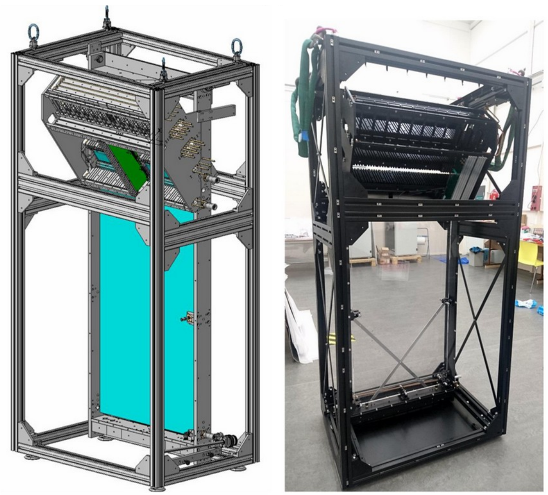
TORCH 2018 Testbeam

Used half-height, full-width TORCH prototype module, using samples of 8 GeV/c pions and protons from the CERN T9 test beam.

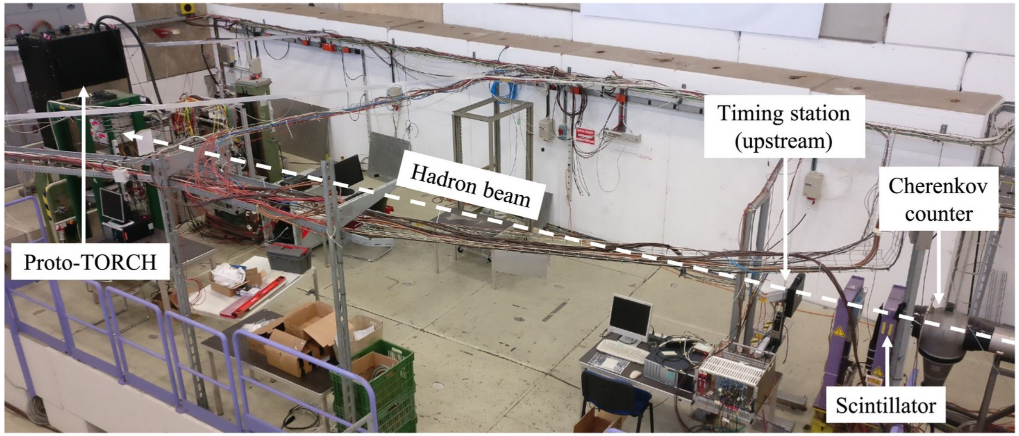
Time references are essential for meaningful measurements.

Single photon resolution differs based on beam position.

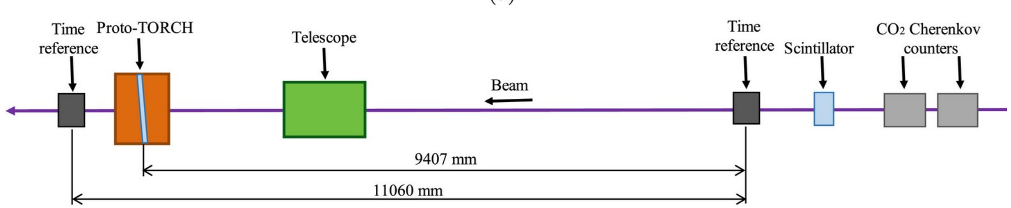
For beam positions close to MCP 70ps is achieved; for far positions path length dependence is greater than expected from simulation.

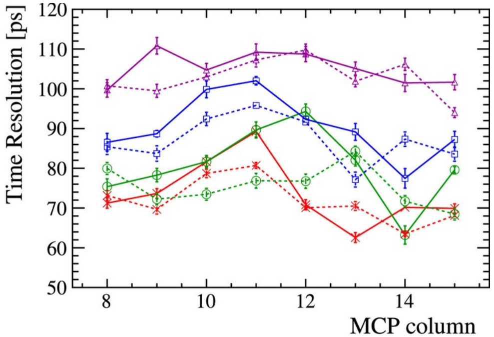


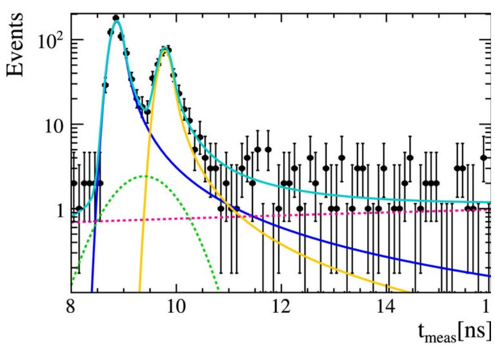
Figures and details from [NIM A 1050 (5) (2023) 168181].

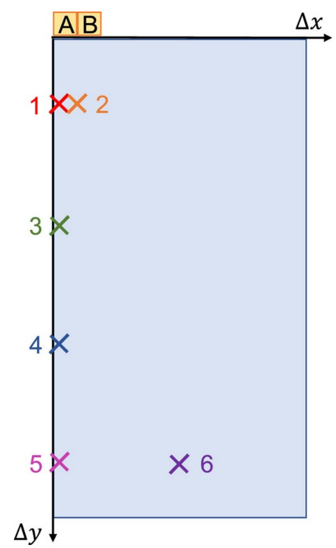


(a)









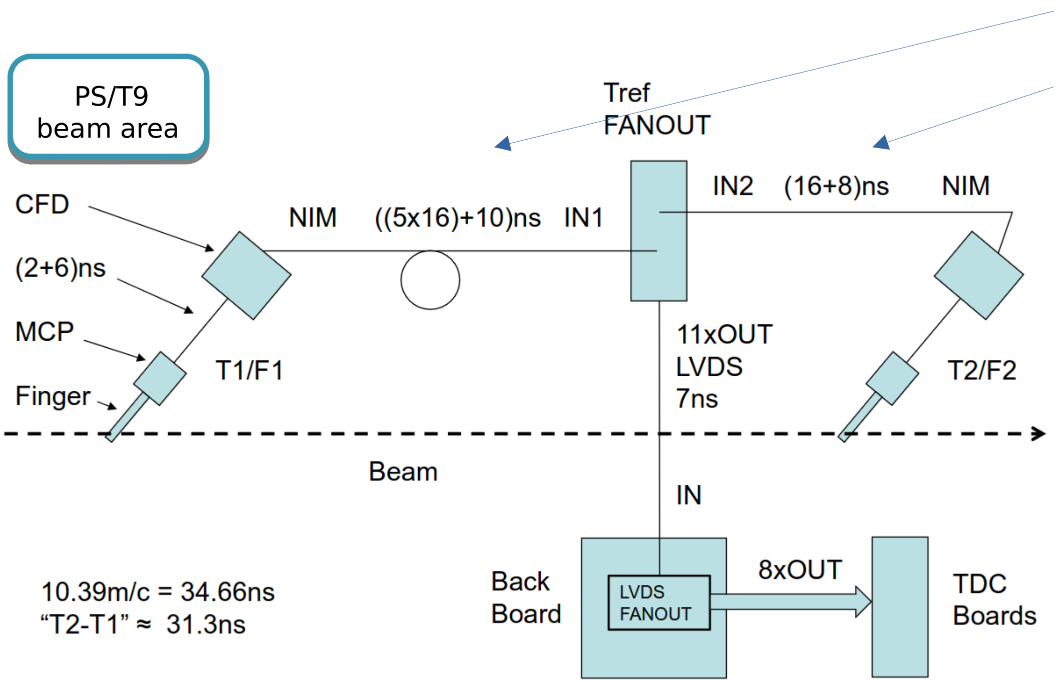
TORCH 2022 Testbeam

Same radiator as 2018 with seven active MCPs.
Measured four beam momenta 3, 5, 8 and 10 GeV/c.

The CFD used for the time reference signals misfired for majority of the runs, contaminating the data with noise, provides major challenge to analysis.

Investigate runs after CFD was fixed to understand data.

Diagram from “Analysis of ORTEC data for T1/T2”, Thierry Gys, https://indico.cern.ch/event/1230087/, presented16/12/2022.



Current challenge to identify time references, T1 and T2.
T2 always arrives at TORCH before T1.

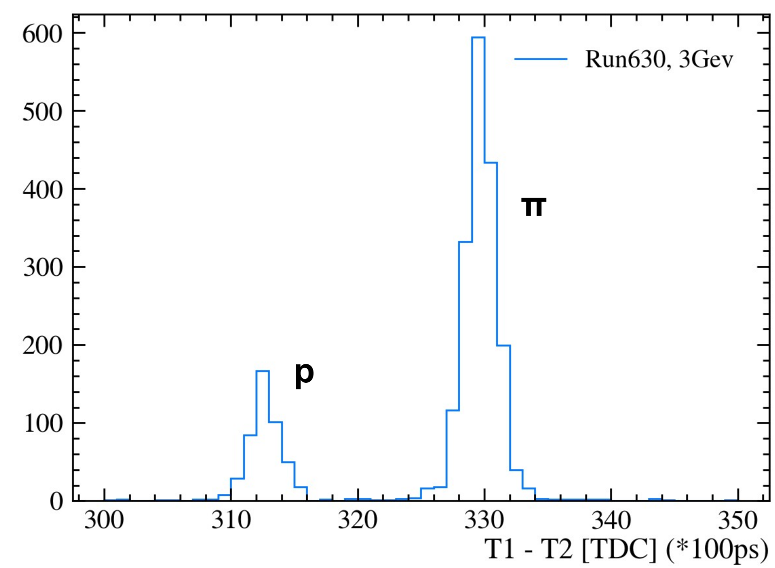
Work with ΔT = T1 – T2, which is always a positive.

Two schemes for identifying time refrences: one by M.Tat and one by M. Lehuraux.

Make a choice (M.Tat), then check the consistency of the data.

T1 delay is ((5 x 16) + 10) = 90ns

T2 delay is ((16) + 8) = 24ns



Method for Consistency Check

We have a system of equations for the measured time

$$t^{s,i}_{measured} = t_{delay} - t^{s,i}_{TOF} \quad (5).$$

Treat t_{delay}, momenta (p_i) and room length (x) as unknowns.

$$t^{s,i}_{measured} = t_{delay} - \left(\frac{x}{c} \sqrt{1 + \left(\frac{m_s}{p_i} \right)^2} \right) \quad (6).$$

We have eight equations: from species s = π, p and momenta i = 3, 5, 8, 10 GeV/c

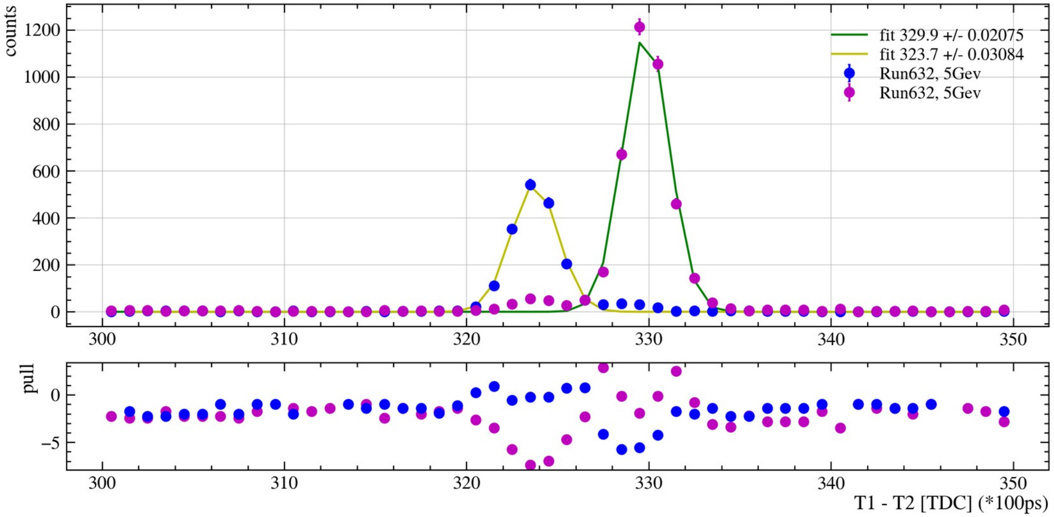
Construct a vector **V** from these equations with covariance matrix C

$$V^{s,i} = \left(t^{s,i}_{measured} - t_{delay} + t^{s,i}_{TOF} \right) \quad (7).$$

Combine these into a χ² and minimise to find unknowns.

Use peak positions (with uncertainty u_{tm}) from fitting data as inputs.

$$C_{jk} = \begin{matrix} u^2_{tm}, if\ j=k \\ 0, if\ j \neq k \end{matrix} \quad (8). \qquad \chi^2 = V_j C^{-1}_{jk} V_k \quad (9).$$



unknowns	value	u_val
x (cm)	1013	0.2
p_3 (GeV/c)	2.909	0.005
p_5 (GeV/c)	4.91	0.012
p_8 (GeV/c)	8.21	0.03
p_{10} (GeV/c)	10.41	0.05
t_{delay} (ns)	66.87	0.01

Next Steps for Testbeam

Results so far show data is consistent with our expectations.

Fitting Improvements

- make simultaneous rather than sequential
- add a fixed-mean misID component
- Fit directly for params using (2).

$$t^{s,i}_{measured} = t_{delay} - \left(\frac{x}{c} \sqrt{1 + \left(\frac{m_s}{p_i} \right)^2} \right) \qquad (2).$$

Data Improvements:

- Use T1 and T2 identification by M. Lehuraux.
- Combine all runs at same energy
- Add equations for ORTEC data (with a corresponding t_{delay})

Below from " Pion-proton time difference fit", Martin Tat, in https://lblogbook.cern.ch/TORCH+testbeam/112, written 12/11/2022