# The TORCH time of flight detector and status of R&D

**Neville Harnew**
University of Oxford
on behalf of the TORCH group

5th Workshop on LHCb Upgrade II
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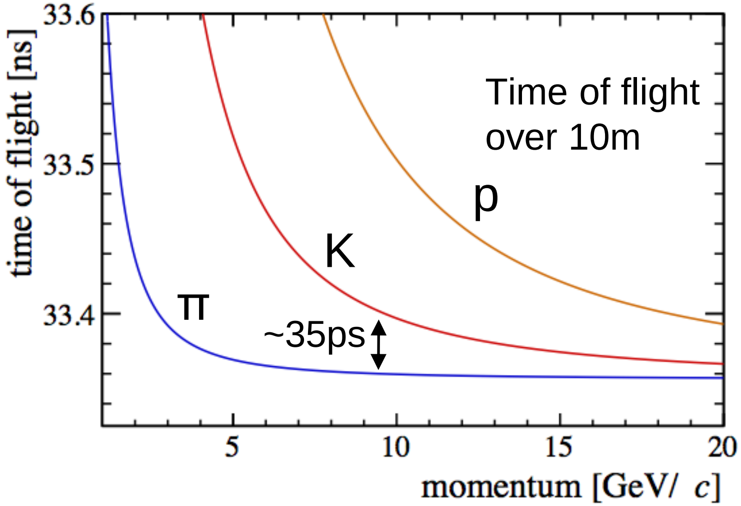
# Outline

- Introduction to TORCH time-of-flight detector
- Status of R&D : TORCH prototype and test beam analysis
- Anticipated costing of TORCH for LHCb
- TORCH simulation at LHCb and physics studies (see Tom Blake)

# General introduction to TORCH

- TORCH (Time Of internally Reflected CHerenkov light) is an R&D project to develop a large-area time-of-flight system

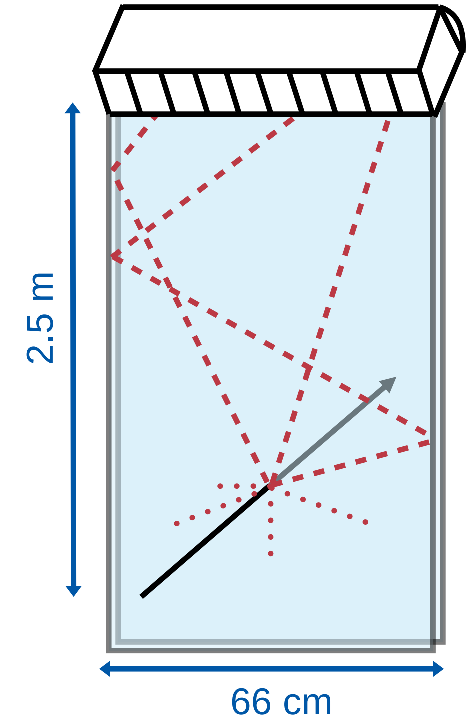
- $\pi$-K TOF difference = 35 ps over a ~10 m flight path. To achieve positive identification of kaons up to p ~ 10 GeV/c, need to aim for ~ 10-15 ps resolution per track



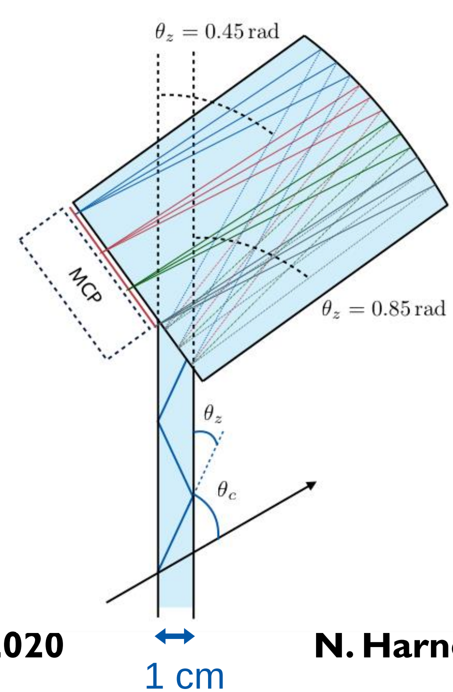

- The $\sigma_{TOF}$ requirement dictates timing single photons to a precision of 70 ps for ~30 detected photons

# The TORCH detector

- A charged track produces Cherenkov light in a plane of 1 cm thick quartz
- Cherenkov photons travel to the periphery of the detector by total internal reflection and focused → their position and arrival time is measured by Micro-Channel Plate PMTs (MCPs)
- The Cherenkov angle $\theta_c$ and path length L in the quartz are measured. The time of arrival is used to correct for the chromatic dispersion in the quartz.
- From simulation, ~1 mrad precision is required on measurement of the angles in both planes to achieve the required intrinsic timing resolution



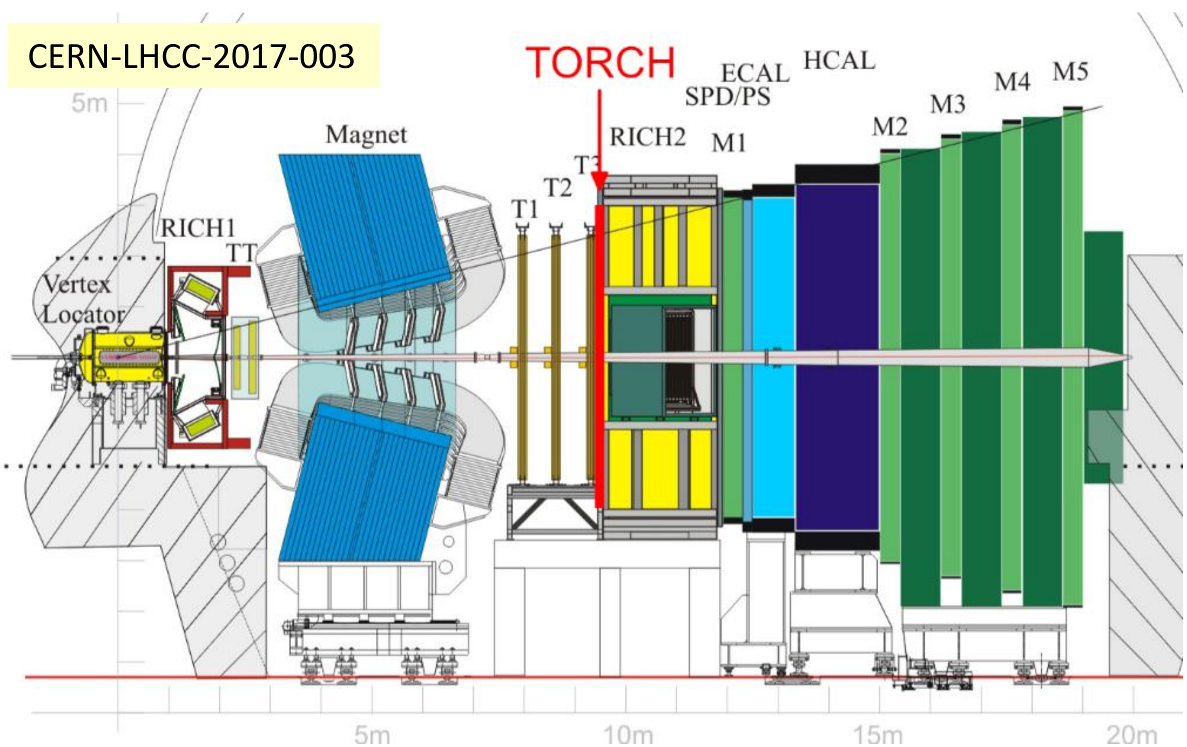

Non-focussing plane



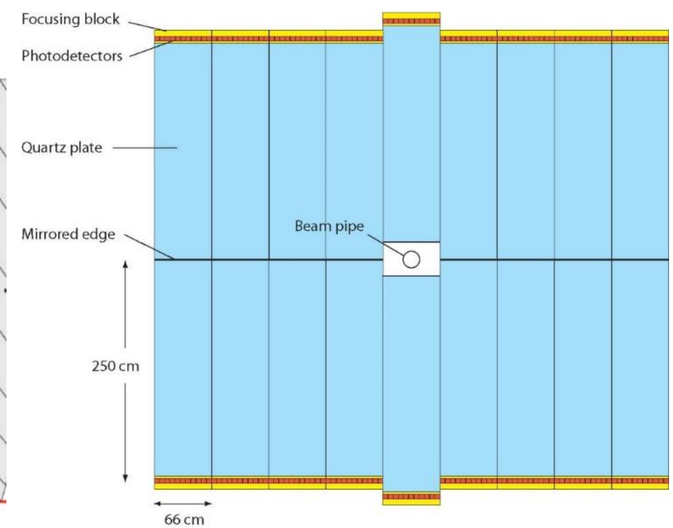

Focussing plane

# TORCH for LHCb Upgrade Ib & 2

- Currently no positive kaon ID or any proton ID below ~10 GeV/c
- Proposal to install TORCH in front of RICH2, hopefully in LS3 (for ~2027)




  - TORCH area 5 x 6 $m^2$
  - 18 module system
  - 11 MCPs per module

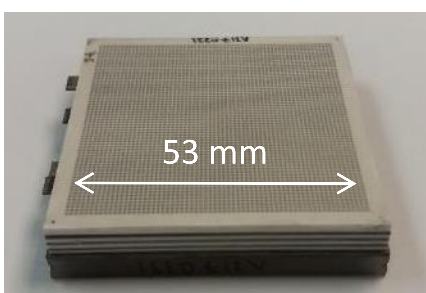


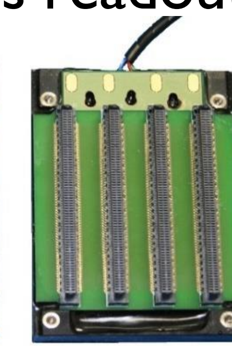
# History of R&D

- TORCH R&D funded on an ERC Senior Investigator's grant and then STFC PRD grant
- We have developed customised Microchannel Plate PMTs with Photek (UK)
- Built a half-length, full width, prototype TORCH detector
- Active collaborators at current time : Bristol, Oxford, Warwick, CERN, Edinburgh, Bath, Photek (other groups also showing interest in getting involved)

# TORCH MCP-PMT development

- Each detector has a granularity of 64 x 64 pixels over a 53 x 53 mm$^2$ active area. A readout PCB is connected via Anisotropic Conductive Film.
- Charge sharing and channel grouping (64 x 8) is used to achieve an effective granularity of 128 x 8 pixels, which is required for the 1 mrad precision
- The MCPs have ALD coating and are designed to withstand an integrated charge of 5 C/cm$^2$ or more (although will likely need to improve on this)
- 10 MCP-PMTs delivered from Photek
- TORCH-developed customised NINO/HPTDC electronics readout



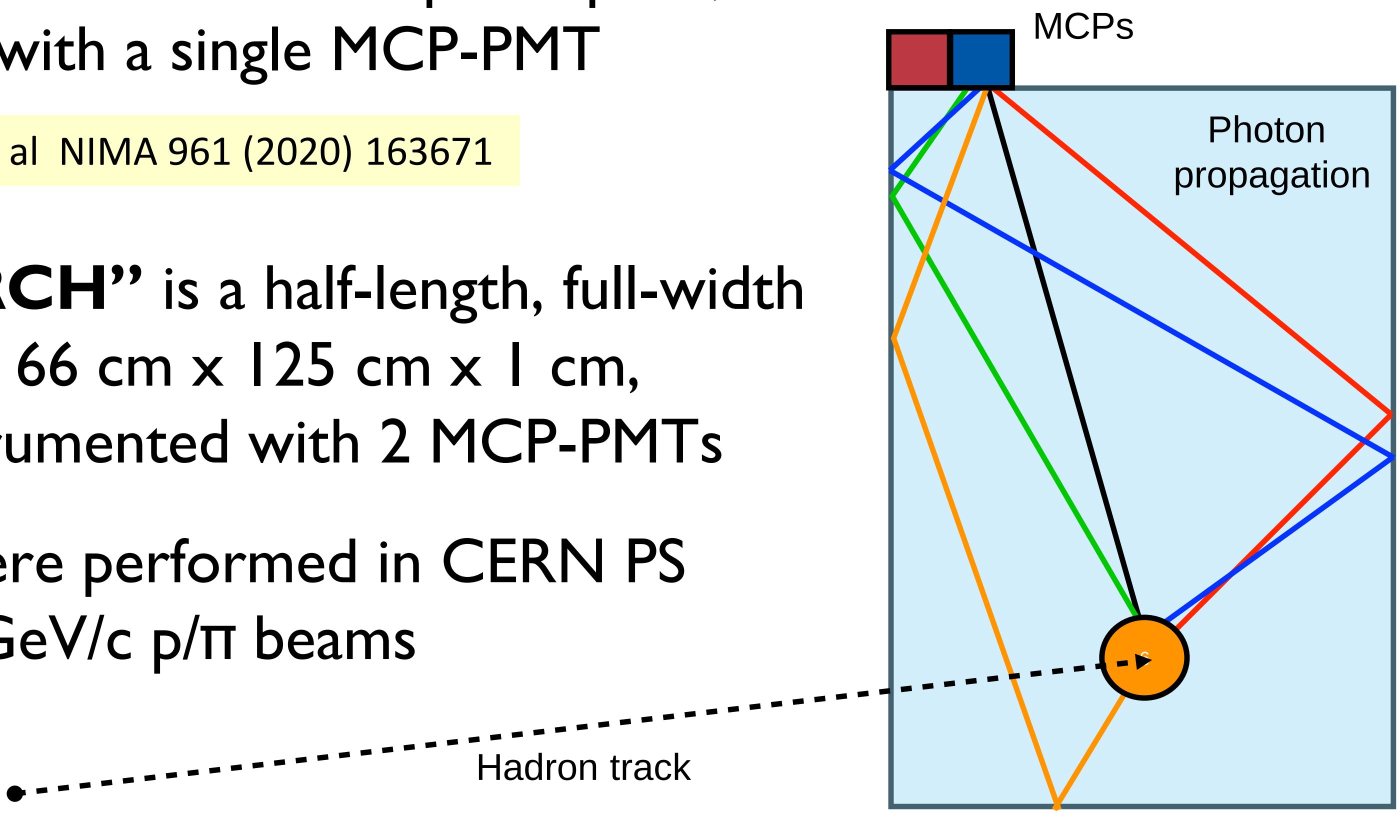



# TORCH prototypes

- TORCH prototypes have been tested in several beam tests between 2015 and 2018
- **“Mini-TORCH”** is a small scale module with a 12 cm x 35 cm x 1 cm quartz plate, instrumented with a single MCP-PMT

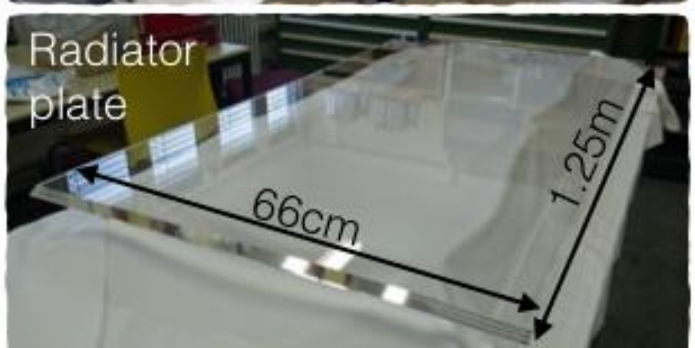
S.Bhasin et al NIMA 961 (2020) 163671

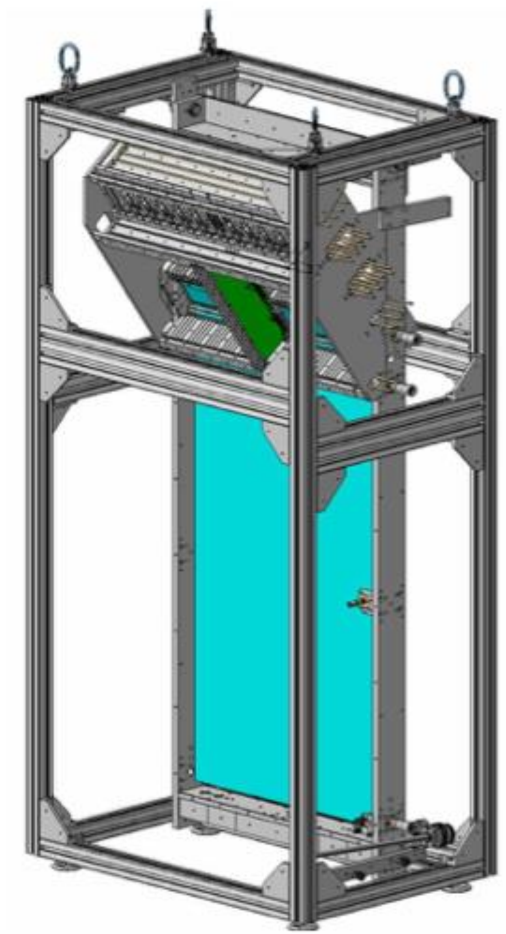
- **“Proto-TORCH”** is a half-length, full-width LHCb module 66 cm x 125 cm x 1 cm, currently instrumented with 2 MCP-PMTs
- Beam tests were performed in CERN PS with 5 and 8 GeV/c p/π beams



# "Proto-TORCH" demonstrator

- A half-sized TORCH module : 125 x 66 x 1 cm$^3$ tested in 2018
- Optical components from Nikon (radiator plate, focusing block)

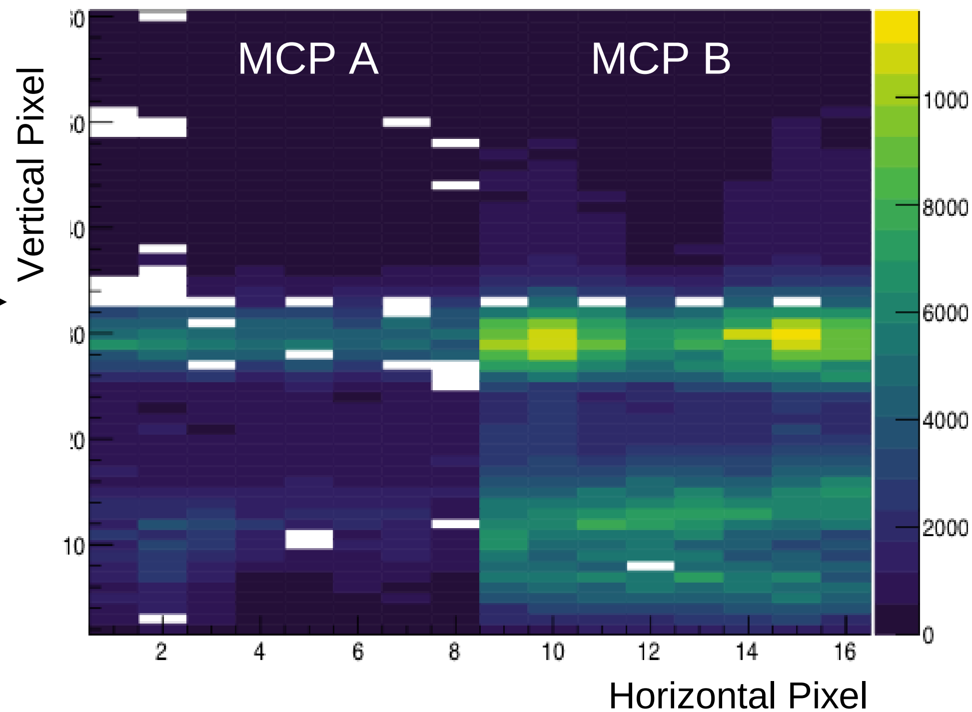



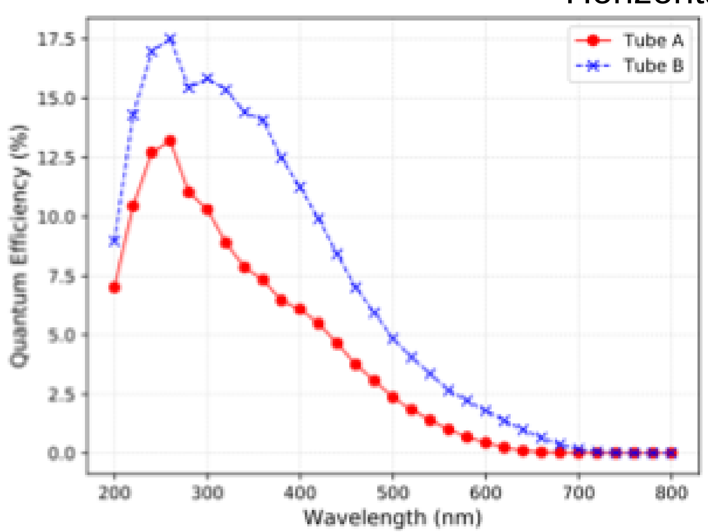



# Proto-TORCH analysis

Hitmap

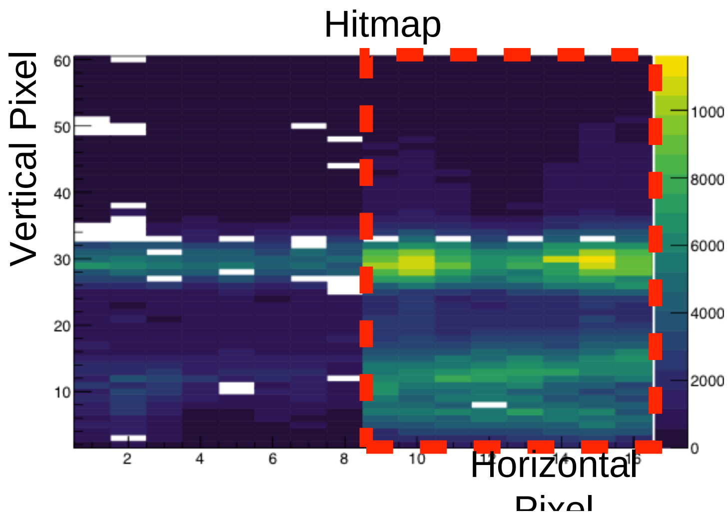
Time reference channels

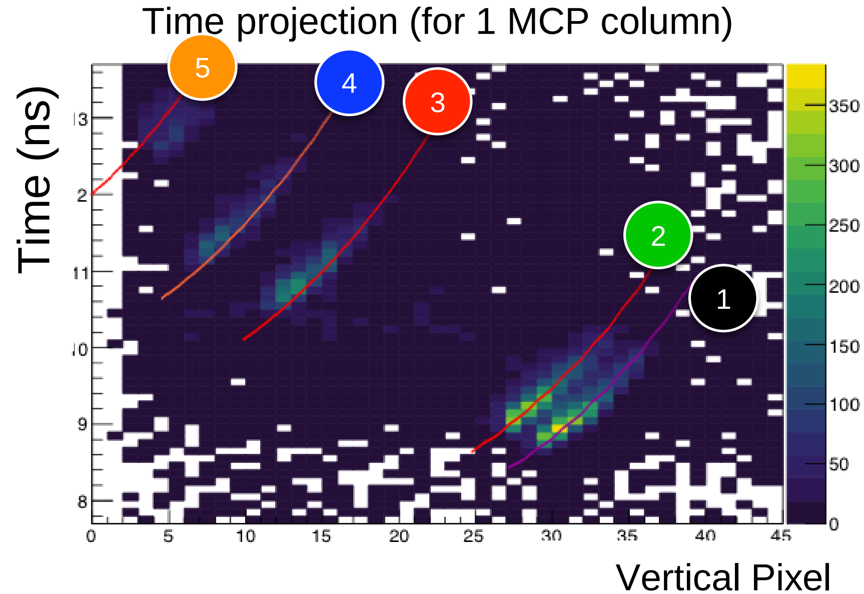


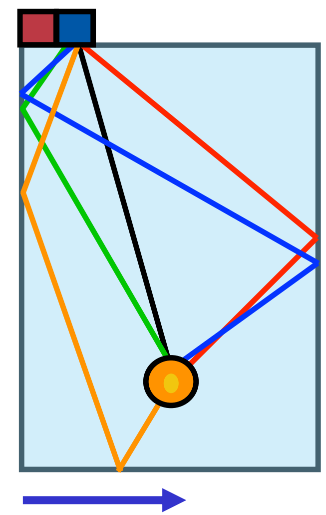

- The analysis focuses on MCP B with the higher quantum efficiency

# Analysis



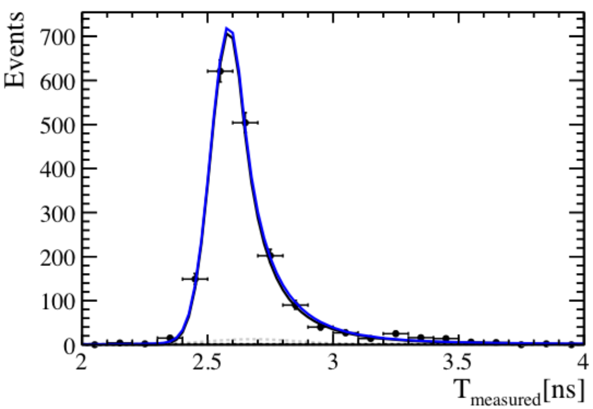



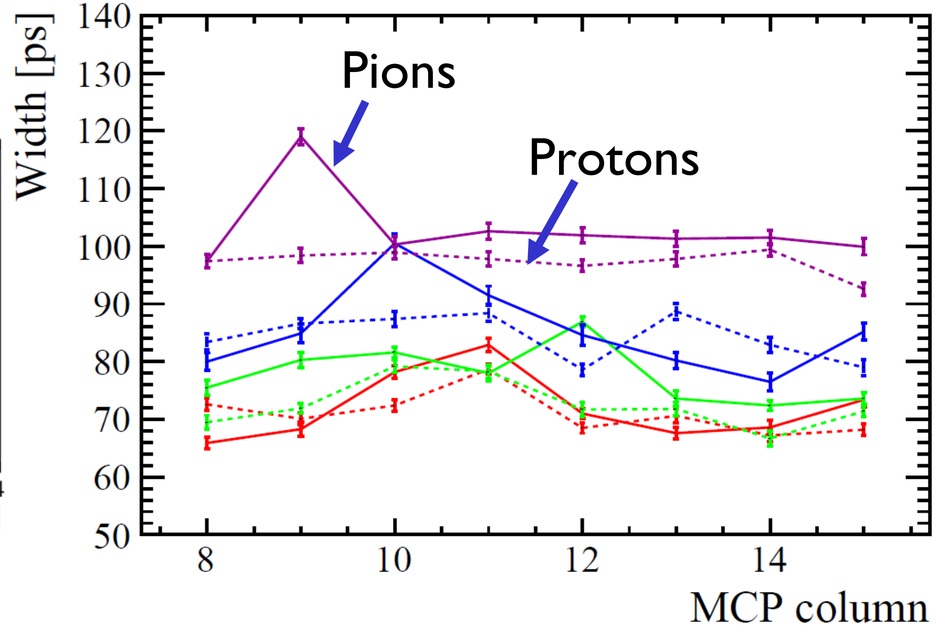

- Project the hits in the time-of-arrival axis to separate the different orders of side reflections
- The overlaid lines represent reconstructed predictions
- The spreads in time for each order of reflection is measured to determine the single photon time resolution
- Note that the HPTDCs were all operated with 100ps binning

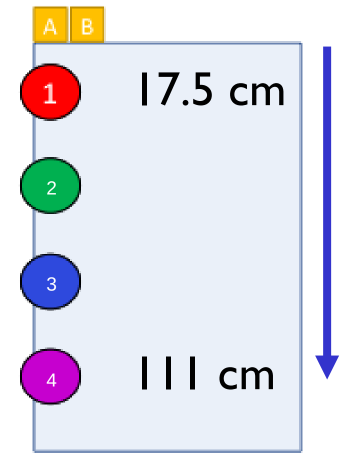


# Time resolution studies

- Plot residual distributions of single-photon time resolution for first order reflections versus MCP column number
- A simultaneous fit determines the spread in the time of arrival at each pixel




- Preliminary analysis shows we see some degradation of time resolution with height in the radiator, somewhat as expected
- Nevertheless, the time resolution is approaching or matches the design goal of 70 ps

# Resolution studies continued

- The time resolution can be parameterized into different contributions
- These individual sources are under study in laboratory tests

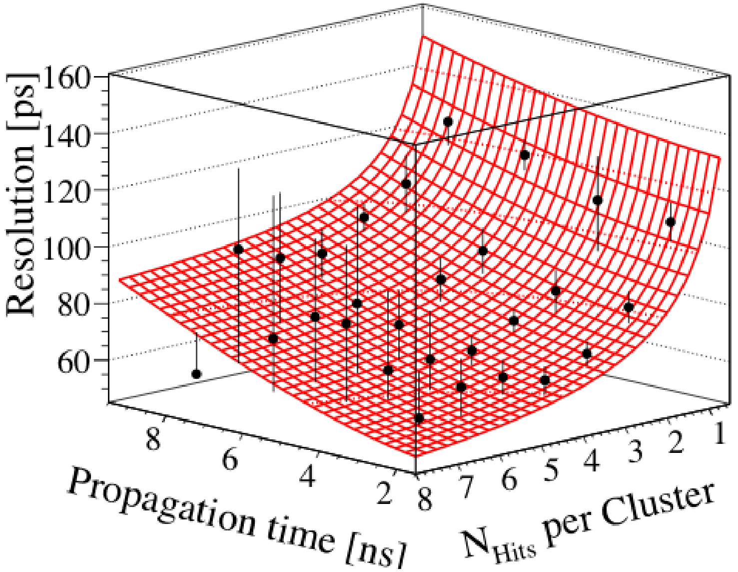
Time resolution parameterisation:

$$\sigma^2_{\mathrm{TORCH}} = \sigma^2_{\mathrm{const}} + \sigma_{\mathrm{prop}}(t_P)^2 + \sigma_{\mathrm{RO}}(N_{\mathrm{Hits}})^2$$

**e.g. MCP**

**Propagation time ($t_P$) dependent effects**

**Electronics and readout resolution**




$$\sigma_{\mathrm{const}} = 33.0 \pm 7.1\,\mathrm{ps}$$
$$\sigma_{\mathrm{prop}}(t_P) = (7.8 \pm 0.7) \times t_P\,\mathrm{ps}$$
$$\sigma_{\mathrm{RO}}(N_{\mathrm{Hits}}) = \frac{100.5 \pm 5.7}{\sqrt{N_{\mathrm{Hits}}}}\,\mathrm{ps}$$

**[with $t_P$ in ns]**

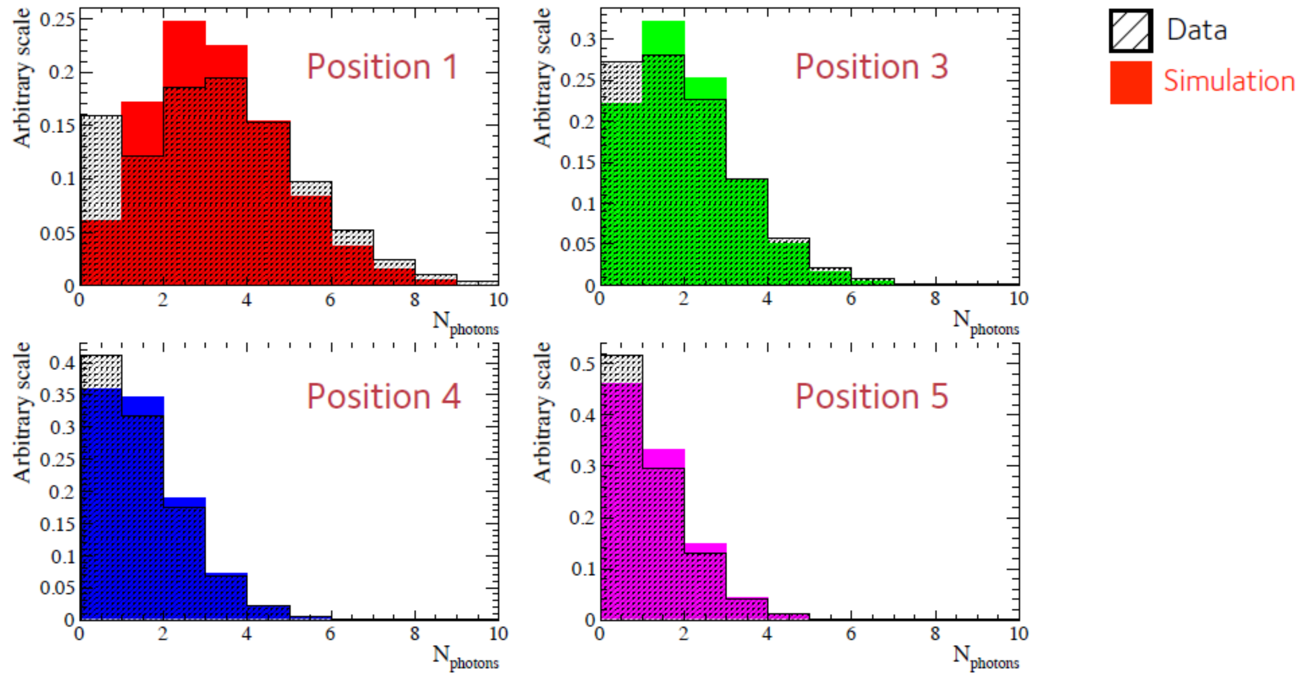
**Ideal values from simulation**

$$\sim 33\,\mathrm{ps}$$
$$\sim (3.75 \pm 0.8) \times t_P\,\mathrm{ps}$$
$$\sim \frac{60}{\sqrt{N_{\mathrm{Hits}}}}\,\mathrm{ps}$$

**Further improvements from calibrations expected**

# Photon yields vs vertical height

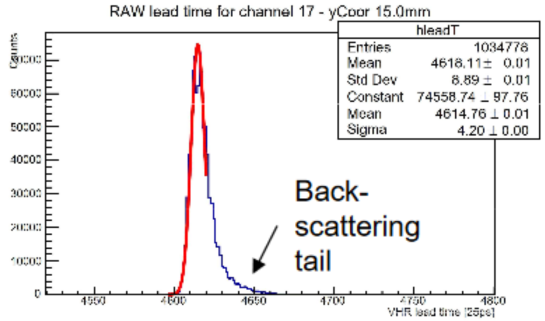
- Photon yields compared to simulation (which includes MCP quantum efficiency, collection efficiency, surface roughness, background rejection etc)
- Plots shown here for primary reflection.
- The current prototype only has 2 out of 11 MCPs
  - Photon yields would be ~5.5 times larger than shown here
- Final MCPs are expected to have improved quantum efficiencies

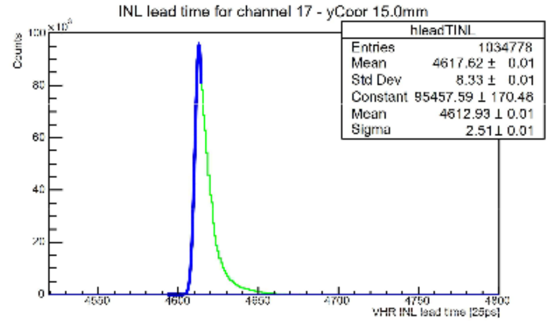



| | Data | Sim | Ratio |
|---|---|---|---|
| Position 1 | 2.77 | 2.75 | 0.99 |
| Position 3 | 1.53 | 1.54 | 1.01 |
| Position 4 | 1.00 | 1.07 | 1.07 |
| Position 5 | 0.74 | 0.81 | 1.09 |

# Recent CERN lab measurements

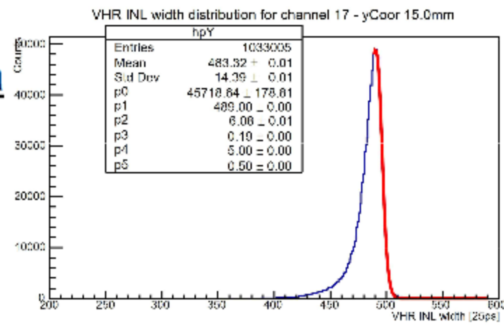
Raw data
Lead time
$\sigma_t$~102.5ps

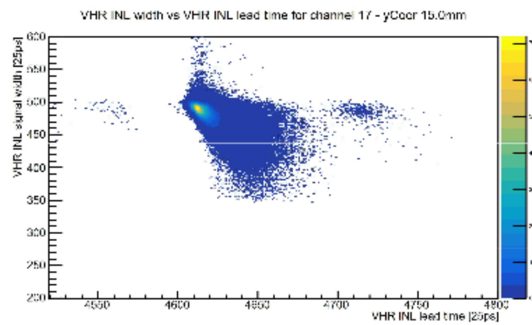



INL-corrected data
Lead time
All time walks
$\sigma_t$~61.3ps

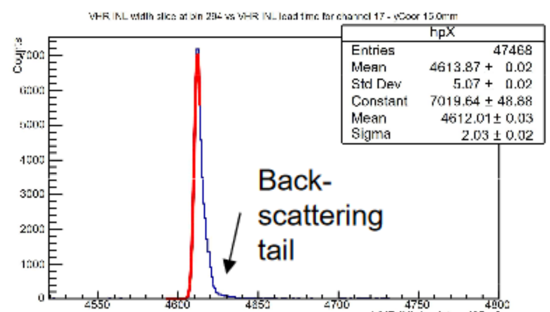
INL-corrected data
Width distribution




INL-corrected data
Width vs lead time

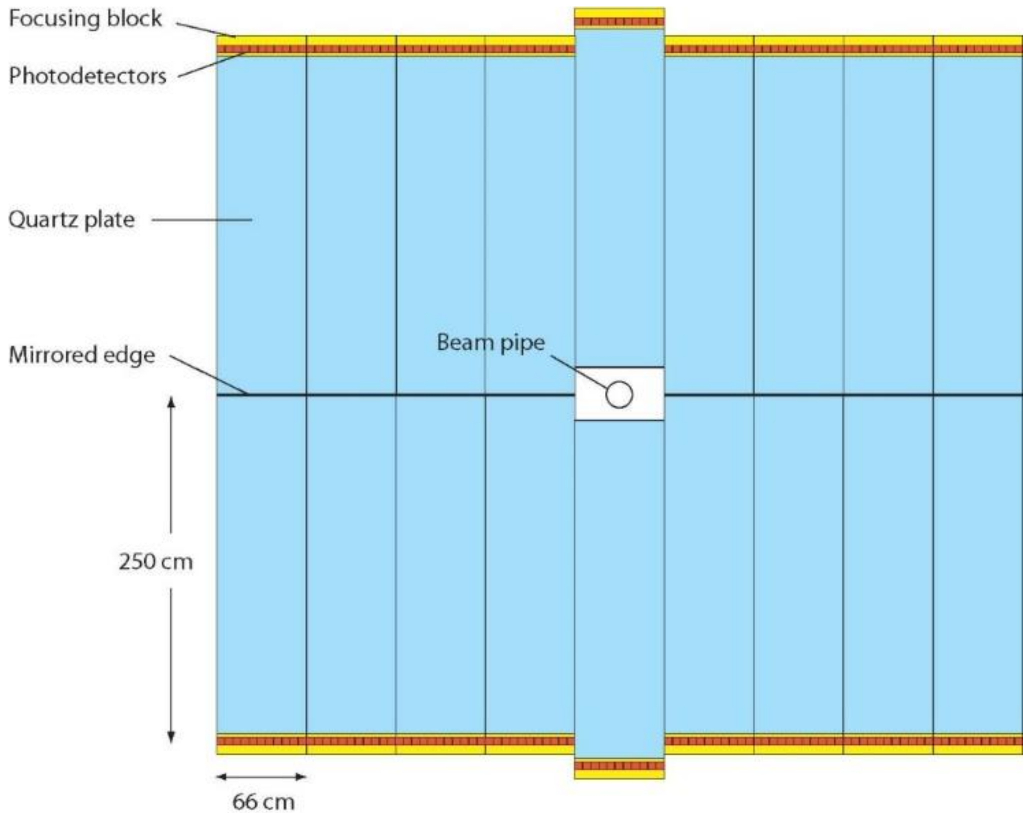
- All these lab results taken with 25ps HPTDC binning
- MCP gain ~2x10$^6$ e$^-$
- Similar results achieved with gain of 1x10$^6$ e$^-$




INL-corrected data
Lead time
@ constant width
**$\sigma_t$~49.6ps**
Required: $\sigma_t$~50ps

# TORCH (Upgrade Ib model)

- Based on the following modular TORCH design :
  - Area 5 x 6 m$^2$
  - 18 module system
  - 11 MCPs per module



# TORCH inventery (Upgrade Ib)

- Quartz radiator : Required 4 [plates] x 9 [modules] = 36 units
- Focussing block : Need 2 (up and down) x 9 modules = 18 units
- MCPs : Need 11 per focussing block 11 x 9 x 2 = 198 units
- Mechanics : likely carbon fibre structure
- Electronics and readout : 198 x 64 x 8 = 101k channels

# TORCH modifications (Upgrade II)

- Our expectation is that no significant change will need to be made to either the optics or mechanics. Only some adaptation where required of the photon detectors and associated electronics in hottest regions.

➢ Hence quartz radiators, focussing blocks : no additional cost

- Photon detectors : Possible replacement of 1/3$^{rd}$ central regions in Upgrade II (MCPs or SiPMs), increasing the granularity including electronics (possible synergy with the RICH upgrade)

- ***OR*** could increase the granularity in central 1/3$^{rd}$ region by a factor 8 using the existing detectors by changing the channel grouping, making 64 x 64 pixels : total detector readout channels (including electronics) increased by a factor ~2

- Mechanics : Assume minimal changes to structure. Electronics mounting and cooling capacity will need to be adapted.

# Opportunities

- Many areas are currently available for collaboration…..
  - Photon detector procurement & testing
  - Electronics
  - DAQ / controls
  - Mechanics / cooling
  - Optics
  - Reconstruction/simulation
  - Testbeam
  - …..

# Summary

- The TORCH R&D has progressed well, with a successful series of beam tests
- The time resolution of the prototype is approaching the design goals : 70 -100 ps timing resolutions per single photon have been achieved. With improvements in calibration hope to achieve consistently the desired 70 ps. Can improve time binning from 100 ps to 15 ps in the future (PicoTDC)
- Further lab tests and electronics calibrations are ongoing
- Future tests will involve the fully instrumented (11 MCP) half-height TORCH module

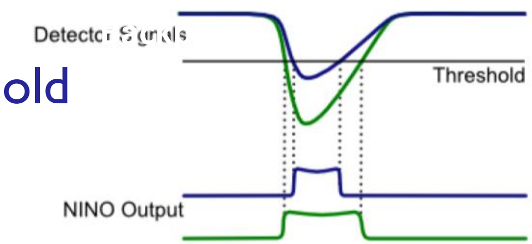
# Simulated performance at LHCb

- Over to Tom …..

# Spare slides

# TORCH readout electronics

- Custom readout electronics developed, based on the ALICE TOF system: NINO + HPTDC [F. Anghinolfi *et al*, Nucl. Instr. and Meth. A 533, (2004), 183, M. Despeisse *et al*., IEEE 58 (2011) 202]

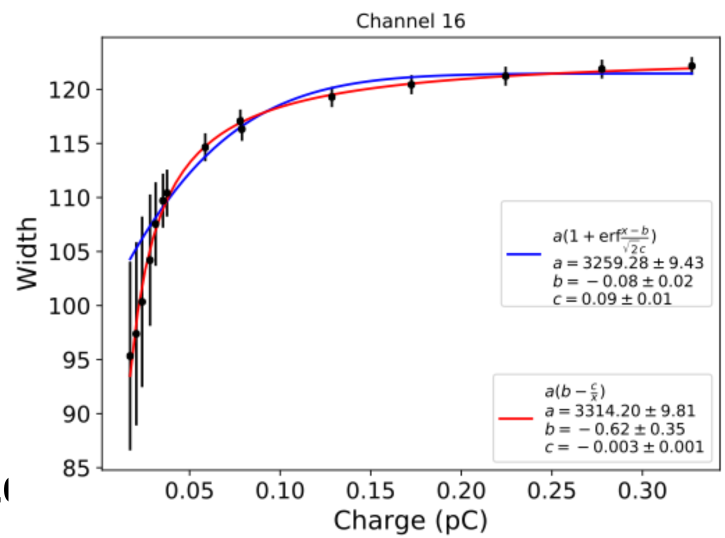



- NINO-32 provides time-over-threshold information which is used to correct time walk & charge to width measurement. Non-linearities of HPTDC time digitization (100 ps bins) are also corrected

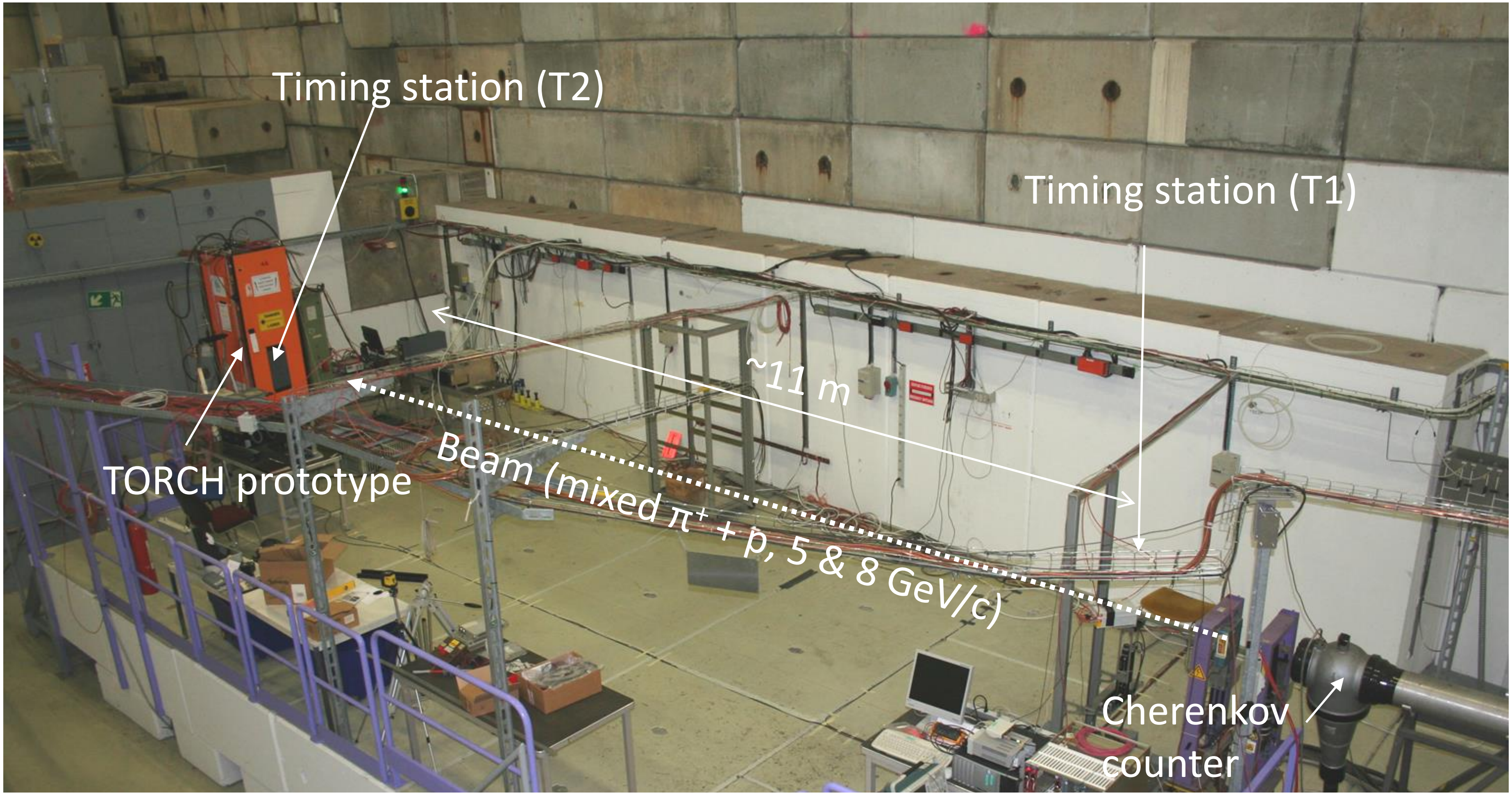
- 128 channel NINO board developed

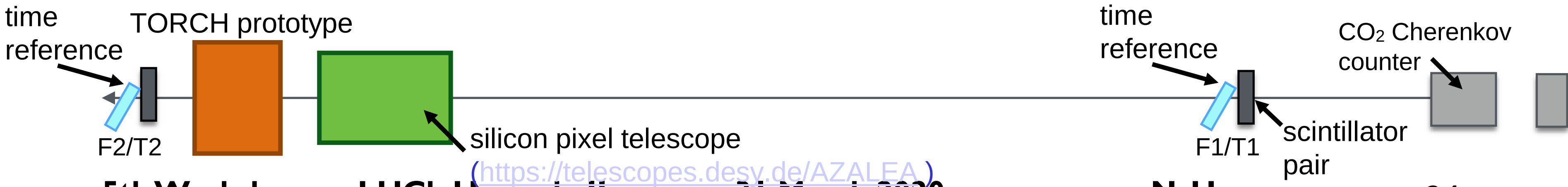
  R. Gao *et al*., JINST 10 C02028 (2015)

- The calibrations are challenging and work is still ongoing to optimize them



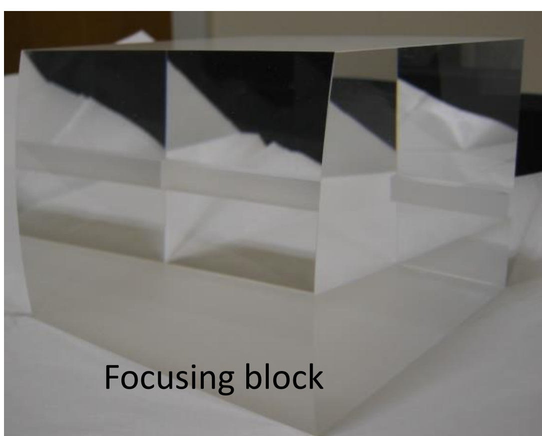
# TORCH beam test infrastructure in PS/T9



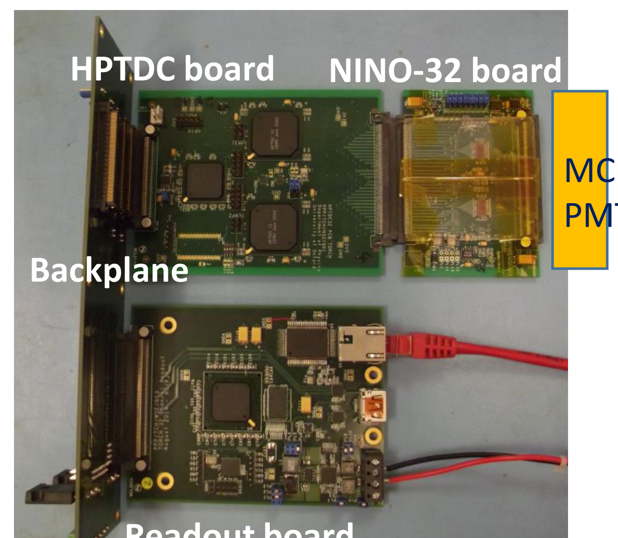



# Mini-TORCH demonstrator

- Quartz radiator ($12 \times 35 \times 1 cm^3$) with matching focusing block (from Schott Germany)
- Early version of NINO board (64-channel)
- Results now finalized – publication in preparation



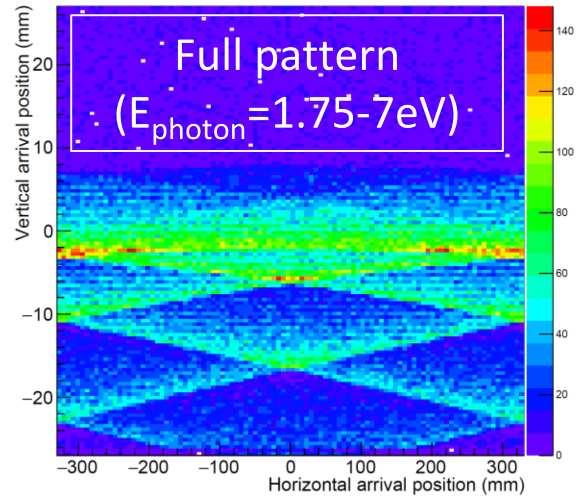

Radiator plate: 35 x 12 x 1 $cm^3$

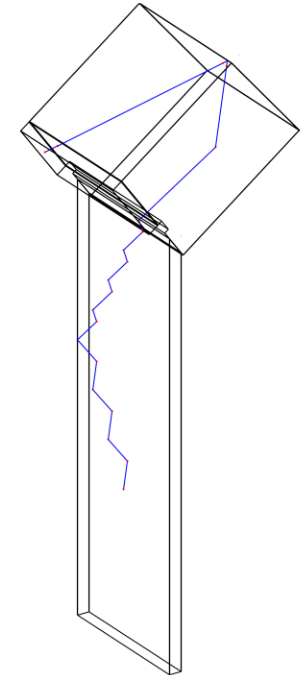


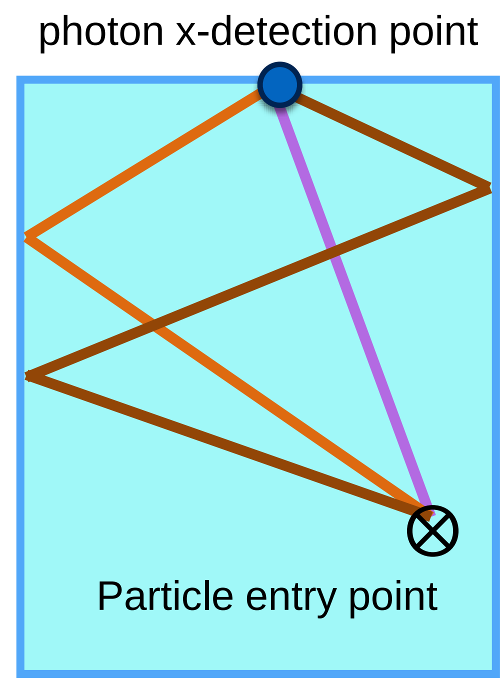
# A word on the pattern folding

- Cherenkov cone results in hyperbola-like patterns at the MCP plane
- Reflections off module sides result in folding of this pattern
- Chromatic dispersion spreads line into band

**Geant simulation**



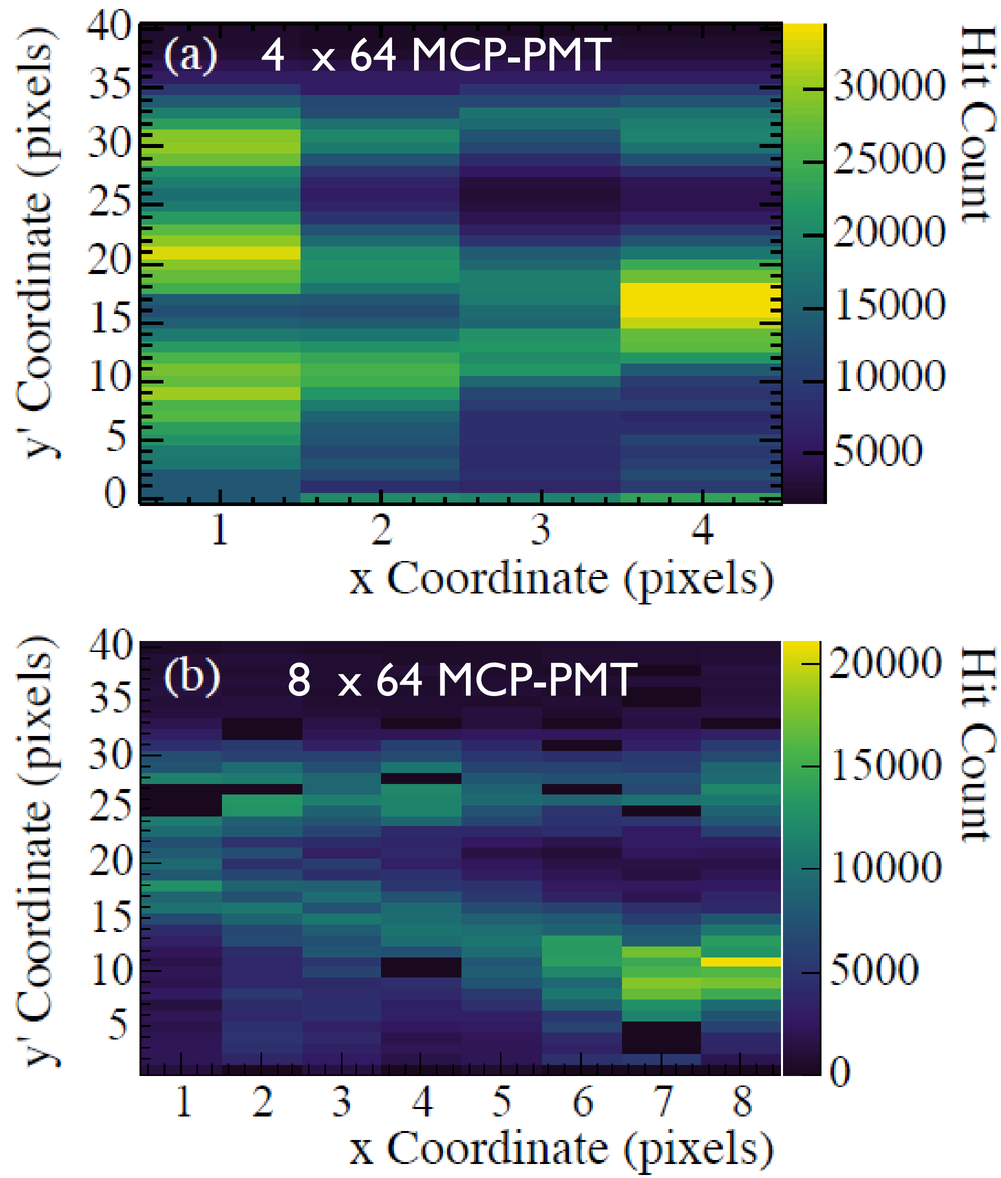






- The pattern shown above for a full TORCH module, however this pattern is only *sampled* with partially instrumented MCPs in the testbeam.
- The nominal test-beam configuration is chosen to give cleanly resolved patterns.

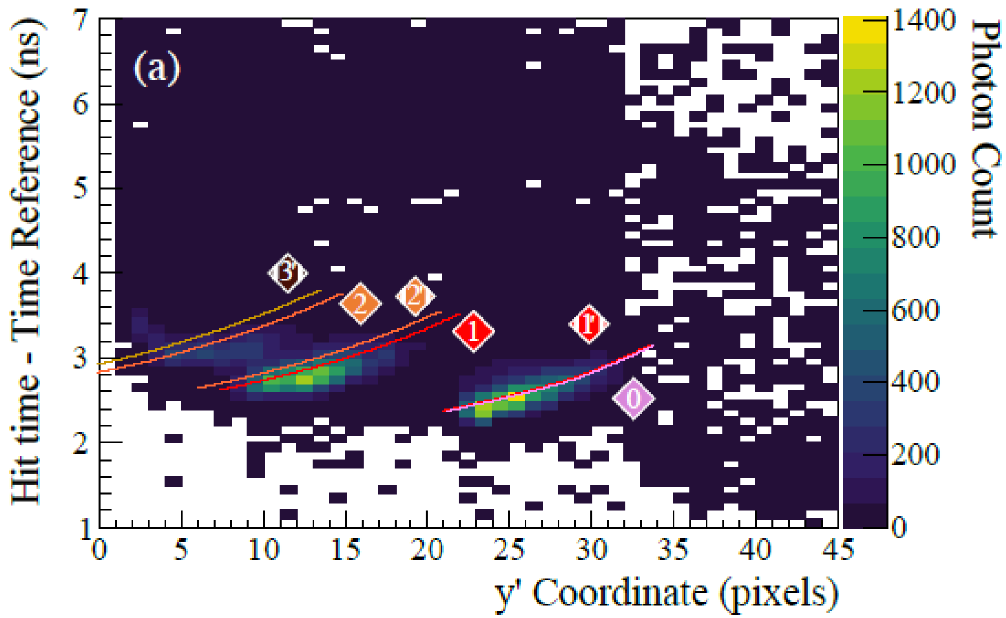
# Mini-TORCH hit maps in MCP-PMT

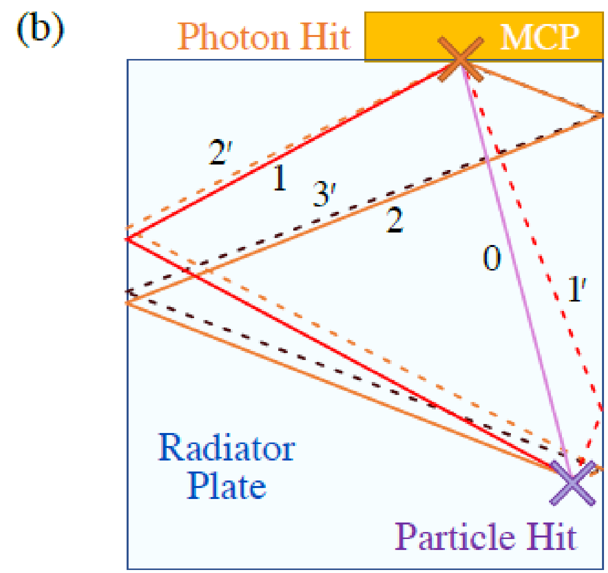
- 4 x 64 and 8 x 64 MCP-PMTs used
- Clustering applied to get MCP centroid hit position
- Correct for non-linearity and time-walk in the TORCH electronics.
- Note: some dead channels in 8 x 64 MCP-PMT due to NINO bonding issues



# Time resolution : mini-TORCH

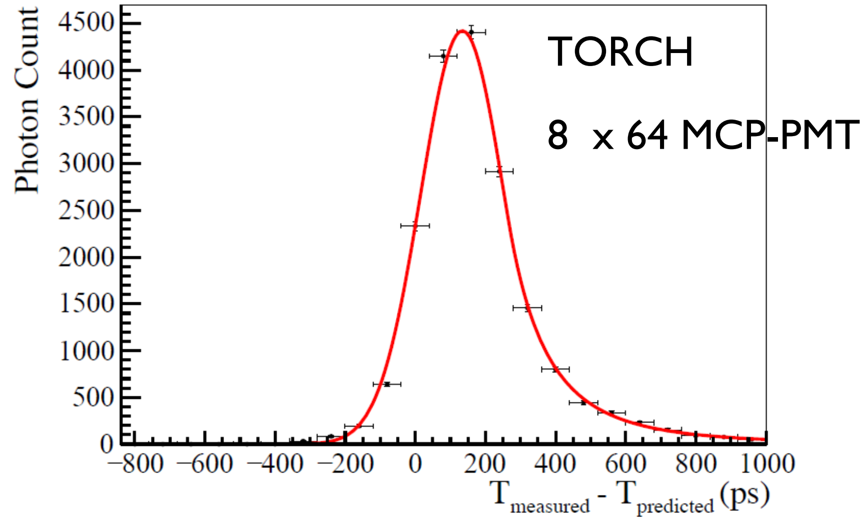
- Shown here is typical data for the 8 x 64 MCP-PMT
- For each column of pixels, plot the time measured for each cluster relative to the timing station T2 *versus* the finely-granulated pixel number (y')
- Reflection bands clearly observed



# Time resolution : mini-TORCH

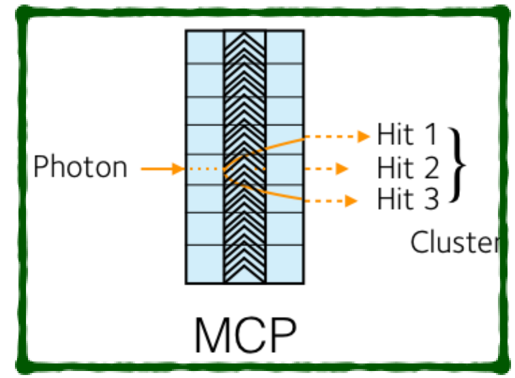
- Plot residuals for reflections 0 and 1'
- Subtract contribution from timing reference (~40 ps)
- We measure resolutions of typically100 ps per photon
- The target resolution is 70 ps per photon: improvements are possible to achieve this :
  - Improved pulse-height to width calibration
  - Limit of 100 ps binning in HPTDC

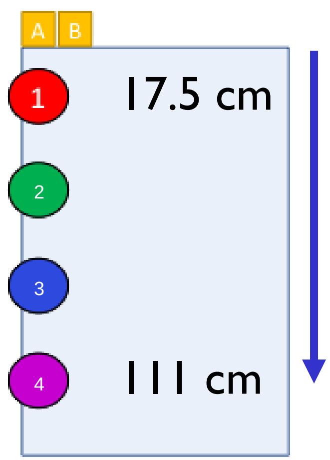


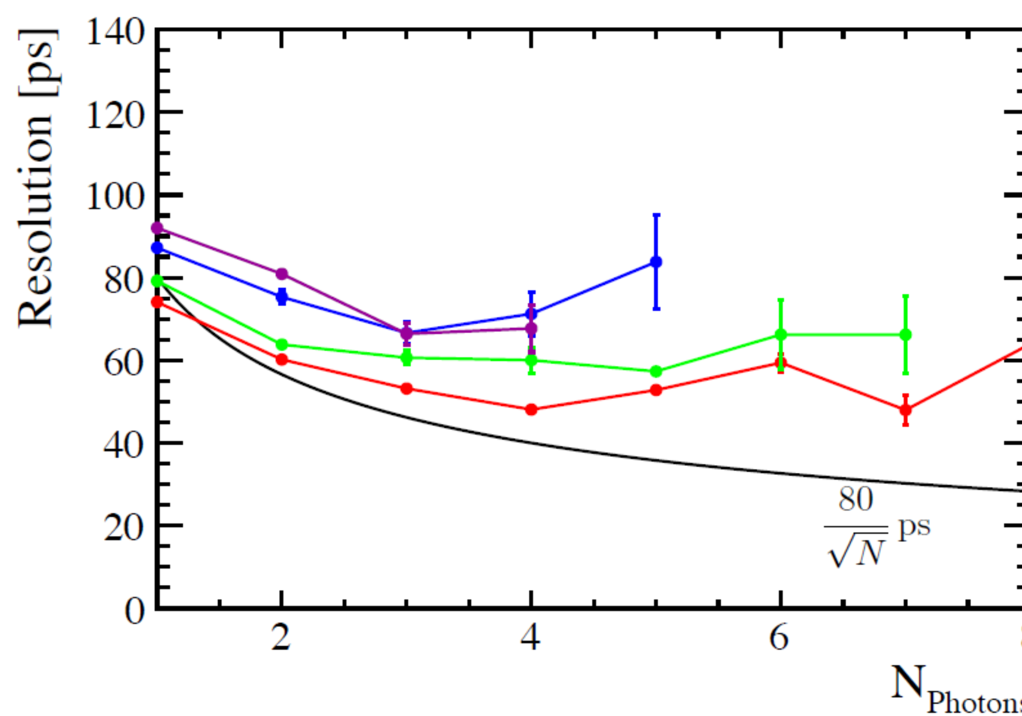

| MCP Column | $\sigma_{TORCH}$ Pions (ps) | $\sigma_{TORCH}$ Protons (ps) |
|---|---|---|
| 1 | $110.6 \pm 1.2$ | $112.7 \pm 1.4$ |
| 2 | $101.7 \pm 1.2$ | $110.6 \pm 1.4$ |
| 3 | $101.5 \pm 1.2$ | $110.6 \pm 1.4$ |
| 4 | $105.5 \pm 1.2$ | $106.2 \pm 1.4$ |
| 5 | $83.8 \pm 1.3$ | $91.0 \pm 1.4$ |
| 6 | $101.3 \pm 1.2$ | $103.4 \pm 1.2$ |
| 7 | $90.3 \pm 1.2$ | $87.5 \pm 1.4$ |
| 8 | $112.4 \pm 1.1$ | $102.8 \pm 1.4$ |

# Resolution studies - ProtoTORCH

- Use charge sharing in the MCP to measure the cluster centroid of each photon hit
- Plot the time resolution for different sizes of clusters of hits
- Events with large numbers of photons might actually have two tracks



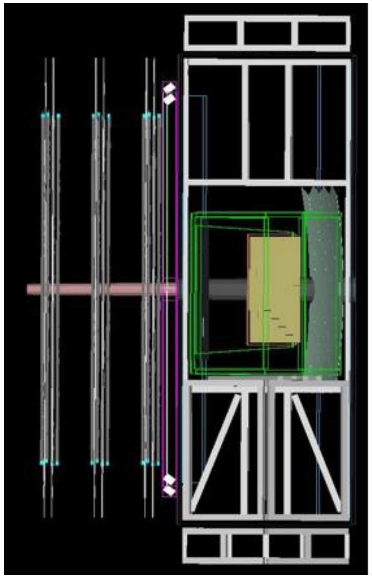
# Simulated performance at LHCb

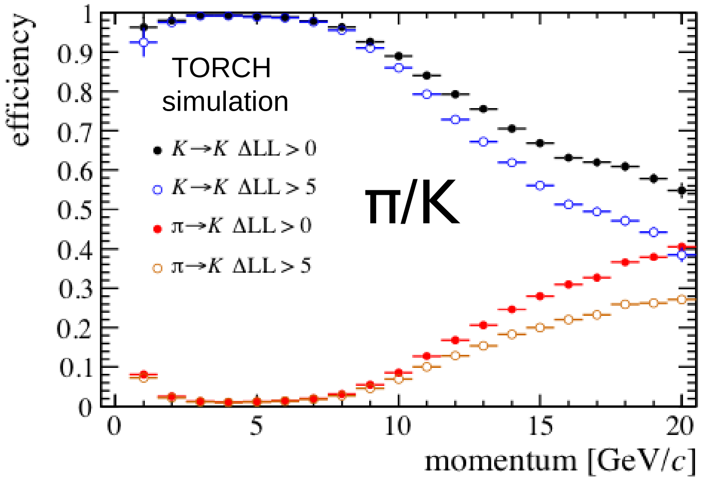
- TORCH has been simulated in the framework of the Upgraded LHCb detector (GEANT4)

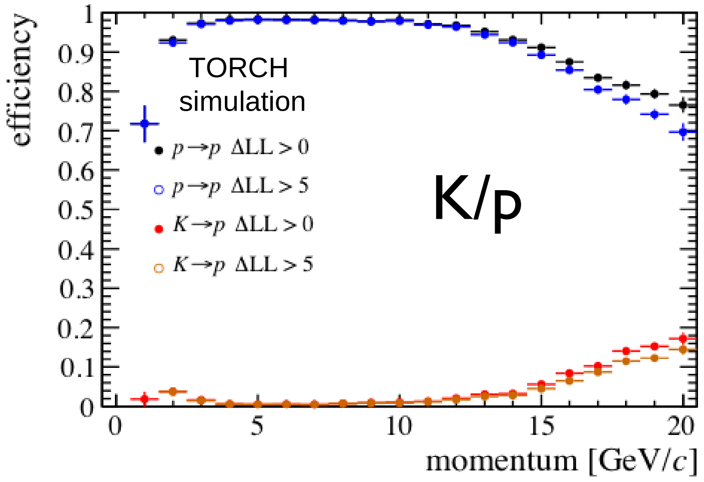
- The PID performance is determined for Upgrade IB conditions (Run 4)

$$\mathcal{L} = 2 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

- Good separation expected between π/K/p in the 2 -10 GeV/c range and beyond.





# Bandwidth Estimation – LHCb Upgrade 1b

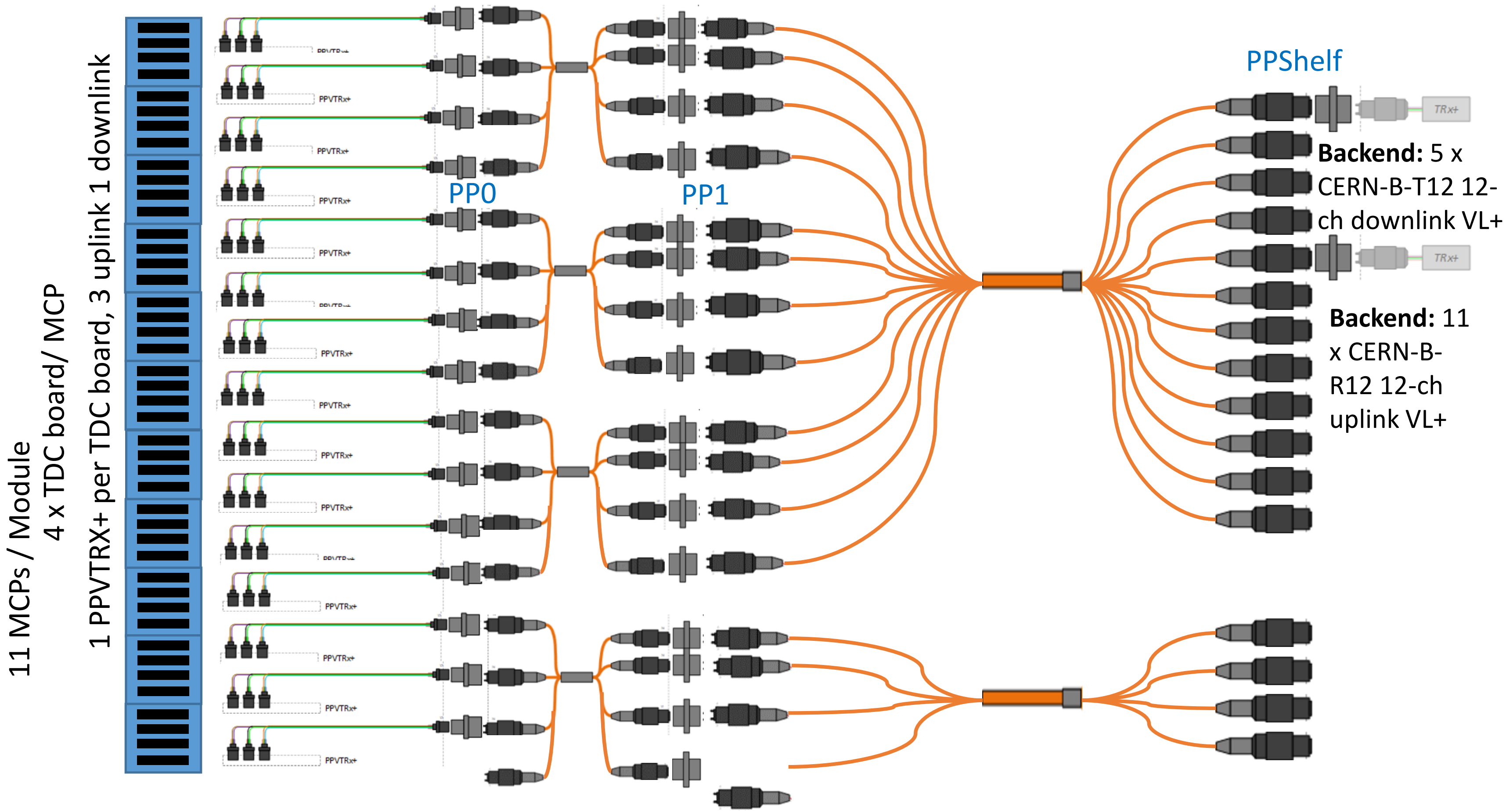
- In LHCb Upgrade 1b, we assume we have 18 modules, 11 MCP (64 x 8 channels) per module and 4 TDC boards to readout a MCP. Each TDC board contains 2 x 64-channel picoTDCs.

- Assume 10% occupancy, and using 32-bit combined TOT. measurement, we have: 18 x 11x 64 x 8 x 0.1x 32bits x 40Mhz = 13Tbps. A 32-bit header need to be sent for every 4 measurement, that gives an extra 3Tbps.

- We have a total 16Tbps bandwidth, further optimisation is possible.

- We would need 18 x11x 4 x 3 = 2376 simplex TX fibres and lpGBT chips. 18 x11x 4 x1 = 792 duplex fibres and lpGBTs.

# TORCH Passive and back-end components for one module

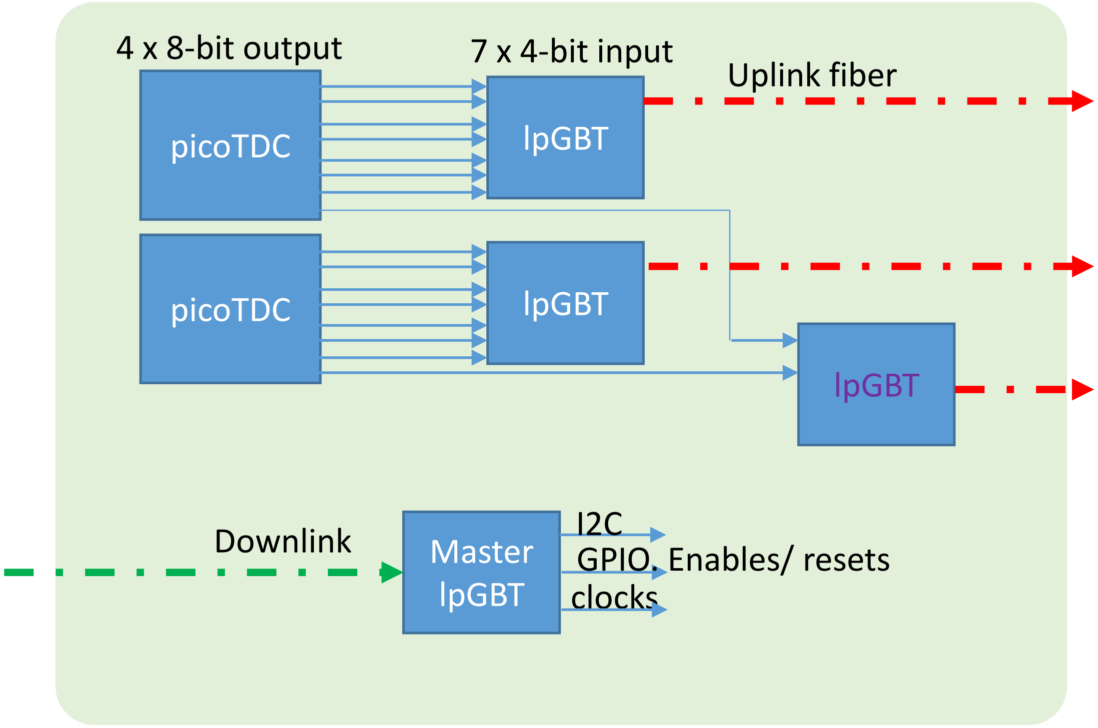



**Naked Fan-out** : 4 fibers(3up, 1 down) / connector, 3 connector fan-out

**Shuffle**: 4xMT-12(mixed up down) in 4x MT-12 out (3x12 up and 1x 12 down)

**Trunk**: 12xMT-12 trunk cable and 4 x MT-12 trunk cable

# A 128-CH TDC board




- Read out 2 columns on MCP
- 2 x picoTDC
- 4 x lpGBT
- 1 x VTRx+, 1 x MT-12 fibre connector