TORCH:
a novel concept for PID

Roger Forty (CERN)

TORCH (<u>**T**</u>ime <u>**O**</u>f internally <u>**R**</u>eflected <u>**CH**</u>erenkov light) is a detector concept intended for fast timing of charged particles over large areas

Currently an R&D project, under study for *next* upgrade of LHCb (in LS3/4)
Potentially interesting for adaptation to use in a future FCC-ee detector?

Previously presented at an FCC-ee detector brainstorming meeting on 4 July 2016—slides updated here with progress made since then

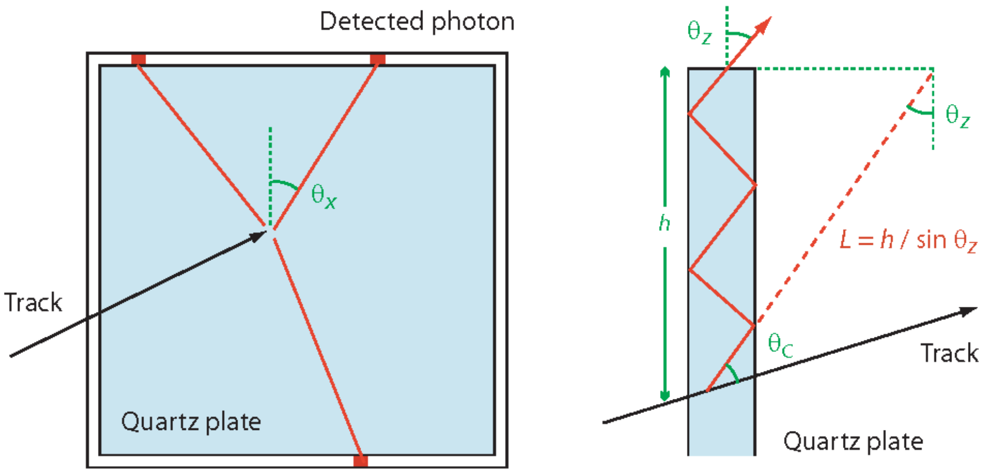
1. TORCH principle
2. R&D project
3. Application in FCC-ee?

FCC-ee workshop (CERN) 9 January 2019

1. TORCH principle

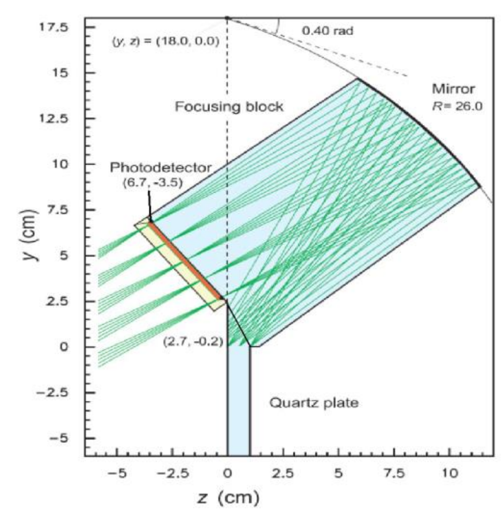
- DIRC-like detector, with a ~1 cm thick quartz radiator plate
  Cherenkov light produced in the plate propagates to the edge by TIR
  focused via a cylindrical lens onto fast photon detectors
- Reconstruction of the Cherenkov angle at emission allows the propagation time in the radiator plate to be corrected for dispersion
  i.e. it combines **RICH + TOF** aspects
- Requires precise angular information (~ 1 mrad) to achieve timing resolution of ~ 70 ps/photon → **10-15 ps/track** by combining ~ 30 detected p.e./track

Front and side views of radiator plate



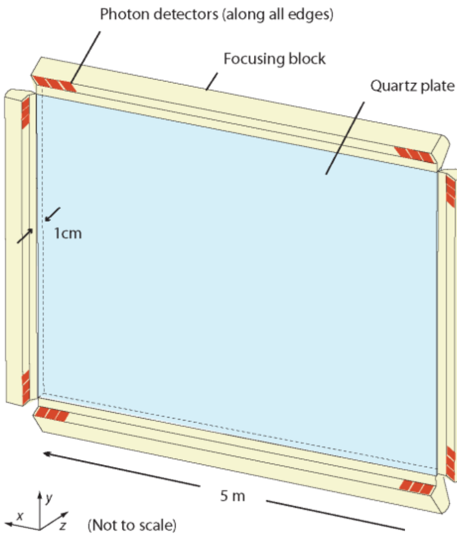
(schematic)

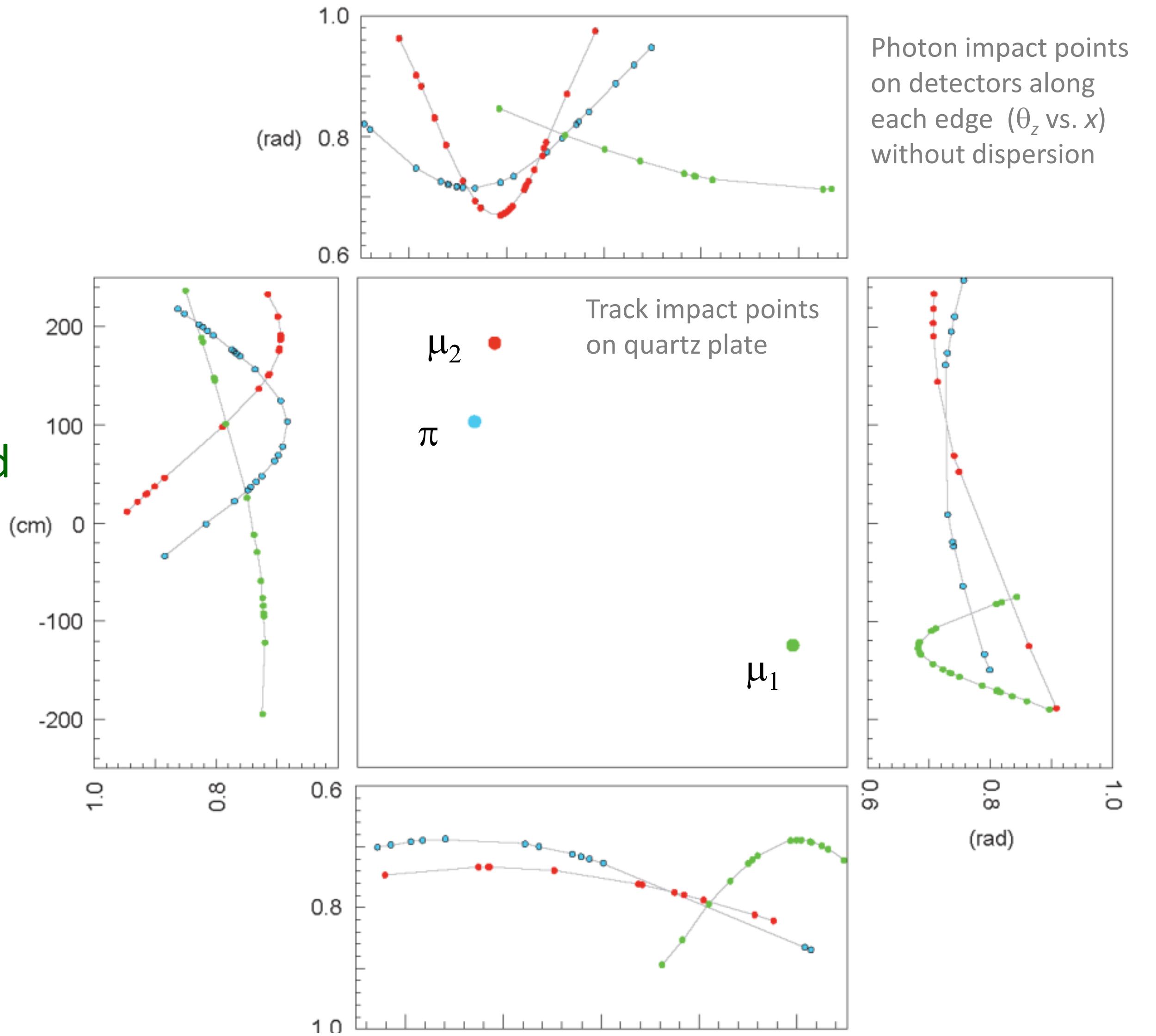
Focusing at edge of plate



Signal form

- Event display of an idealised TORCH detector in simulation of sterile neutrinos (low multiplicity)
- Photon hits colour-coded to match parent track

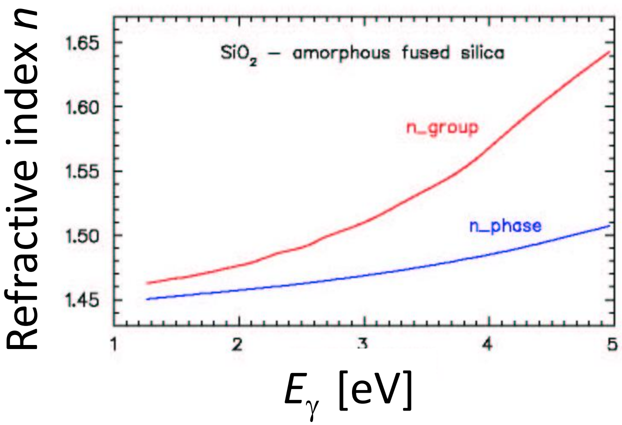


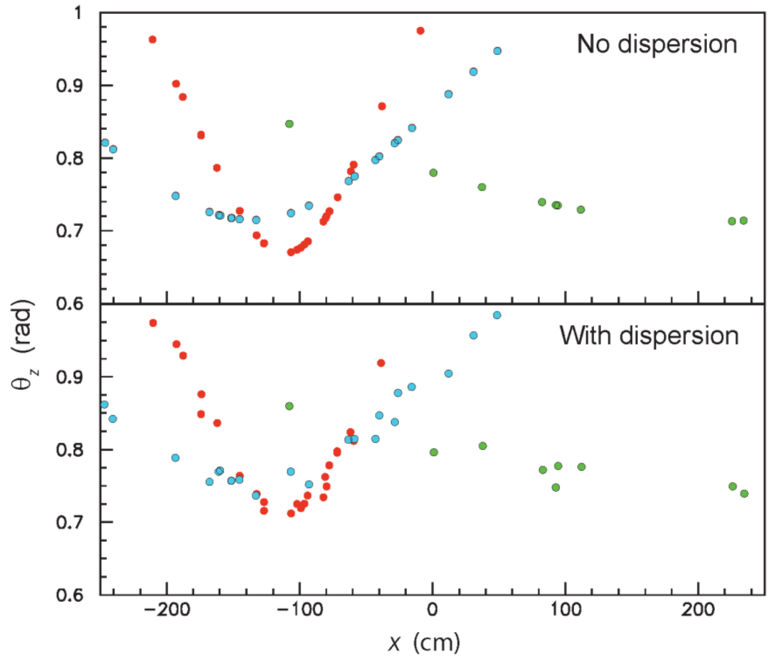


→ TORCH is also a candidate for use in such SHiP-type experiments e.g. included in the design of proposed **TauFV** (considered by PBC)

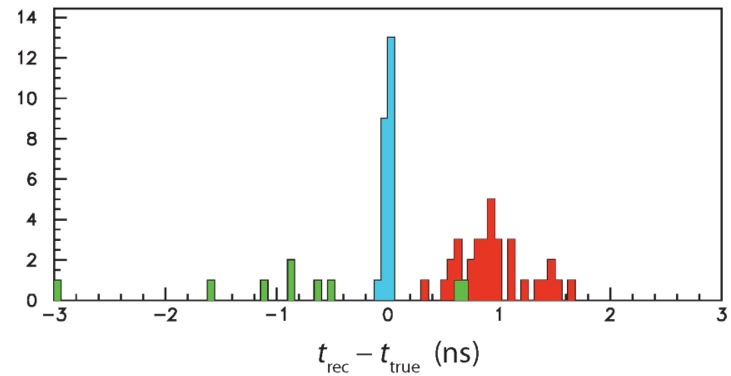
Reconstruction

- Smearing from **dispersion** in quartz:





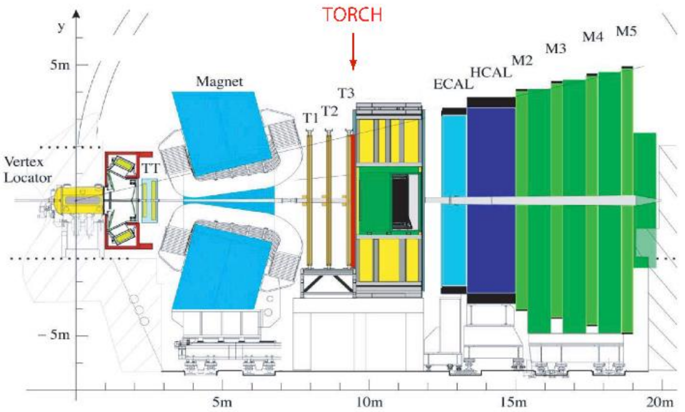
- Use timing information as well as spatial information from detector to separate signals from each track
- Calculate time of propagation of all photons relative to the blue track (π)
- Hits from that track peak at true time
  Hits from other tracks spread out
  (but peak in time distribution when it is calculated relative to *that* track)



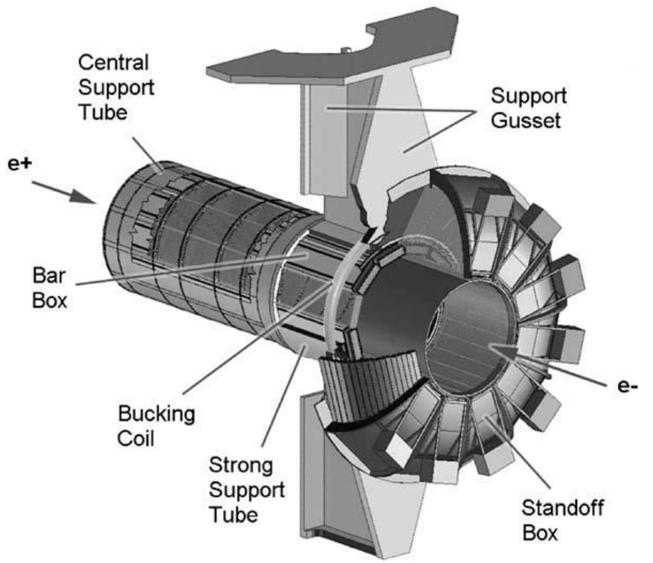
TORCH in LHCb

- Conceived for low-momentum PID in **LHCb** replacing aerogel radiator of RICH system (could not handle increased occupancy)
- Nominal position of TORCH (z = 9.5 m) chosen to be as close as possible to tracker and to reduce area to be covered (~30 m^2)
- Original DIRC of **BaBar** required large water-filled standoff volume for readout, achieved K/π separation up to ~ 3.5 GeV (based on Cherenkov *angle*, not timing)
- **Belle-II** TOP "time-of-propagation" detector adds timing but limited focusing → 4–5 GeV? (see previous talk from Roberto Mussa)
- **TORCH** uses measured Cherenkov angle to *correct* timing, aiming for "ultimate" resolution K/π separation up to 10 GeV/c ($\Delta_{TOF} \approx 40$ ps)

LHCb

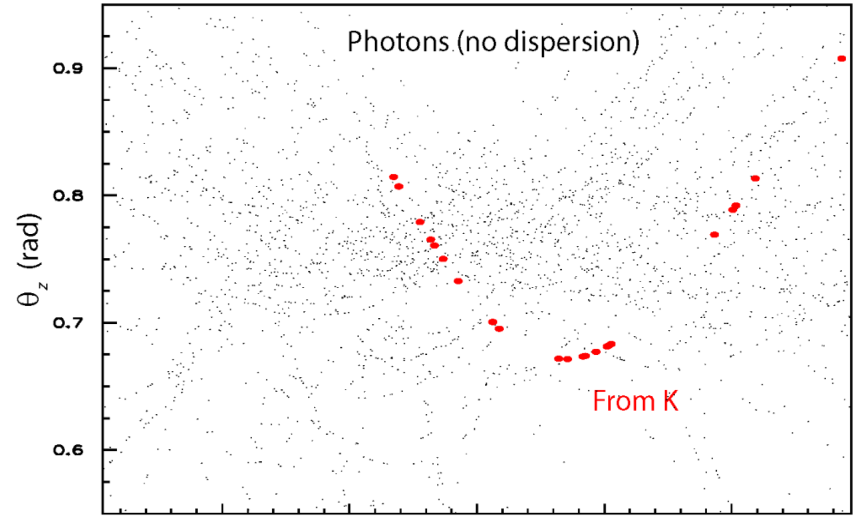


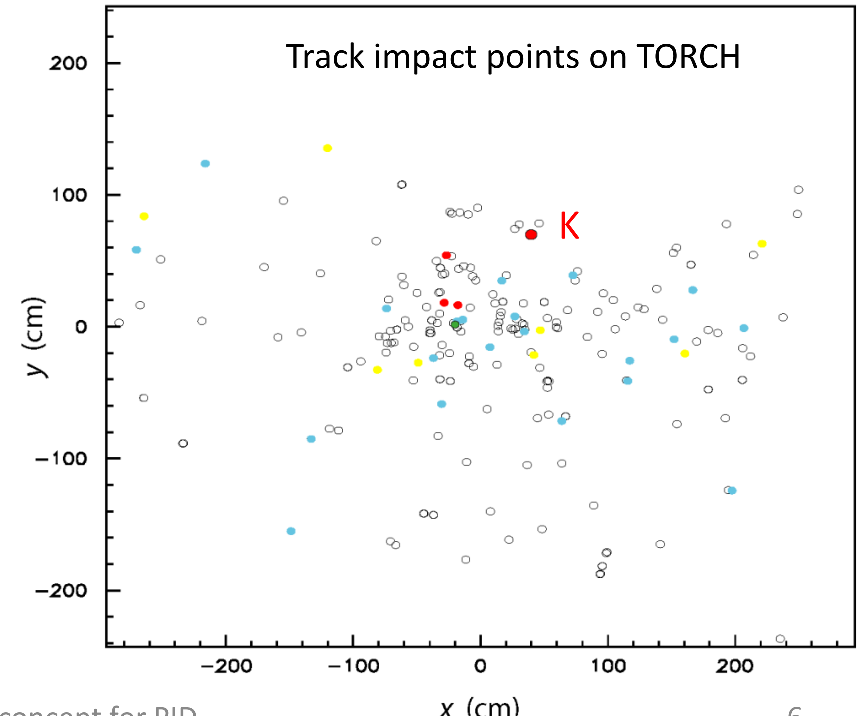
BaBar DIRC



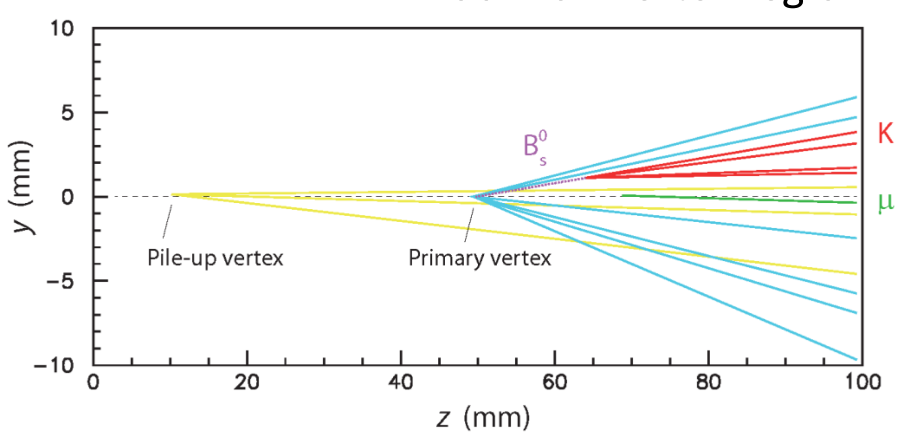
LHCb event

- Typical LHCb event, at luminosity of 10^{33} $cm^{-2}s^{-1}$ (only photons reaching the upper edge shown)
  High multiplicity! >100 tracks/event
- Tracks from vertex region colour-coded according to the vertex they come from (others are secondaries)
- "Start time" for TOF determination can be extracted from primary tracks (see backup)



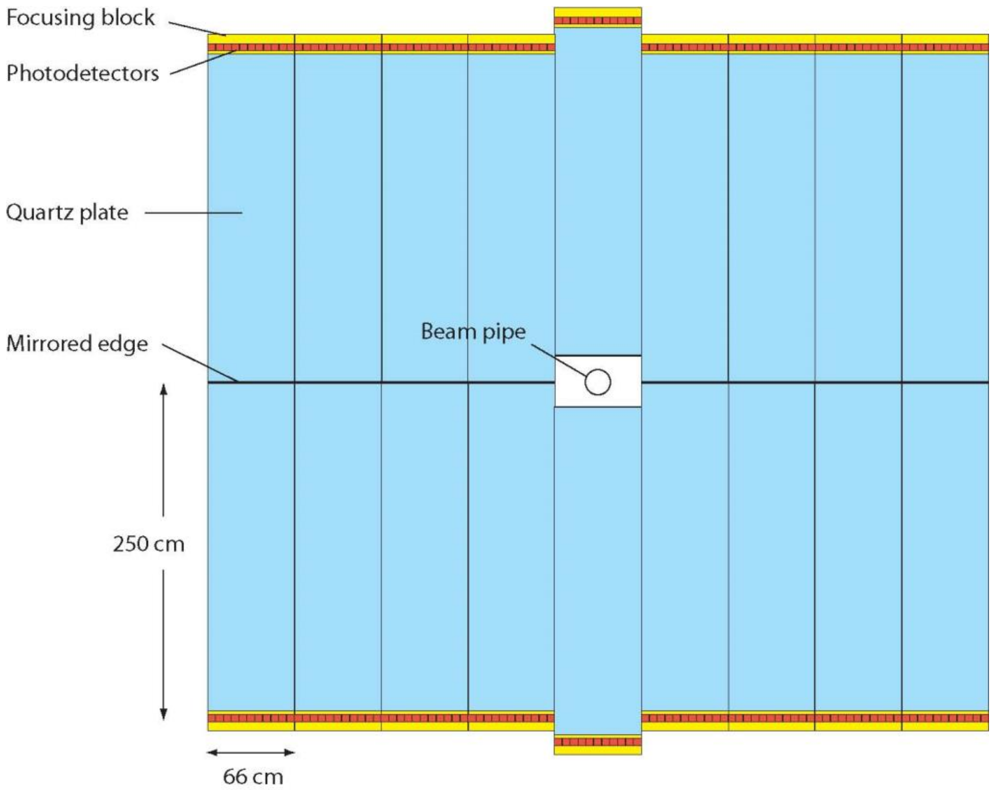


Zoom on vertex region



Modular design

- For the application in LHCb, transverse dimension of plane to be instrumented is ~ 5 × 6 m^2 (at z = 9.5 m) + central hole for beam pipe
- Unrealistic to cover with a single quartz plate → modular layout developed:

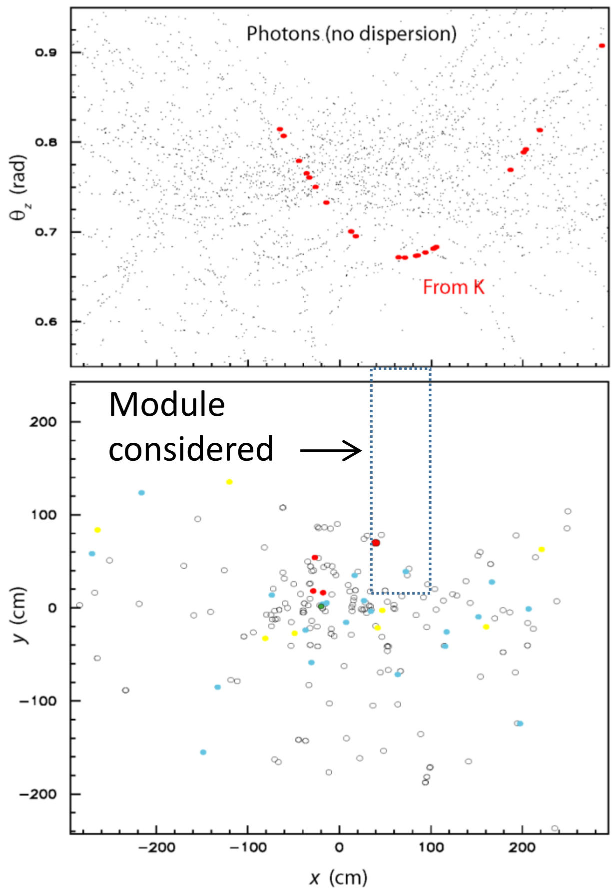


- 18 identical modules each 250 × 66 × 1 cm^3 → ~ 300 litres of quartz in total (less than BaBar)
- Reflective lower edge → detectors only on top
18 × 11 = 198 detectors
Each with 1024 pixels
→ 200k channels total

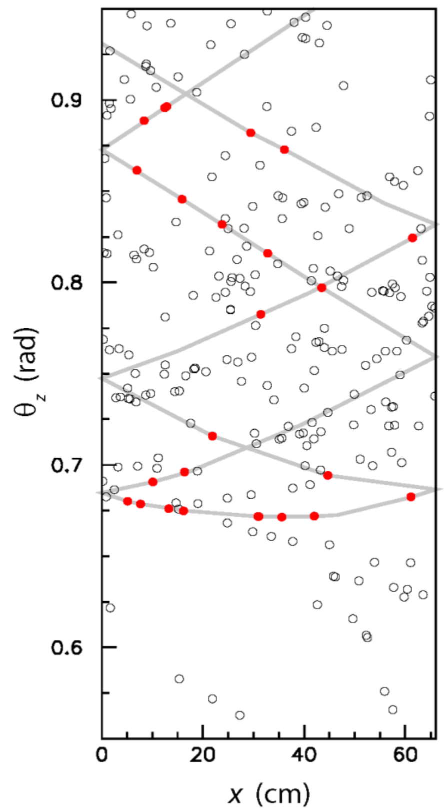
Channel count halved by using charge sharing to improve spatial resolution

Effect of modules

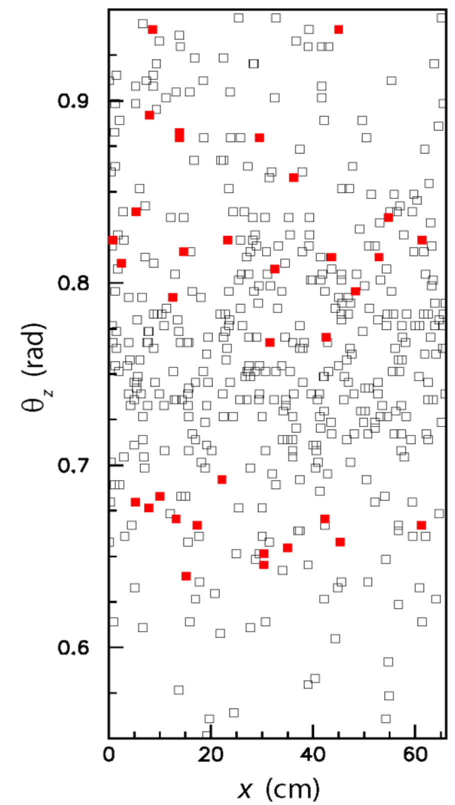
- Illustrate the effect of introducing modules, using the same event
- Far fewer hit-track combinations, but reflections from sides give ambiguities, which can be resolved in the reconstruction



Without dispersion or reflection off lower edge

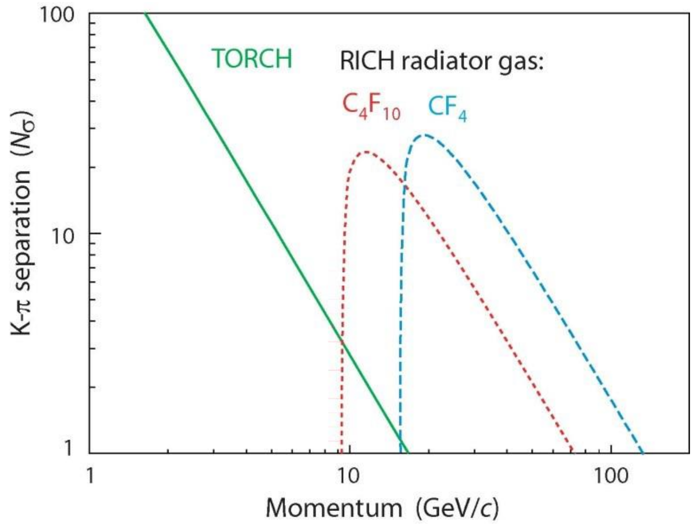


Including dispersion and reflection off lower edge

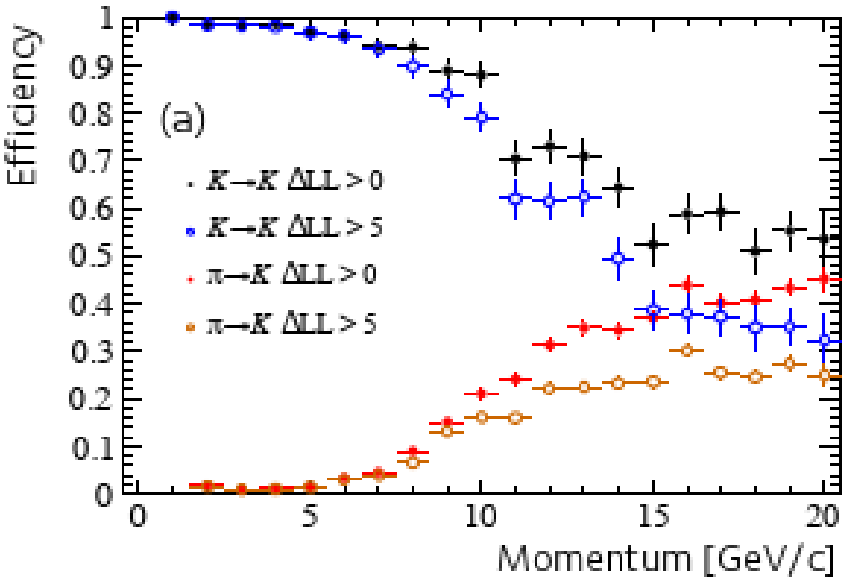


Performance

Isolated tracks (TOF only)



LHCb simulation: efficiency vs. *p*

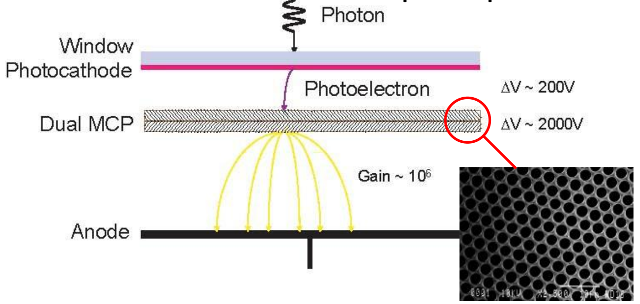


- Expected performance for low-momentum particle ID from full simulation: excellent, and robust to increasing luminosity
- Results shown are from a stand-alone simulation of the TORCH detector coupled to full LHCb simulation at the upgrade (i.e. post-LS2) luminosity
- Integration of TORCH into the LHCb simulation is in progress

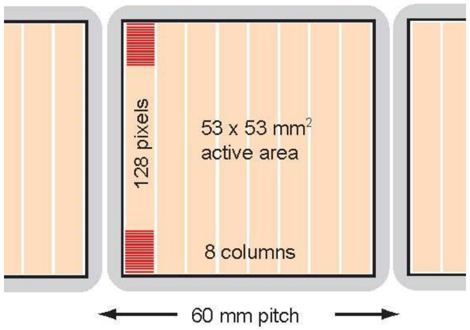
2. R&D project

- **Fast photon detectors** required: <70 ps for single photons—use microchannel plate (MCP) PMTs
- Fine spatial granularity needed (~ 0.4 mm) in one dimension (due to focusing) + long lifetime (> 5 C/cm^2) + large active area
  Requirements were not available in commercial tubes when R&D effort started (6 years ago)
- **R&D project** set up to develop suitable photodetector, funded by ERC: collaboration between CERN, Oxford, Bristol and UCL, with industrial partner Photek (UK); Warwick and Edinburgh have now also joined the collaboration
- Granularity and lifetime (using ALD coating) achieved in round tubes, final phase developed square tubes with large active area
  64 x 64 ch/tube!—we group pixels as required

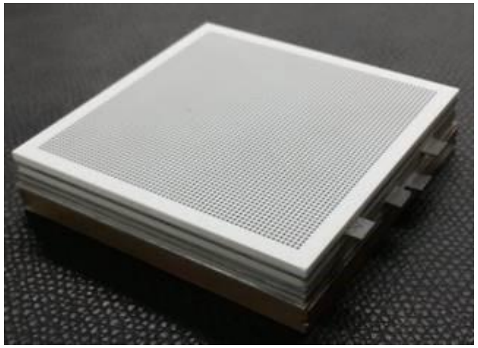
MCP principle



TORCH pixellization



Photek MCP

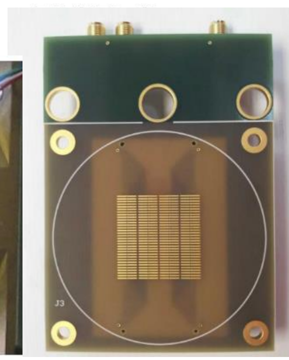


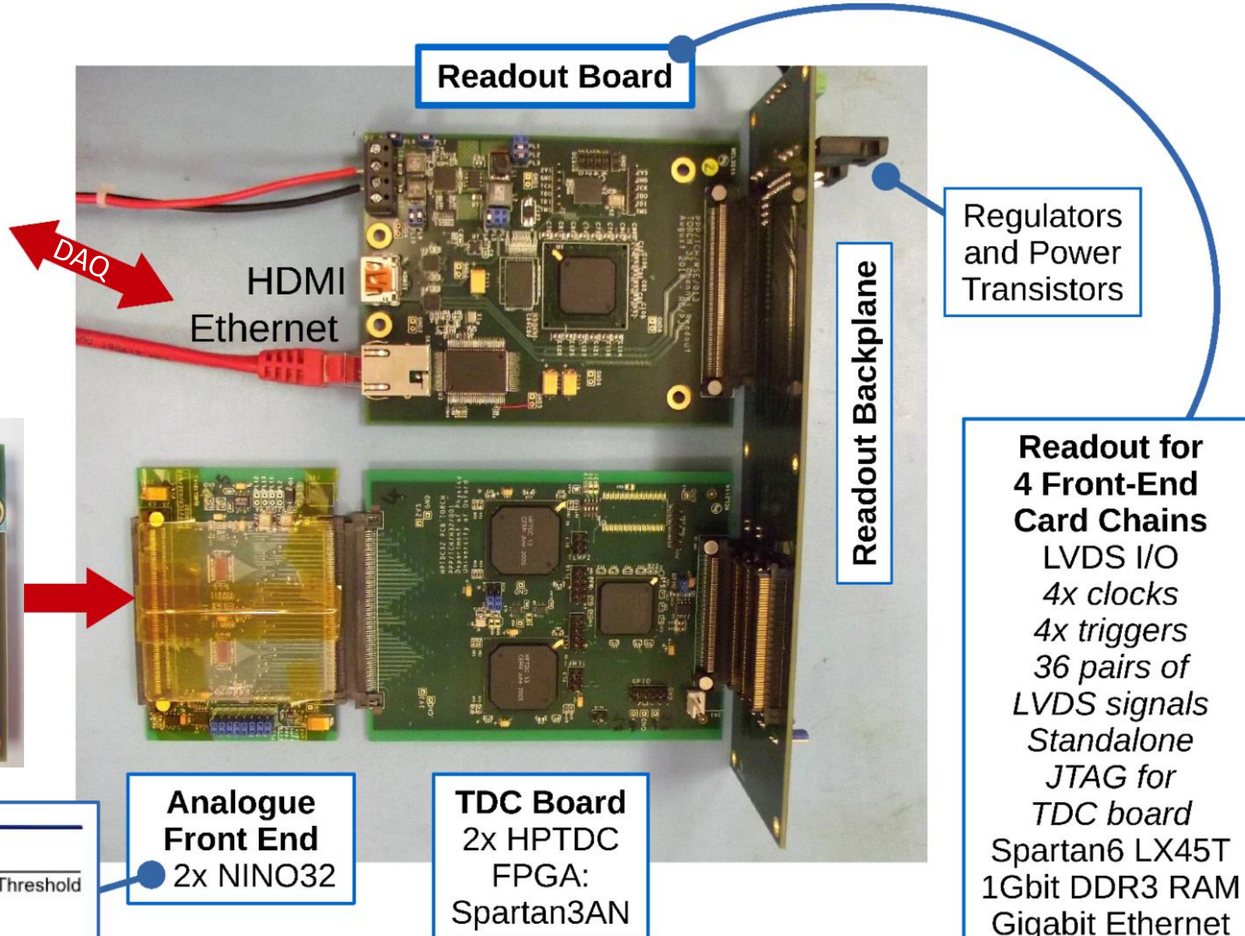
Custom electronics

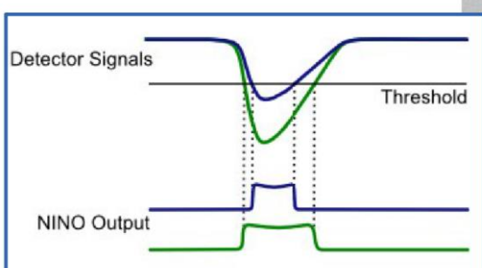
- Full readout for prototype tubes developed based on 32 ch NINO (ALICE) and HPTDC chips

Photek MCP

Anode pads





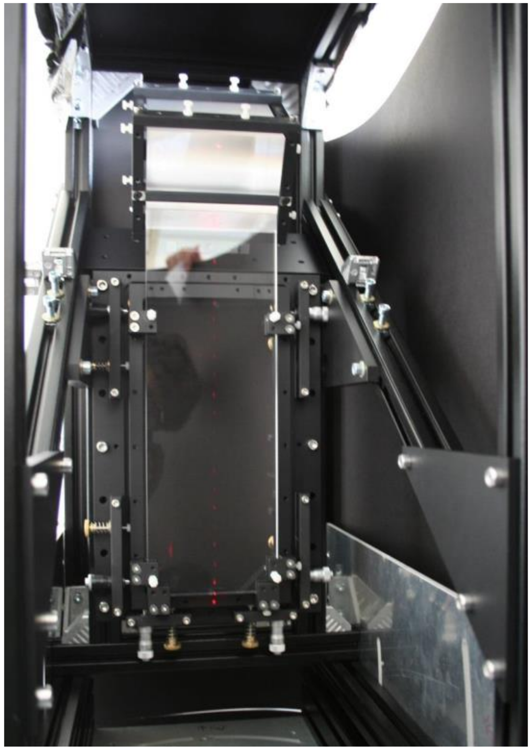


Time-over-threshold used for charge estimate → reduce number of pixels in fine direction (to 64)

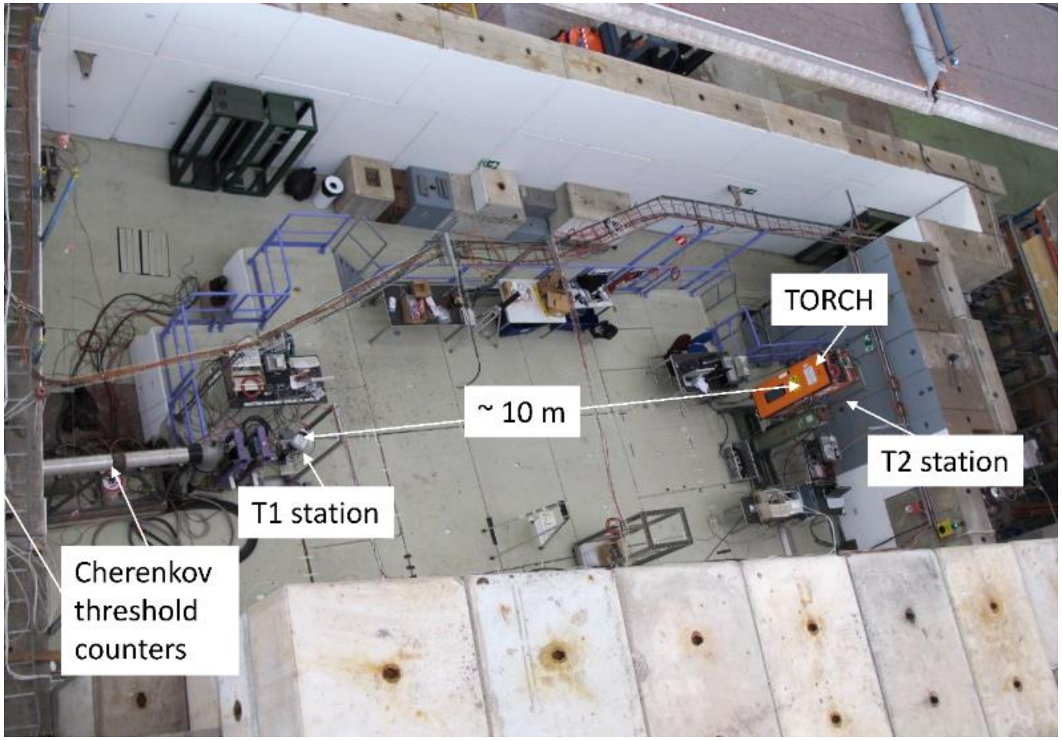
Test-beam studies

- Small prototype TORCH module made with 35 x 12 x 1 cm^3 radiator plate
- Coupled to focusing block and MCP with readout electronics + timing stations
- Data taken successfully in several test-beam campaigns at the PS (T9, 5 GeV/*c*)

TORCH prototype

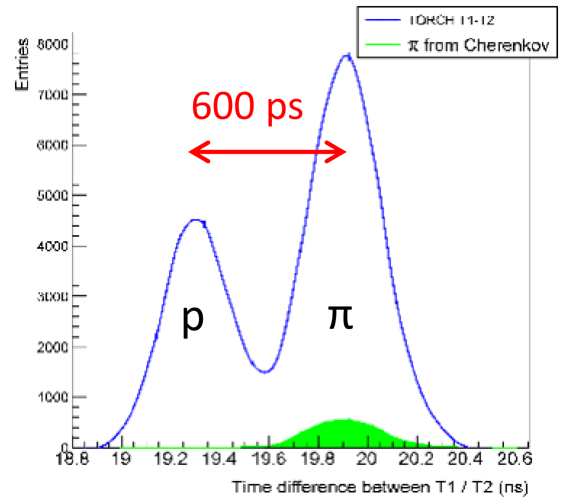


Test-beam setup

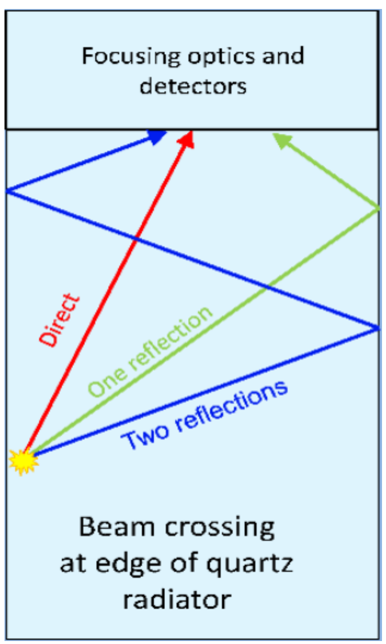


Data analysis

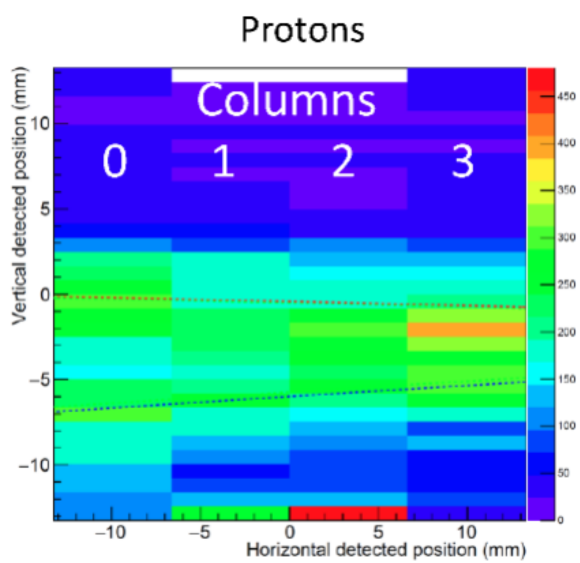
- Time-of-flight determined using timing stations (T1, T2) → separate p / π components of beam
  Confirmed using Cherenkov counter



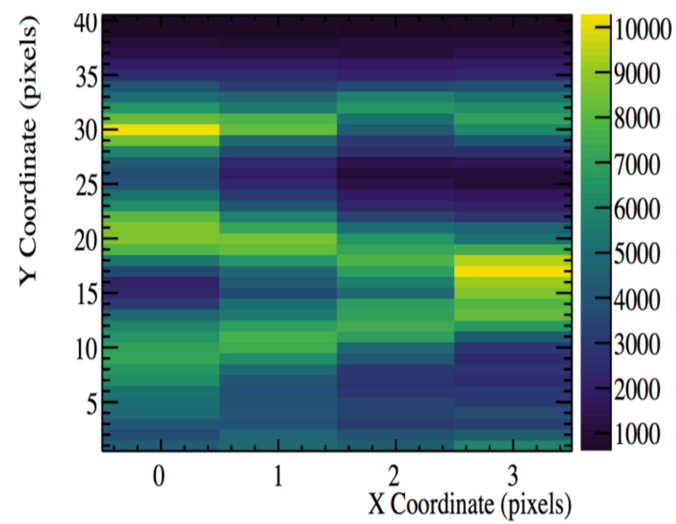
- Hits seen in MCP match expected pattern (taking into account reflections from edges)
  Difference in Cherenkov angle for π and p visible



Hit pattern in MCP (32x4 ch)



More recent data (64x4 ch)



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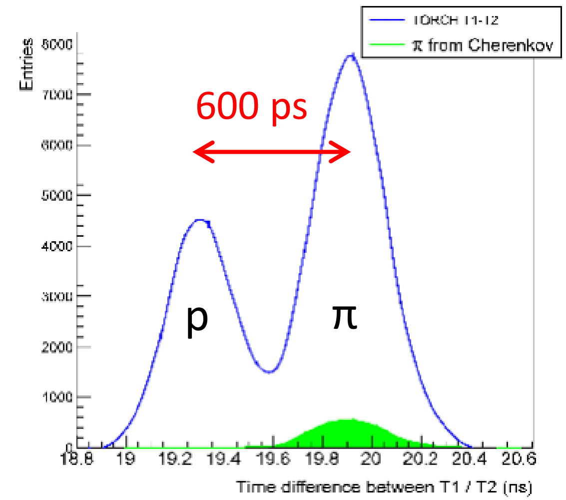

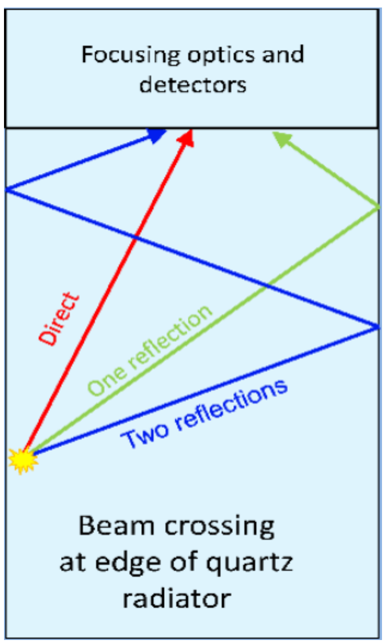

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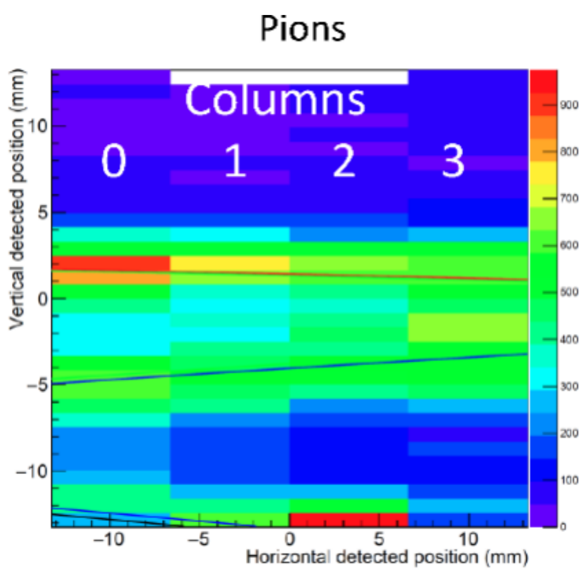
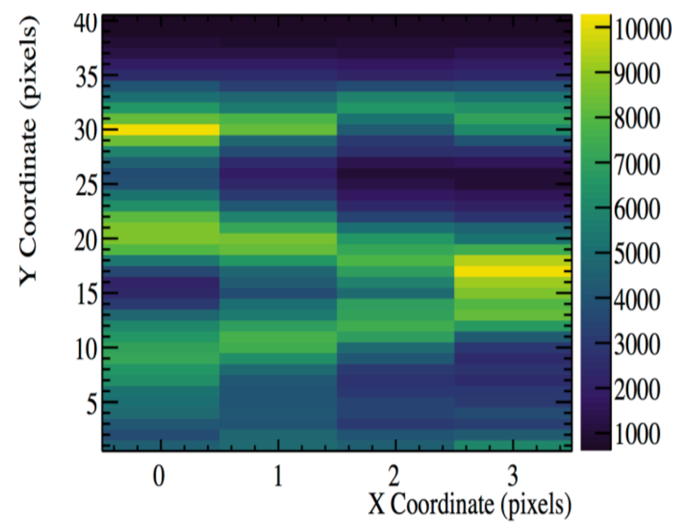


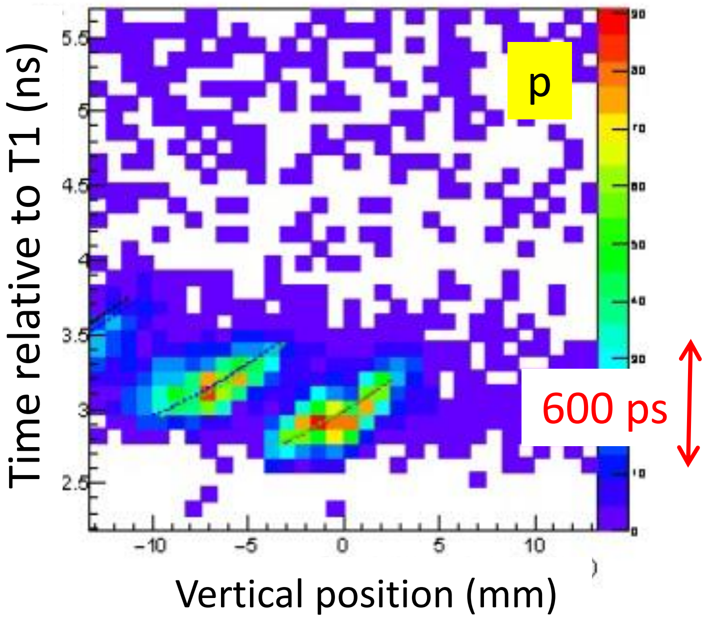
More recent data (64x4 ch)



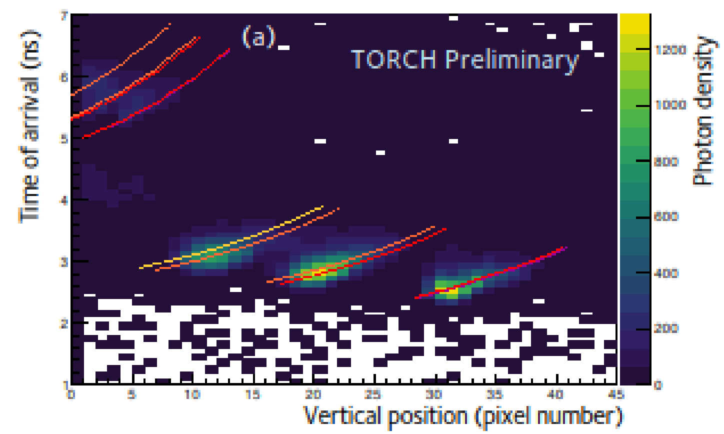
Timing performance

- Plot time measured for each cluster vs. vertical position along column of pixels
  - Reflections clearly separated
  - p-π time-of-flight difference cleanly resolved
- Project along timing axis relative to prediction for the earliest pion signal, for each column of pixels
  (relative to T2 as timing reference)
- Core distribution has σ ≈ 100 ps

  → approaching target resolution of 70 ps / photon
- Tails under study, due to imperfect calibration and back-scattering effects [see e.g, https://arxiv.org/abs/1812.09773]



More recent data (64 x 4 ch)



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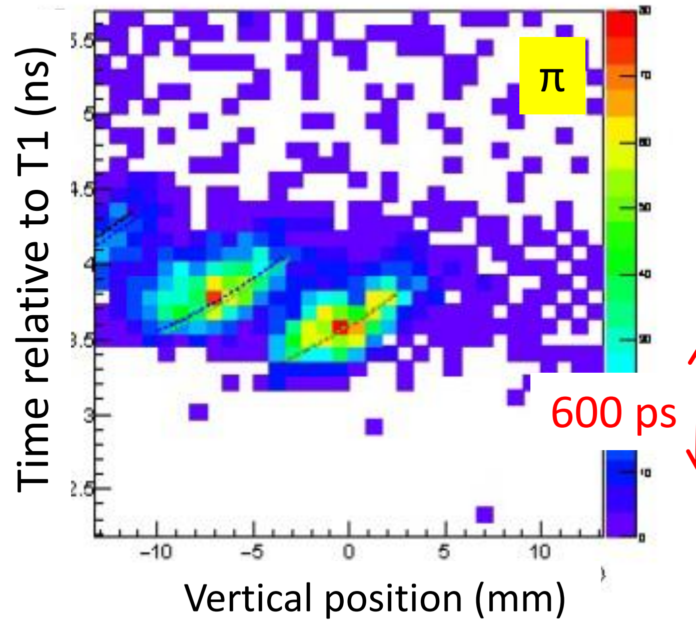
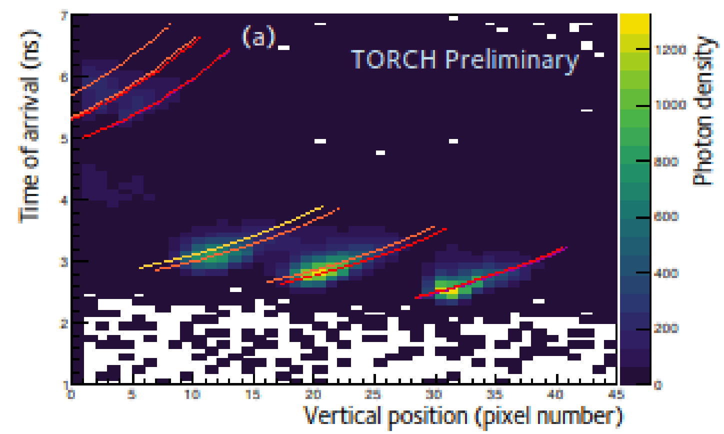


More recent data (64x4 ch)



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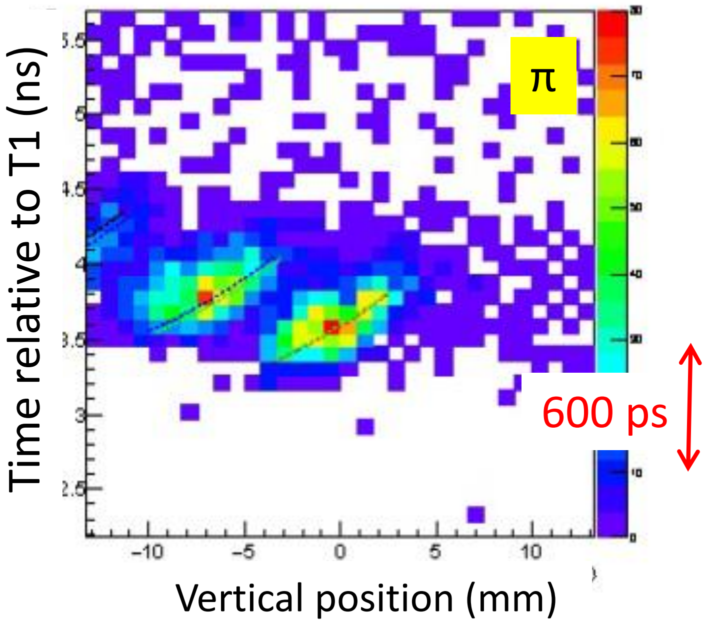
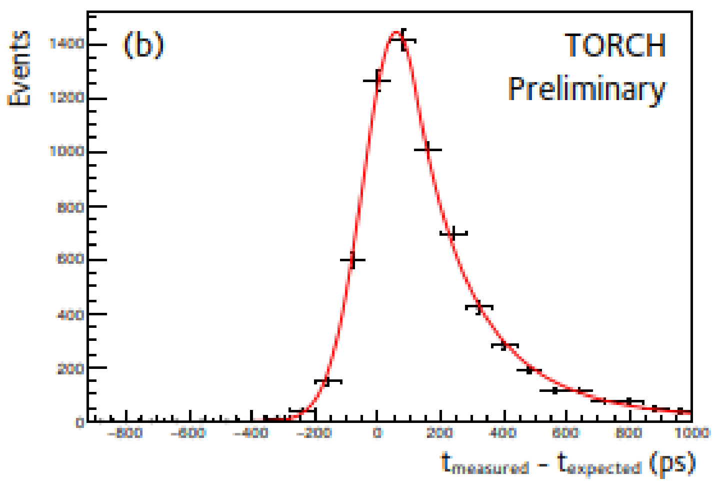
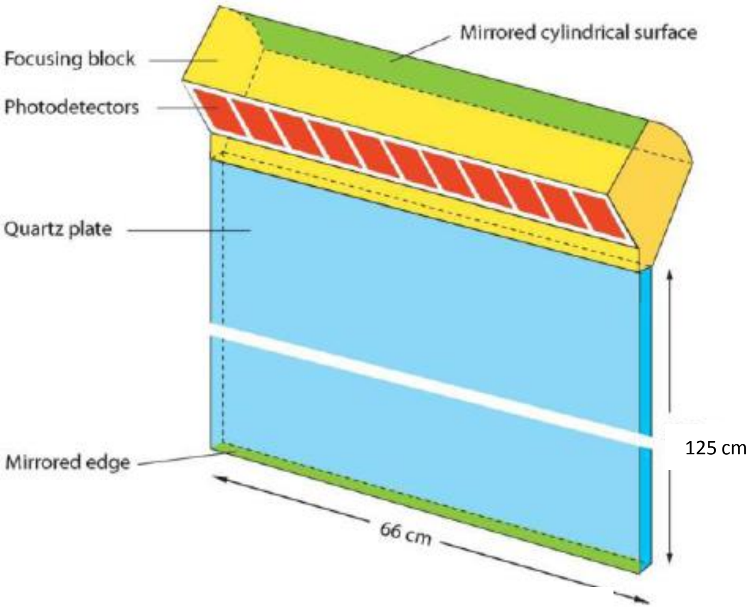
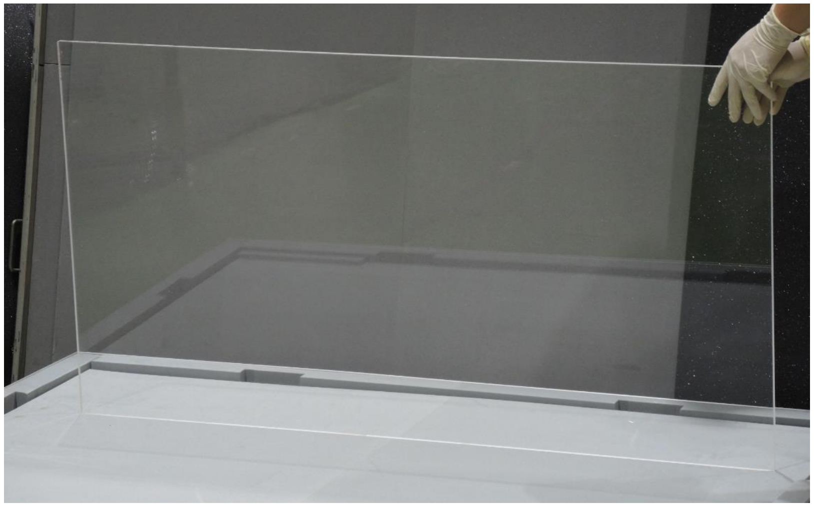




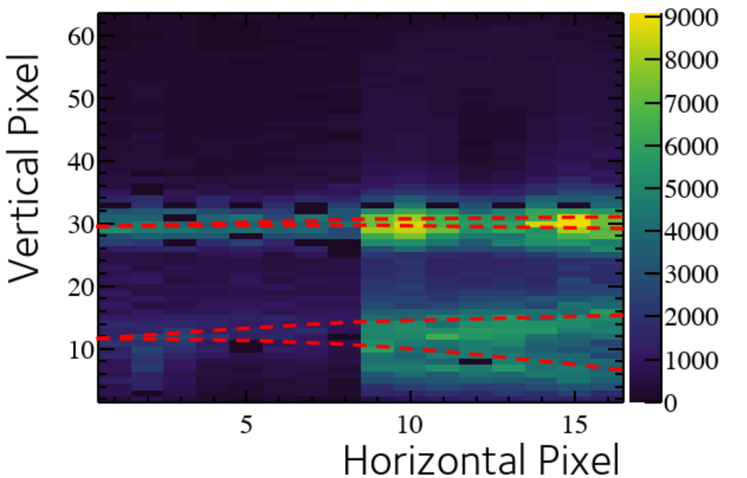
Full-scale prototype

- Final goal of the ERC-funded R&D project was to prototype a TORCH module accommodating 10 MCPs
  They have now been delivered (Photek) (64 x 8 ch, with charge sharing)
- Highly polished synthetic quartz plate $66 \times 125 \times 1\ \text{cm}^3$ (procured from Nikon)
- Mechanics completed at end of last year so far instrumented with 2 MCPs



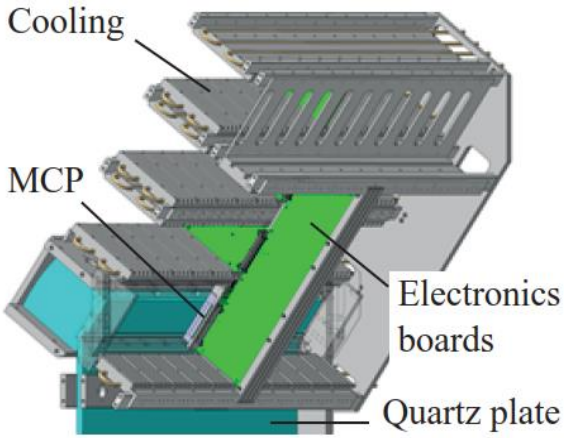


Hits in 2 (64x8 ch) MCPs



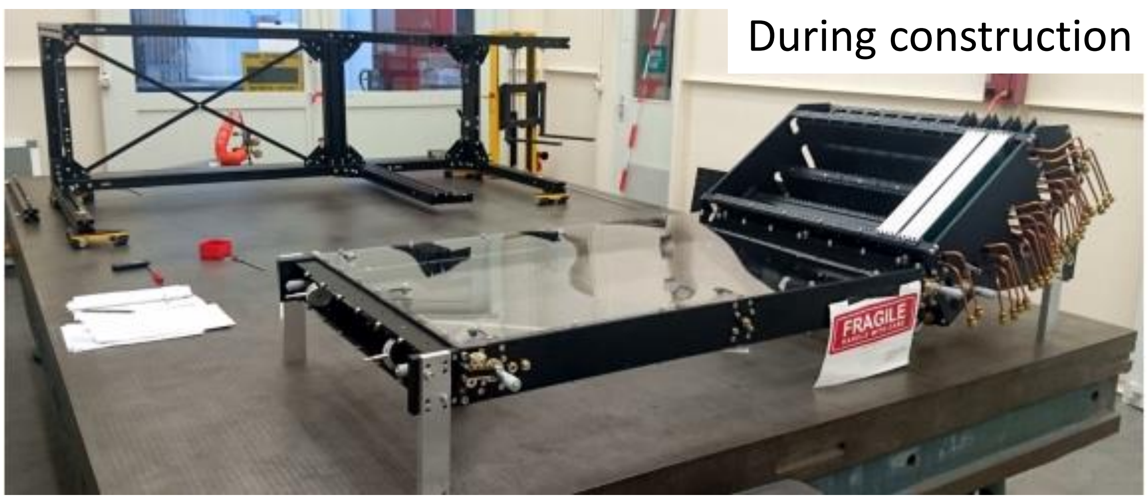
Prototype construction

- Required significant engineering!



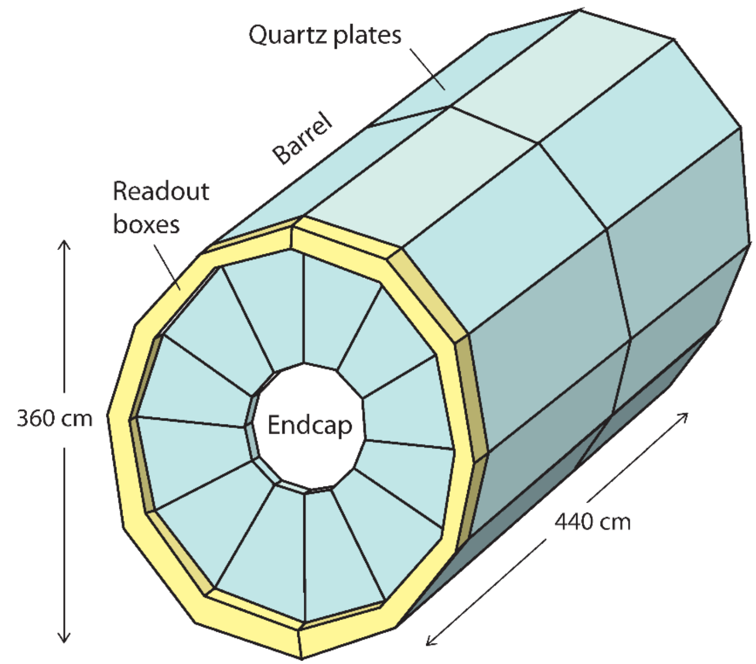
Rotated vertical

During construction



3. Application in FCC-ee?

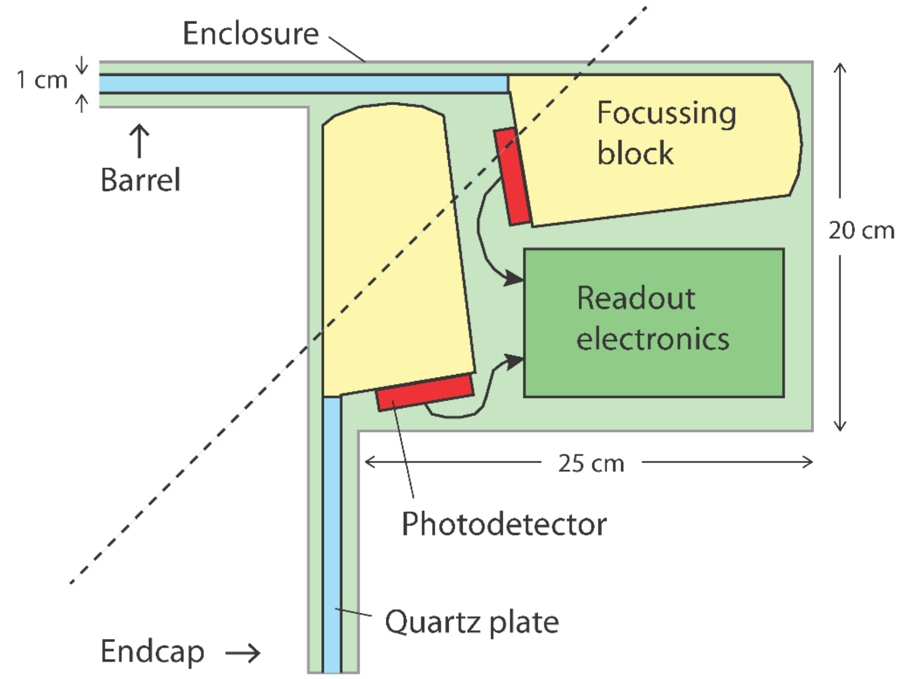
- *In the spirit of brainstorming…*
  I was not sure of current design for a detector at FCC-ee last time so assumed something ALEPH-like (easily scaled for other designs)
- Best place for TORCH would be just after tracking volume, R ~ 180 cm i.e. between TPC and ECAL
- Adapt to barrel geometry following 12-fold symmetry
  Endcap modules (if required) could be optically coupled together



- Some space required for focusing, photodetectors, electronics
  → place in overlap region ("readout boxes") – *far* smaller than BaBar!
- 24 barrel modules 96 x 220 cm^2 = 50 m^2
  12 modules for each endcap ~ 10 m^2 (i.e. total area ~ 2x LHCb design)

Readout box

- Possible layout illustrated, to give idea of what would be required
- Focusing scheme should be adapted according to constraints (here arranged to lie on one side of modules only)
- Assuming 6 x 6 cm^2 photo-detectors along edge of module → 16 tubes per module
- 48 modules → 768 tubes in total
  512 channels each (using charge sharing)
  → 400 k total — i.e. not outrageous



- Practical details would need to be optimized: e.g. separating barrel/endcap… achieving full coverage of overlap? material budget from readout box, etc. (for LHCb the readout box can be arranged to be outside the acceptance)

Performance considerations

- **Time-of-flight** from IP to quartz plate is less in this layout than in LHCb (distance 2–3 m instead of 10 m) However, **time-of-propagation** of the Cherenkov photons in quartz is similar (distance 2–3 m)
- Total time difference of K/π is sum of the two (they add constructively) so overall performance would be somewhat degraded, but still good Could be compensated by pushing the timing/photon and granularity — simulation would be required, to be quantitative
- What is required momentum range for flavour physics PID at FCC-ee? On the Z, b fragmentation ~ 0.7 → p_b ~ 30 GeV, interesting b decays typically have few – 10 daughters → $p_{daughter}$ ~ few – 10 GeV (?) Other physics cases? How well can *dE/dx* compete in this range?
- **Occupancy** should be much lower at FCC-ee than in LHCb However, for high luminosity operation would timing of all tracks be useful? (as it will be for pile-up suppression at HL-LHC, separately from PID aspect)
- **Material budget:** 1 cm quartz = 8% X_0 (plus light-weight support/enclosure) MCPs are generally insensitive to magnetic field

Conclusions

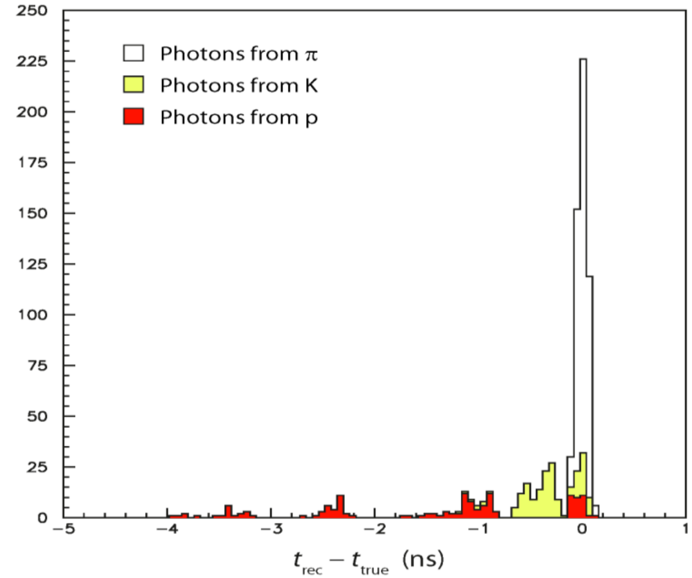
- **TORCH** is a novel detector concept designed to provide high-precision timing over large areas, pushing the limits of the DIRC technique
- Developed in **LHCb** to provide clean K/π separation up to 10 GeV/*c*
  R&D project progressed well, has developed the required photodetectors and is now focused on completing the full-scale prototype module (proposal submitted to ATTRACT) + demonstrating the physics case
- TORCH technique may be interesting for application in an **FCC-ee detector**: it has been developed to tolerate LHC-levels of radiation and occupancy, compact for integration in experiment + affordable for large area coverage
  Cost of prototype module ~ 400 kCHF split between optics + photodetectors
  Hope for economy of scale to reduce cost/module for final detector (?)
- Estimating the performance at FCC-ee would require **simulation** study
  Physics requirements should be clearly defined, so design can be optimized

  Happy to hear if there is interest to pursue this in the FCC-ee community!

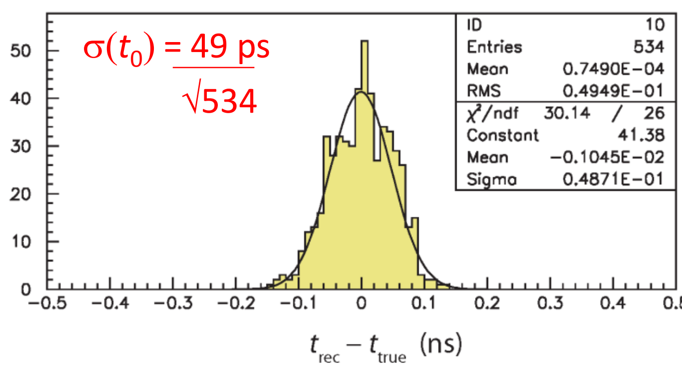
Backup

- To determine the time-of-flight, also need a **start time** (t_0)
- Might consider using timing information from the machine, but bunches are long and their collisions are spread in time
- Instead use the other tracks in the event from the primary vertex
- Typically most of them are pions, so the reconstruction logic can be reversed, and the start time is determined from their average *assuming* they are all π
- Outliers from other particles removed, and procedure iterated
- Can achieve few-ps resolution on t_0

Example from PV of same event



After removing outliers

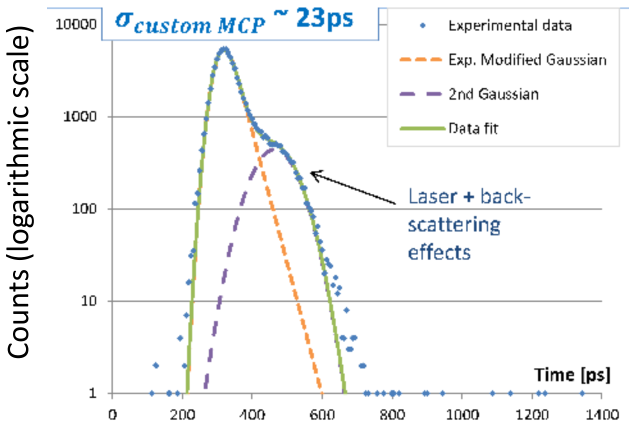


MCP-PMT development

- Intrinsic **timing** performance of *Phase-1* tubes measured with fast laser and single-channel commercial readout electronics
- Prototype tubes use dual-MCP in chevron configuration, 10 µm pores
  Lifetime addressed by ALD (atomic layer deposition) treatment of MCP

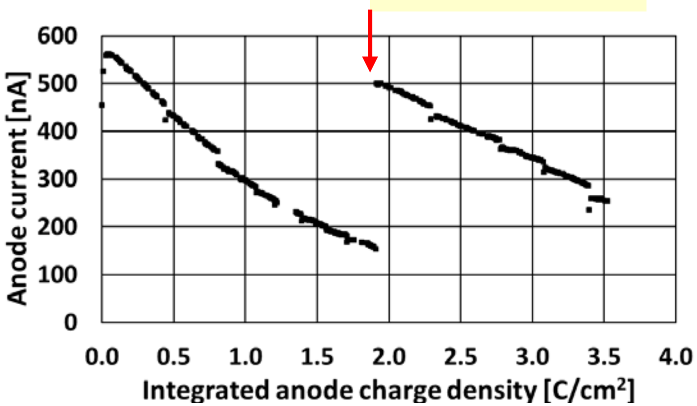
As introduced by Argonne/LAPPD

T. Gys et al., NIM A766 (2014) 171

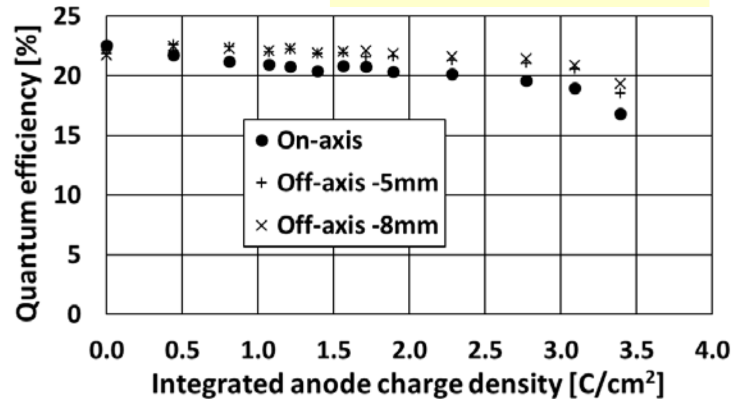


Long-term test
blue LED illumination

HV increased:
2300 → 2450 V



T. Gys et al., RICH2016

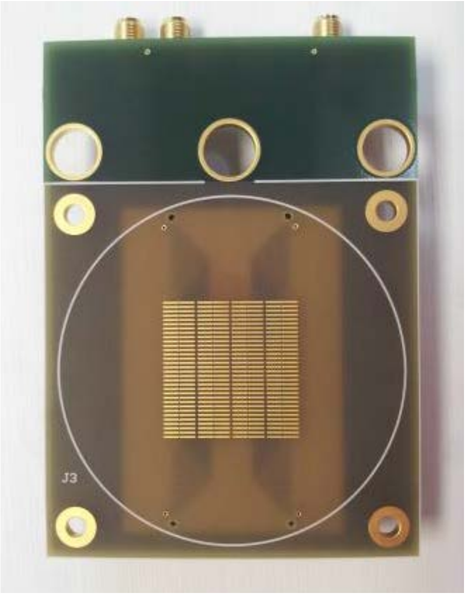


Spatial resolution

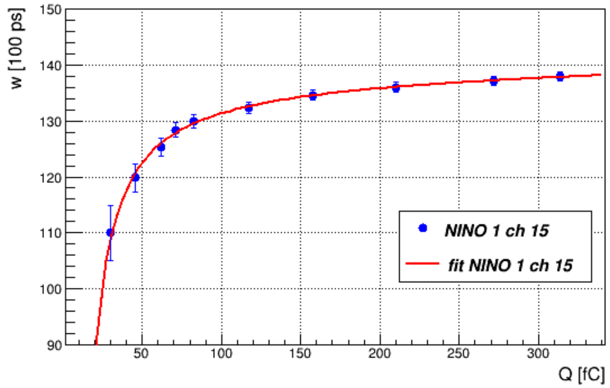
- Effective resolution equivalent to 0.4 mm achieved with 2x larger pixels by making use of charge-sharing between neighbouring pixels
  Point-spread function adjusted to share charge over 2-3 pixels
- Requires calibration of the relationship between pulse width and charge

L. Castillo García, IPRD16

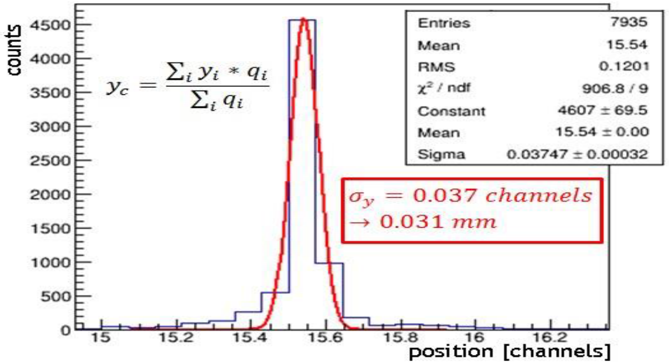
Anode segmentation of *Phase-2* tube
Active area 25 x 25 mm^2, 32 x 4 pixels



Charge-to-width calibration



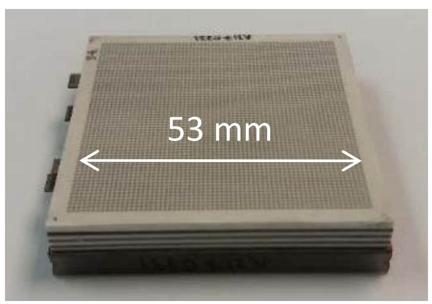
Spatial resolution measured with laser illumination (charge-weighted cluster centroid)

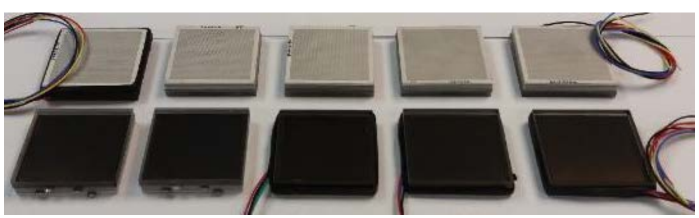


Final photon detector

- Final *Phase-3* tube integrates the features that have been developed in earlier phases, in a square format with 53 x 53 mm^2 active area
  Quartz window and AC-coupled anode, so window can be at ground
- Readout connectors mounted on PCB, 64 x 8 pixels per tube
  which is attached to tube using ACF (anisotropic conductive film)
- Delivery of final tubes from Photek planned in the coming weeks

Bare tubes





After potting, before readout PCB is attached