TORCH

a large-area detector for high resolution time-of-flight

Roger Forty (CERN)
on behalf of the TORCH collaboration

1. TORCH concept
2. Application in LHCb
3. R&D project
4. Test-beam studies

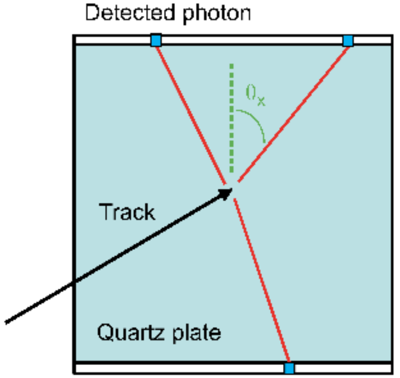
TIPP 2017, Beijing, 25 May 2017

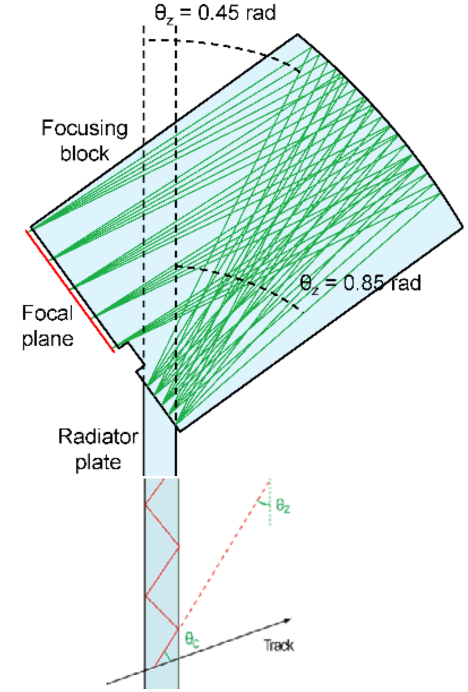
1. TORCH concept

- **TORCH** (**T**iming **O**f internally **R**eflected **CH**erenkov light) is an evolution of the DIRC technique, adding precision timing and angular information
- Uses a highly polished plate of synthetic quartz as Cherenkov radiator (1 cm thick, ~8% X_0) → photons propagate to edge by total internal reflection
- **Innovation:** along with their hit position, measure the *angle* of propagation of the photons, achieved by adding a focusing block at the edge, and using an extended plate (rather than bar) of quartz

Related developments in Belle II and PANDA

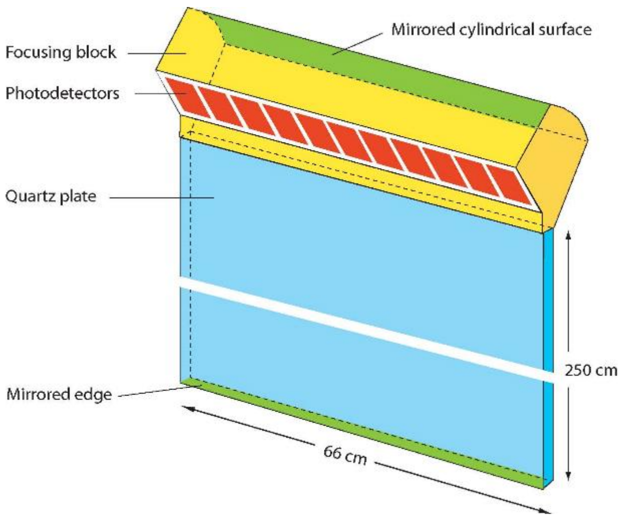
- When a detected photon is correctly matched to the charged particle track that emitted it, the distance of propagation can then be determined
- By measuring the Cherenkov angle at emission, the *wavelength* of photon can also be calculated, to correct for dispersion in the quartz

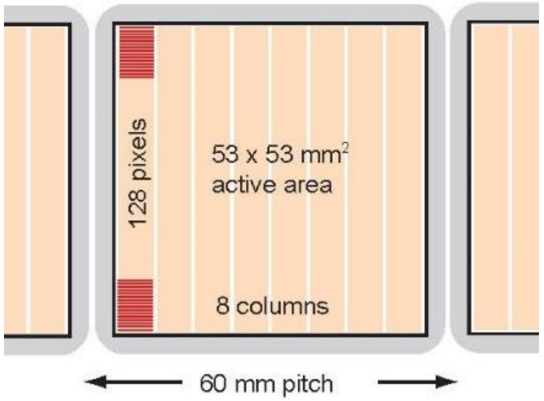




Photon detection

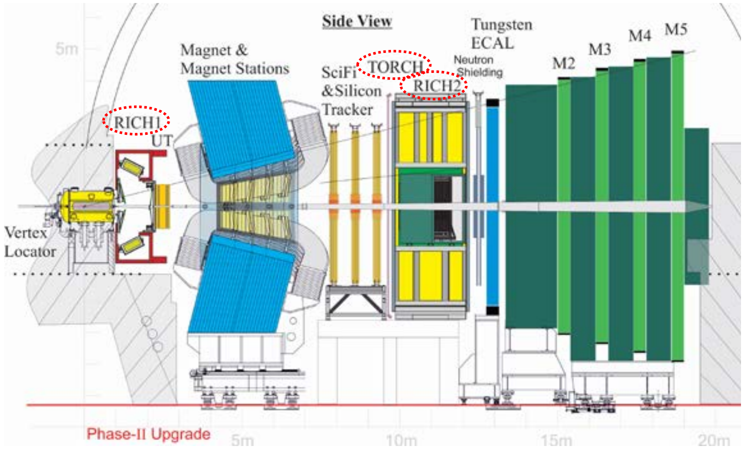
- Fast photon detectors are used: micro-channel plate (**MCP**)-PMTs
  Target for intrinsic timing resolution of 50 ps per detected photon
- Focusing scheme requires a linear array of detectors, with fine pixellization in one direction, coarse in the other
- For 2-inch tubes (60 mm pitch) the pixellization should be 128 x 8
  i.e. 0.4 x 6.6 mm^2 pixels, to give angular resolution of ~1 mrad in both projections
  → contribution to the resolution of 50 ps
- Total resolution per detected photon:
  50 (intrinsic) ⊕ 50 (pixel size) ps = 70 ps
  For 30 photons/track → 70/ √30 = 15 ps



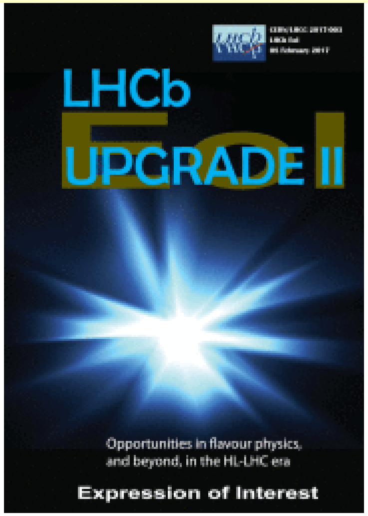


2. Application in LHCb

- **LHCb** is the dedicated flavour physics experiment at LHC, studying CP violation + rare decays of beauty & charm hadrons
- Arranged as a forward spectrometer although it operates in pp collider mode
- Upgrade in preparation for 2019-20, to move to a fully software trigger, reading out the detector at the bunch-crossing rate of 40 MHz, with levelled luminosity 2×10^{33} cm^{-2}s^{-1}
- Further "Phase II" upgrade is now under discussion, to push the luminosity further towards what is available from the LHC in the HL-LHC era (from 2024 onwards)



CERN-LHCC-2017-003

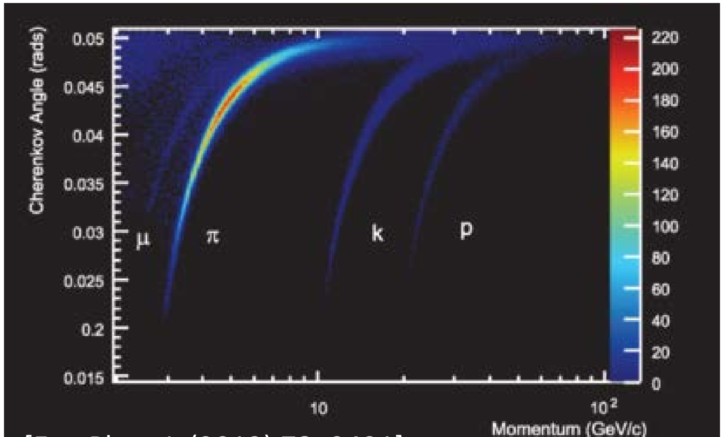


Particle Identification

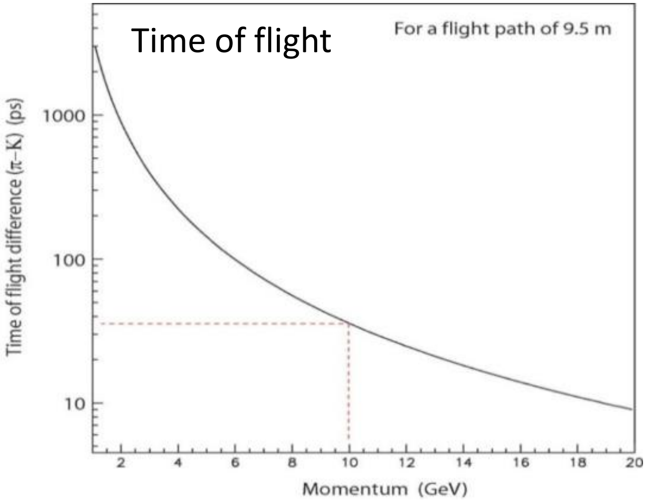
- Particle ID (distinguishing p, K and π) is crucial for much of hadronic physics of LHCb, currently provided by RICH system
- Low-momentum particle ID previously provided by aerogel radiator, but not suitable for the higher occupancy expected in the upgrade, so *removed*

  → currently no positive ID below kaon threshold in C_4F_{10} gas radiator ~10 GeV/*c*
- Δ time-of-flight (π – K) over 10 m = 40 ps at 10 GeV/*c* → 15 ps resolution would provide clear (3σ) separation
- Start time for TOF could be provided by accelerator clock, or using TORCH itself to time tracks from production vertex (see backup slide)

RICH C_4F_{10} data

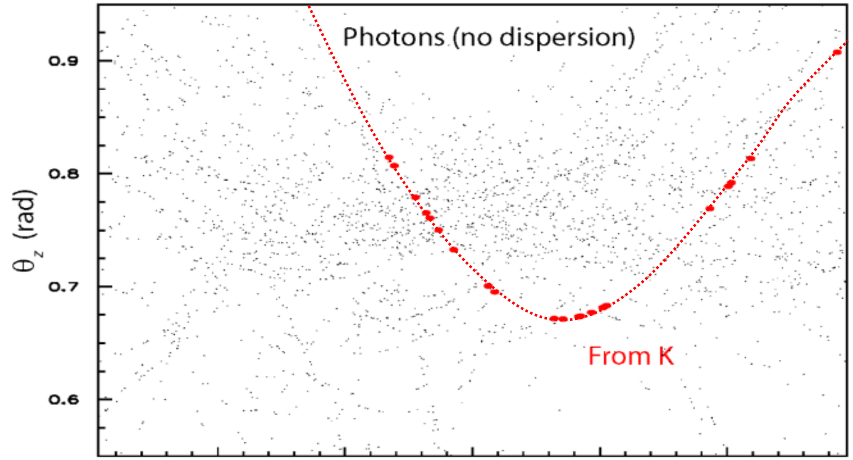


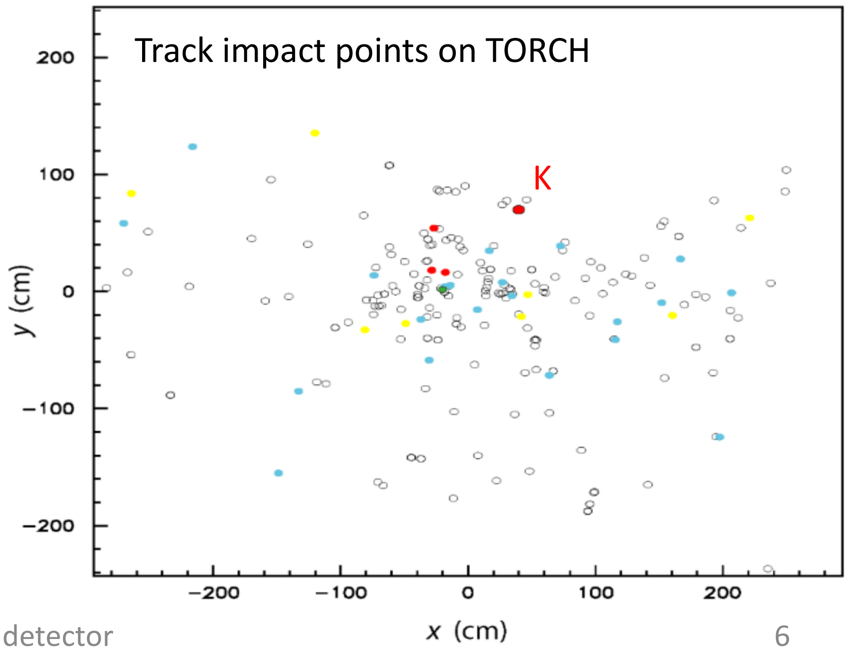
[Eur. Phys. J. (2013) **73**: 2431]

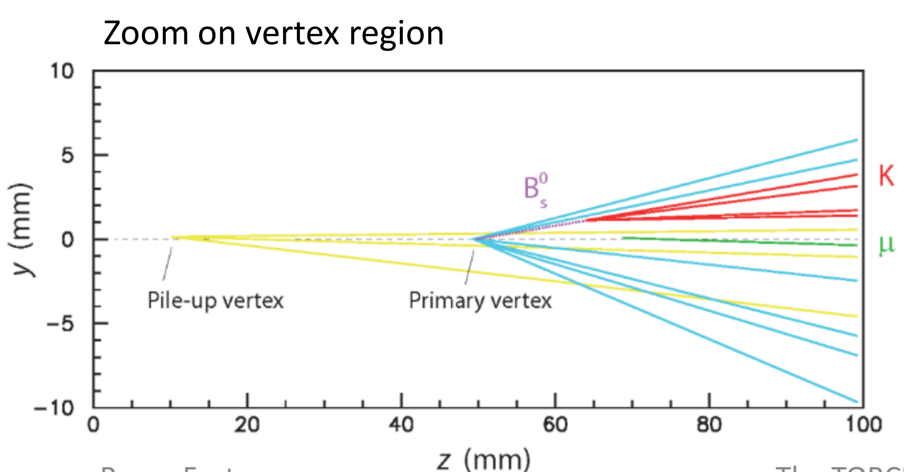


An LHCb event

- Simulated LHCb event at luminosity of 10^{33} cm^{-2}s^{-1} – photons reaching the upper edge of TORCH radiator shown:
- High multiplicity! ~100 tracks/event
- Tracks from vertex region coloured according to the vertex they come from, the others are secondaries
- Fast timing will also be very useful for pile-up suppression at high luminosity





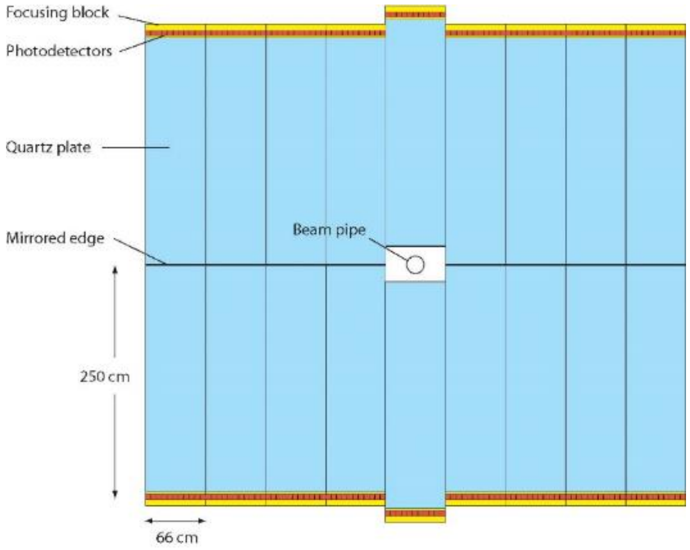


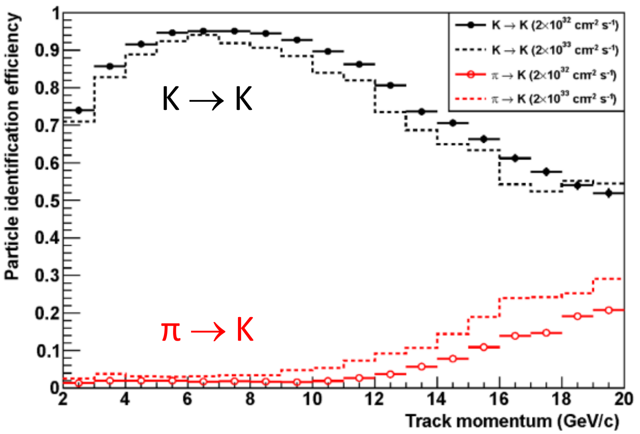
Modular layout

- At foreseen location in LHCb (z = 10 m) need to cover an area of 5 x 6 m^2
- Not feasible with a single plate, and anyway need an aperture for beam pipe
- Baseline proposal is to tile the surface using 18 identical modules (66 x 250 cm^2)

  → 198 photon detector tubes in total
  ~100 k channels

- Reflections from transverse edges of modules will lead to ambiguities in the reconstruction, but at a level that can be resolved by the pattern recognition
- Simulated performance is excellent





Full LHCb simulation:
PID efficiency *vs.* momentum

3. R&D project

- An EU-funded R&D project for TORCH has been running for 5 years: to develop suitable photon detectors, and provide proof-of-principle with a prototype module
- Project is a collaboration between Oxford (lead institute), Bath, Bristol, CERN and industrial partner Photek (UK)
- At the start of the project, commercial tubes were not available that satisfied the requirements of TORCH:
  - Fast timing (< 50 ps per detected photon)
  - High active area (> 80% for the linear array)
  - fine pixellization (128 x 8 rectangular pixels in a 60 x 60 mm^2 tube)
  - Long lifetime (up to 5 C/cm^2 charge density at the anode)
- A *three-phase* R&D program has been followed, to develop these characteristics separately, and then bring them together in a final prototype tube—for details see dedicated talk by James Milnes

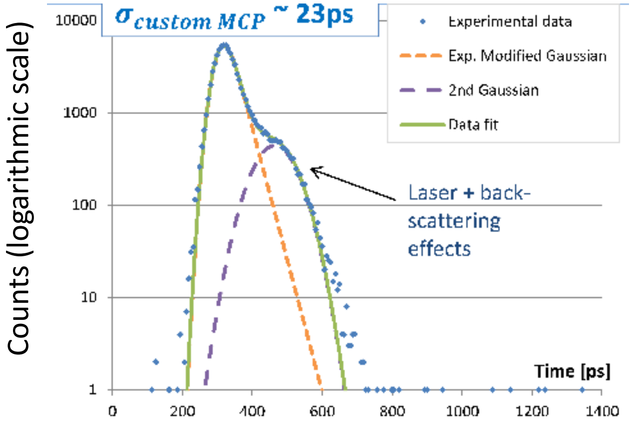
TIPP2017 Photon detector session 3

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

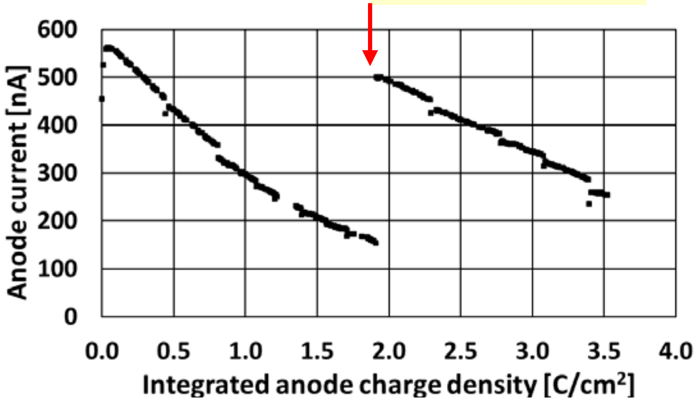
As introduced by Argonne/LAPPD

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

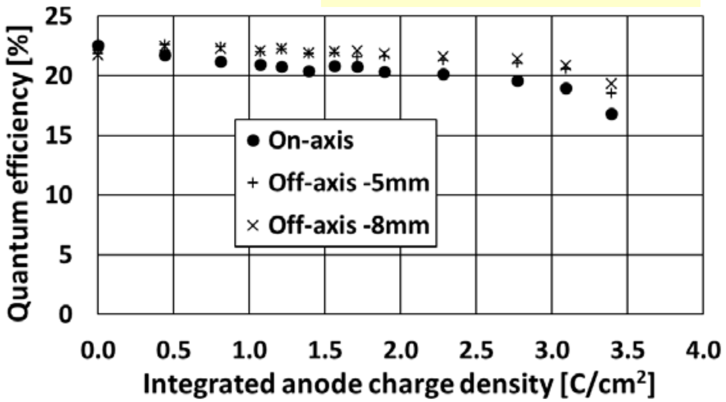


Long-term test
blue LED illumination

HV increased:
2300 → 2450 V

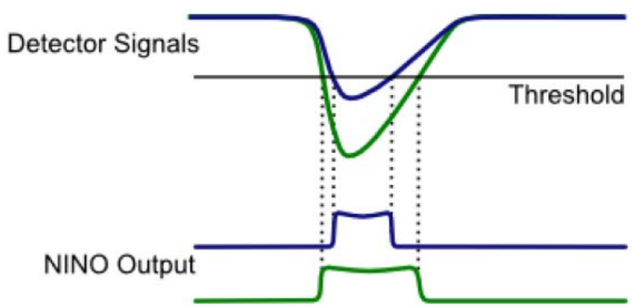


T. Gys et al., RICH2016



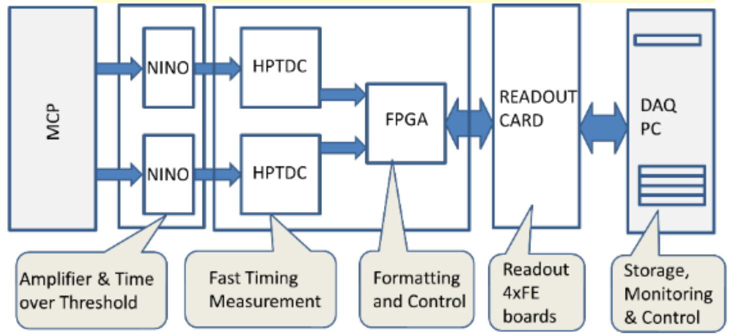
Multichannel electronics

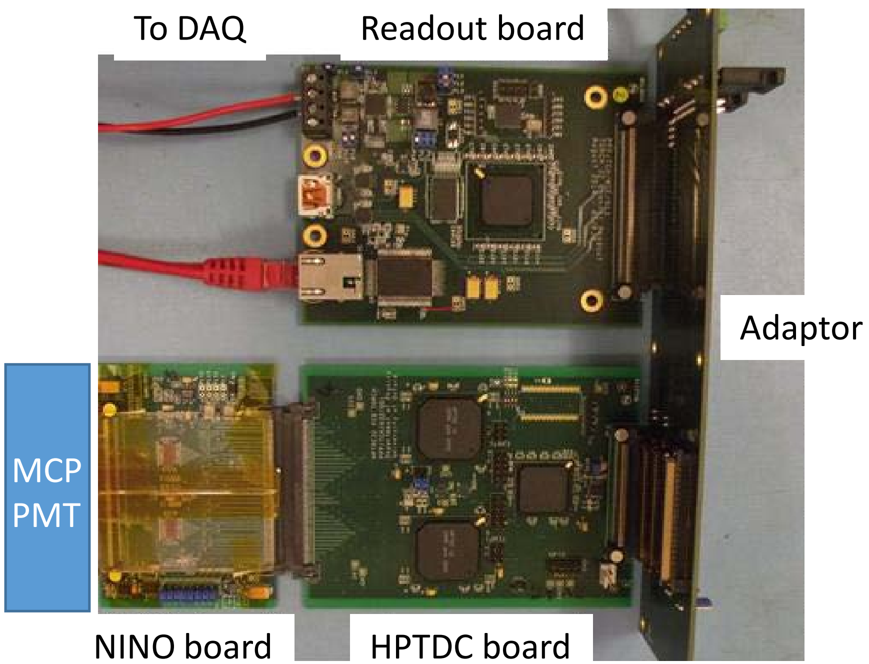
- Custom readout electronics developed, based on NINO + HPTDC chips (originally developed for ALICE TOF)
- 32-channel **NINO** chip provides fast amplification and time-over-threshold as an estimate of input charge



- **HPTDC** chip performs digitization (100 ps bins)

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



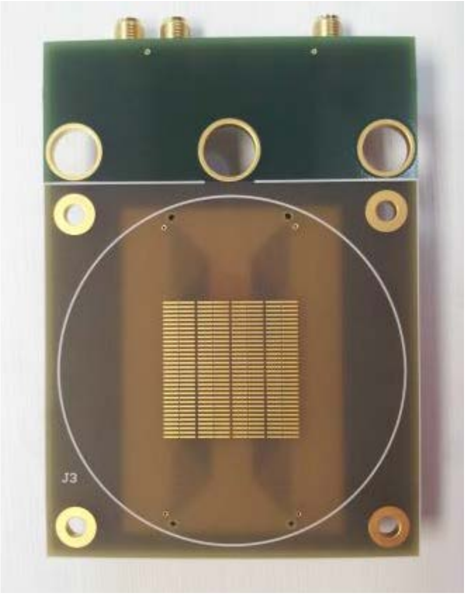


Spatial resolution

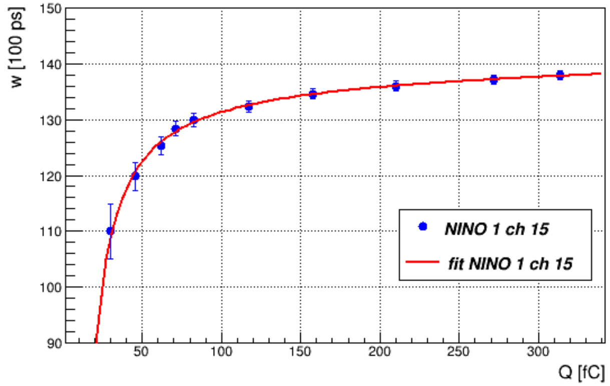
- Effective resolution equivalent to 0.4 mm achieved with 2x larger pixels by making use of charge-sharing between neighbouring pixels
  Point-spread function adjusted to share charge over 2-3 pixels
- Requires calibration of the relationship between pulse width and charge

L. Castillo García, IPRD16

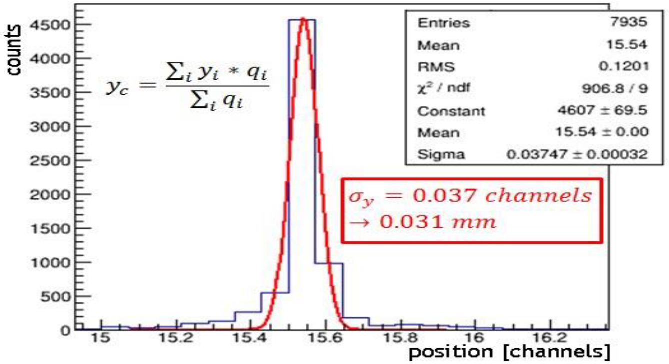
Anode segmentation of *Phase-2* tube
Active area 25 x 25 mm^2, 32 x 4 pixels



Charge-to-width calibration



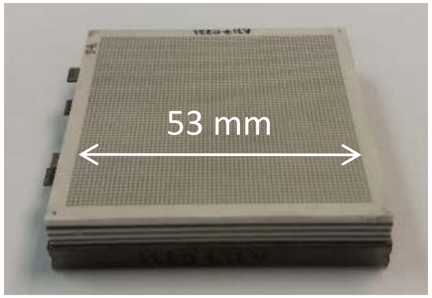
Spatial resolution measured with laser illumination
(charge-weighted cluster centroid)

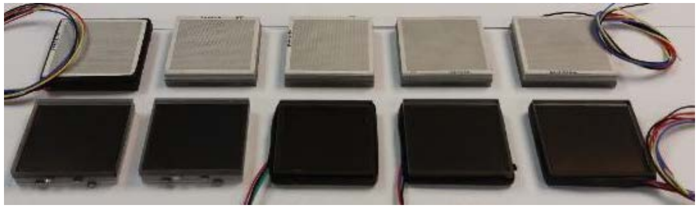


Final photon detector

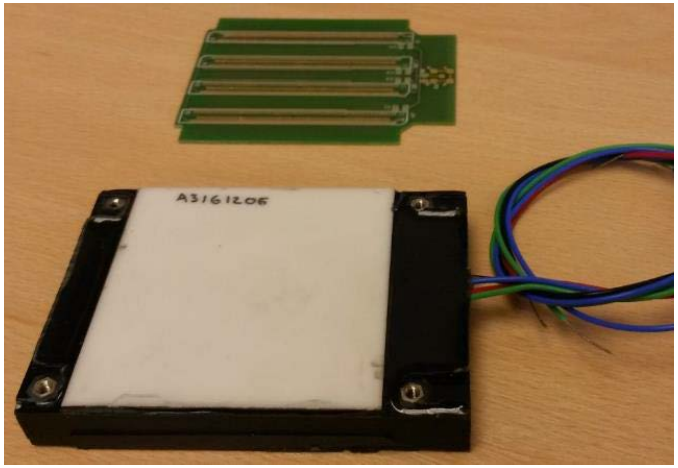
- Final *Phase-3* tube integrates the features that have been developed in earlier phases, in a square format with 53 x 53 mm^2 active area
  Quartz window and AC-coupled anode, so window can be at ground
- Readout connectors mounted on PCB, 64 x 8 pixels per tube
  which is attached to tube using ACF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

Bare tubes





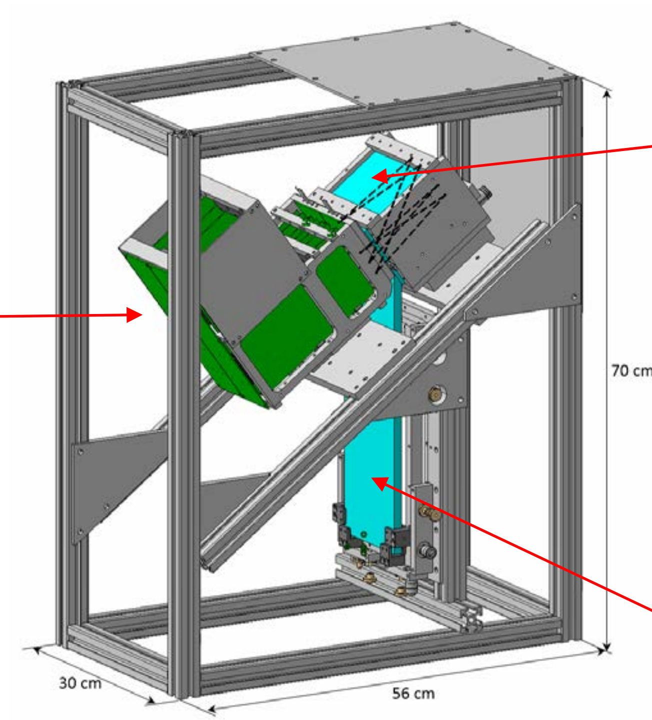
After potting, before readout PCB is attached



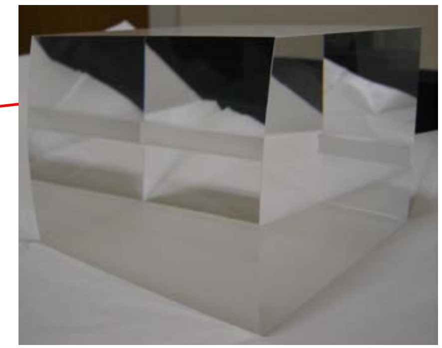
4. Test-beam studies

- A small prototype module has been constructed for beam tests
  Optical components from Schott, *Phase-2* MCP-PMT from Photek

MCP-PMT and electronics



Focusing block



Radiator plate: 35 x 12 x 1 cm^3

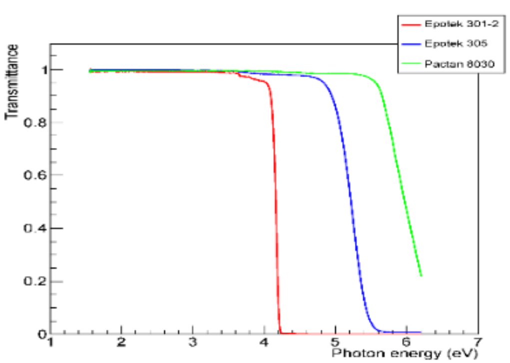
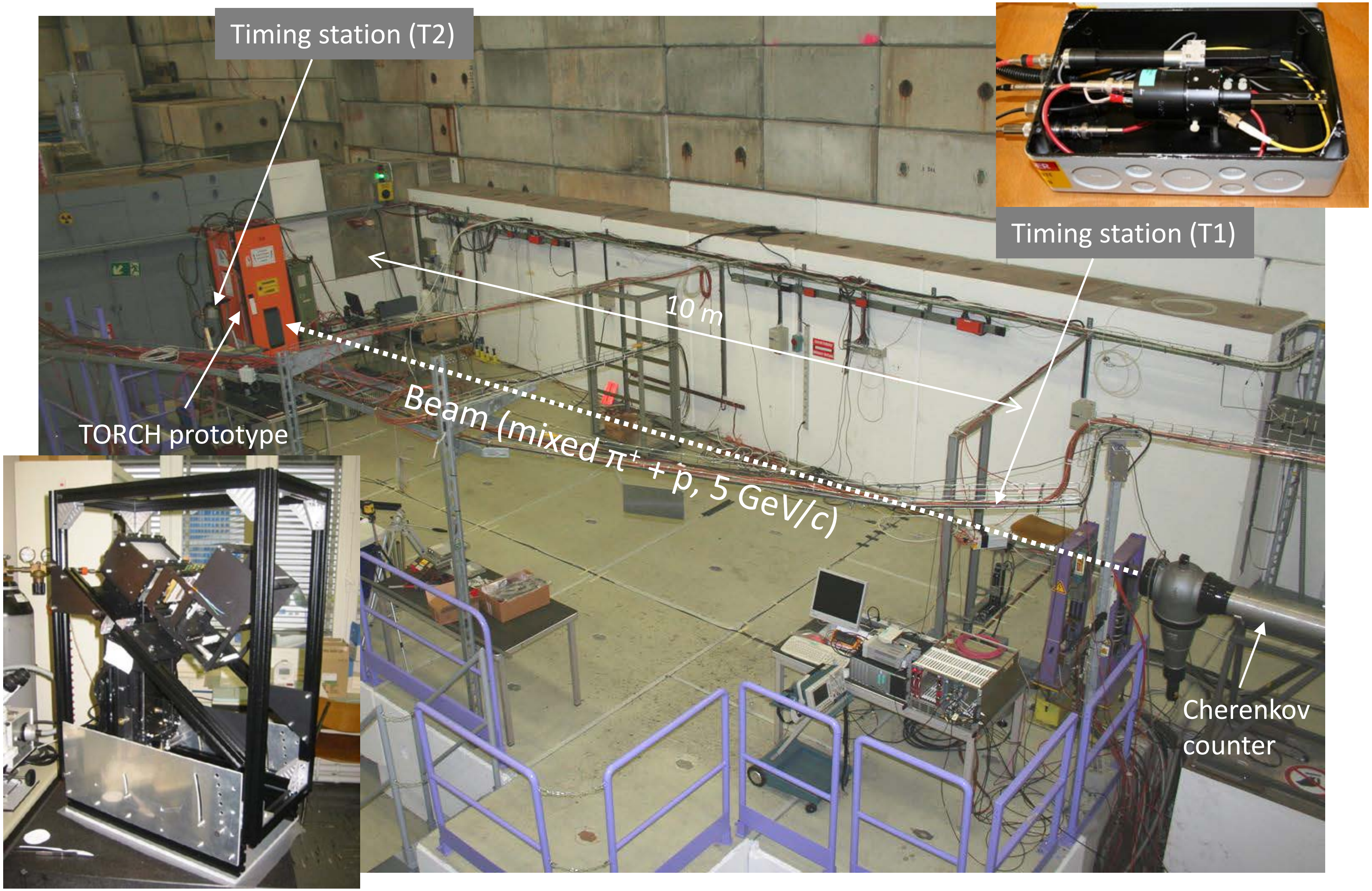


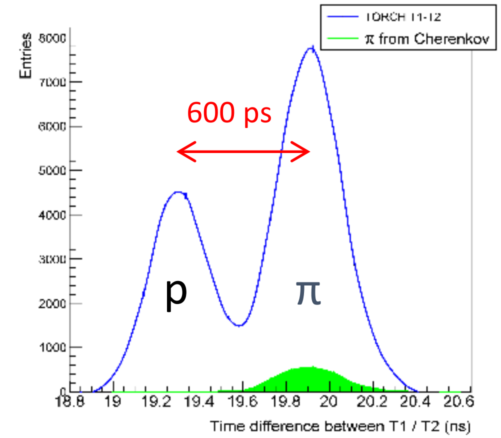
Plate and block glued together using silicone (Pactan 8030)

CERN PS-T9 area

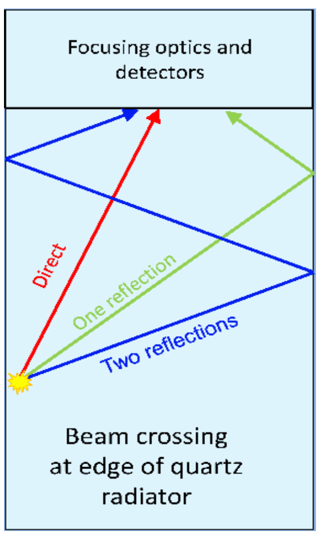


Data analysis

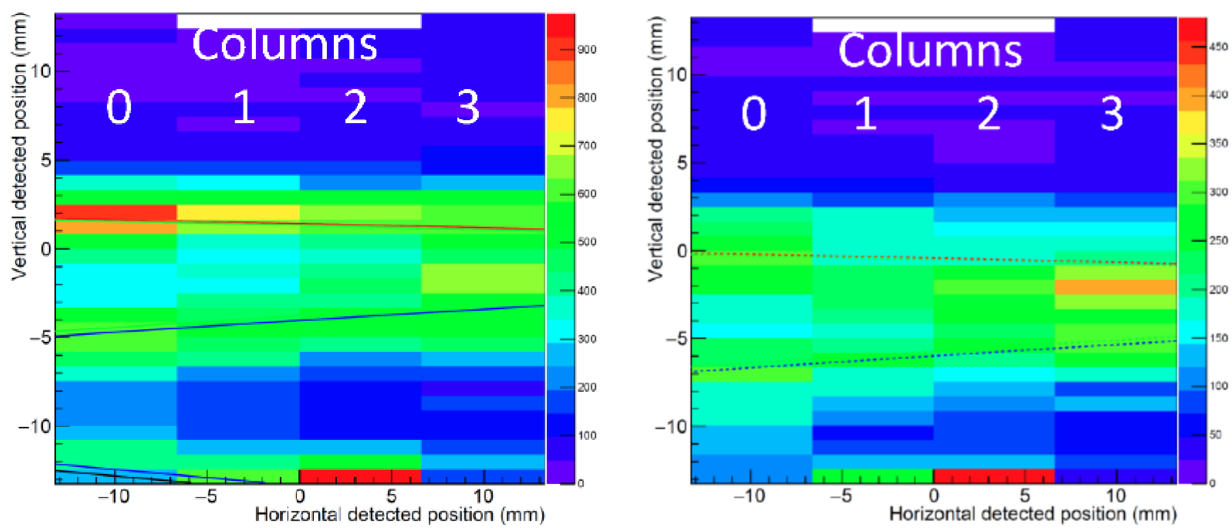
- Time-of-flight determined using timing stations (T1, T2) → separate p / π components of beam
  Confirmed using Cherenkov counter



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

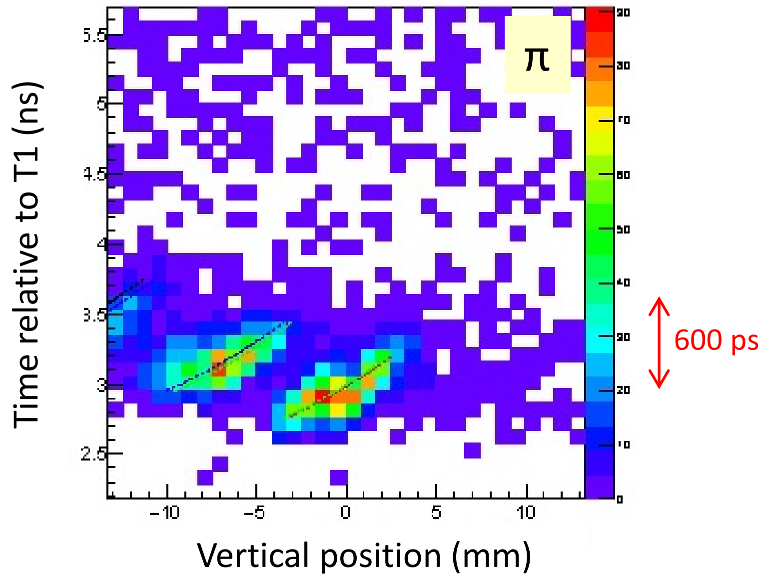


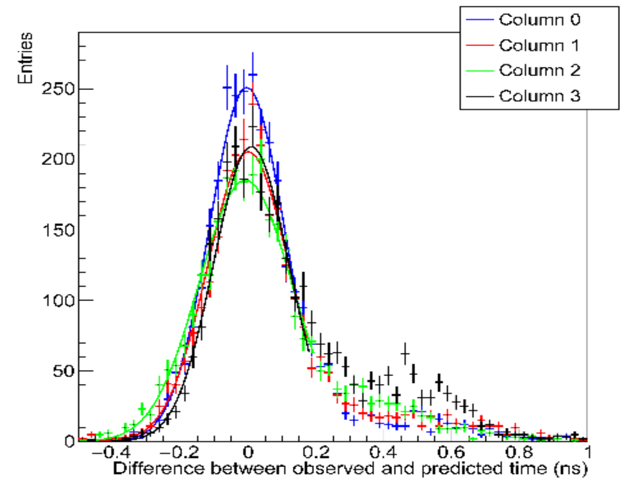
Pions Hits in MCP-PMT Protons



Timing performance

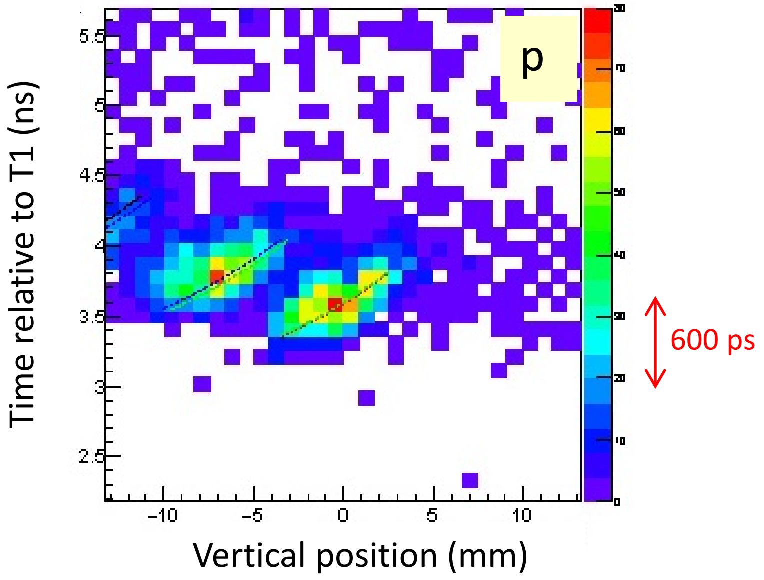
- Plot time measured for each cluster *vs.* vertical position along column of pixels
  - Reflections clearly separated
  - p-π time-of-flight difference cleanly resolved
- Project along timing axis relative to prediction for the earliest pion signal, for each column of pixels
  (relative to T2 as timing reference)
- Core distribution has σ ≈ 110 ps
  This is before subtraction of contribution from timing reference → approaching the target resolution of 70 ps / photon
- Tails under study, due to imperfect calibration and back scattering effects

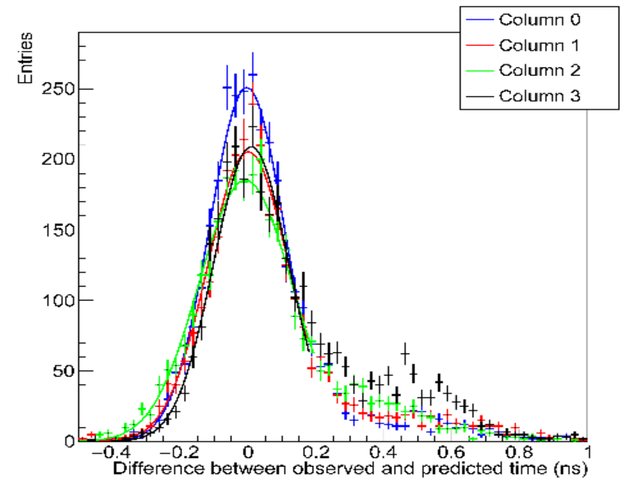




Timing performance

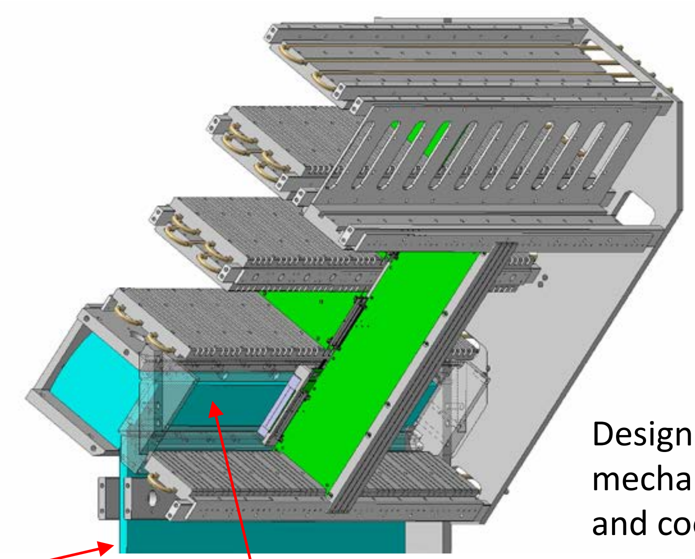
- Plot time measured for each cluster *vs.* vertical position along column of pixels
  - Reflections clearly separated
  - p-π time-of-flight difference cleanly resolved
- Project along timing axis relative to prediction for the earliest pion signal, for each column of pixels
  (relative to T2 as timing reference)
- Core distribution has σ ≈ 110 ps
  This is before subtraction of contribution from timing reference → approaching the target resolution of 70 ps / photon
- Tails under study, due to imperfect calibration and back scattering effects



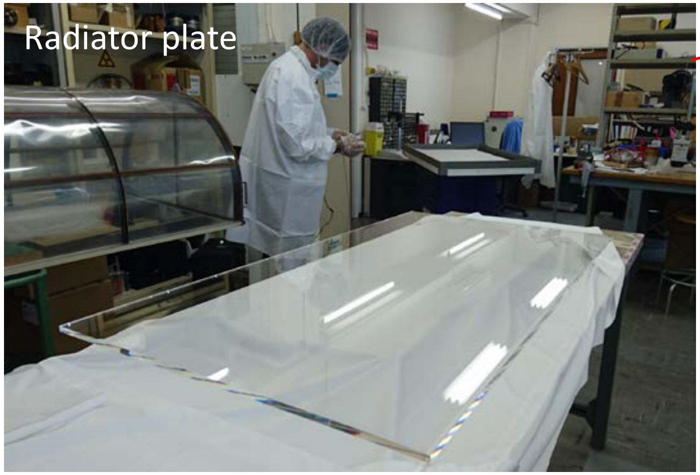


Full-scale prototype

- Large prototype of a TORCH module for LHCb is under construction
  Full width, half height: 125 x 66 x 1 cm^3
  Will be equipped with 10 MCP-PMTs
  5000 channels
- Optical components from Nikon (radiator plate, focusing block)
  Detailed measurements provided by supplier, match the specifications

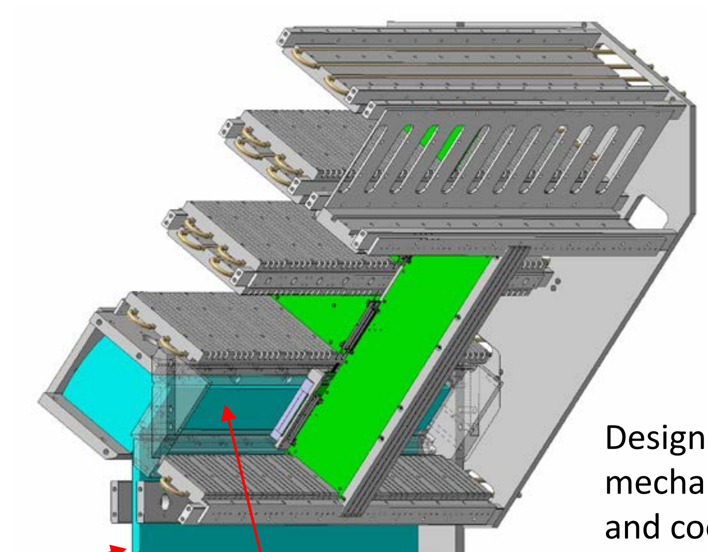


Design for mechanics and cooling

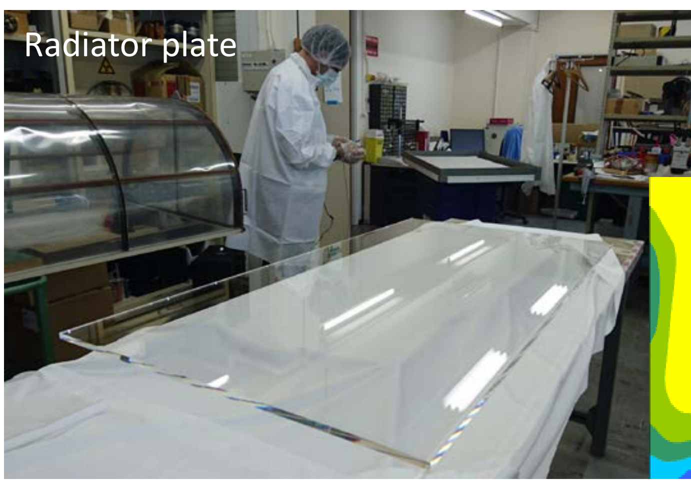


Full-scale prototype

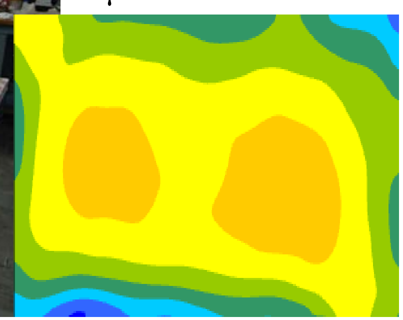
- Large prototype of a TORCH module for LHCb is under construction
  Full width, half height: $125 \times 66 \times 1\ cm^3$
  Will be equipped with 10 MCP-PMTs
  5000 channels
- Optical components from Nikon (radiator plate, focusing block)
  Detailed measurements provided by supplier, match the specifications



Design for mechanics and cooling

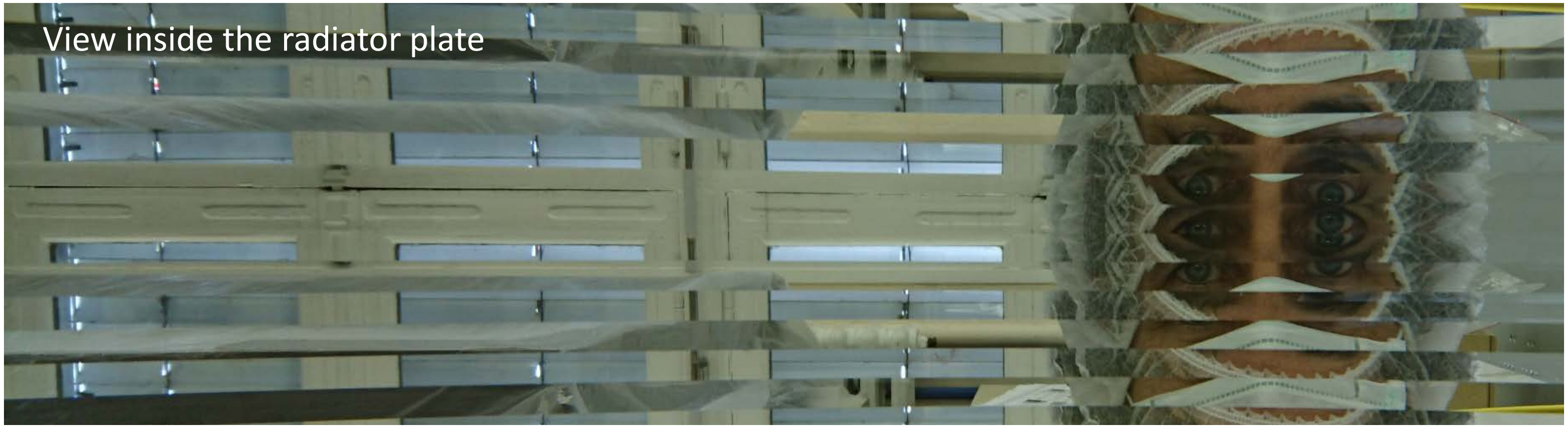


Surface flatness
1 μm contours



Conclusions

- The TORCH concept adds precise angular and timing information to a DIRC providing high-precision time-of-flight over large areas
- It is included in the plans for a future upgrade of the LHCb experiment
- The fast photon detectors required have been developed with industry with final prototypes expected to be delivered in the next weeks
- Test-beam studies have achieved close to the nominal performance
- A full-scale prototype module is under construction for testing this year

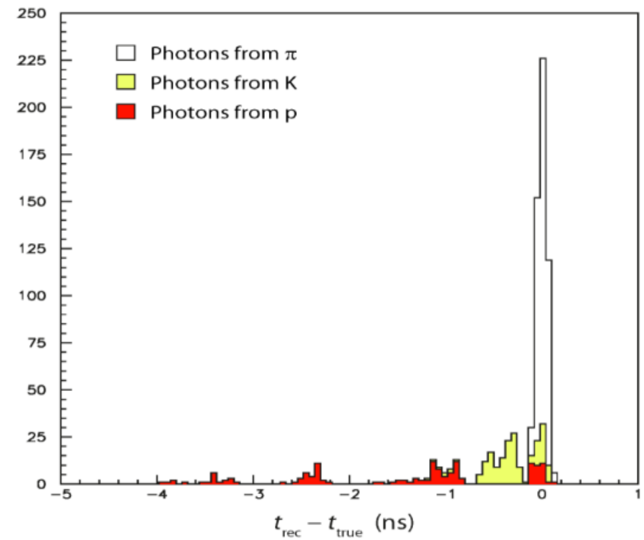


→ it is an exciting time for the project!

Determining start-time

- To measure the time-of-flight, also need a start time (t_0)
- This could be achieved using timing clock from the accelerator, but would need to correct for timing spread in beam bunches
- Alternatively use signals from other tracks in the event, from the primary vertex, in the TORCH detector itself
- 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)
- Can achieve few-ps resolution on t_0

PV of the same simulated event



After removing outliers