Status of the TORCH time-of-flight detector

Neville Harnew

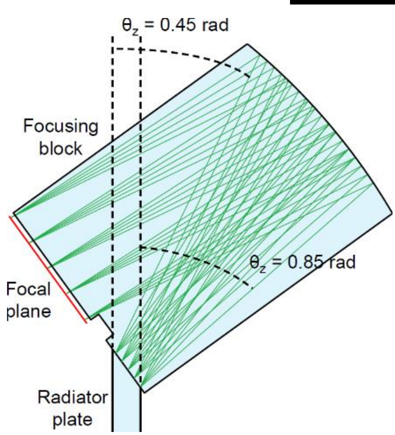
University of Oxford

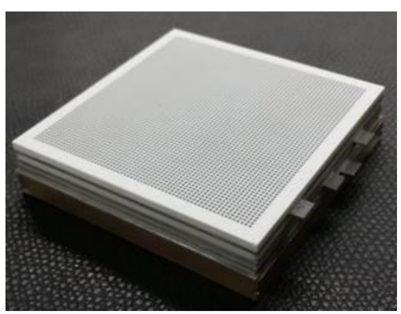
(On behalf of the TORCH collaboration : the Universities of Bath, Bristol and Oxford, CERN, and Photek)

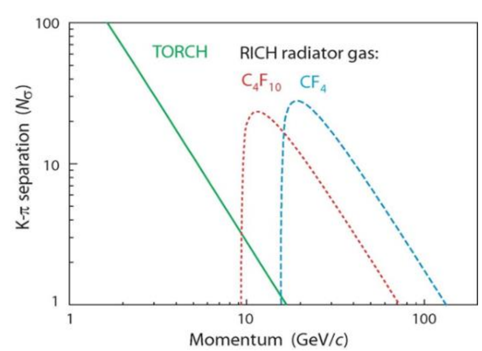
August 7-9, 2017

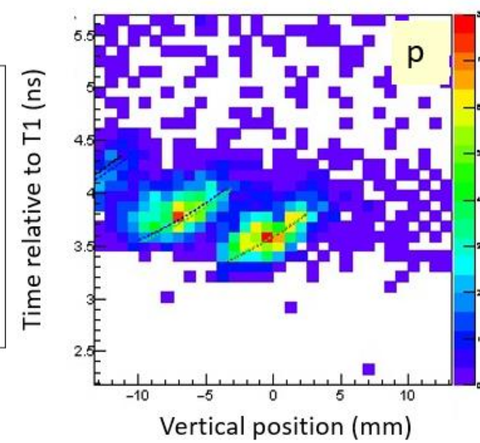
DIRC 2017 International Workshop on Fast Cherenkov Detectors

Photon detection, DIRC design and DAQ









Outline

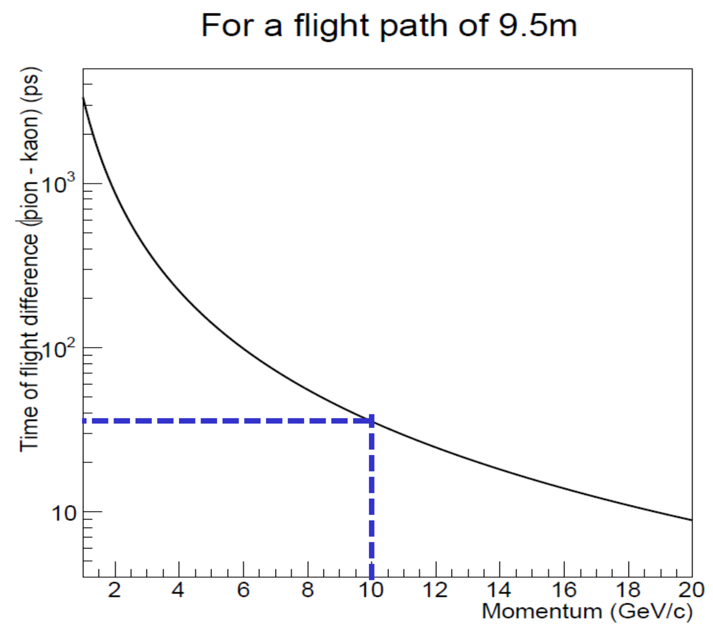
- TORCH R&D project and concept
- Development of Microchannel Plate (MCP)-PMTs
- Test beam results
- Future R&D
- TORCH at LHCb
- Summary

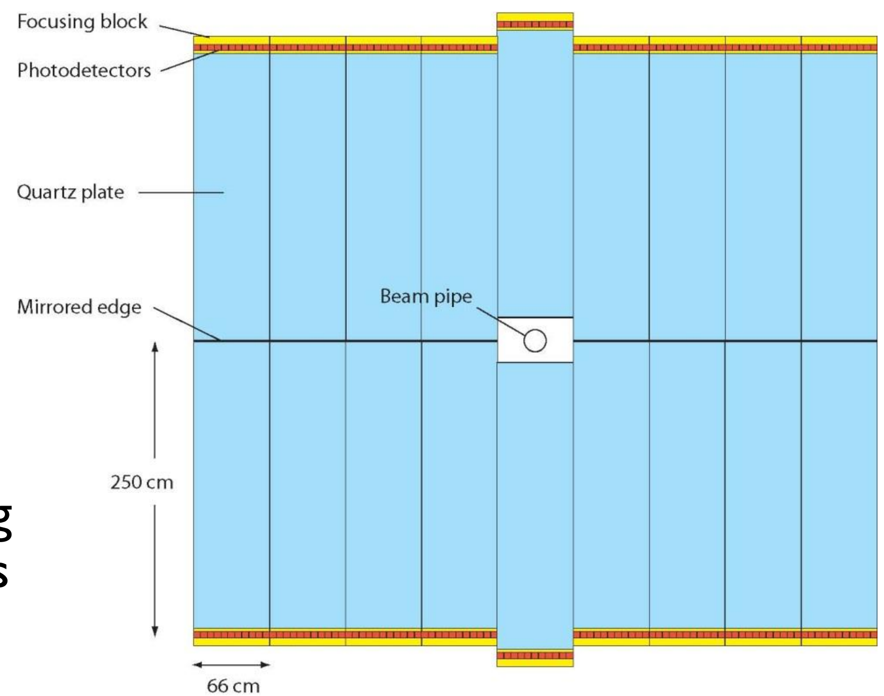
1. The TORCH R&D project

- The TORCH (Time Of internally Reflected CHerenkov light) detector is an R&D phase to develop a large-area time-of-flight system for LHCb.
- TORCH combines timing information with DIRC-style reconstruction (cf. Belle TOP detectors & the PANDA DIRC) : aiming to achieve a ToF resolution ~10-15 ps (per track).
- A 5-year grant for R&D on TORCH by the ERC has just ended : to develop customised photon detectors in collaboration with industrial partners (Photek) and to provide proof-of-principle with a demonstrator ToF module.

The TORCH detector

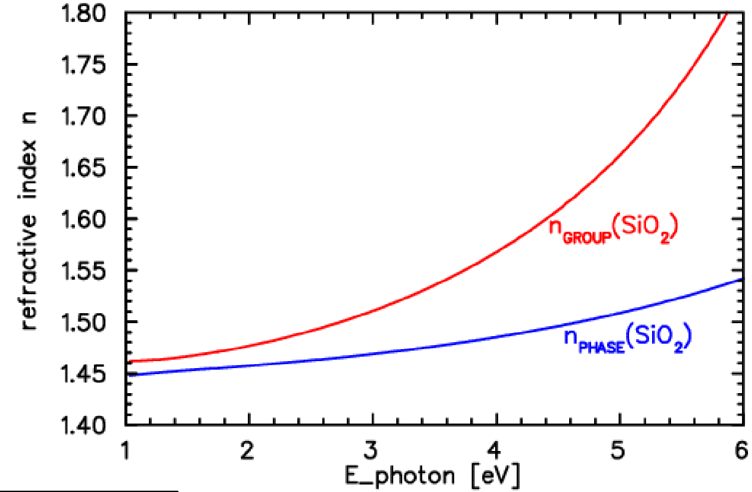
- To achieve positive identification of kaons up to p ~ 10 GeV/c, Δ_{TOF} (π-K) = 35 ps over a ~10 m flight path → need to aim for ~ 10-15 ps resolution per track
- Cherenkov light production is prompt → use a plane in a modular structure of 1 cm thick quartz (~5 x 6 m^2) as a source of fast signal
- Cherenkov photons travel to the periphery of the detector by total internal reflection and focused → time their arrival by Micro-Channel Plate PMTs (MCPs)
- The σ_{TOF} requirement dictates timing single photons to a precision of 70 ps for ~30 detected photons



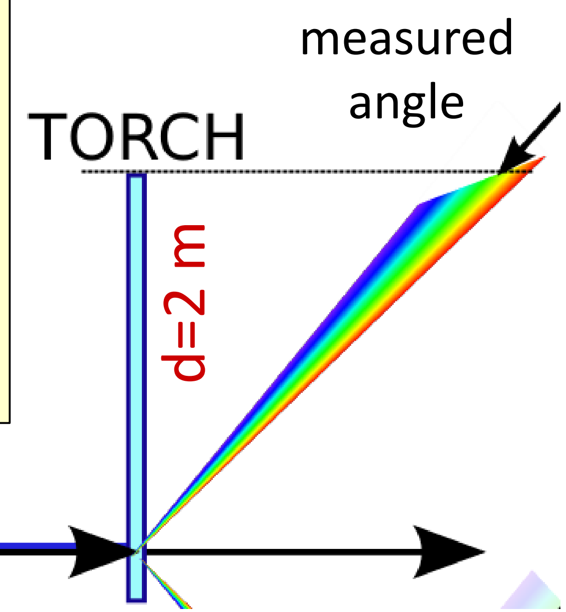


Reconstruction of time of flight

- Cherenkov angle : $\cos\theta_c = (\beta\, n_{phase})^{-1}$
- Time of propagation (ToP) in quartz :
  $t = L / v_{group} = n_{group}\, L / c$

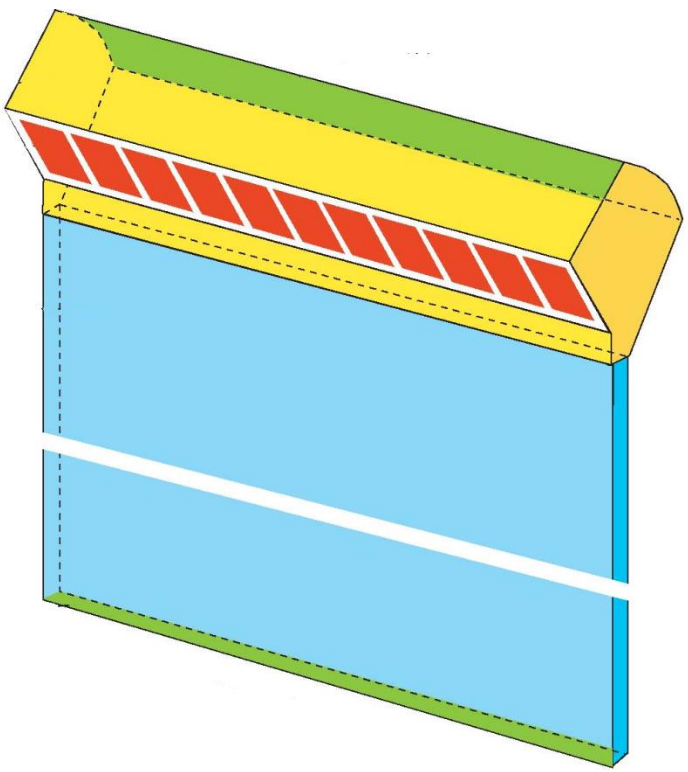


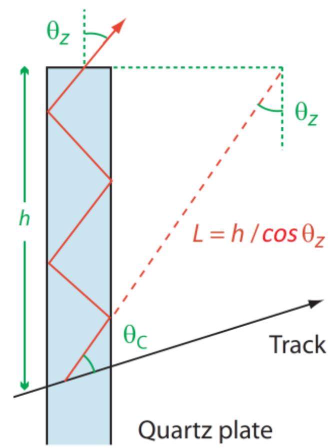
- Need to correct for the chromatic dispersion of the quartz
- Measure Cherenkov angle θ_c and path length L in the quartz.
- Can associate n_{phase} to get photon wavelength for K, π, p hypotheses → use dispersion relation for n_{group}
- Measure arrival time at the top of a radiator bar → $L = (t - t_0)\, c / n_{group}$ then reconstruct ToP and ToF for K, π, p hypotheses

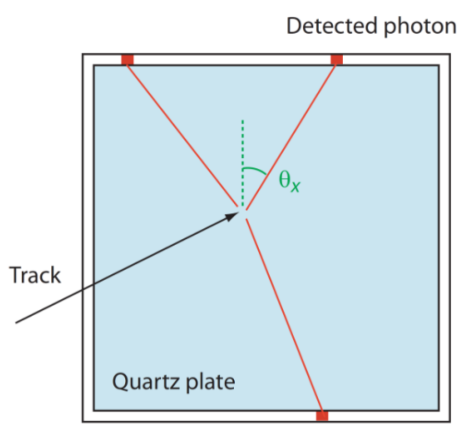


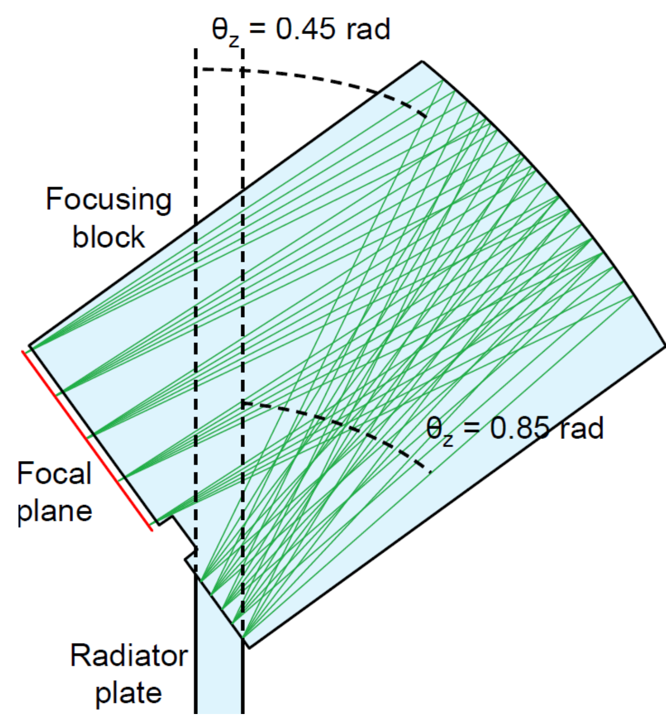
Basics of the TORCH design

- From simulation, ~1 mrad precision is required on measurement of the angles in both planes to achieve an intrinsic resolution of ~50 ps
- Need a photon detector with coarse granularity (non-focussing) and fine granularity (focussing) to achieve the 1 mrad angular resolution
- Anode pixel size: 128 × 8 pixels over ~60 mm pitch : 11 microchannel plate (MCP) detectors per module



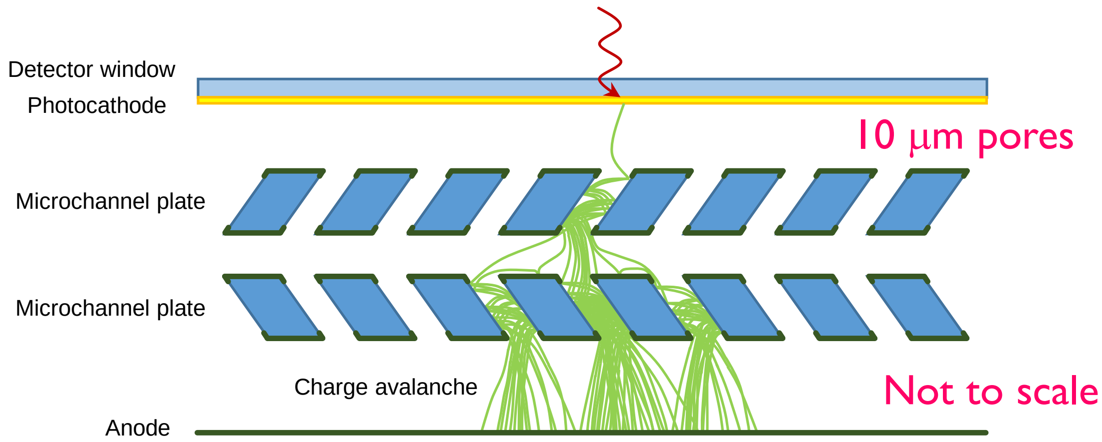






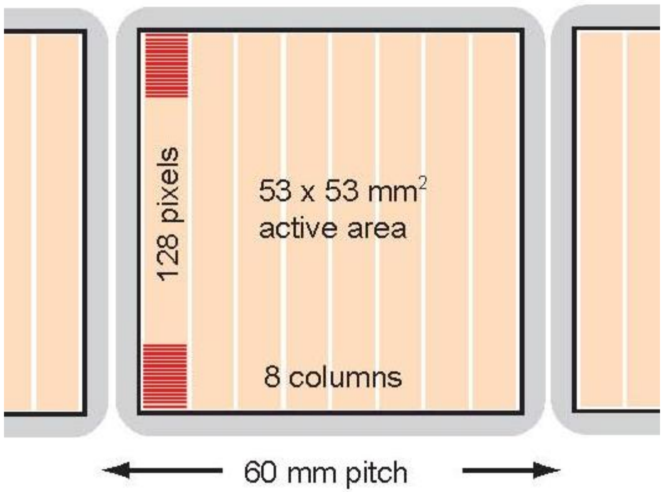
2. MCP development

- Micro-channel plate (MCP) photon detectors are well known for fast timing of single photon signals (~30 ps). Tube lifetime has been an issue in the past.



See talk of Tom Conneely at this Workshop

- Anode pixel structure can in principle be adjusted according to resolution required as long as charge footprint is small enough: $\rightarrow$tune to adapted pixel size: 128 $\times$ 8 pixels

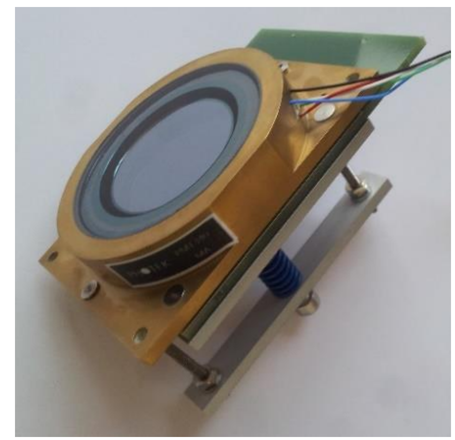


MCP-PMT three phase programme

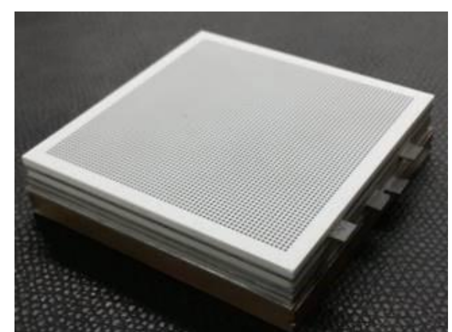
A major TORCH focus is on MCP R&D with our industrial partner : Photek (UK).

Three phases of R&D defined:

- Phase 1 : MCP single channel focuses on extended lifetime (> 5 C/cm^2) and ~35ps timing resolution. COMPLETED



- Phase 2 : Circular MCP with customised granularity (32x32 pixels (1/4 size) with charge sharing between neighbouring pads to get fine dimension). COMPLETED



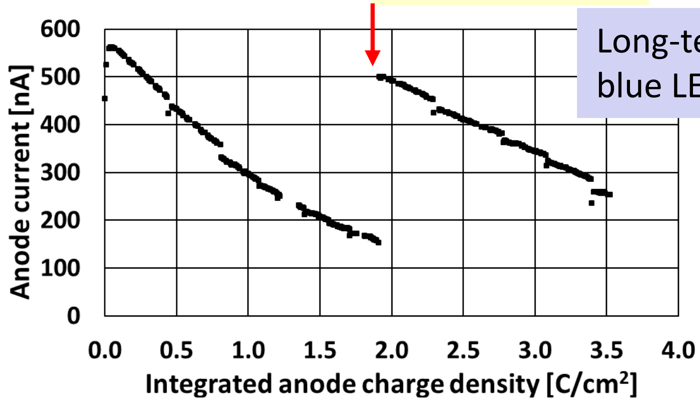
- Phase 3 : Square tubes (64x64) with high active area (>80%) and with required lifetime, granularity and time resolution. TUBES JUST DELIVERED

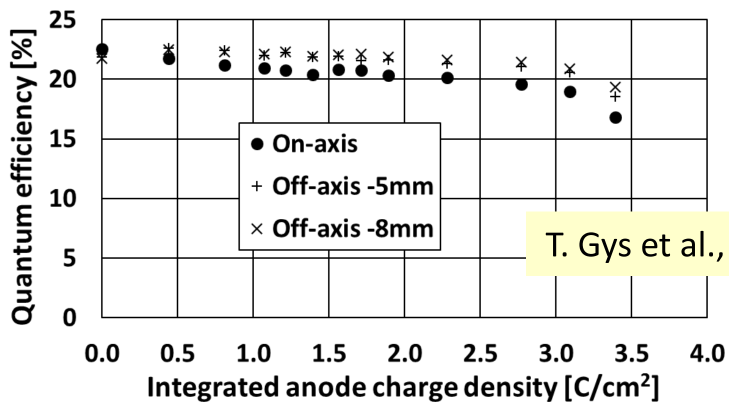
Laboratory measurements : Phase I tubes

- Lifetime requirement 5 C/cm^2 .   ALD coating.
  - Gain drop observed, recovered by increase of HV
  - Marginal loss in quantum efficiency (at 3.1 C/cm^2)

HV increased:
2300 → 2450 V

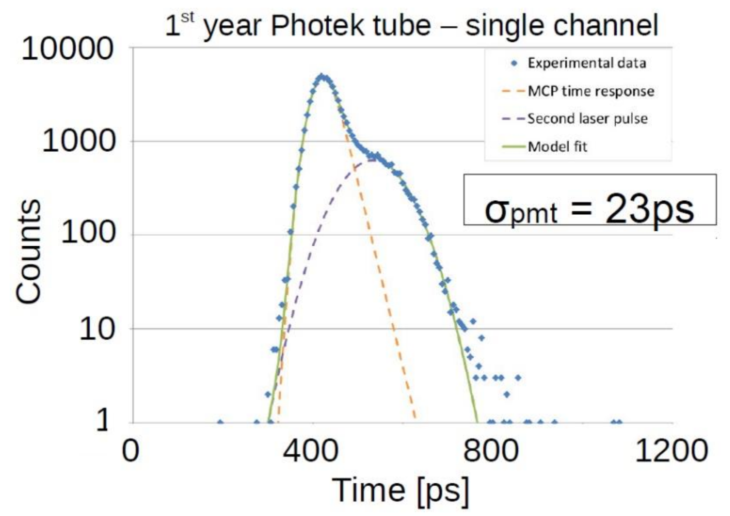
Long-term test
blue LED illumination





T. Gys et al., RICH2016

- Phase I Photek tubes : excellent timing resolution obtained with fast laser and with commercial electronics

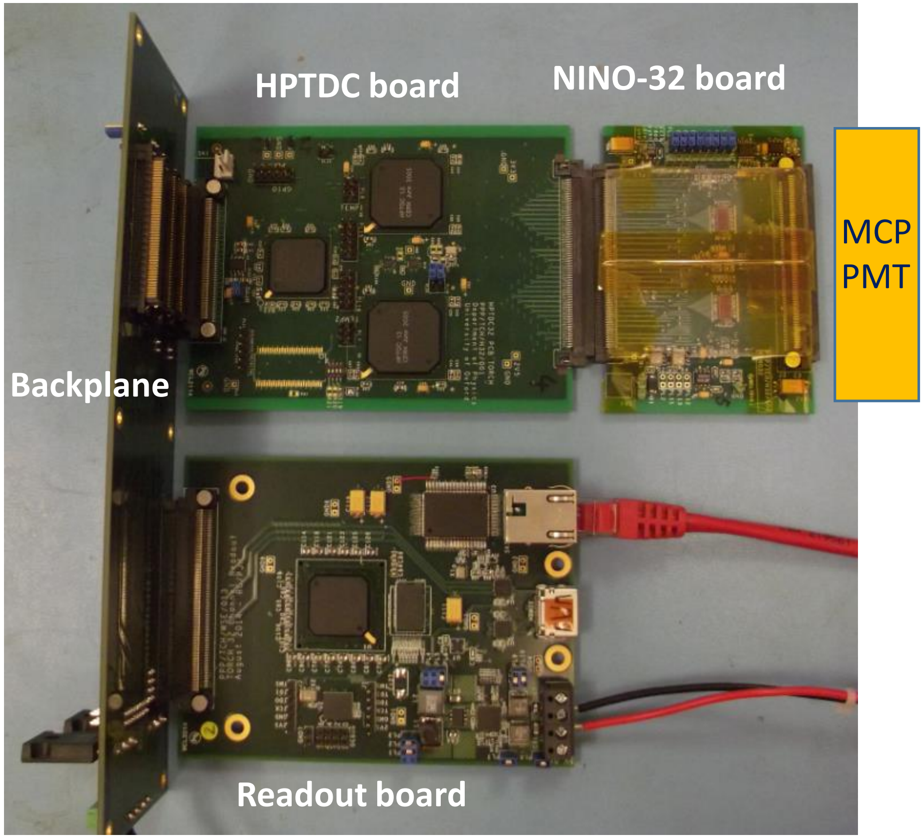


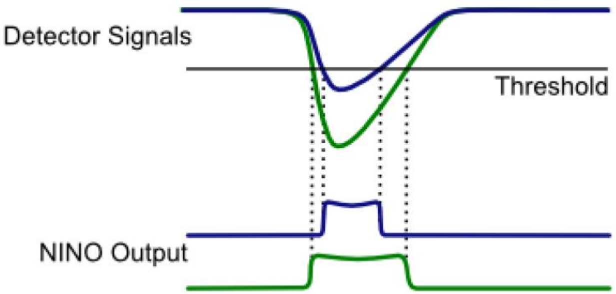
T. Gys et al., NIM A766 (2014) 171

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]
- TORCH is using 32 channel NINOs, with 64 channels per board (128 ch. board for the next phase)
- NINO-32 provides time-over-threshold information which is used to correct time walk & charge to width measurement - together with HPTDC time digitization (100 ps bins) non-linearities
- The calibration has proved challenging

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



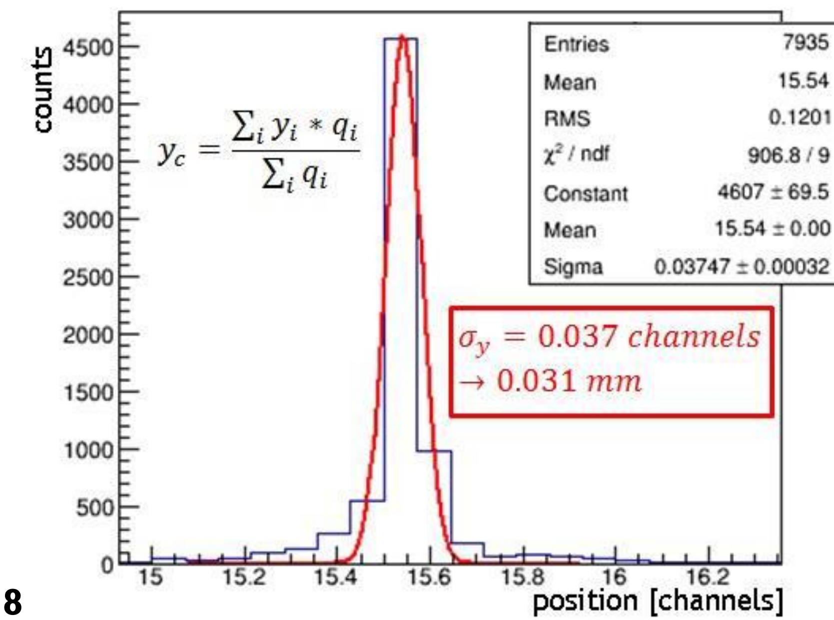


Position resolution

- Phase 2 tubes : tests of charge sharing between pixels: requires pulse charge to width calibration
- Point-spread function of MCP-PMT adjusted to share charge over 2-3 pixels
- TORCH requirement is ~ 0.41mm/√12 = 0.12 mm. Improvement with charge division between adjacent channels → measure x4 better than that required in optimal scenario

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

L. Castillo García et al, JINST 11 C05022 (2016)



3. Demonstrator TORCH module

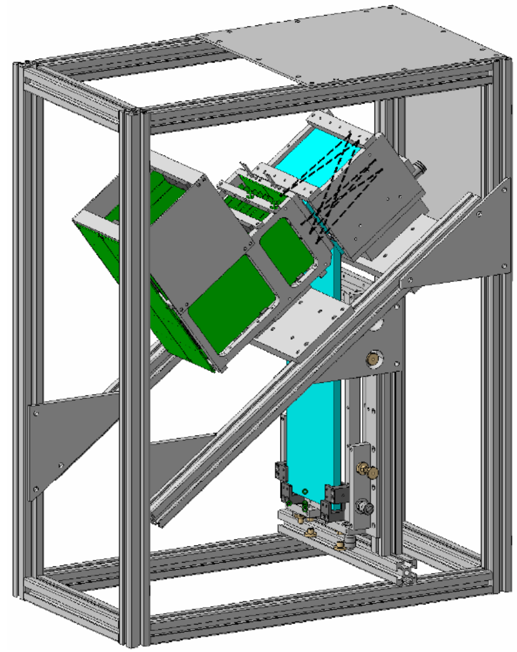
- Quartz radiator ($12\times35\times1\,cm^3$) with matching focusing block

- Single Phase-II MCP-PMT located in centre of focusing plane (4×32 pixels)

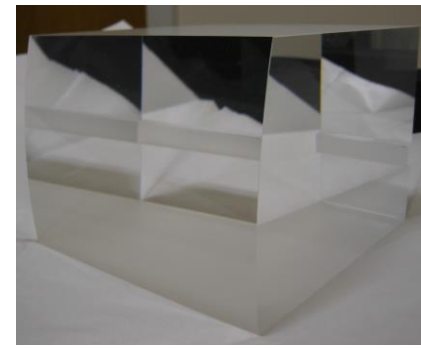
- Testbeam in 2015 and 2016 at CERN PS / T9

- Trigger defined by two $8\times8\,mm^2$ scintillators spaced 11m apart

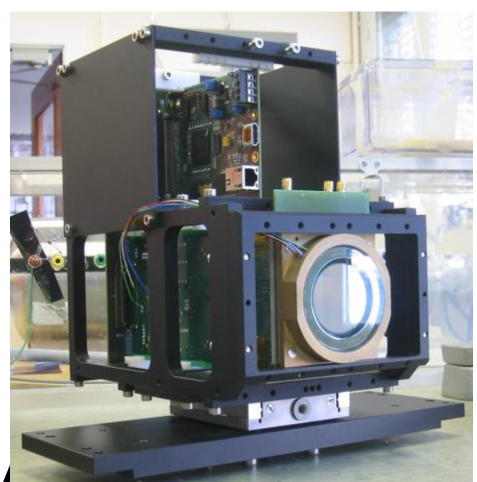
- Timing reference taken from two borosilicate bars with single-channel MCP-PMT



Focusing block

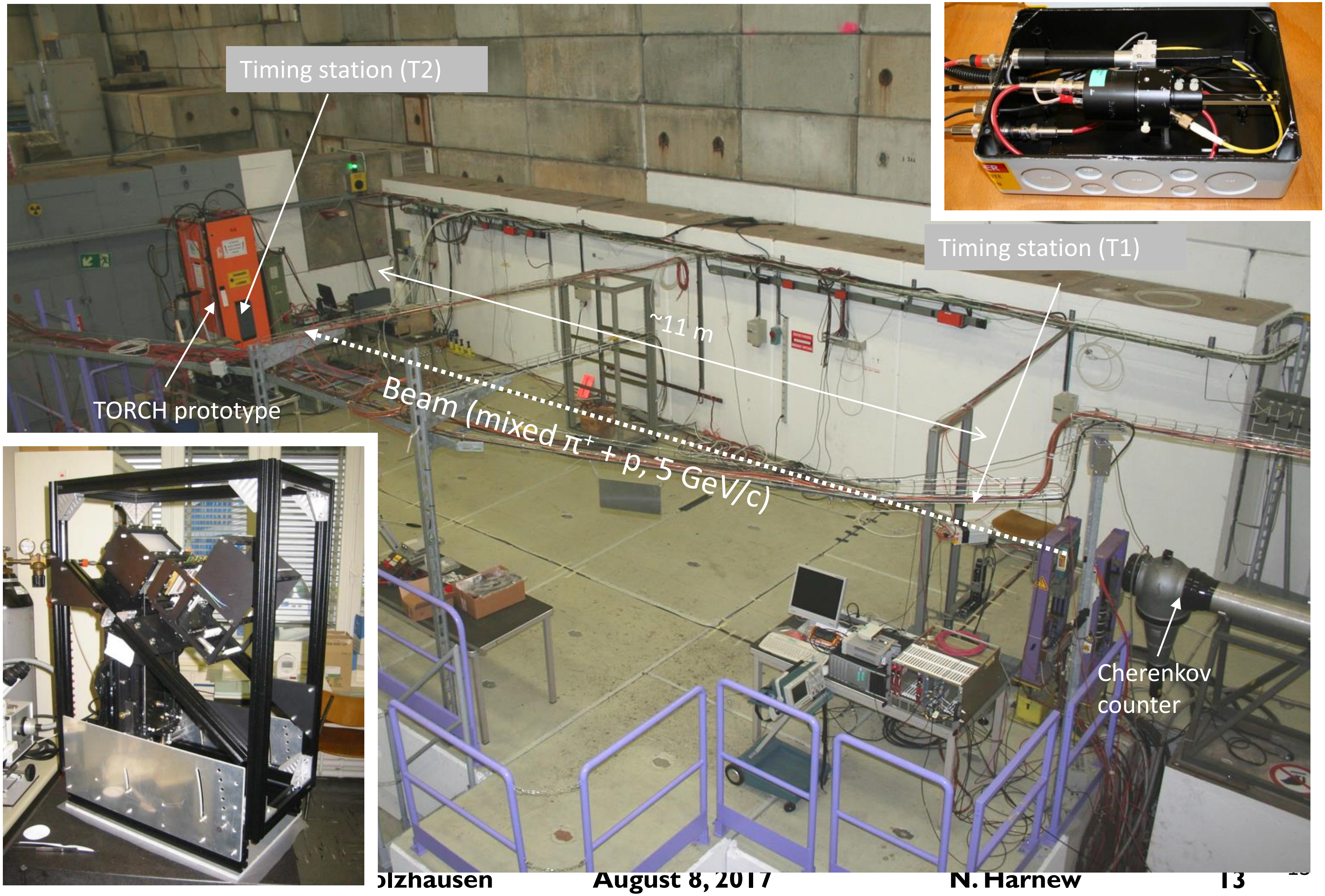


MCP-PMT and electronics



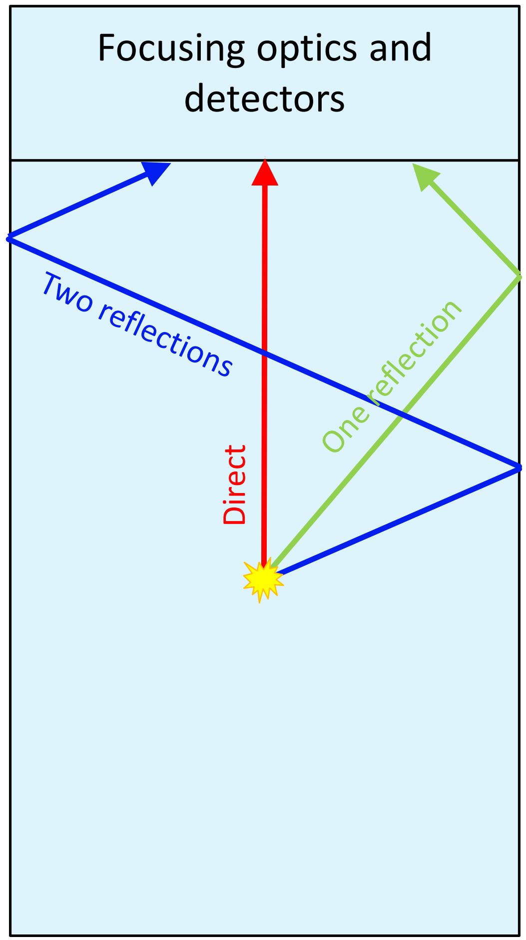
Radiator plate: $35 \times 12 \times 1\ cm^3$

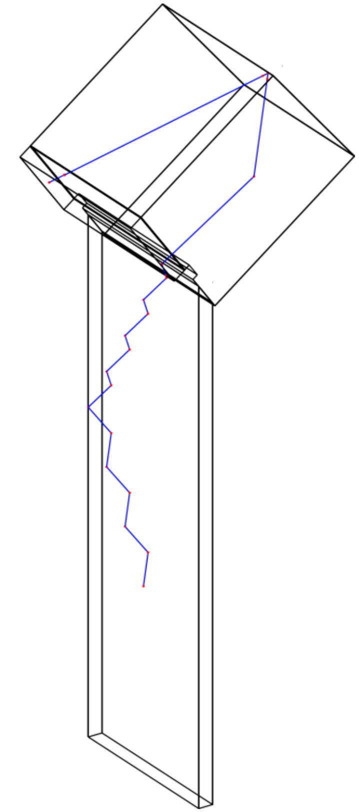
TORCH beam test infrastructure in PS/T9



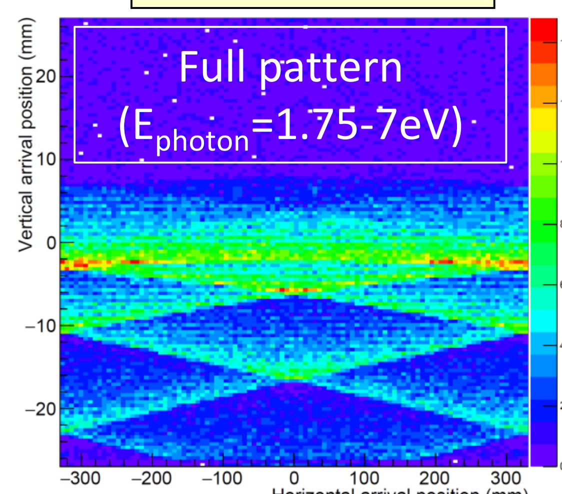
Pattern folding

- Cherenkov cone results in hyperbola-like patterns at MCP plane
- Reflections off module sides result in folding of this pattern
- Chromatic dispersion spreads line into band
- Pattern shown here for full TORCH module, however this pattern is only *sampled* in testbeam



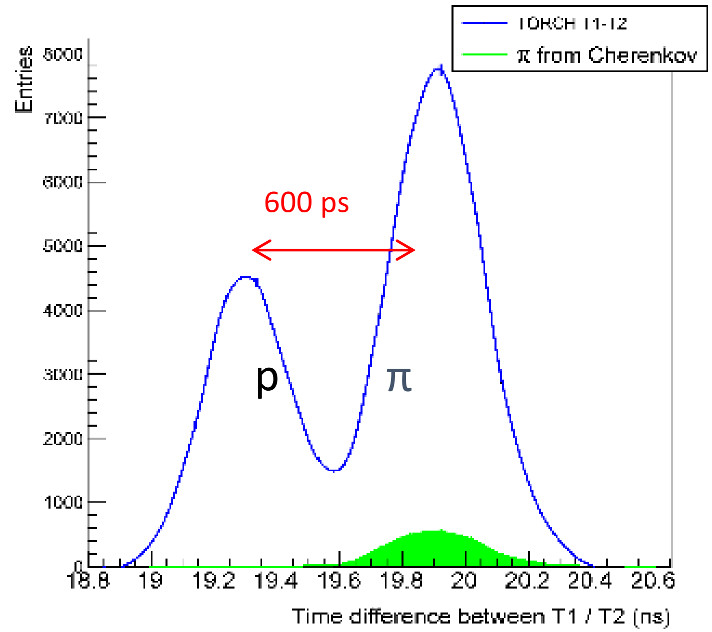


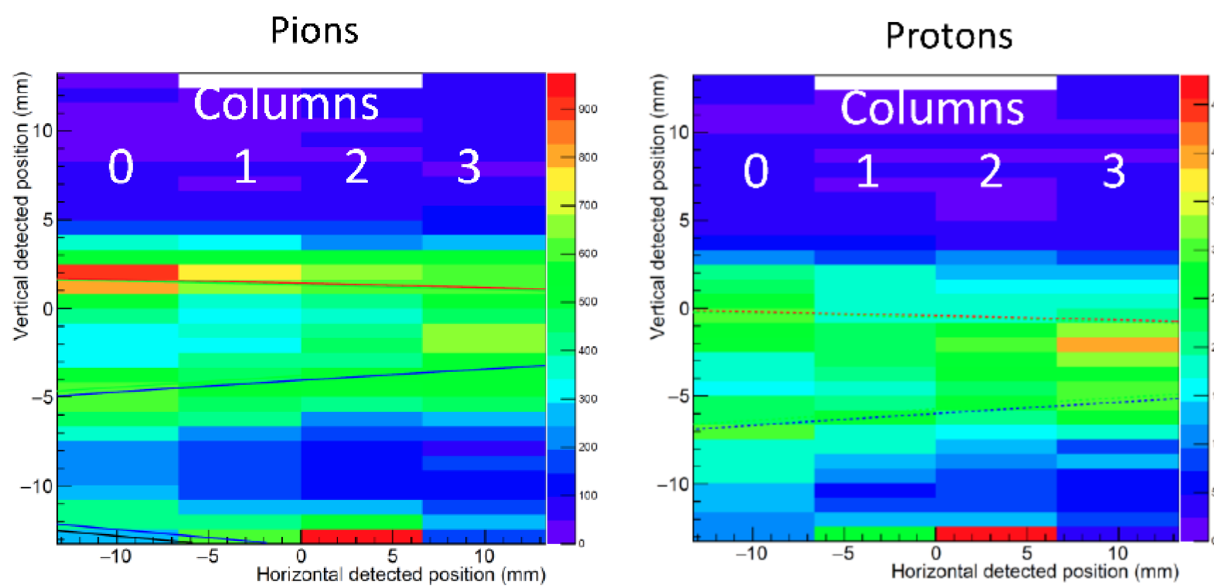
Geant simulation



Hit maps in MCP-PMT

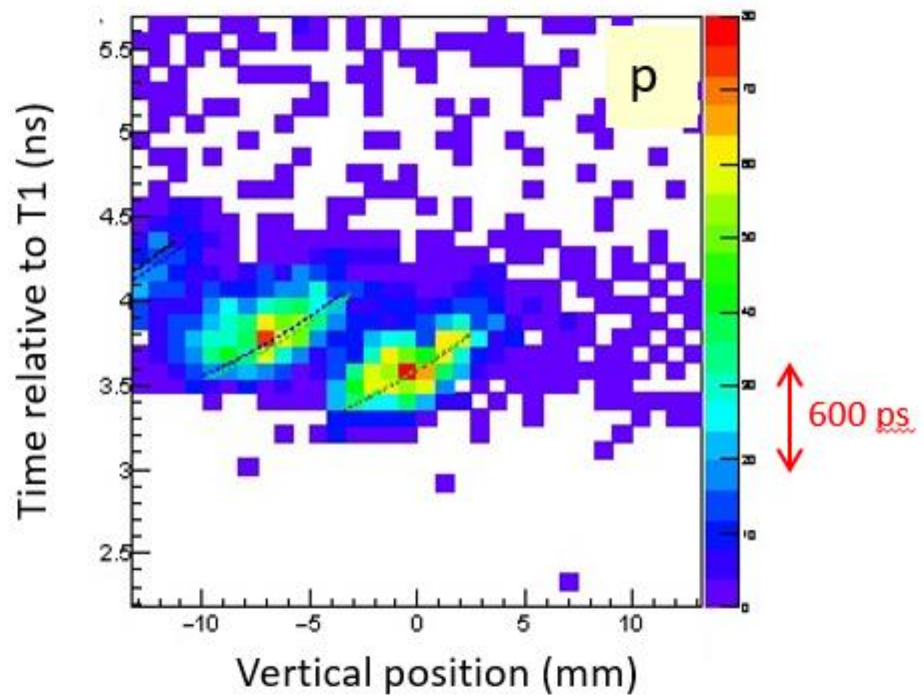
- Particle selection from ToF over ~11m distance using beam telescope
- Charge weighting applied to get centroid of clusters
- Reflections are clearly separated
- Proton – pion difference cleanly resolved

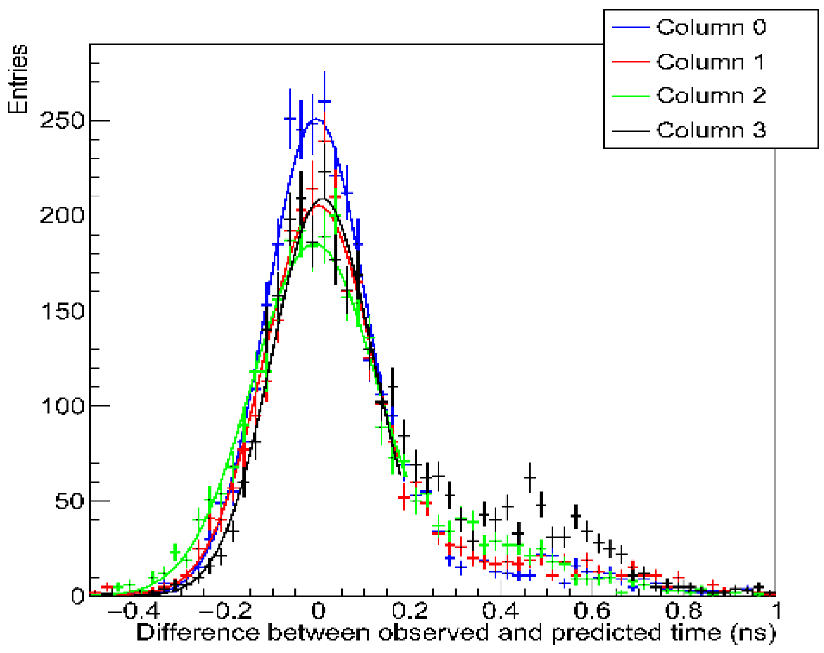




Time resolution

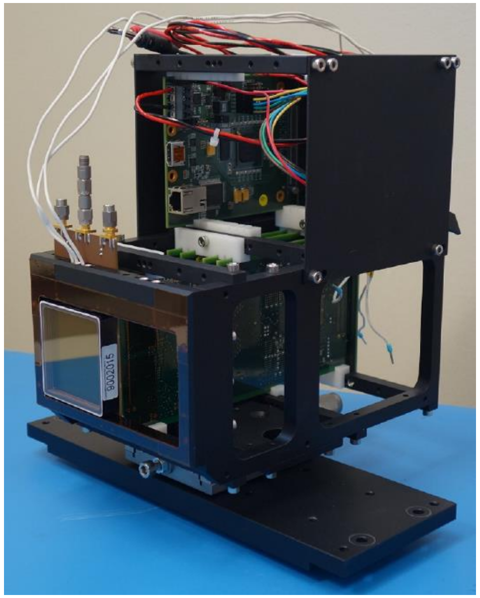
- Plot time measured for each cluster relative to T1 *vs.* vertical position along column of pixels (protons shown)
- Project along timing axis relative to prediction for each column of pixels (relative to T1 as timing reference)
- Core distribution has σ ≈ 110 ps
  After subtraction of contribution from timing reference measure ~85 ps, approaching the target resolution of 70 ps per photon
- Improvements possible:
  - Include tracking (beam currently defined by small scintillators)
  - Limit of 100ps binning in HPTDC
- Tails due to imperfect calibration and back scattering effects

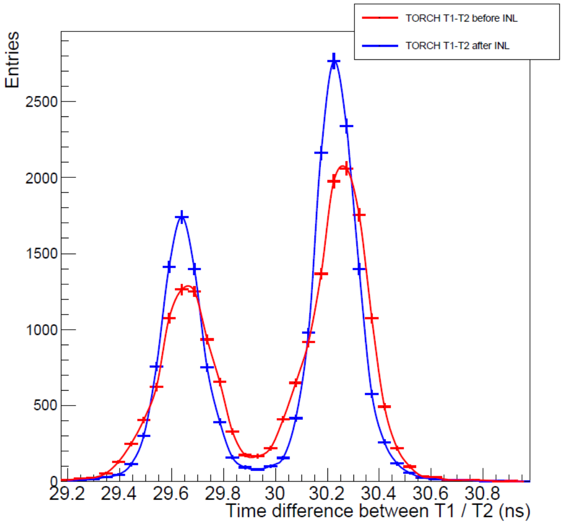


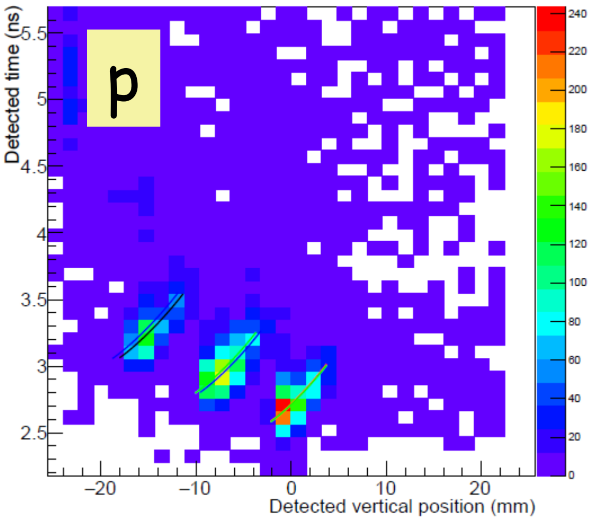


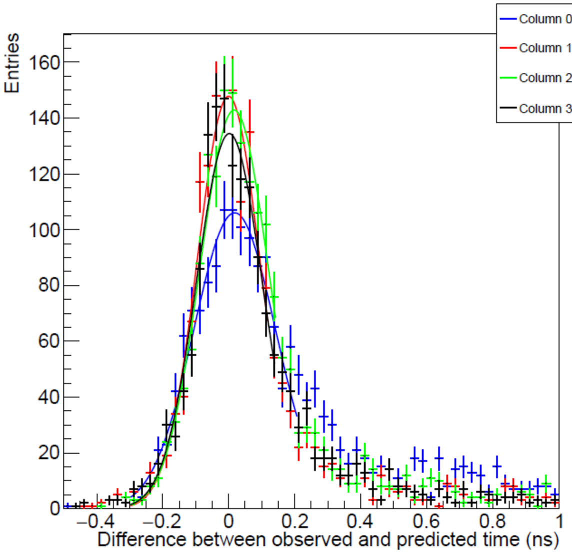
Time resolution studies with Planacon

- Measurements repeated using Photonis Planacon MCP-PMT in 2016 testbeam period
- Planacon MCP-PMT has 32 x 32 pixels within 2x2-inch^2 active area
- Working experience gave significant improvements in calibration and better experimental control
- Mean core distribution is unchanged, despite coarser granularity : σ ≈ 110 ps (as before, T1 timing station contribution not subtracted)
- Tails are likely dominated by back scattering effects



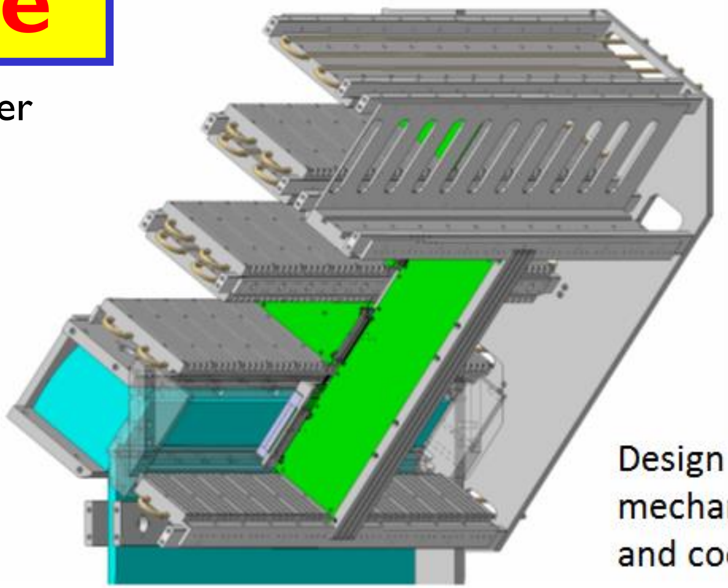






4. Full-scale prototype

- Large prototype of a half-sized TORCH module 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
- Testbeam October/November and in 2018

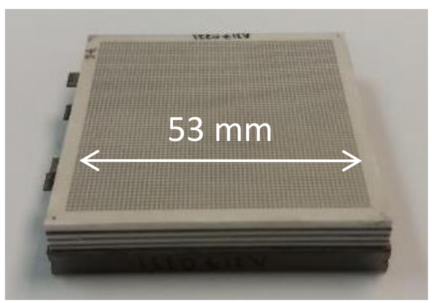


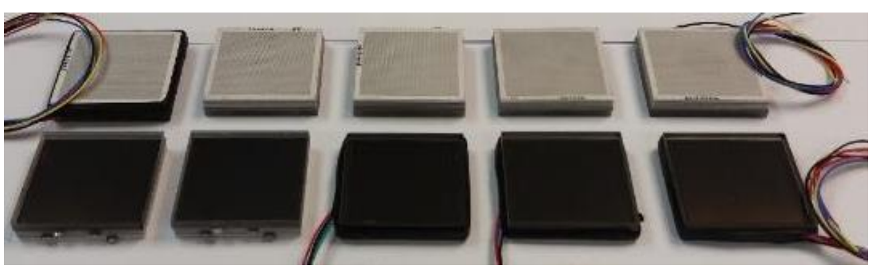
Design for mechanics and cooling

Final photon detectors

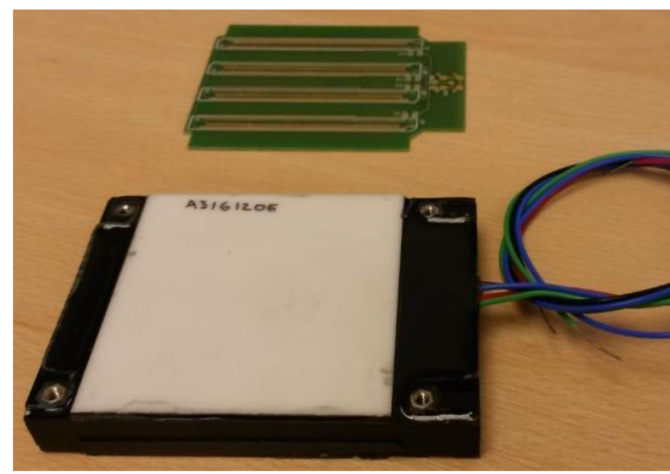
- Final Phase-3 tube has a square format with 53 x 53 mm^2 active area
  AC-coupled anode, so window can be at ground.
- Readout connectors mounted on PCB, 64 x 8 pixels per tube
  which is attached to tube using ACF (anisotropic conductive film)
- Tubes recently delivered and currently under test at CERN

Bare tubes



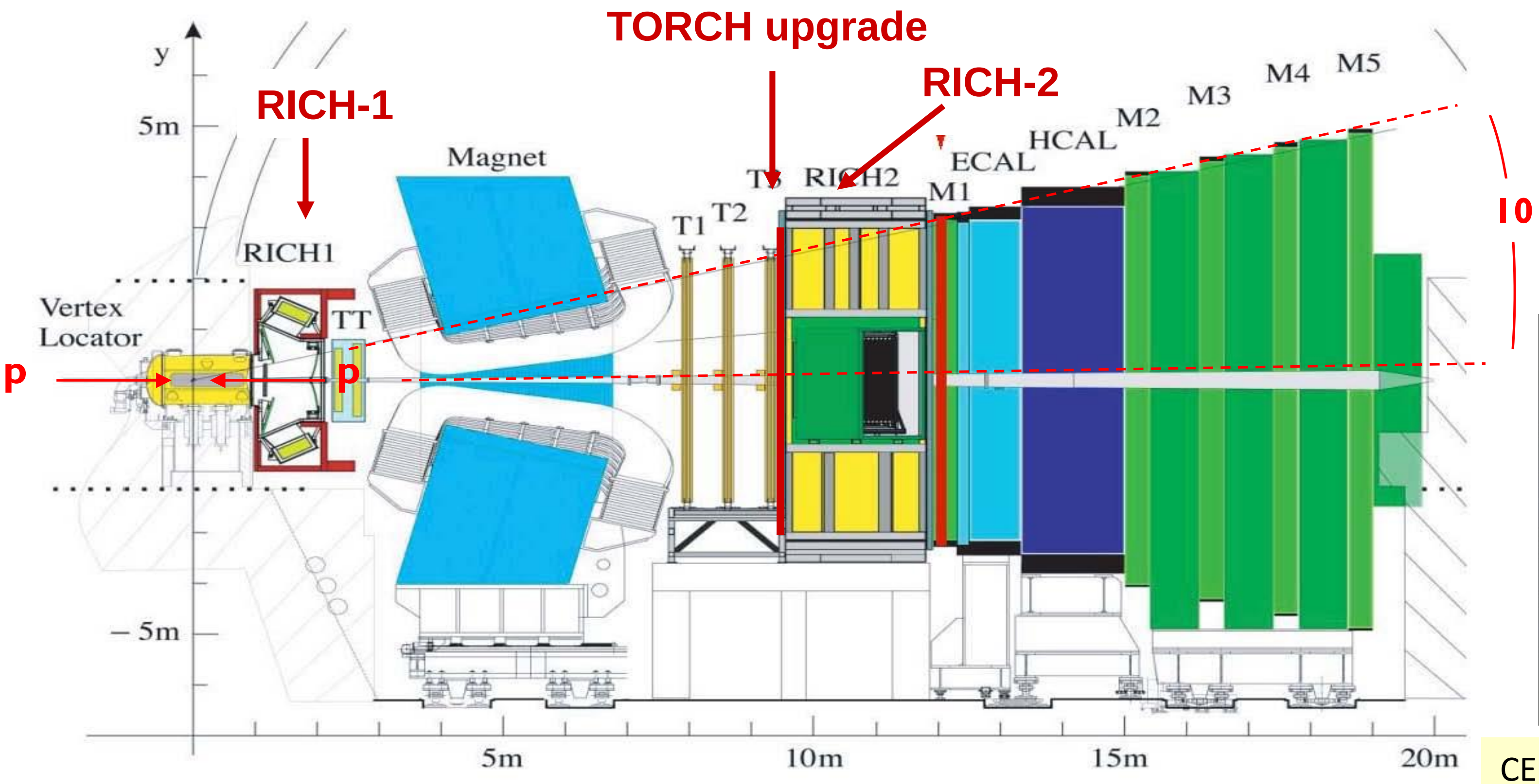


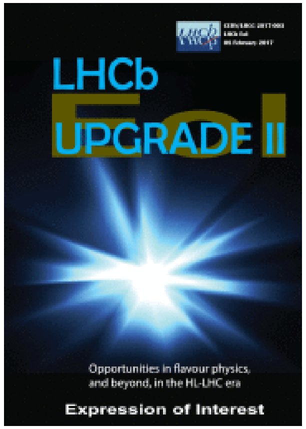
After potting, before readout PCB is attached



5. TORCH for the LHCb Upgrade

- LHCb is a dedicated flavour physics experiment at the LHC : PID is essential
- The RICH system will be retained for particle ID, but with no aerogel
- Proposal to install TORCH in front of RICH2 (or replacing muon station M1), most likely in LS3

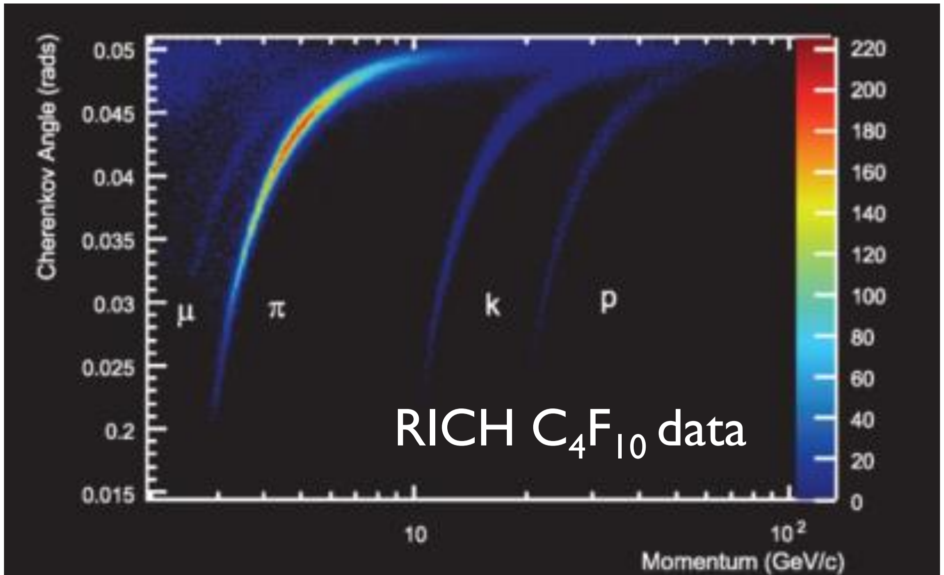




CERN-LHCC-2017-003

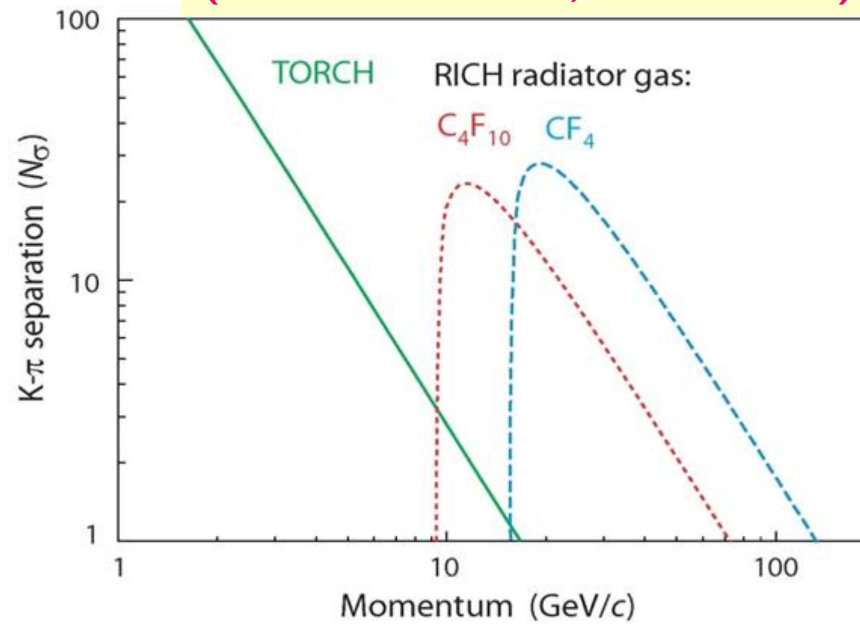
LHCb particle identification

- K-π separation (1–100 GeV) is crucial for the hadronic physics of LHCb. Currently achieved with two RICH radiators: C_4F_{10} and CF_4



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

(Ideal reconstruction, isolated tracks)

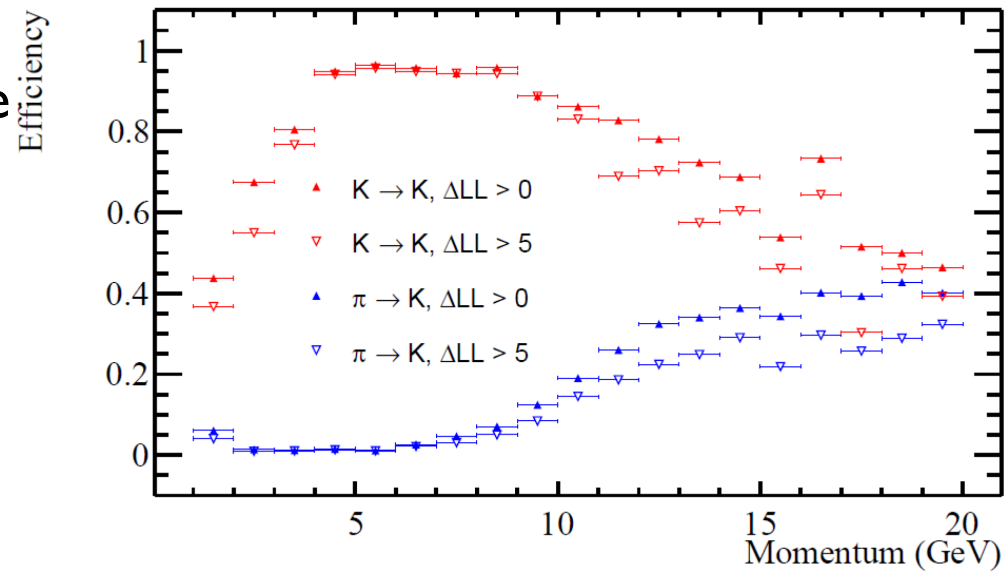


- Currently no positive kaon ID below ~10 GeV/c nor any proton ID. Aim is to achieve this via a ToF measurement with TORCH
  - Area of 5 x 6 m^2 at z = 10 m
  - 18 identical modules (66 x 250 cm^2)
  - 198 MCPs (~100k channels)

TORCH performance studies at LHCb

- Simulation of the TORCH detector & interface to a simulation of LHCb events, plus TORCH pattern recognition in GEANT is ongoing.
- Excellent particle ID performance achieved, up to and beyond 10 GeV/c (with some discrimination up to 15 GeV/c). Seems to be robust against increased luminosity
- Can obtain a start time t_0 from the other tracks in the event originating from the primary vertex

Full LHCb Simulation, single B events



Summary

- TORCH is a DIRC-type detector to achieve high-precision time-of-flight over large areas aiming to achieve K-π separation up to 10 GeV/c and beyond (with a TOF resolution of ~15 ps per track for ~30 photons)

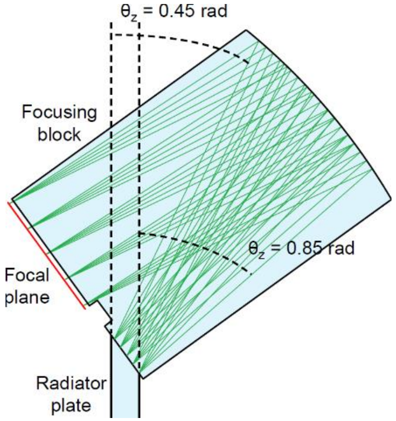
- Ongoing R&D programme aims to produce suitable MCP-PMT, satisfying challenging requirements of lifetime, granularity, charge sharing and active area.

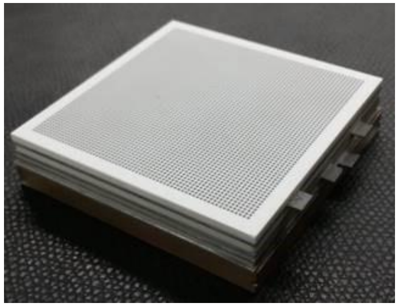
- Testbeam results very promising
  - Performance has been shown to be very good ~approaching 70ps time resolution per photon

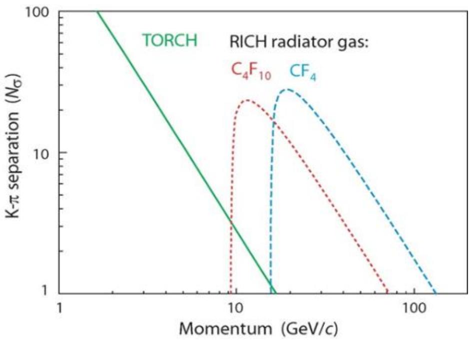
- TORCH future : beam tests over the coming year
  - New optics half-sized module have been delivered
  - Phase-III MCP-PMTs are under test
  - New generation of electronics being commissioned
  - Included in future plans of the LHCb experiment

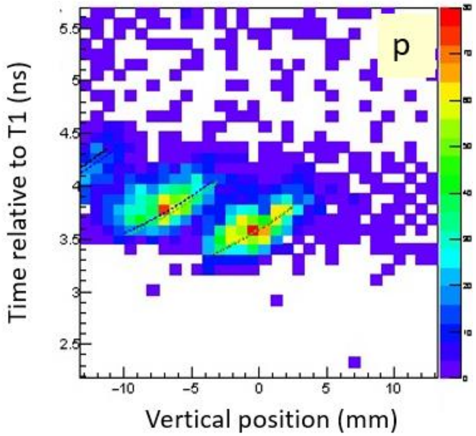
- After R&D demonstration, prepare physics case & technical proposal for LHCb

Thanks for listening !









The TORCH project has been funded by an ERC Advanced Grant under the Seventh Framework Programme (FP7), code ERC-2011-ADG proposal 299175.

erc
European Research Council
Established by the European Commission