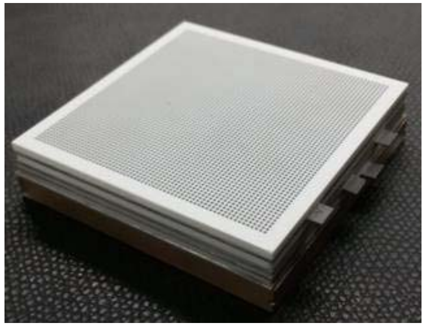
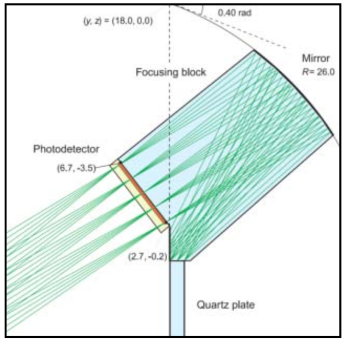
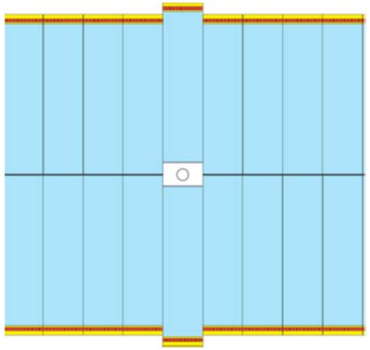
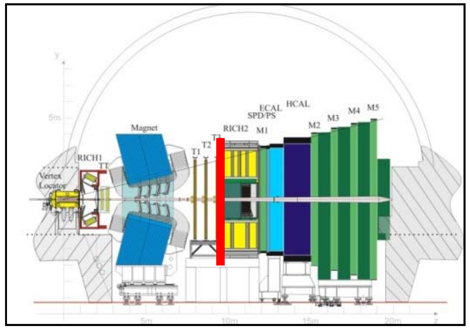
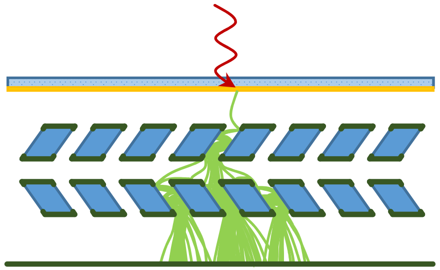
TORCH: A large-area time-of-flight detector for LHCb Phase II Upgrade





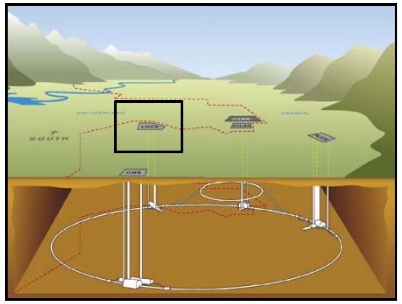






Neville Harnew
University of Oxford

(Universities of Bath, Bristol and Oxford, CERN, and Photek)



Beyond the LHCb Phase-I Upgrade
Elba   29 May 2017

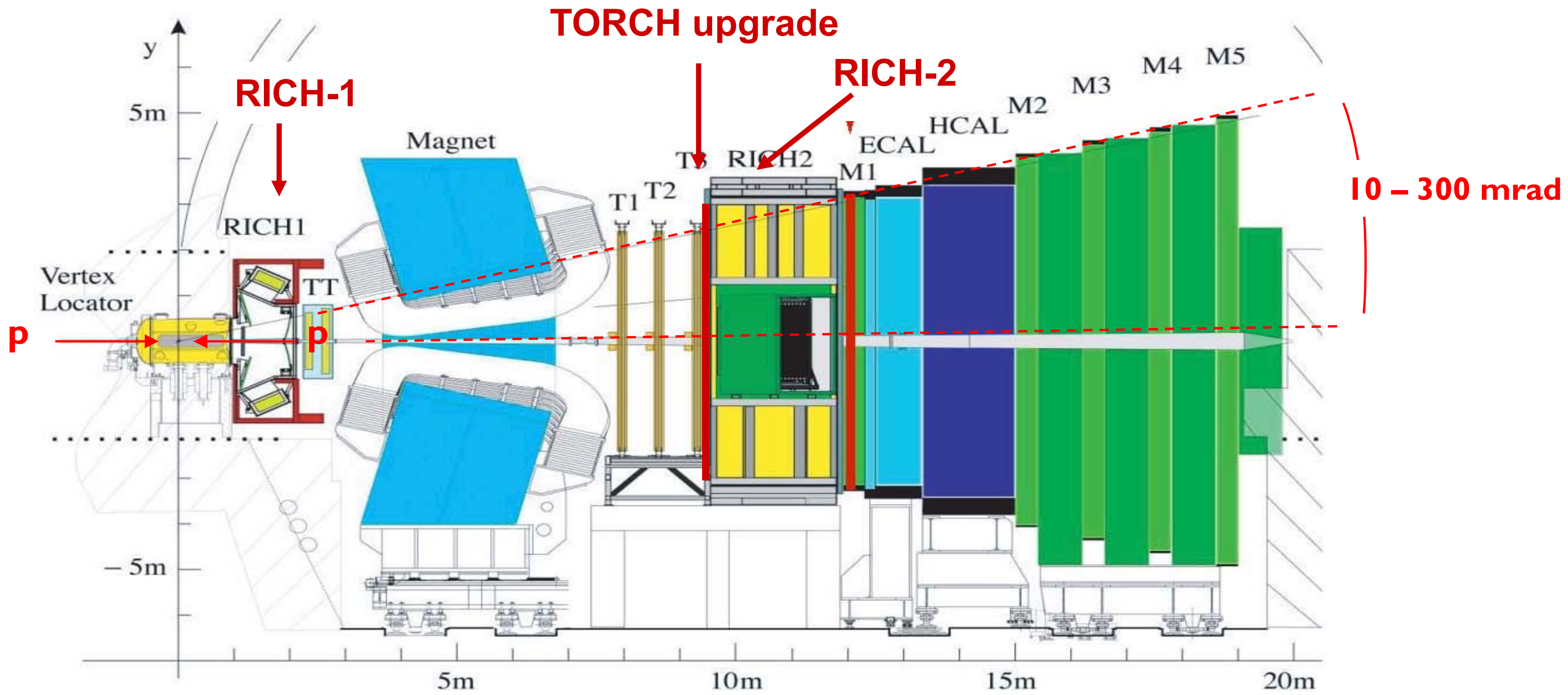
European Research Council
Established by the European Commission

Outline

- TORCH concept
- Development of Microchannel Plate (MCP)-PMTs
- Test beam results
- Future prospects and summary

1. PID and the LHCb Upgrade

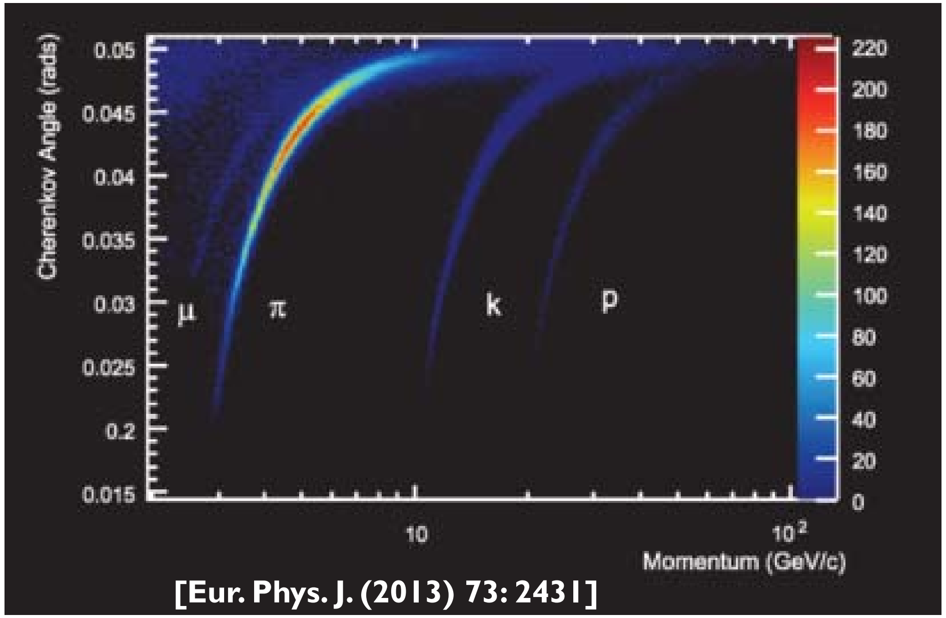
- The RICH system will be retained for particle ID, but with aerogel removed
- Possibility install a time-of-flight detector (TORCH) in front of RICH2 (or replacing muon station M1), most likely in LS3

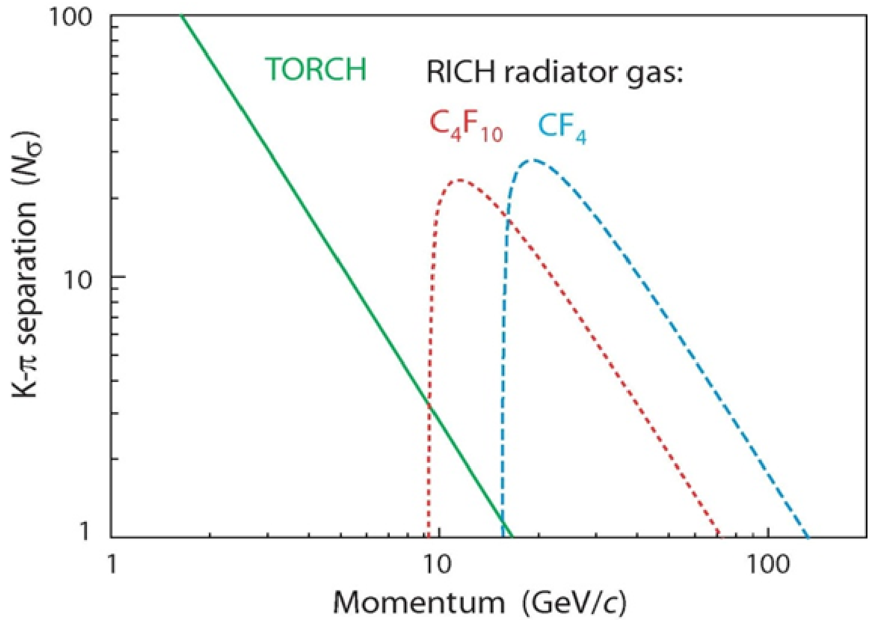


LHCb particle identification

- 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
- Currently no positive kaon ID below ~10 GeV/c. Aim is to achieve this via a time of flight (ToF) measurement with a new detector (TORCH)

RICH C_4F_{10} data





2. The TORCH R&D project

- The TORCH (Time Of internally Reflected CHerenkov light) detector is an R&D project to develop a large-area time-of-flight system.
- 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 has been awarded by the ERC: to develop customised photon detectors in collaboration with industrial partners and to provide proof-of-principle with a demonstrator ToF module.

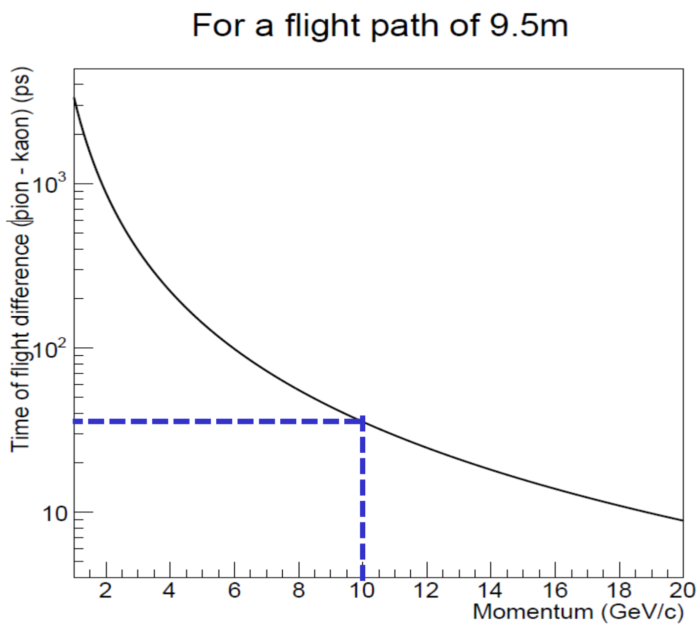
The TORCH detector

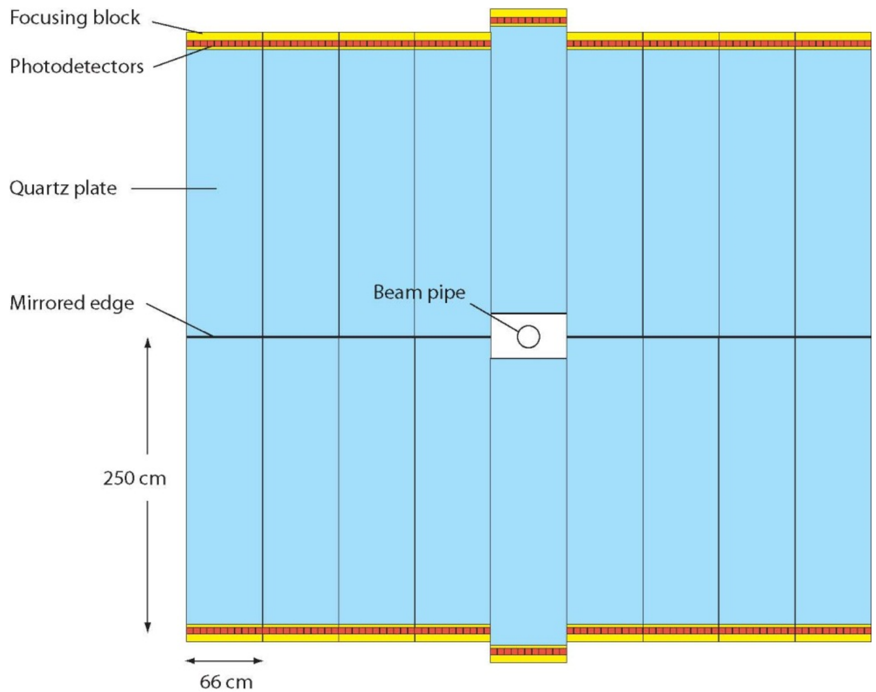
- To achieve positive identification of kaons up to p ~ 10 GeV/c, ΔTOF (π-K) = 35 ps over a ~10 m flight path → need to aim for ~ 10-15 ps resolution per track

- Cherenkov light production is prompt → use a plane of 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 → time their arrival by Micro-Channel Plate PMTs (MCPs)

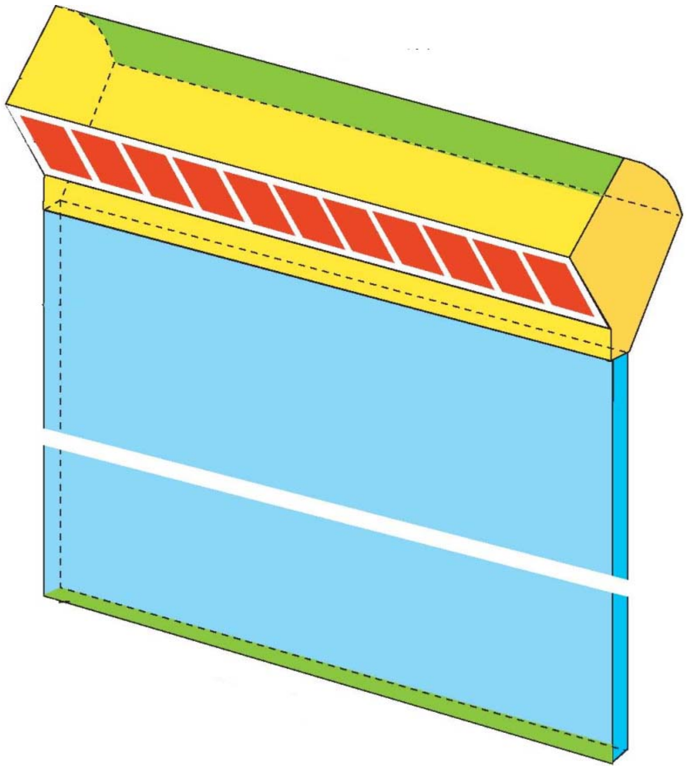
- The ΔTOF requirement dictates timing single photons to a precision of 70 ps for ~30 detected photons)

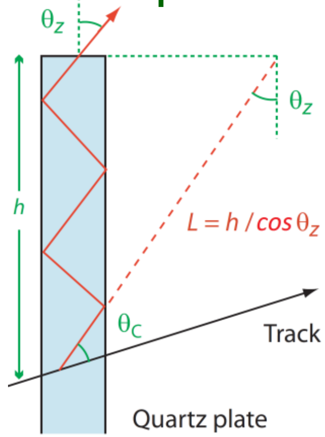


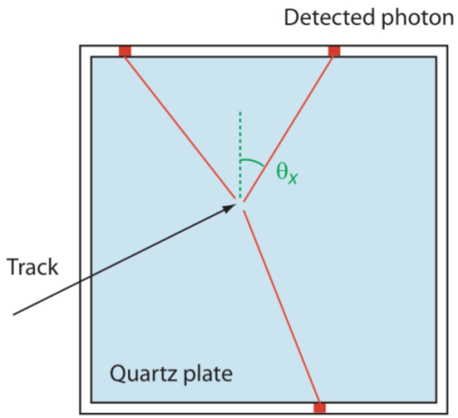


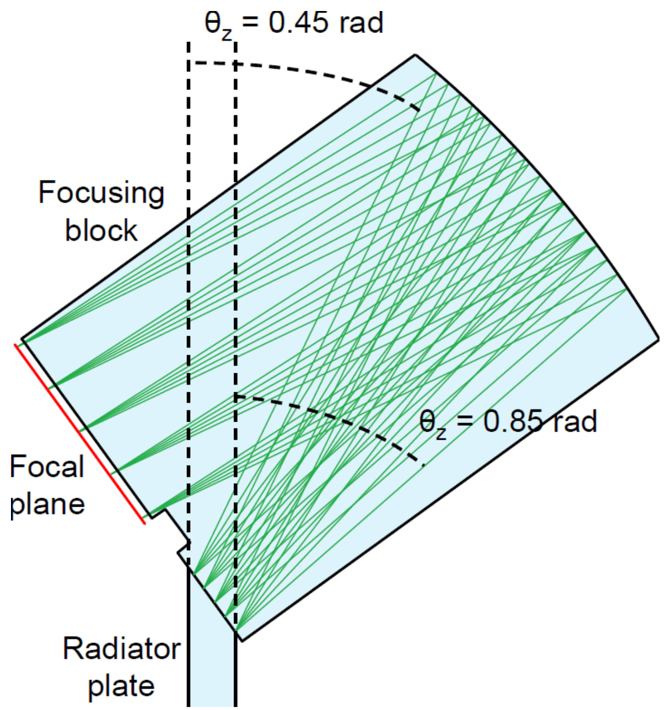
Basics of the TORCH design

- Measure *angles* of photons: then reconstruct their path length L, make correction dispersion effects - then time of propagation
- From simulation, a ~1 mrad precision is required on the angles in both planes for intrinsic resolution of ~50 ps
- Need a photon detector with anode pixel size: 128 × 8 pixels over 60mm pitch : (11 microchannel plate (MCP) detectors per module)



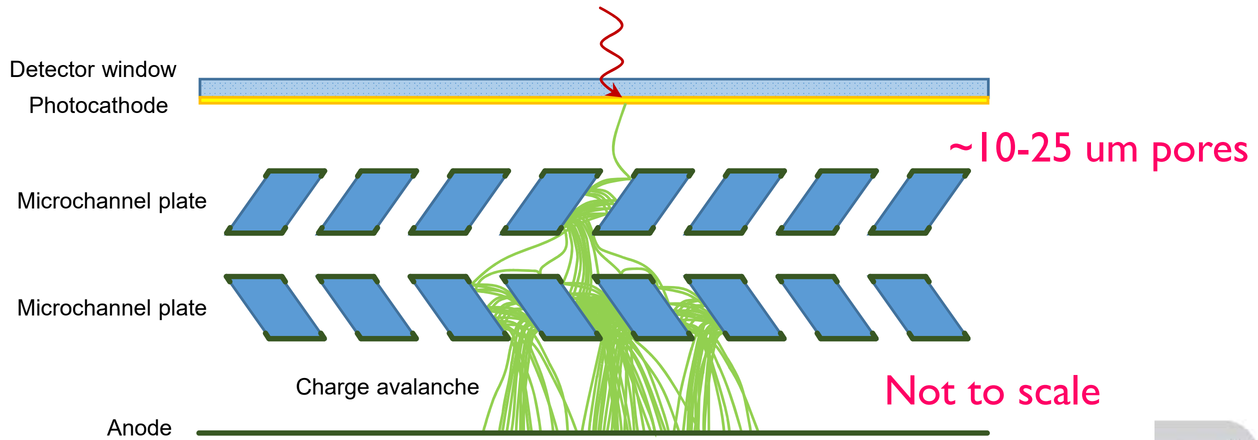




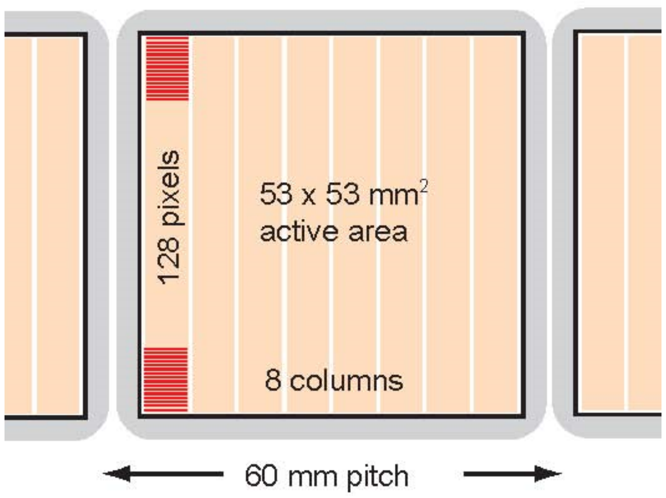


3. MCP development

- 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.



- 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

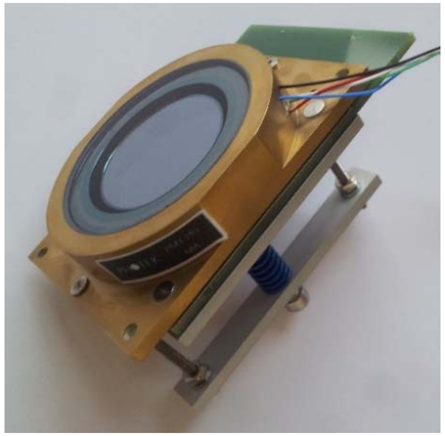


TORCH MCP developments

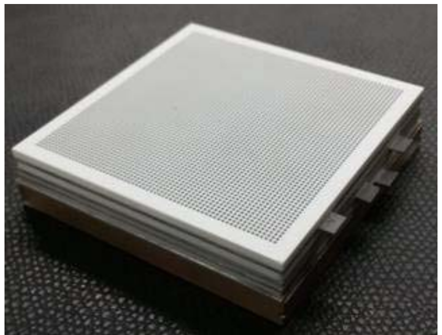
A major TORCH focus is on MCP R&D with an industrial partner : Photek (UK).

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. DELIVERY SOON

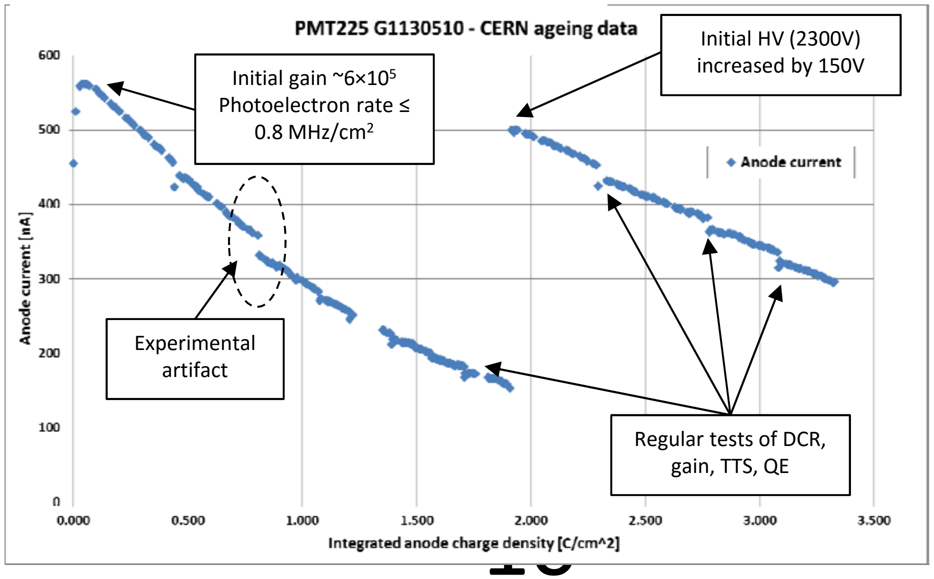
Laboratory measurements

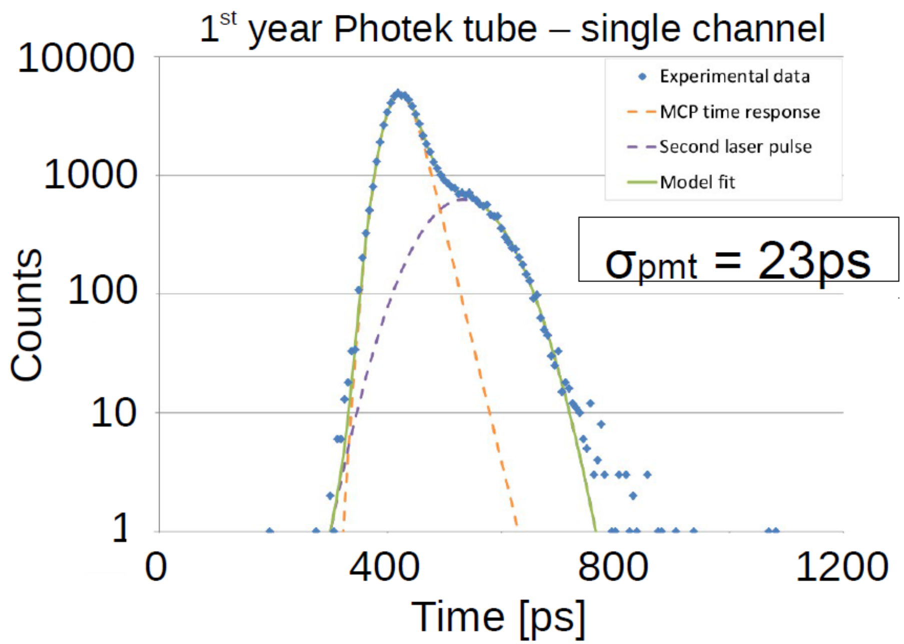
- Lifetime requirement 5C/cm^2
  - Gain drop observed
  - Recovered by increase of HV
  - Marginal loss in quantum efficiency (at 3.1 C/cm^2)

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

Lifetime test by TORCH @ CERN

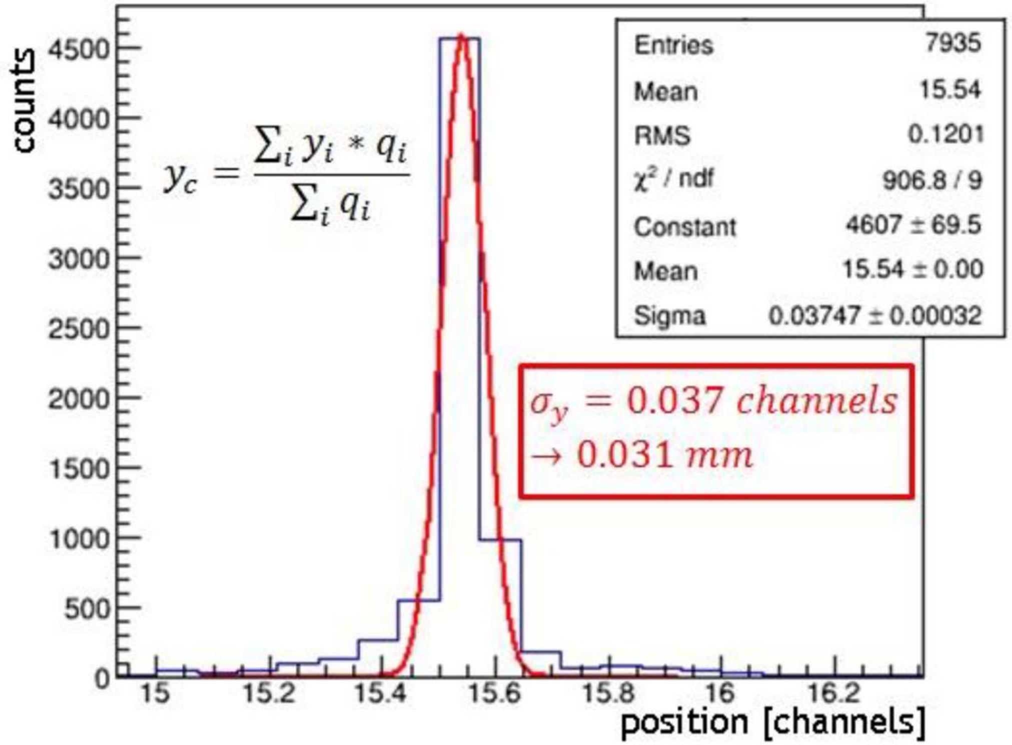
T. Gys, presented at RICH2016 (Bled)





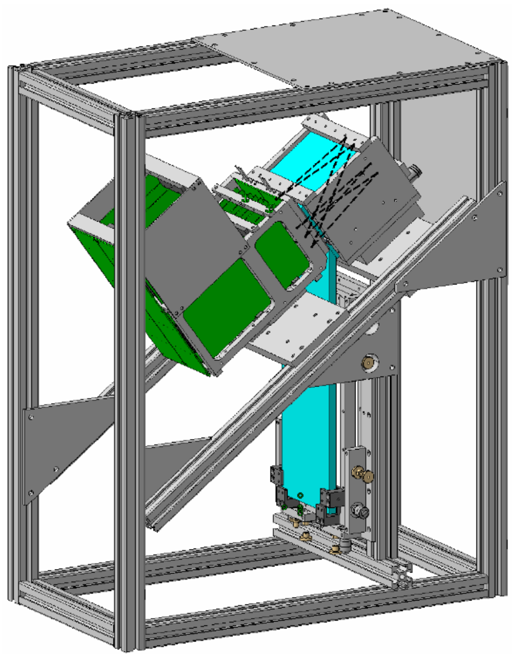
Laboratory measurements (2)

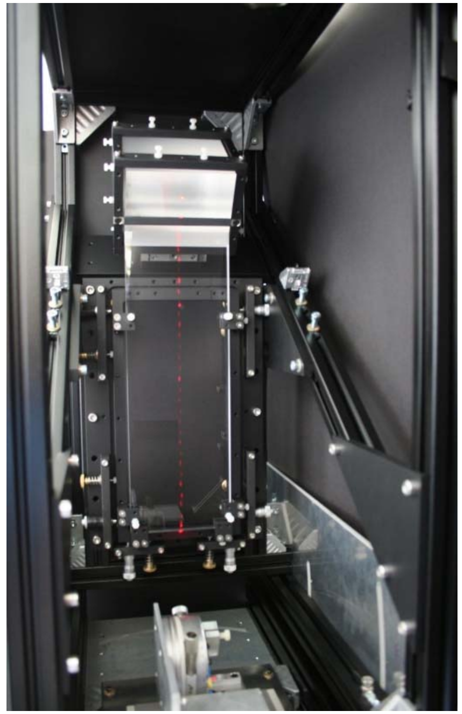
- Phase 2 tubes : tests of charge sharing between pixels.
- TORCH requirement is ~ 0.41mm/√12 = 0.12 mm. Improvement with charge division between adjacent channels → x4 better than that required
- See L. Castillo García et al, JINST 11 C05022 (2016)

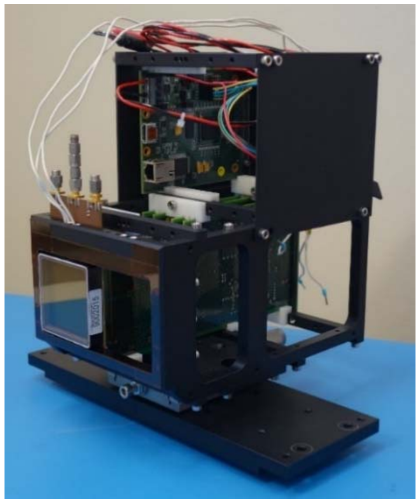


4) Demonstrator TORCH module

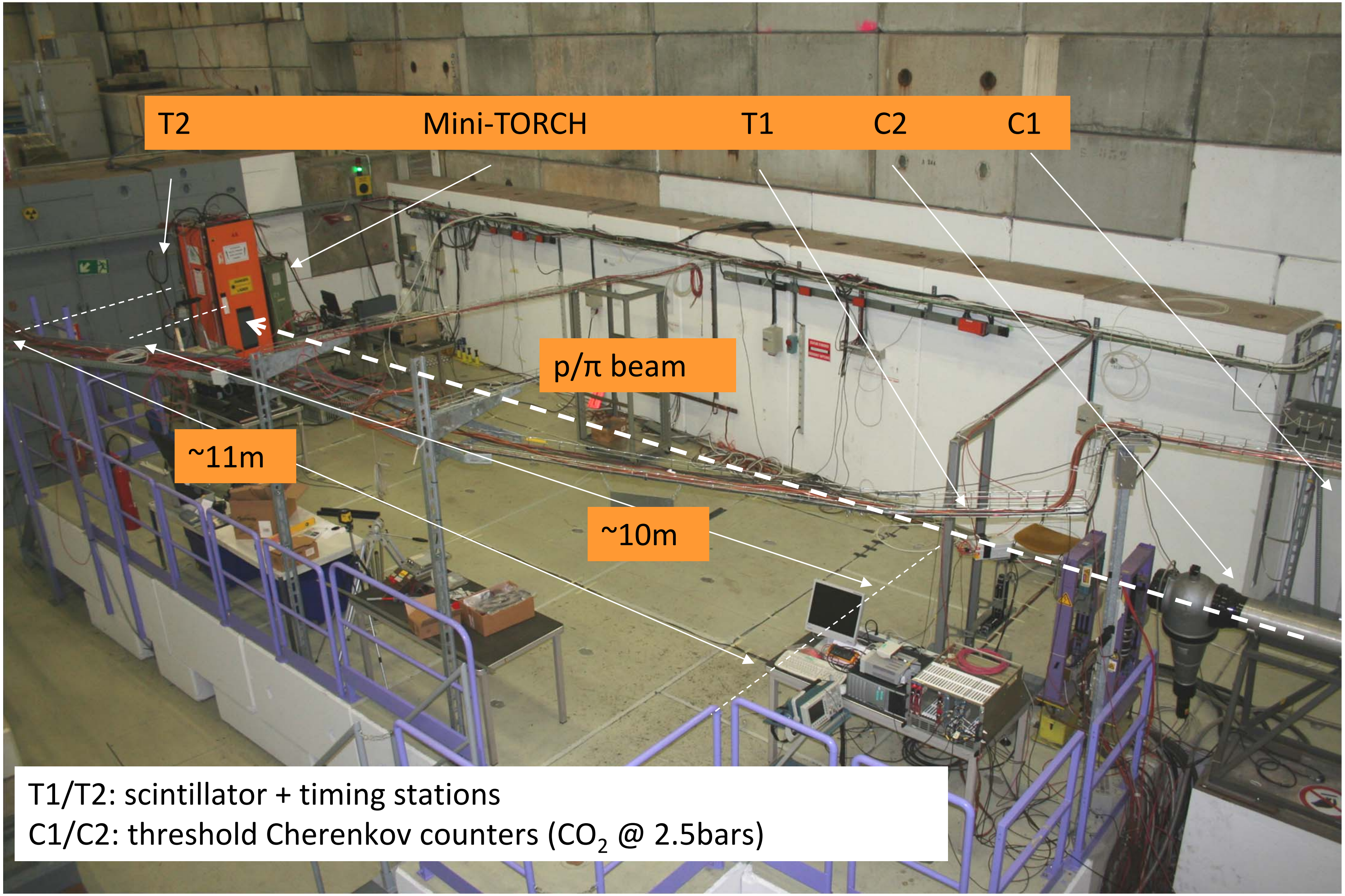
- Quartz radiator (12×35×1cm^3) with matching focusing block
- Single Phase-II MCP-PMT in centre of focusing plane (4×32 pixels)
- Testbeam at CERN PS / T9
- Trigger defined by two 8×8mm^2 scintillators spaced 11m apart
- Timing ref taken from two borosilicate bars with single-channel MCP-PMT





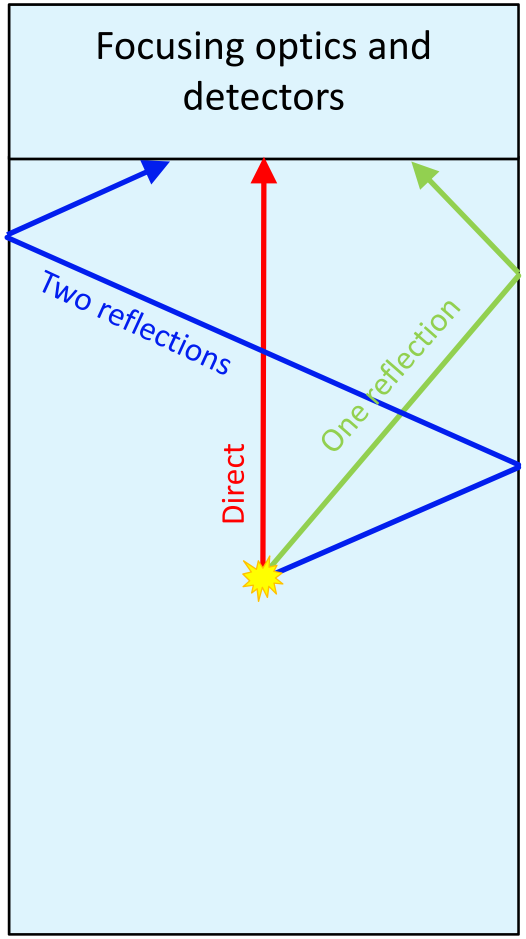


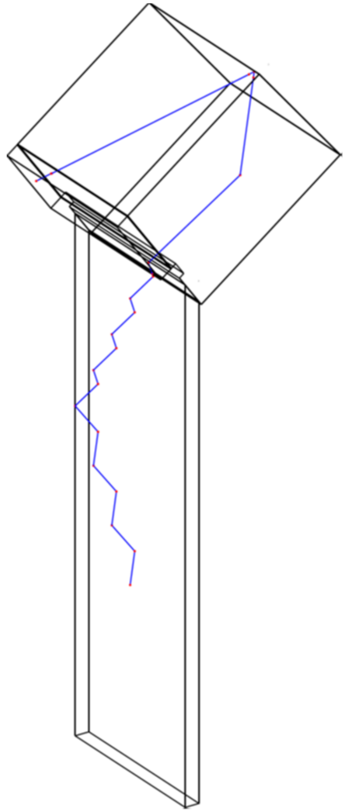
TORCH beam test infrastructure in PS/T9



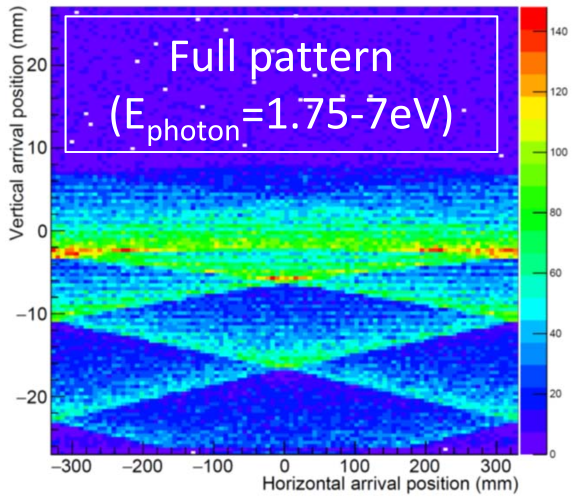
Pattern folding

- Cherenkov cone results in hyperbola-like patterns
- Reflections off module sides result in folding of this pattern
- Chromatic dispersion spreads line into band
- Pattern shown here for full TORCH module, also very prevalent in testbeam



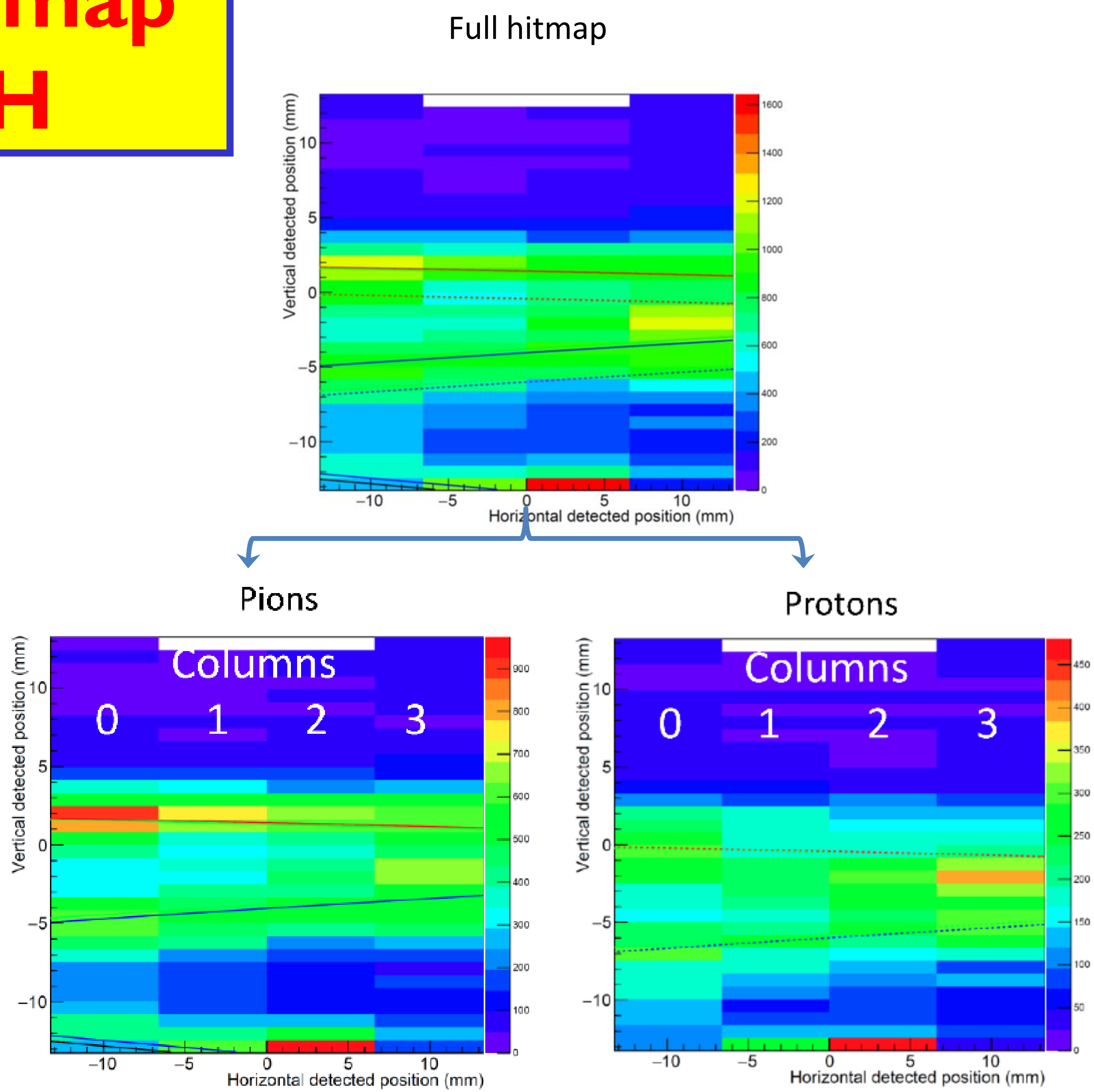


Geant simulation



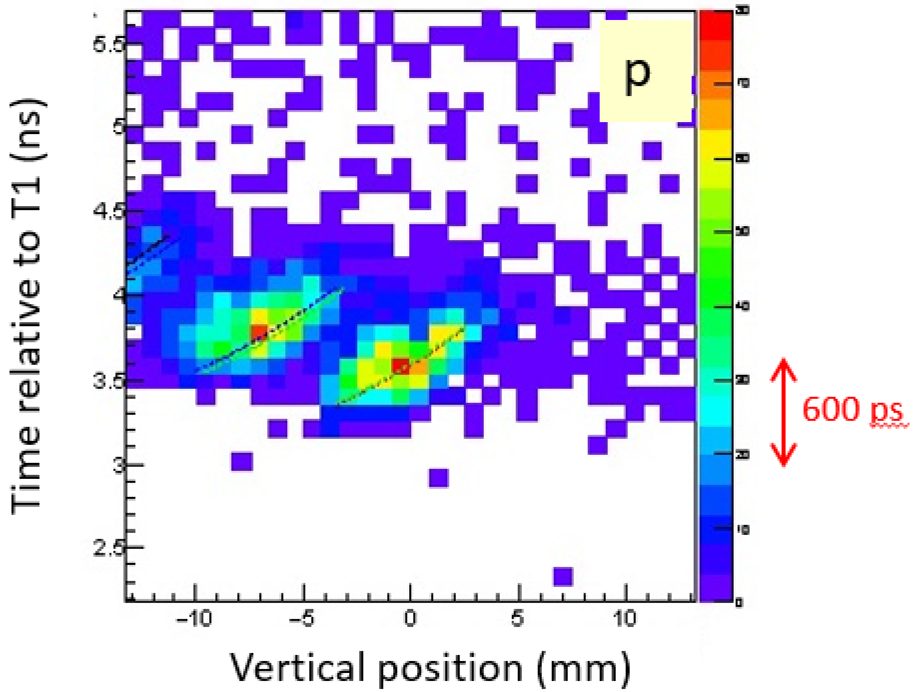
Cluster hit map in TORCH

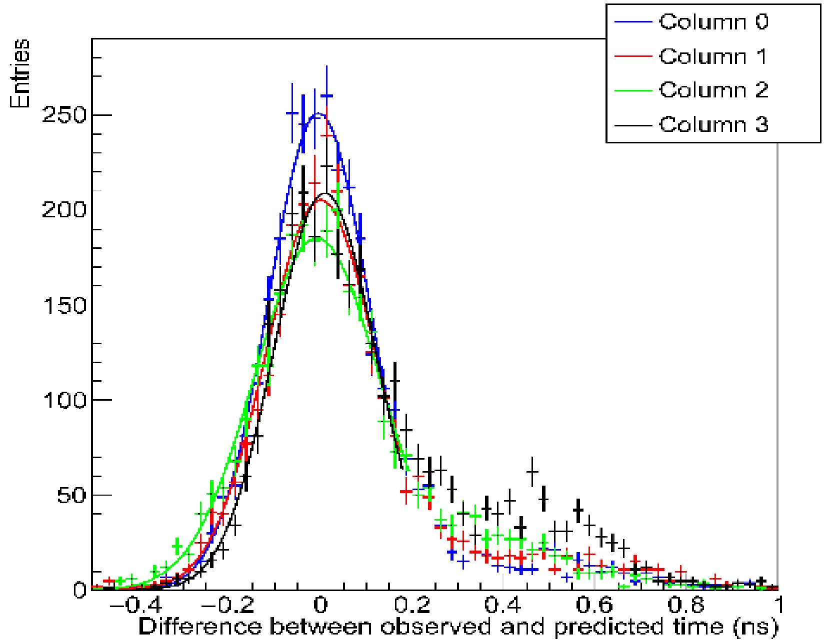
- Charge weighting applied to get centroid of clusters
- Particle selection from beam telescope ToF
- Reflections clearly separated
- Proton – pion difference cleanly resolved



Time resolution

- Plot time measured for each cluster relative to T1 *vs.* vertical position along column of pixels
- 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 / photon
- Improvements possible:
  - Beam defined by small scintillators with no tracking
  - 100ps binning in HPTDC
- Tails under study, due to imperfect calibration and back scattering effects

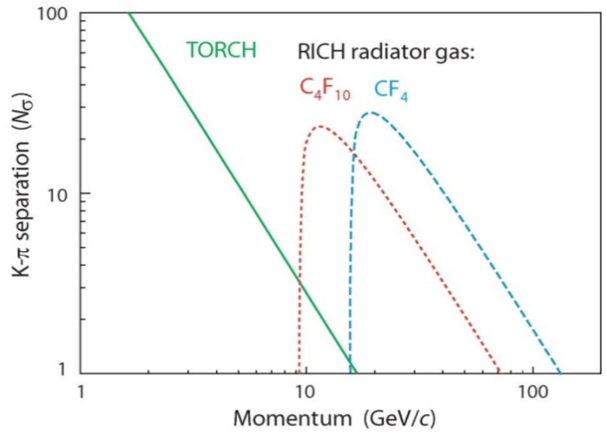




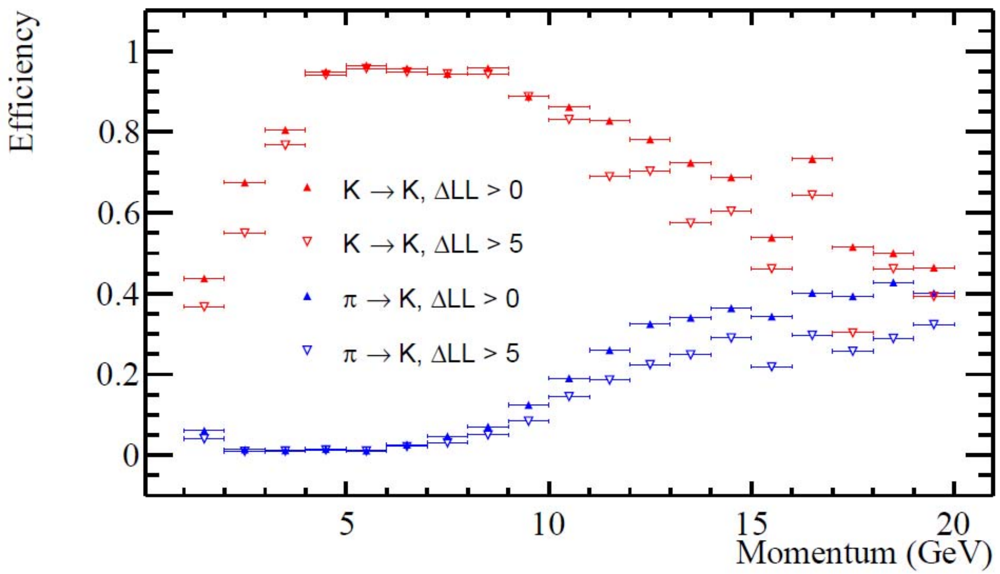
TORCH expected performance at LHCb

- Simulation of the TORCH detector & interface to a simulation of LHCb events, plus TORCH pattern recognition in GEANT.
- Obtain a start time t_0 from the other tracks in the event originating from the primary vertex
- 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

(Ideal reconstruction, isolated tracks)

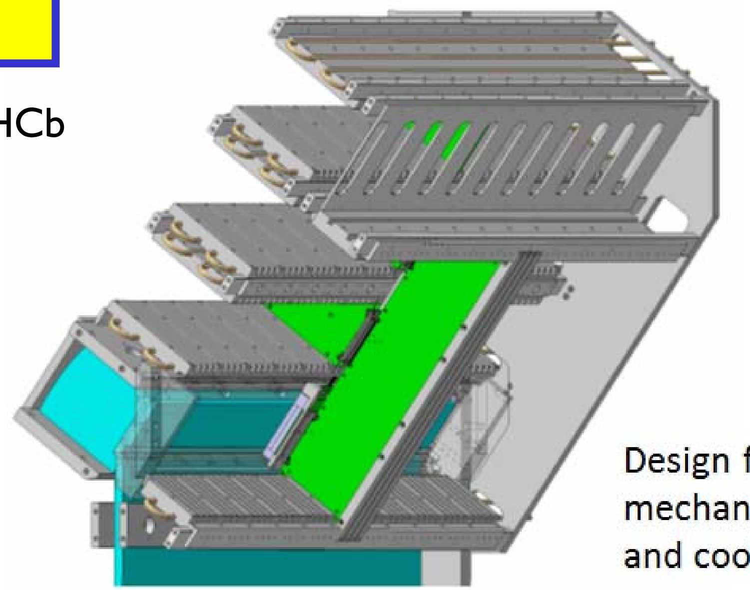


Full LHCb Simulation, single B events

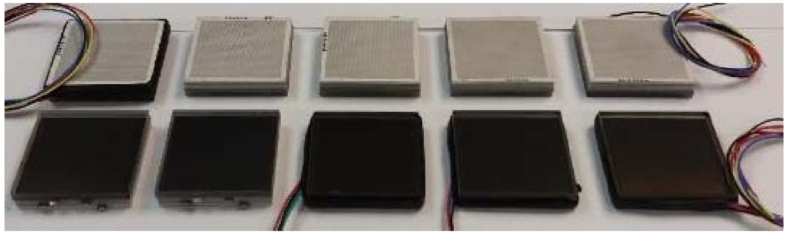


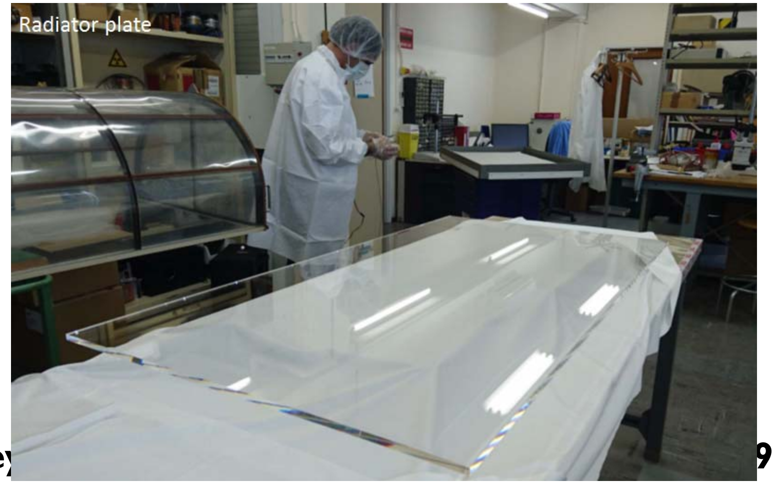
Full-scale prototype

- Large prototype of a half sized 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
- Testbeam October/November



Design for mechanics and cooling



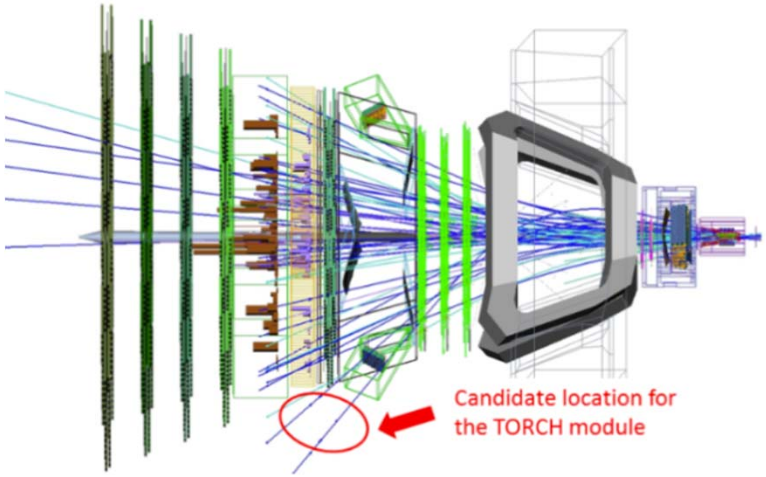


Radiator plate

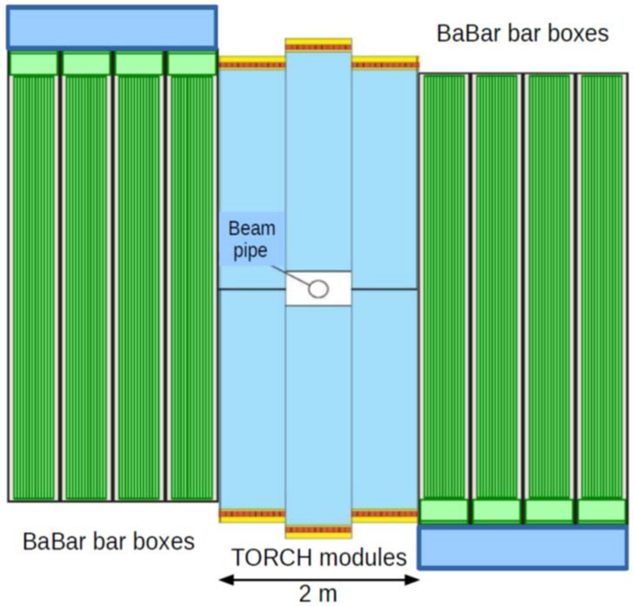
Focusing block

Future developments

- A proposal to mount the large-scale TORCH module inside LHCb (outside acceptance) has been discussed for winter shutdown
  - Would still have tracking for low energy particles
  - Test bench for full application
  - Require successful testbeam campaign and lots of work to be done.



- Possibility of re-use of BaBar DIRC quartz bars. Assigned bar still at SLAC and on hold for now.

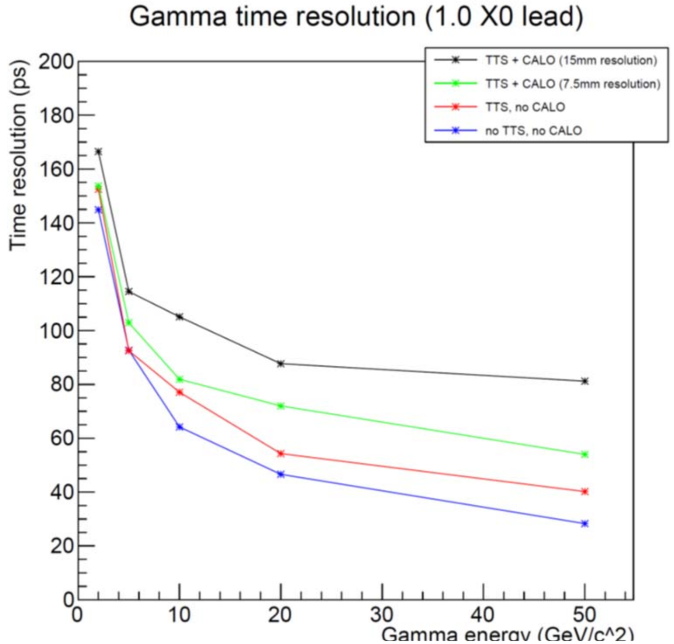


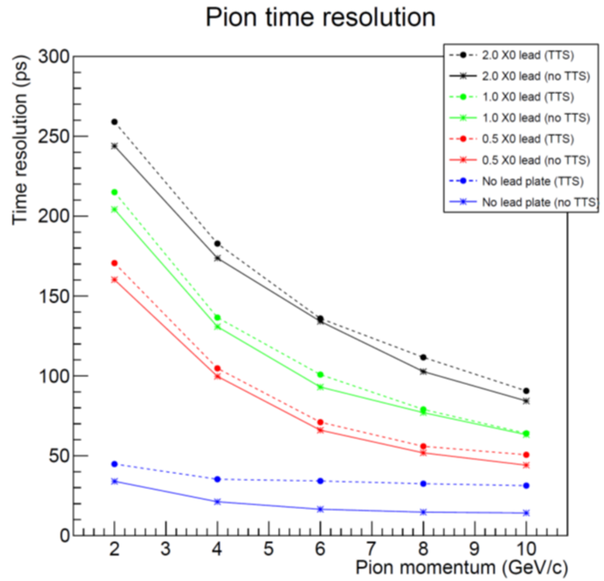
TORCH for timing photons

Maarten van Dijk,
Sneha Malde

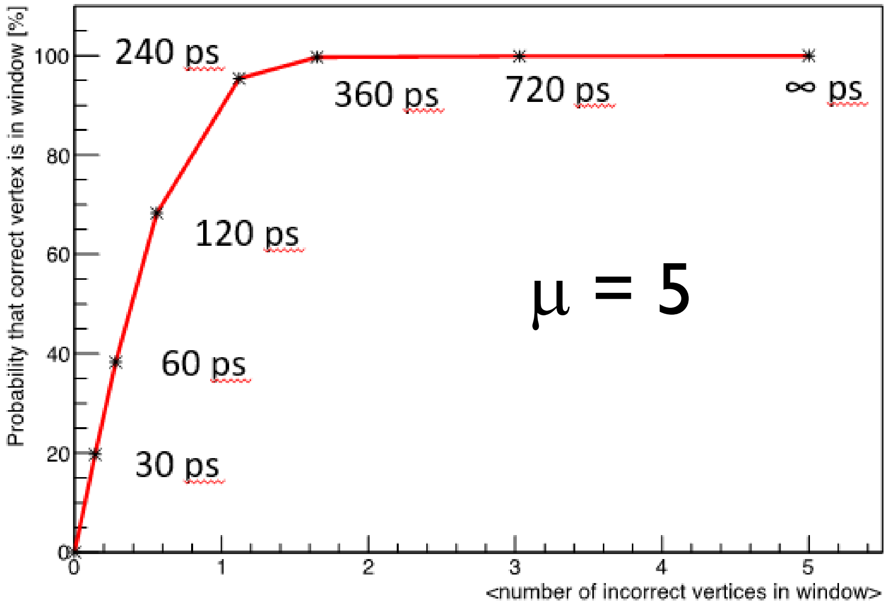
- An idea for application of TORCH in LHCb :
  - TORCH would be placed in front of LHCb calorimeter
  - Use lead plate in front ($1X_0 \approx 6$mm) for conversion of high energy photons
  - Time tagging high energy photons can associate event vertex
  - Limited by spatial resolution of calorimeter (replaces tracking)

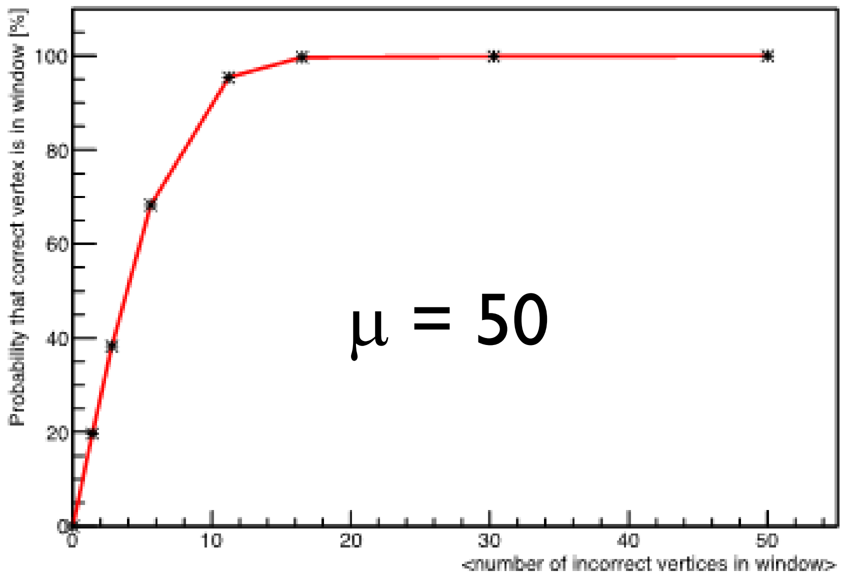
- Assessed with simulation
  - Time resolution is sufficient to be of great help in resolving pile-up
  - However, the PID capability will degrade due to MCS





TORCH for timing photons, continued





For a given photon from a PV + timing information from TORCH can open a window with width x ps around the given timing information.

- A loose cut with window 360ps reduces combinatoric and has almost 100% efficiency of containing the correct PV
- A cut of 120ps has reasonable efficiency for correct PV, but likely to have no incorrect vertices

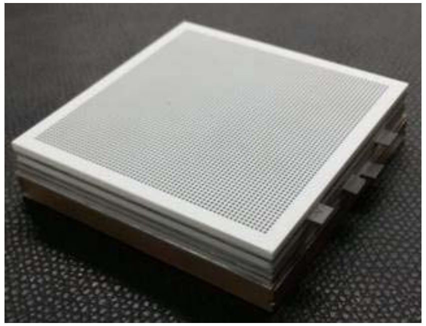
Summary

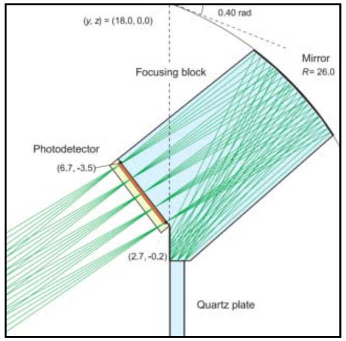
- TORCH is a novel concept for a DIRC-type detector to achieve high-precision time-of-flight over large areas aiming to achieve K-π separation up to 10 GeV/c and beyond (with a TOF resolution of ~15 ps per track)

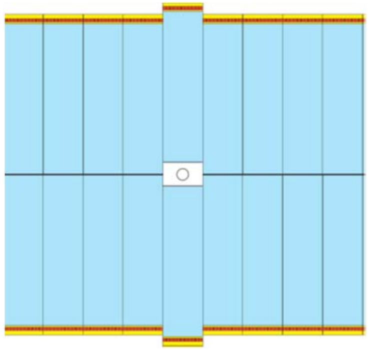
- Ongoing R&D programme aims to produce suitable MCP, satisfying challenging requirements of lifetime, granularity, and active area.
  - First two phases of MCP results show promising results for lifetime, timing measurements, granularity with charge sharing

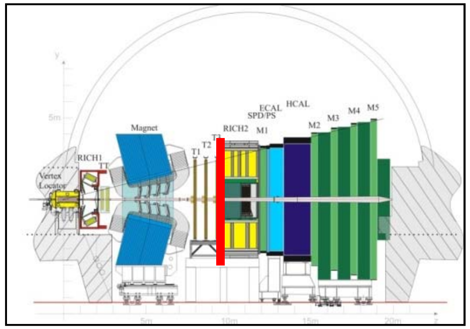
- Testbeam results very promising
  - Performance has been shown to be very good ~approaching 70ps time resolution per photon

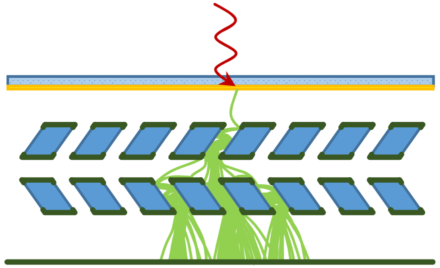
- TORCH future
  - New optics half-sized module have been delivered
  - Delivery of Phase-III MCP-PMTs is very close
  - New generation of electronics being designed



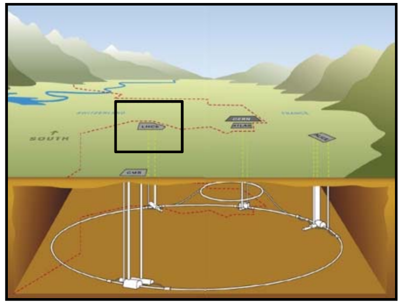








That's all folks!



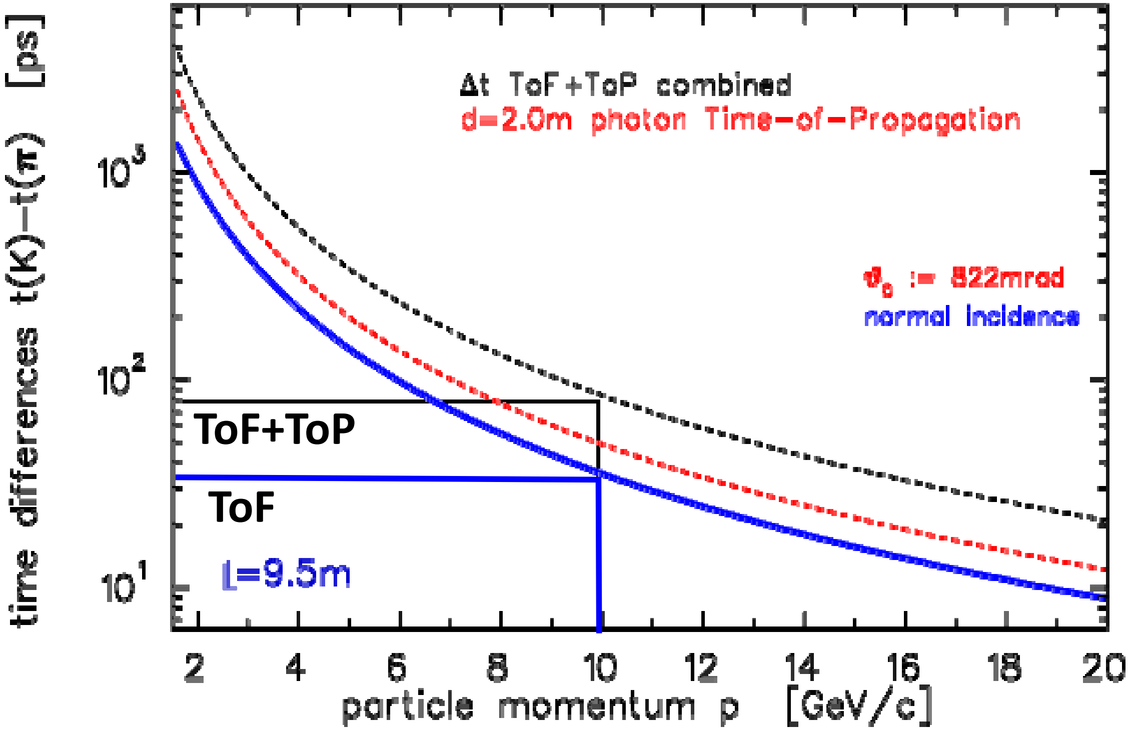
The TORCH project is funded by an ERC Advanced Grant under the Seventh Framework Programme (FP7), code ERC-2011-ADG proposal 299175.

European Research Council

Established by the European Commission

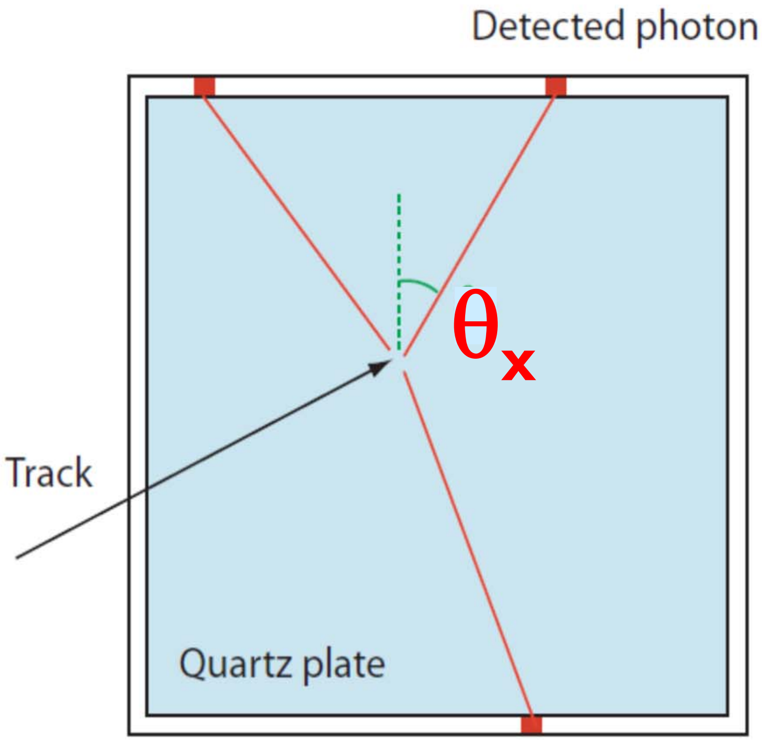
Spare slides from here on

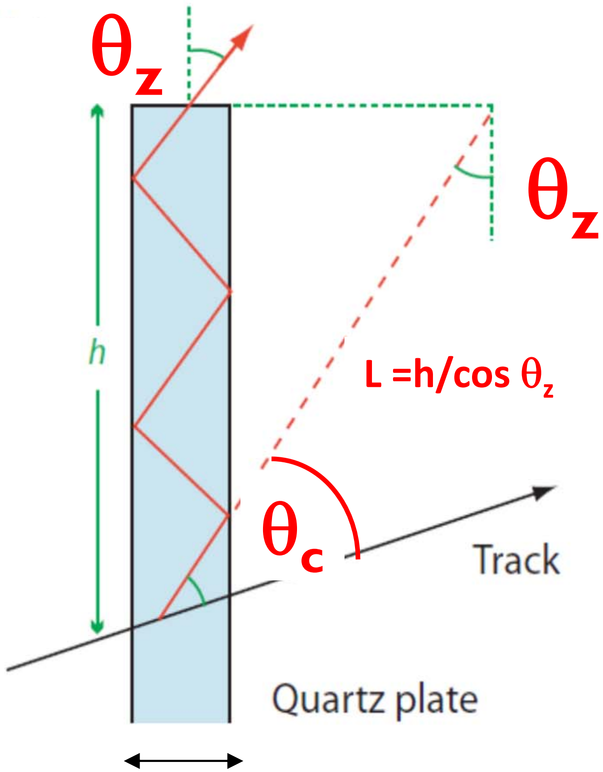
Time of flight and time of propogation



TORCH Angular measurement (θ_x)

- Need to measure *angles* of photons: their path length can then be reconstructed
- In θ_x typical lever arm ~ 2 m
  - → Angular resolution ≈ 1 mrad x 2000 mm / √12
  - → Coarse segmentation (~6 mm) sufficient for the transverse direction (θ_x)
  - → ~8 pixels of a "Planacon-sized" MCP of 53x53 mm^2 active dimension



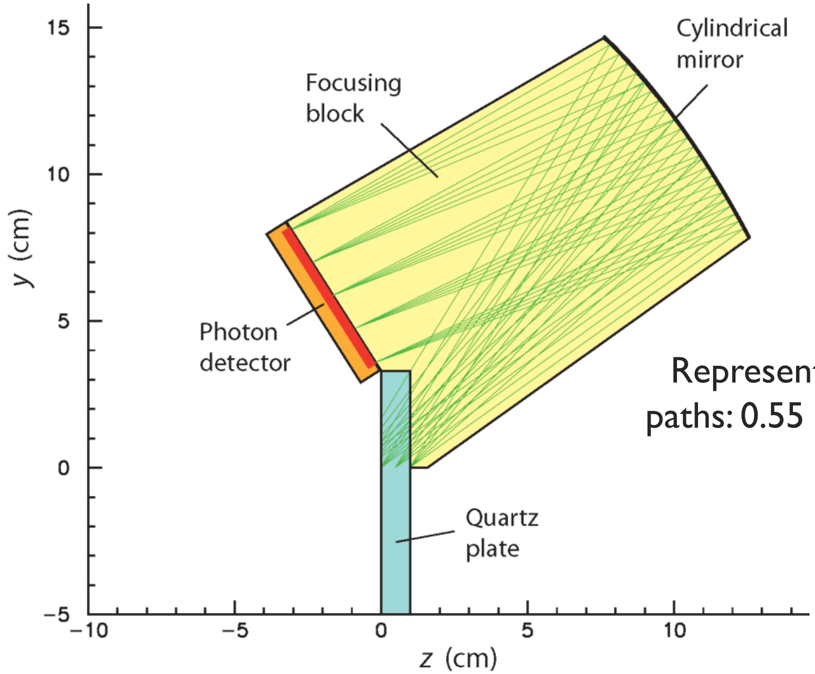


TORCH Angular measurement (θ_z)

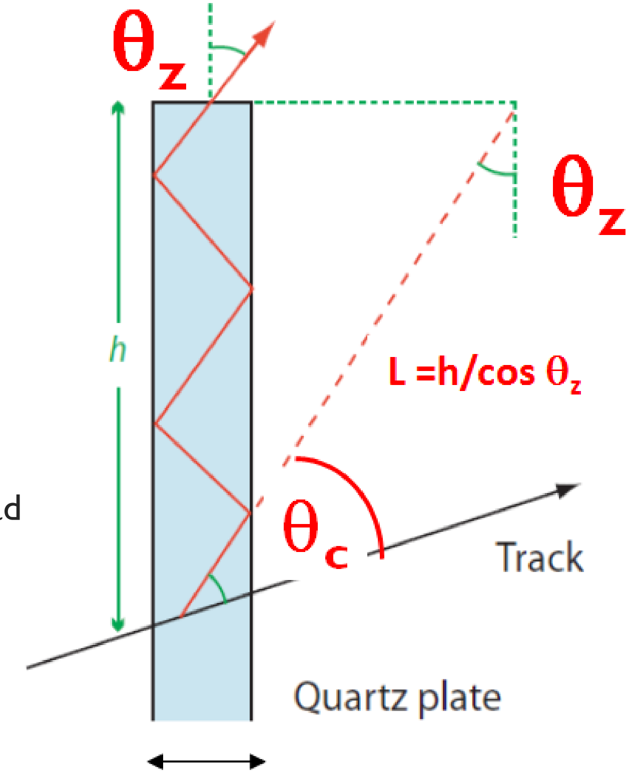
- Measurement of the angle in the longitudinal direction (θ_z) requires a quartz (or equivalent) focusing block to convert angle of photon into position on photon detector
- $\rightarrow$ Cherenkov angular range = 0.4 rad

  $\rightarrow$ angular resolution ~ 1 mrad: need ≈ 400/ (1 x √12) ~ 128 pixels

  $\rightarrow$ fine segmentation needed along this direction

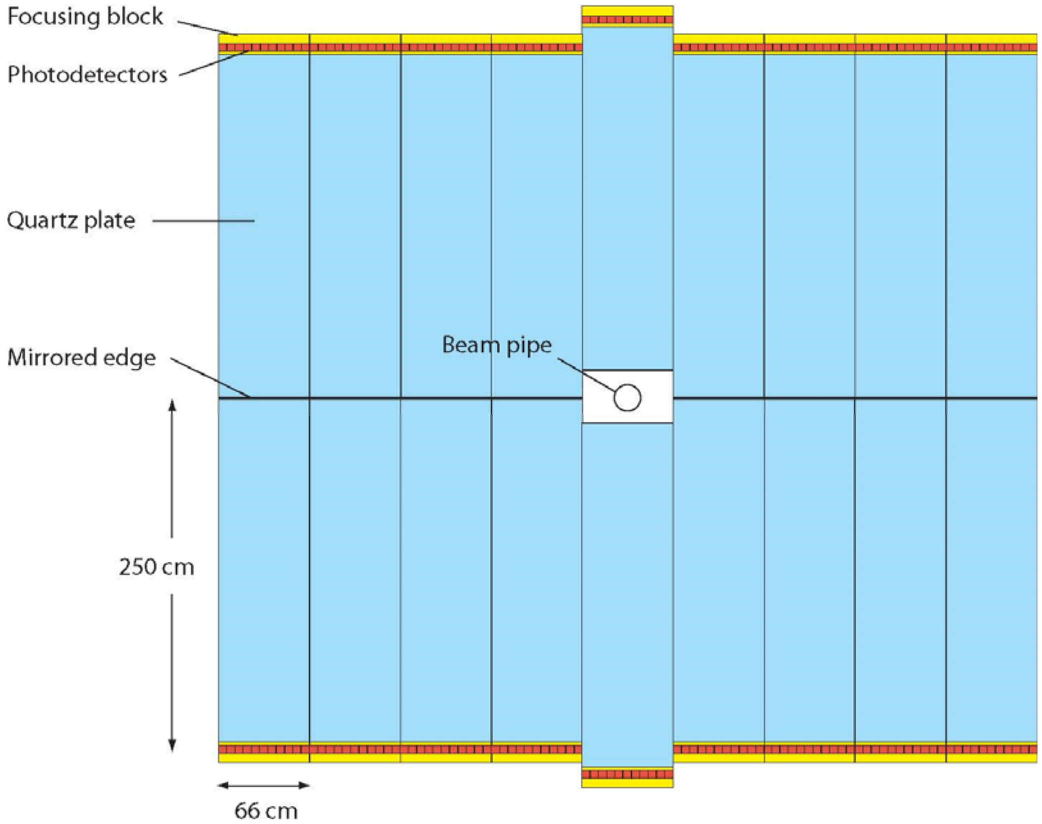


Representative photon paths: $0.55 < \theta_z < 0.95$ rad



TORCH modular layout

- Dimension of quartz plane is ~ 5 × 6 m^2 (at z = 10 m)
- Unrealistic to cover with a single quartz plate → evolve to modular layout

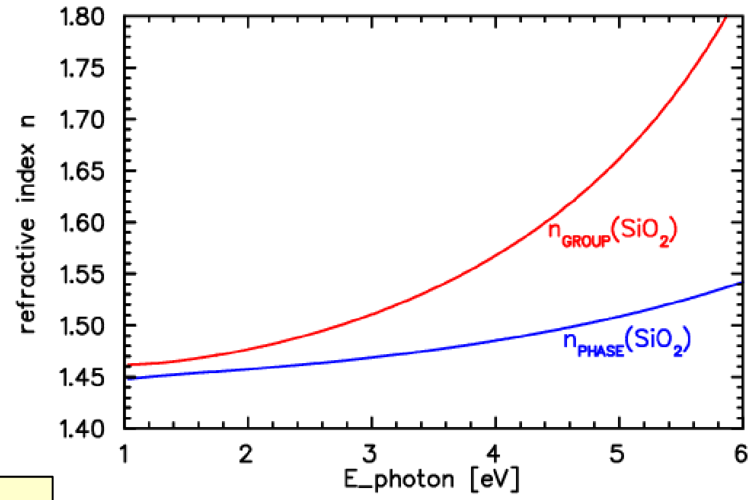


- 18 identical modules each 250 × 66 × 1 cm^3 → each with 11 MCPs to cover the length
- MCP photon detectors at the top and bottom edges
  18 × 11 = 198 units
  Each with 1024 pads
  → 200k channels total

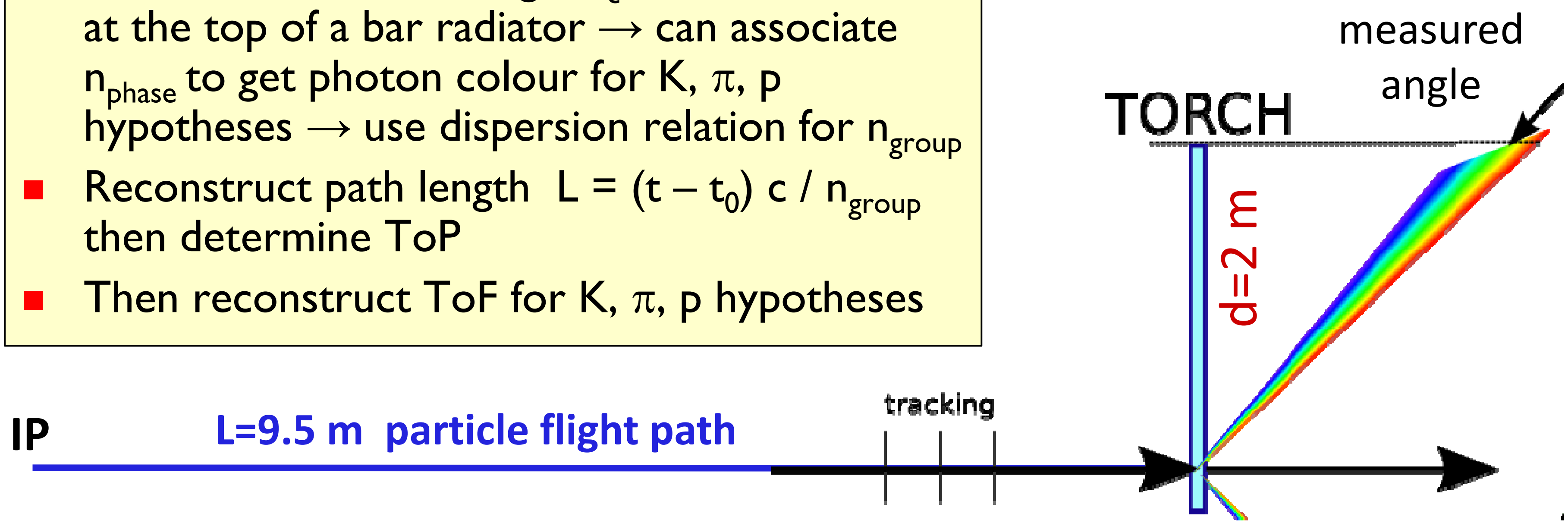
Chromatic dispersion correction

Cherenkov angle : $\cos\theta_c = (\beta\, n_{phase})^{-1}$

Time of propagation (ToP) in quartz :
$t = L / v_{group} = n_{group} L / c$

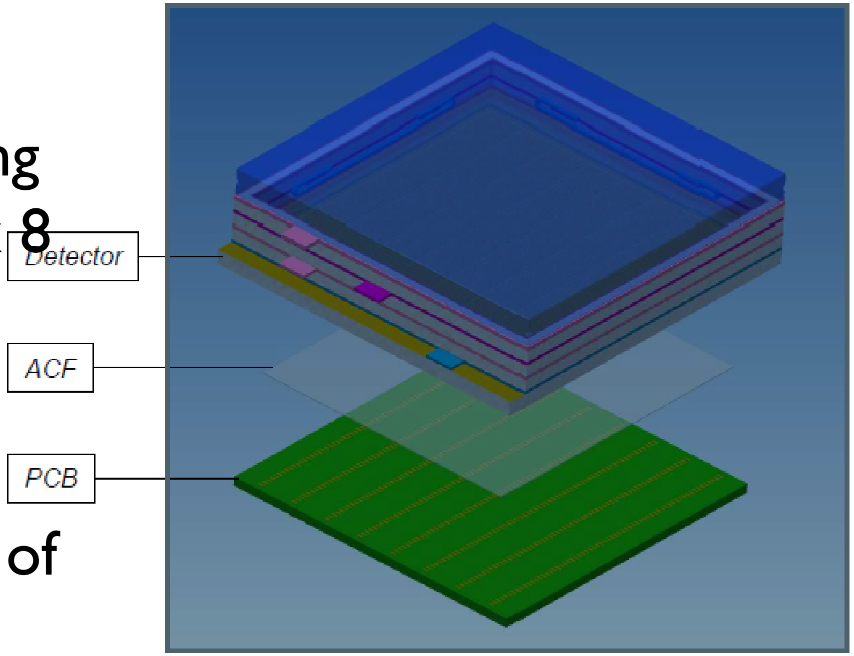


- Need to correct for the chromatic dispersion of the quartz
- Measure Cherenkov angle θ_c and arrival time at the top of a bar radiator → can associate n_{phase} to get photon colour for K, π, p hypotheses → use dispersion relation for n_{group}
- Reconstruct path length $L = (t - t_0)\, c / n_{group}$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

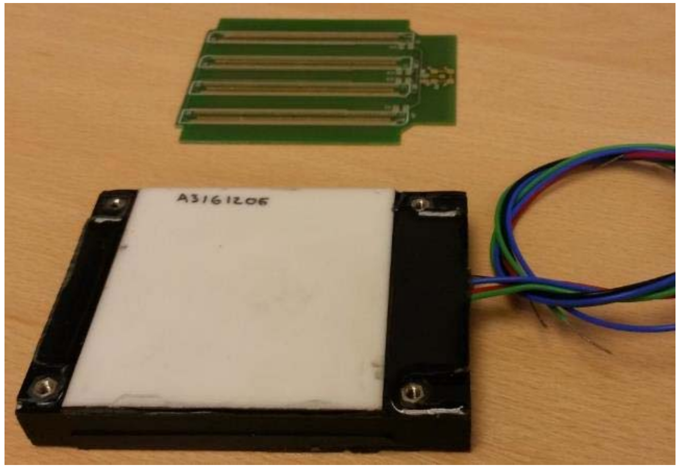


Customized pad layout

- Traditional multi-anode manufacturing uses multiple pins : difficult for 128 x 8 array – plan therefore for 64 x 8 : gang together 8 pixels in coarse direction
- Have charge division between a pair of pads recovers pixel resolution 64→128 and reduces total number of channels
- TORCH pixel pads are 0.75 mm wide on a 0.88 mm pitch. Contact made to readout PCB by Anisotropic Conductive Film (ACF)



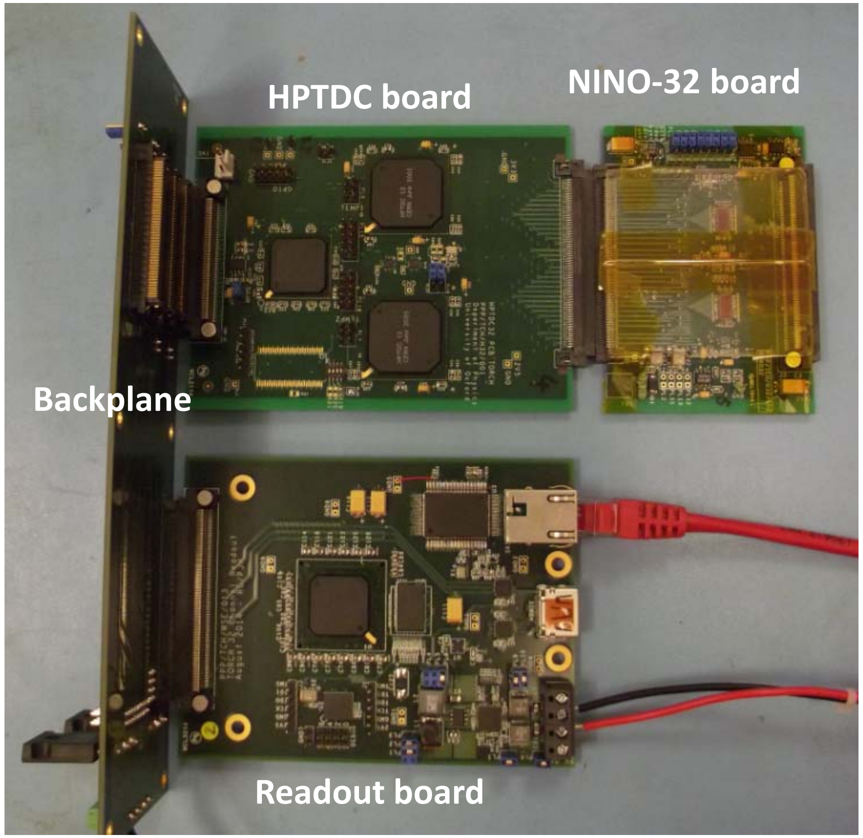
After potting, before readout PCB is attached

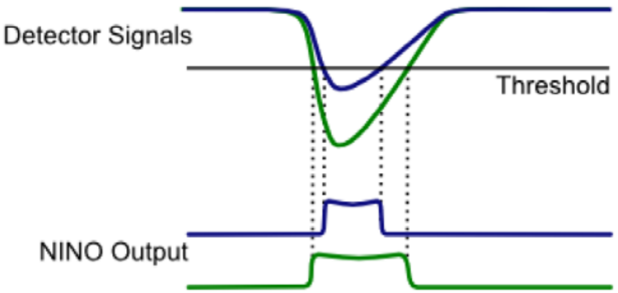


Readout Electronics

Rui Gao, Oxford

- Readout electronics are crucial to achieve desired resolution.
- Suitable front-end chip has been developed for 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 in development)
- NINO-32 provides time-over-threshold information which is used to correct time walk & charge measurement - together with HPTDC time digitization



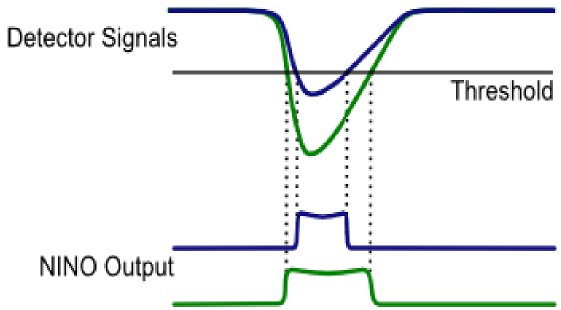


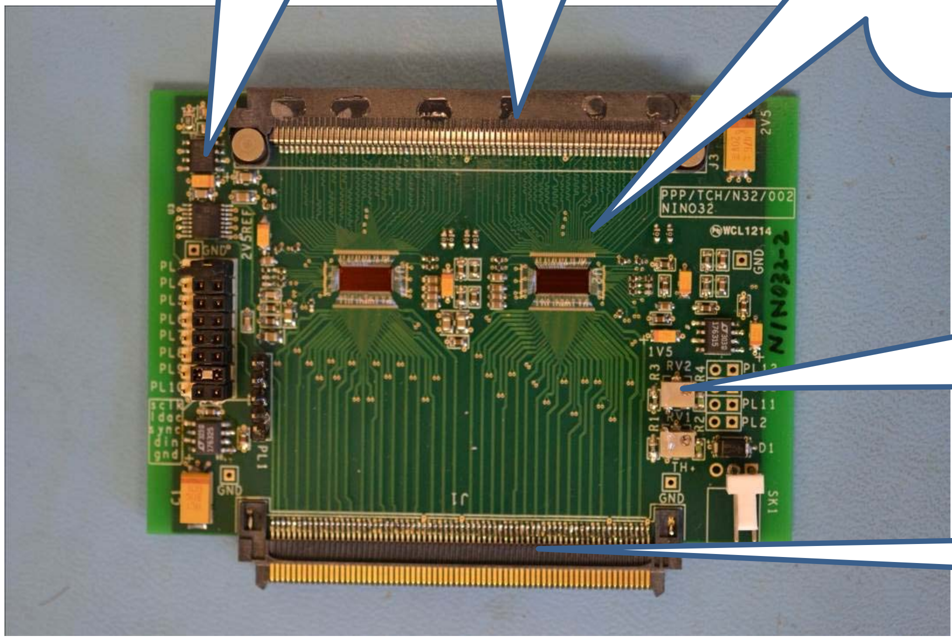
NINO analogue front end

DAC – Setting threshold

Input – negative phase only

2xNINO - Time Over Threshold Measurement, 64-ch per board





Potentiometer – threshold quick settings

LVDS output

Rui Gao, 23rd September 2014
TWEPP 2014, Aix En Provence, France

HPTDC board – Time to Digital conversion

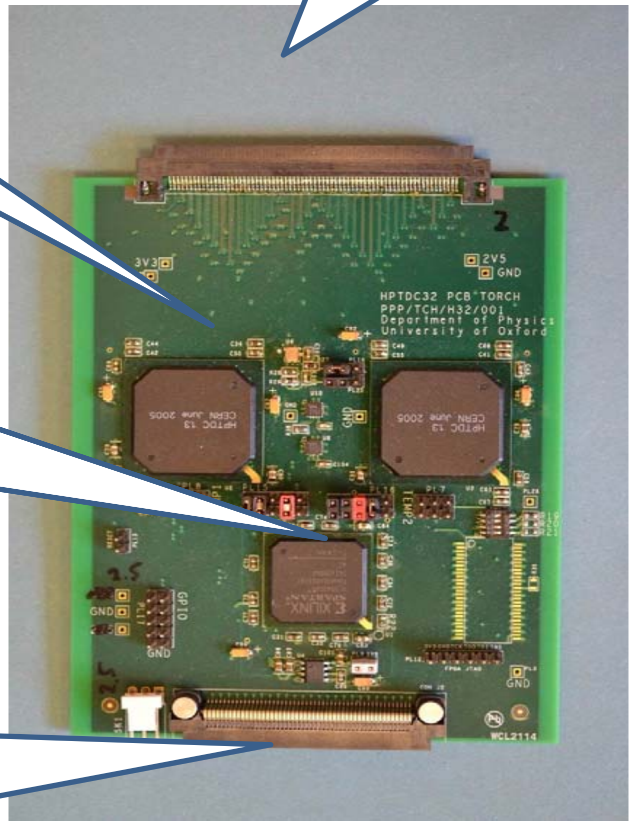
LVDS input from NINO

2x HPTDC[4]

ASICs 64ch

Spartan3AN
HPTDC configuration and control
Data formatting and buffering

Power
Input: clock, trigger, serial slow control, fast control
Output: TDC data, all signals in LVDS



Rui Gao, 23rd September 2014
TWEPP 2014, Aix En Provence, France

Readout board

LVDS I/O
Fan out 4 x clocks, 4 x triggers
and 36 pairs of LVDS signals
Standalone JTAG for TDC board
2.5v and 3.3v @ 3A max

Gigabit Ethernet

HDMI Connector
External clock and 3 bi-directional LVDS pairs, pinout compatible with Timepix3 Telescope TLU.

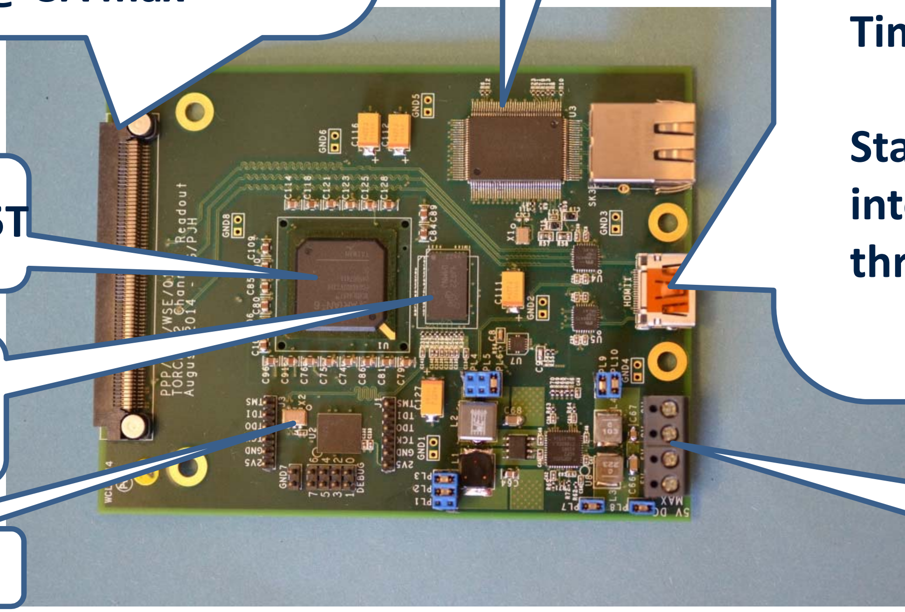
Standard LEMO/ SMA interface are available through adaptor.

Spartan6 LX45T

1Gbit DDR3 RAM

200MHz OSC

Single 5V power supply



Rui Gao, 23rd September 2014
TWEPP 2014, Aix En Provence, France

Lifetime measurements

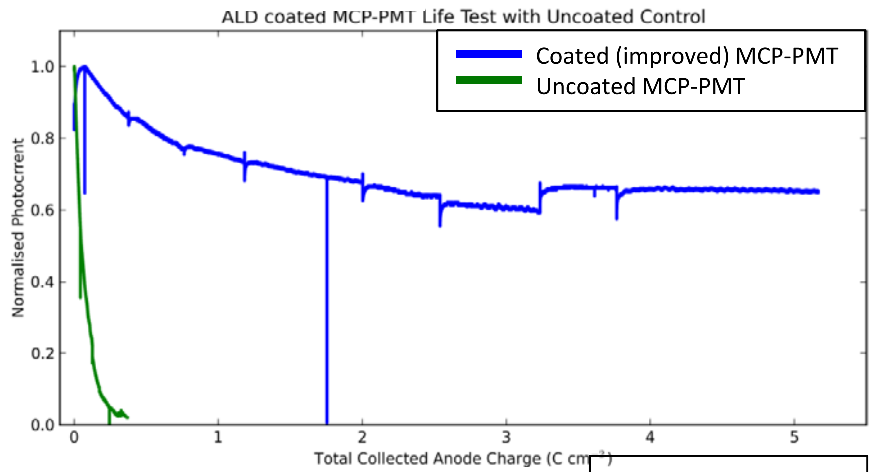
- Use Atomic Layer Deposition (ALD) to coat atomic layers onto the MCP

- Lifetime requirement set at $5C/cm^2$ for Phase-I MCP-PMTs

- Testing at Photek and CERN
  - Gain drop observed
  - Recovered by increase of HV
  - Marginal loss in quantum efficiency (at $3.1\ C/cm^2$)

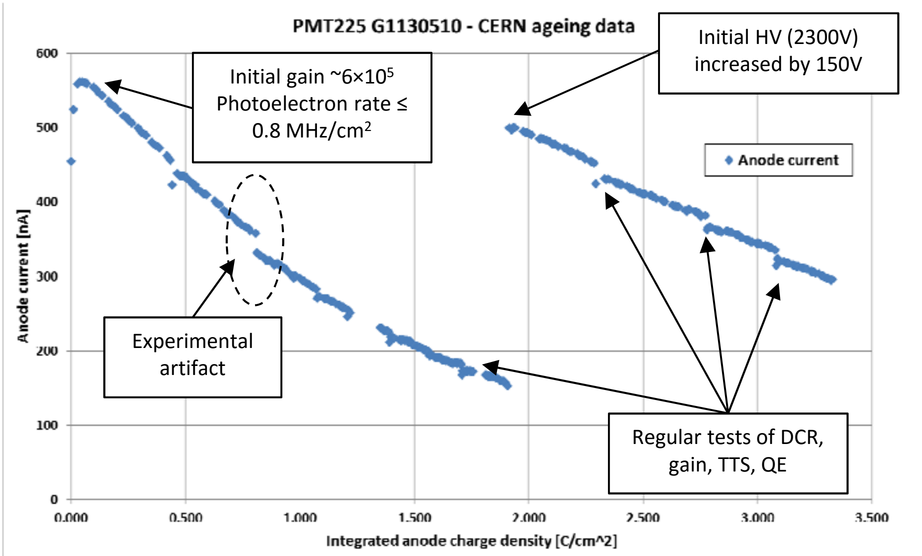
Lifetime test by Photek

T.M. Conneely et al., NIM A **732** (2013) 388-391



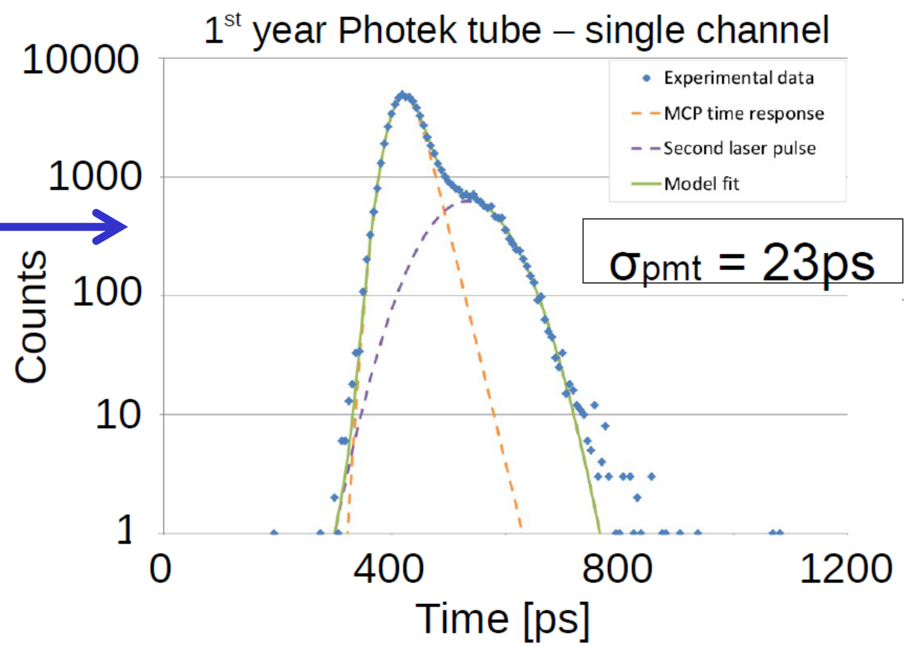
Lifetime test by TORCH @ CERN

T. Gys, presented at RICH2016 (Bled)



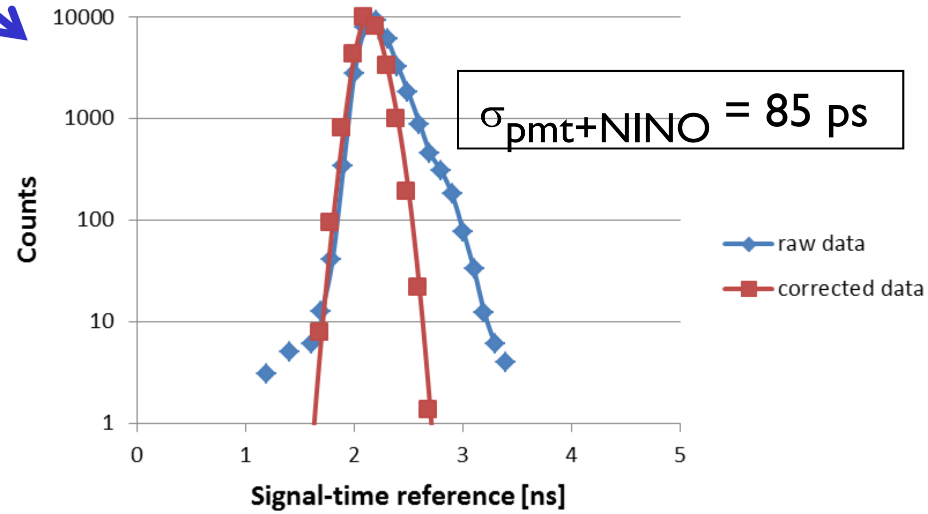
MCP timing resolution measured in Lab

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



- Phase 2 Photek tube : timing resolution obtained with fast laser and customised NINO-32 and HPTDC electronics with HPTDC time binning set to 100 ps
  - Correction needs to be made for integral non-linearity (INL) of the HPTDC and time-walk effects from the time-over-threshold (TOT) information from the NINO

Photek Phase 2 tube: NINO electronics



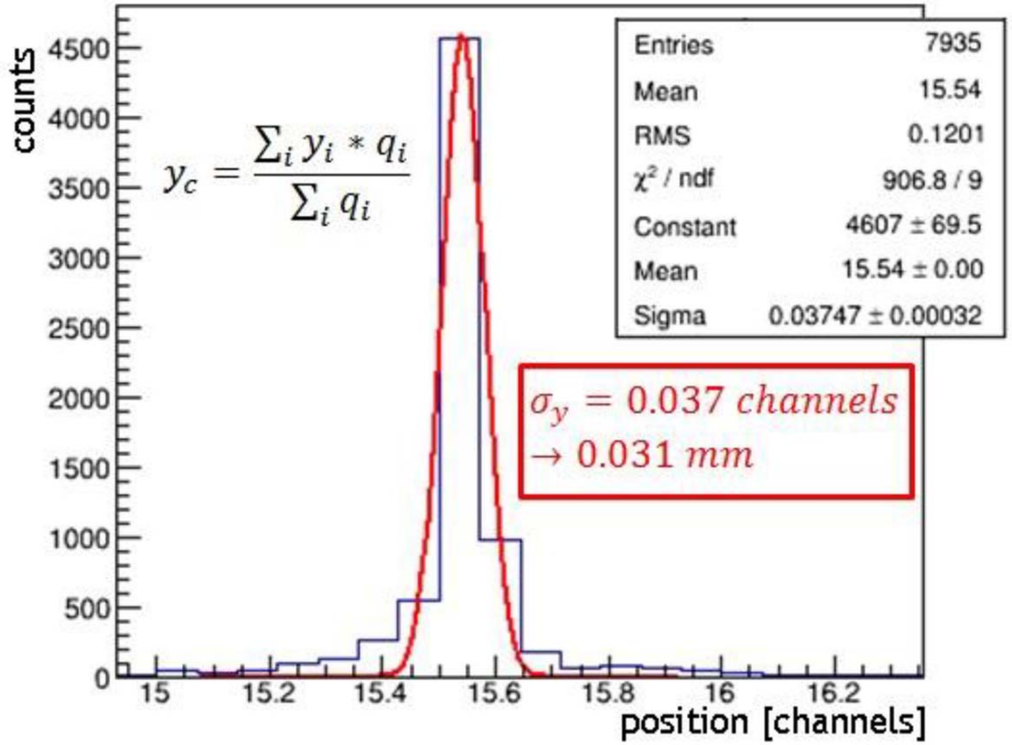
- All timing properties measured at an MCP gain of 1×10^6

MCP charge sharing (Lab)

- Tests of charge sharing between pixels. Pad dimensions 0.75 mm. Fast laser to the centre of a pixel

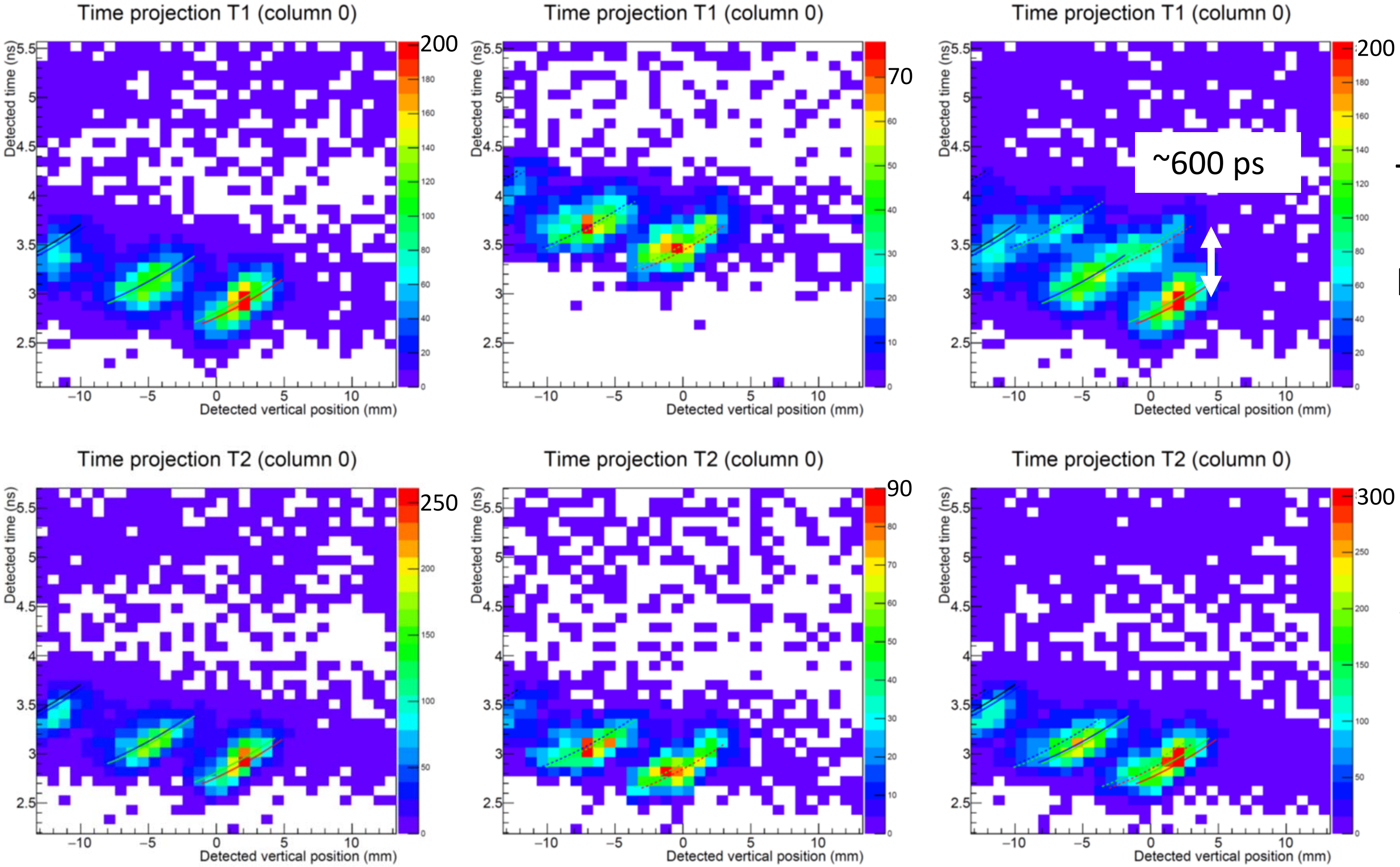
- TORCH requirement is ~ 0.41mm/√12 = 0.12 mm. Improvement with charge division between adjacent channels → x4 better than that required

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



Timing results continued

Pions only | Protons only | All



T1 reference

Flight path 10m

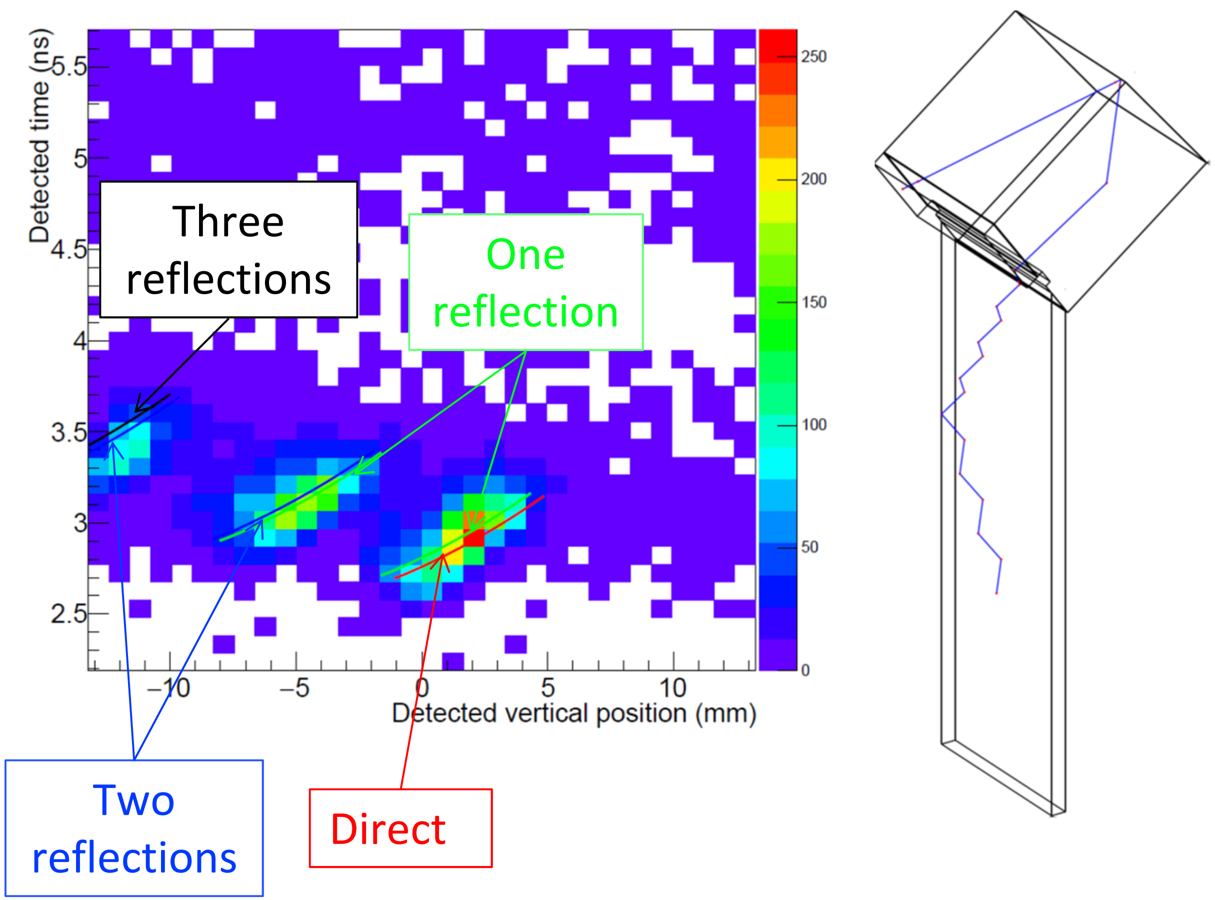
T2 reference

Flight path 1m

Timing results

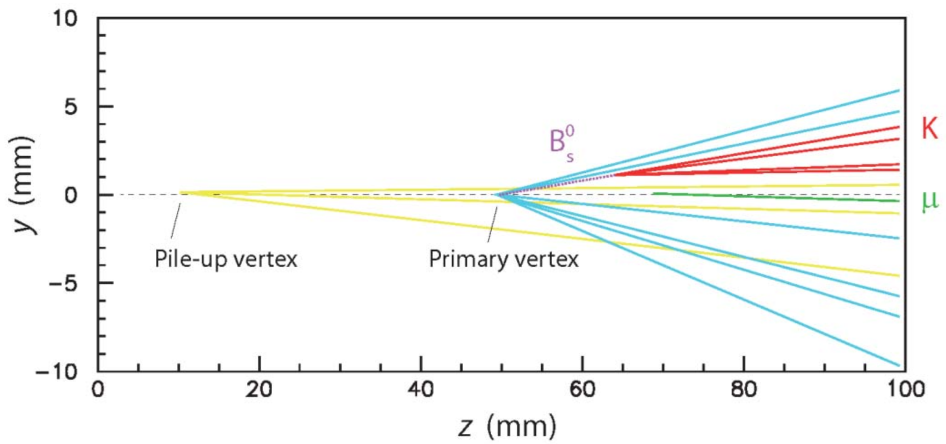
- Displayed as time projection per single (vertical) column
- Superimpose predictions and data

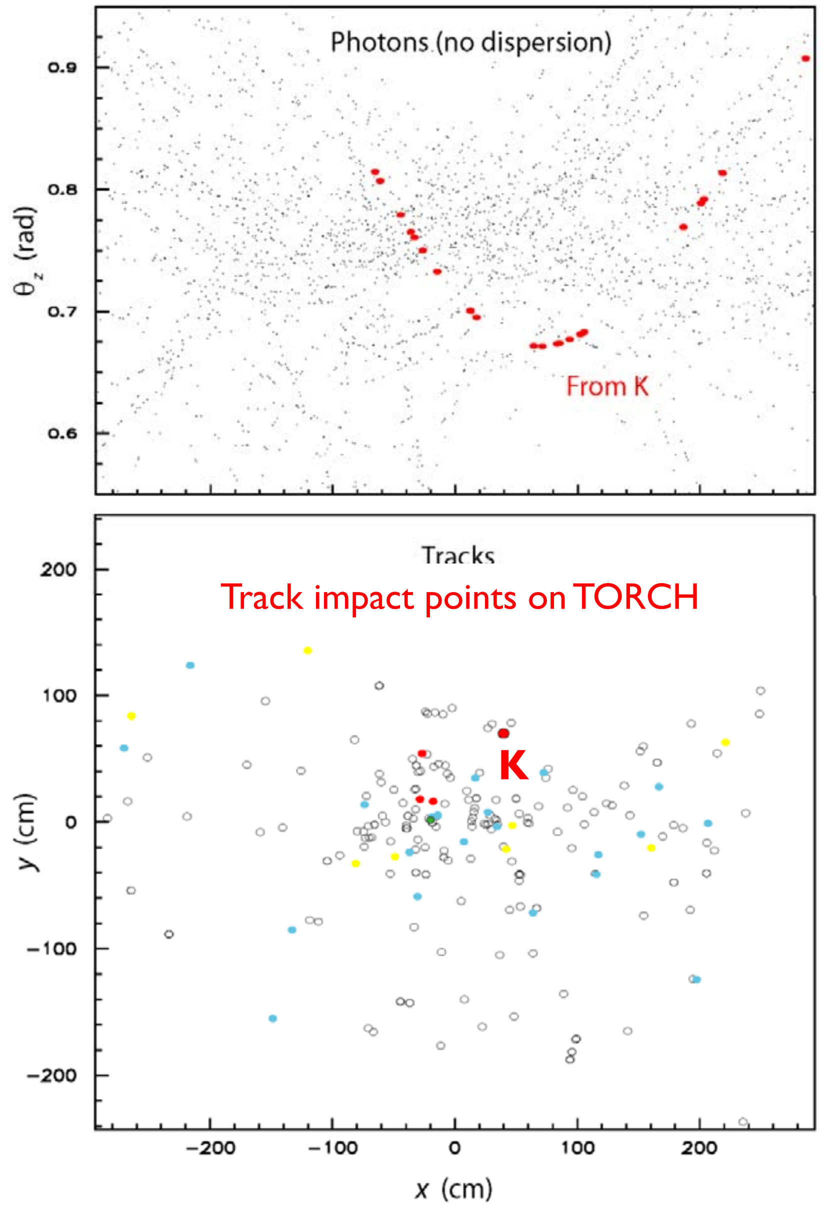
Pions only



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 (rest are secondaries)

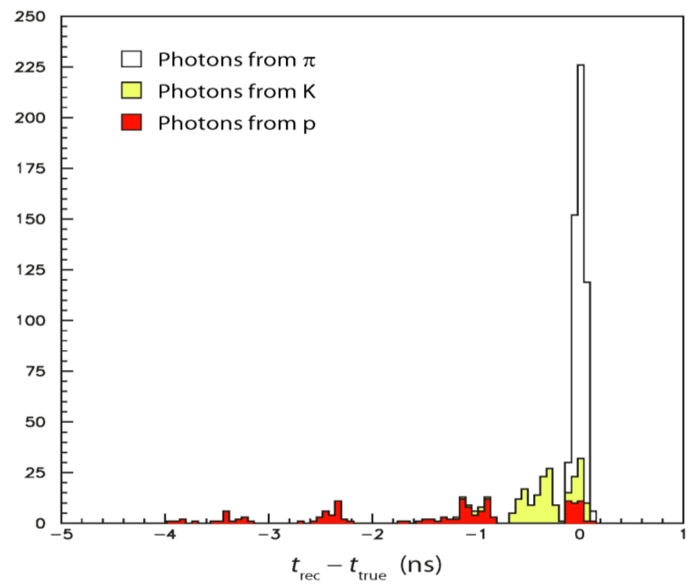




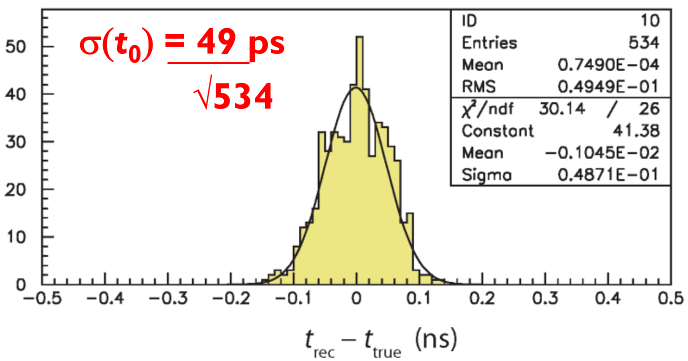
Measuring start-time at LHCb

- To determine the time-of-flight, also need a start time (t_0)
- This might be achieved using timing information from the accelerator, but bunches are long (~ 20 cm) → must correct for vertex position
- Alternatively use other tracks in the event, from the primary vertex
- 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

Example from PV of same event



After removing outliers



TORCH possible re-use of BaBar quartz bars

- BaBar DIRC quartz bars are available following SuperB cancellation : made up of 12 planar "bar-boxes" each containing 12 quartz bars 1.7 x 3.5 x 490 cm^3
- Bar length (at z = 950 cm) and total area ~ 30 m^2 matches TORCH needs. Adapting the bars requires focusing in both projections; can use a cylindrical lens for this, at the end of each bar.
- Effect of wedge (glued to bars) is to give two separate beams: depending on whether photons reflected or not.
- Split detector plane: assuming 60 mm square MCPs (53 mm active) requires two PMTs to cover $0.5 < \theta_z < 0.9$ rad
- Adapting the TORCH optics to re-use the BaBar DIRC seems viable: no degradation seen compared with single projection. Studies are ongoing.