Status of the TORCH time-of-flight project

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

3rd August 2018

Outline

- The TORCH concept

- Development of Microchannel Plate PMTs

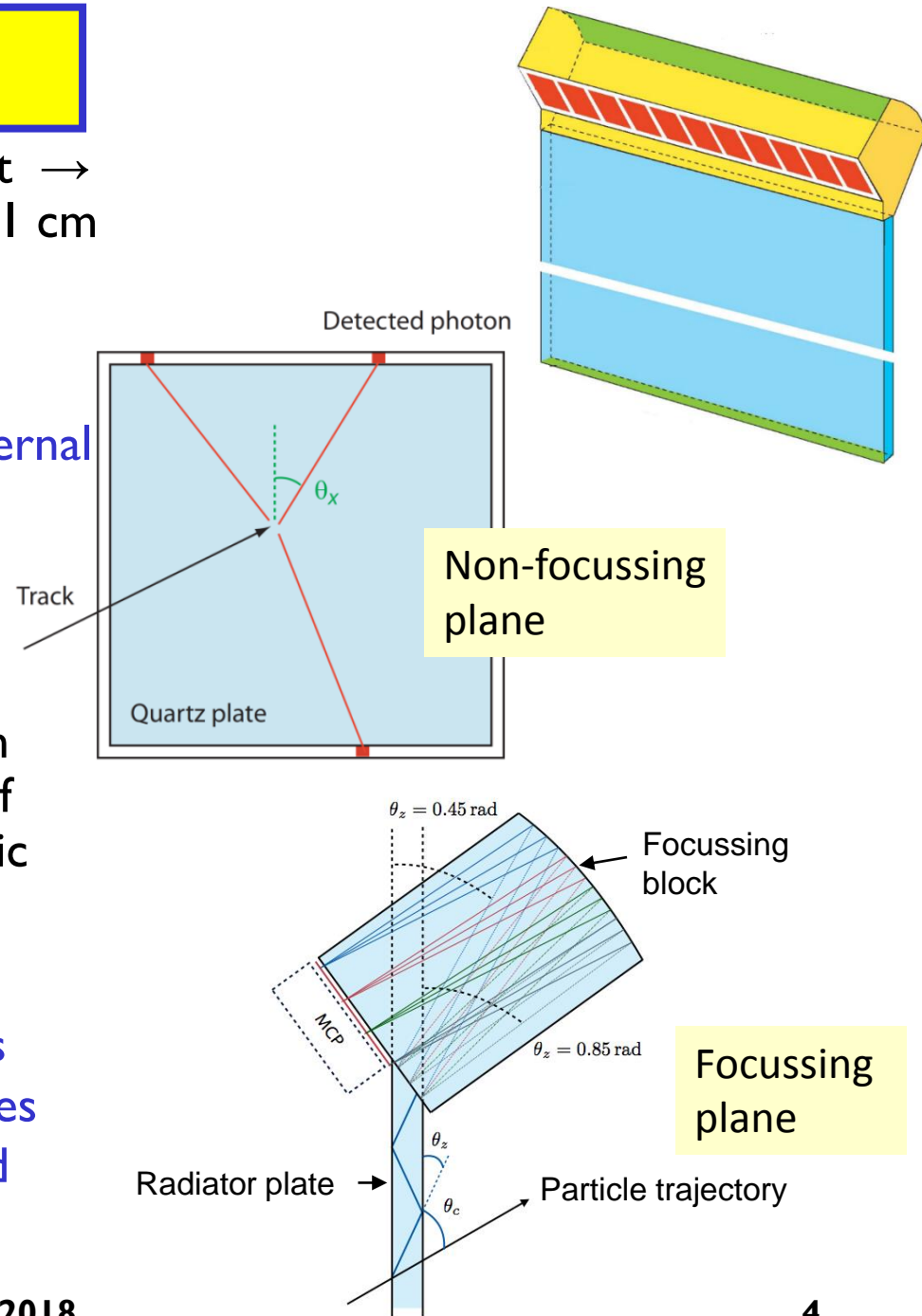- Test beam results

- Future R&D

- TORCH at LHCb

- Summary

1. The TORCH R&D project

- The TORCH (Time Of internally Reflected CHerenkov light) R&D project – to develop a large-area time-of-flight system eg. for the LHCb Upgrade II.

- TORCH combines timing information with DIRC-style reconstruction (BaBar DIRC, Belle II TOP detector, SuperB).

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

- The σ_{TOF} requirement dictates timing single photons to a precision of 70 ps for ~30 detected photons
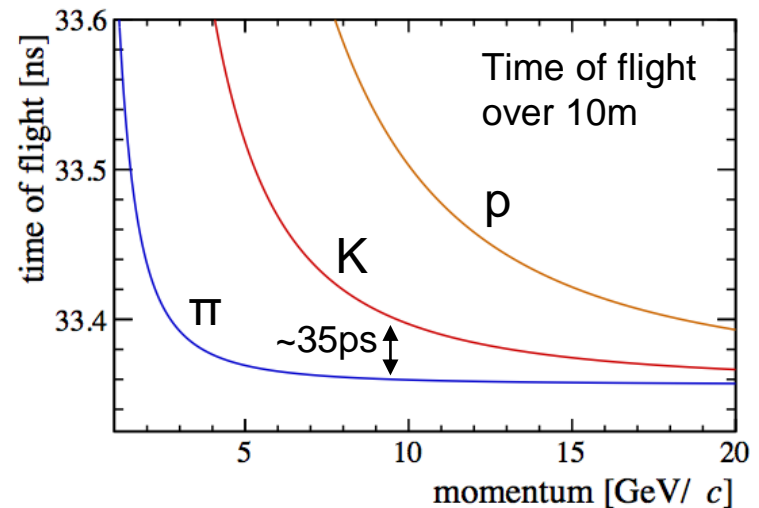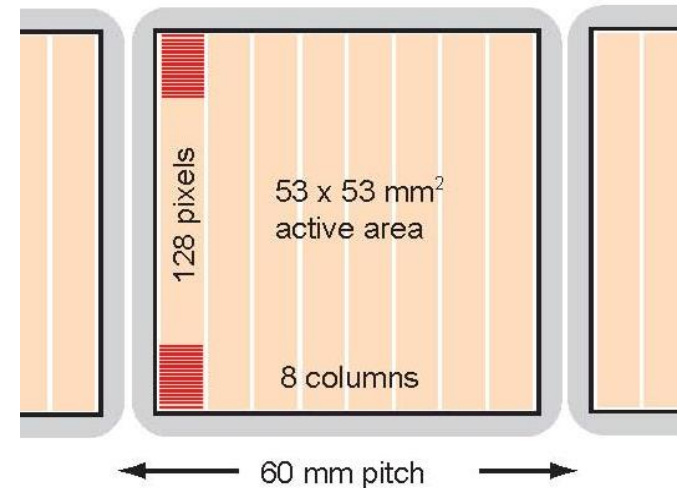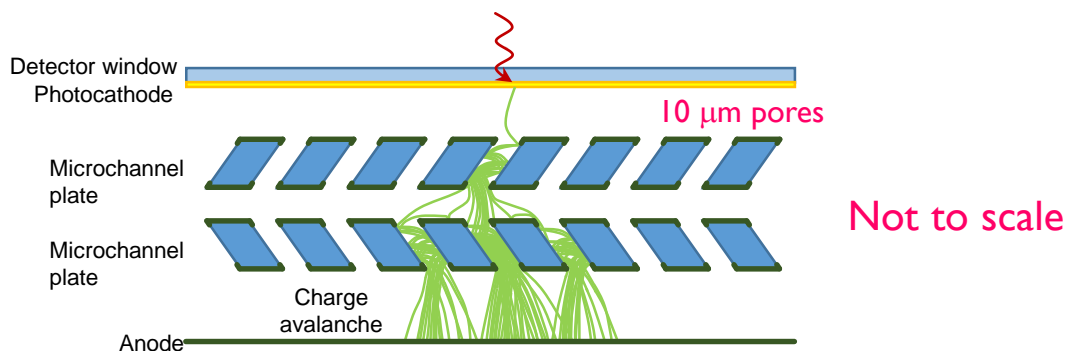
The TORCH detector

- Cherenkov light production is prompt → use a plane in a modular structure of 1 cm thick quartz 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)

- Measure Cherenkov angle θ_c and path length L in the quartz, plus the time of arrival. Then correct for the chromatic dispersion in the quartz.

- From simulation, ~1 mrad precision is required on measurement of the angles in both planes to achieve the required intrinsic timing resolution

Detected photon

θ_x

Track

Quartz plate

Non-focussing plane

$\theta_z = 0.45\,\text{rad}$

Focussing block

MCP

$\theta_z = 0.85\,\text{rad}$

Focussing plane

Radiator plate →

θ_z

θ_c

Particle trajectory

2. MCP development

- Need a photon detector with coarse granularity (in the non-focussing direction) and fine granularity (in the focussing direction) to achieve the 1 mrad angular precision.

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

- Choose an anode pixel size: 128 × 8 pixels with a ~53 mm active area on a 60 mm pitch. The MCP-PMT pixel structure can in principle be adjusted according to resolution required as long as charge footprint is small enough.

Detector window
Photocathode

10 μm pores

Microchannel plate

Microchannel plate

Not to scale

Charge avalanche

Anode

128 pixels

53 x 53 mm² active area

8 columns

60 mm pitch

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 (up to 5 C/cm^2) and ~35ps timing resolution.   COMPLETED   [JINST 10 (2015) C05003]

◆ Phase 2 : Circular MCP with customised granularity (1/4 size active area). Beam tests 2015/16 COMPLETED   [arXiv:1805.04889]
https://doi.org/10.1016/j.nima.2018.07.023

◆ Phase 3 : Square tubes with high active area (>80%) and with required lifetime, granularity and time resolution.   UNDER TEST
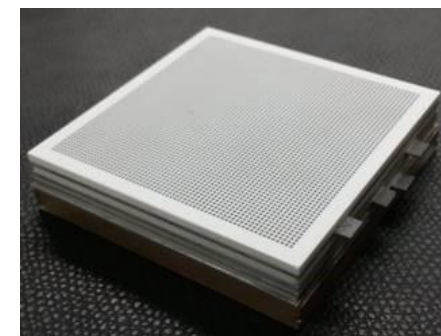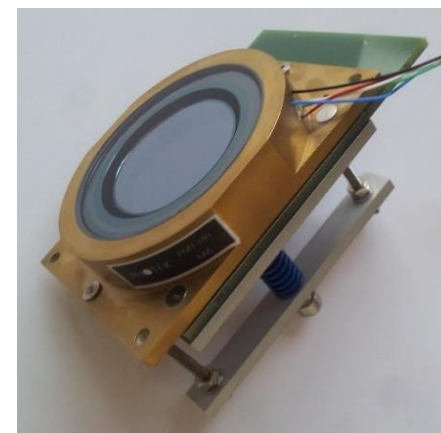
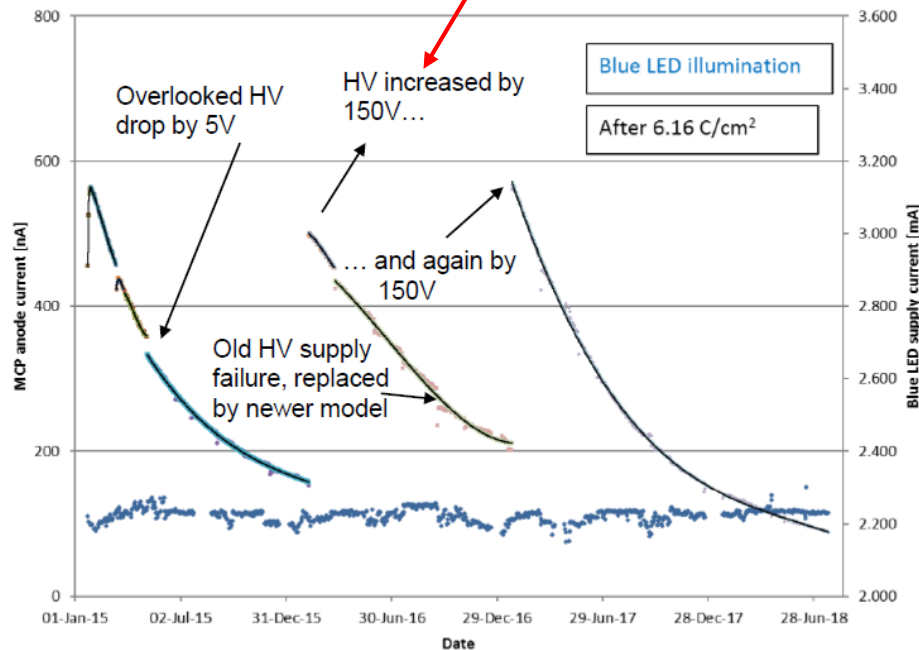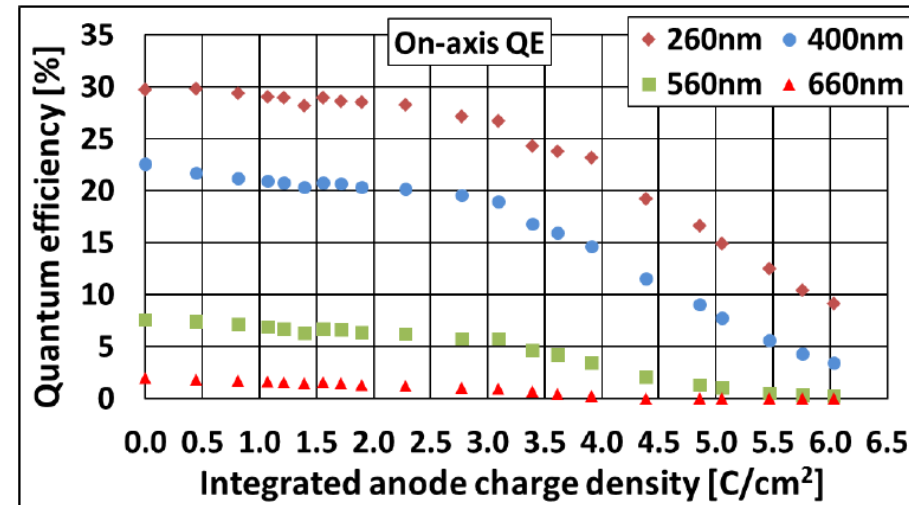- Lifetime requirement 5 C/cm^2 : implement ALD coating.
  - Illumination up to 6.16 Ccm^{-2}
  - Gain drop observed, recovered by increase of HV
  - Marginal loss in quantum efficiency (at 3 C/cm^2) : a factor ~2 loss at 5 Ccm^{-2}. Hope is Phase 3 tubes will improve on this.

Long-term test blue LED illumination

HV increased:
2300 → 2450 V

Results updated from :
T. Gys et al., (RICH2016)
NIM 876 (2017) 156.
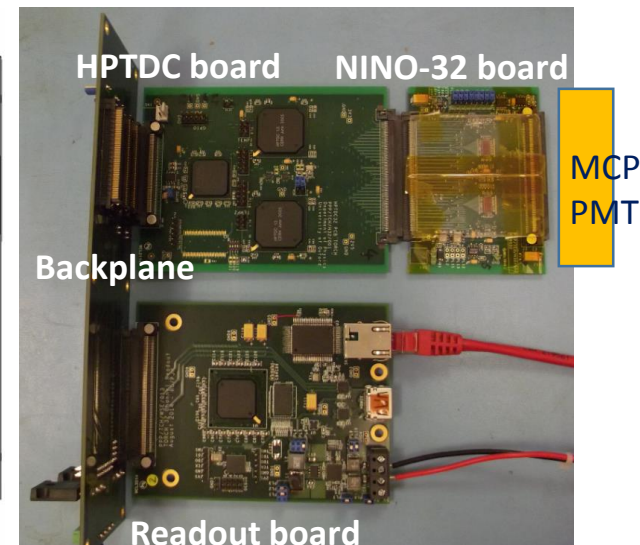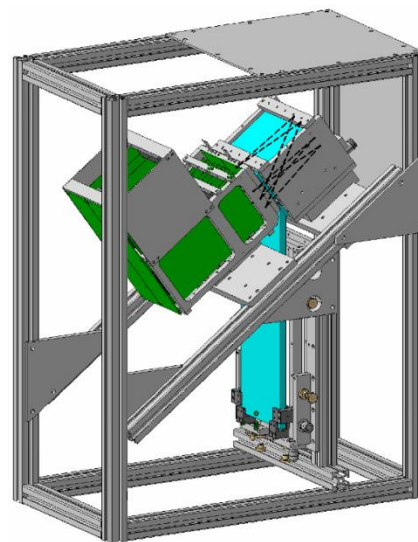
Phase 3 photon detectors

- 10 x Phase 3 MCP-PMTs delivered from Photek and are under test

- The MCP-PMT has a square 53 x 53 mm^2 active area, 64 x 64 pixels. Resolution of 128 x 8 pixels by exploiting charge sharing. L. Castillo García et al, JINST 11 C05022 (2016)

- Readout connectors mounted on a PCB which gangs 64 pixels into 8 (or 4) and connected to anode via ACF (Anisotropic Conductive Film).

- Two types of readout PCB :

  - Readout connectors mounted on PCB, 64 x 4 pixels per tube (for use with previous version of NINO electronics – test-beam Nov 2017)

  - Readout connectors mounted on PCB, 64 x 8 pixels per tube (for use with new NINO electronics – test-beam June 2018)
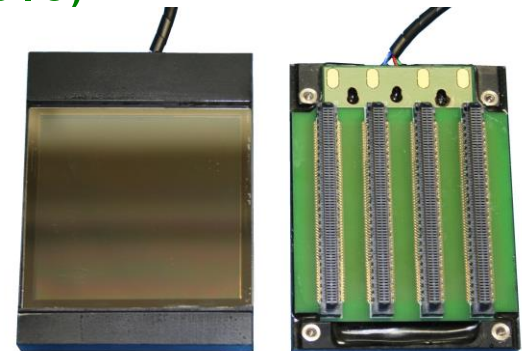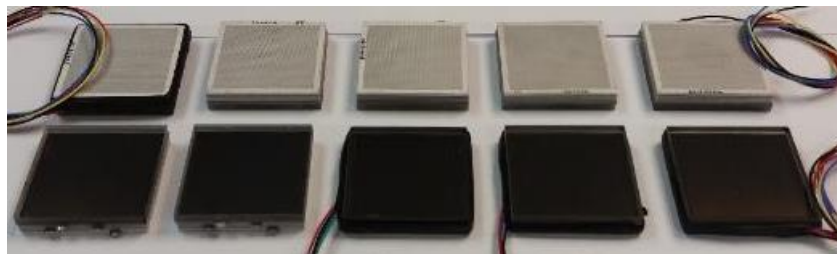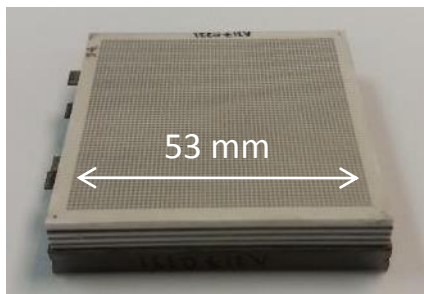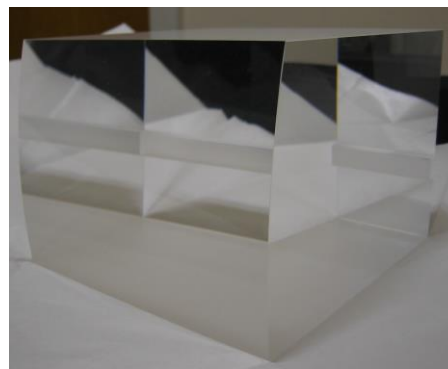
3. Demonstrator TORCH module

- Several test-beam campaigns between 2015 & 2018 at CERN PS / T9 (~5 GeV/c p/π beam)

- Quartz radiator ($12 \times 35 \times 1 cm^3$) with matching focusing block (from Schott Germany)

- NINO and HPTDC electronics

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

- Report here results from Nov 2017, read out with single Phase 3 MCP-PMT with 4×64 pixels
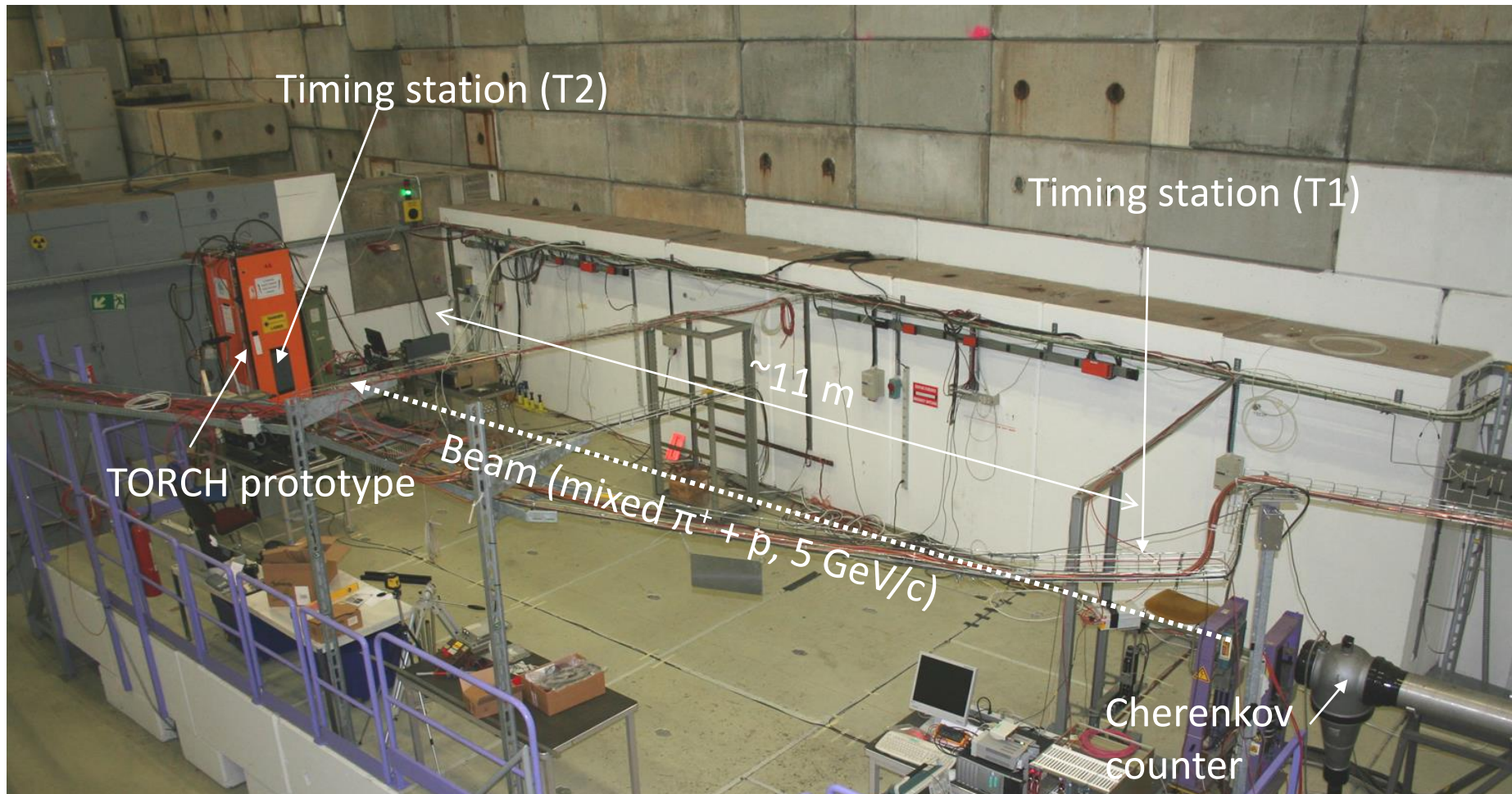

HPTDC board   NINO-32 board

MCP PMT

Backplane

Readout board

Focusing block

Radiator plate: 35 x 12 x 1 cm³

Timing station (T2)

Timing station (T1)

~11 m

TORCH prototype

Beam (mixed π^+ + p, 5 GeV/c)

Cherenkov counter

time reference

TORCH prototype

time reference

CO_2 Cherenkov counter

F2/T2

silicon pixel telescope
(https://telescopes.desy.de/AZALEA)

F1/T1

scintillator pair
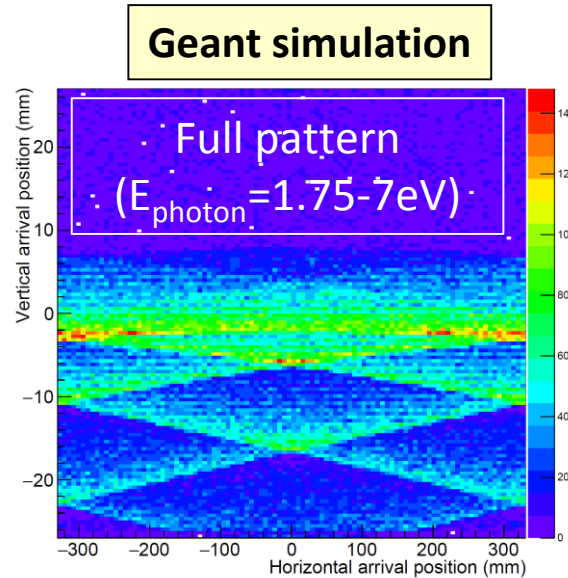
Pattern folding

- 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 above for full TORCH module, however this pattern is only *sampled* in testbeam.

- Nominal test-beam configuration chosen to give cleanly resolved patterns.
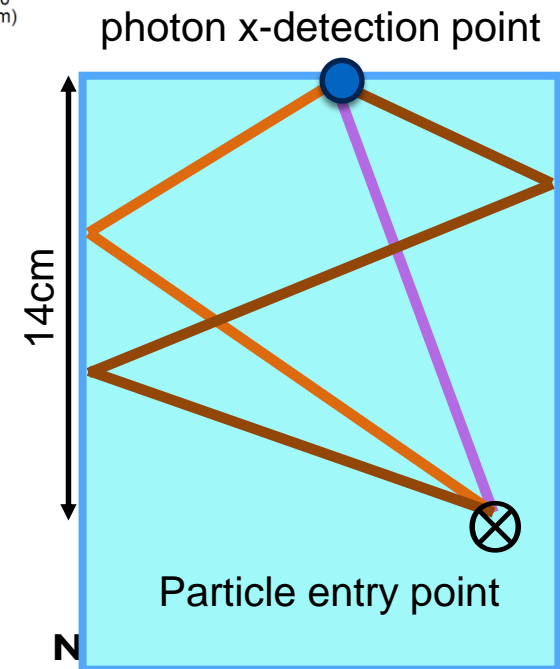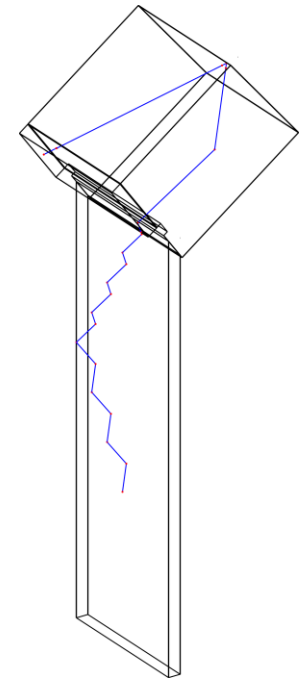
Geant simulation

Full pattern
(E_{photon}=1.75-7eV)

Vertical arrival position (mm)

Horizontal arrival position (mm)

photon x-detection point

14cm

Particle entry point

Hit maps in MCP-PMT

Timing station ToF
T1-T2
5 GeV/c

~600 ps

P   π

Events / (1)

ToF (100 ps bins)

- Proton-pion particle selection from ToF over ~11m distance using beam-line borosilicate counters

- Clustering applied to get MCP centroid hit position

- Correct for non-linearity and time-walk in the TORCH electronics.

Proton – pion difference cleanly resolved

TORCH Preliminary   5 GeV/c pions

y-coordinate (pixels)

x-coordinate (pixels)

Hit maps in MCP-PMT

Timing station ToF
T1-T2
5 GeV/c

~600 ps

P   π

ToF (100 ps bins)

- Proton-pion particle selection from ToF over ~11m distance using beam-line borosilicate counters

- Clustering applied to get MCP centroid hit position

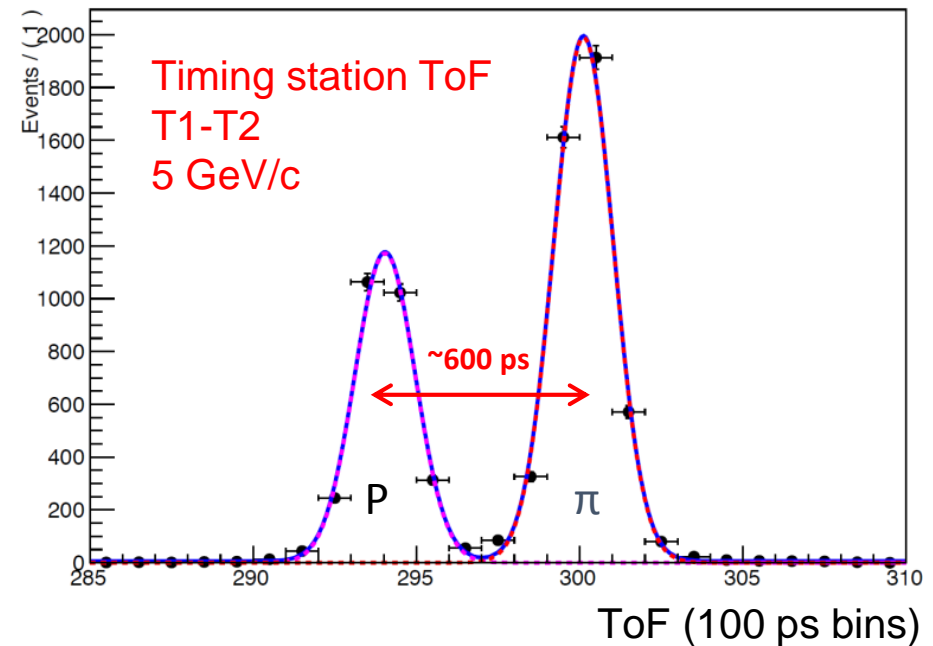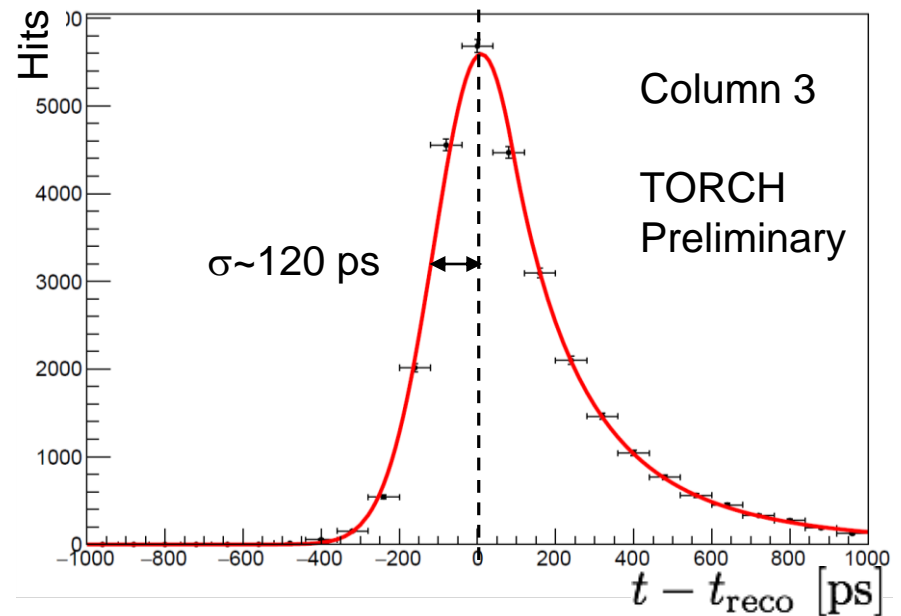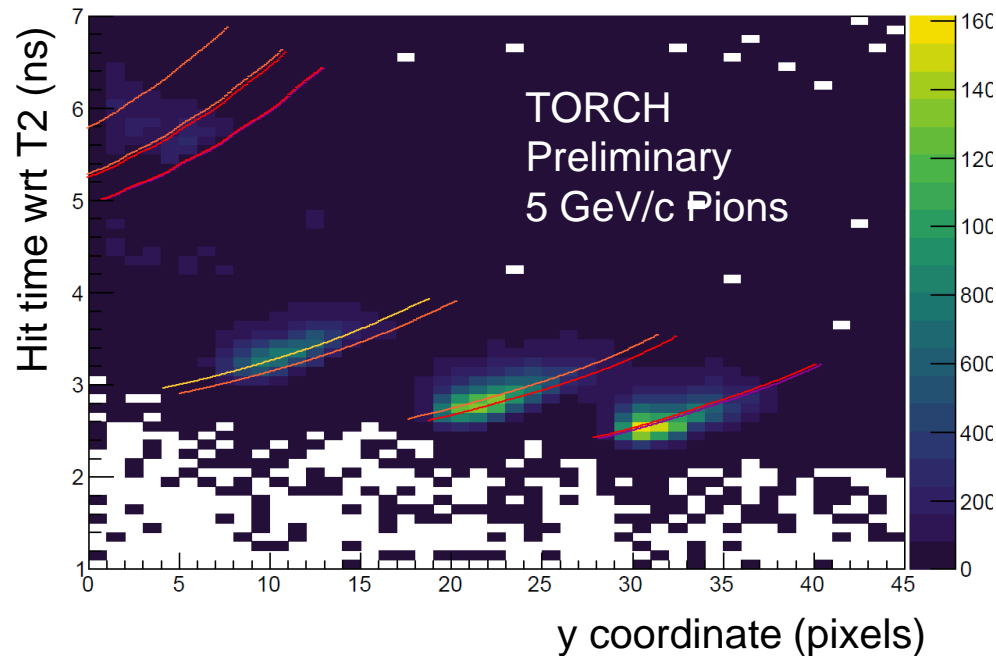- Correct for non-linearity and time-walk in the TORCH electronics.

Proton – pion difference cleanly resolved
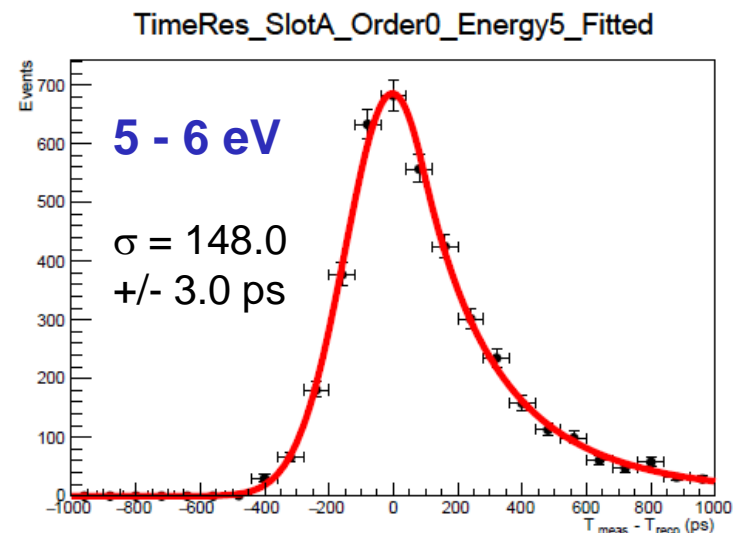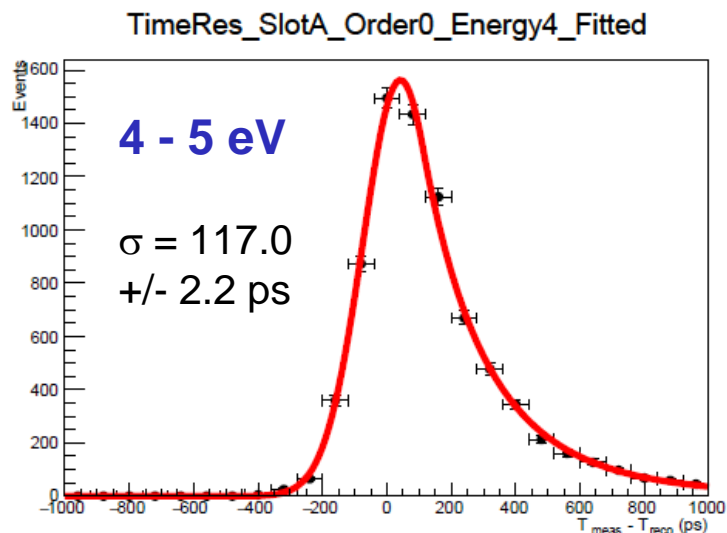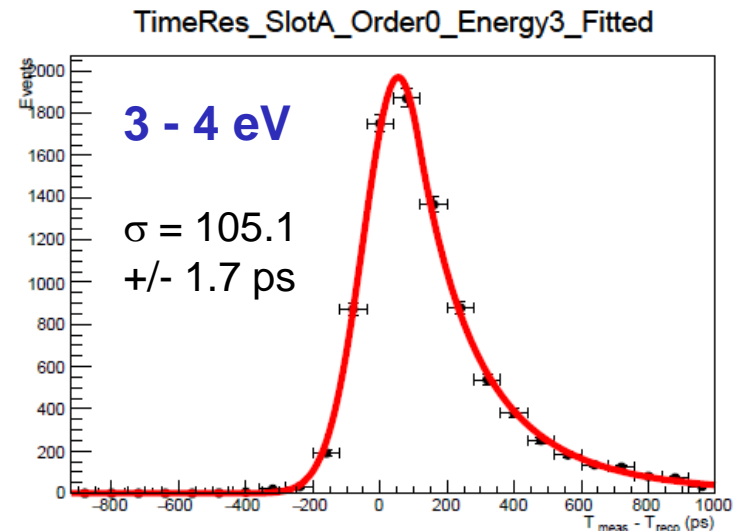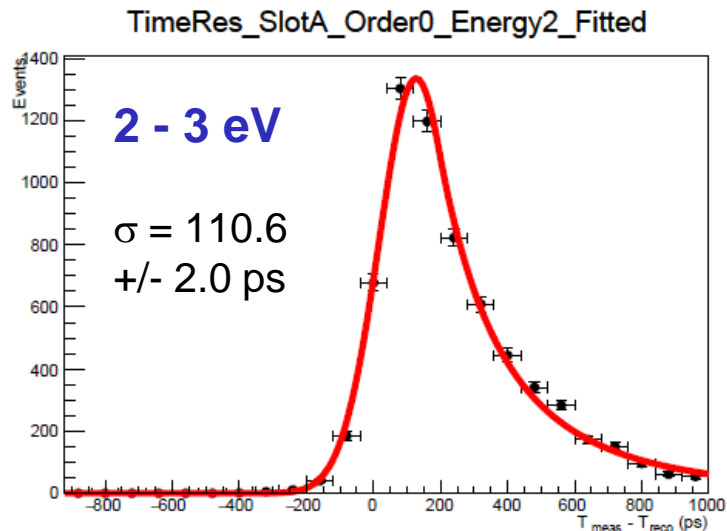
TORCH Preliminary   5 GeV/c protons
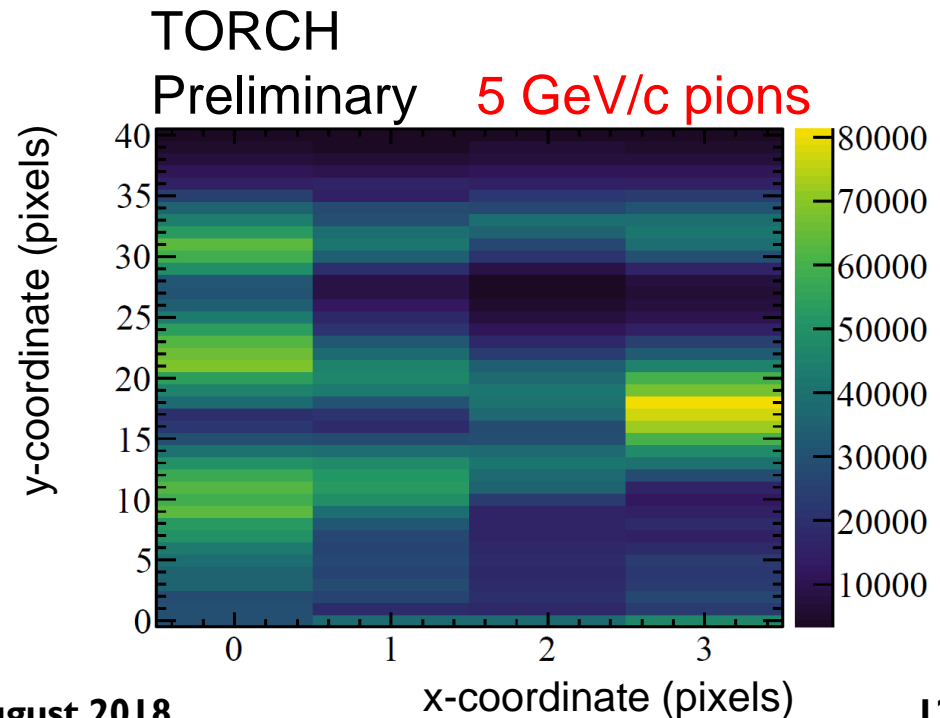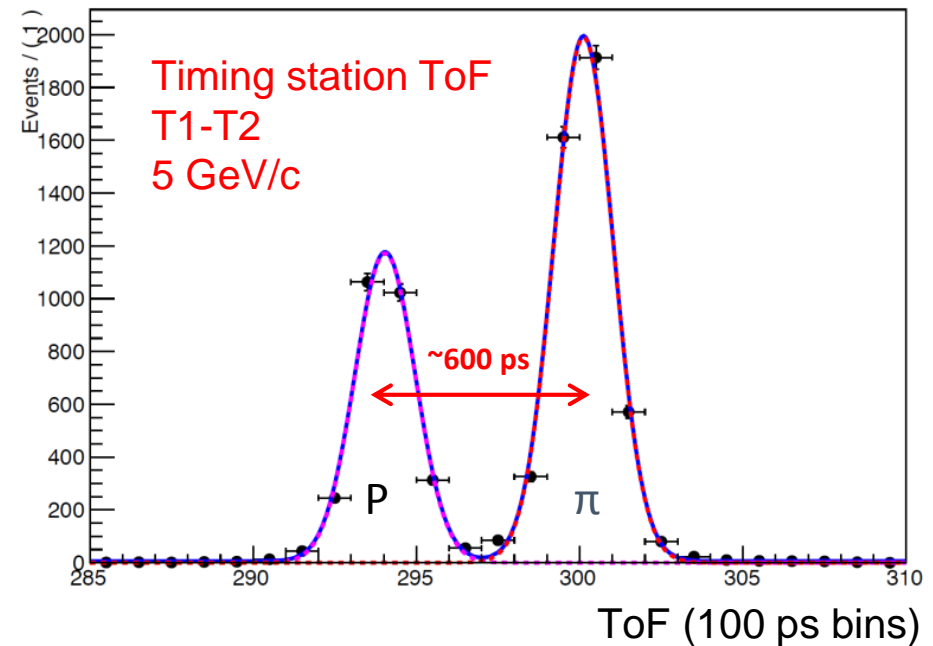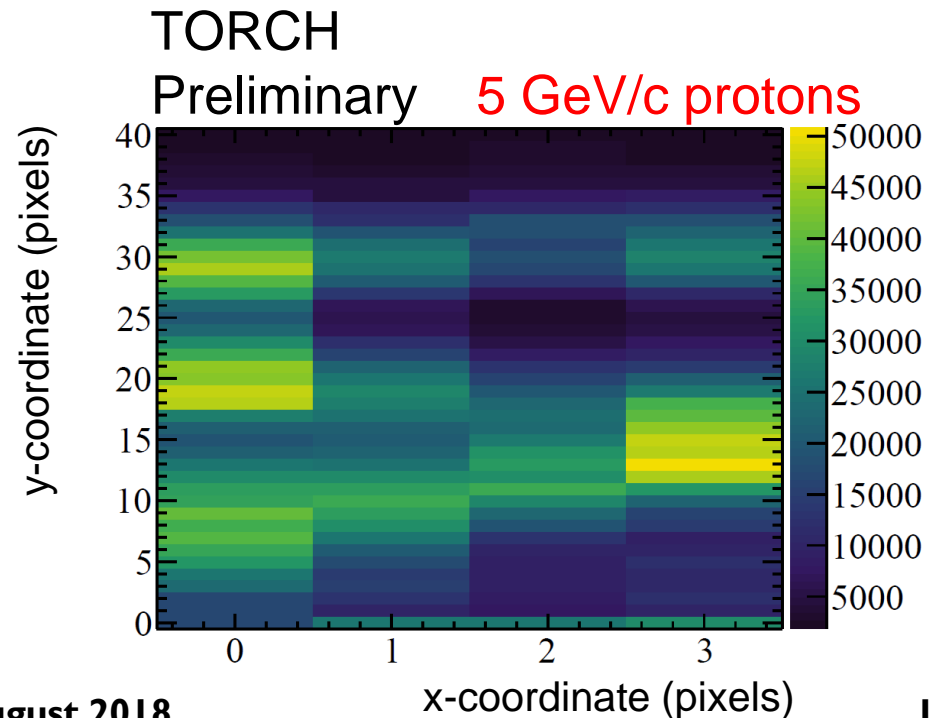
Time resolution

- For each column of pixels, plot time measured for each cluster relative to station T2 *vs.* vertical y-position

- Compare patterns relative to simulation

- Core distributions σ ≈ 100 −125 ps (energy and column dependent)

- Subtract contribution from timing reference, measure ∼ 85 − 100 ps, approaching the target resolution of 70 ps per photon

- Tails due to imperfect calibration, backscattering

- Improvements are possible:
  - Pulse-height to width calibration
 - Limit of 100 ps binning in HPTDC

TORCH
Preliminary
5 GeV/c Pions

Column 3

TORCH
Preliminary

σ∼120 ps

$t − t_{reco}$ [ps]

Photon energy dependence

TimeRes_SlotA_Order0_Energy2_Fitted

2 - 3 eV

$\sigma = 110.6$
$+/- 2.0$ ps

TimeRes_SlotA_Order0_Energy3_Fitted

3 - 4 eV

$\sigma = 105.1$
$+/- 1.7$ ps

Column 3

TORCH
Preliminary

TimeRes_SlotA_Order0_Energy4_Fitted

4 - 5 eV

$\sigma = 117.0$
$+/- 2.2$ ps

TimeRes_SlotA_Order0_Energy5_Fitted

5 - 6 eV

$\sigma = 148.0$
$+/- 3.0$ ps

$$t - t_{\text{reco}} \; [\text{ps}]$$

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)

HPTDC

NINO board

MCP-PMT

Radiator plate

Focussing block

Radiator plate

Focusing block
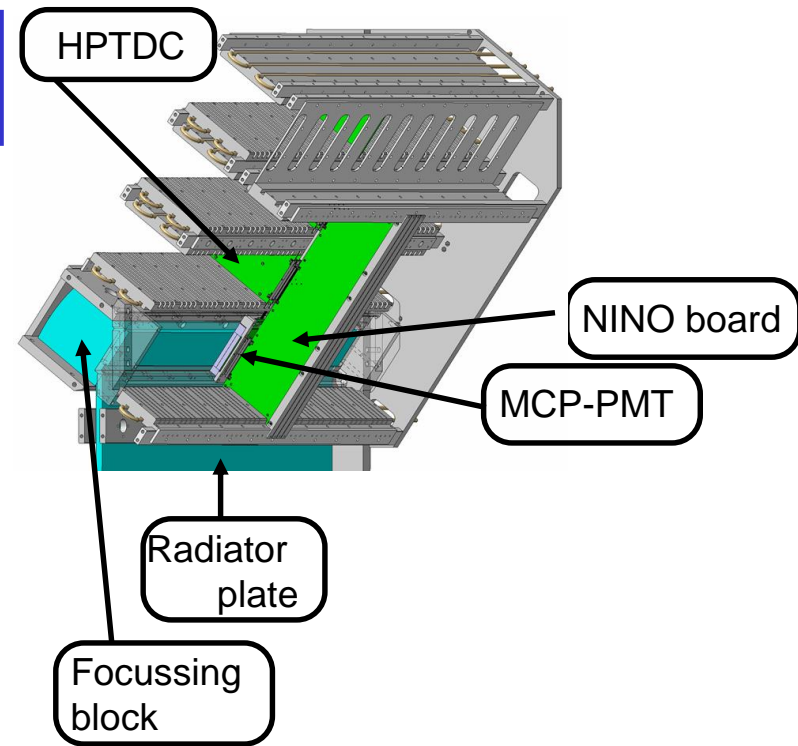
June 2018 beam tests

- As an incremental step, single 64 x 8 pixel MCP-PMT and upgraded electronics have already been demonstrated in the small-scale TORCH in a beam test in June this year.

- Results are being analysed: calibrations and timing measurements in progress

Nominal Position   Opposite Position (Flipped)

TORCH Preliminary 5 GeV/c Pions

y pixel

x pixel
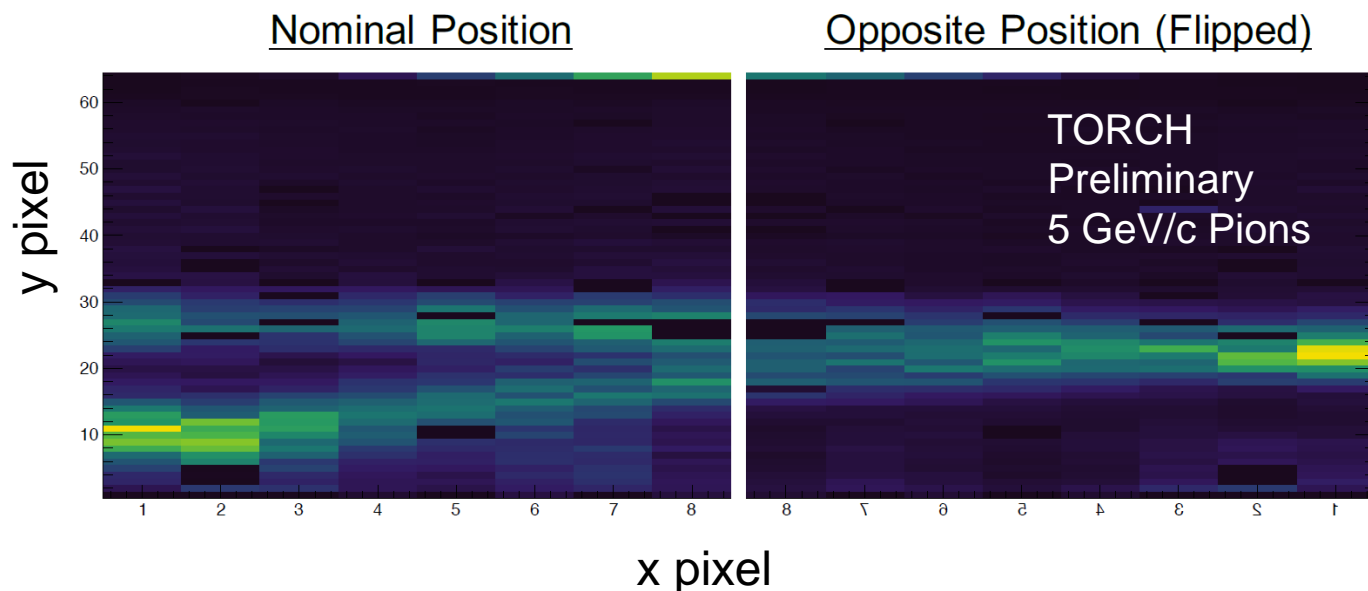
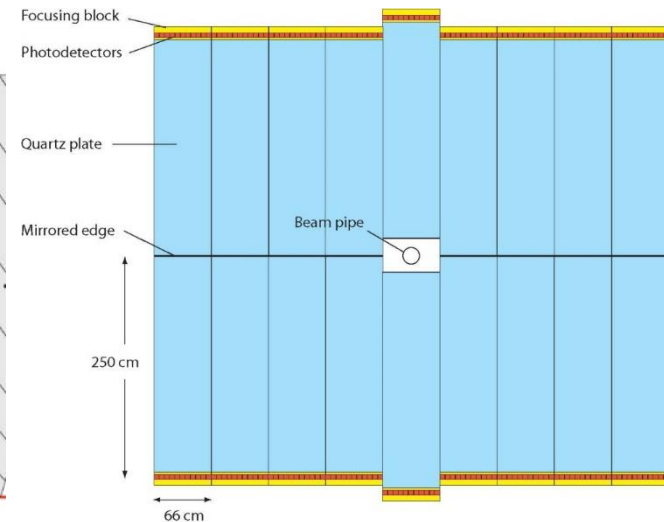- The full-scale module is planned for test-beam October/November 2018

5. TORCH for the LHCb Upgrade II

- The RICH system provides particle ID in LHCb

- But currently no positive kaon or proton ID below ~10 GeV/c

- Proposal to install TORCH in front of RICH2, possibly already in LS3 (2024)
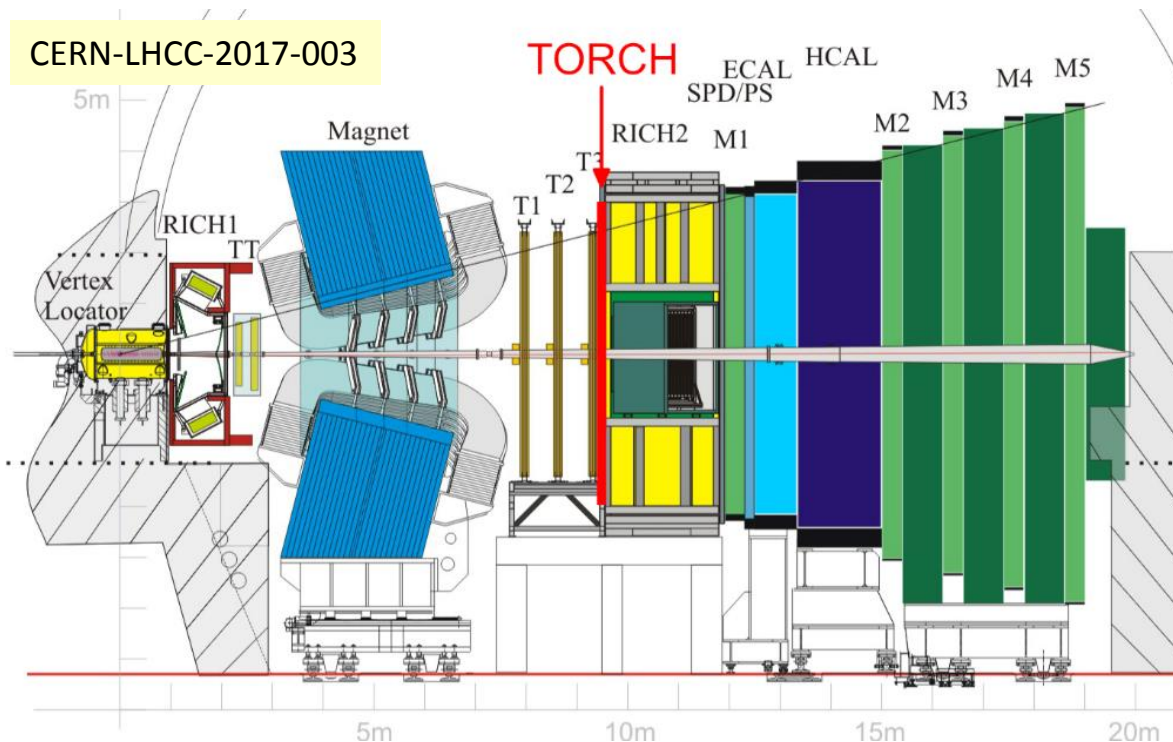
- TORCH area 5 x 6 m^2
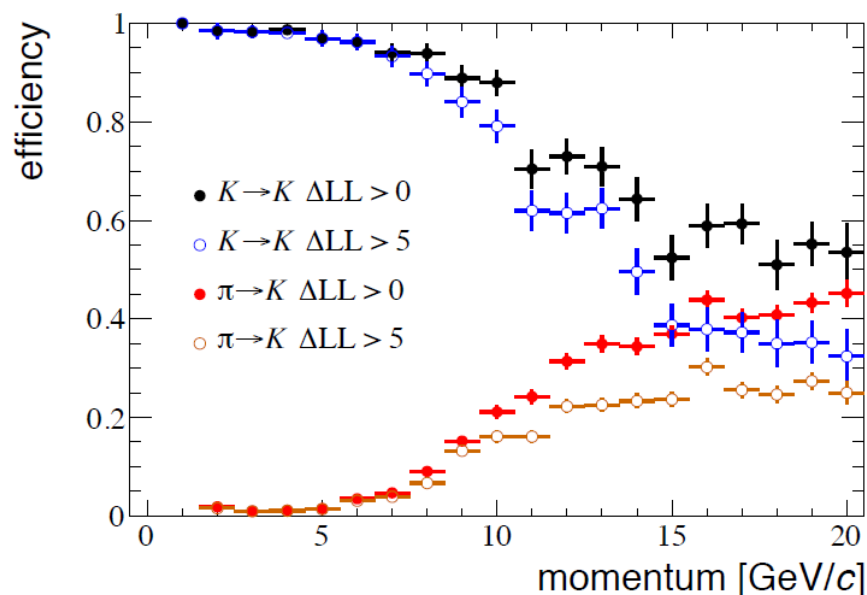- 18 module system
- 11 MCPs per module

CERN-LHCC-2017-003

TORCH performance studies at LHCb

- Simulated PID performance for charged particles produced in pp collisions and in heavy flavour decays (at $\mathcal{L} = 2 \times 10^{33}$ cm^{-2}s^{-1}).

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

- Physics studies started on key physics channels and tagging performance.
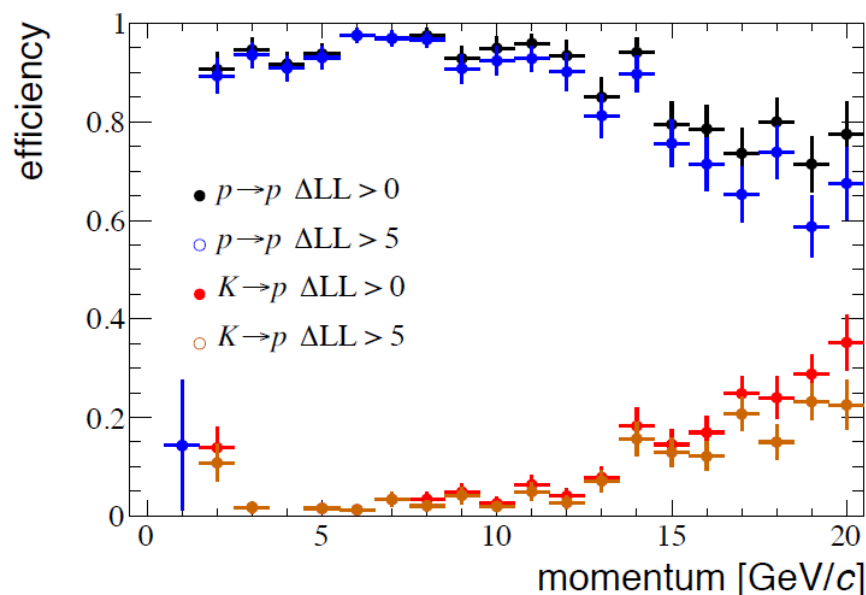
Summary

■ Performance of a prototype detector in beam tests is very encouraging : 85-100 ps timing resolutions per photon achieved. With improvements hope to approach the desired 70 ps.

■ TORCH future :

♦ New optics half-sized module under construction

♦ Final phase-3 MCP-PMTs are under test

♦ New generation of electronics being commissioned

♦ Physics studies underway for Technical Proposal for the Upgrade-II of the LHCb experiment
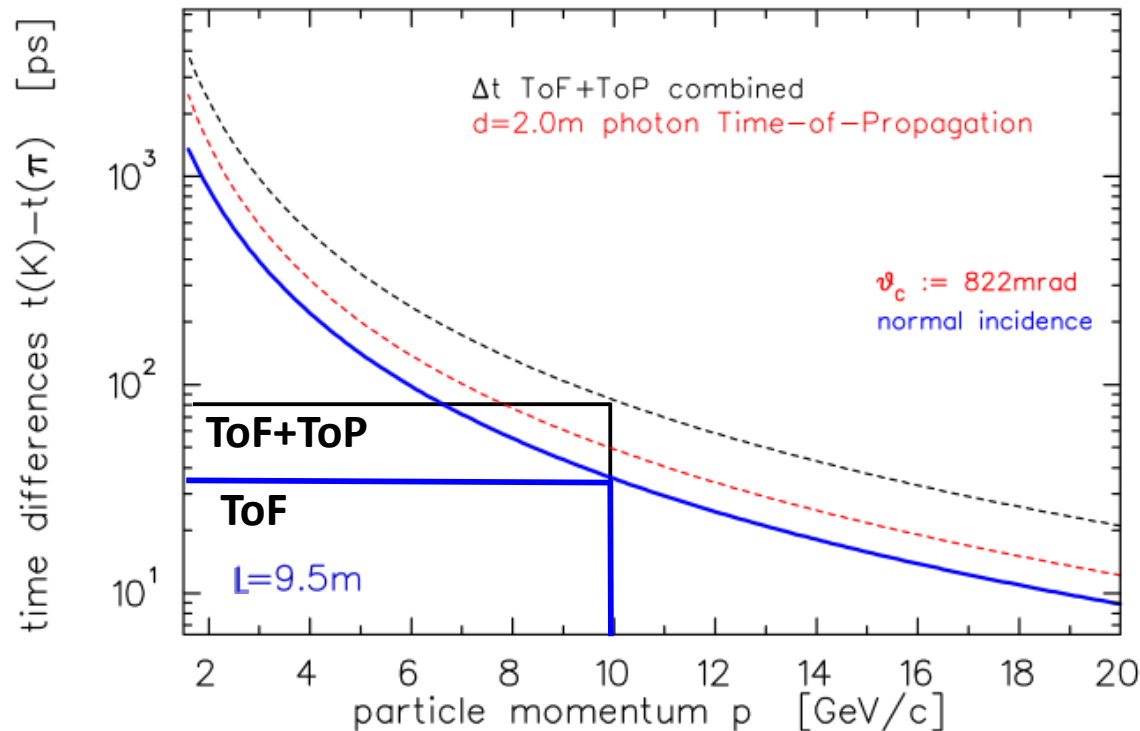
The end !

erc

European Research Council

Established by the European Commission

Spare slides from here on

Time of flight and time of propogation

Δt ToF+ToP combined
d=2.0m photon Time−of−Propagation

$\vartheta_c := 822$mrad
normal incidence

ToF+ToP

ToF

L=9.5m

Principle of ToF reconstruction

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

- Time of propagation (ToP) in quartz :
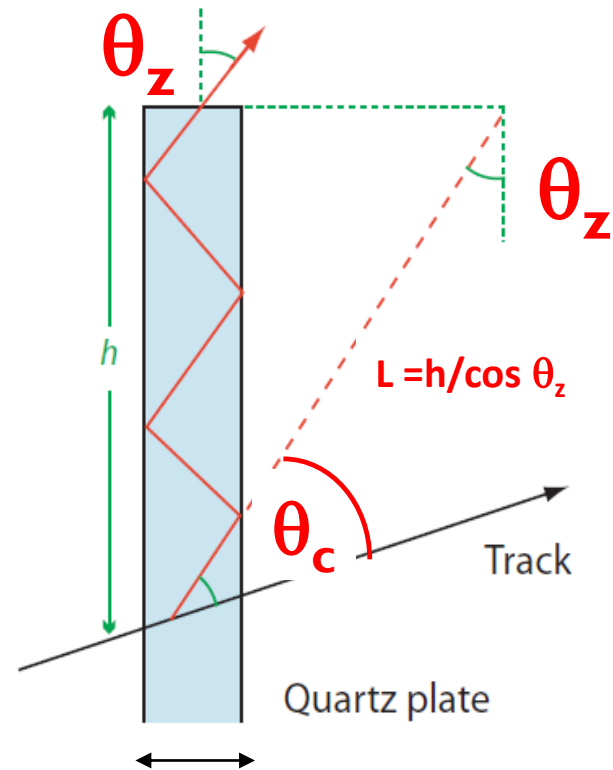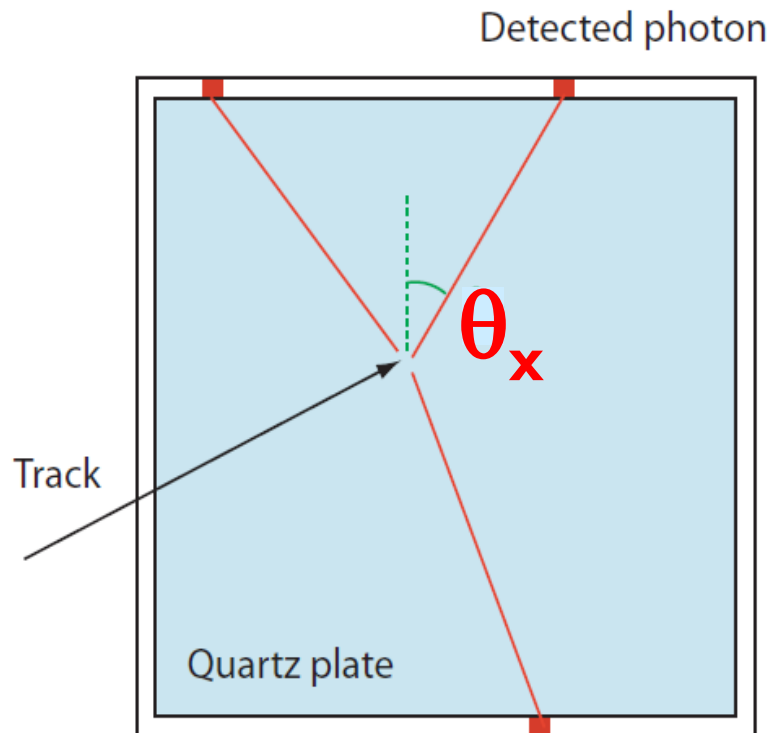 $t = L / v_{group} = n_{group}\, L / c$
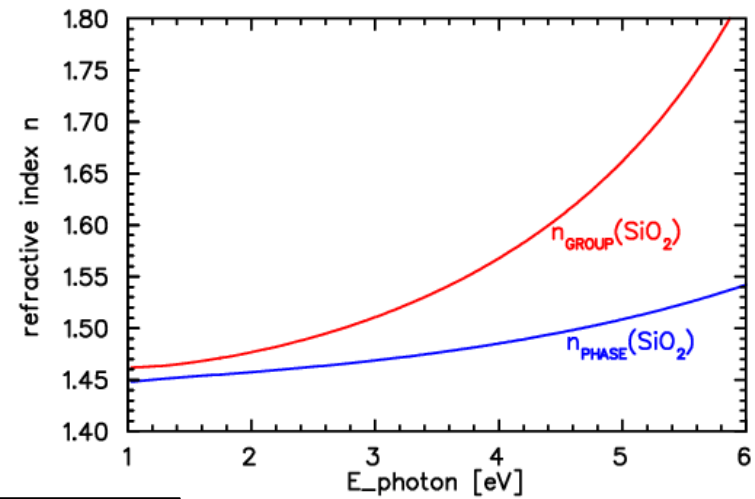
- Measure Cherenkov angle θ_c and path length L in the quartz. Need to correct for the chromatic dispersion of the quartz.

- Can associate n_{phase} for K, π, p hypotheses from $\cos \theta_c$ to get photon wavelength $\rightarrow$ use dispersion relation for n_{group}

- $L = (t - t_0)\, c / n_{group}$, measure arrival time at the top of a radiator bar $\rightarrow$ then assign most likely K, π, p hypothesis from ToP and ToF

measured angle

TORCH

d=2 m

IP

L=~10 m particle flight path

tracking
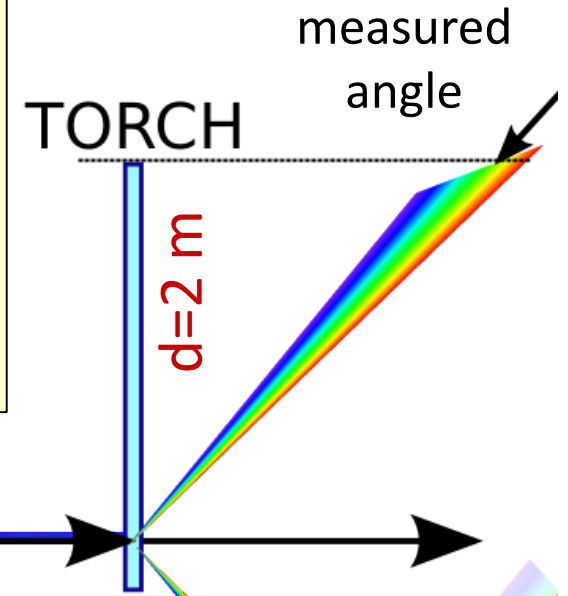
TORCH angular measurement (θ_x)

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

Detected photon

θ_x

Track

Quartz plate

θ_z

θ_z

h

$L = h/\cos\theta_z$

θ_c

Track

Quartz plate

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

- → Cherenkov angular range = 0.4 rad

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

  → fine segmentation needed along this direction

Representative photon paths: $0.55 < \theta_z < 0.95$ rad
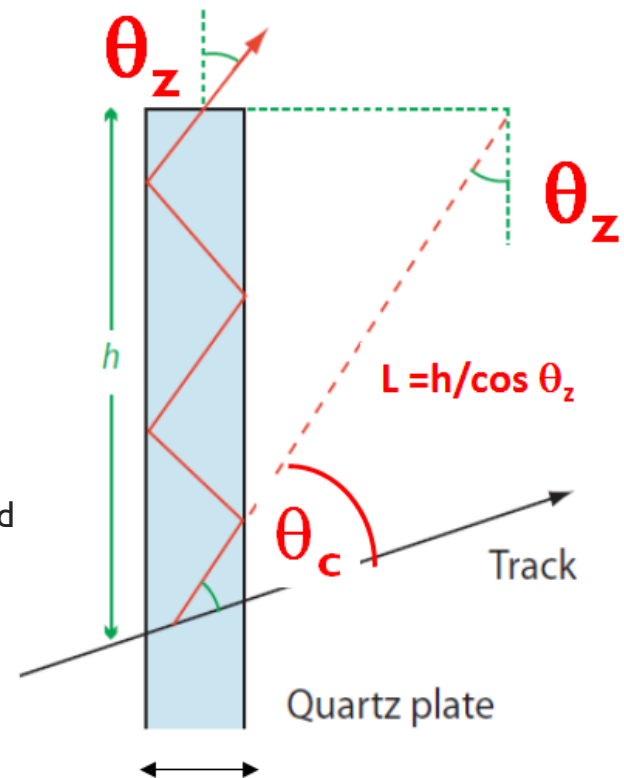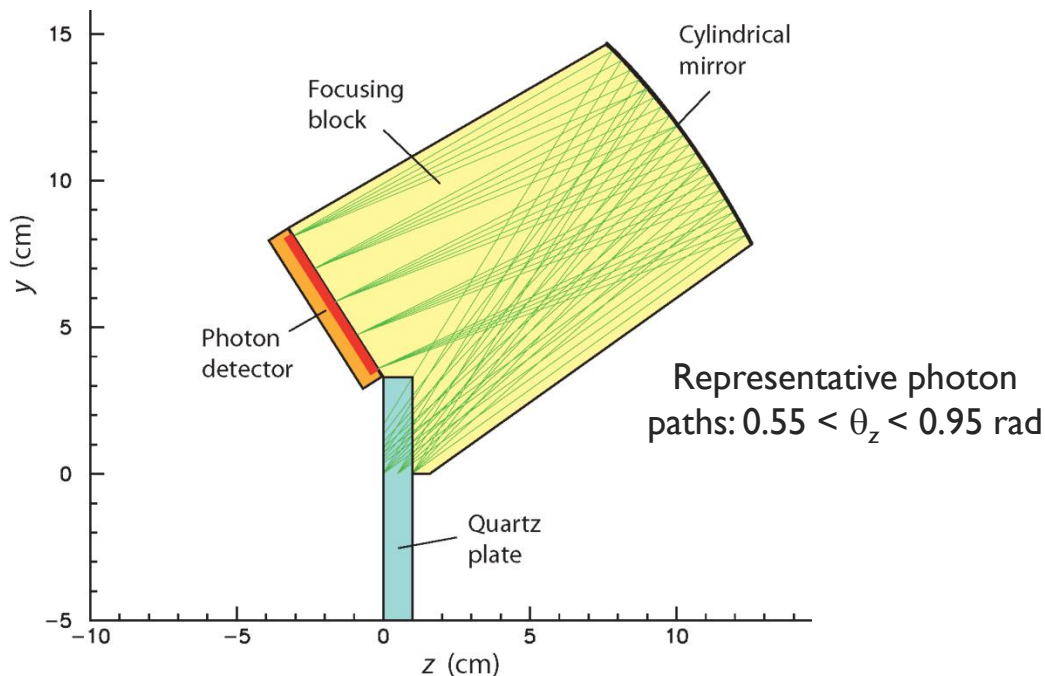
Phase 1 tubes : timing resolution

■ Phase 1 Photek tubes : excellent timing resolution obtained in laboratory tests with fast laser and with commercial electronics
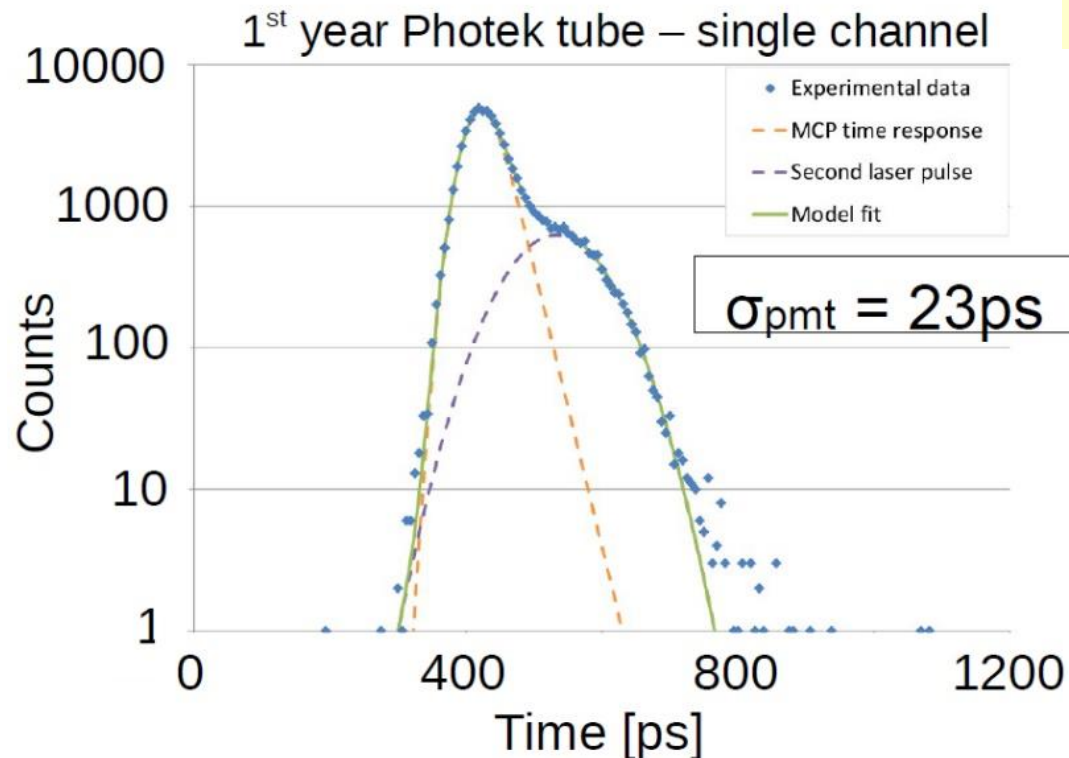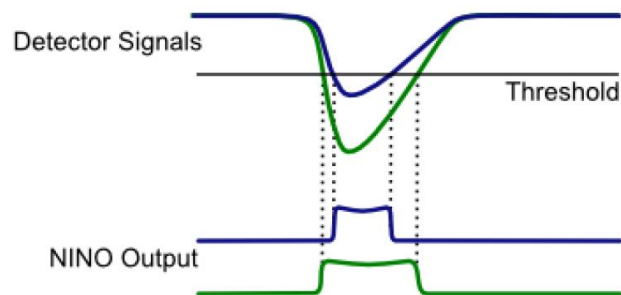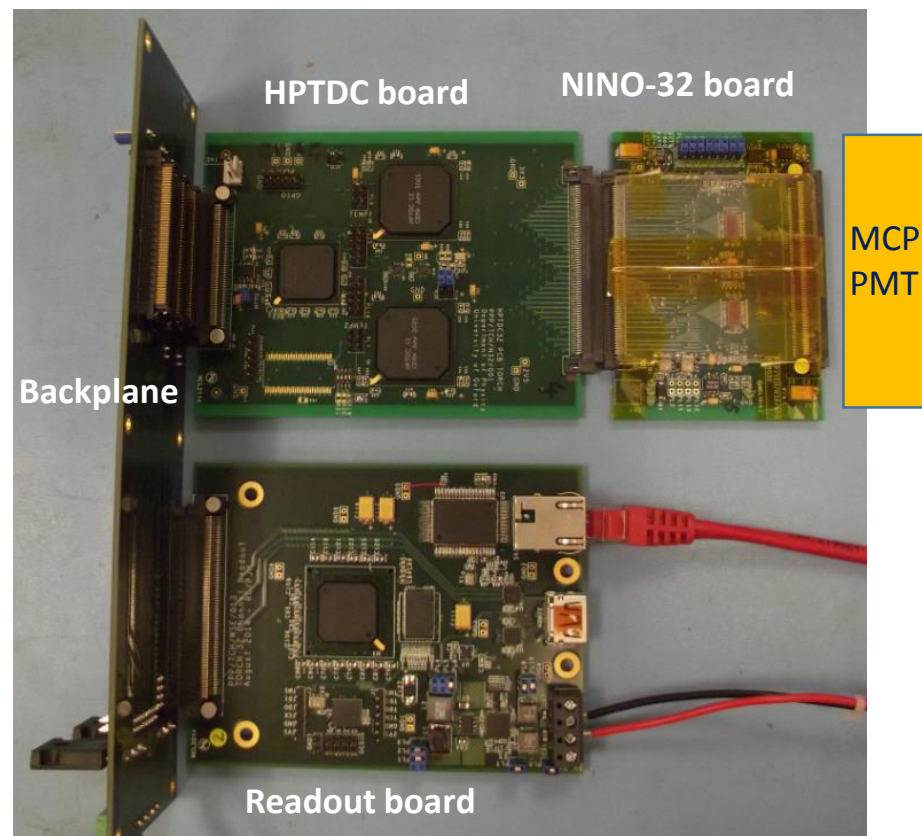

T. Gys et al., NIM A766 (2014) 171

$\sigma_{pmt} = 23ps$

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
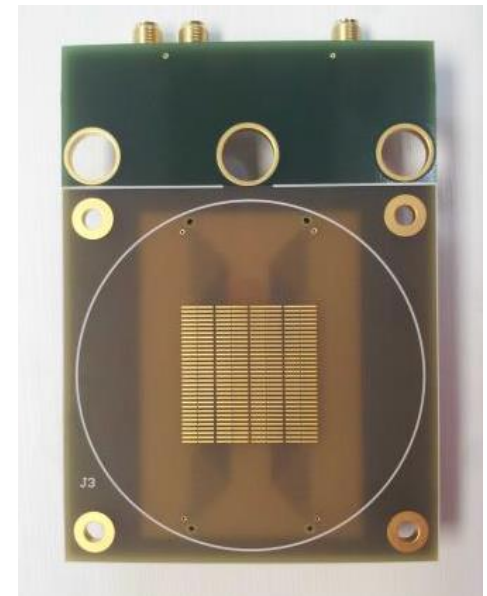
- The calibration has proved challenging

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

HPTDC board   NINO-32 board

Backplane

MCP PMT

Readout board

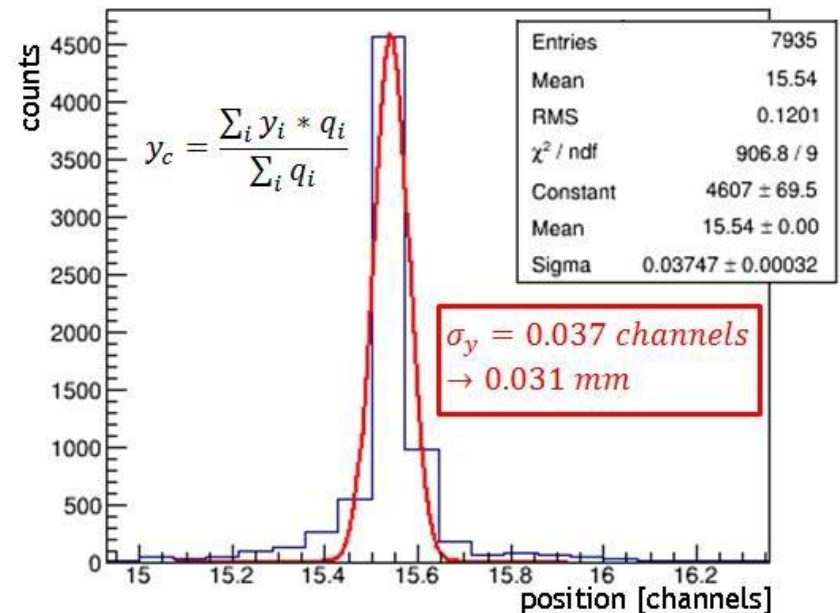Detector Signals

Threshold

NINO Output

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
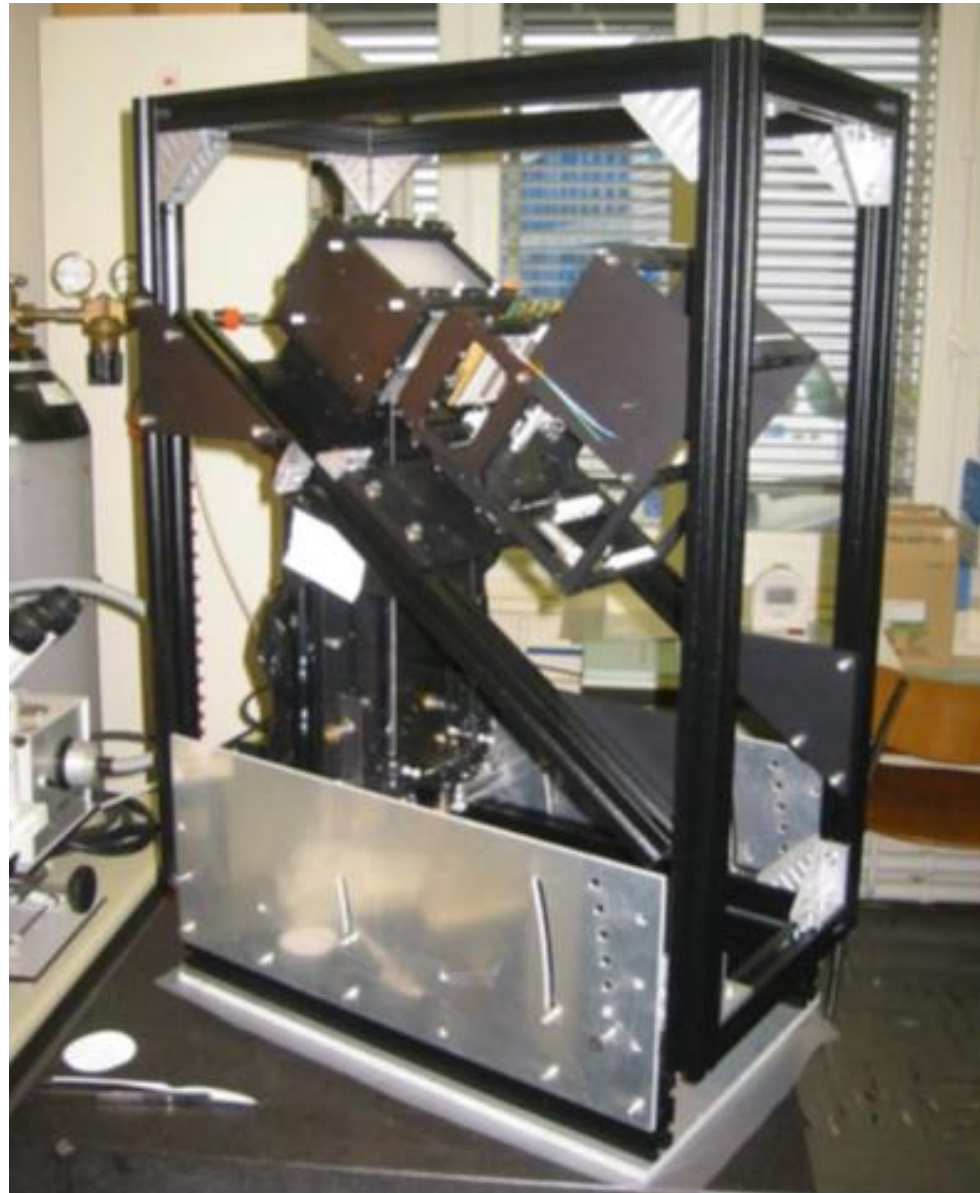Active area 25 x 25 mm², 32 x 4 pixels

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

$$y_c = \frac{\sum_i y_i * q_i}{\sum_i q_i}$$

Entries	7935
Mean	15.54
RMS	0.1201
χ^2 / ndf	906.8 / 9
Constant	4607 ± 69.5
Mean	15.54 ± 0.00
Sigma	0.03747 ± 0.00032

$\sigma_y = 0.037$ *channels*
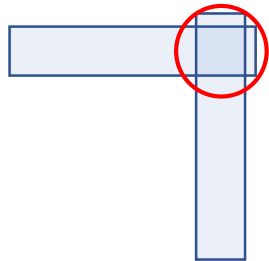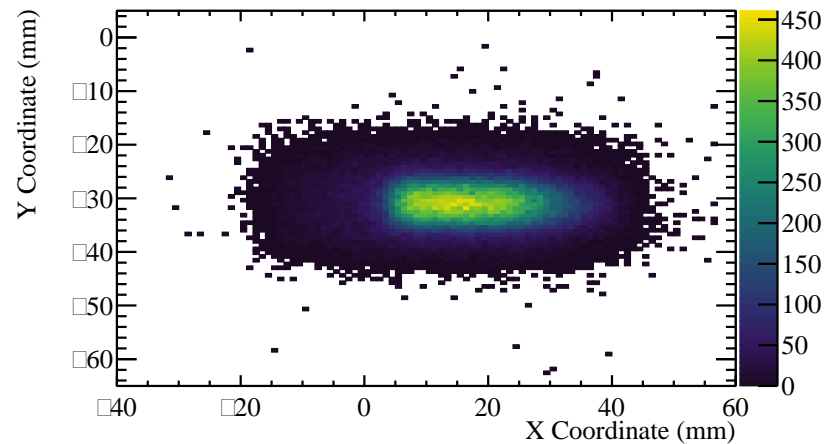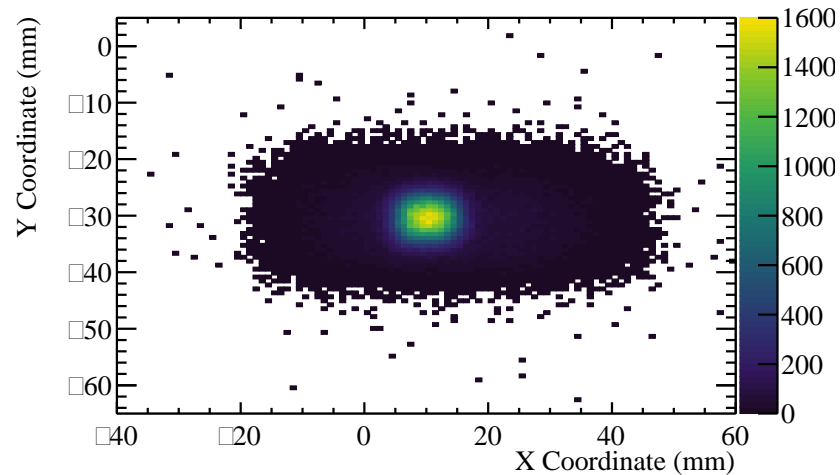→ 0.031 *mm*

TORCH Prototype module

Beam telescope profiles

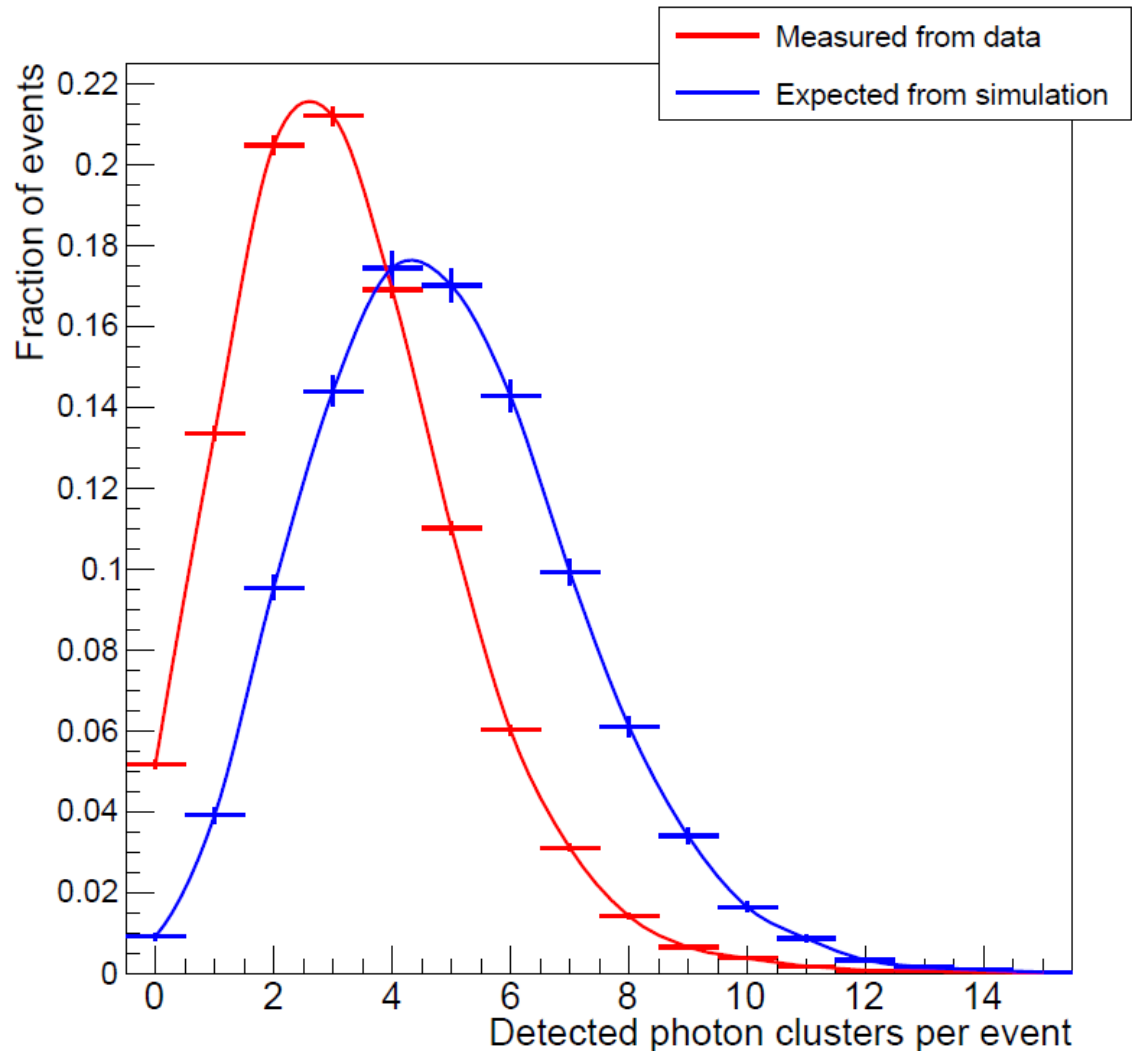Silhouette of T2 Scintillator coincidence

Silhouette of F2 finger

Photon counting with Planecon

- Numbers of photon clusters measured in testbeam

- Mean number of photons expected from simulation 4.89±0.02

- Mean number of photons measured in data 3.23±0.01

- Around 33% fewer photons observed as expected

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
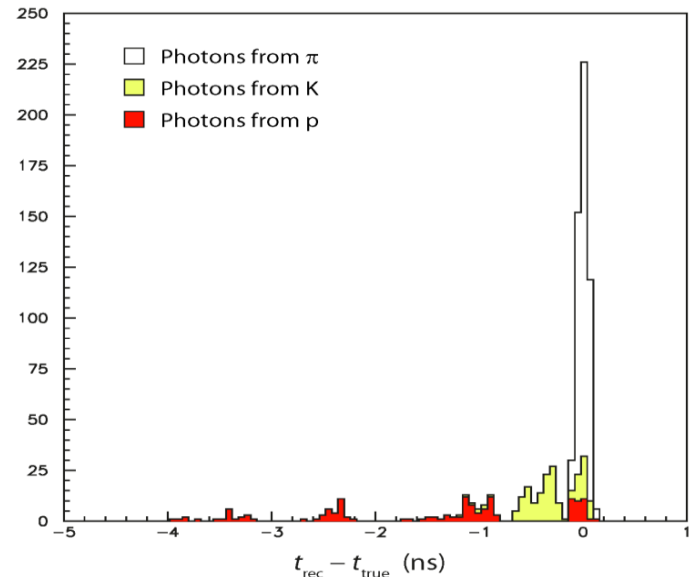

(Ideal reconstruction)
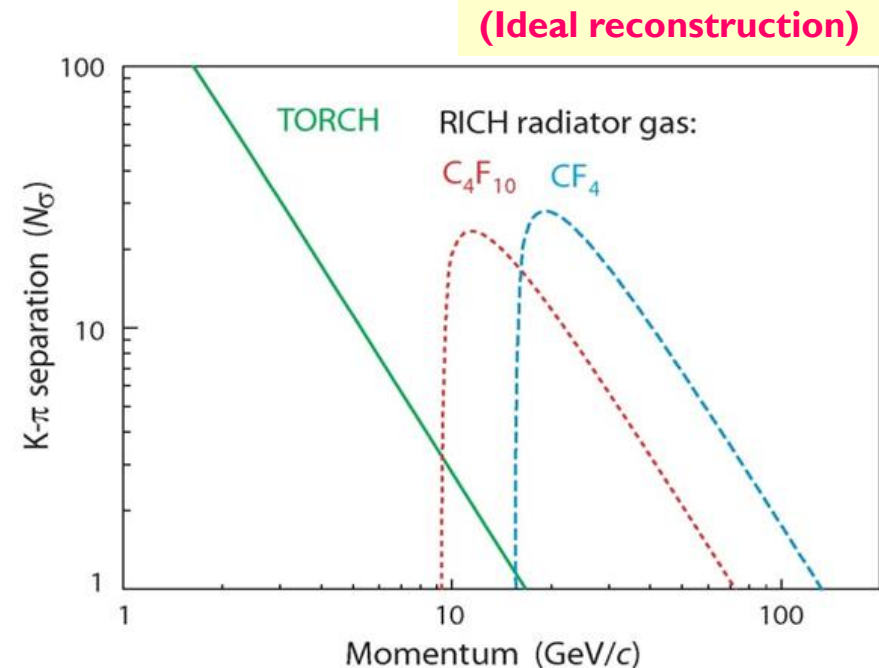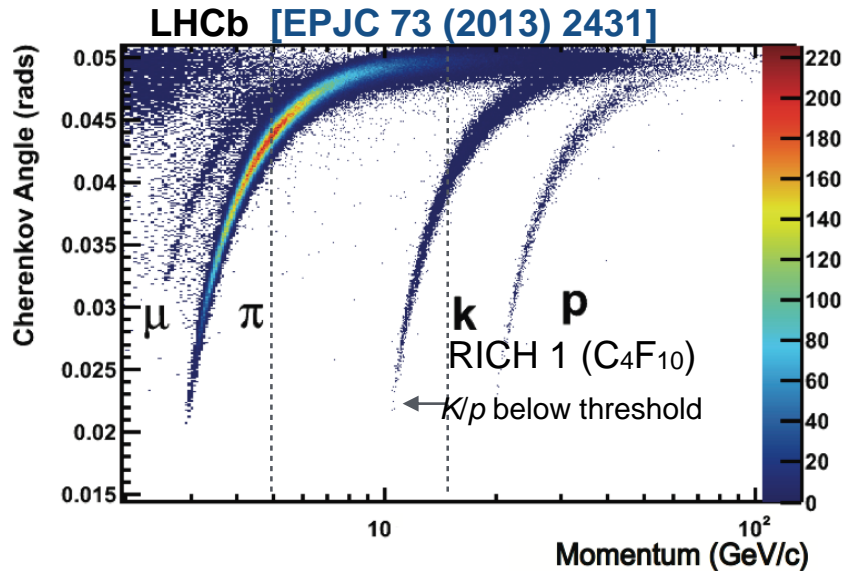
■ Currently no positive kaon ID below ~10 GeV/c nor any proton ID. The plan is to achieve this via a ToF measurement with TORCH

  – Area of 5 x 6 m² at z = 10 m

  – 18 module system (66 x 250 cm²)

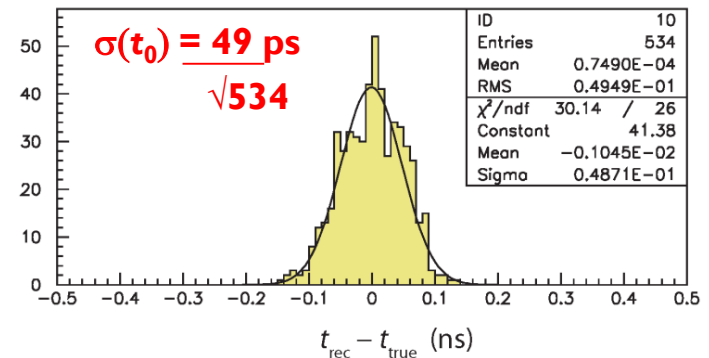 – 198 MCPs (~100k readout channels)

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

Photons from π
Photons from K
Photons from p

$t_{rec} - t_{true}$ (ns)

After removing outliers

$\sigma(t_0)$ **= 49** ps

$\sqrt{534}$

ID	10
Entries	534
Mean	0.7490E-04
RMS	0.4949E-01
χ^2/ndf	30.14 / 26
Constant	41.38
Mean	-0.1045E-02
Sigma	0.4871E-01

$t_{rec} - t_{true}$ (ns)

- An idea for application of TORCH in LHCb :
  - TORCH would be placed in front of LHCb calorimeter
  - Use lead plate in front ($1X_0 \approx$ 6mm) 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
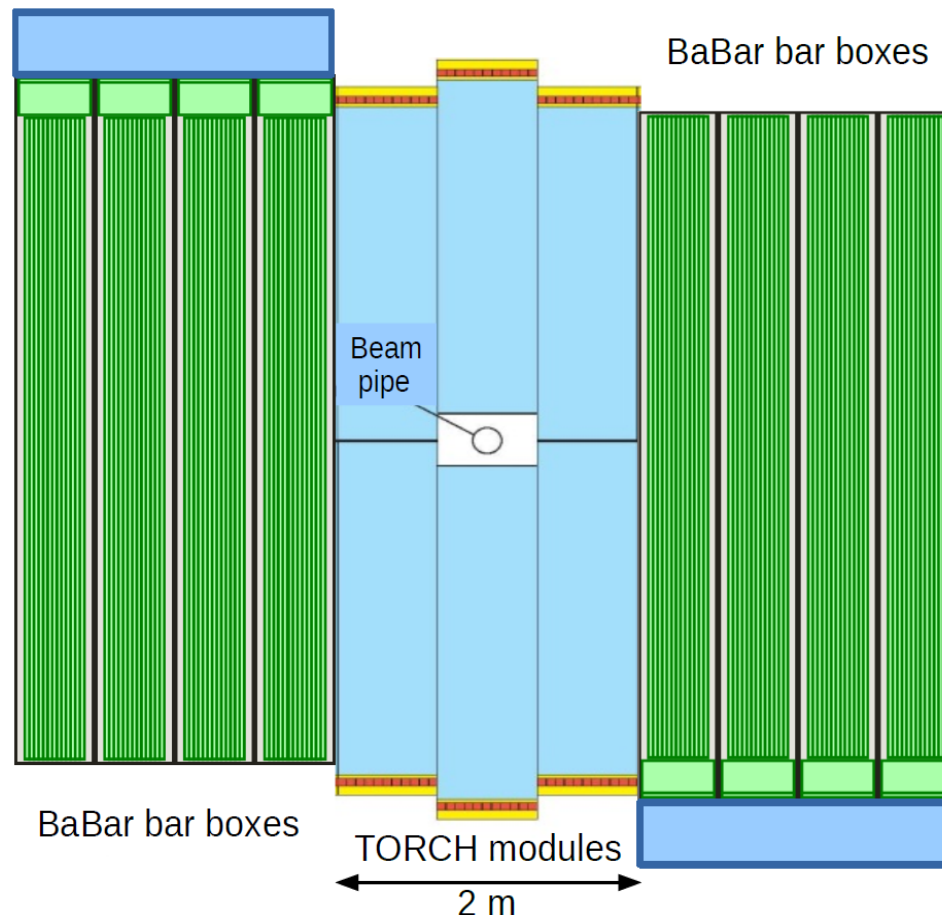 - However, the PID capability will degrade due to MCS

Gamma time resolution (1.0 X0 lead)

Pion time resolution
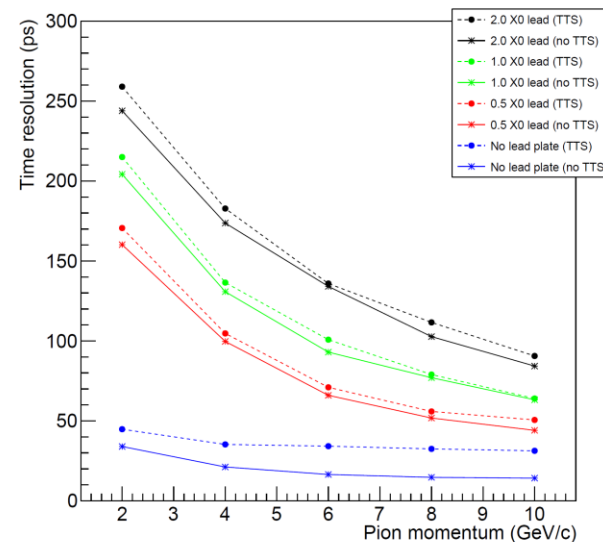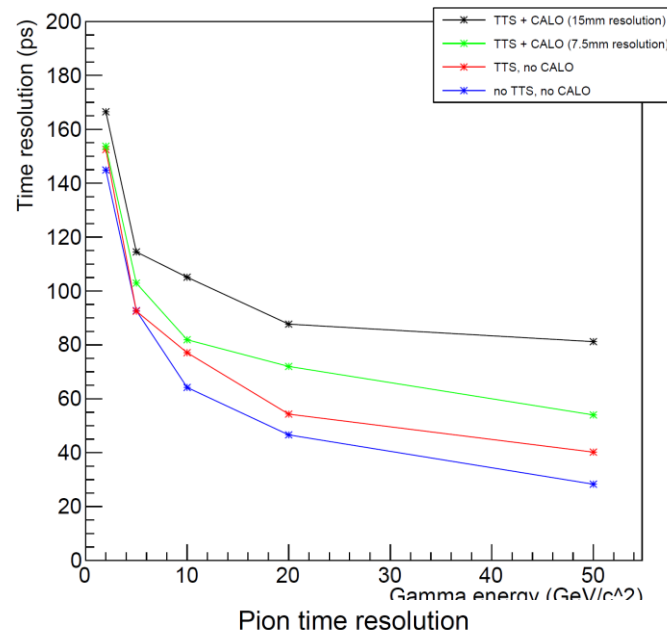
Possible use of BaBar DIRC bars

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

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BaBar bar boxes

Beam pipe

BaBar bar boxes

TORCH modules

2 m

TORCH possible re-use of BaBar quartz bars

- Bar length (at z = 950 cm) and total area ~ 30 m^2 matches TORCH needs. Adapting the bars requires focusing in both projections.

- Effect of wedge (glued to bars) is to give two separate beams: depending on whether photons reflected or not : made up of 12 planar "bar-boxes" each containing 12 quartz bars 1.7 x 3.5 x 490 cm^3

- Split detector plane: assuming 60 mm square MCPs (53 mm active) requires two PMTs to cover 0.5 < θ_z < 0.9 rad

- Adapting the TORCH optics to re-use the BaBar DIRC seems viable: much more complicated optics, but no degradation seen compared with single projection.

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