The TORCH Time of Flight Detector

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On behalf of the TORCH Collaboration

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Outline

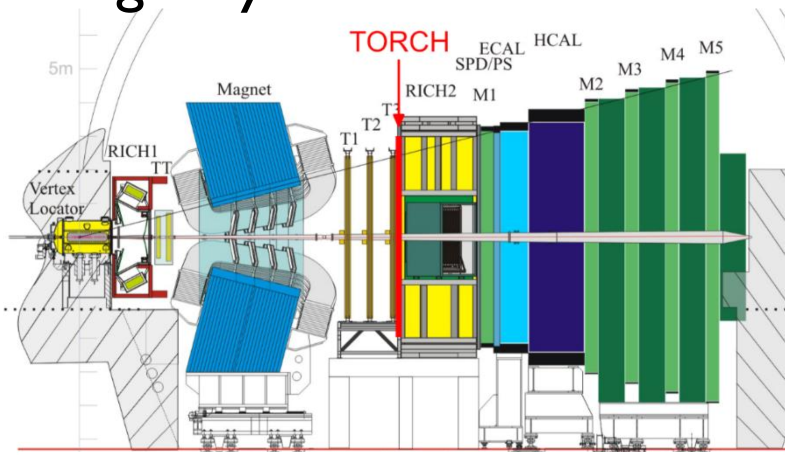
- Introduction to TORCH
  - TORCH principle
- Development of Microchannel Plate PMTs
- TORCH prototype & test beam analysis
  - Time resolution and photon yield performance
- TORCH for LHCb Upgrade II
- A few words about FCC-ee
- Summary

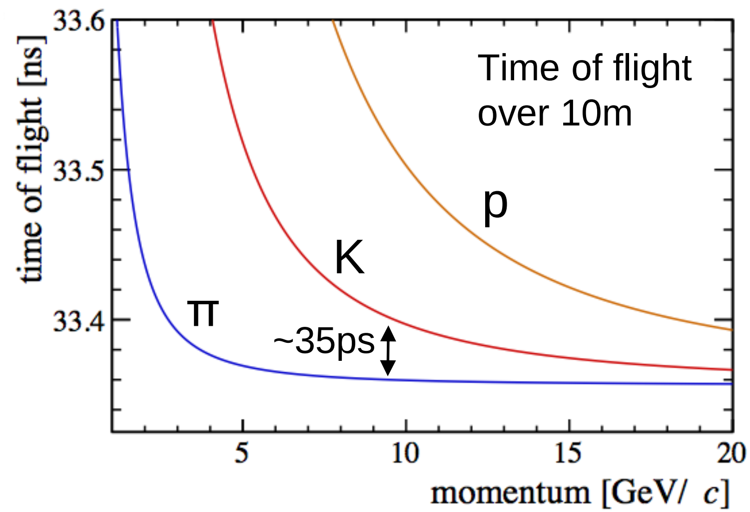
General introduction to TORCH

- TORCH (Time Of internally Reflected CHerenkov light) is an project to develop a large-area time-of-flight system for LHCb Upgrade II.

- π-K TOF difference = 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

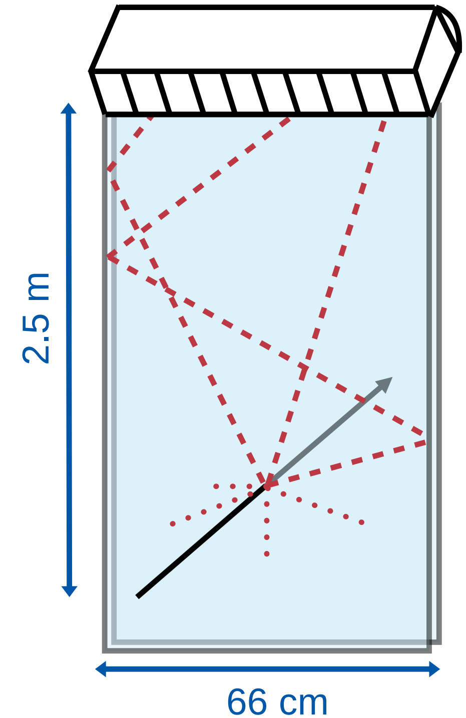
- The σ_{TOF} requirement dictates timing single photons to a precision of 70 ps for ~30 detected photons



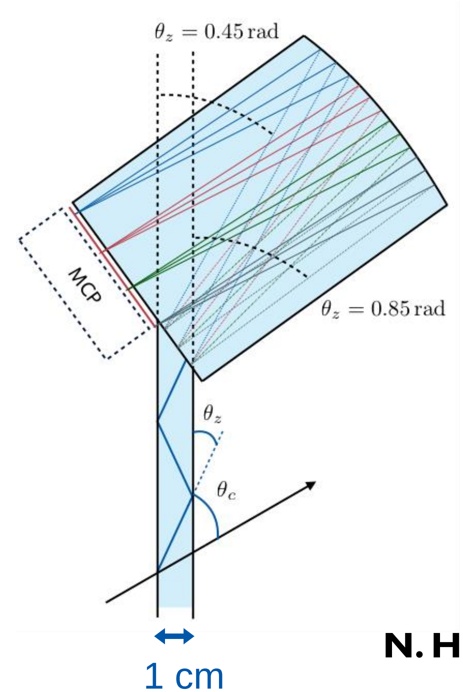


The TORCH detector

- A charged track produces Cherenkov light in a plane of 1 cm thick quartz
- Cherenkov photons travel to the periphery of the detector by total internal reflection and focused → their position and arrival time is measured by Micro-Channel Plate PMTs (MCPs)
- The Cherenkov angle θ_c and path length L in the quartz are measured. The time of arrival is used to correct for the chromatic dispersion in the quartz and thence the ToF.
- From simulation, ~1 mrad precision is required on measurement of the angles in both planes to achieve the required intrinsic timing resolution



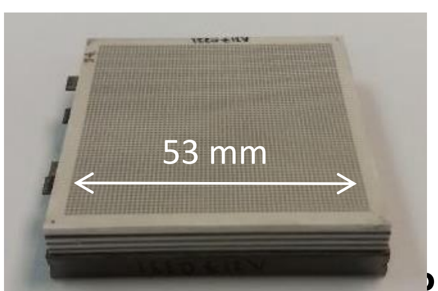
Non-focussing plane

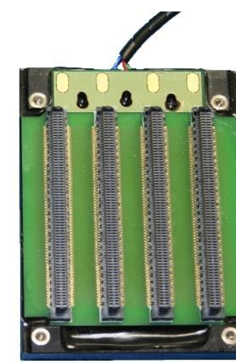


Focussing plane

TORCH MCP-PMT development

- The Cherenkov photons are focused onto Micro-Channel Plate PMTs, custom designed to give the 1 mrad precision
- These have been developed by industrial partner Photek UK in a phased development programme
- Each detector has a granularity of 64 x 64 pixels over a 53 x 53 mm^2 active area. A readout PCB is connected via Anisotropic Conductive Film
- Charge sharing and channel grouping is used to achieve an effective granularity of 128 x 8 pixels, to give the 1 mrad precision
- The MCPs have ALD coating and are designed to withstand an integrated charge of 5 C/cm^2
- 10 MCP-PMTs have been delivered from Photek





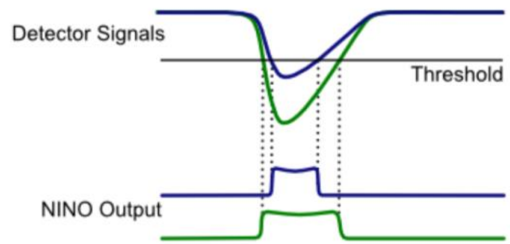
TORCH readout electronics

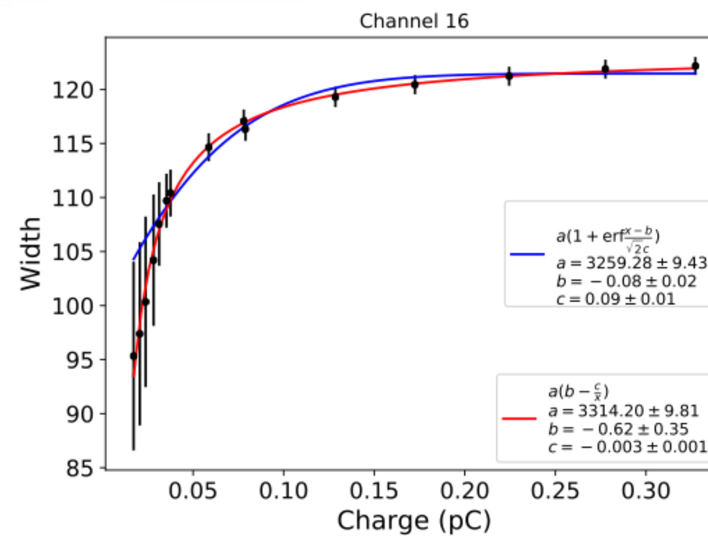
- Customised 128-channel system (4 boards/MCP) developed based on the ALICE TOF system: NINO + HPTDC [F. Anghinolfi *et al*, Nucl. Instr. and Meth. A 533, (2004) 183, M. Despeisse *et al*., IEEE 58 (2011) 202]

- NINO-32 provides time-over-threshold information which is used to correct time walk & charge to width measurement. Non-linearities of HPTDC time digitization (100 ps bins) are also corrected

- The calibrations are challenging and work is still ongoing to optimize them

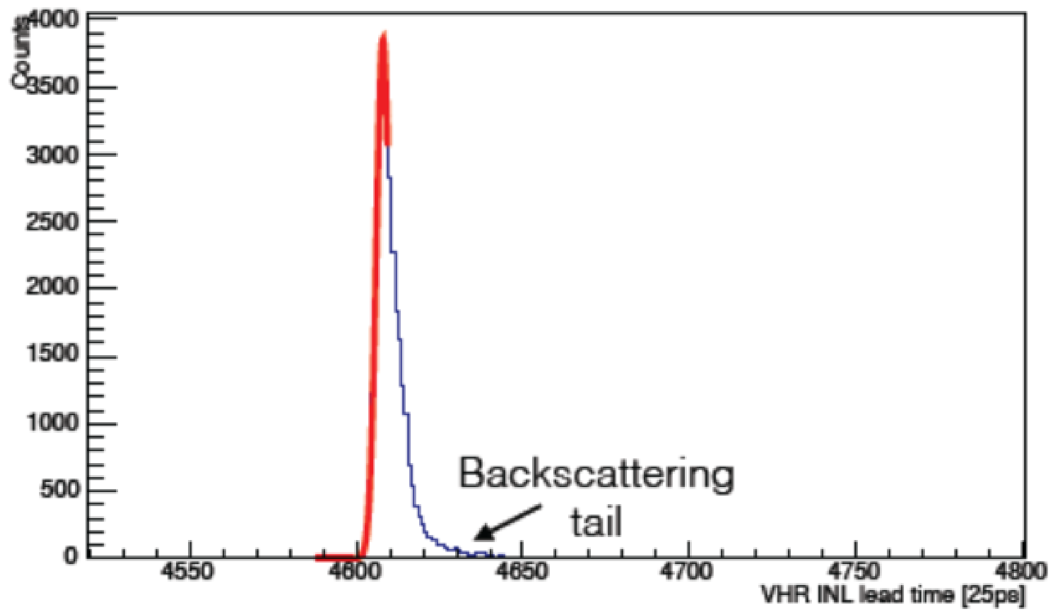
R. Gao *et al*., JINST 10 C02028 (2015)





Time resolution – lab measurements

- Illuminate single pixel of MCP-PMT with fast pulsed laser
- Operate HPTDC in 25 ps mode (compared to 100 ps in the testbeam)
- For analysis, select signals of ~same width to control time walk effects
- Measured resolution of 49.6 ps (comparable to expectation of 50 ps)



TORCH prototypes

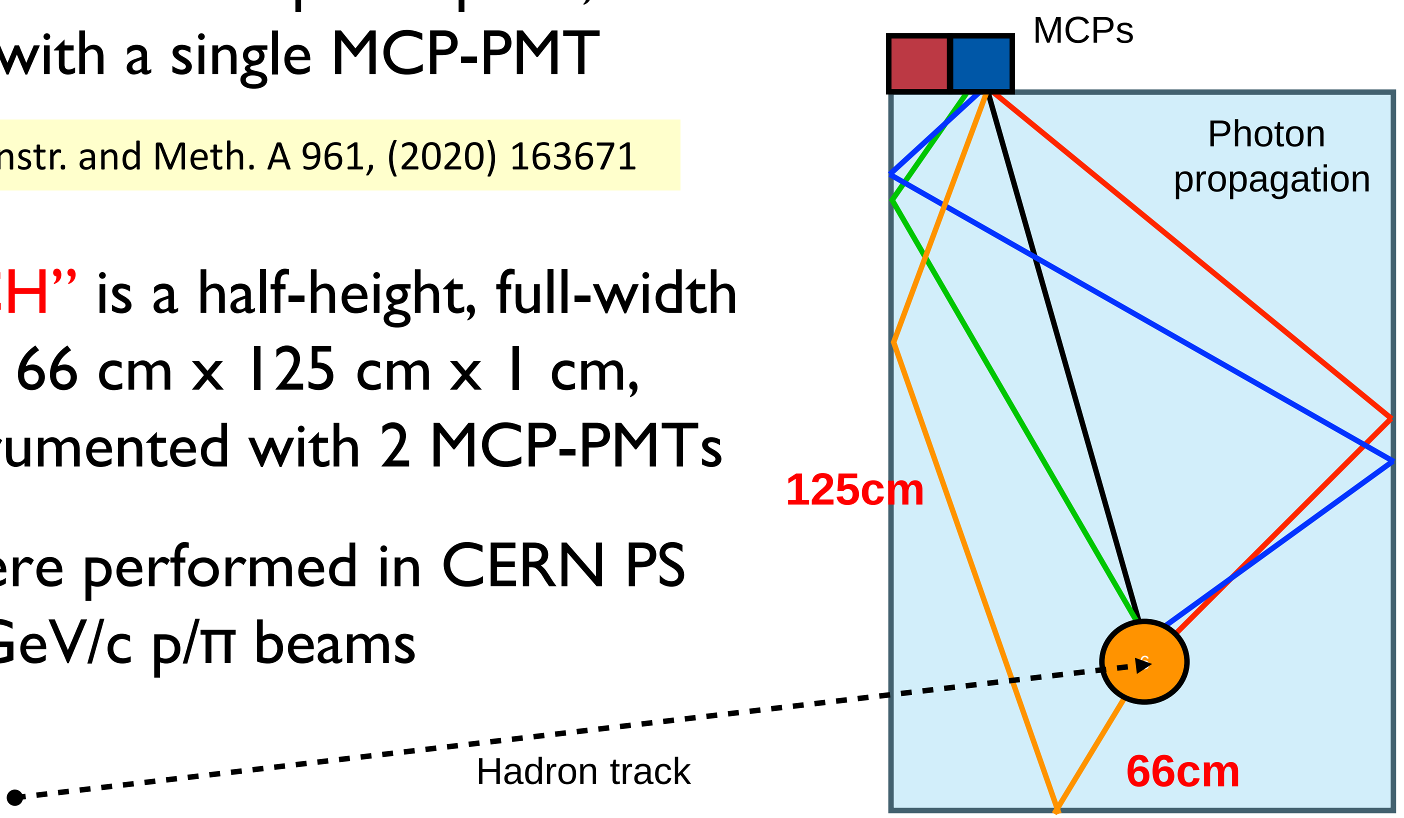
- TORCH prototypes have been tested in several beam tests between 2015 and 2018

- "Mini-TORCH" is a small scale module with a 12 cm x 35 cm x 1 cm quartz plate, instrumented with a single MCP-PMT

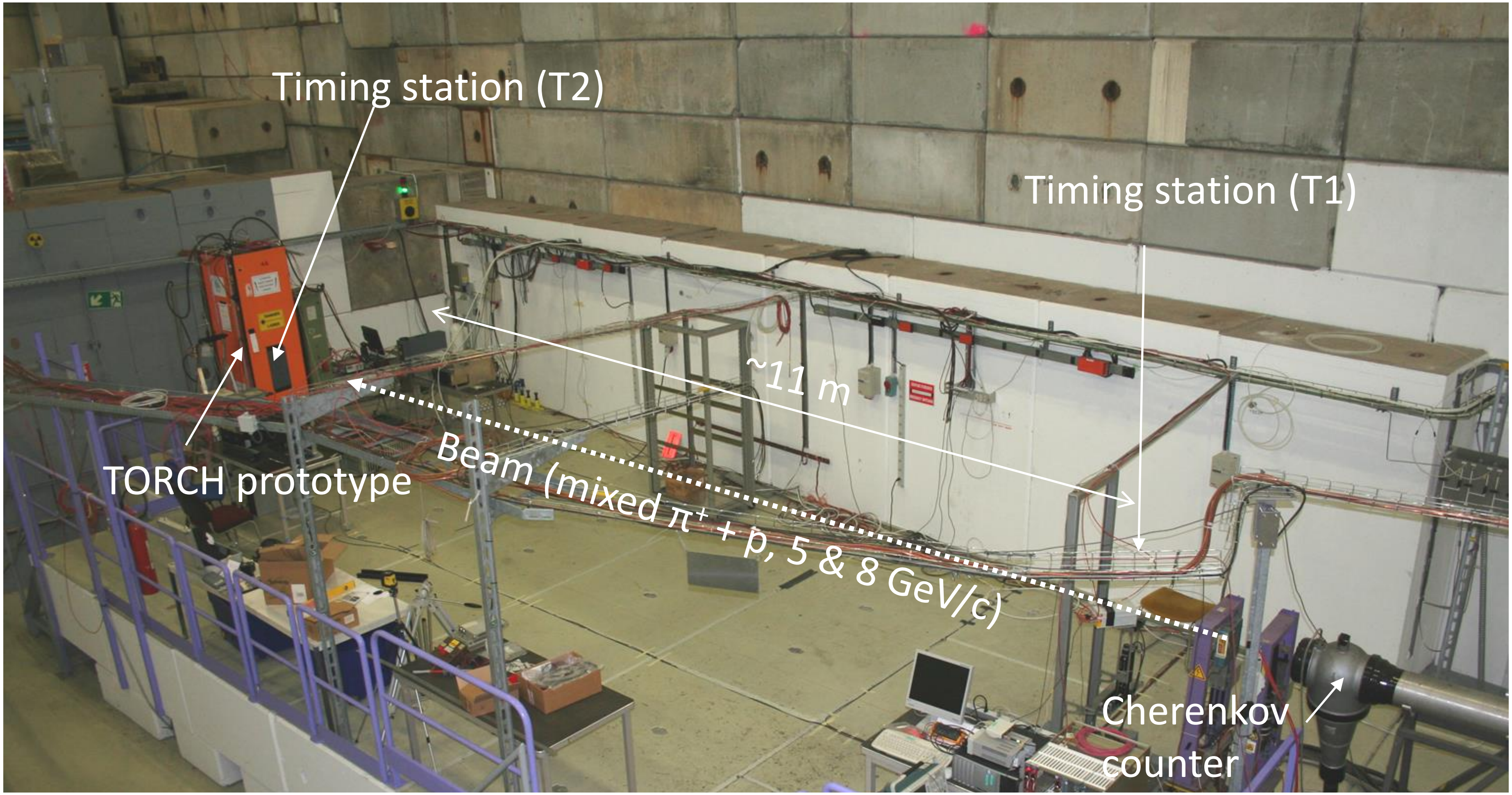
S. Bhasin et al Nucl. Instr. and Meth. A 961, (2020) 163671

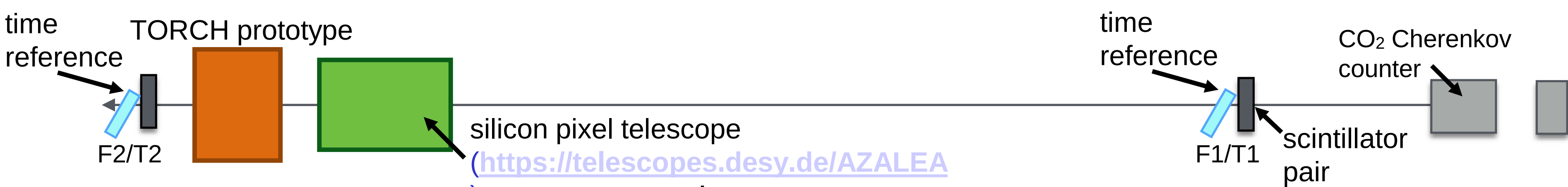
- "Proto-TORCH" is a half-height, full-width LHCb module 66 cm x 125 cm x 1 cm, currently instrumented with 2 MCP-PMTs

- Beam tests were performed in CERN PS with 5 and 8 GeV/c p/π beams



TORCH beam test infrastructure in PS/T9



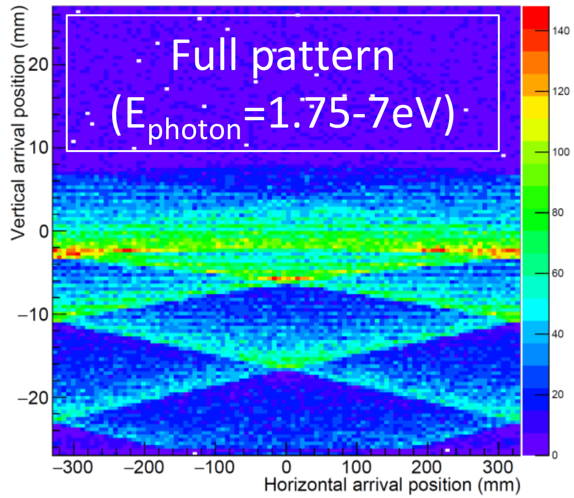


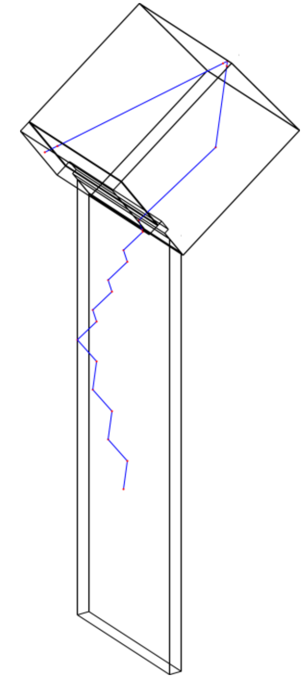
(https://telescopes.desy.de/AZALEA)

A word on the pattern folding

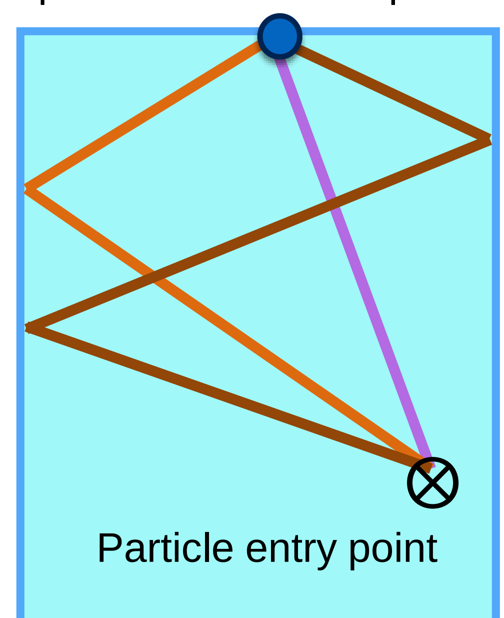
- Cherenkov cone results in hyperbola-like patterns at the MCP plane
- Reflections off module sides result in folding of this pattern
- Chromatic dispersion spreads line into band

Geant simulation





photon x-detection point



- The pattern shown above for a full TORCH module, however this pattern is only *sampled* with partially instrumented MCPs in the testbeam.
- The nominal test-beam configuration is chosen to give cleanly resolved patterns.
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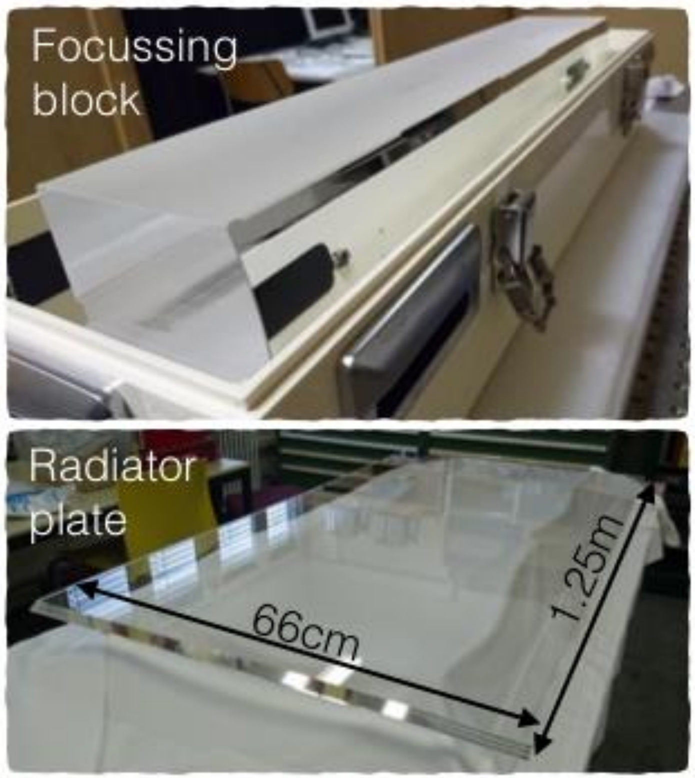
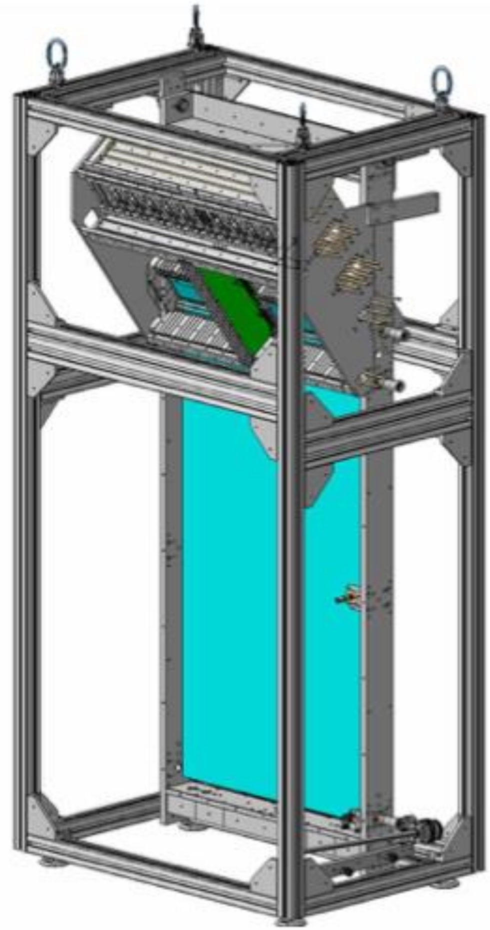
"Proto-TORCH" demonstrator

- A half-sized TORCH module : $125 \times 66 \times 1\ cm^3$ tested last year
- Optical components from Nikon (radiator plate, focusing block)

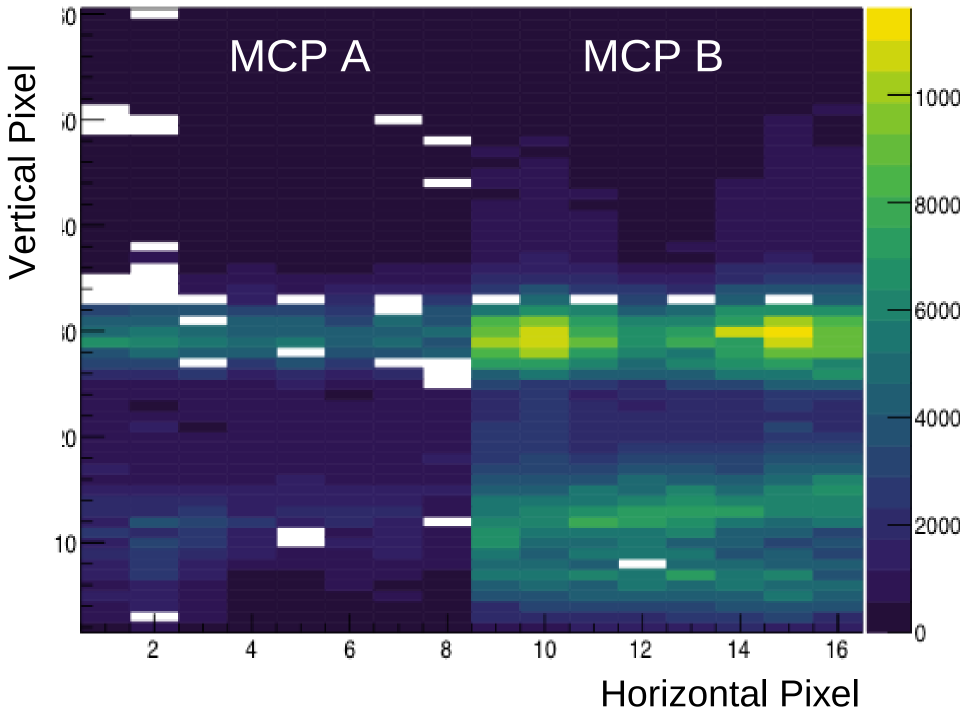


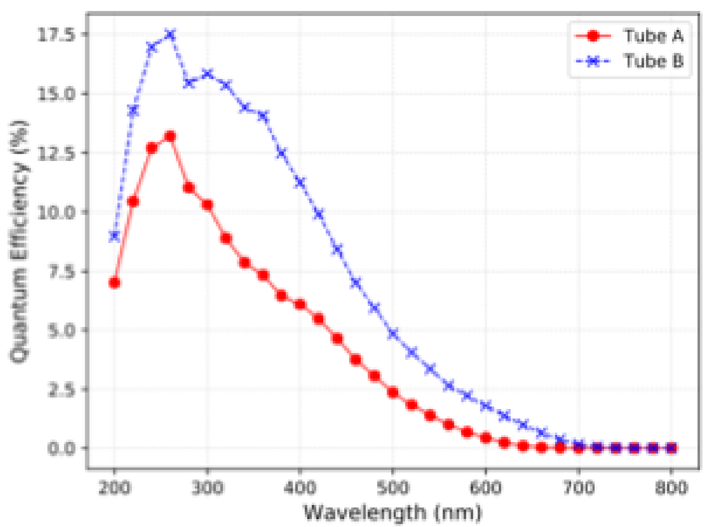


Proto-TORCH hitmap

Hitmap

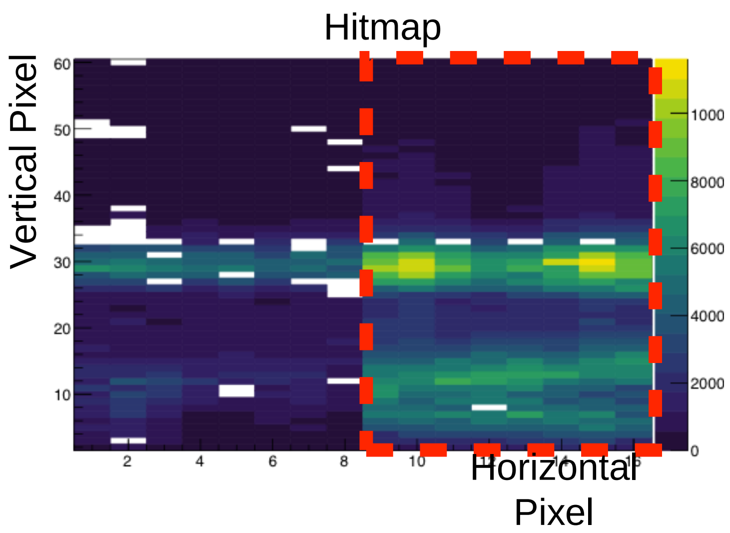
Time reference channels

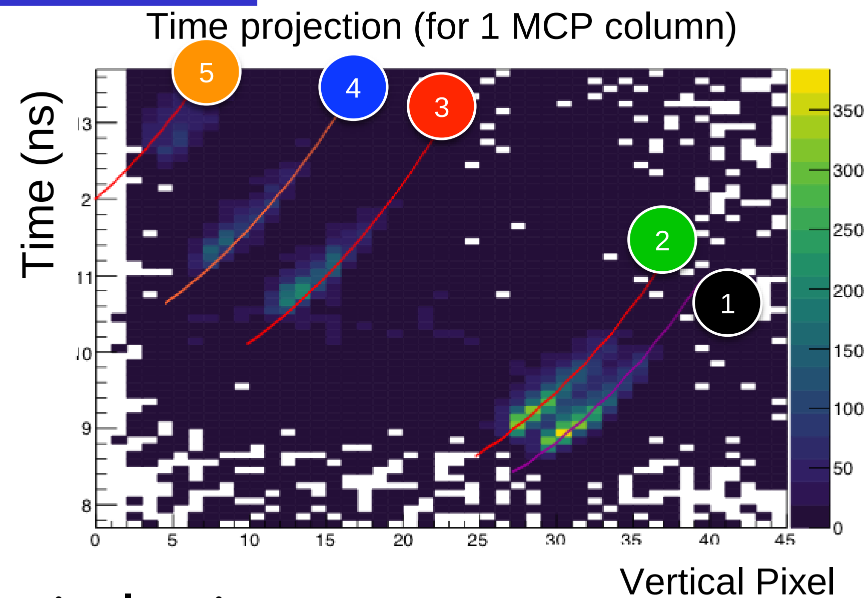




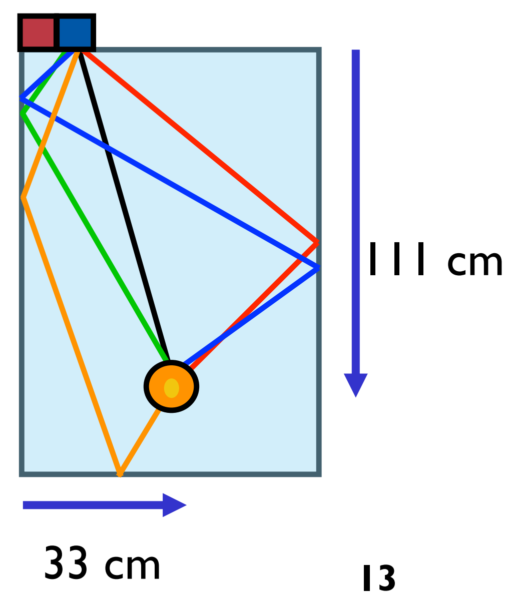
- The analysis focuses on MCP B with the higher quantum efficiency
- Use charge sharing in the MCP to measure the cluster centroid of each photon hit

Reflection patterns



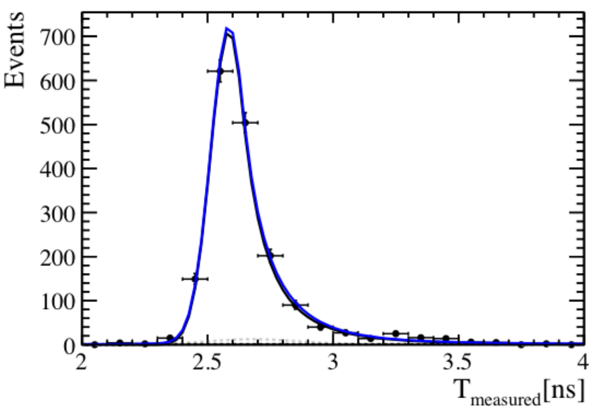


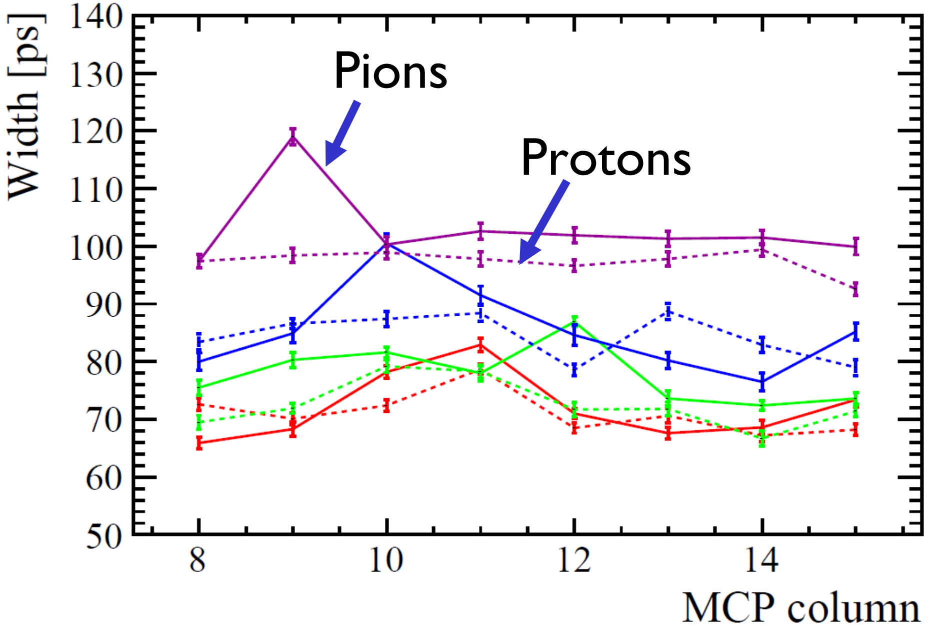
- Project the hits in the time-of-arrival axis to separate the different orders of side reflections
- The overlaid lines represent reconstructed predictions
- The spread in times for each order of reflection is measured to determine the single photon time resolution

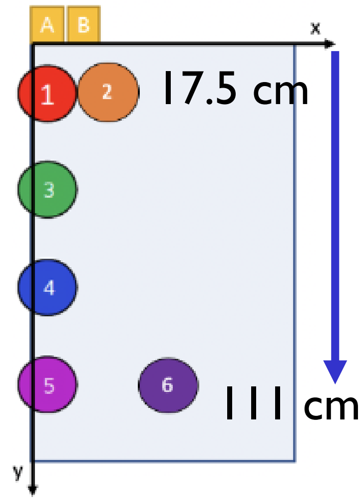


Time resolution studies

- Plot residual distributions of single-photon time resolution for first order reflections versus MCP column number
- A simultaneous fit determines the spread in the time of arrival at each pixel







- As expected, we see some degradation of time resolution with height in the radiator
- Nevertheless, the time resolution is approaching or matches the design goal of 70 ps

Resolution studies continued

- The time resolution can be parameterized into different contributions

T. Hadavizadeh et al. PoS EPS-HEP2019 (2020) 140

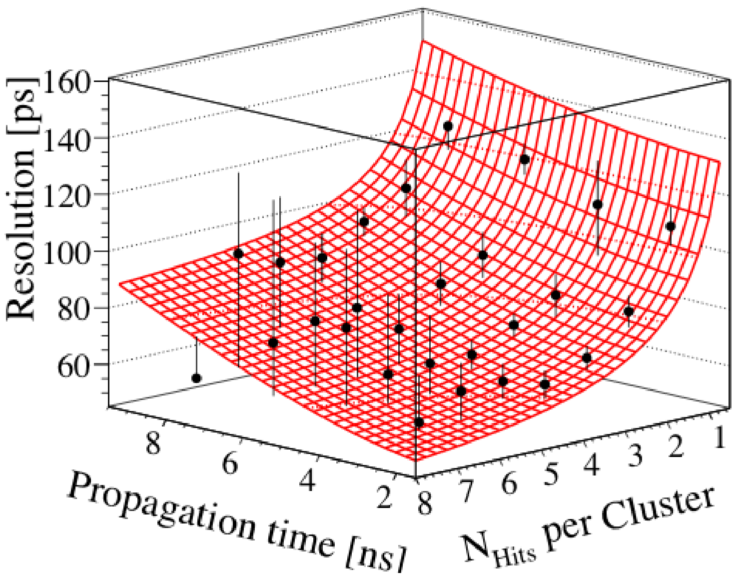
Time resolution parameterisation:

$$\sigma^2_{\mathrm{TORCH}} = \sigma^2_{\mathrm{const}} + \sigma_{\mathrm{prop}}(t_P)^2 + \sigma_{\mathrm{RO}}(N_{\mathrm{Hits}})^2$$

e.g. MCP

Propagation time (t_P) dependent effects

Electronics and readout resolution



$$\sigma_{\mathrm{const}} = 33.0 \pm 7.1\,\mathrm{ps}$$
$$\sigma_{\mathrm{prop}}(t_P) = (7.8 \pm 0.7) \times t_P\,\mathrm{ps}$$
$$\sigma_{\mathrm{RO}}(N_{\mathrm{Hits}}) = \frac{100.5 \pm 5.7}{\sqrt{N_{\mathrm{Hits}}}}\,\mathrm{ps}$$

[with t_P in ns]

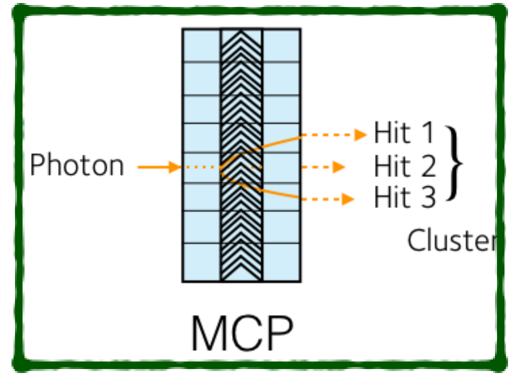
Ideal values from simulation

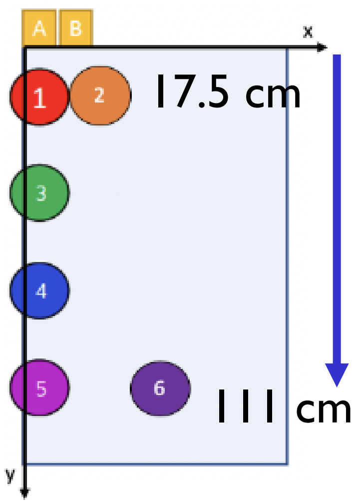
$$\sim 33\,\mathrm{ps}$$
$$\sim (3.75 \pm 0.8) \times t_P\,\mathrm{ps}$$
$$\sim \frac{60}{\sqrt{N_{\mathrm{Hits}}}}\,\mathrm{ps}$$

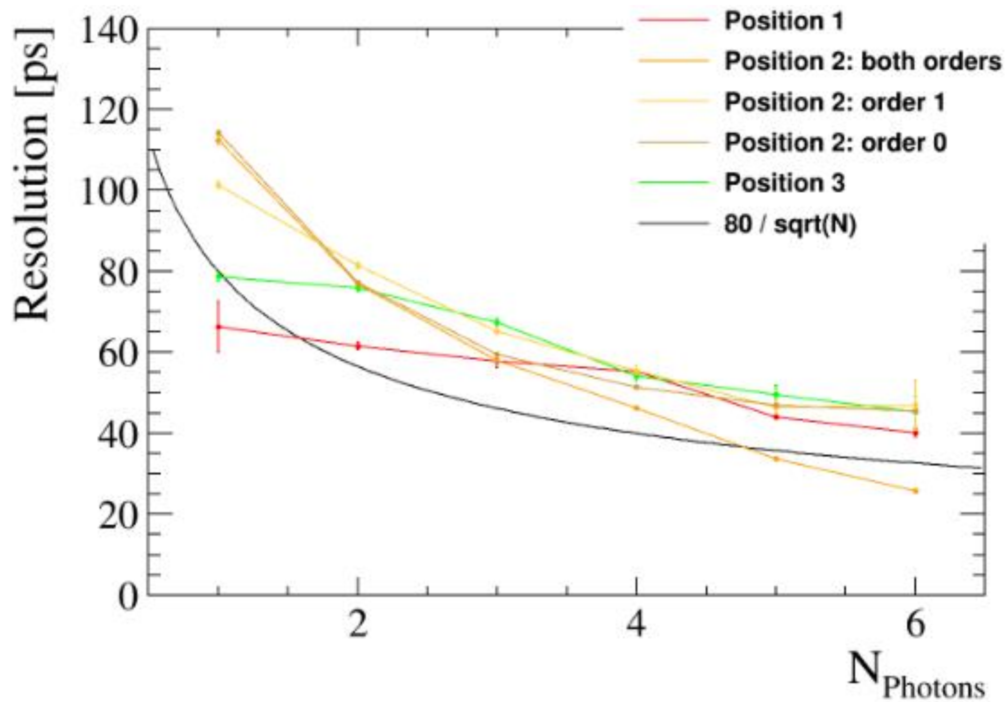
Further improvements from calibrations expected

Resolution studies continued

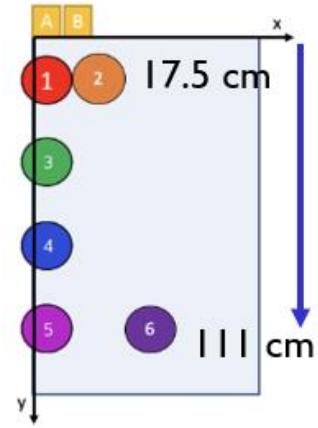
- Plot the time resolution for increasing number of photon clusters
- Compare to $1/\sqrt{N_{photon}}$ dependence





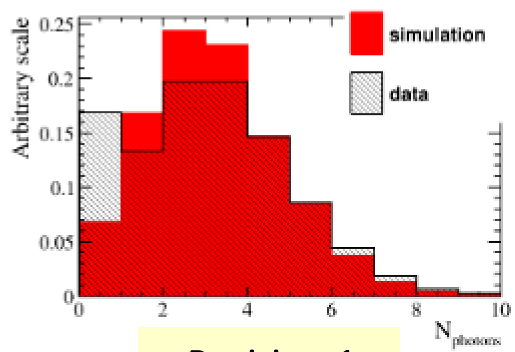


Photon yields vs vertical height

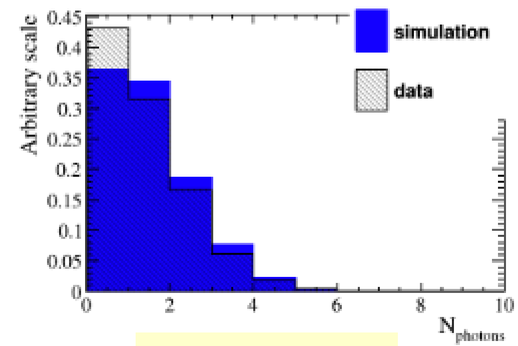


- Photon yields compared to simulation (which includes MCP quantum efficiency, collection efficiency, surface roughness etc)

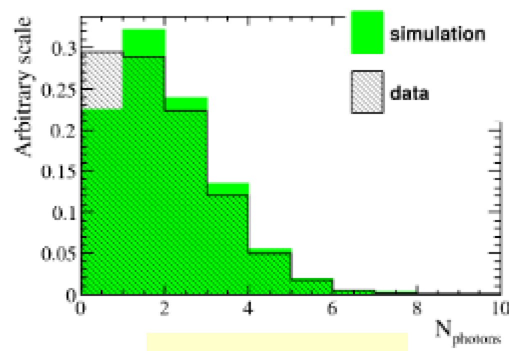
- Excellent agreement with MC – acceptance effects well modelled
- Note: the current prototype only has 2 out of 11 MCPs
  - Photon yields would be ~5.5 times larger than shown here
- Also final module expected to have much improved quantum efficiency



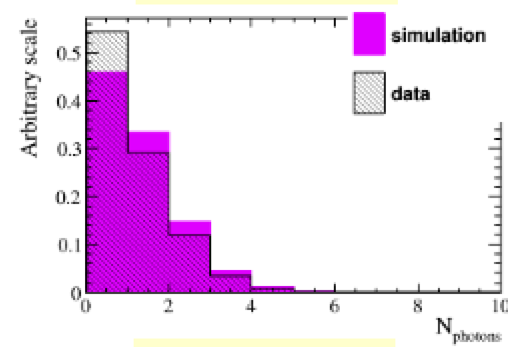
Position 1



Position 4



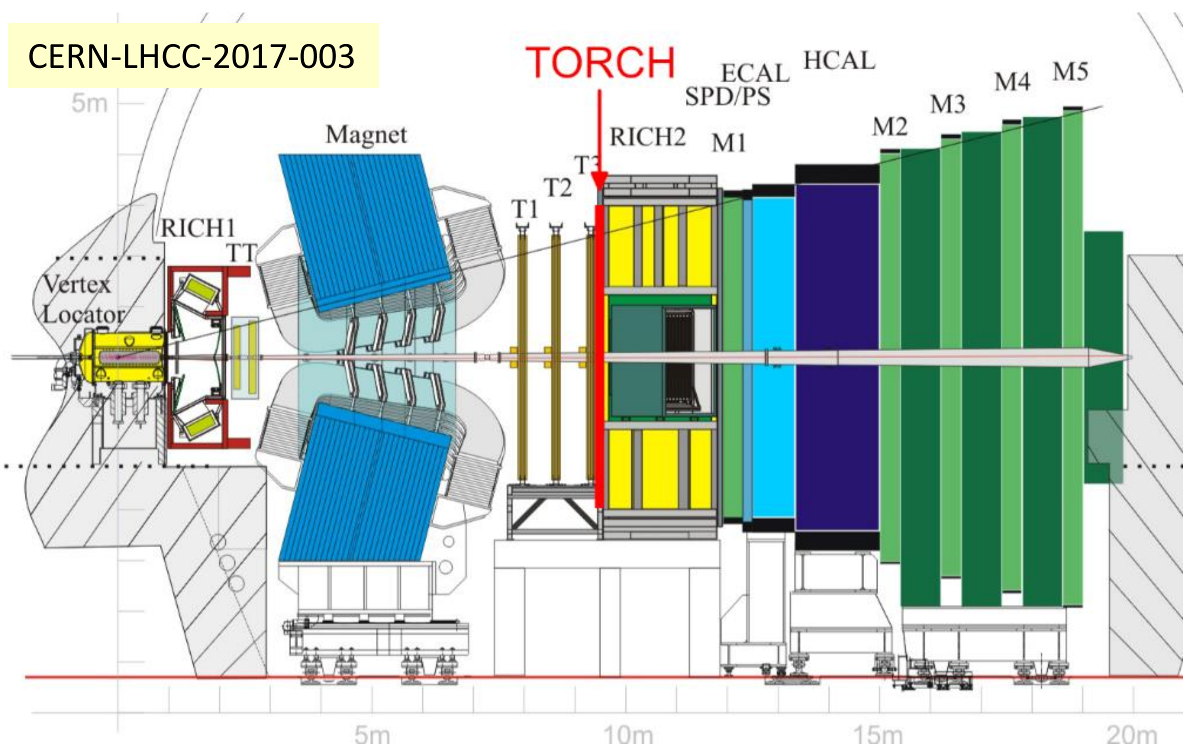
Position 3



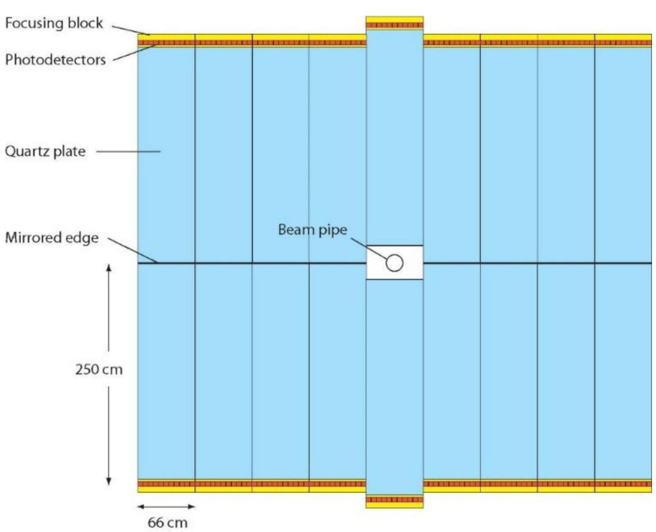
Position 5

TORCH for LHCb

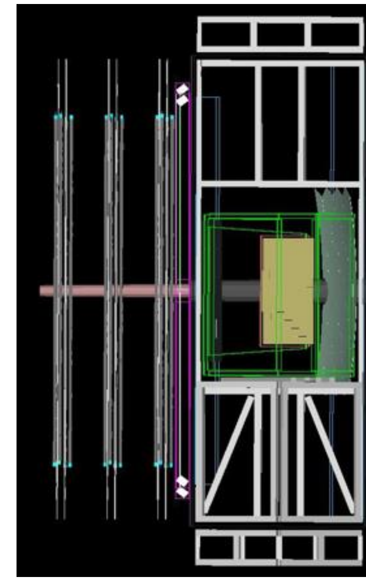
- The RICH system provides particle ID in LHCb
- But currently no positive kaon or proton ID below ~10 GeV/c
- Proposal to install TORCH in front of RICH2



- TORCH area 5 x 6 m^2
- 18 module system
- 11 MCPs per module



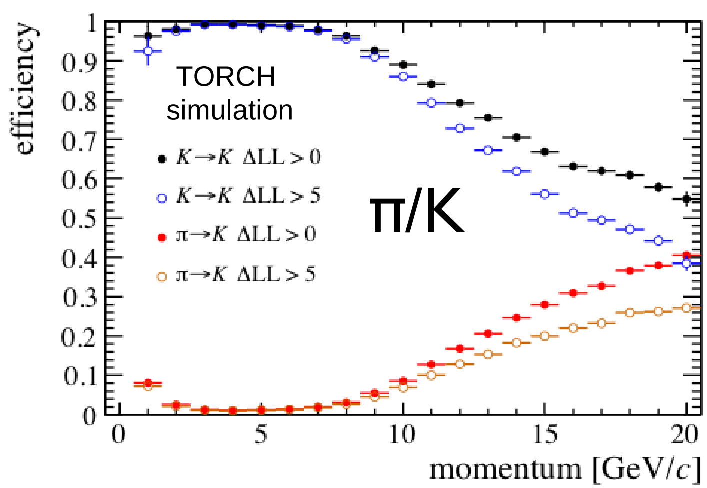
Simulated performance at LHCb

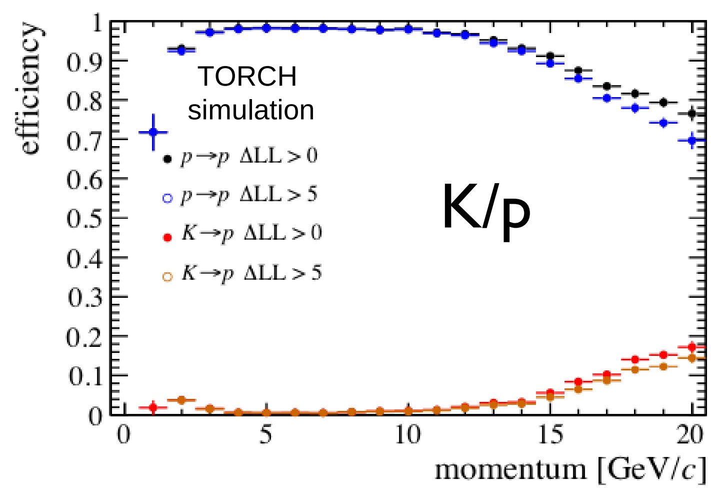


- TORCH has been simulated in the framework of the Upgraded LHCb detector (GEANT4)
- The PID performance was first determined for Upgrade IB conditions (Run 4)

$$\mathcal{L} = 2.0 \times 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

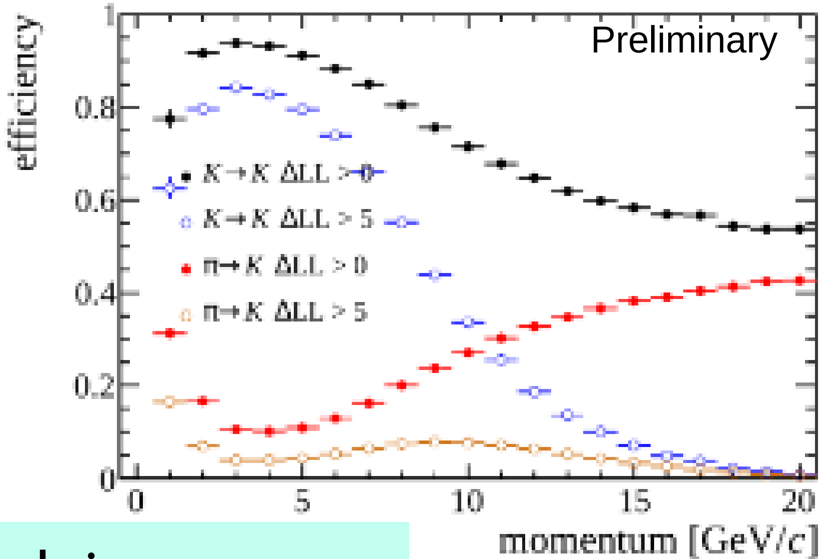
- Excellent separation expected between π/K/p in the 2 -10 GeV/c range and beyond.

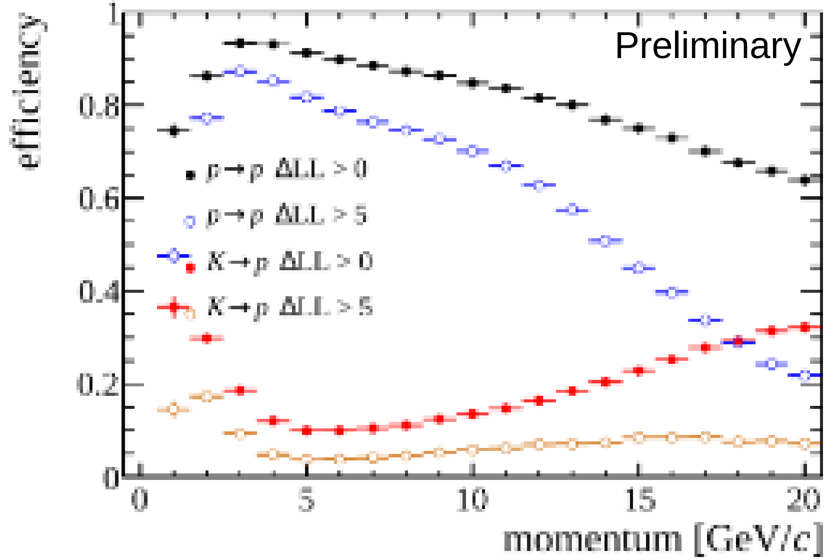




PID performance @ high luminosity

- The PID performance has next been simulated for Upgrade II conditions $\mathcal{L} = 1.5 \times 10^{34}\ cm^{-2}\ s^{-1}$
- "Out of the box" performance shows degradation, but is quite robust against the huge (>50-60%) occupancies for baseline 64 x 8 MCP, and there is still significant separation power
- Significant improvements expected (i.e. tuning granularity across modules to keep average occupancies everywhere below 20%)

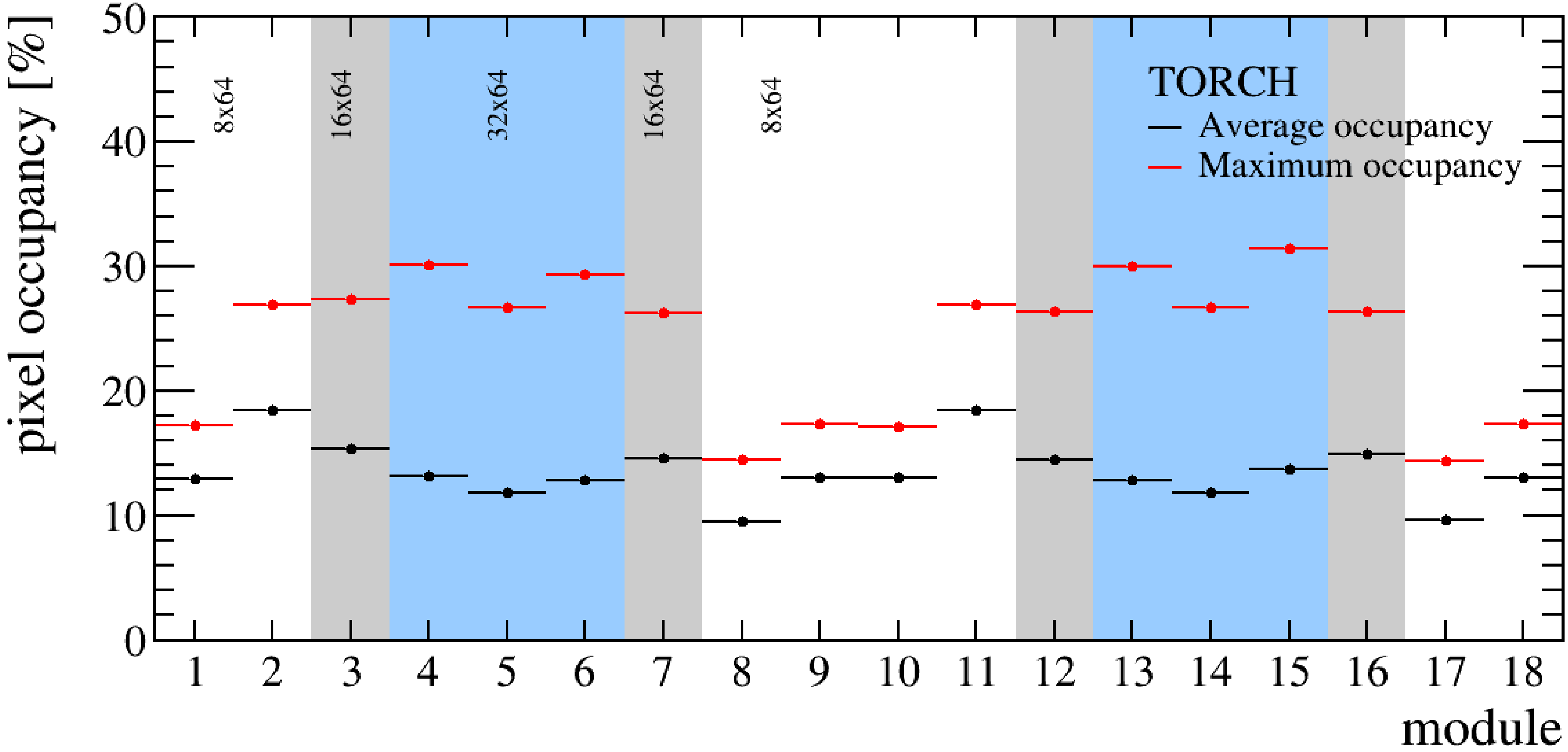




Work in progress

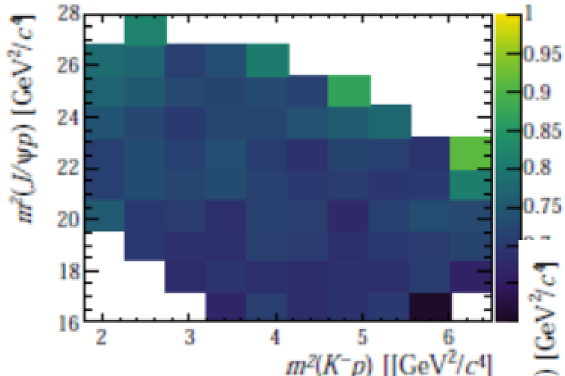
Optimization of occupancies

Work in progress

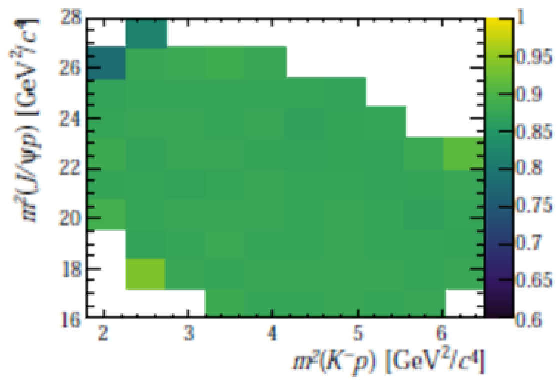


LHCb physics studies

- The simulated PID performance is used to quantify the benefits of TORCH to the LHCb experiment in various physics channels
- Modes with low-momentum kaons and protons benefit the most
- TORCH will provide
  - Increased signal efficiencies
  - Reduced Particle mis-ID backgrounds
  - Reduced dependence on PID efficiencies on momentum



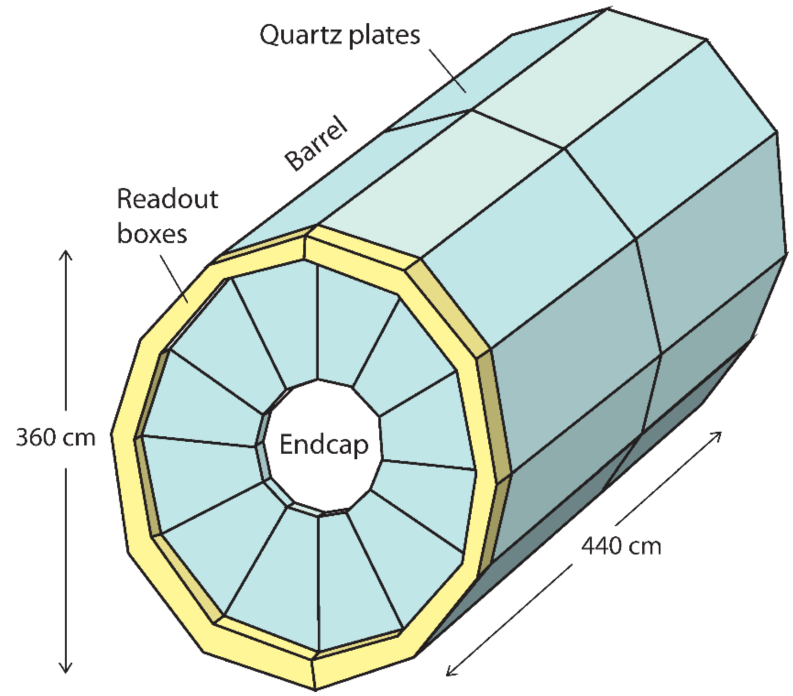
Pentaquark mode
$\Lambda_b^0 \rightarrow J/\psi p K^-$



- TORCH also brings benefit to flavour tagging algorithms
  - ~25-50% improvement to OSKaon & SSkaon taggers
  - Potential to impact a range of analyses

TORCH possibilities for FCC-ee

- Some ideas of possible geometry has been discussed
  See Maarten van Dijk https://indico.cern.ch/event/838435/contributions/3658402/
- Strawman barrel geometry with 12-fold symmetry
- Assume placing TORCH detector at the end of tracking volume (at radius of 180 cm)
- Larger distance from PV helps, but amount of material in front is also important
- One could possibly add endcap modules



Challenges for FCC-ee

- At FCC-ee, flight distance is of order 2m compared to almost 10m at LHCb
- The K-π time difference for arrival of particles to TORCH is given by $t_K - t_\pi \approx \frac{x}{c}\frac{1}{2p^2}[m_K^2 - m_\pi^2]$
- With p=10 GeV/c and x=1.8 m the time difference is about 6.7 ps (cf. ~35 ps at LHCb)
- Additional separation comes from the photon propagation time inside radiator bar of about 7.3 ps
  - Effect due to the small difference in Cherenkov angle
- i.e ~14 ps time difference between K & π

Challenges for FCC-ee continued

- ~30 detected photons for 1cm quartz (same as LHCb)
- For 3σ separation, need ~4.7 ps per track time resolution
- With 30 photons, need 25.6 ps per photon time resolution
- Need to significantly improve angular resolution ⇒ smaller pixels (would need 192 x 44)
  - Compare to current LHCb prototype with 64x8
  - Maximum we are aware of is 96 x 96, so significant development would be needed to double that
- Best single channel MCP-PMT has about σ=10 ps
  - σ=20-30 ps probably achievable with eg. picoTDC, but scaling to sufficiently granular detector requires work
  - SiPMs with high granularity and QE could be a good way forward

Summary and outlook

- The TORCH project is progressing well, with a successful series of beam tests

- The time resolution of the prototype is approaching the design goals : 70 -100 ps timing resolutions per single photon achieved. With improvements in calibration hope to achieve consistently the desired 70 ps. Photon yields are consistent with expectations.

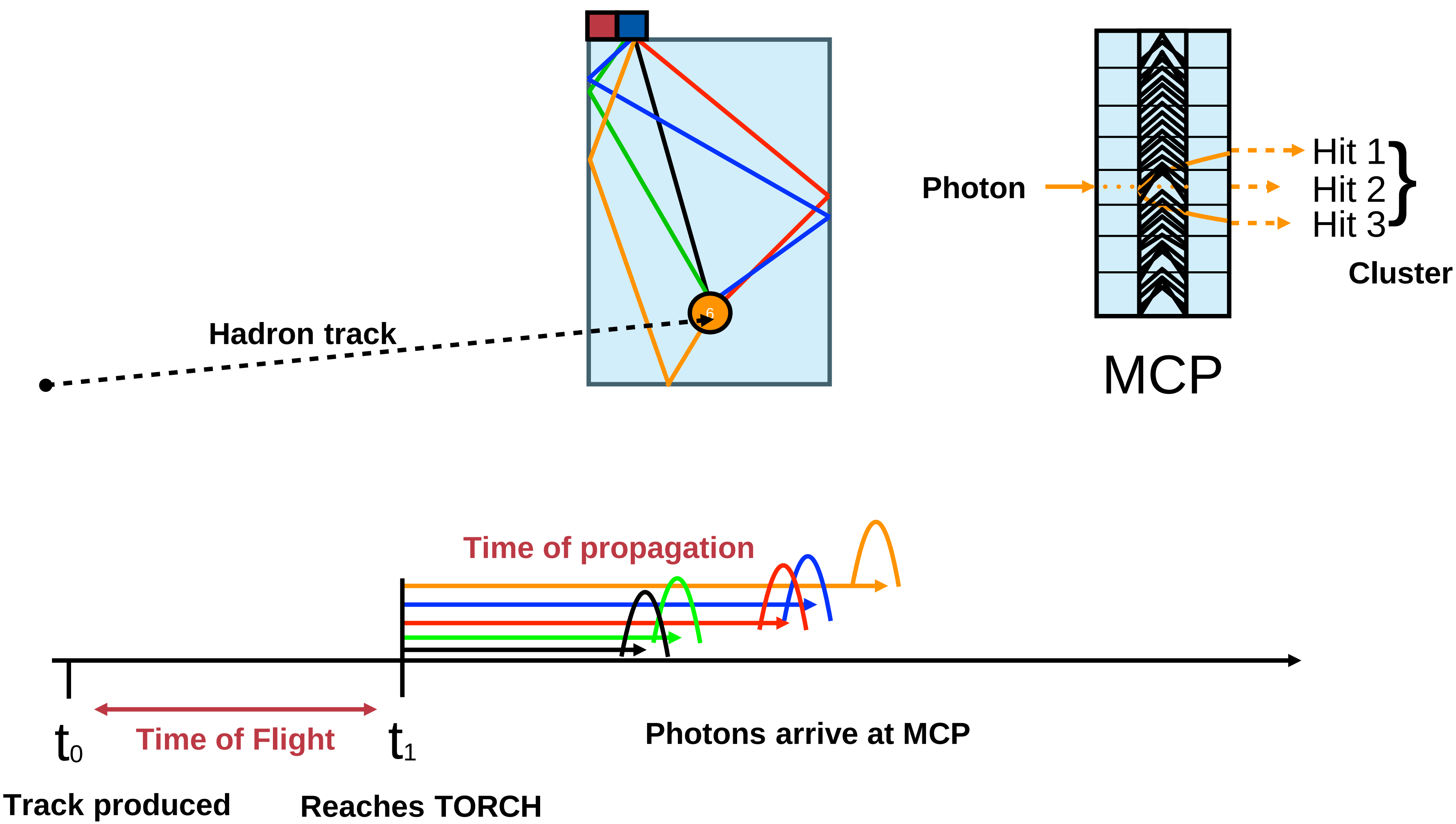
- TORCH has been simulated in the LHCb experiment. Studies have indicated significant improvements to the LHCb physics potential. Also possibilities for FCC-ee but needs R&D.

- Future beam tests in ~1 year will involve the fully instrumented (11 MCP) half-height TORCH module

Thanks for your attention

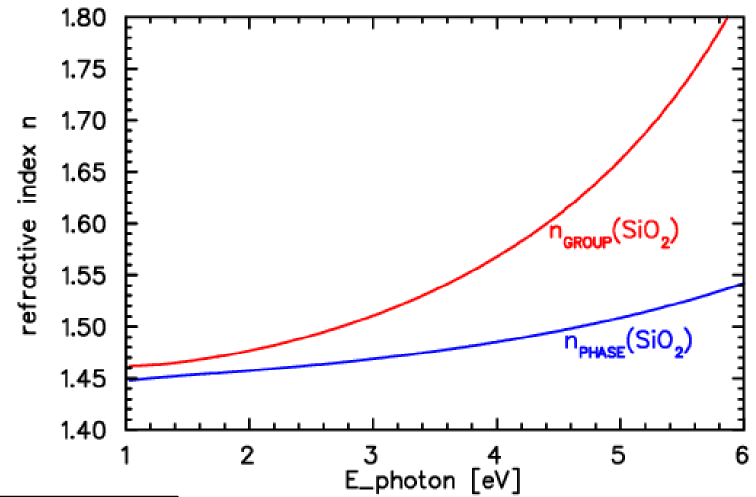
Spare slides from here on

TORCH schematic

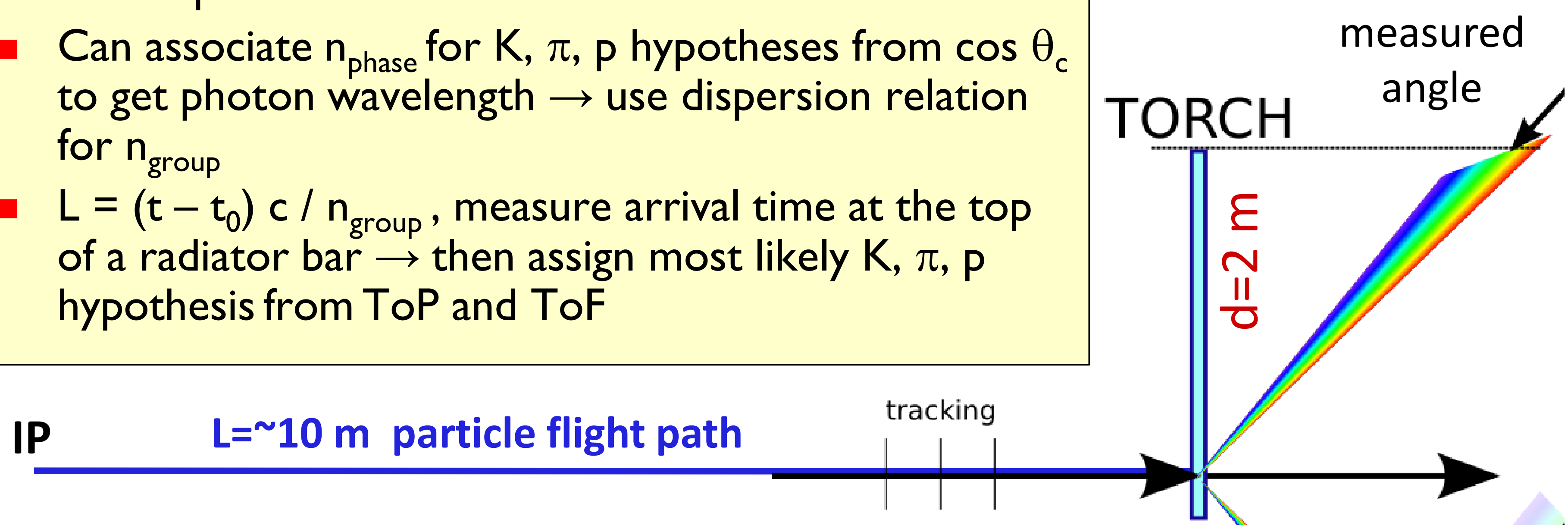


Principle of ToF reconstruction

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

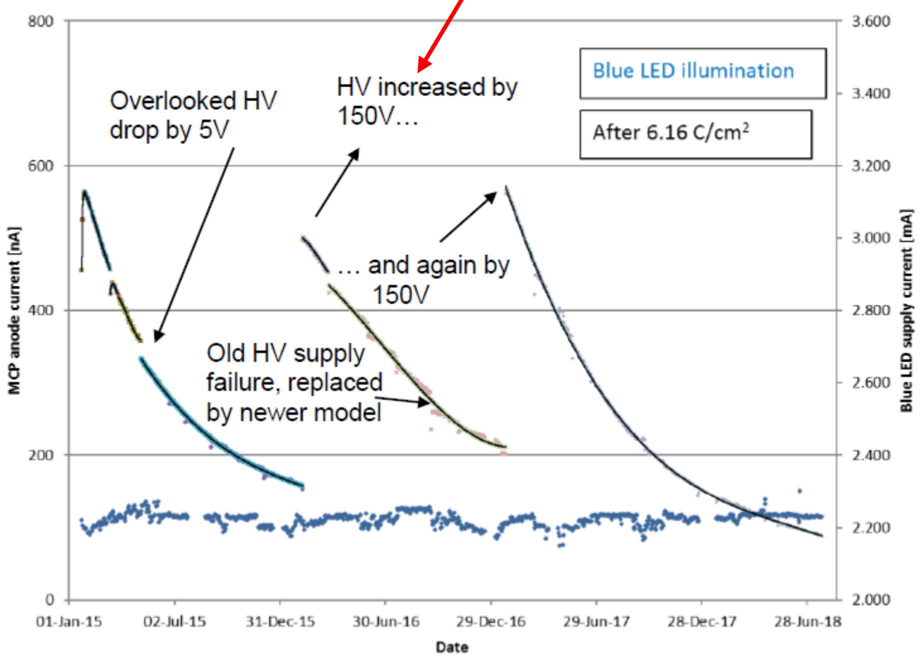


Lifetime measurements (Phase 1 tube)

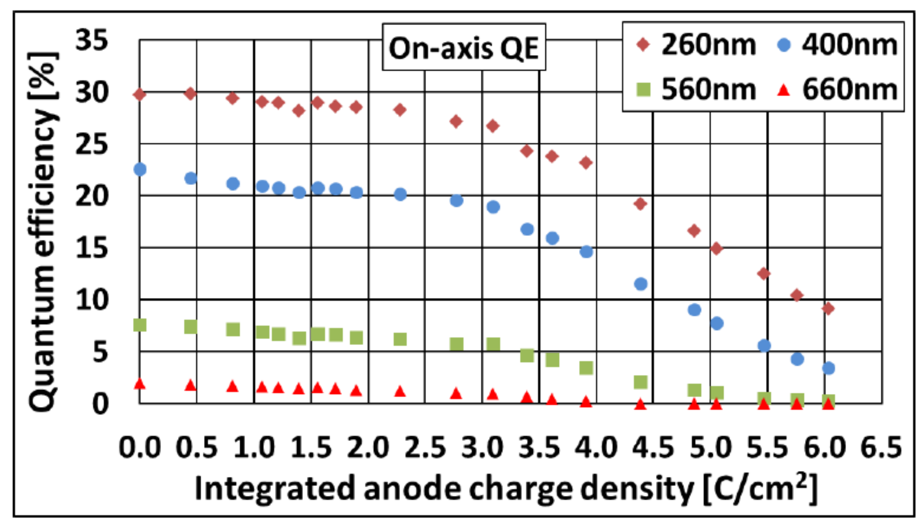
- Lifetime requirement 5 C/cm^2 : implement ALD coating.
  - Illumination up to 6.16 Ccm^{-2}
  - Gain drop observed, recovered by increase of HV
  - Marginal loss in quantum efficiency (at 3 C/cm^2) : a factor ~2 loss at 5 Ccm^{-2}. Hope is Phase 3 tubes will improve on this.

Long-term test
blue LED illumination

HV increased:
2300 → 2450 V

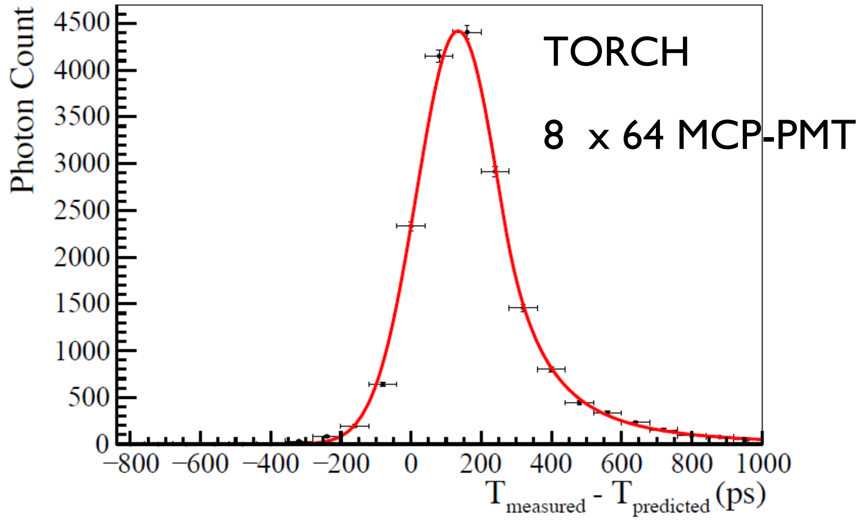


Results updated from :
T. Gys et al., (RICH2016)
NIM 876 (2017) 156.



Time resolution : mini-TORCH

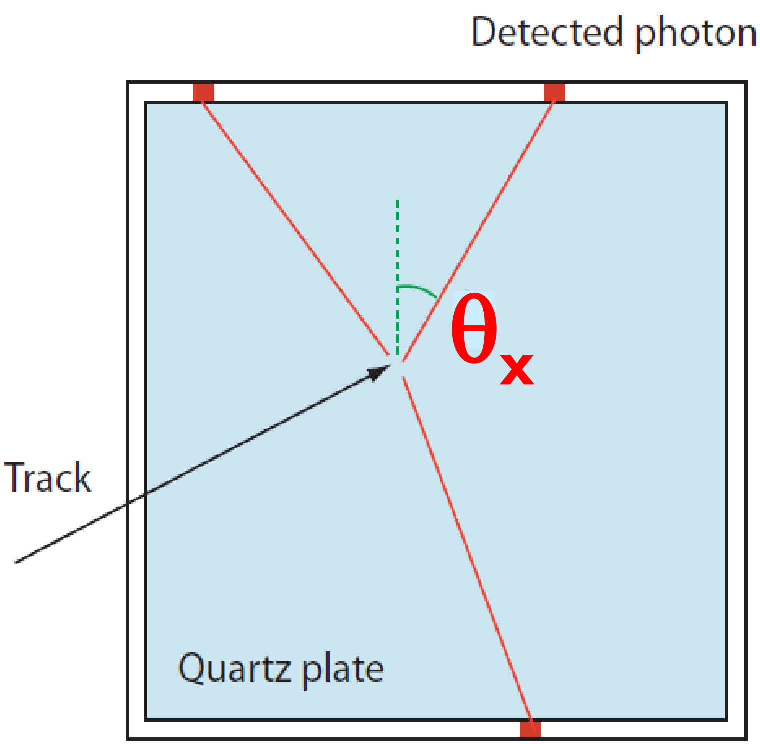
- Plot residuals for reflections 0 and 1'
- Subtract contribution from timing reference (~40 ps)
- We measure resolutions of typically100 ps per photon
- The target resolution is 70 ps per photon: improvements are possible to achieve this :
  - Improved pulse-height to width calibration
  - Limit of 100 ps binning in HPTDC

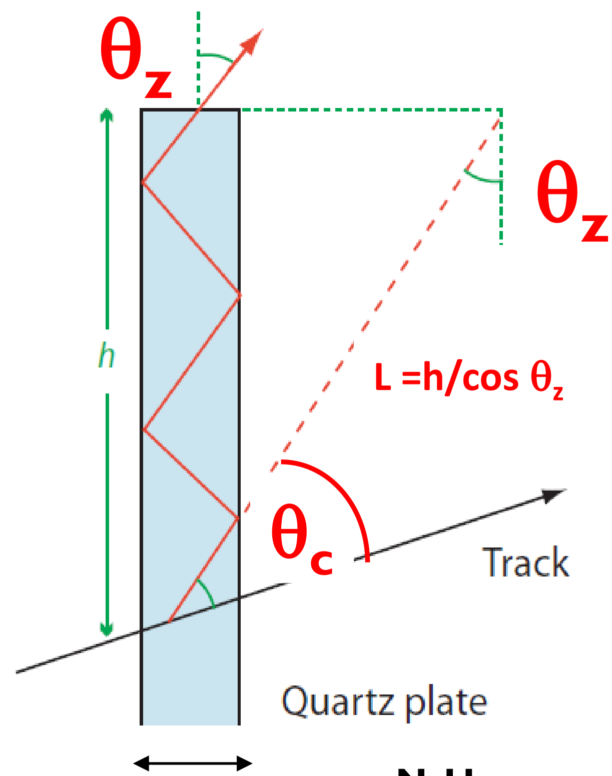


MCP Column	σ_{TORCH} Pions (ps)	σ_{TORCH} Protons (ps)
1	110.6 ± 1.2	112.7 ± 1.4
2	101.7 ± 1.2	110.6 ± 1.4
3	101.5 ± 1.2	110.6 ± 1.4
4	105.5 ± 1.2	106.2 ± 1.4
5	83.8 ± 1.3	91.0 ± 1.4
6	101.3 ± 1.2	103.4 ± 1.2
7	90.3 ± 1.2	87.5 ± 1.4
8	112.4 ± 1.1	102.8 ± 1.4

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



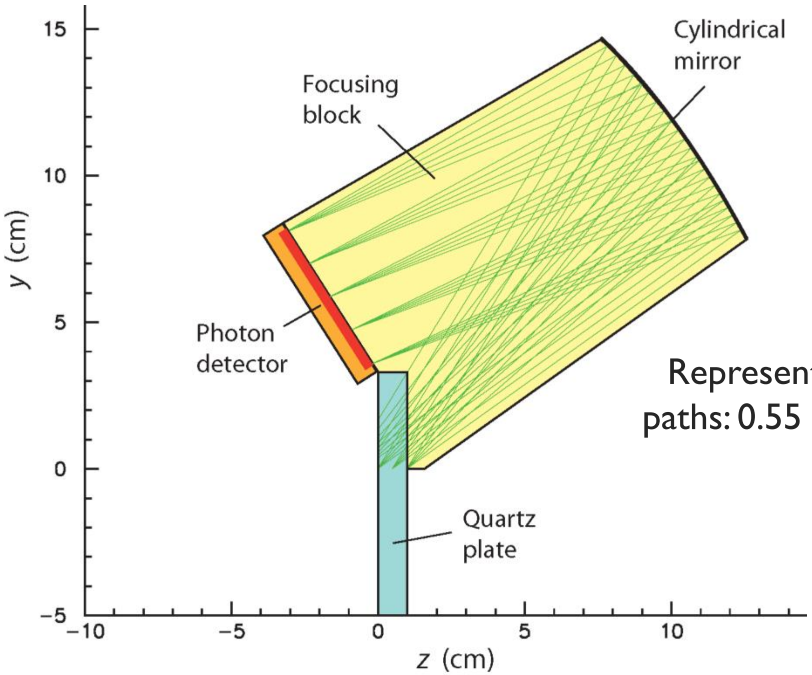


TORCH angular measurement (θ_z)

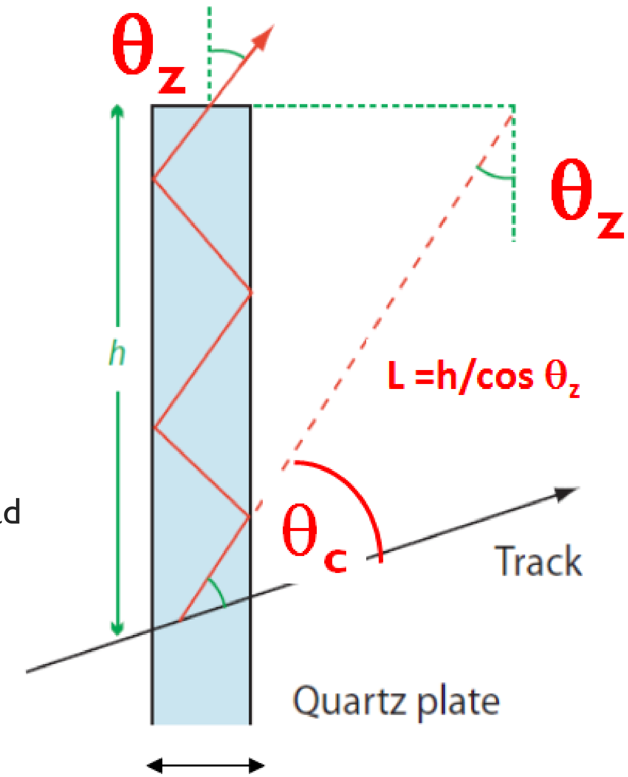
- Measurement of the angle in the longitudinal direction (θ_z) requires a quartz (or equivalent) focusing block to convert angle of photon into position on photon detector
- $\rightarrow$ Cherenkov angular range = 0.4 rad

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

  $\rightarrow$ fine segmentation needed along this direction



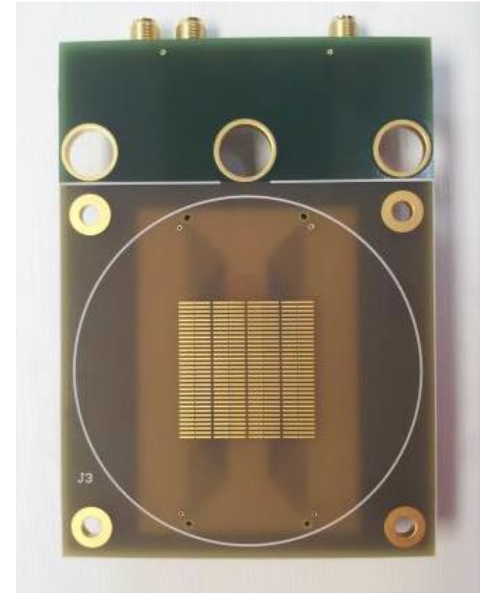
Representative photon paths: $0.55 < \theta_z < 0.95$ rad



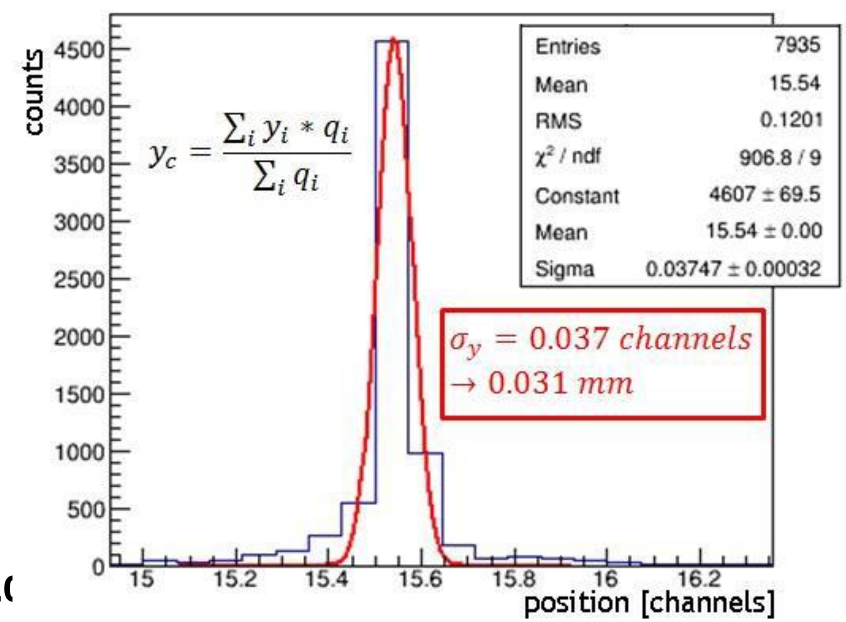
Position resolution

- 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

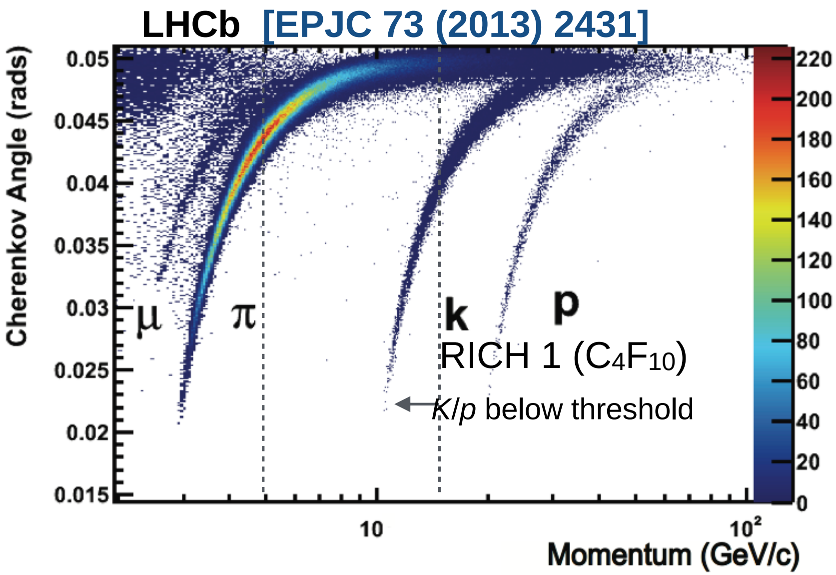


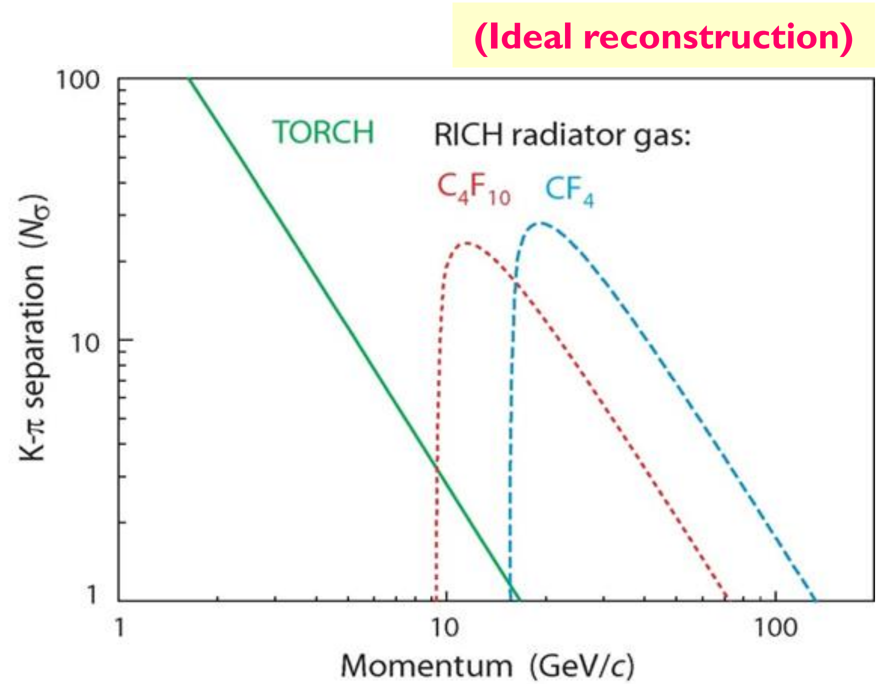
L. Castillo García et al, JINST 11 C05022 (2016)



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 nor any proton ID. The plan is to achieve this via a ToF measurement with TORCH
  - Area of 5 x 6 m^2 at z = 10 m
  - 18 module system (66 x 250 cm^2)
  - 198 MCPs (~100k readout channels)

LHCb Upgrade planning

Install Upgrade I

Consolidation

Upgrade II

Luminosity $4\text{x}10^{32}$ $\text{cm}^{-2}\text{s}^{-1}$
~1.1 visible interactions/crossing
~9 fb^{-1} collected

Luminosity $2\text{x}10^{33}$ $\text{cm}^{-2}\text{s}^{-1}$
~5.5 visible interactions/crossing
Up to 50 fb^{-1} collected

Luminosity $2\text{x}10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$
~55 visible interactions/crossing
300 fb^{-1} collected

TORCH for timing photons

- 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