TORCH: a fast timing detector for LHCb

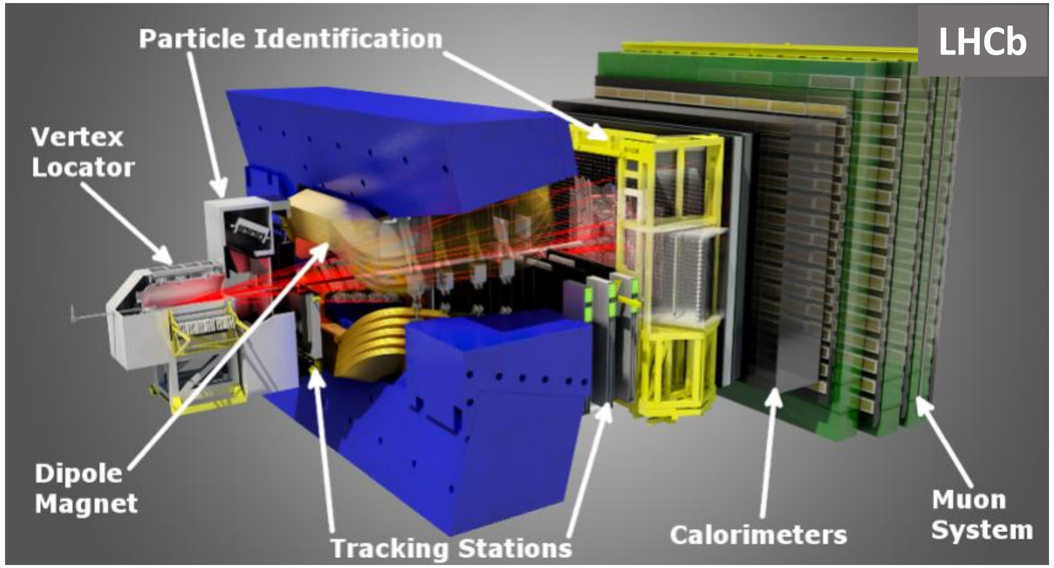
Roger Forty (CERN)
on behalf of the TORCH collaboration

- TORCH is a large-area time-of-flight detector, designed to enhance the particle identification performance of LHCb over the momentum range 2–15 GeV/*c*, foreseen to be installed in 2033–34 as part of Upgrade II of the experiment
- It uses a DIRC-like radiator with MCP-PMTs to provide fast timing of Cherenkov light produced by traversing charged particles, aiming for 10 ps precision/track

LHCb CERN UNIVERSITY OF OXFORD University of BRISTOL WARWICK THE UNIVERSITY OF WARWICK THE UNIVERSITY OF EDINBURGH Jožef Stefan Institute

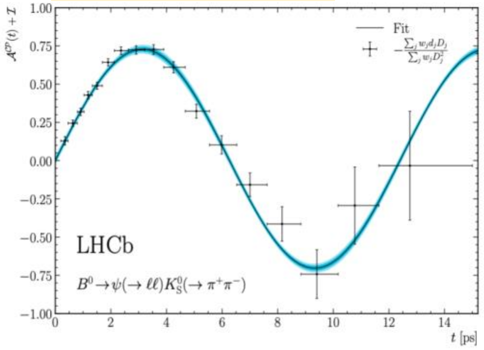
LHCb experiment

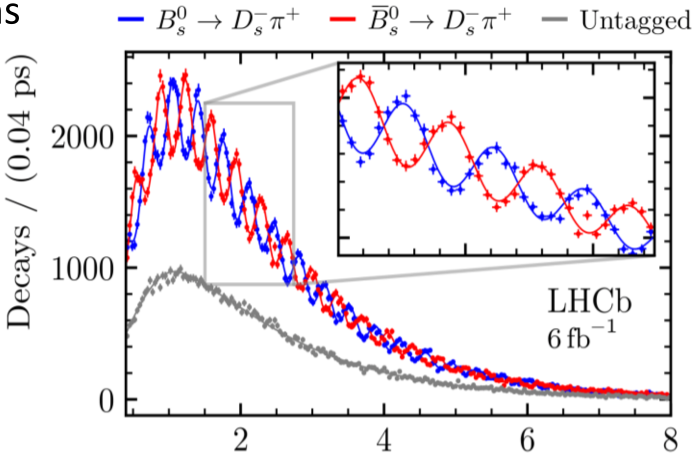
- The LHCb experiment at the LHC has produced many world-leading flavour physics results: e.g. for B^0–$\bar{B}^0$ oscillations, CP violation, and much more
- 70 new hadrons have been discovered at the LHC so far: 62 of them by LHCb, including many exotics (pentaquarks, tetraquarks)
- This has been achieved with combination of
  - *High statistics:* large hadronic cross-section of the LHC in proton-proton collisions
  - *Precision tracking:* the VELO approaches a few mm from the beamline → 15 μm impact parameter resolution at high p_T
  - *High performance particle identification:* charged hadron separation with RICHes



B^0–$\bar{B}^0$ and B_s–$\bar{B}_s$ oscillations

C. Gobel, LHCP 2023

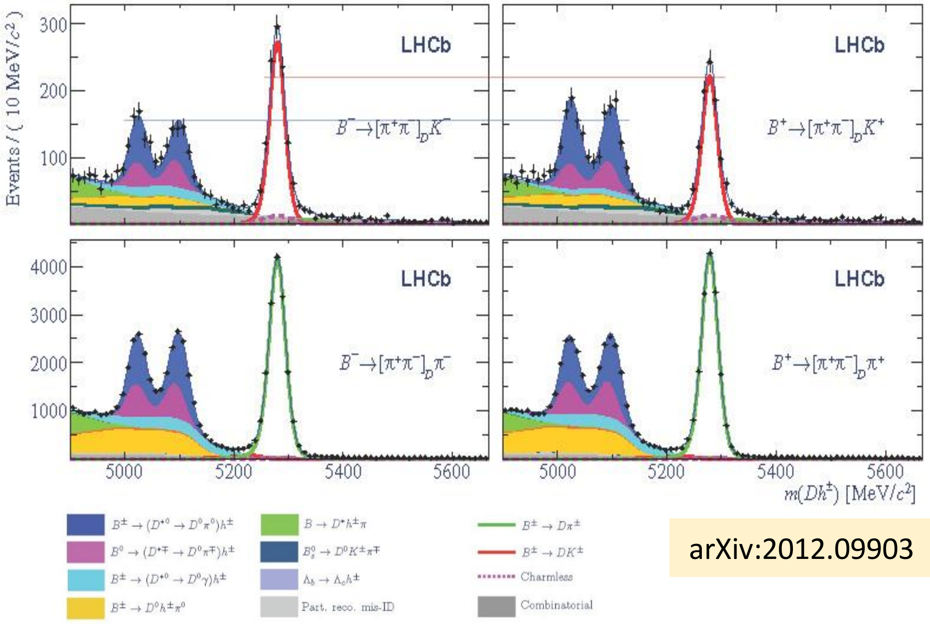




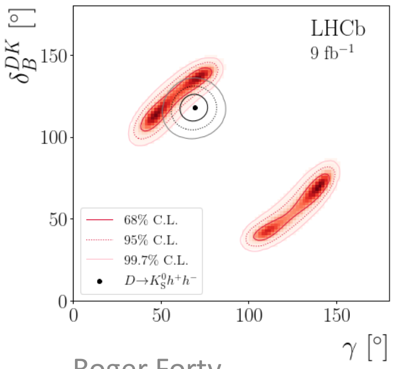
arXiv:2104.04421

LHCb physics examples

- Clean CP violation signatures:



arXiv:2012.09903

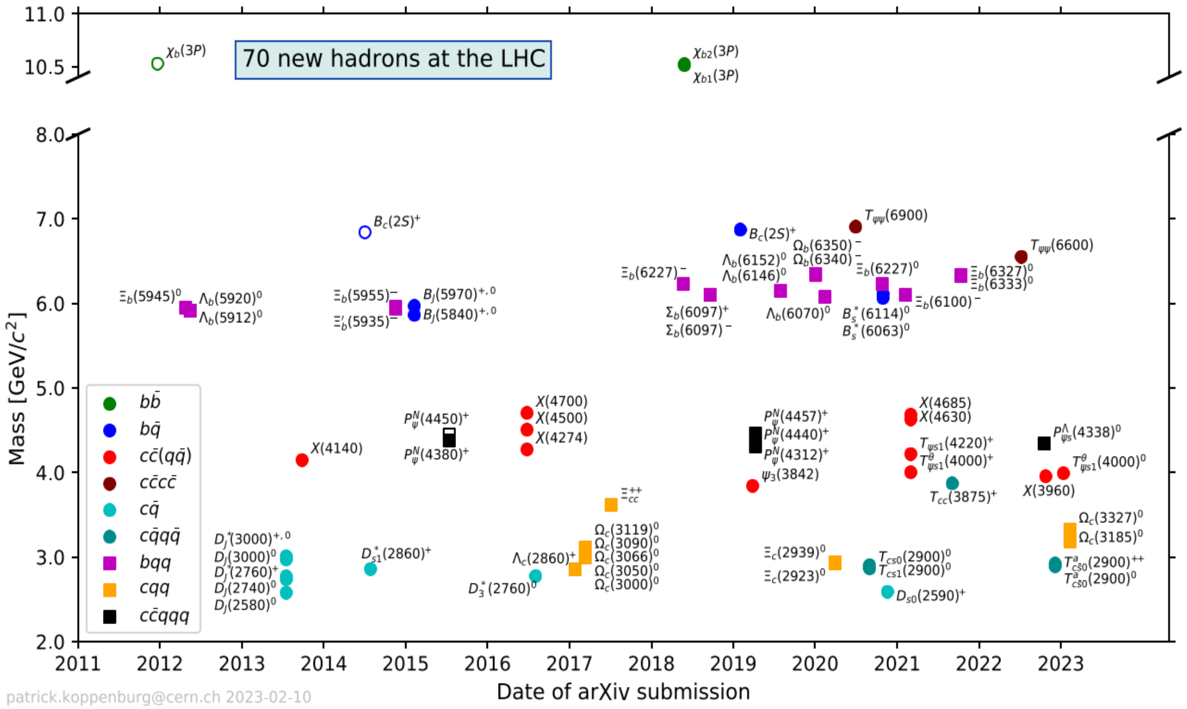


Current combined value of the CP phase γ from LHCb

$\gamma = 63.8\,^{+3.5}_{-3.7}\,^{\circ}$

LHCb-CONF-2022-022

- First convincing pentaquark:



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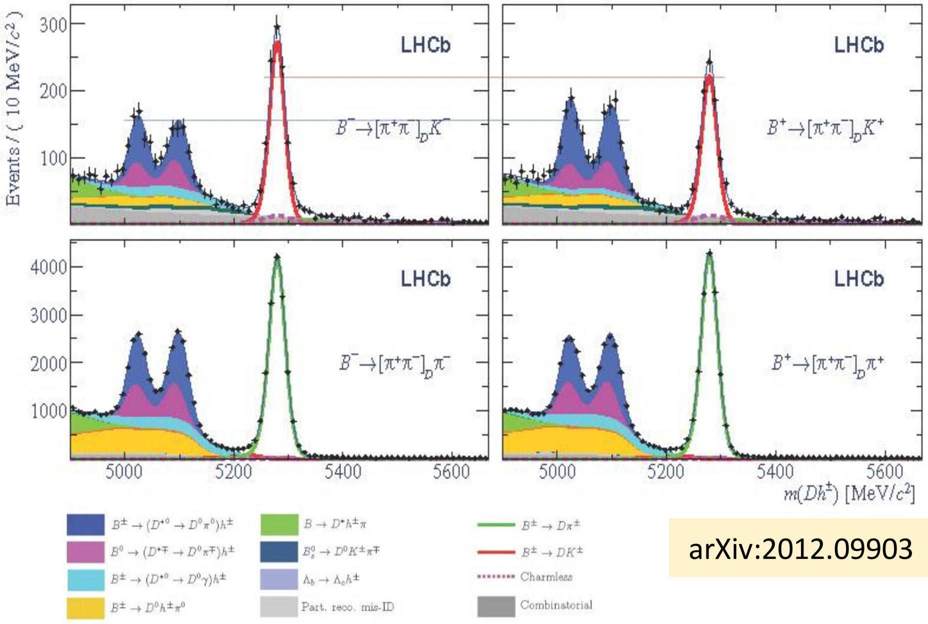

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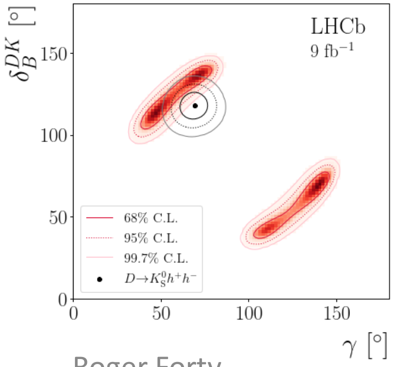

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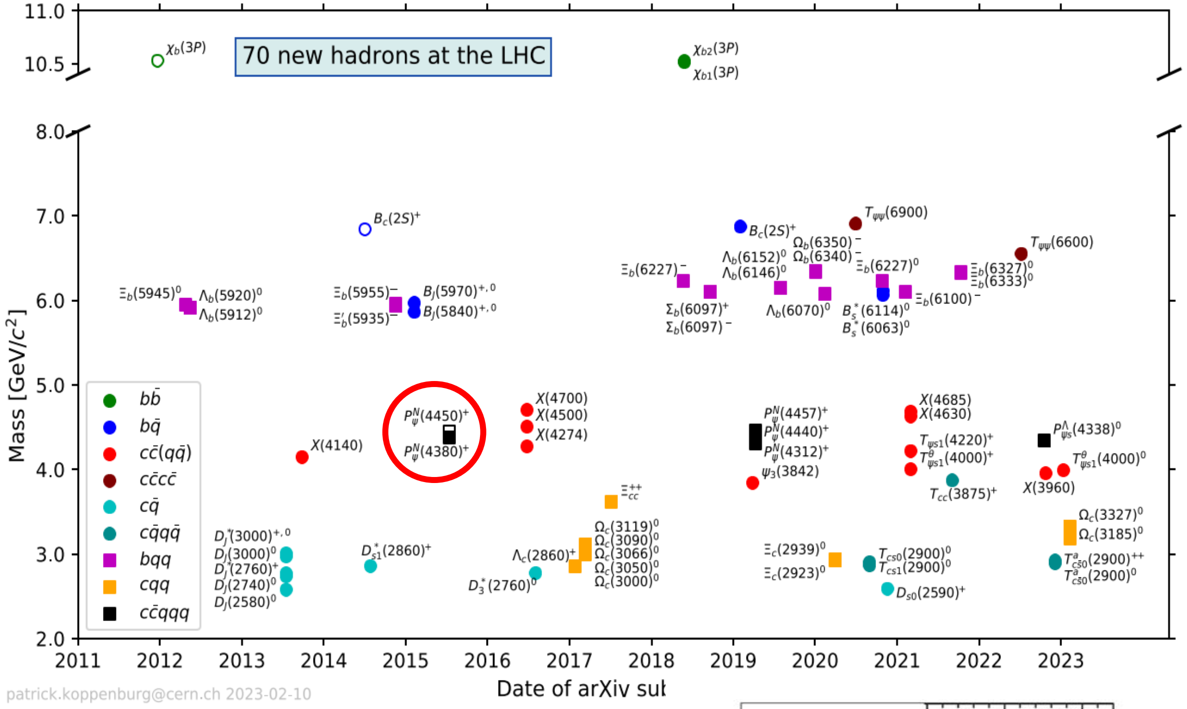
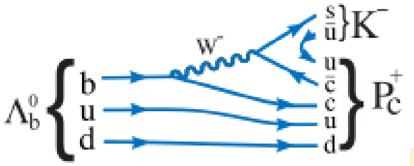
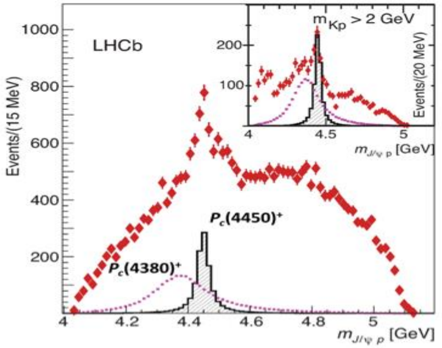




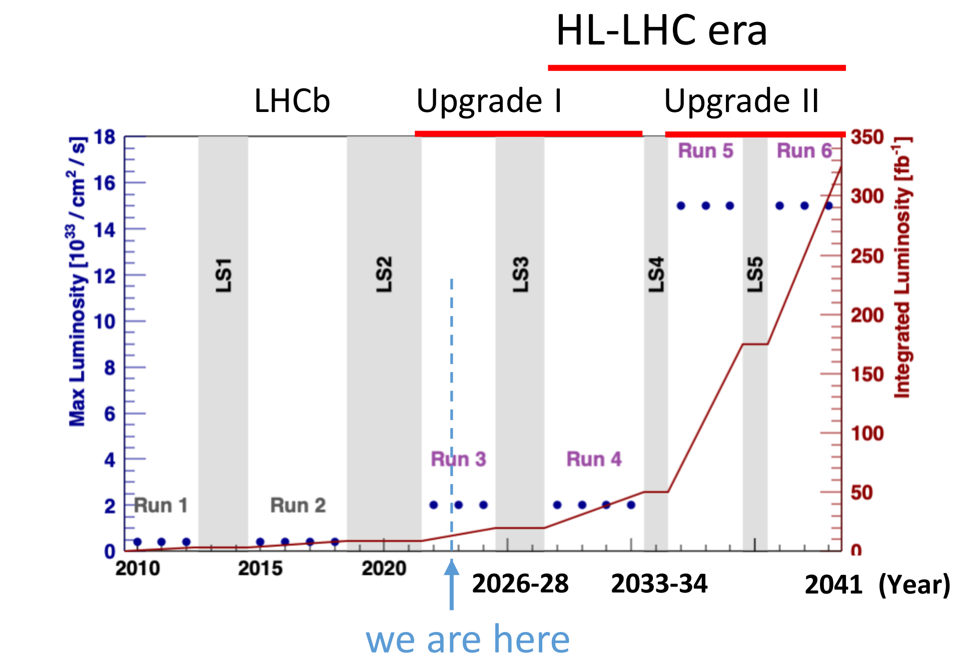
$\to J/\psi\ p$

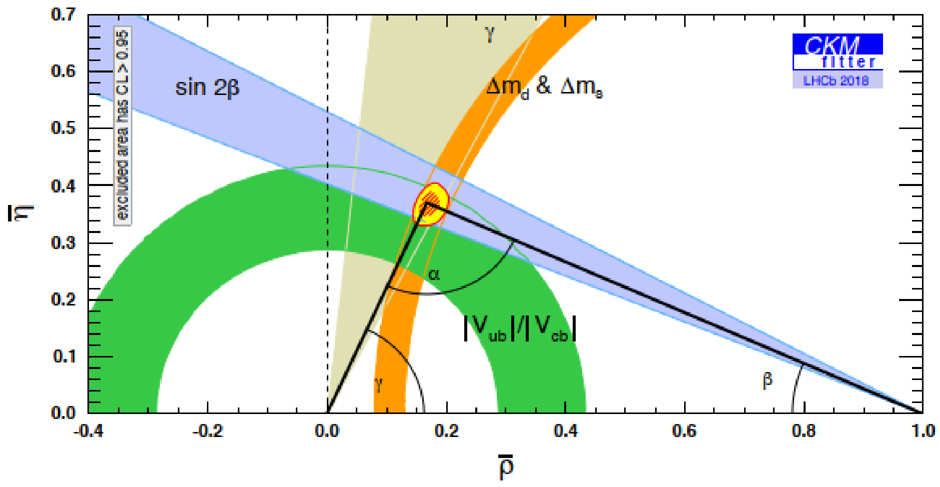
PRL 115, 072001



LHCb time-line

- **Original LHCb** (Run 1–2): Luminosity = 4 x 10^{32} $cm^{-2}s^{-1}$
  Conservative approach: pioneering flavour physics at a proton collider, ~ 1 visible interaction per crossing
  Integrated dataset 9 fb^{-1}
- **Upgrade I** recently installed during LS2, now being commissioned—vacuum incident in January → RF foil of VELO damaged, will be replaced at end of this year
  L = 2 x 10^{33} $cm^{-2}s^{-1}$, ~ 5 visible interactions per crossing
  Read out detector at 40 MHz with *fully software trigger*
  Targeting 50 fb^{-1} by the end of Run 4
- **Upgrade II** is planned for installation during LS4 to exploit the high luminosity available in the HL-LHC era
  L = 1.5 x 10^{34} $cm^{-2}s^{-1}$ → 300 fb^{-1}, pile-up ~ **40**
- Potential to dramatically improve flavour constraints e.g. on the Unitarity Triangle of quark mixing, improve precision on γ from current 4° → 0.35°





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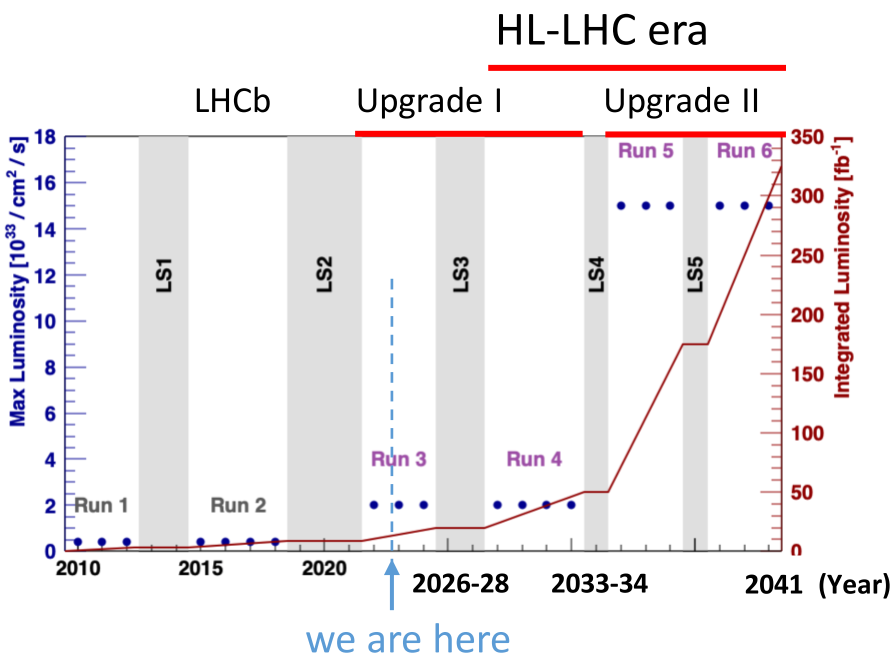
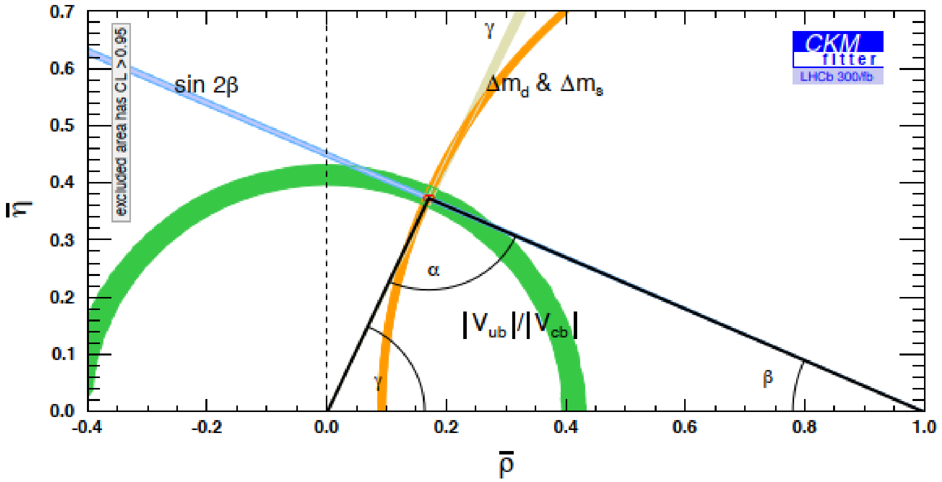
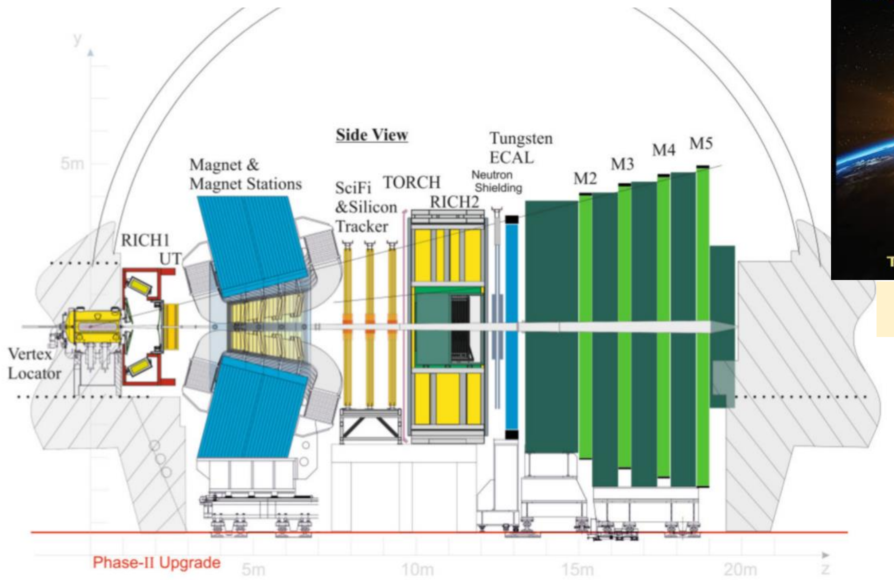




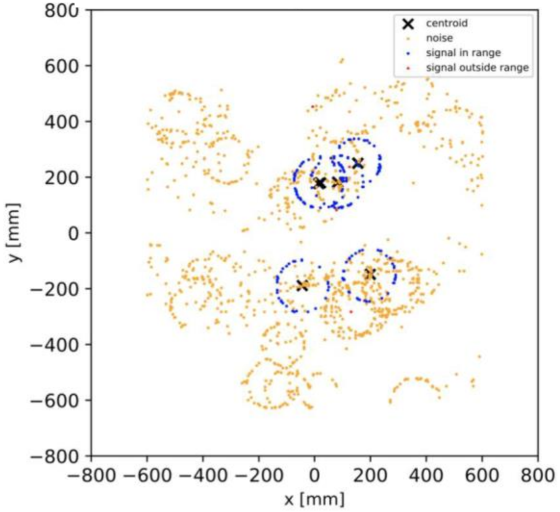
Fast timing in Upgrade II

- Fast timing will be important to suppress background from pileup, as in Phase II upgrades of ATLAS & CMS
- LHCb Upgrade II scheduled later (LS4: 2033–34), so there is still some time for R&D, e.g. in the context of the new DRD collaborations currently being set up
- Upgraded spectrometer described in Framework TDR —at first sight it looks similar to the current LHCb
- LHCb detectors investigating fast timing:
  - **VELO** (talk at this workshop by Stefano De Capua)
  - **Calorimeter** (talks from Dominique Breton, Daniele Manuzzi, and Philipp Roloff)
  - **RICH** (developing ASIC with 25 ns time binning, based on FastIC discussed by David Gascon)

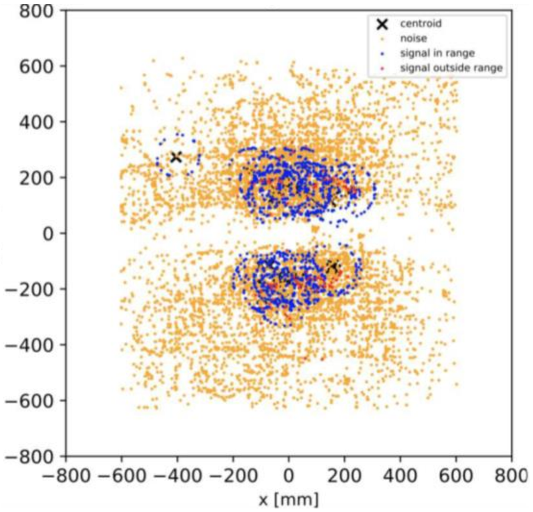
LHCb-TDR-023



Single pp collision in RICH



Pileup of 10 collisions



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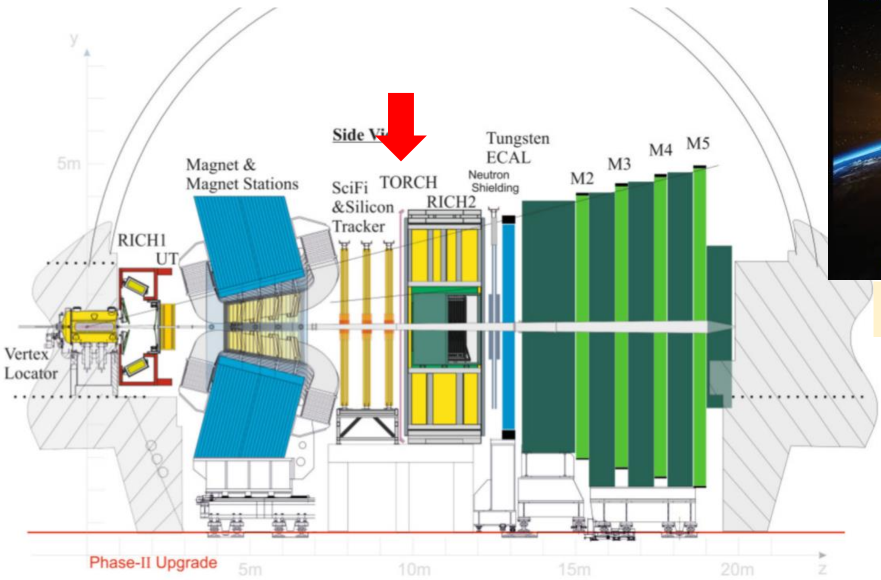
  - **RICH** (developing ASIC with 25 ns time binning, based on FastIC discussed by David Gascon)
  - *New detector:* **TORCH**, for time-of-flight over 10 m

LHCb-TDR-023



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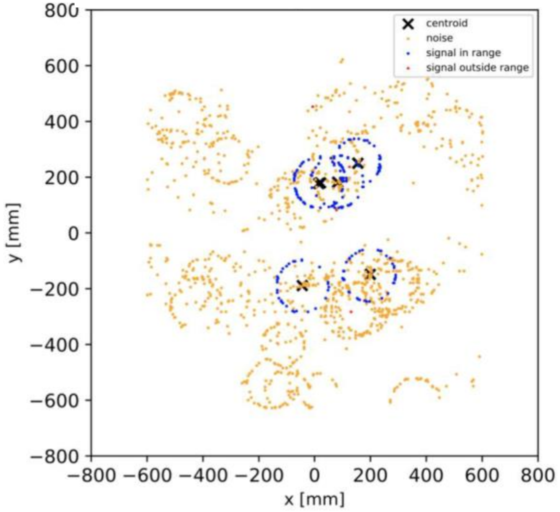

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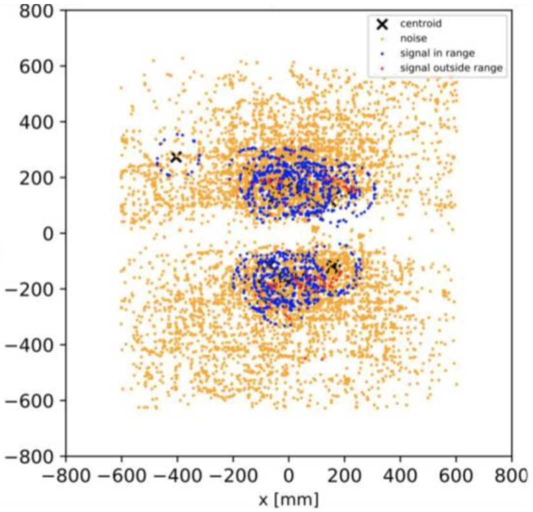
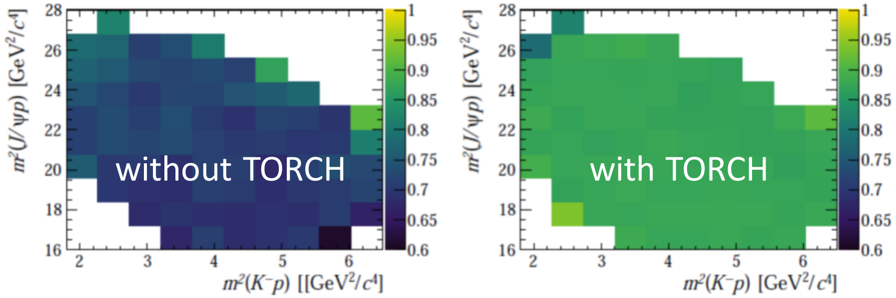


TORCH motivation

- Fast timing useful not only for background suppression, but also to extend the particle identification performance
- RICH radiator gas (C_4F_{10}) gives K threshold at ~ 10 GeV/c
  Below, only veto-mode for K-π, and no K-p separation
  Adding TORCH will bring:
  - Improved flavour tagging (cut-based analysis showed gains of 25–50% in effective tagging power)
  - Improved uniformity of angular/Dalitz distributions, analyses requiring p-K/π separation (e.g. for Λ_b decays), + deuteron and He separation (e.g. for hyper-nuclei)

Dalitz plot distribution of $\Lambda_b \to J/\psi\, pK^-$ decays

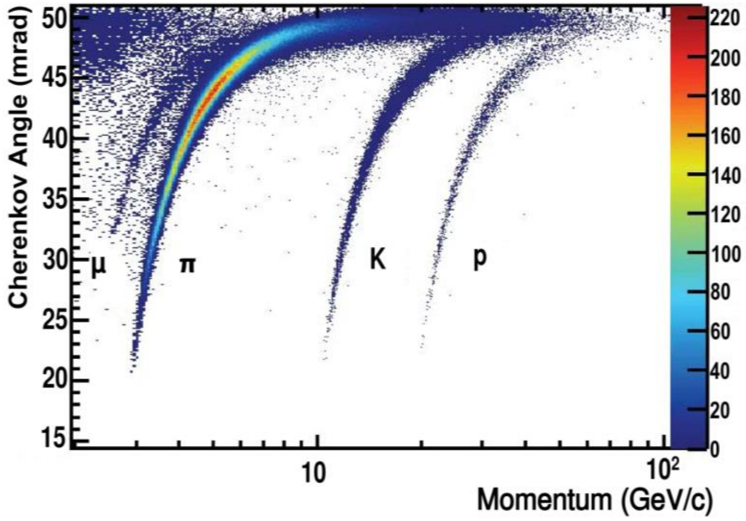
LHCb-TDR-023

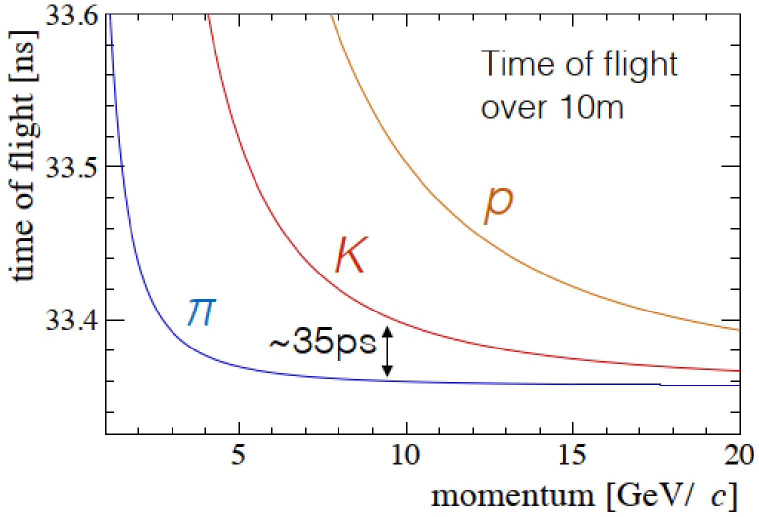


- K-π separation up to 10 GeV/c at 3σ requires resolution ~ 10 ps

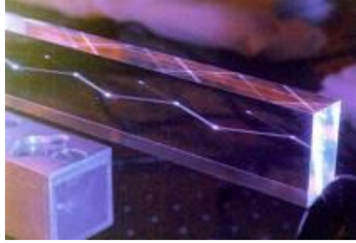
LHCb RICH1

EPJC 73 (2013) 2431



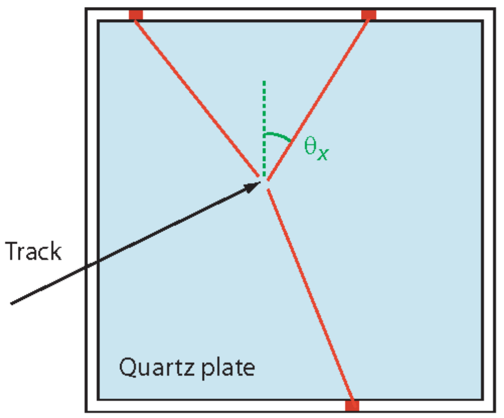


TORCH concept



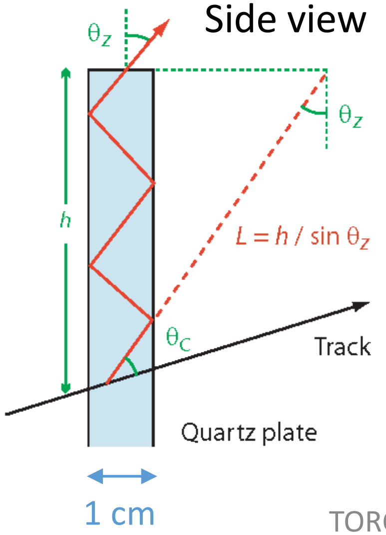
- Use Cherenkov light, since promptly produced—i.e. similar approach to earlier talk on the PPS of CMS but must cover *much* larger area: LHCb acceptance is ~ ± 300 mrad → at 10 m the area is 5 x 6 = 30 m^2
- If the full area were to be tiled with photodetectors (e.g. LAPPD) it would be very expensive: many hundreds of detectors, readout electronics would be in acceptance, track density is very high
- Instead use DIRC-like solution of a 1 cm-thick quartz plate: signal photons propagate to edges by total internal reflection, detected with fast photon detectors (**T**iming **O**f internally **R**eflected **CH**erenkov light)
  Focusing block at edge allows *angle* of photon to be measured; using knowledge of the track impact, both the distance *L* of photon propagation and its Cherenkov emission angle θ_C can be determined

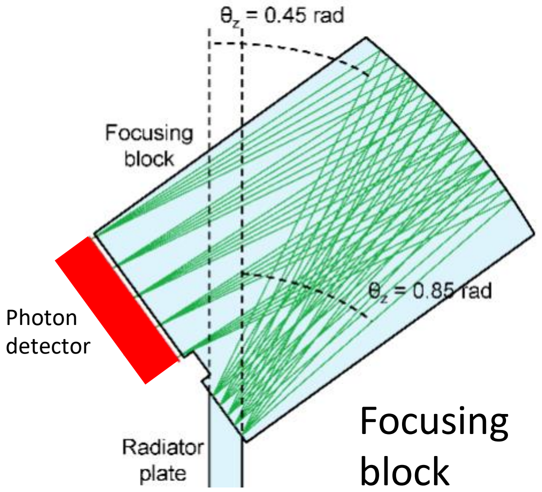
Front view



NIM A 639 (2011) 173

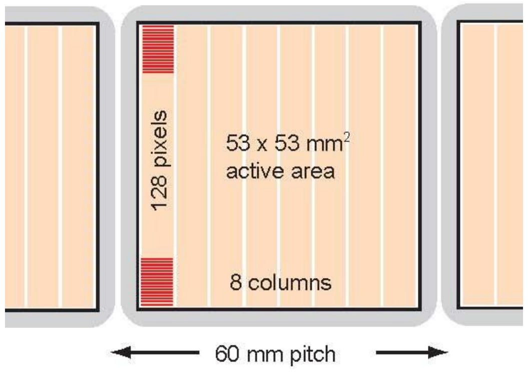
Side view





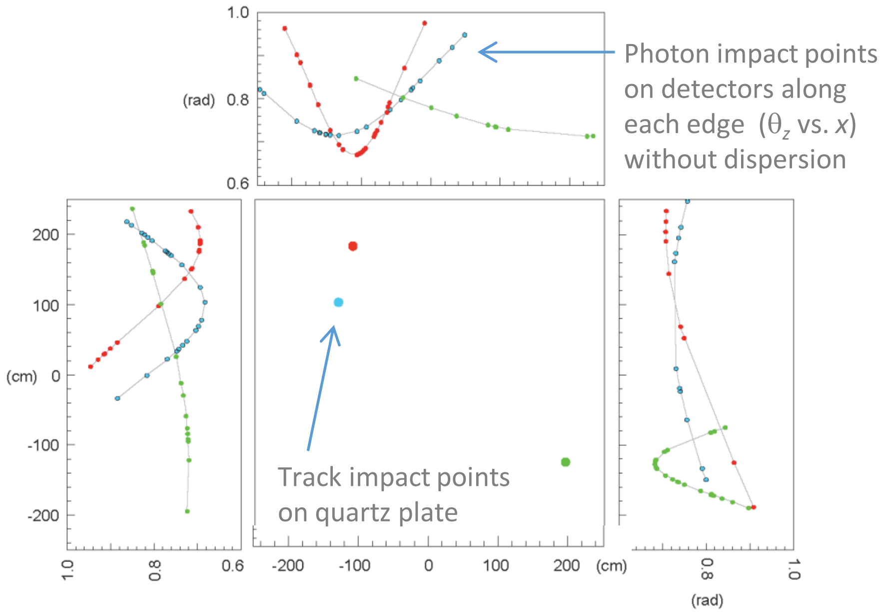
Focusing block

Photon detector pixellization (to achieve 1 mrad precision)



Dispersion correction

- Such an idealized detector layout might be used in a neutrino or beam-dump experiment; for application in LHCb use a **modular** construction: image “folded” by reflections off edges
- Chromatic dispersion in the quartz smears the image
  Corrected using the *measured* Cherenkov angle
  → effectively measure the wavelength of the photons
- In a DIRC, timing is used to improve the angular resolution;
  in TORCH, angular information is used to correct the timing



Covering the LHCb acceptance

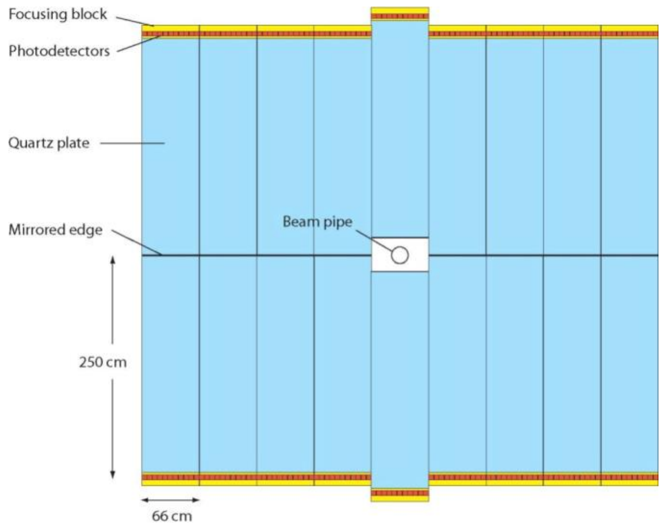
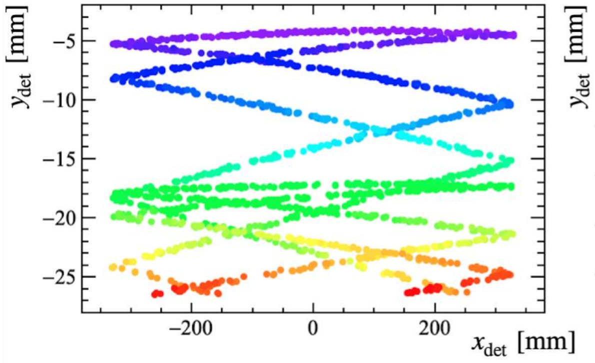
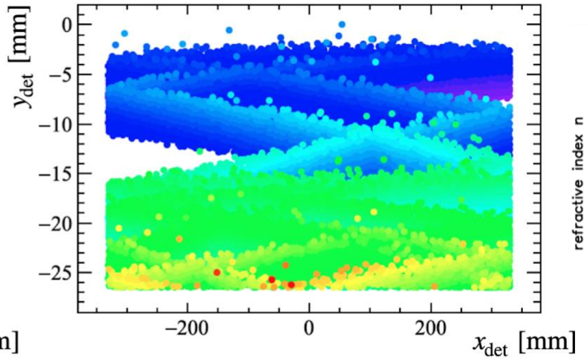


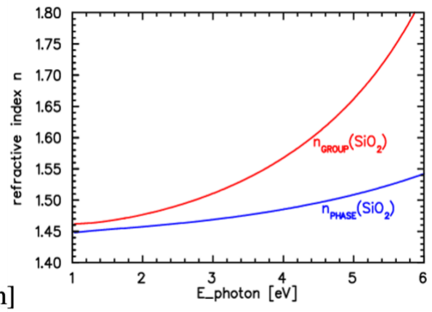
Image without dispersion



With chromatic dispersion



Dispersion in quartz



Colour indicates time of arrival (red = latest)

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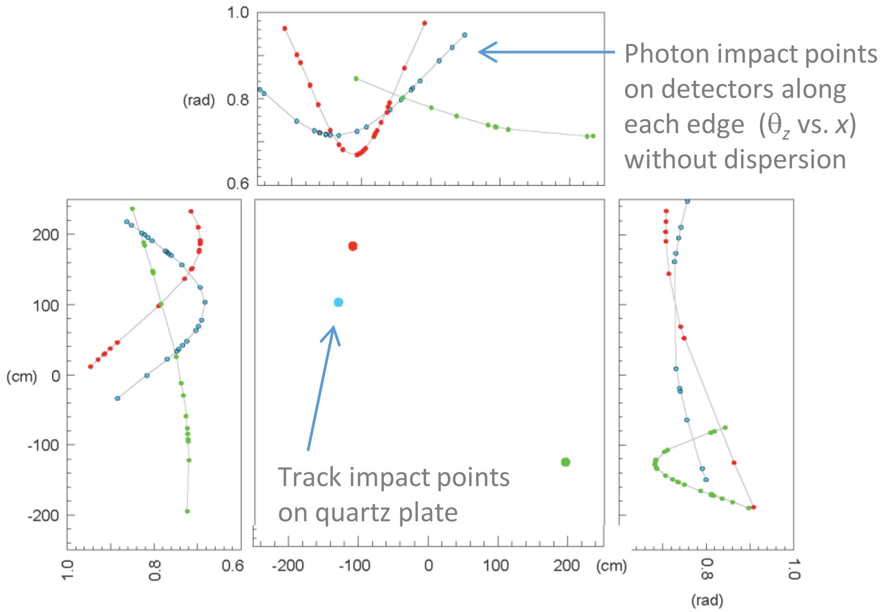

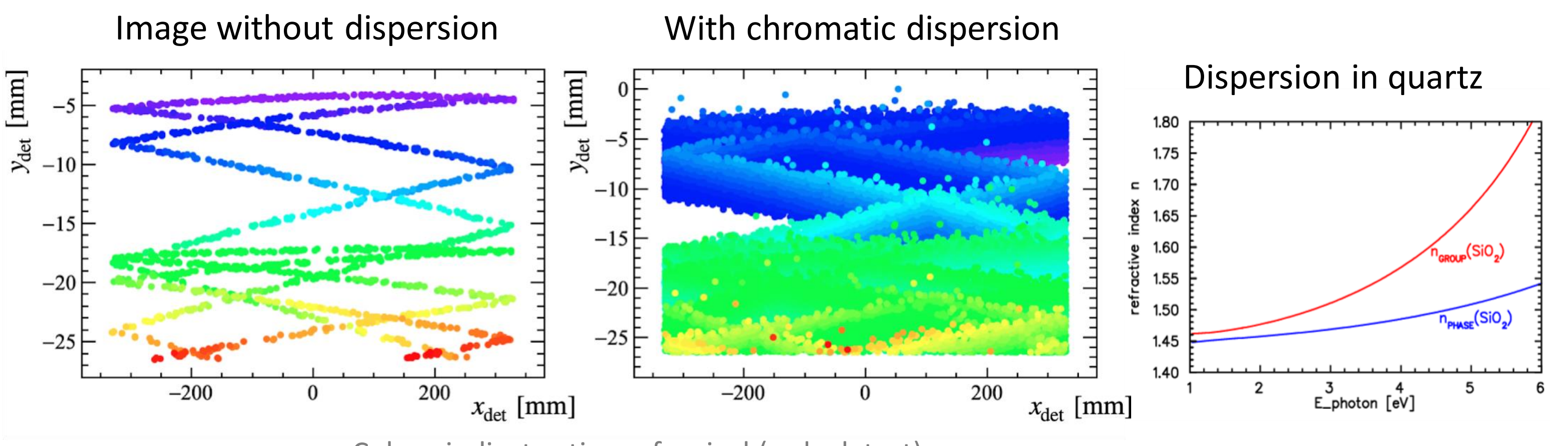

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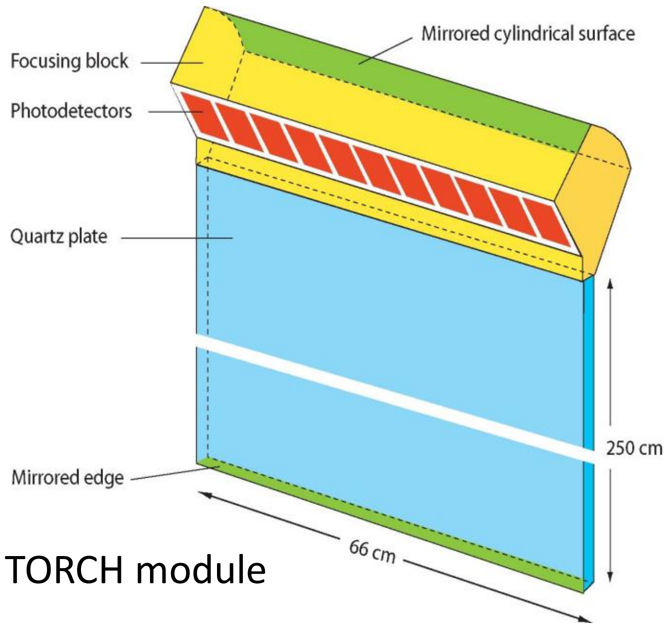
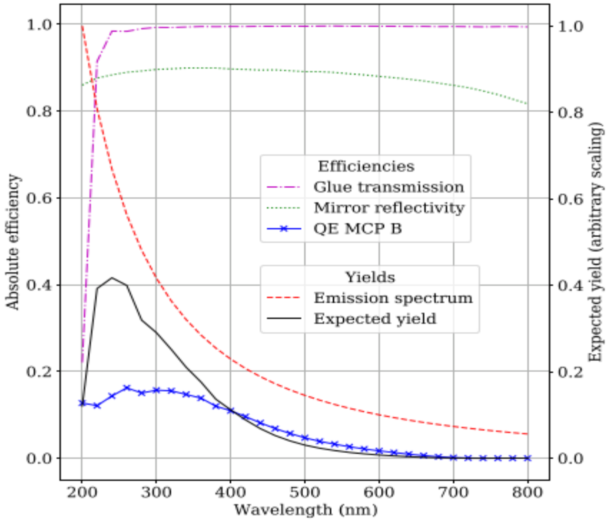


TORCH module

Optical elements

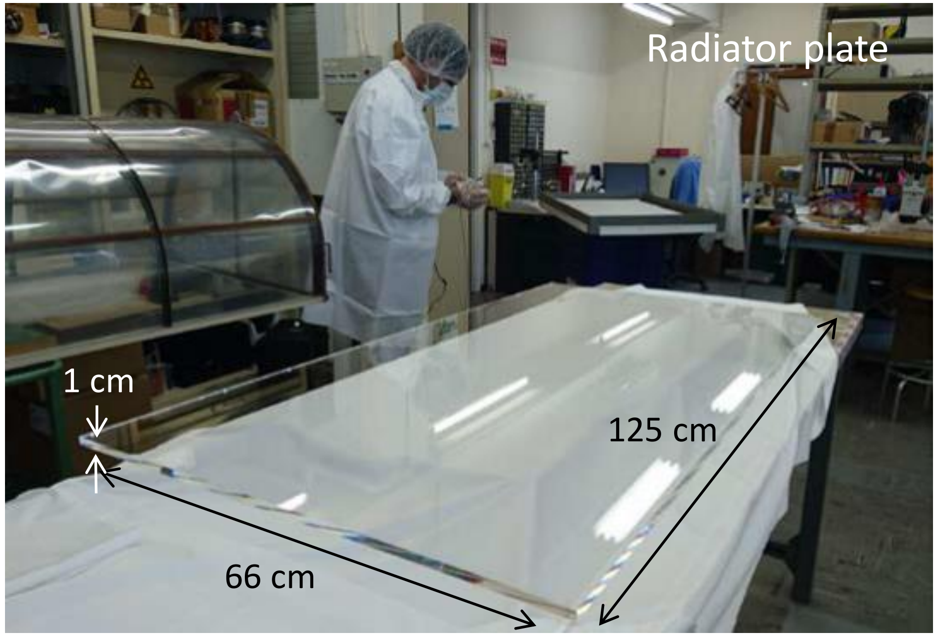
- Quartz (fused silica) radiator plate procured to equip a half-length but otherwise full-scale prototype module from Nikon Glass
- Stringent requirements on surface quality by polishing of plate to preserve angles of reflected photons:
  - thickness variation $\leq 3\ \mu m$
  - surface roughness ≤ 0.5 nm



Focusing block also made of polished quartz, cylindrical mirrored surface aluminized

Block cemented to radiator plate with silicone-based Pactan 8030 glue, at CERN

NIMA 1050 (2023) 168181



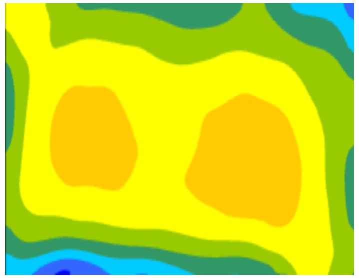
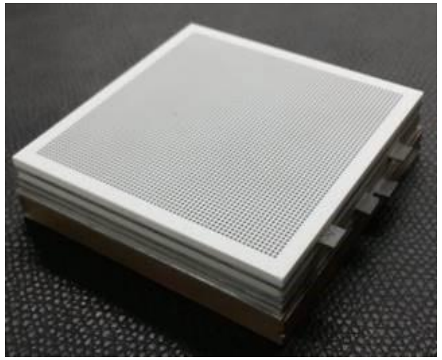


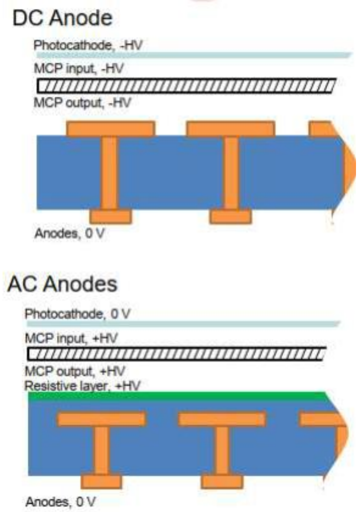
Plate surface flatness: measured 1 μm contours

Photodetector

- **Microchannel plate** PMT chosen for the fast photodetector
  Optics arranged to focus the image onto a close-packed linear array of 2-inch square MCP-PMT tubes
- Given N_{pe} ~ 30 detected photons per track, requirement on intrinsic timing precision is more modest ~ 50 ps per photon
  Combined with the other contributions e.g. from limited pixel size gives a total of 70 ps $/\surd N_{pe} \approx$ 10 ps per track
- MCP with suitable pixellization developed by Photek*
  - Dual microchannel plates in chevron with 15 µm pores
    Atomic-layer deposition (ALD) used to extend lifetime
  - Readout PCB groups pads in one direction to give **8 x 64** connectors attached to ceramic back surface via ACF (anisotropic conductive film)
  - *Capacitively-coupled* anode pads allow photocathode to be at ground, charge sharing between pads provides excellent spatial resolution required in focusing plane

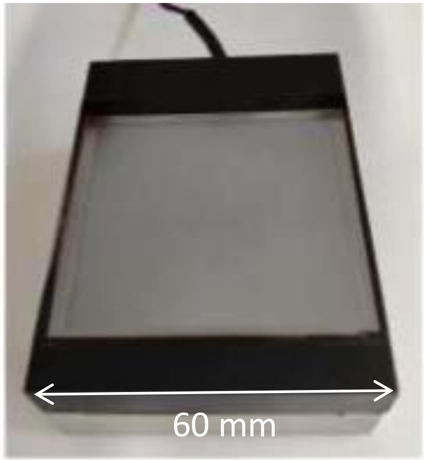
64 x 64 pads on anode



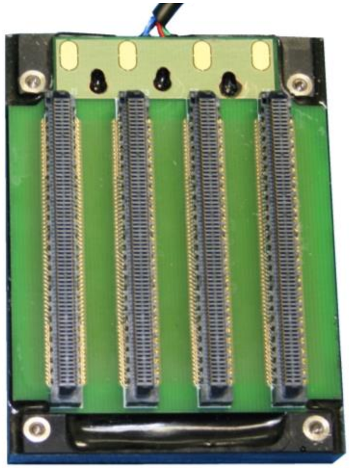


JINST 10 (2015) C05003

Front of potted MCP



Rear of MCP with PCB



*via ERC-funded R&D programme with TORCH

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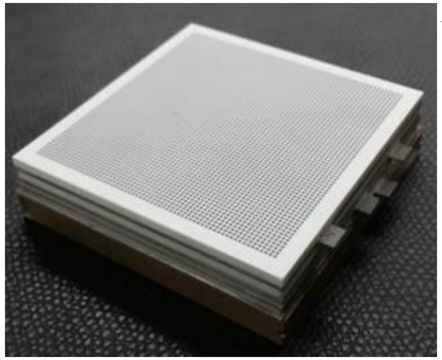
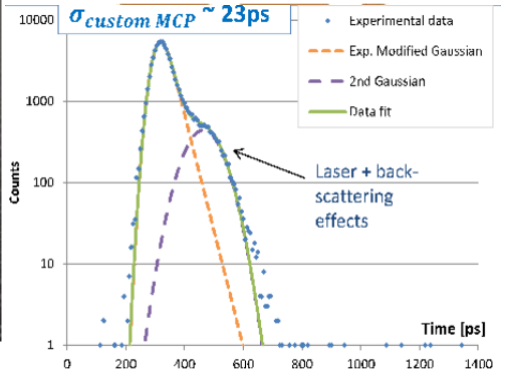


JINST 10 (2015) C05003

Time resolution
(from earlier tube version)



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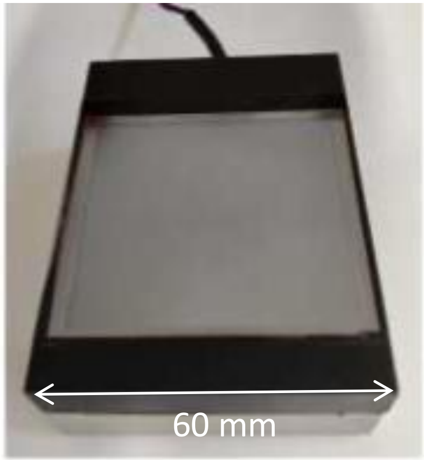
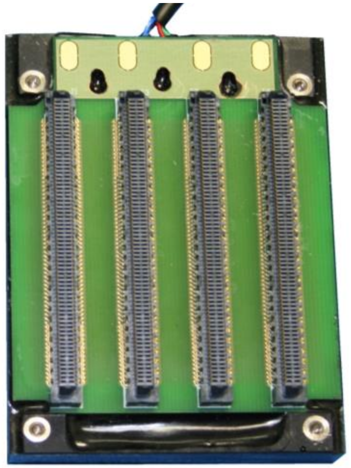
Front of potted MCP



Rear of MCP with PCB



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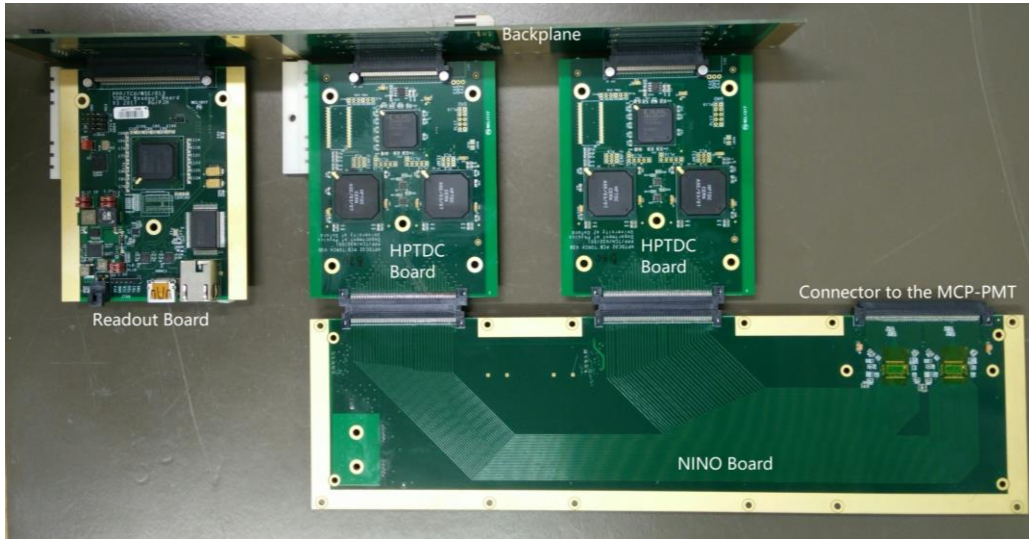
Readout electronics

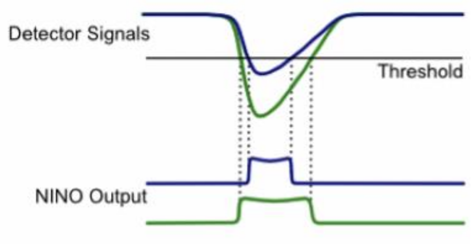
- Current electronics based on **NINO** + **HPTDC** chipset with 100 ps bins, originally developed for ALICE TOF (i.e. designed for MRPC signals)

NIM A533 (2004) 183
IEEE 58 (2011) 202

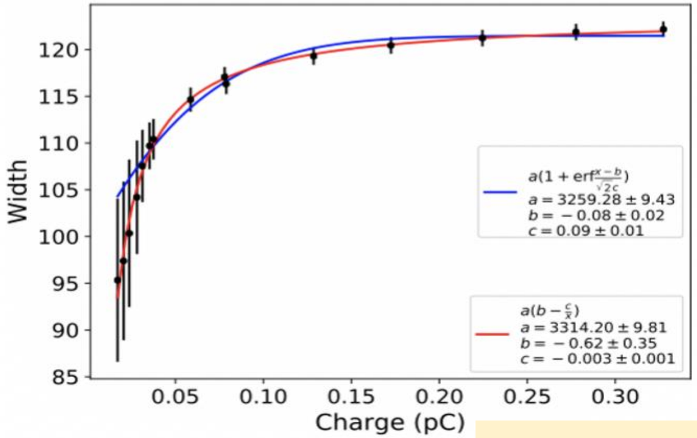
- Calibration required for charge-to-width and time-walk in NINO and integral nonlinearity (INL) of TDC



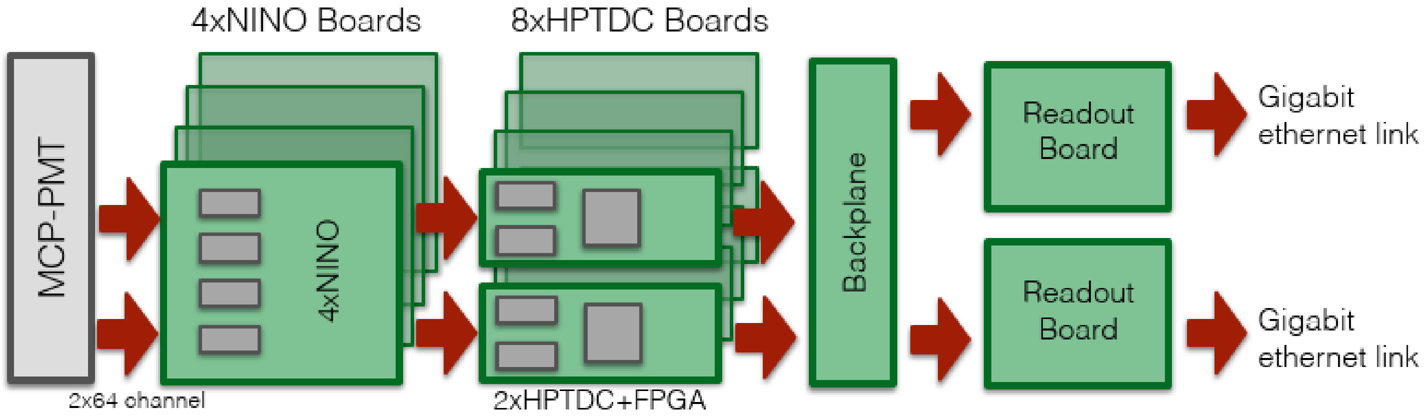
JINST 11 (2016) 04 C04012



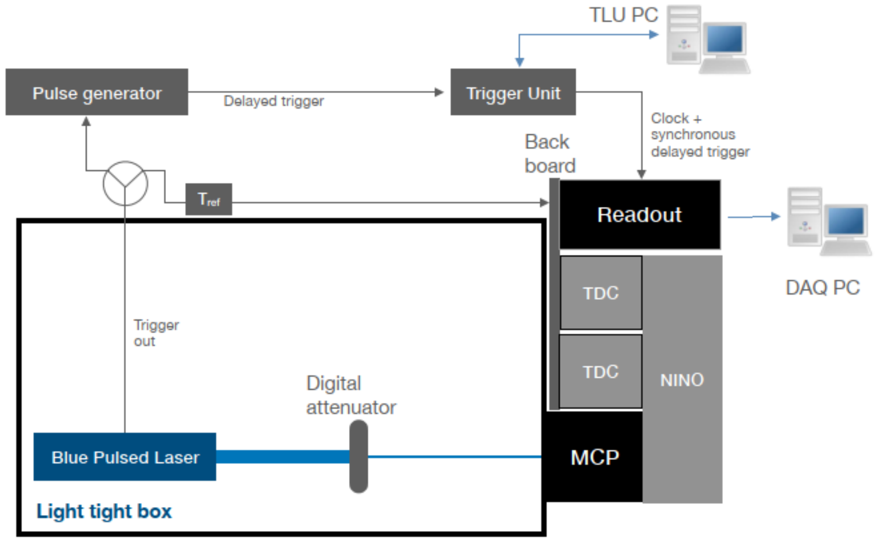
Calibration system developed to inject a known charge into each channel



J. Smallwood, TIPP2021

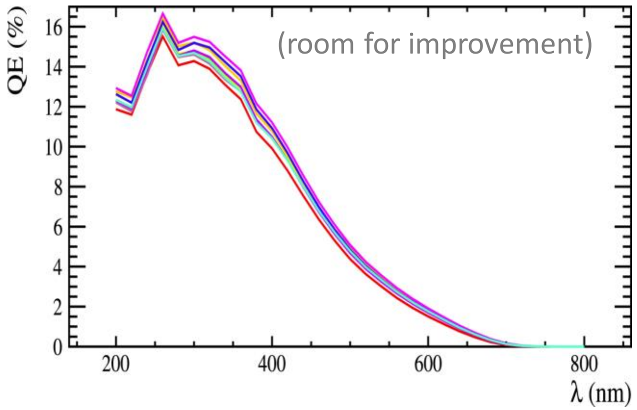


Results from the lab



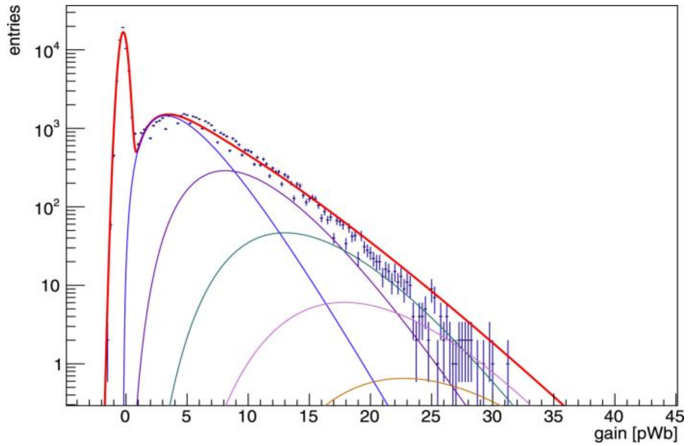
- Measurements performed in the lab to qualify the MCP-PMTs used in the TORCH prototype:
  - Quantum efficiency (QE) + gain uniformity
    Typical gain used = 6 x 10^5 (100 fC)
  - Intrinsic time response of MCP + electronics
    with 405 nm picosecond pulsed laser
  - Spatial resolution from charge sharing
    (using an earlier prototype tube)

QE at different positions using xenon lamp and monochromator



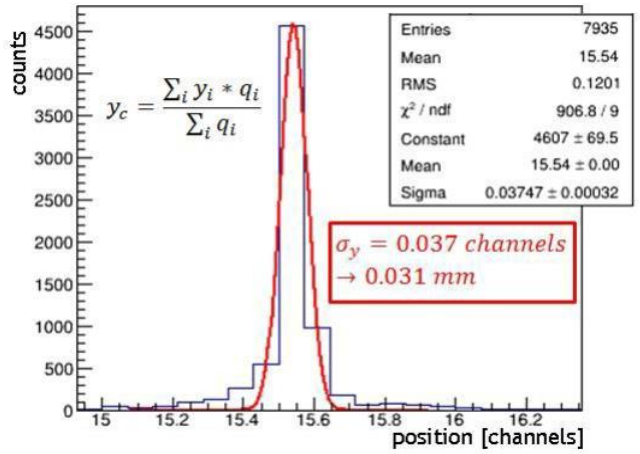
Gain distribution

T. Jones, NDIP 2020



Spatial resolution

JINST 11 (2016) C05022



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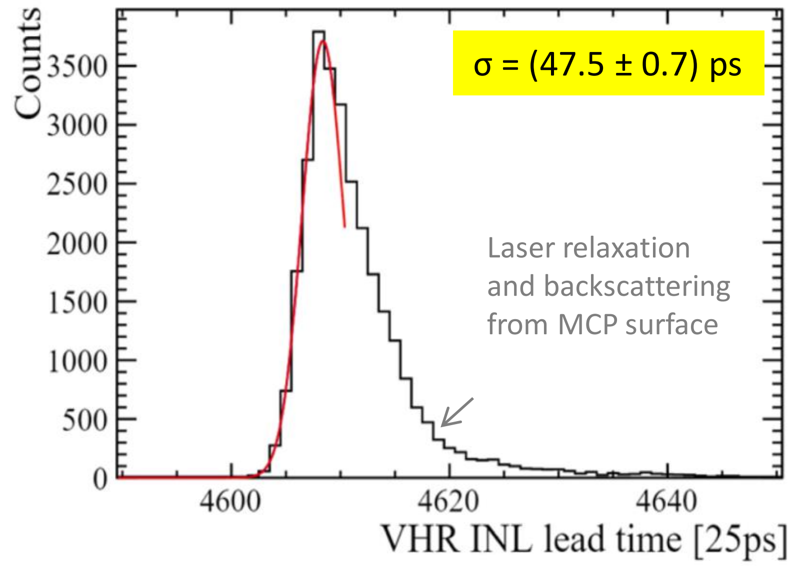
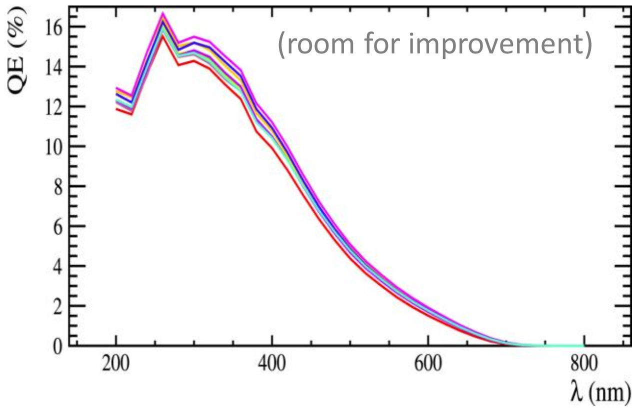
    with 405 nm picosecond pulsed laser
  - Spatial resolution from charge sharing
    (using an earlier prototype tube)

Time resolution (MCP + electronics)

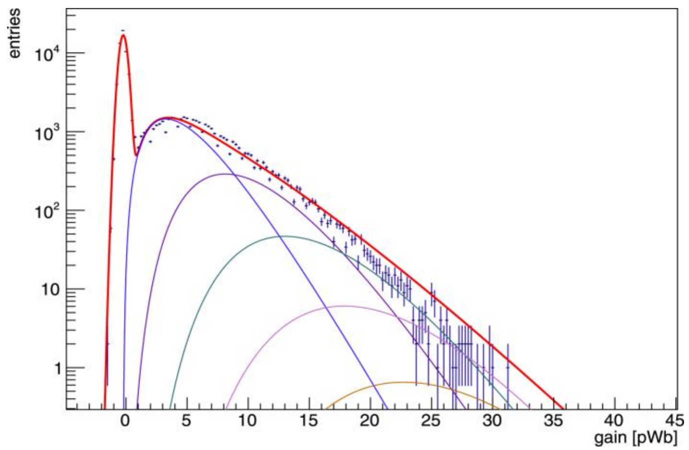


QE at different positions using xenon lamp and monochromator



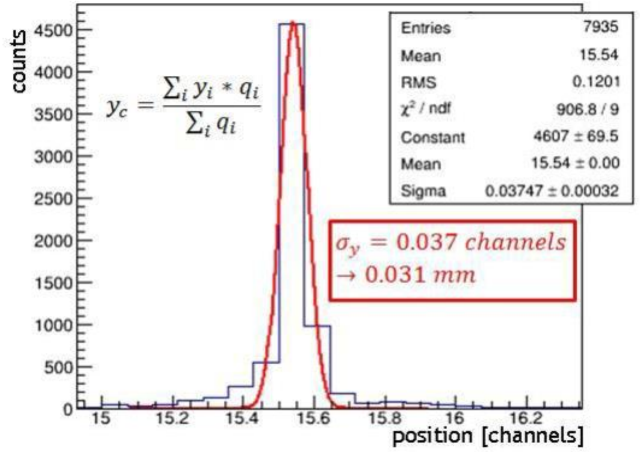
Gain distribution

T. Jones, NDIP 2020



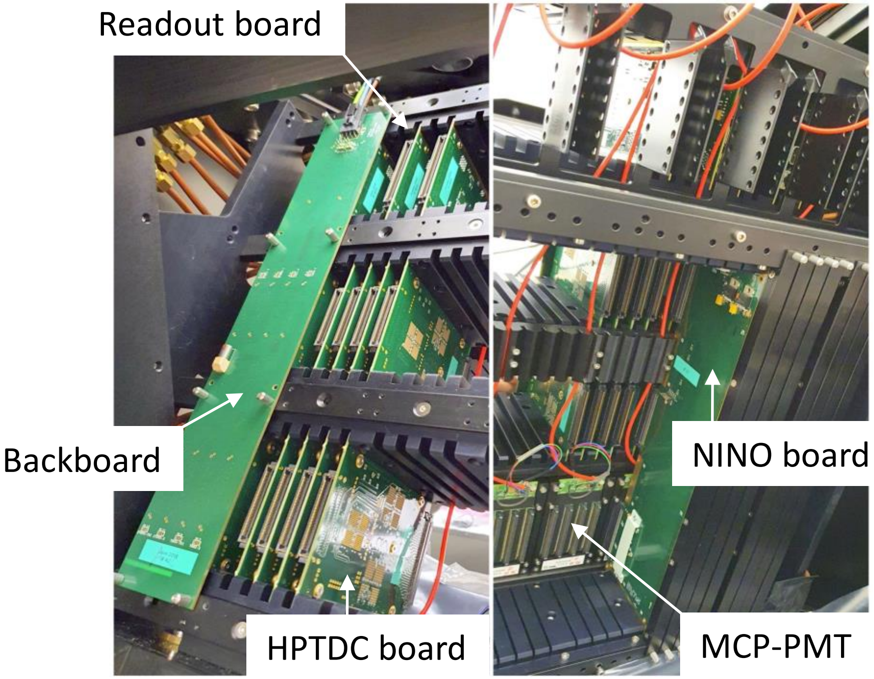
Spatial resolution

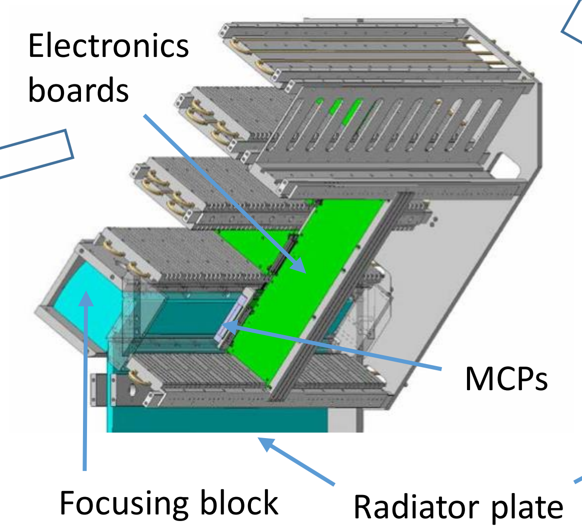
JINST 11 (2016) C05022



Module prototype

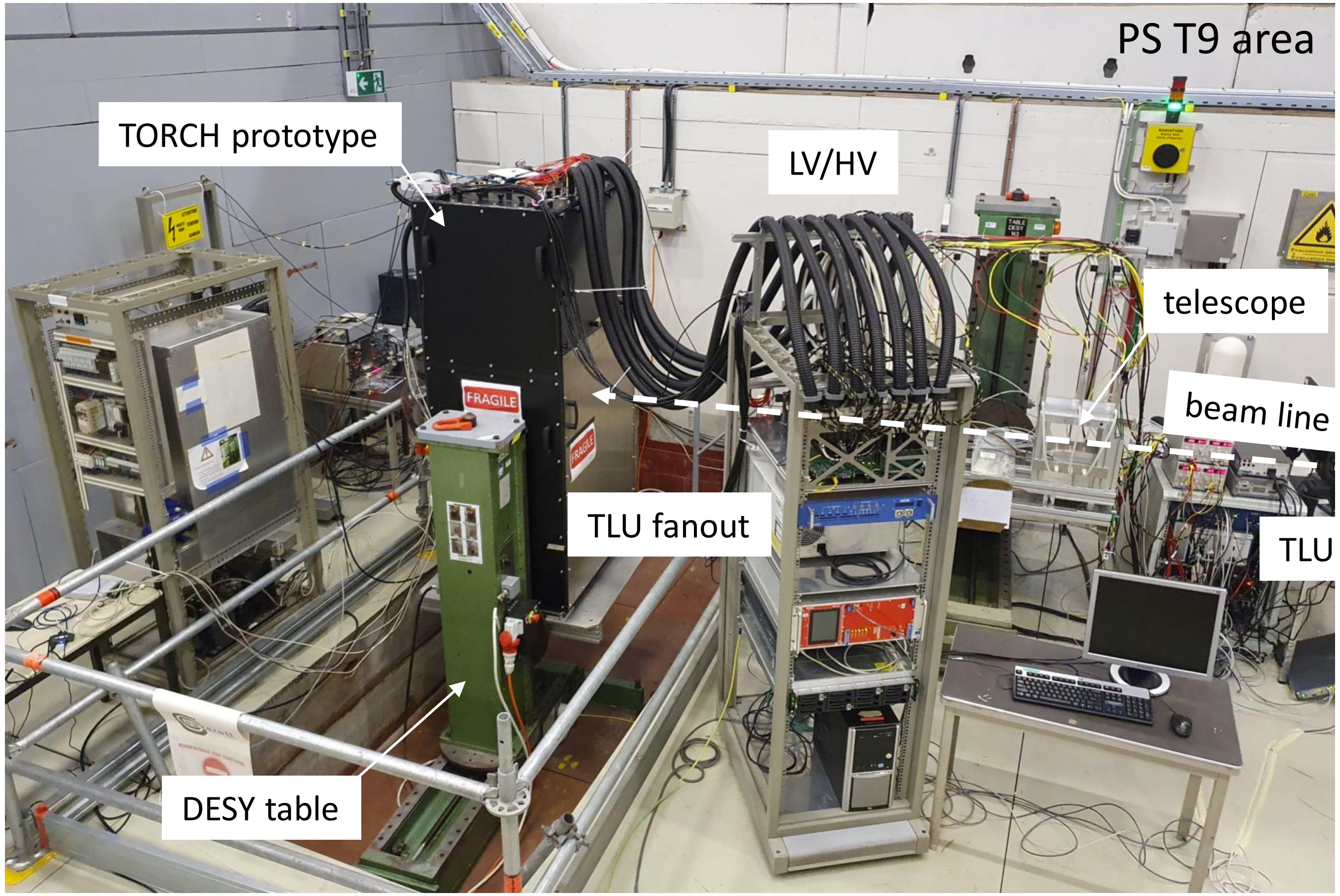
- The large scale TORCH prototype was constructed and initially tested in beam with two MCP-PMT tubes in 2018
- Last year the instrumentation was extended to 6 MCP-PMTs with a total of 3072 channels, and returned to the (renovated) T9 test beam area at the CERN PS

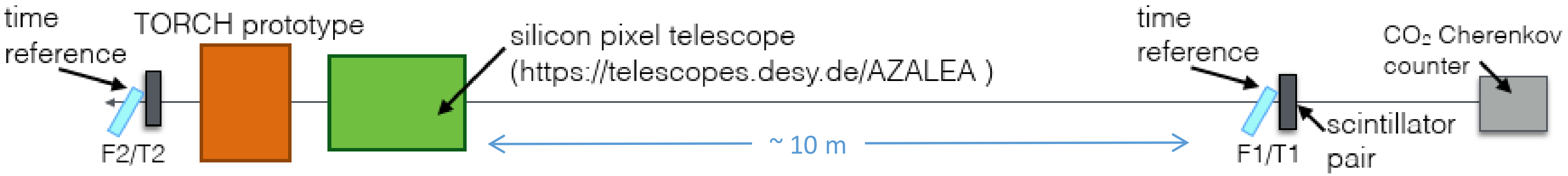




Beam test

- Mixed p/π beam at energy 3–10 GeV
- Clock and trigger distributed by an AIDA TLU JINST 14 (2019) 09 P09019
- Time reference provided by borosilicate-glass fingers coupled to dedicated MCP-PMTs
- DAQ, LV and HV distribution improved from the 2018 test beam campaign —it has become a substantial set-up
- Data was taken over a few weeks in November 2022





Results from 2018 data

- Test-beam results from the 2018 data recently published
- Photon yield reasonably well described as a function of propagation distance (apart from rate of empty events)
  Overall data/simulation ratio 82–85%
- Timing resolution studied for the different possible paths of photon reflections off the plate edges, approaching the requirement of 70 ps/photon

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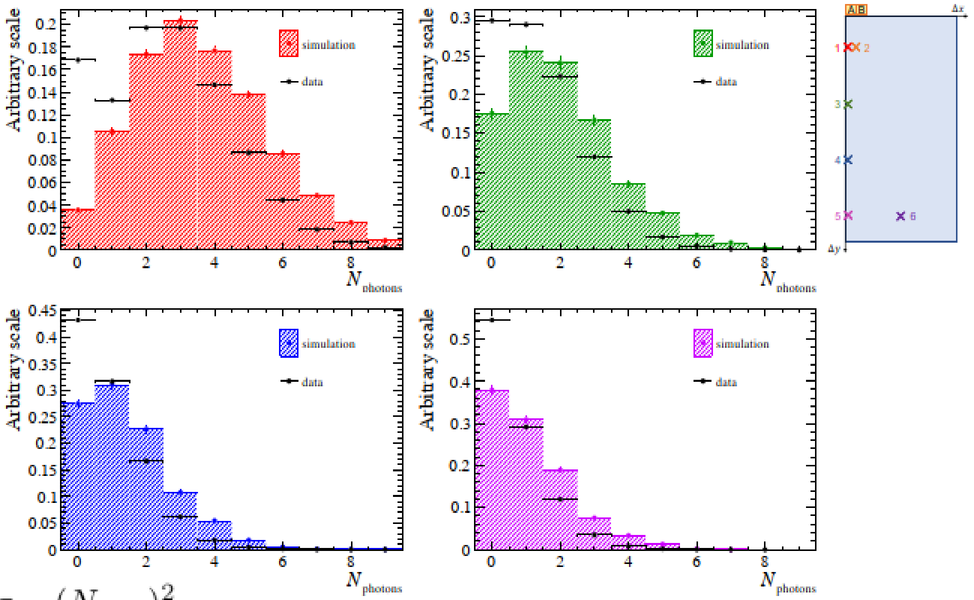
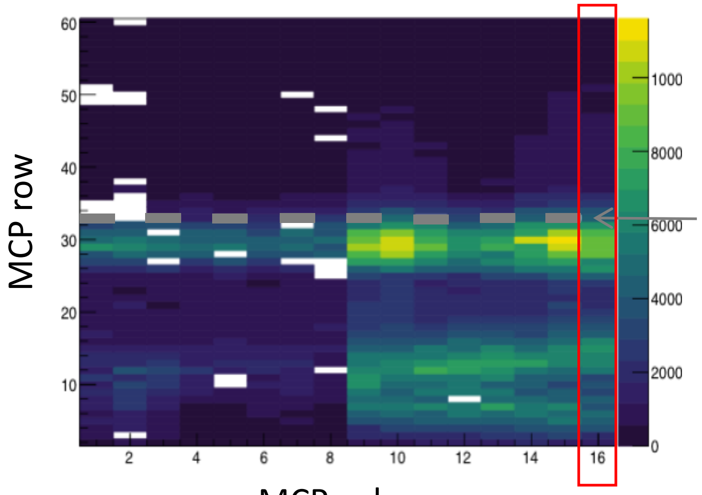
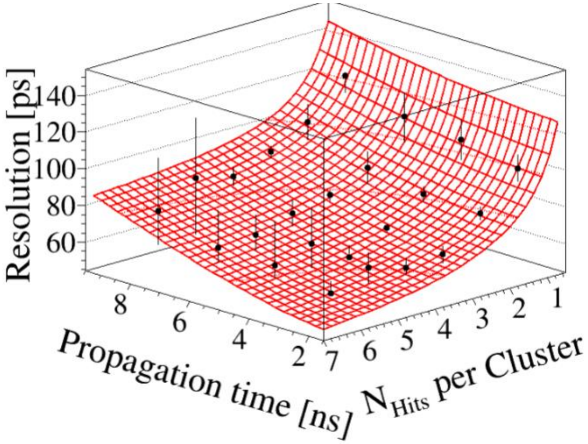
Photon yield for different beam positions

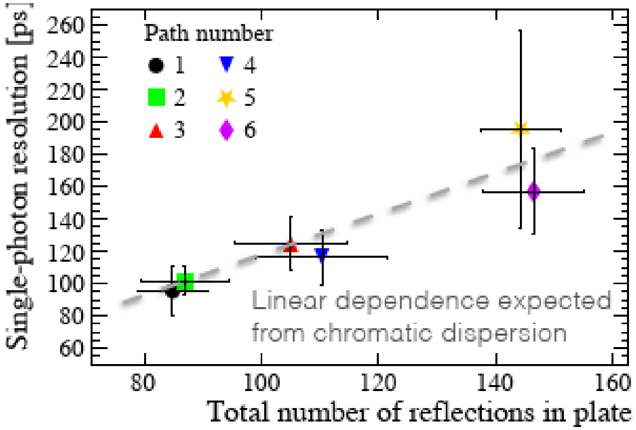


Pattern of light seen (2 MCPs)



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





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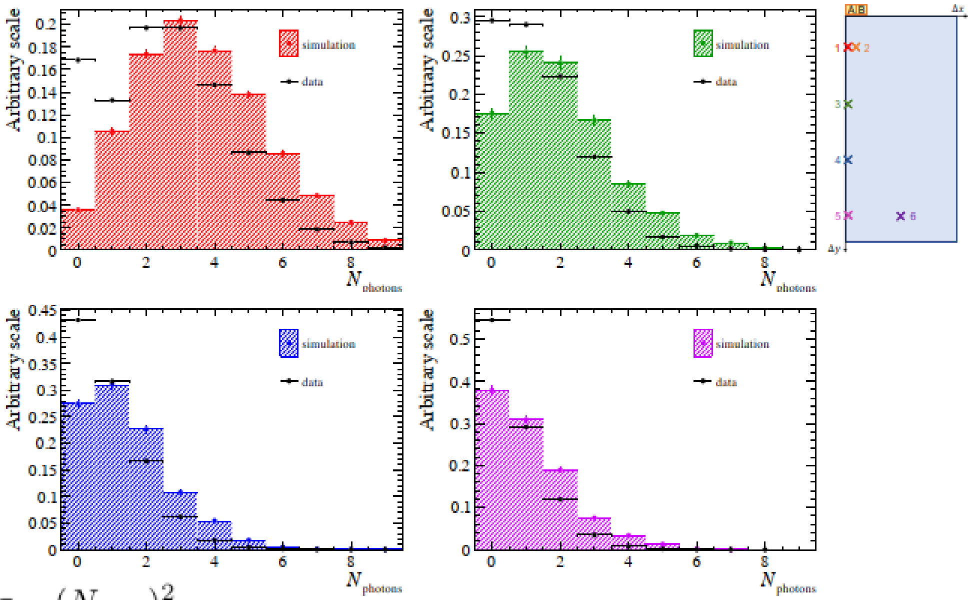

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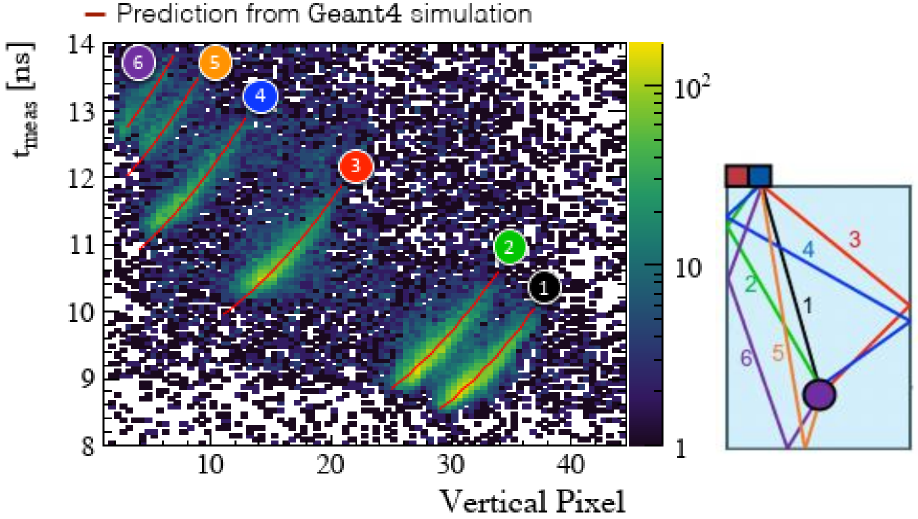
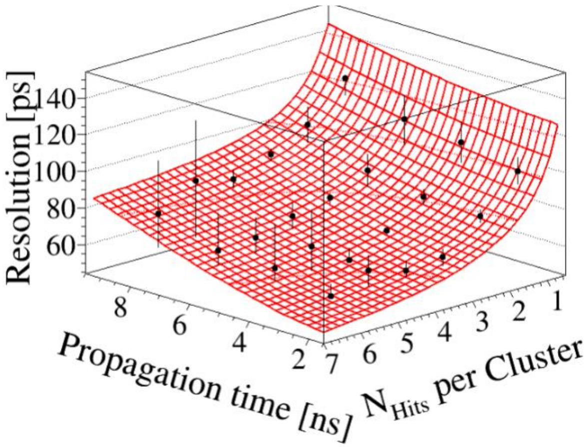
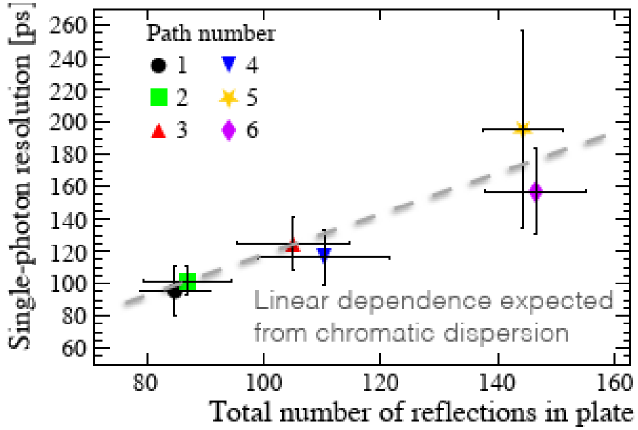
Time *vs* position in one MCP column

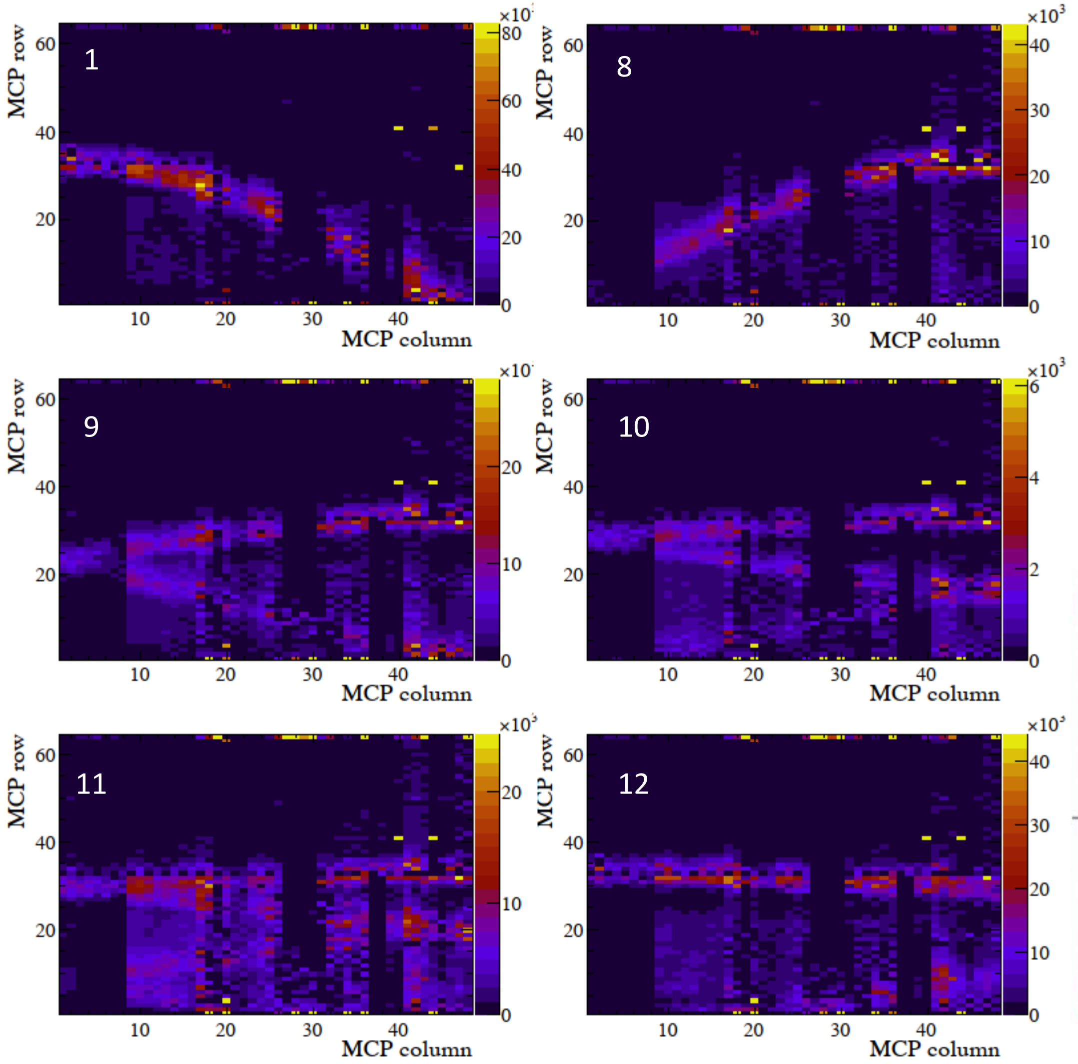


$$\sigma^2_{\mathrm{TORCH}} = \sigma^2_{\mathrm{const}} + \sigma_{\mathrm{prop}}(t_P)^2 + \sigma_{\mathrm{RO}}(N_{\mathrm{Hits}})^2$$

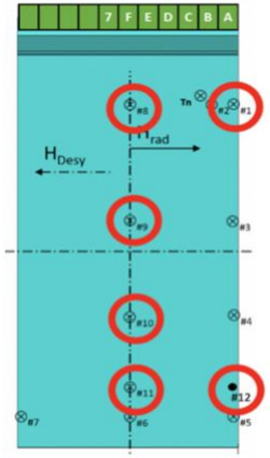




Data from 2022 beam test



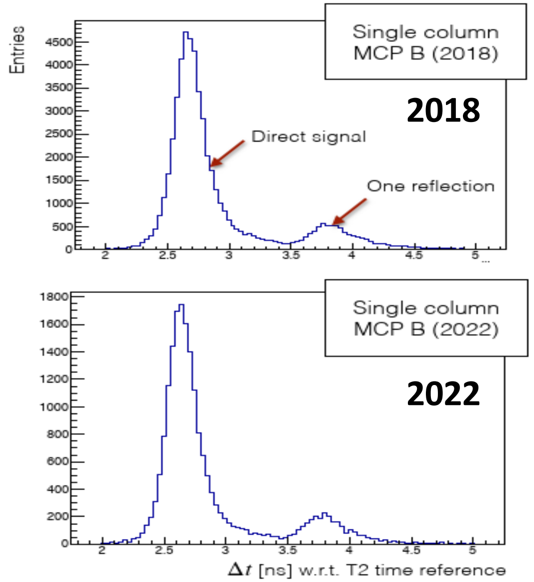
- Data taken for six beam positions over radiator plate at 3, 5, 8 and 10 GeV/c beam momenta
- Detailed analysis in progress, first indications that time resolution has been maintained with the larger system (or even slightly improved)
- Further improvement expected with better calibration and event-by-event tracking



Data from array of 6 MCPs at 10 GeV/c labelled with the beam positions

Striking patterns seen! Issues with configuring all of the electronics simultaneously → some gaps in coverage

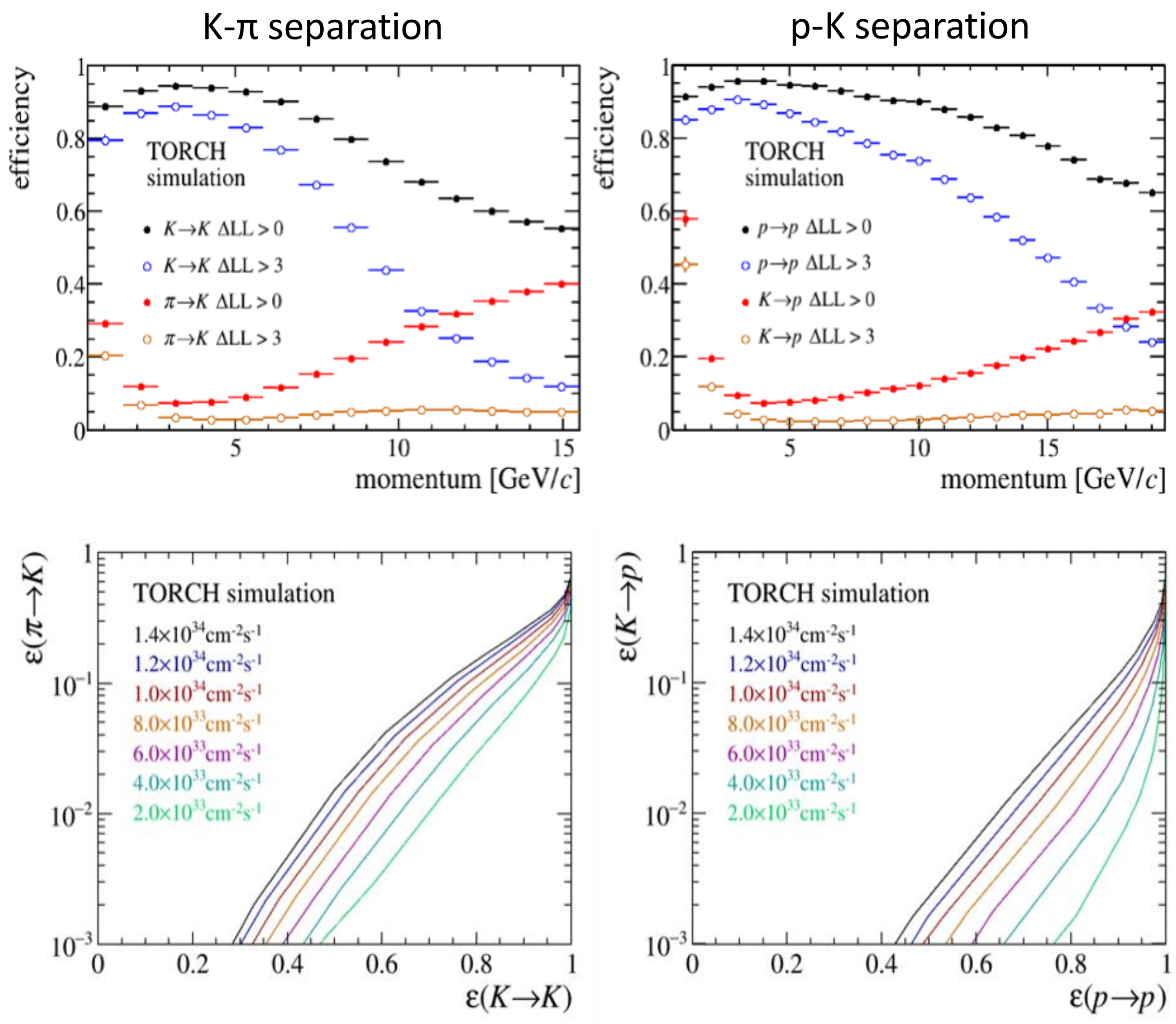
Timing comparison



Expected performance in LHCb

- Fully simulated event from Geant4 are merged to study expected particle ID performance of TORCH in LHCb, as a function of luminosity
- Assumes that *start-time* information with 30 ps precision will be available from upgraded VELO

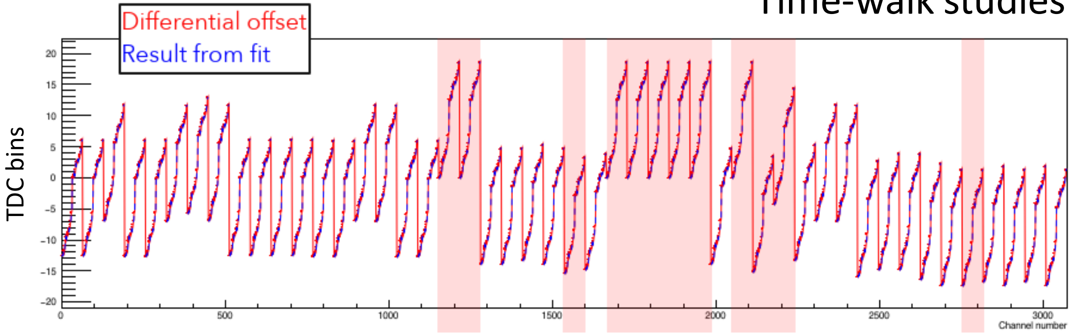
  If not, start-time can be reconstructed by TORCH using the other tracks from the primary vertex (predominantly pions) by running the usual reconstruction in reverse
- Good performance seen at Upgrade II luminosity (shown for two different cuts on the likelihood)
- Performance is strongly dependent on the detector occupancy—modules closer to the beam line have poorer performance



Future developments

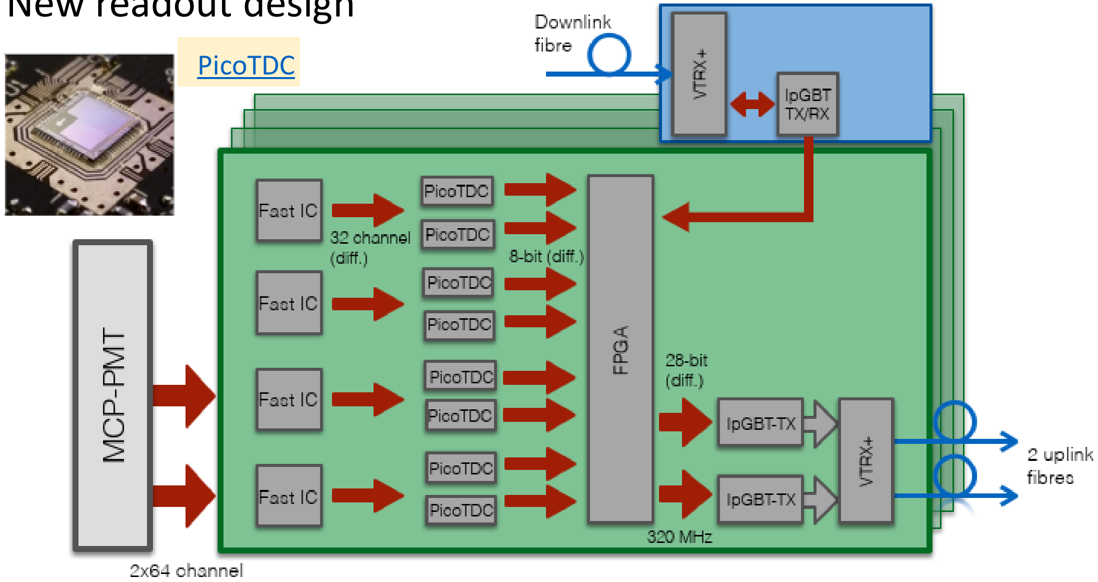
- R&D on TORCH continues, with the following goals:
  - Detailed understanding of the calibration of the test-beam data + using tracking from telescope
  - Preparing a *full-length* prototype, requires procuring and attaching another radiator plate
  - Prototyping a light-weight module housing and support, suitable for integration in LHCb
  - Developing new readout electronics based on **FastIC** JINST 17 (2022) C05027 + **PicoTDC** (12 ps bins)
  - Possible synergy with RICH for FastRICH ASIC* development (integrated FastIC + 25 ps TDC)
  - Developing a photodetector with increased *granularity* and longer *lifetime*, for the high occupancy region near to the beam pipe
- Some further details are given in the following slides

Time-walk studies



New readout design

PicoTDC

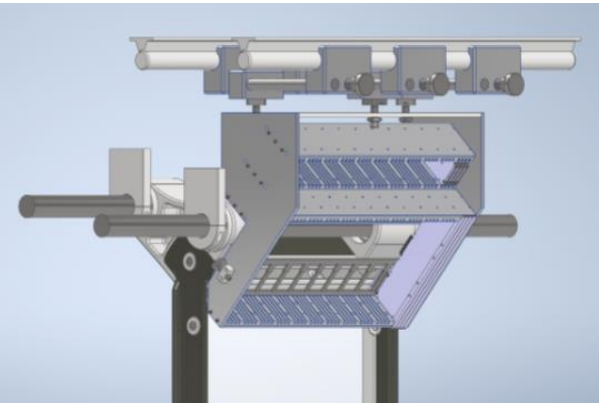


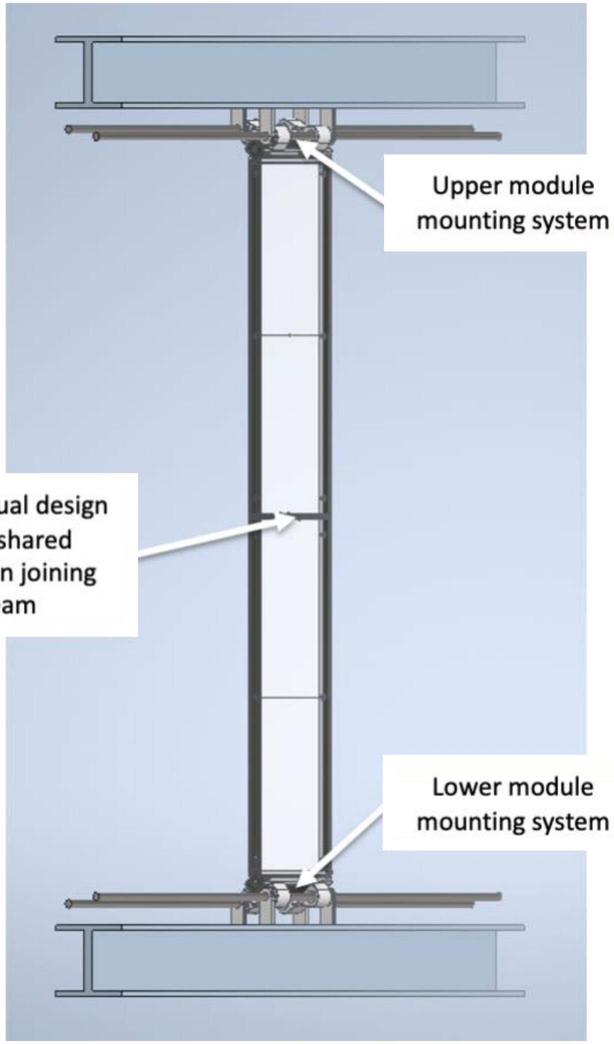
*FastRICH specifications listed in a backup slide

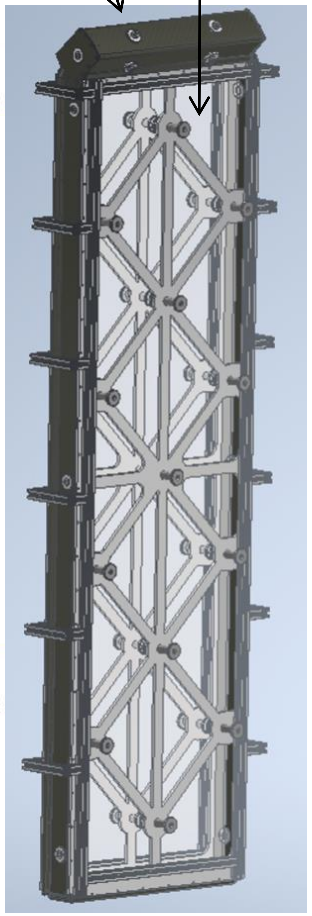
Mechanical support in LHCb

- Conceptual design is in progress for a light-weight carbon-fibre housing and support for TORCH modules
- The design aims to *minimize material* in the detector acceptance: 1 cm of quartz corresponds to 8% of X_0 wish to keep total material budget as low as possible and minimize optical contact with the radiator plate
- Robust exoskeleton will be used for quartz handling and jigging, and removed once module is in place
- Separate support of the (heavy) readout electronics enclosure under study
- Finite-element analysis and prototyping underway

Electronics housing support



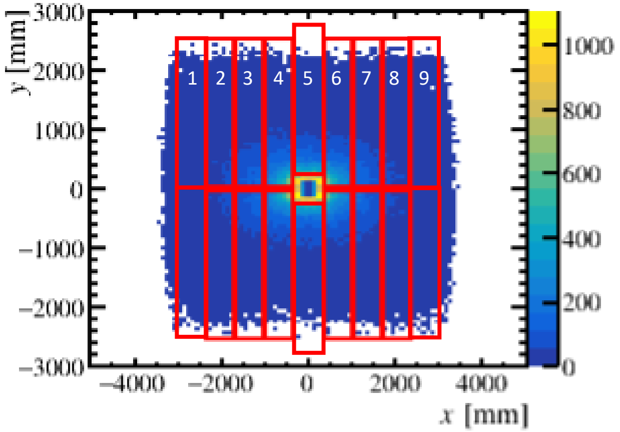




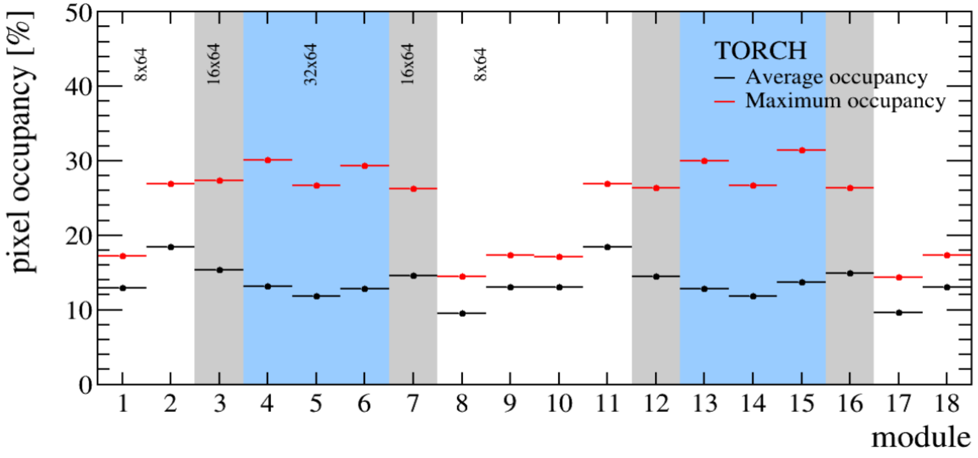
Photodetector development

- The track distribution is highly non-uniform in LHCb, peaked close to the beam-pipe, and would lead to uncomfortably high photodetector occupancy in the central TORCH modules
- A drawback of the current capacitively-coupled devices is that the significant cluster size increases the occupancy → move to direct feedthroughs, within the same 2-inch square tube body
  Granularity increased from 8 x 64 to 16 x 96 to compensate for reduced spatial resolution
- New MCP being developed with Photek using many high-density connectors (110 pins each, with 96 connected channels and 14 ground pins)—delivery expected later this year

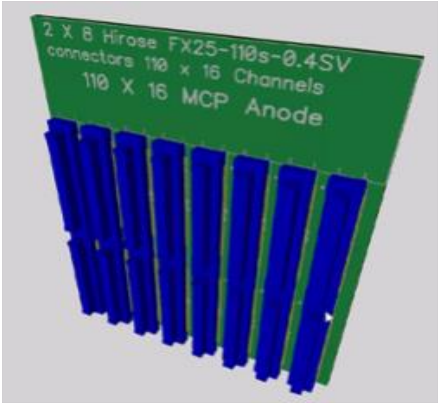
Track distribution at TORCH



TORCH pixel occupancy by module

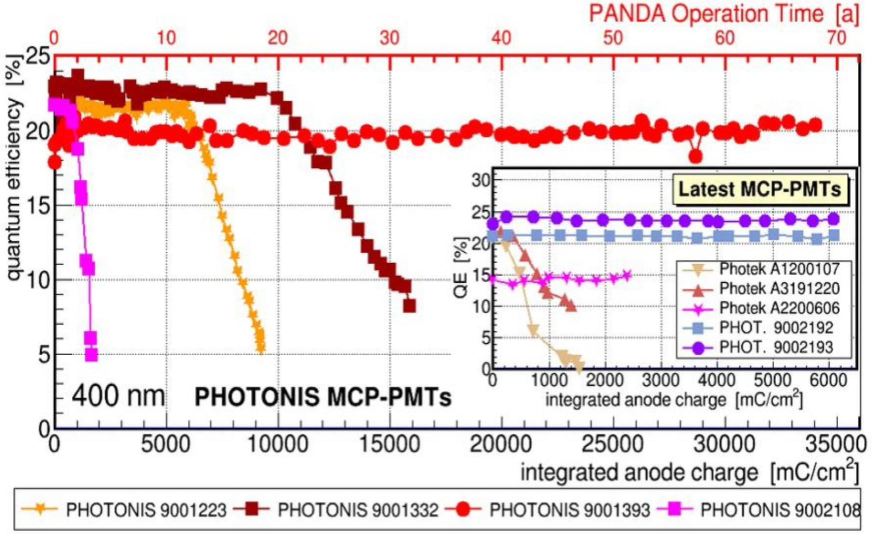


Connector layout for new MCP

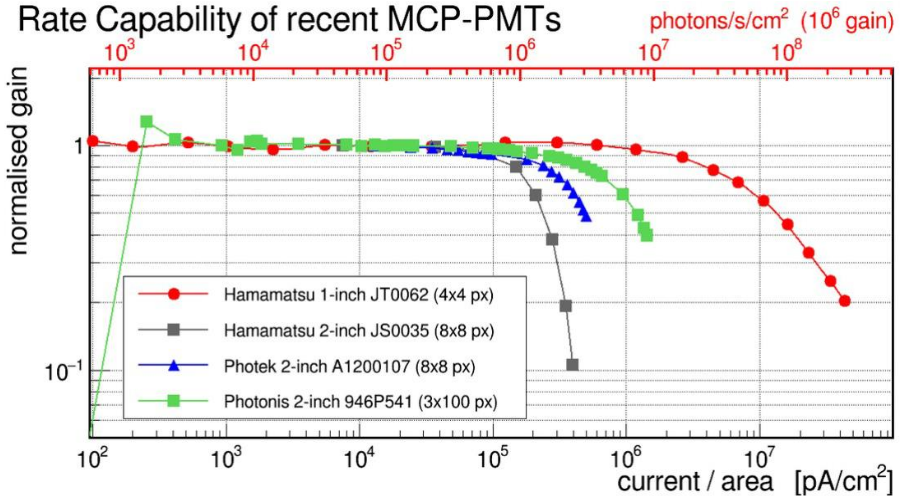


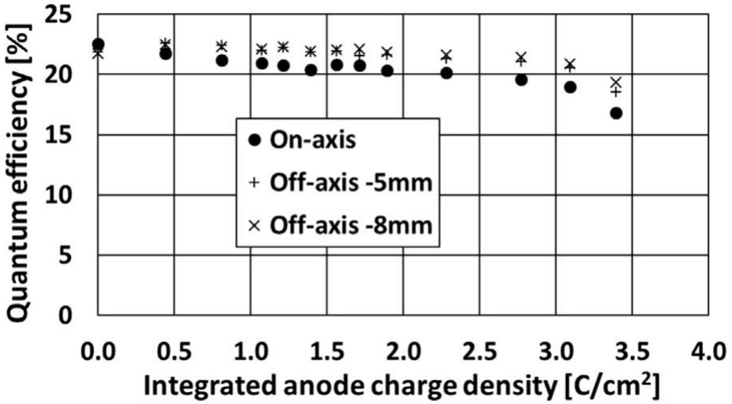
Photodetector lifetime

- It will be necessary to increase the lifetime and rate capability of the MCP-PMTs for the central modules
- Current tubes show some degradation after ~ 3 C/cm^2 of integrated anode charge, > 10 C/cm^2 required
- Other MCP tubes (studied for PANDA) have achieved longer lifetimes and higher rate capability, which can hopefully be implemented for the tube eventually used
- Otherwise SiPMs may be an alternative, to be explored



A. Lehmann, RICH 2022





Lifetime of earlier prototype MCP measured at 400 nm

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Conclusions

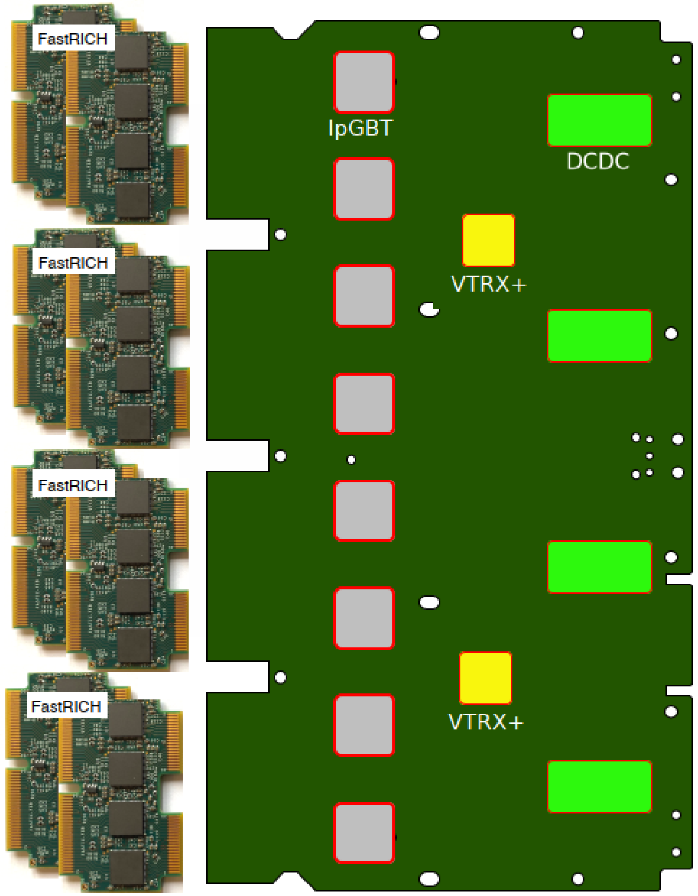
- **LHCb** has an ambitious programme for a 30-fold increase of its current dataset
  The TORCH detector is a component of Upgrade II, to be installed 10 years from now
- **TORCH** aims to push the current state-of-the-art for time-of-flight, towards 10 ps precision over a large area of 30 m^2, to enhance particle identification in the region 2–15 GeV/*c*
- **Beam tests** of a large-scale prototype have demonstrated the feasibility of the detector, providing a wealth of data from over 3000 MCP-PMT channels, that is now being analyzed
- **Further developments** are underway to prepare for the eventual implementation in LHCb:
  - Lightweight *mechanical support* for a full-size module, minimizing the material budget
  - New *readout*, to profit from the improved electronics that is now available
  - Photodetectors with further *improved granularity* and *lifetime*, for the innermost region
- We would like to extend the collaboration for this next phase, please get in contact if interested

FastRICH front-end ASIC specifications

Specifications are tailored to ensure backwards-compatibility with the Run 3 mechanics whilst equipping the detector for Upgrade II.

- Time resolution: TDC with ~ 25 ps time bins.
- Power consumption: ~ 8 mW per channel (analogue + digital).
- Radiation hardness: ASIC solution for ~ 10^{13} n_{eq}/cm^2 and ~ 5 kGy.
- Dynamic range: 5 μA to few mA for coupling to MAPMT / SiPM / MCP.
- LHCb compatibility: direct compatibility with lpGBT / VTRX+ chipset.
- Readout rate: 40 MHz (LHC).
- Number of channels: 16.
- Hardware shutter time (configurable) to limit timestamp range to ~ 1 ns.
- Constant-fraction discrimination (CFD).
- Zero-suppressed output, aiming for ~ 12 bits per hit or less.

The FastRICH design is progressing well by the CERN-EP-ESE group and the University of Barcelona. The analogue part of the design is near completion and the digital design ongoing.



Note: Sketch for illustrative purposes. The numbers and placement of components will be subject to R&D and optimisation.