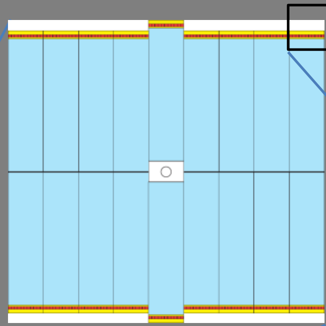
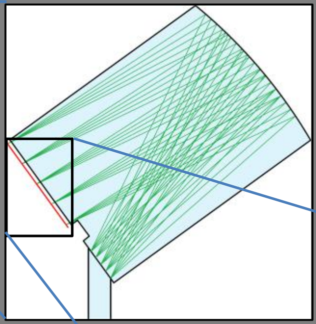
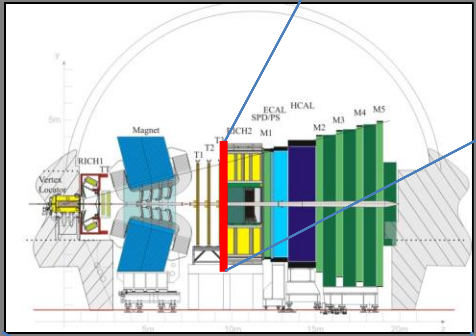
maarten.vandijk@physics.ox.ac.uk



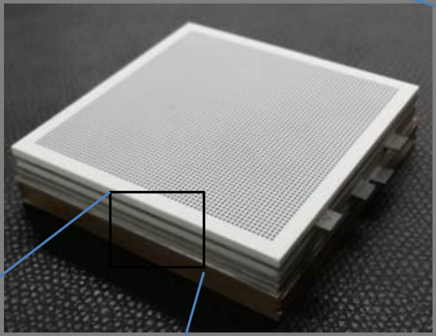


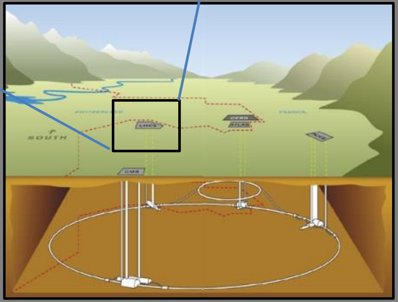


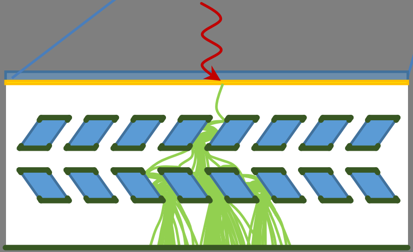
The TORCH project

Testbeam results & current status

Workshop on Picosecond Timing Detectors
Kansas City, Missouri, United States
September 15, 2016





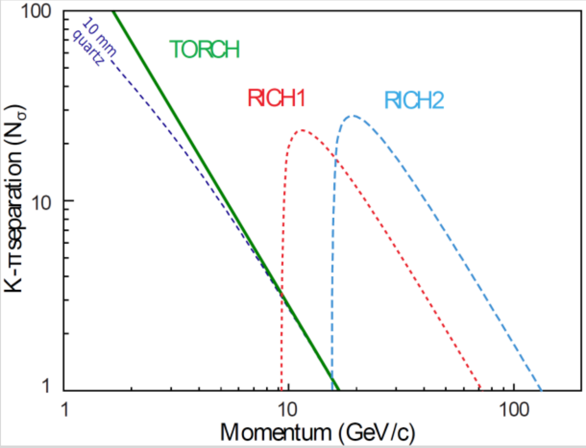


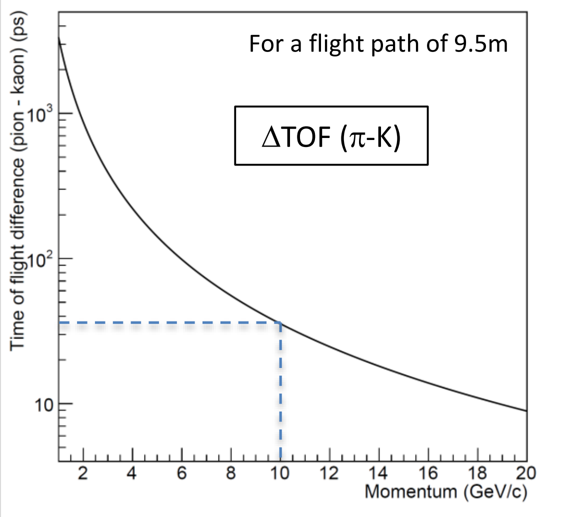
M.W.U. van Dijk

TORCH

- TORCH: Time Of internally Reflected CHerenkov light
  - DIRC-like detector
- Proposed as upgrade for LHCb
  - TORCH has the potential to complement the existing PID system (RICH1, RICH2) in the low momentum regime (2-10 GeV/c)
- Principle of operation
  - High precision timing of particle at known momentum provides PID
  - ΔTOF(π-K) = 37.5ps at 10 GeV/c
  - Target (three sigma separation) is ~15ps / track

M. J. Charles, R. Forty,
*NIM A **639** (2011) 173-176*

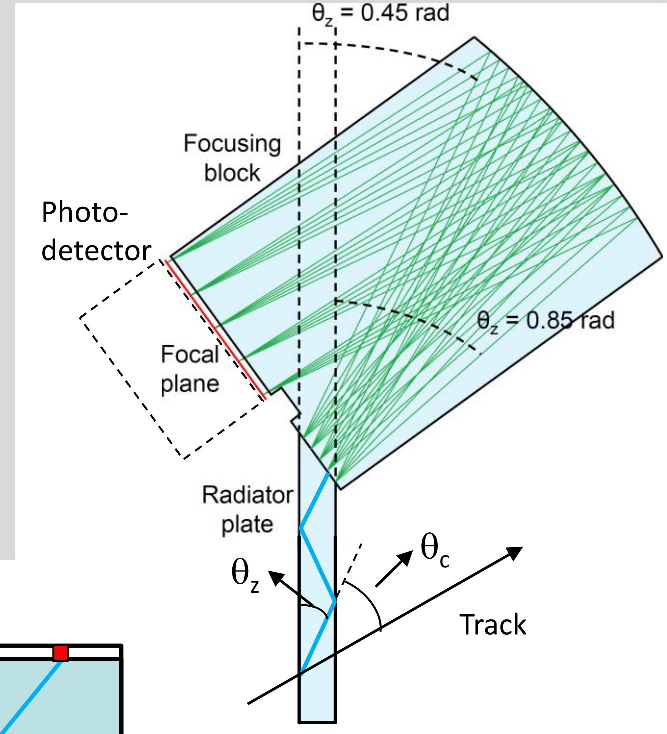


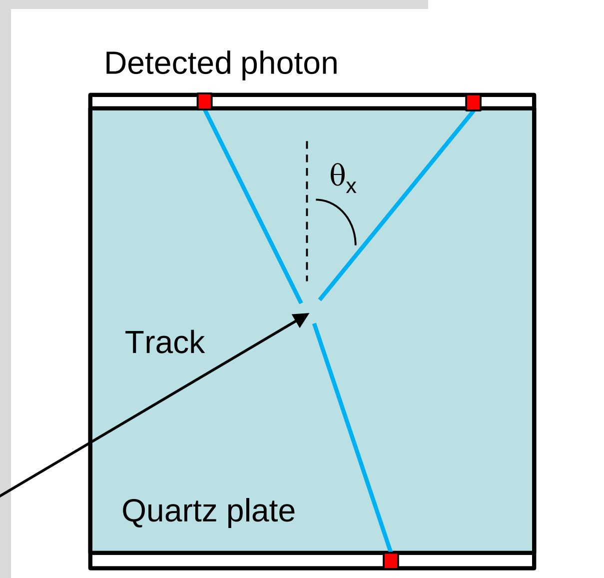


maarten.vandijk@physics.ox.ac.uk

TORCH

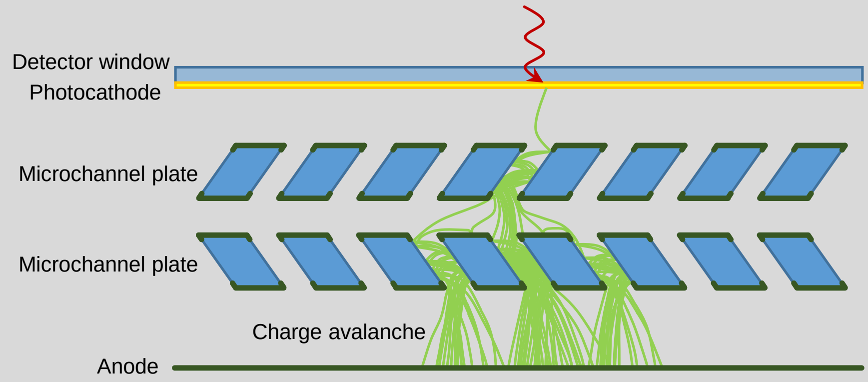
- Cherenkov light generated in radiator is transported to periphery by total internal reflection
- Measure angles θ_z and θ_x to reconstruct photon trajectory – 1 mrad precision
- Infer Č angle to correct for chromaticity
- Around 30 photon timestamps are measured and combined into track timestamp

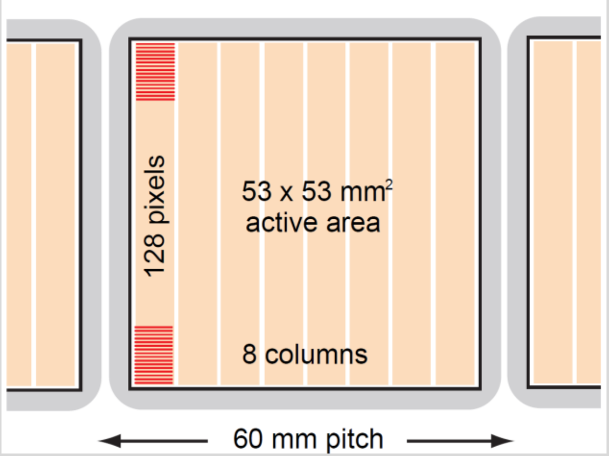




Photodetectors for TORCH

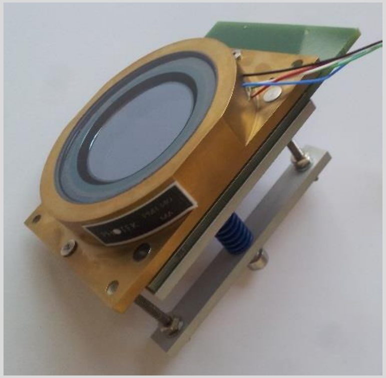
- Single photon time resolution of about 70ps required
- Requirement met by MCP-PMT
- TORCH design calls for 128×8 pixels on a 53×53mm^2 area
  - Pixel size set by requiring 1 mrad precision on measured angles θ_z and θ_x
- Required performance
  - ~50ps for electronics + MCP-PMT
  - ~50ps for effects of pixel size and reconstruction





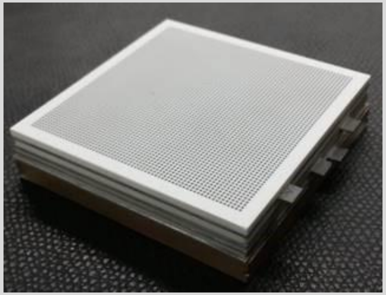
MCP-PMT development

- Phase I
  - Circular prototype – 25mm active diameter
  - Single channel MCP-PMT with extended lifetime



- Phase II
  - Circular prototype - 40mm active diameter
  - 4×32 pixelated anode embedded in center
  - Resolution demonstrator
  - Introduces charge sharing

T.M. Conneely et al.,
JINST **10** C05003 (2015)



- Phase III
  - Square tube with 53×53mm^2 active area
  - 8×64 pixels with charge sharing
  - Prototypes expected to be delivered this fall

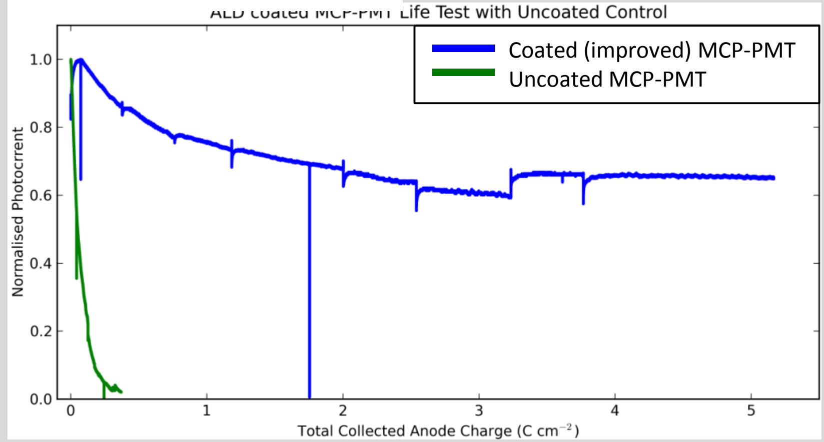
maarten.vandijk@physics.ox.ac.uk

Lifetime testing

- Lifetime requirement set at $5C/cm^2$ for Phase-I MCP-PMTs
- Have undergone tests at Photek
  - Phase-I equivalent MCP-PMT
- Tests have been verified at CERN
  - Phase-I MCP-PMT
  - Stabilized blue LED
- Tests successful
  - Gain drop deeper than expected
  - Recovered by increase of HV
  - Marginal loss in quantum efficiency ($3.1\ C/cm^2$)

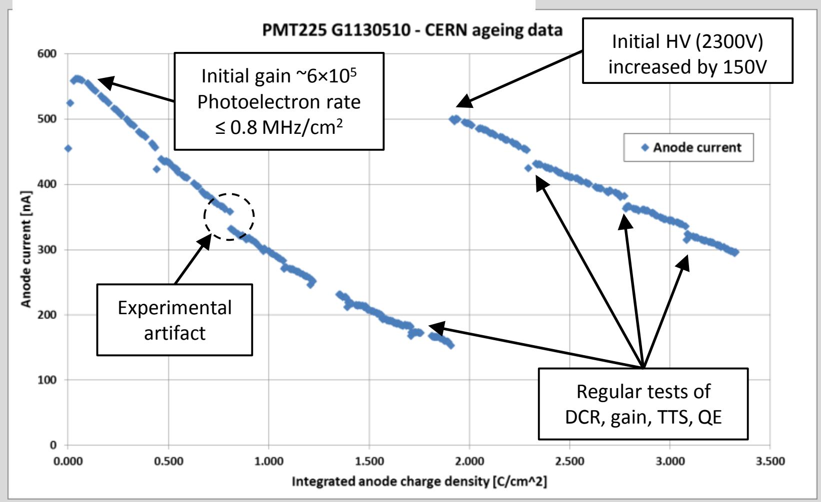
Lifetime test by Photek

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



Lifetime test by TORCH @ CERN

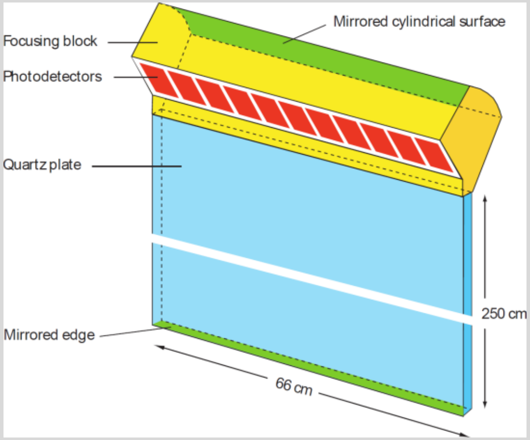
T. Gys, presented at RICH2016 (Bled)

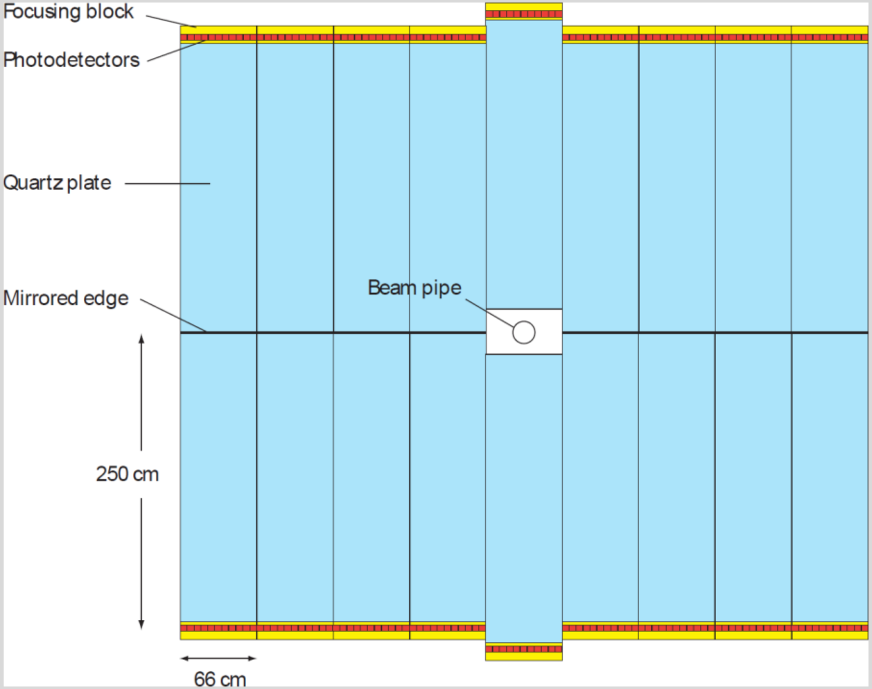


maarten.vandijk@physics.ox.ac.uk

Modular layout

- For application in LHCb a plane of about 5×6m² needs to be instrumented
- Not feasible to do this with a single plane of quartz
- Uses modules of 66×250cm²
- Reflections off vertical sides give ambiguities in reconstruction
- Referred to as pattern folding





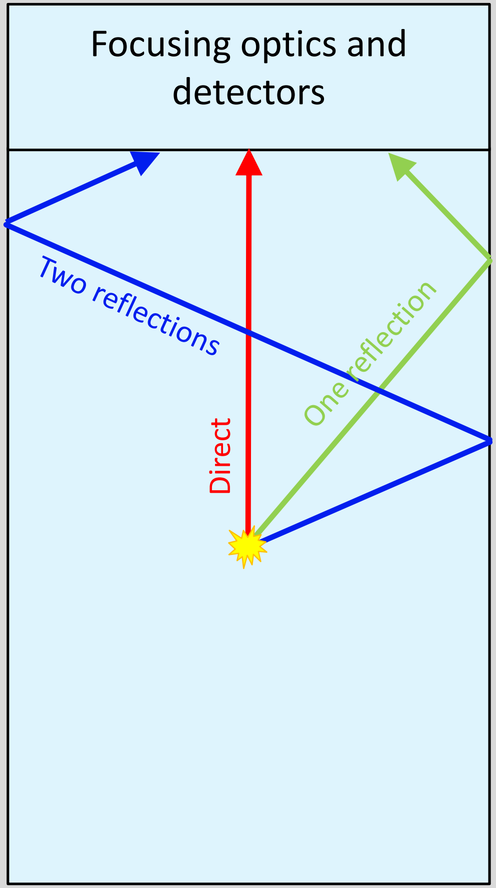
maarten.vandijk@physics.ox.ac.uk

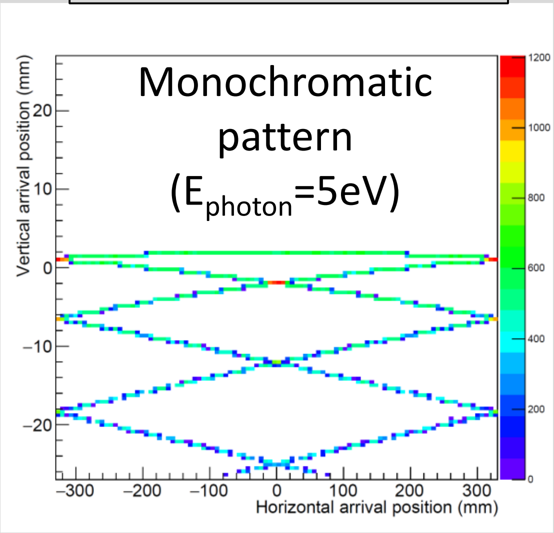
UNIVERSITY OF OXFORD

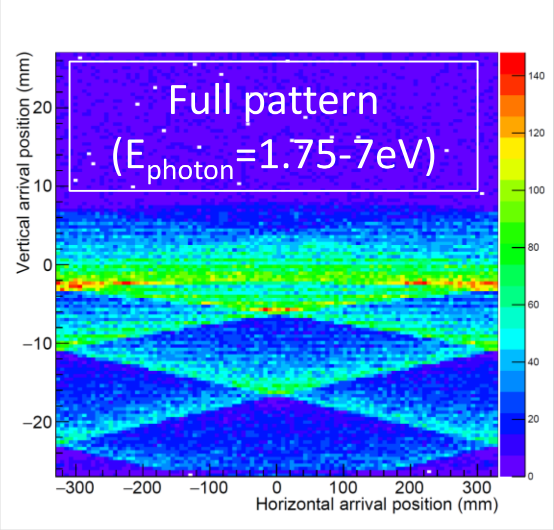
Pattern folding

Different X and Y scales
Compressed view in X

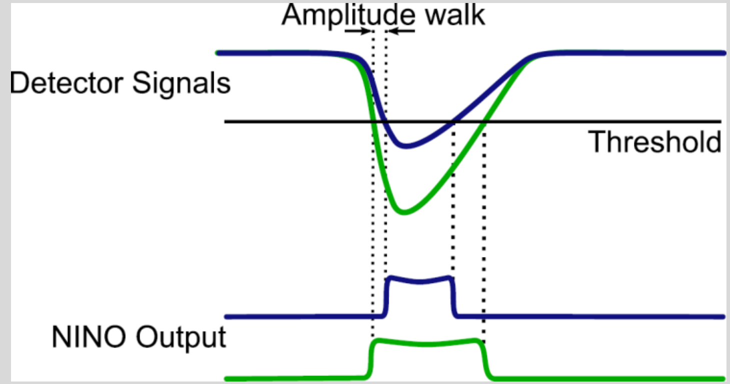
- Cherenkov cone results in hyperbola-like pattern
- Reflections off module edges result in folding of this pattern
- Chromatic dispersion spreads line into band
- Pattern shown here for full TORCH module, but also very prevalent in testbeam







TORCH electronics



- Electronics consist of combination of NINO and HPTDC ASICs
- NINO is discriminator with TOT information
- HPTDC timestamps leading / falling edge of NINO pulse
  - 100ps bins
- NINO introduces time walk
  - To be addressed with calibration and further analysis
- 128ch board in development

R. Gao et al., JINST **11** C04012 (2016)

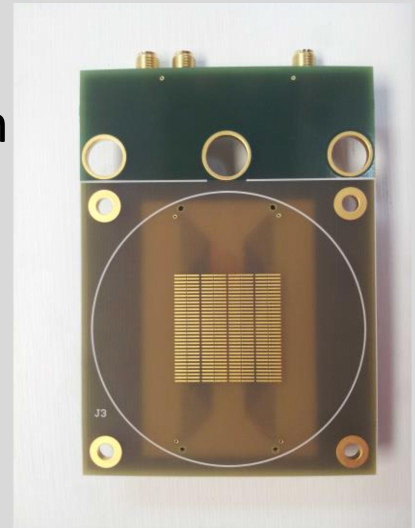
2x NINO

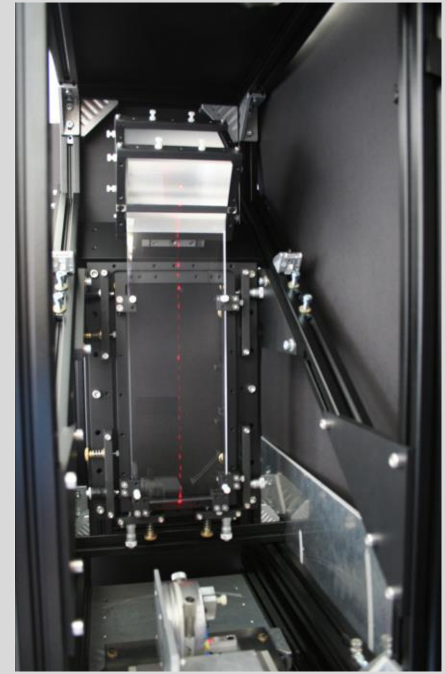
2x HPTDC

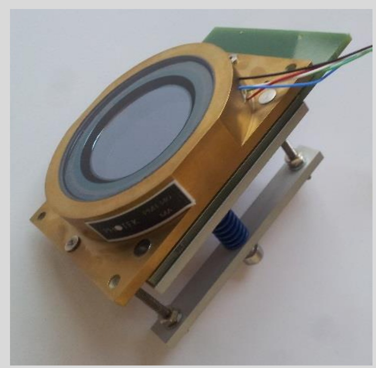
maarten.vandijk@physics.ox.ac.uk

Testbeam setup

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

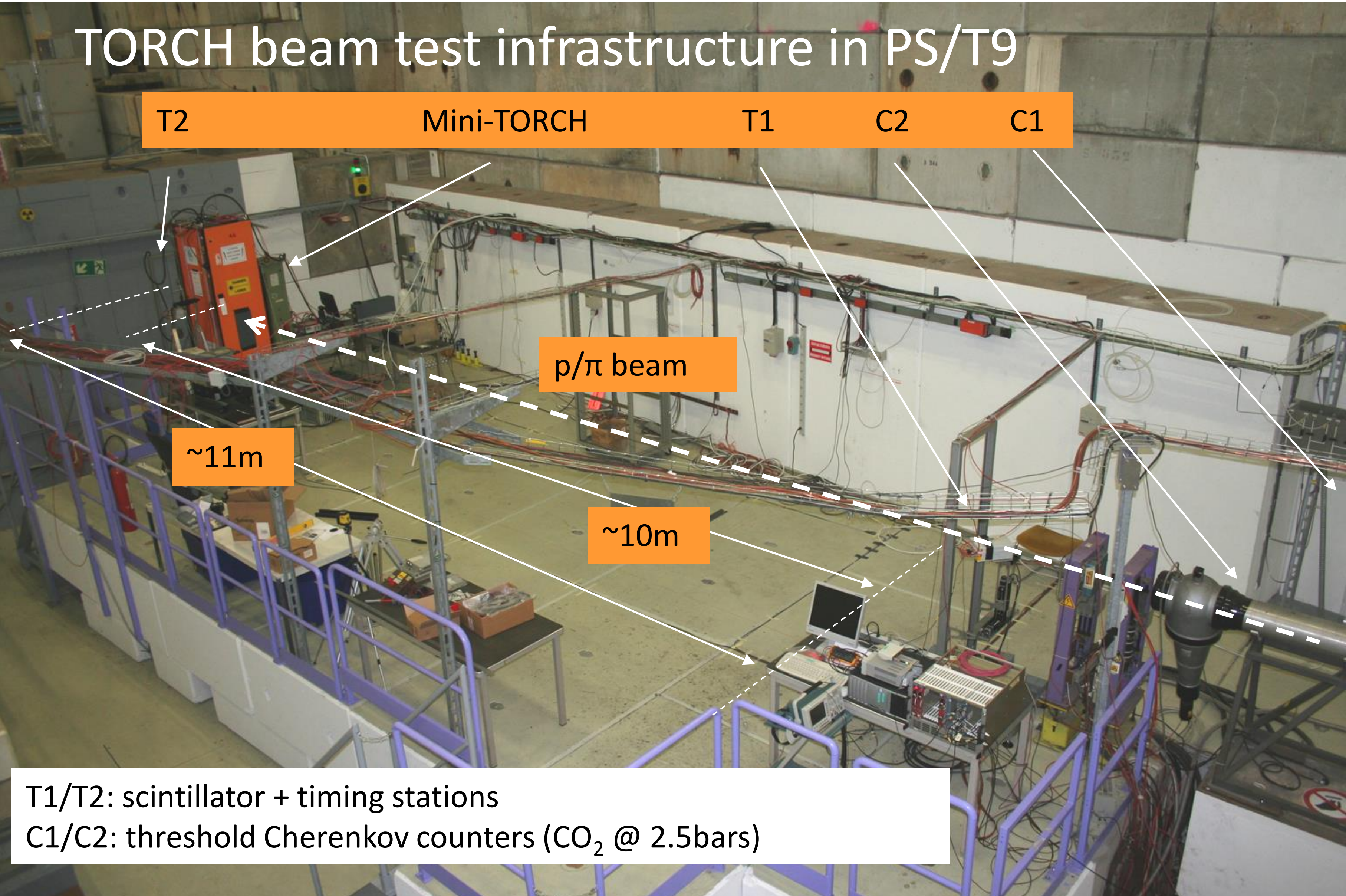






maarten.vandijk@physics.ox.ac.uk

TORCH beam test infrastructure in PS/T9



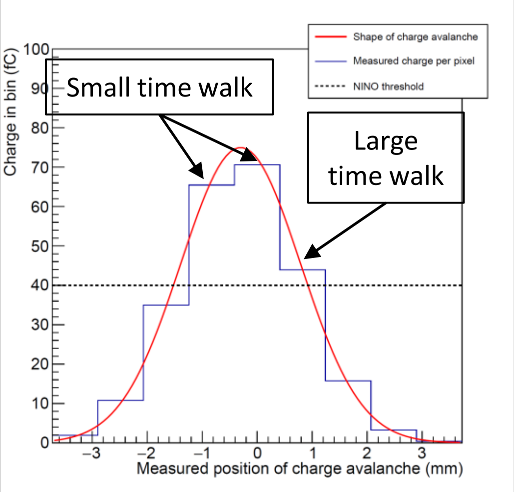
T1/T2: scintillator + timing stations
C1/C2: threshold Cherenkov counters (CO_2 @ 2.5bars)

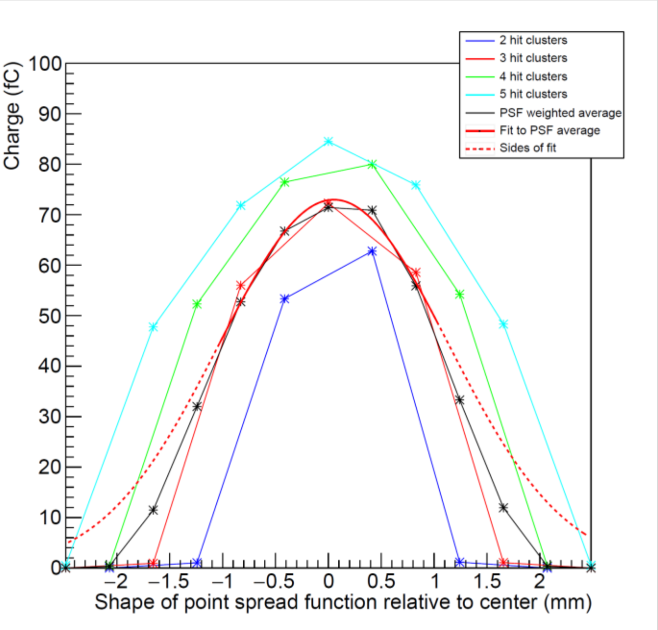
Cluster analysis

- NINO + HPTDC gives charge in avalanche plus leading timestamp

- Information extracted per cluster
  - Charge weighted position
  - Timestamps also charge weighted
    - Lower resolution on low-charge hits

- Information avalaible from within cluster
  - Shape of avalanche extracted from hit position and charge
  - Time of all hits in cluster should be identical – all come from same avalanche
    - Gives possibility to do time walk calibration from data



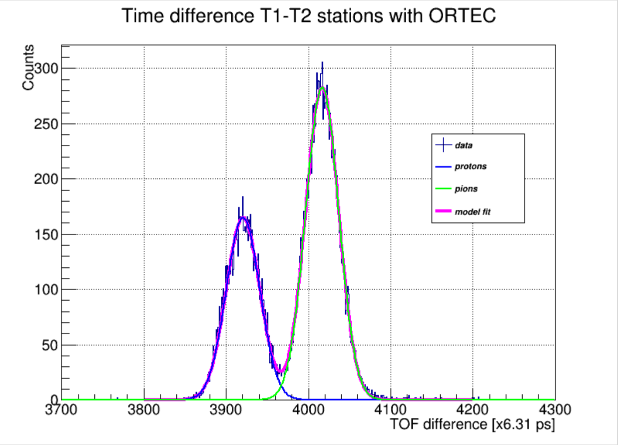


maarten.vandijk@physics.ox.ac.uk

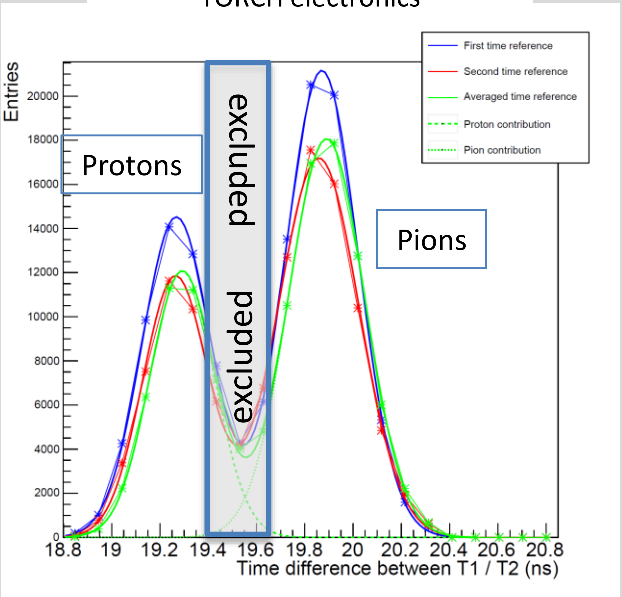
UNIVERSITY OF OXFORD

Particle selection

- Goal is to measure time resolution of TORCH – but different particle species overlay in time / space
- Mixed particle beam (positive, 5 GeV/c)
  - Protons / pions
  - Cherenkov counters not fully efficient at 5 GeV/c
  - Difference in time of flight about 600ps
- Measured by injecting T1 and T2 timing signals into TORCH electronics
  - Verified with commercial system (ORTEC)
- Additionally, exact TOF difference also used for calibrating momentum



TOF difference measured with TORCH electronics



maarten.vandijk@physics.ox.ac.uk

UNIVERSITY OF OXFORD

Cluster hitmap

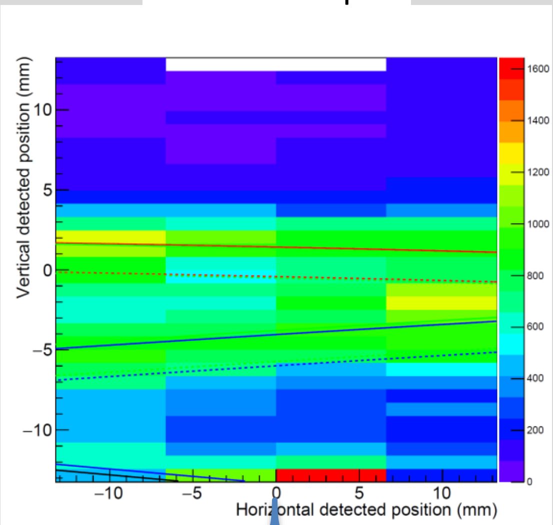
- Charge weighting applied for clusters

- Particle selection from TOF

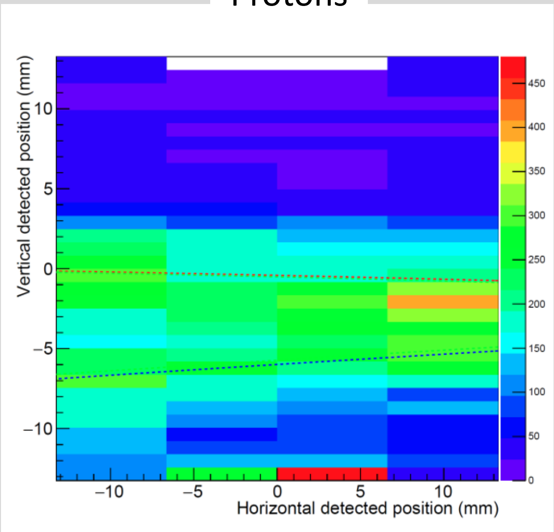
- Hitmap splits into two contributions
  - Pion (solid line)
  - Proton (dashed line)

- Difference in Cherenkov angle clearly visible

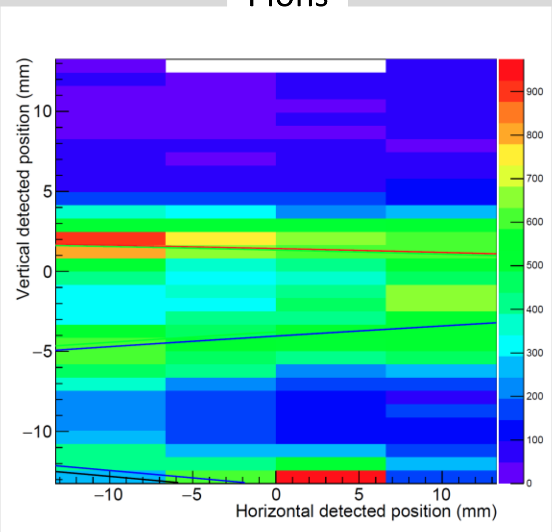
Full hitmap



Protons



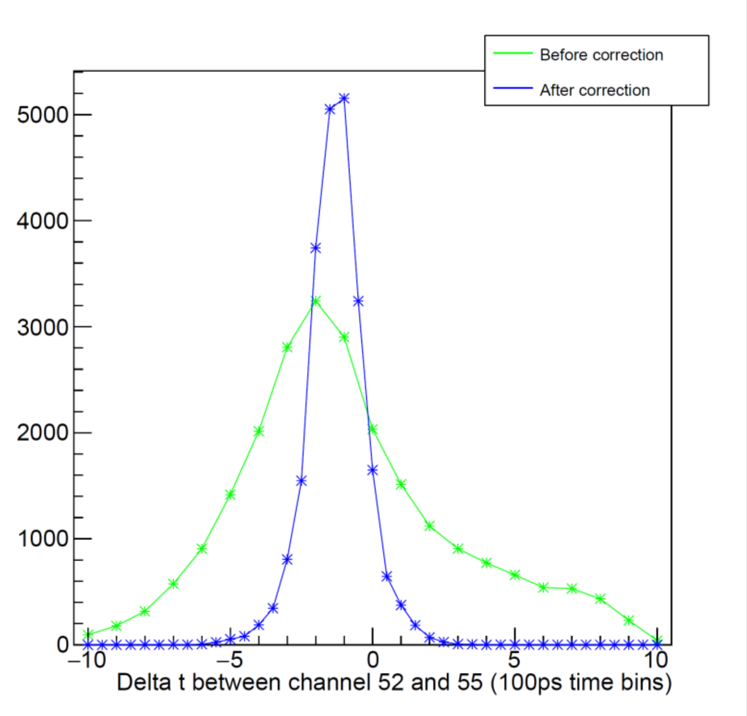
Pions



maarten.vandijk@physics.ox.ac.uk

Time walk correction

- Time difference within cluster between neighbouring pixels is mapped as a function of charge in both
- Resulting shape $\Delta t(Q_1, Q_2)$ is fitted
- Shape of $\Delta t(Q_1)$ and $\Delta t(Q_2)$ is extracted
- Only the shape of the time walk is corrected for – still channel to channel offset
- Map out cumulative offset between channels

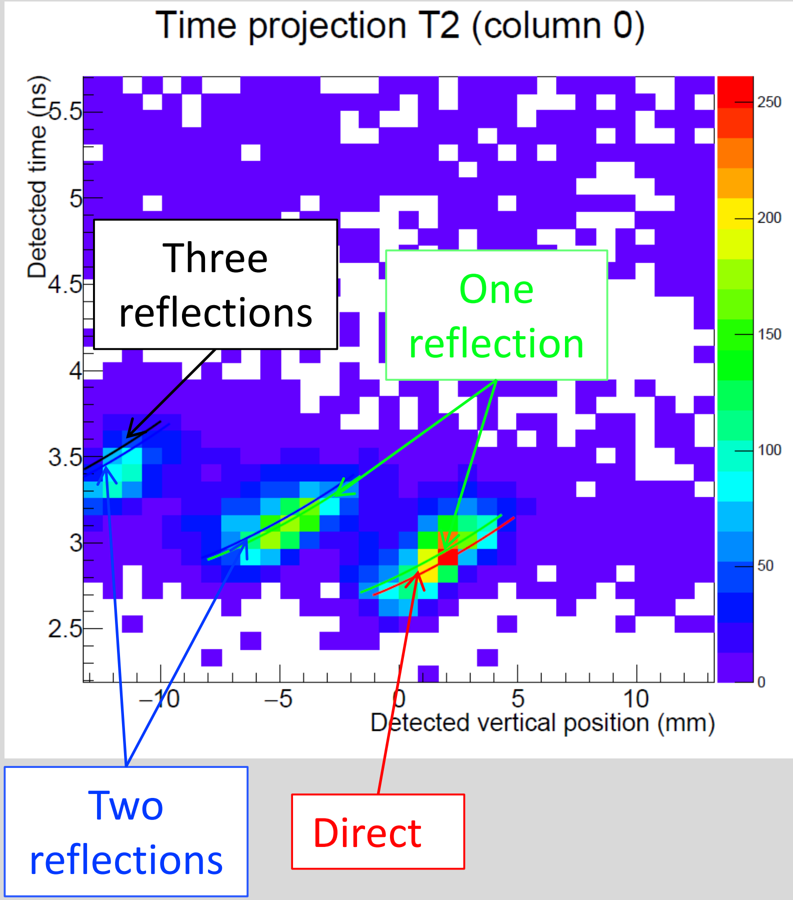


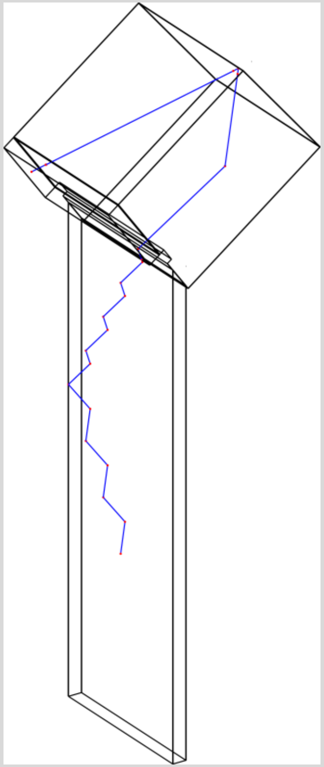
Channel 52 and 55 are connected to neighbouring pads – oddity in channel mapping

Timing results

- Displayed as time projection per single (vertical) column
- Predict expected photon positions
  - Superimpose predictions and data
- Reflections occur twice – once for each vertical side

Pions only

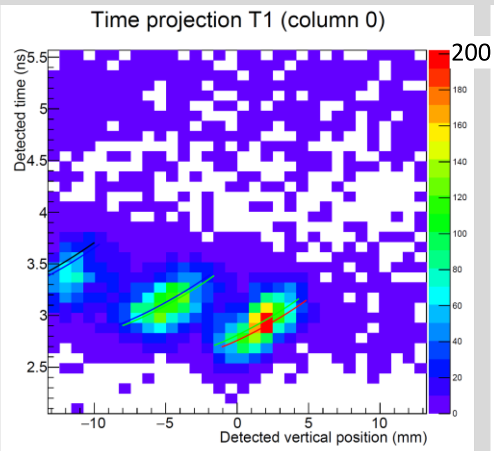


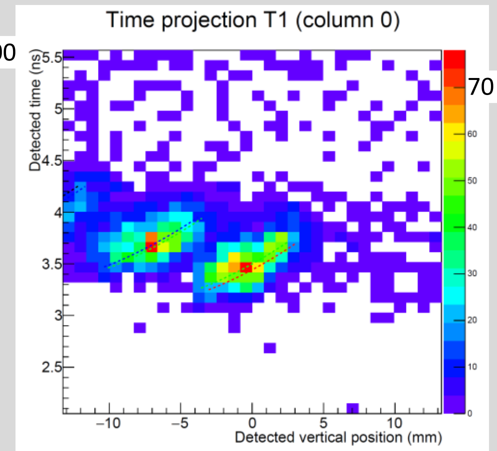


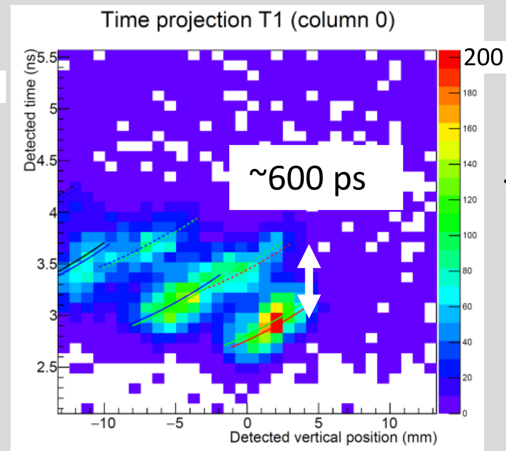
maarten.vandijk@physics.ox.ac.uk

Timing results

Pions only	Protons only	All

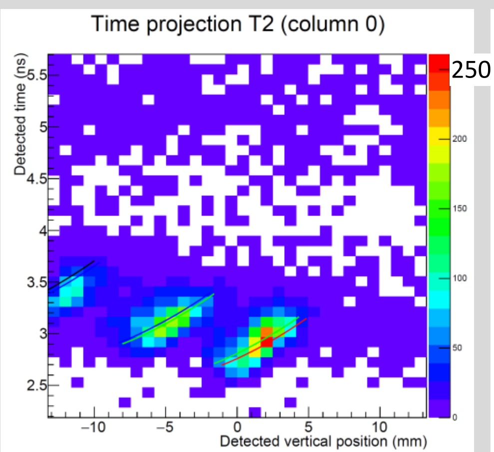


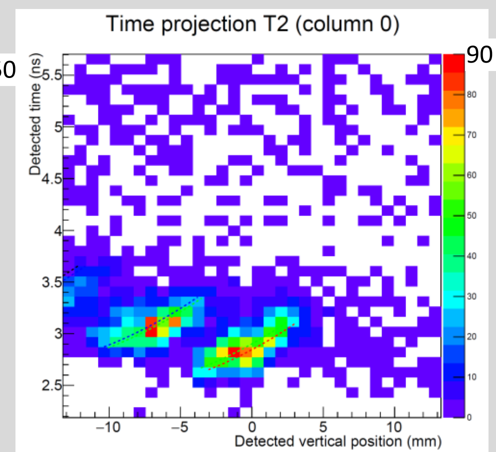


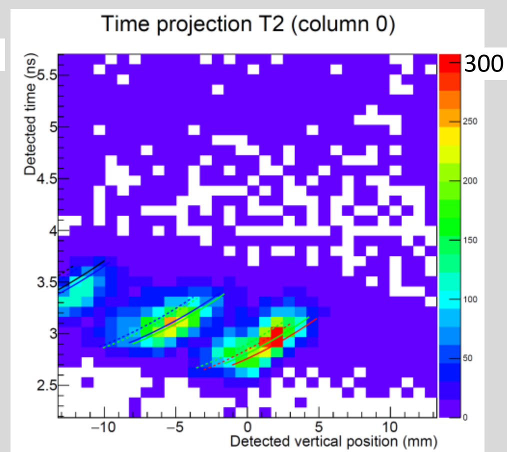


T1 reference

Flight path 10m







T2 reference

Flight path 1m

maarten.vandijk@physics.ox.ac.uk

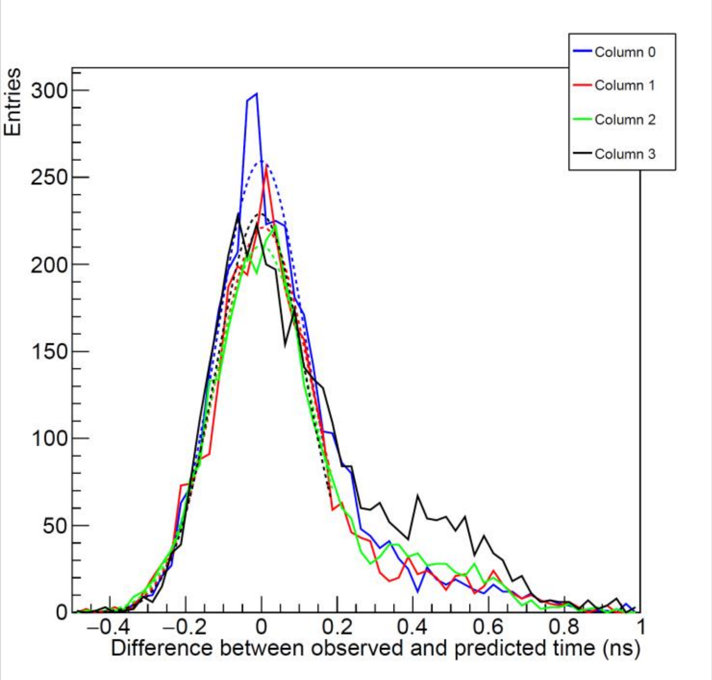
Time resolution

- Predicted photon arrival time
  - Full reconstruction based on:
    - Track position
    - Particle momentum (measured from TOF difference)
    - Particle selection

- Time resolution estimates
  - Gaussian fit of main peak

- Time resolution (for now) dominated by time reference
  - Beam defined by small scintillators
  - No tracking
  - 100ps bins in HPTDC

Pions only
T2 reference
1m flight path

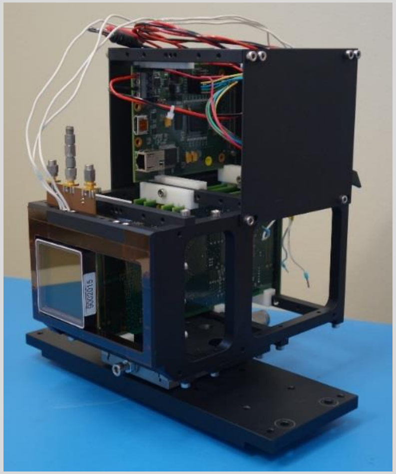


Col. #	Mean [ps]	Sigma [ps]
0	-0.6	117.2
1	4.7	124.9
2	-0.3	126.9
3	-3.0	117.7

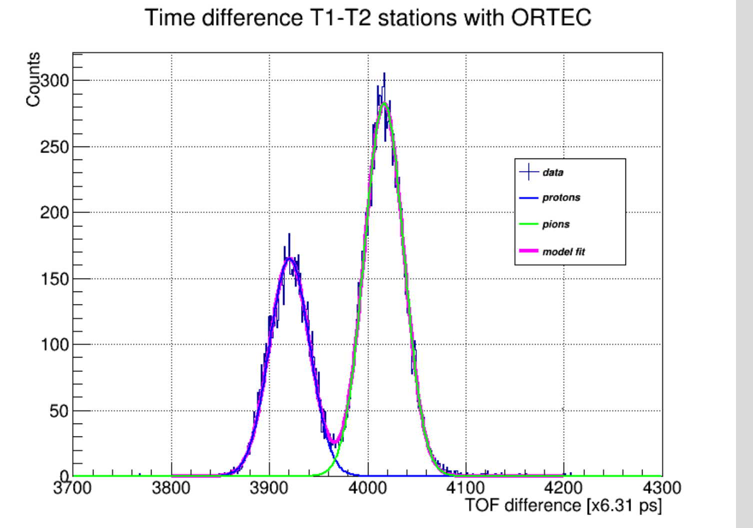
maarten.vandijk@physics.ox.ac.uk

Perspectives

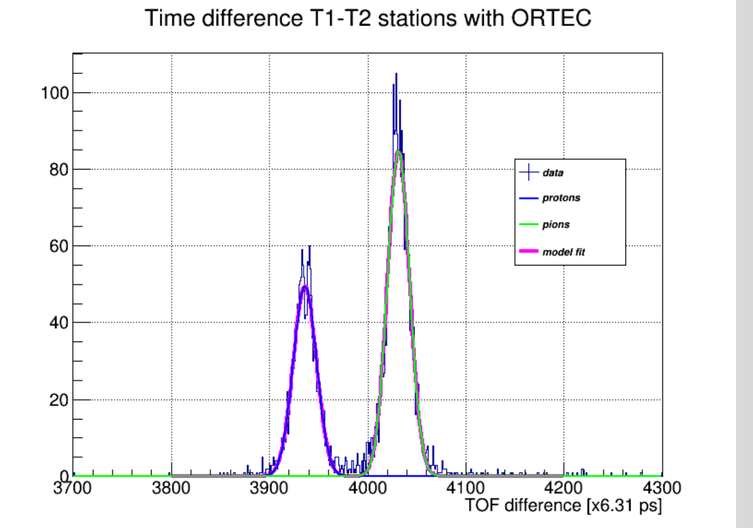
- New testbeam setup
  - Setup has been adapted to accommodate 32×32 Planacon
  - Timing from individual stations has been improved significantly
  - Completed – results looking good so far!
- Further tests foreseen with Phase-III tubes
- New optics ordered ($66{\times}125{\times}1cm^3$)
  - Test outside LHCb acceptance under discussion



November 2015



September 2016



maarten.vandijk@physics.ox.ac.uk

UNIVERSITY OF OXFORD

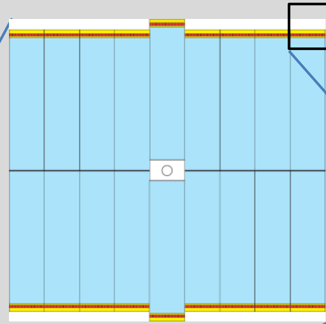
Conclusions

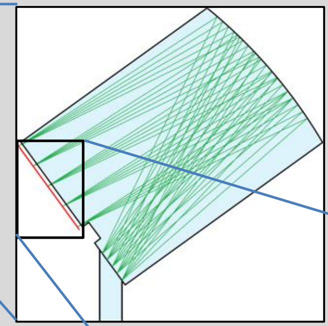
- TORCH is a solid Cherenkov detector proposed for the PID system of LHCb, using time of flight, in the region 2-10 GeV/c

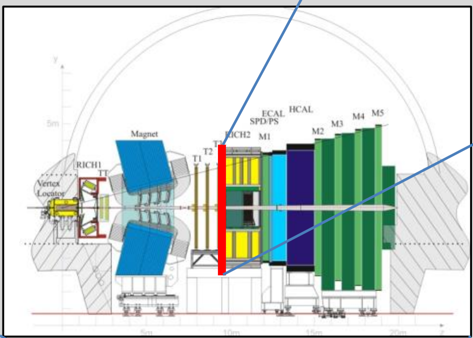
- Results on required specifications very satisfactory
  - Lab measurements complementing testbeam
  - Performance has been shown to be very good – 117ps time resolution
  - Significant improvements expected from recently finished testbeam

- TORCH has a bright future
  - New optics are in the process of being ordered
  - Testing outside of LHCb acceptance is under discussion
  - Delivery of Phase-III MCP-PMTs is very close
  - New generation of electronics being designed

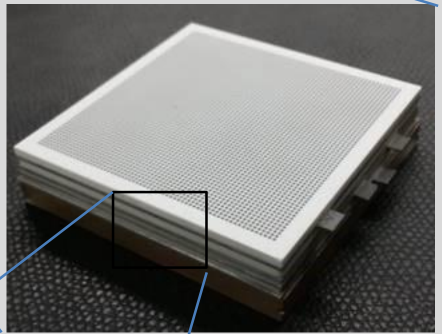
maarten.vandijk@physics.ox.ac.uk

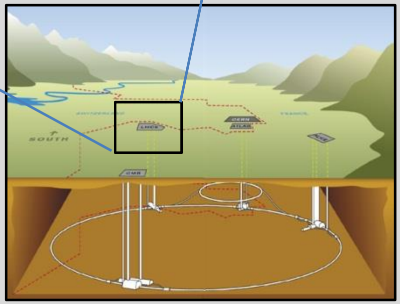


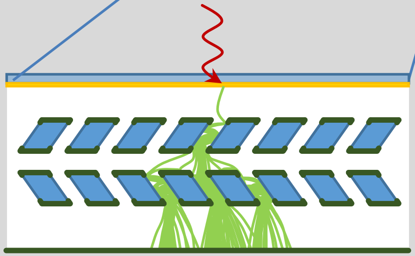




Thank you!







The support of the European Research Council in funding this work is gratefully acknowledged: ERC-2011-ADG proposal 299175, http://cordis.europa.eu/projects/rcn/103813_en.html

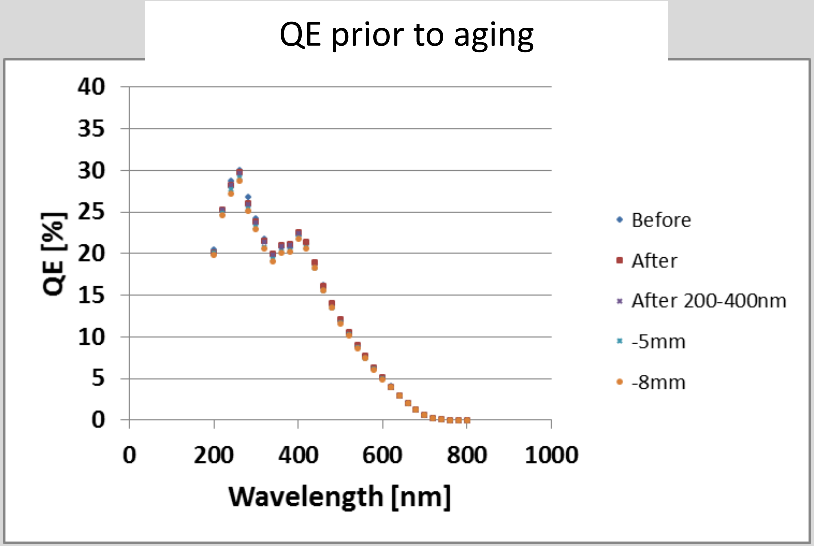
Backup slides

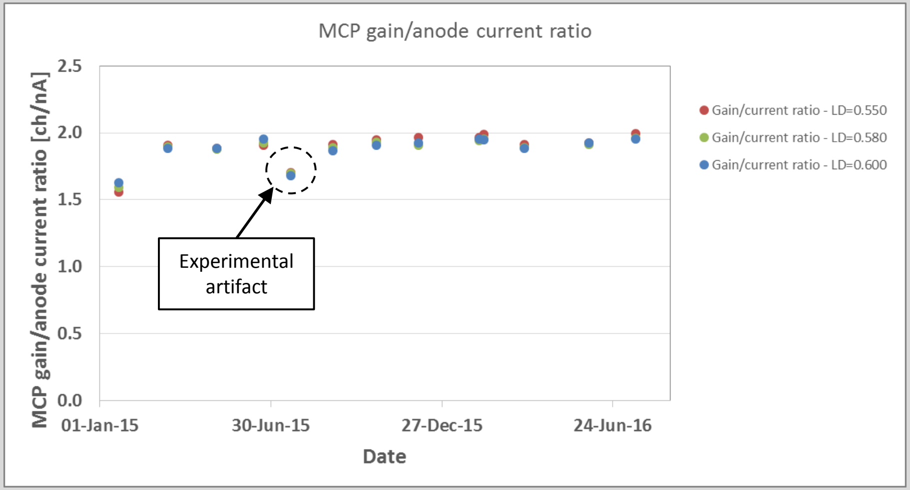
maarten.vandijk@physics.ox.ac.uk

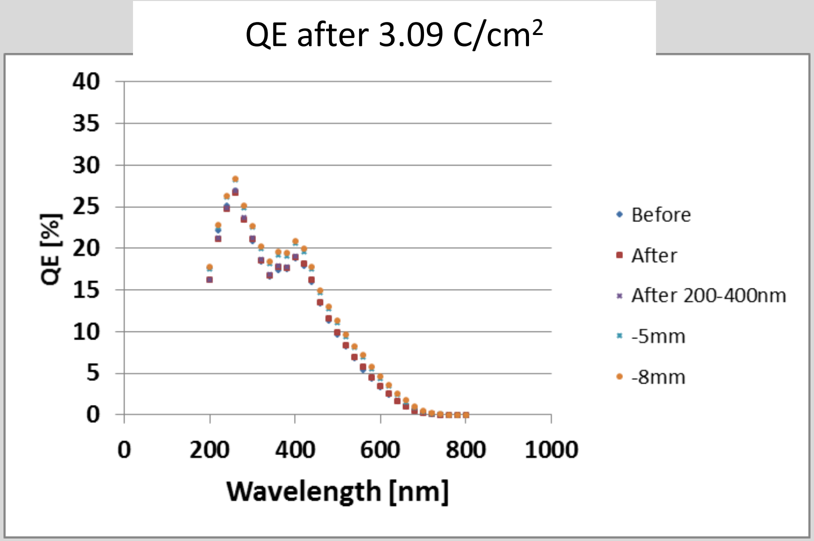
Lifetime testing

- Quantum efficiency of MCP-PMTs monitored over length of lifetime tests
- Tests performed (so far) up to 3.09 C/cm²

T. Gys, presented at RICH2016 (Bled)







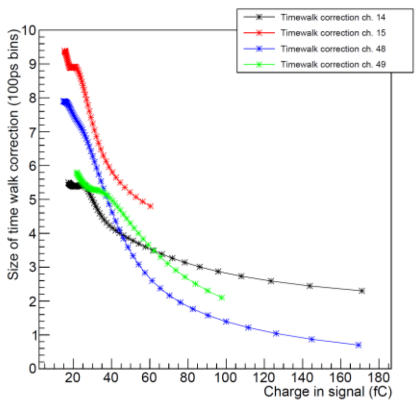
maarten.vandijk@physics.ox.ac.uk

Time walk

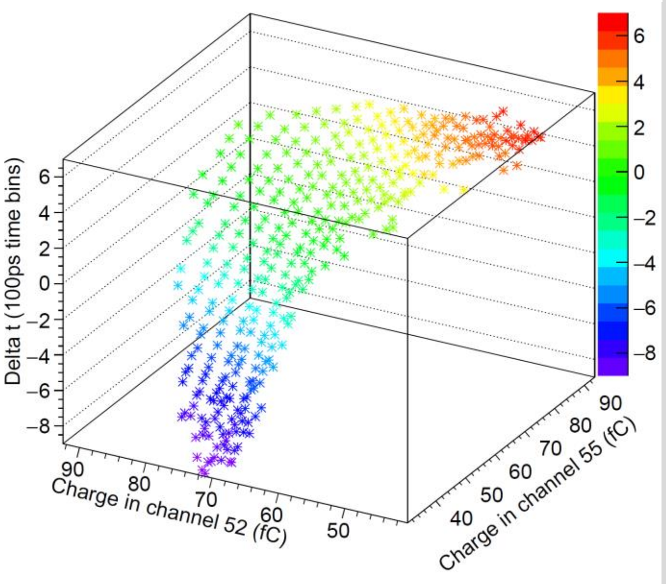
- First attempt: Manual calibration
  - Measured on a subset of "representative" channels
  - Not successful – large channel to channel differences

- Second attempt: measure from testbeam data
  - Charge sharing between pixels
  - Map out time differences between neighbouring channels as a function of charge
  - Parameterize 2D function and fit
  - Reconstitute fit parameters into calibration for individual channels

Time walk in laboratory



Time walk measured in testbeam data

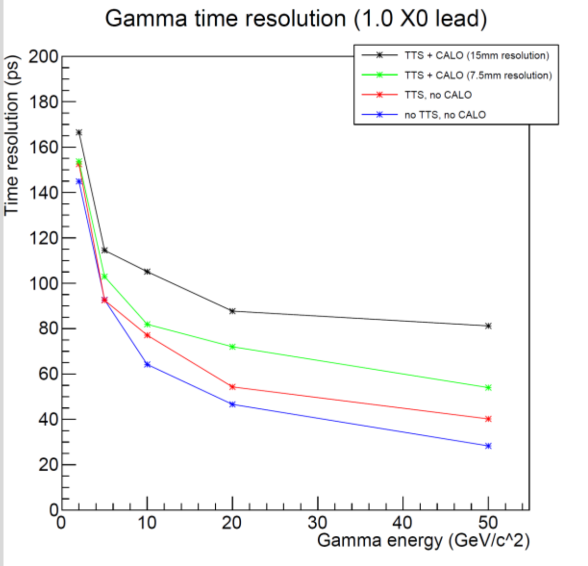


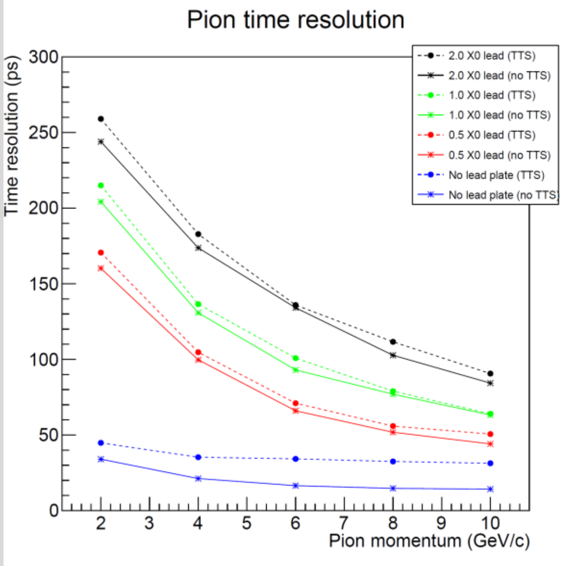
maarten.vandijk@physics.ox.ac.uk

Further applications

- New idea for application of TORCH in LHCb
  - TORCH would be placed in front of LHCB calorimeter
  - Use lead plate in front ($X_0 \approx 6$mm) for conversion of high energy photons
  - Time tagging high energy photons helps resolve pile-up
  - 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, a large part of the PID capability is lost





Perspectives

- A design to use existing quartz from BaBar is under investigation
- Quartz for a new, larger prototype is being ordered
  - Will be half the size of a full-scale TORCH module: $66\times125\times1\text{cm}^3$
- Test has been proposed to put this TORCH module outside LHCb acceptance
  - Would still have tracking for low energy particles
  - Testbench for full application
- Full PID Algorithm under preparation