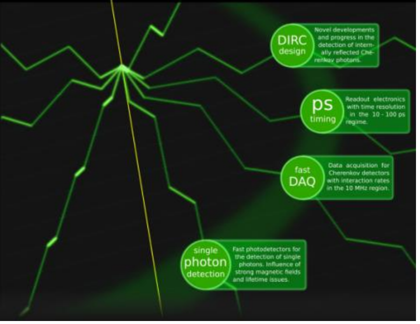


The TORCH project

a proposed detector for precision time-of-flight over large areas

Roger Forty (CERN)

DIRC 2013, Giessen, 4–6 September 2013

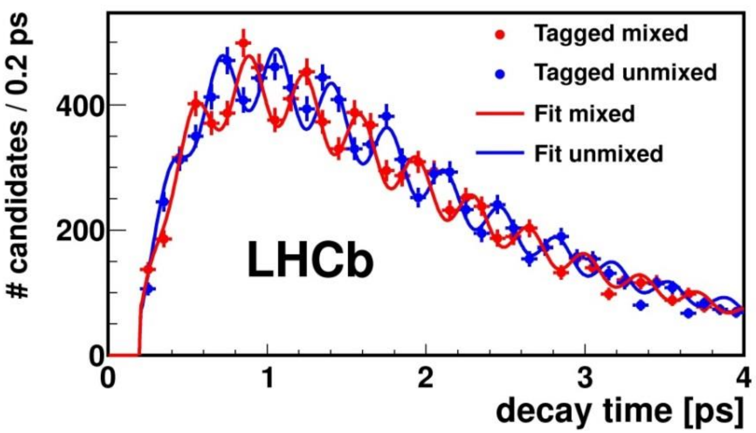
Introduction

- **TORCH** (**T**ime **O**f internally **R**eflected **CH**erenkov light) is a closely related concept to the PANDA DIRC and Belle TOP detectors, combining timing information with DIRC-style reconstruction
  But aiming for higher resolution, to achieve 10–15 ps (per track) for TOF
- Initial motivation for the development was for particle identification in the upgrade of LHCb, the dedicated flavour experiment at the LHC
  Another possible application is shown here for a sterile neutrino search
- Grant for 4 years' R&D on TORCH awarded by ERC: to develop suitable photon detectors, and provide proof-of-principle with a prototype module

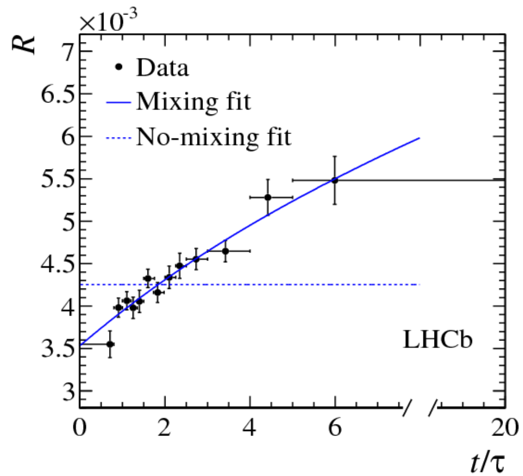
1. Motivation
2. The TORCH concept
3. Application in LHCb
4. R&D project

1. Motivation

- LHCb searches for new physics beyond the Standard Model at the LHC via the precision study of CP violation and rare decays of heavy quarks
- Successful run in 2010–12, accumulating 3 fb^{-1} of data ($\sqrt{s}$ = 7–8 TeV)
Corresponds to > 10^{12} produced $b\bar{b}$ events, and many more charm
→ largest recorded samples in the world
- LHC currently shutdown until end-2014, will then continue at ~ 14 TeV
- Substantial physics ouput from LHCb: already ~ 150 papers published
e.g. world's best measurement of neutral meson oscillations:

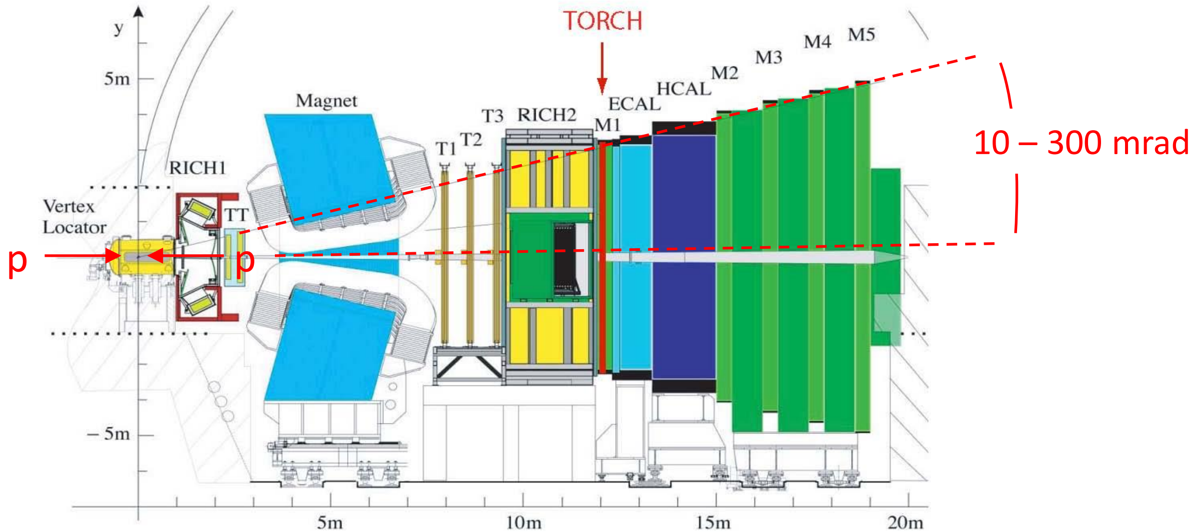


B_s



D^0

LHCb upgrade

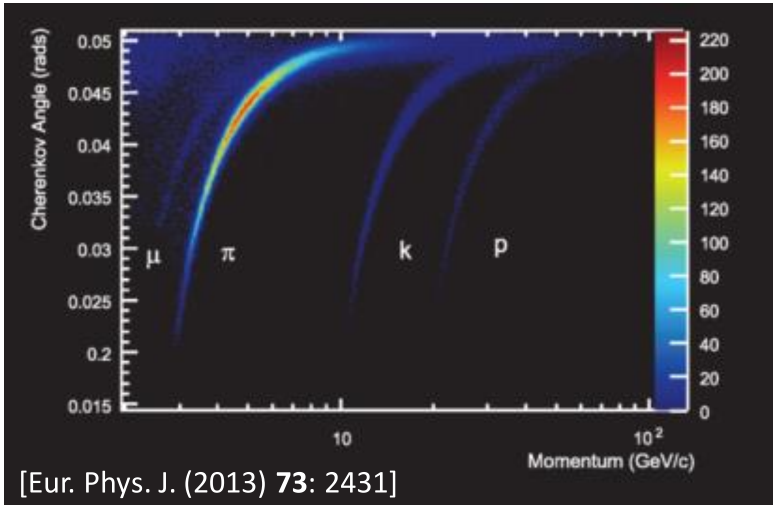


- Upgrade of LHCb approved to increase data rate by an order of magnitude to run at luminosity $1–2 \times 10^{33}$ cm^{-2} s^{-1}, for installation in 2018
- Current bottleneck is hardware trigger level that reduces the 40 MHz bunch crossing rate to 1 MHz, for readout into the high-level trigger in a CPU farm
  $\rightarrow$ read out *complete* experiment at 40 MHz, fully software trigger
- RICH system will be kept for particle ID, but one radiator removed (aerogel)
  Space for TORCH in place of M1 (which is part of hardware trigger)

Particle identification

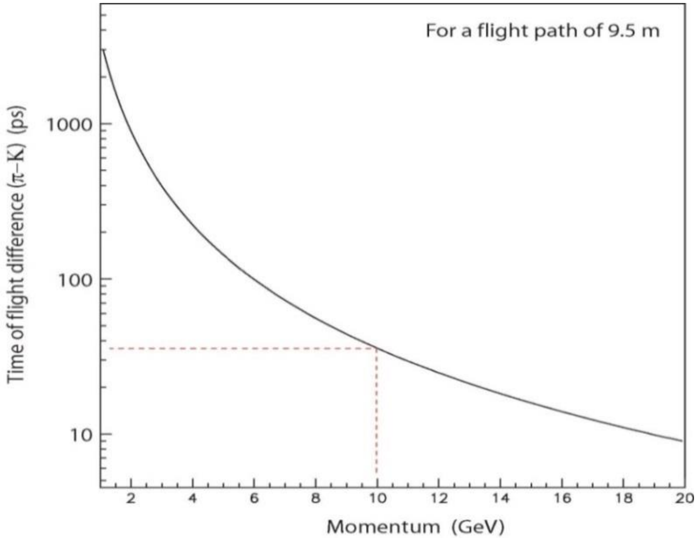
- K-π separation (1–100 GeV) is crucial for hadronic physics of LHCb
  Currently achieved with three RICH radiators: aerogel, C_4F_{10} and CF_4
- Aerogel unsuitable for the upgrade, due to low photon yield + high occupancy
  Wish to maintain positive identification of kaons in region below threshold for producing light in the C_4F_{10} gas, i.e. $p < 10$ GeV
- ΔTOF (K–π) ≈ 40 ps over 10 m at 10 GeV, so resolution 10–15 ps required

RICH C_4F_{10} data

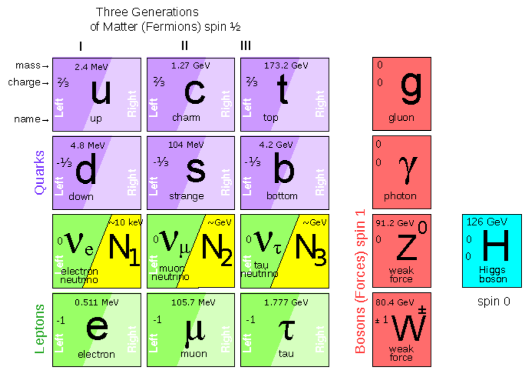


[Eur. Phys. J. (2013) **73**: 2431]

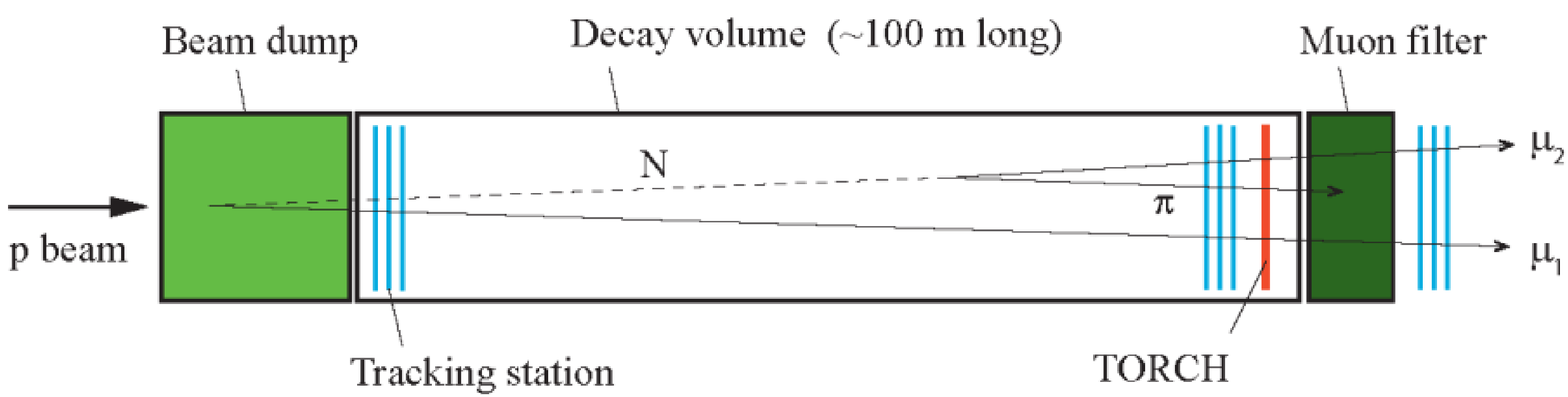
Time of flight



Sterile neutrino search

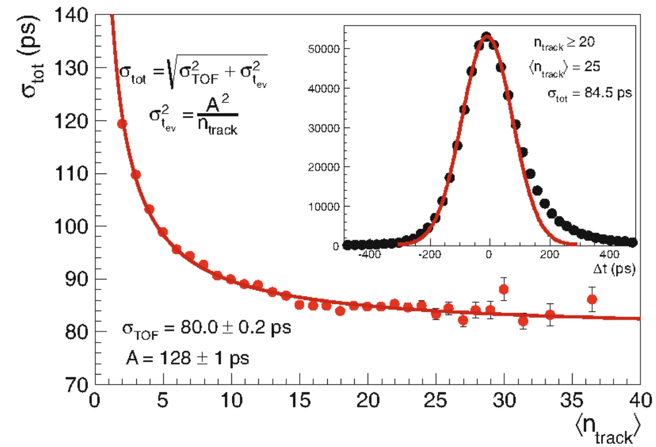


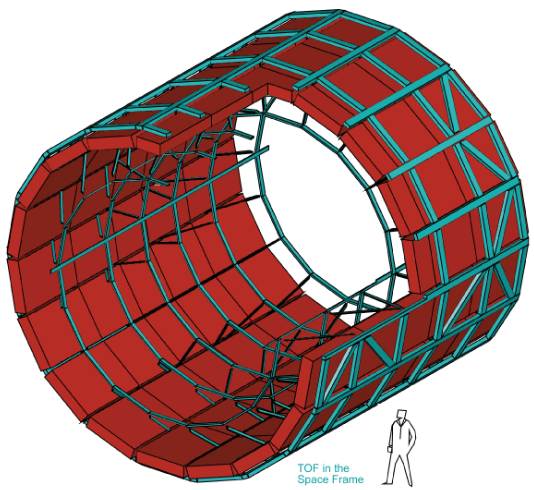
- Another (very different) possible application: perhaps new physics is hidden in the lepton sector
- Extension of the Standard Model with introduction of three heavy right-handed neutrinos $N_{1\text{–}3}$
  [M. Shaposhnikov *et al.*, Ann. Rev. Nucl. Part. Sci. **59** (2009) 191]
- If $m_N \sim 1$ GeV, could be produced in charm decay: $D \rightarrow N\mu X$, $N \rightarrow \mu\pi$
  Conceptual design of an experiment to search for them:
  Due to its mass N would arrive later than a light neutrino by *O*(100 ps)

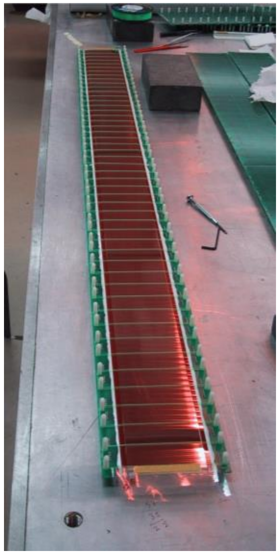


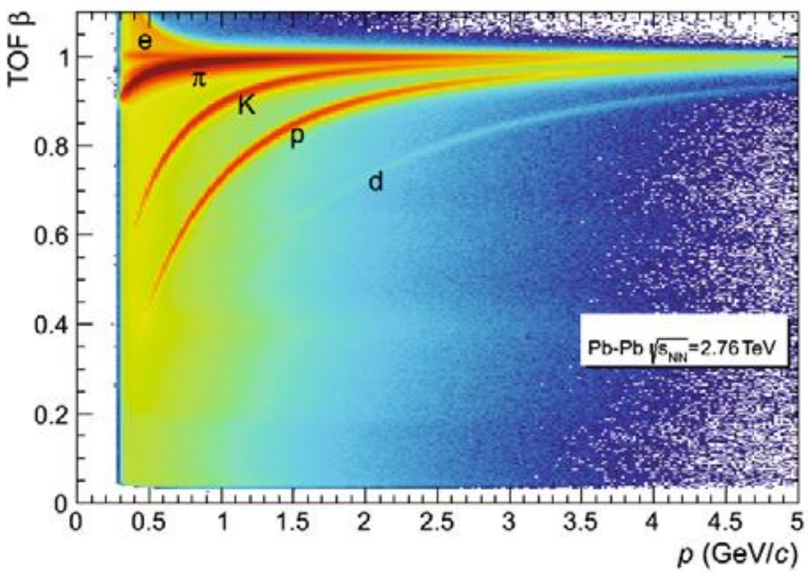
ALICE TOF

- Current state-of-the-art for large-area TOF: Multigap Resistive Plate Chambers (MRPCs) of ALICE (Heavy Ion experiment at the LHC)
- 80 ps resolution achieved, providing K-π separation up to ~ 2.5 GeV
  [Eur. Phys. J. Plus **128** (2013) 44]
- 160 m^2 total area!





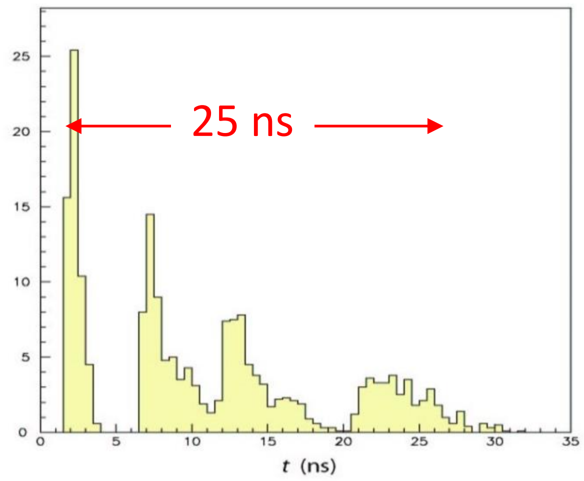




2. The TORCH concept

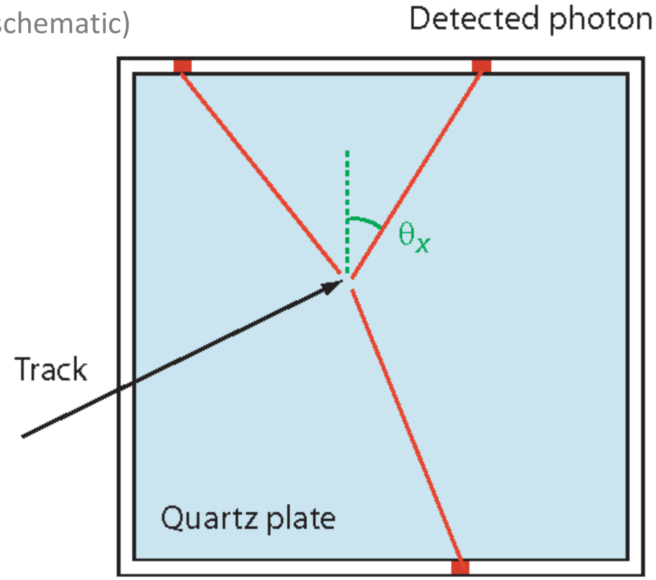
- How can we go further, to achieve ~ 10 ps resolution?
  Large-area fast photon detectors under development, e.g. by the Picosecond Timing project [psec.uchicago.edu], but not yet available
- Cherenkov light production is prompt → instead use quartz as source of fast signal in DIRC-style radiator, with photon detectors around edge
- Consider a simple design based of quartz bars (as in BaBar): Cherenkov photons produced in quartz propagate to end of bar by total internal reflection and their arrival time is measured
- 1 cm thickness of quartz is enough to produce ~ 30 detected photons/track
  → 70 ps resolution required/photon
- However, spread arrival times is *much* greater than this, due to different paths taken by photons in the bar

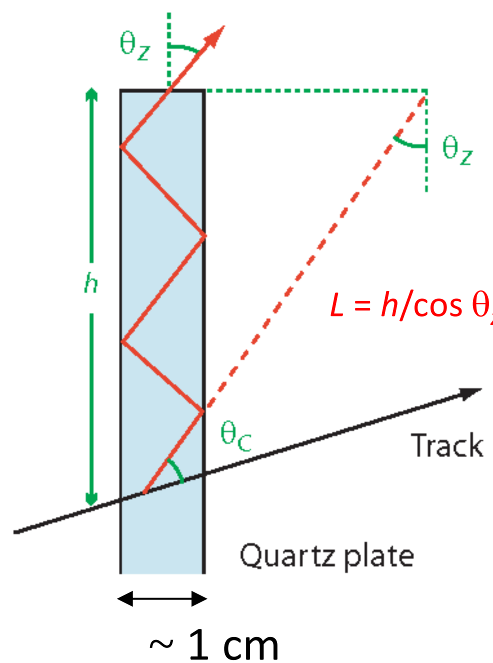
Photon arrival time



Planar detector

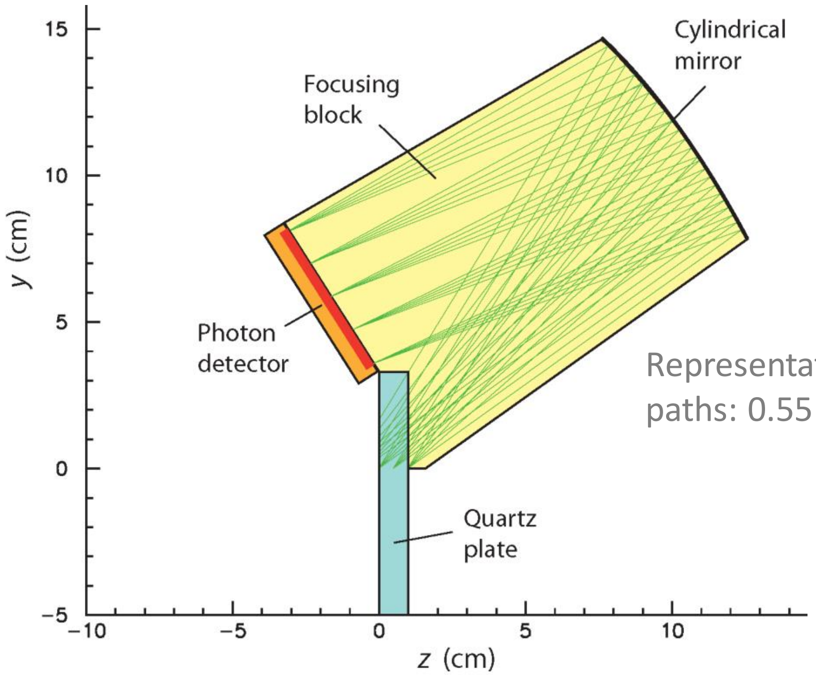
- Need to measure *angles* of photons, so path length can be reconstructed: ~ 1 mrad precision required on the angles in both transverse planes
- This would be prohibitive for a set of thin quartz bars, but borrow the nice idea from PANDA: use a *plane* of quartz
  → coarse segmentation (~ 6 mm) is sufficient for the transverse direction (θ_x)
  Typical lever arm ~ 2 m → angular resolution ≈ $6/(2000\sqrt{12})$ ~ 1 mrad



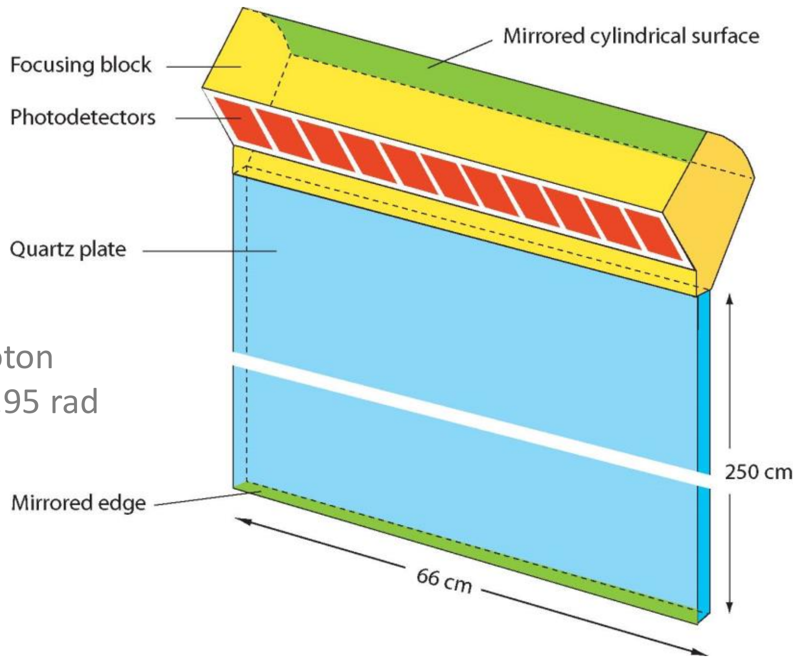


Focusing system

- To measure the angle in the longitudinal direction (θ_z) use a focusing block (also quartz) to convert angle of photon into position on photon detector
  Design shown for a photon detector of 53 mm active dimension
- Fine segmentation needed along this direction: for angular range = 0.4 rad need ~ 128 pixels → angular resolution ≈ 400/(128 √12) ~ 1 mrad

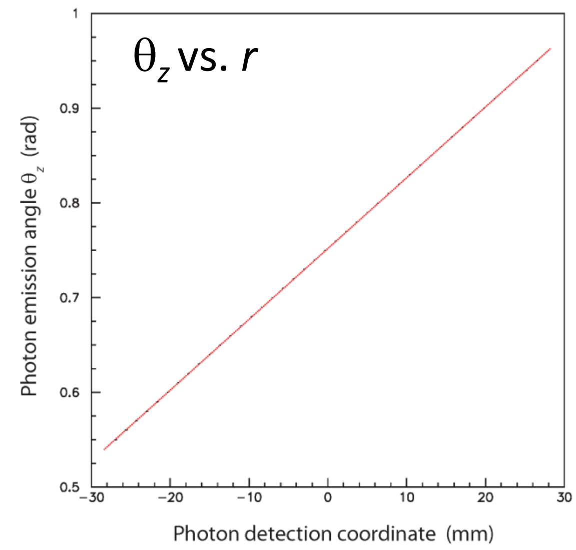


Representative photon paths: $0.55 < \theta_z < 0.95$ rad

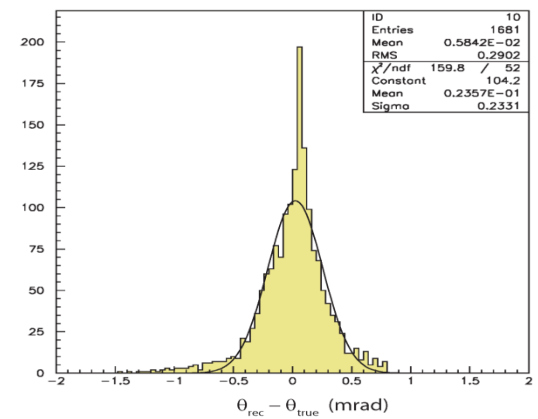


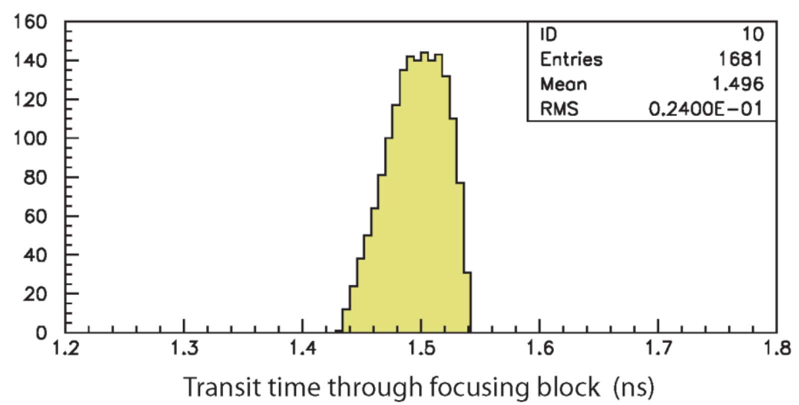
Focusing quality

- Determine detection point *r* on photon detector as a function of photon emission angle θ_z
- Calibration curve is very close to linear
  Small quadratic term to minimize aberration:
  $\theta_{rec} = 0.7528 + 0.00749\, r - 2.22\times10^{-6}\, r^2$
- Contribution of focusing quality to angular resolution = 0.29 mrad (i.e. small)
- RMS of transit time through block = 24 ps



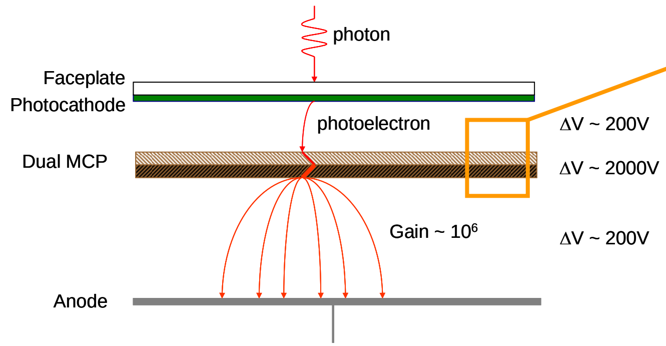
Residuals

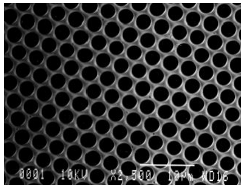




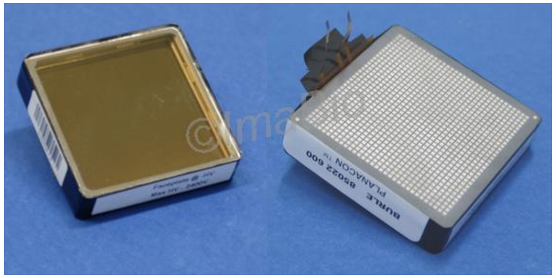
Photon detectors

- Micro-channel plate (MCP) photon detectors are suitable for fast timing of *single* photon signal



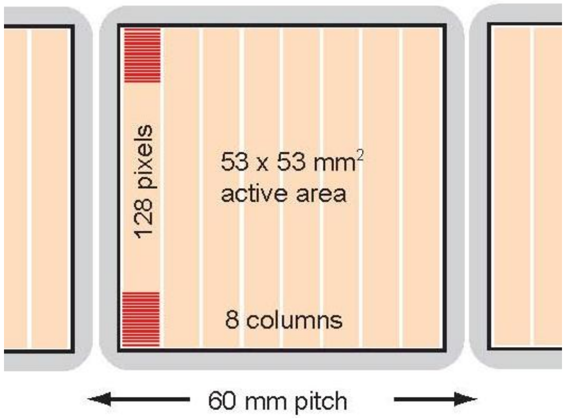


~10 μm pores



32 × 32 channel Planacon

- Anode pad structure can in principle be adjusted according resolution required, as long as charge footprint is small enough

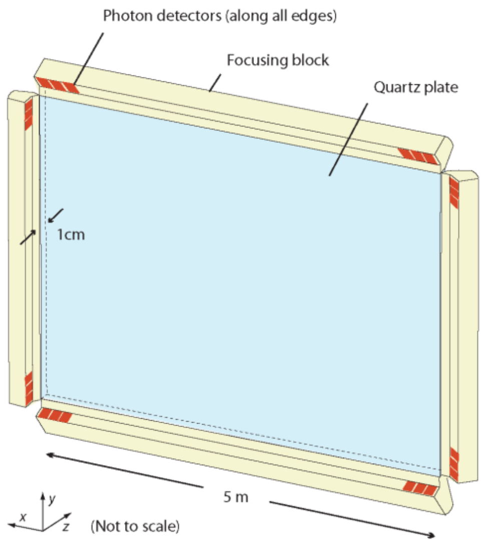


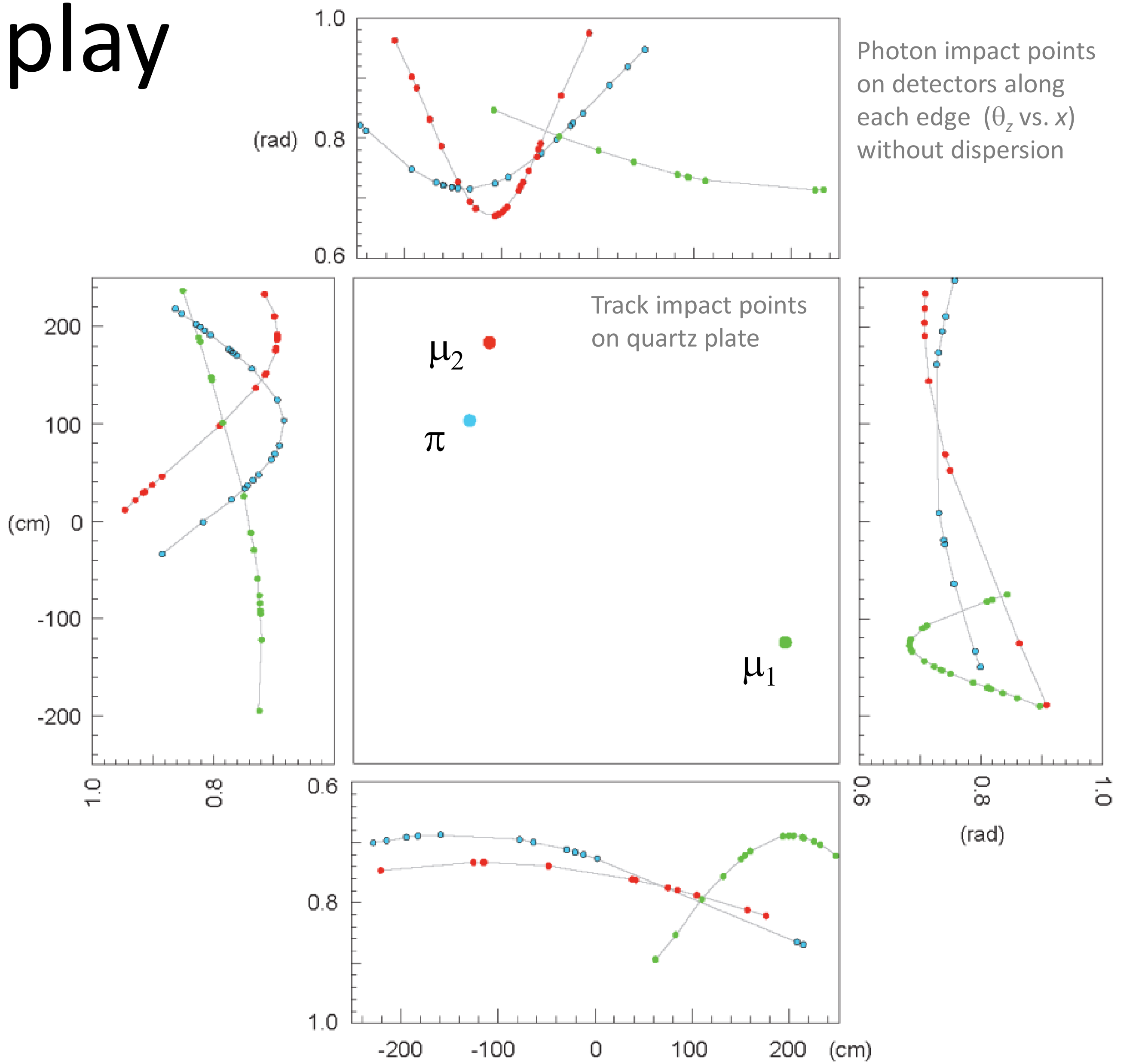
- Highest granularity commercially-available MCP is the Planacon from Photonis
- We want a linear array of photon detectors with adapted pixel size: 128 × 8 pixels

  Development of suitable detector with this layout is a focus of the R&D

Event display

- Typical event in TORCH detector from simulation of sterile neutrinos
- Photons colour-coded to match their parent track

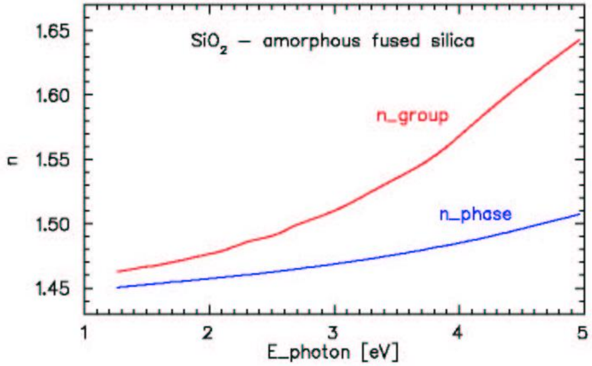




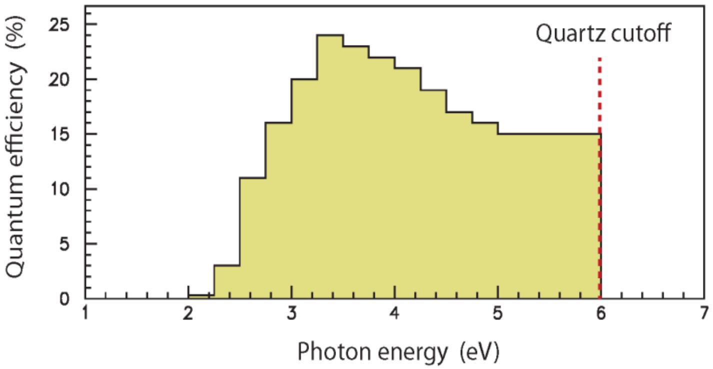
Dispersion

- Chromatic dispersion in quartz leads to smearing of the photon images
- Want to keep wide bandwidth of photon detector QE, to maximize photon yield
- To determine time of propagation in quartz need to correct for dispersion:
  From E_γ = 3 to 5 eV, $\Delta\theta_C$ = 24 mrad
- Achieved by measuring photon angles + knowing path of track through quartz
  $\rightarrow$ determine Cherenkov emission angle
  $\cos \theta_C = 1/\beta n_{phase}$
  $t - t_0 = L\, n_{group}/c$
  Effectively determine energy of photon

Refractive index vs. E_γ

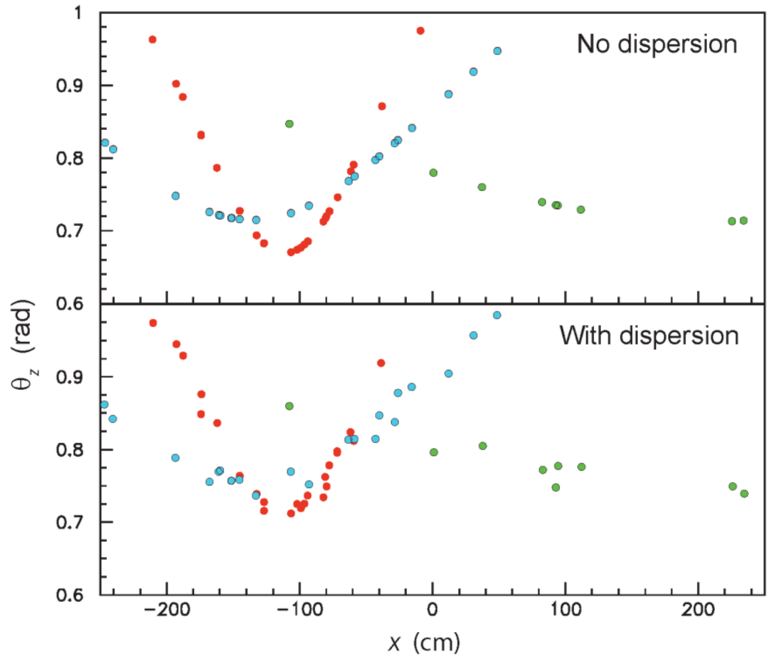


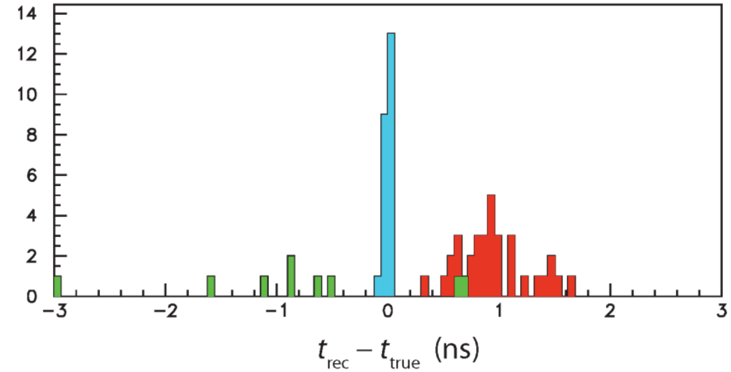
Assumed QE (multi-alkali photocathode)



Reconstruction

- Effect of smearing from dispersion:
- Use timing information as well as spatial information from detector to separate signals from each track
- In this case, calculate time of propagation of all photons relative to the blue track (π)
- Hits from that track peak at true time
  Hits from other tracks spread out
  (but peak in time distribution when it is calculated relative to *that* track)
- Essence of **pattern recognition**:
  make all track–hit combinations with physical E_γ, and optimize assignment





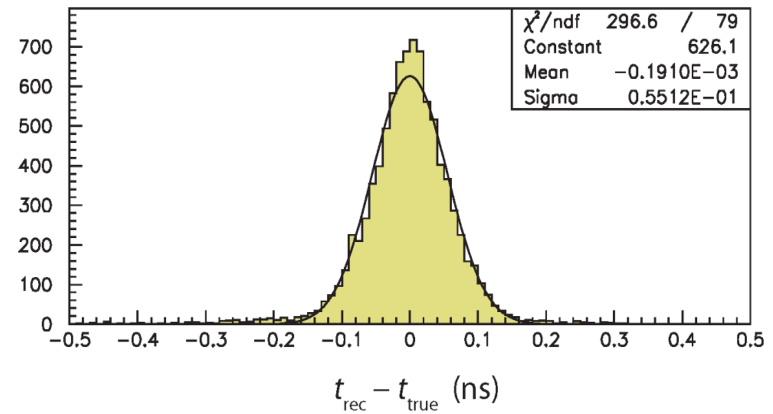
Resolution

- Smearing of photon propagation time due to detector granularity ~ 50 ps
- This assumes uncertainty on track angles significantly less than 1 mrad (which is the case for applications considered here)
- Assume an intrinsic resolution on arrival time per photon of ~ 50 ps
- c.f. MCP results for single photons:

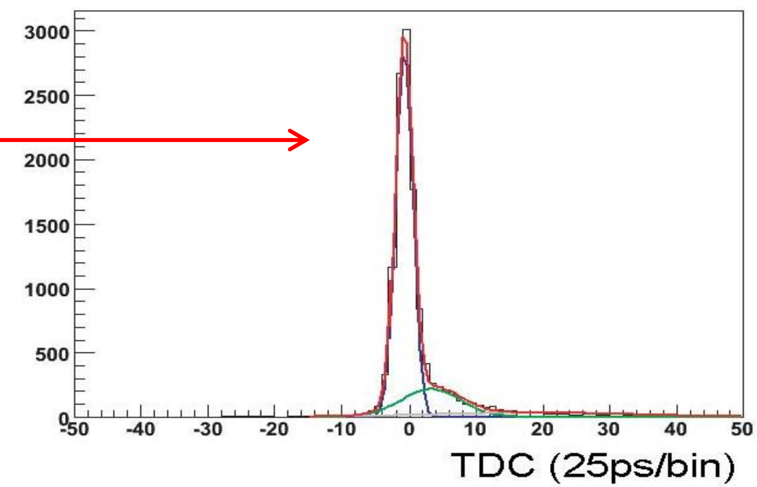
  $\sigma(t) = 34.2 \pm 0.4$ ps

  [K. Inami *et al.*, RICH2010]
- Total resolution per detected photon: $50 \oplus 50 \approx 70$ ps, as required

Resolution due to pixellization

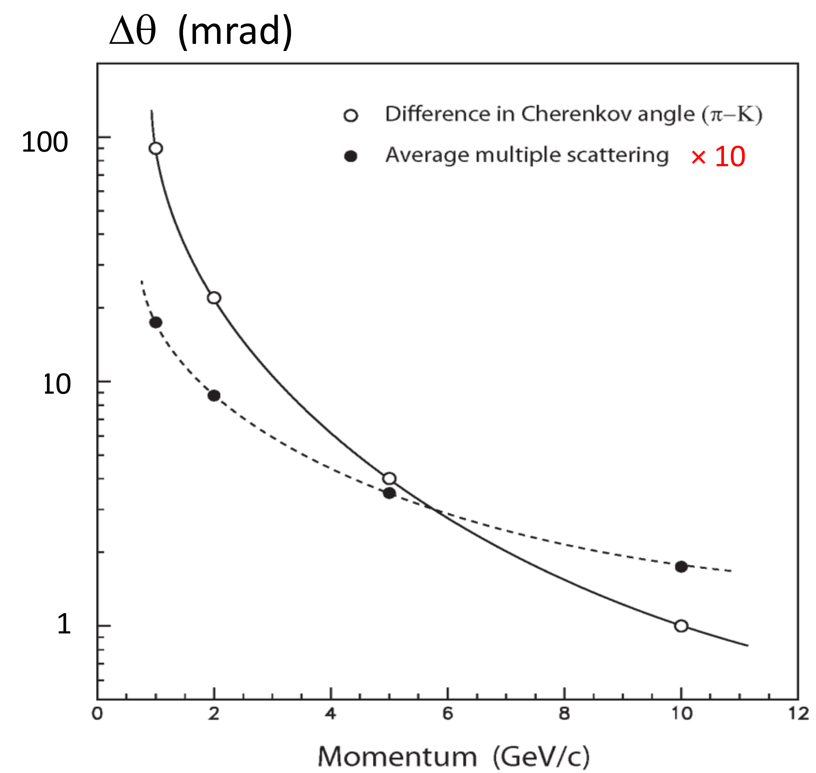


Resolution on photon detection



3. Application in LHCb

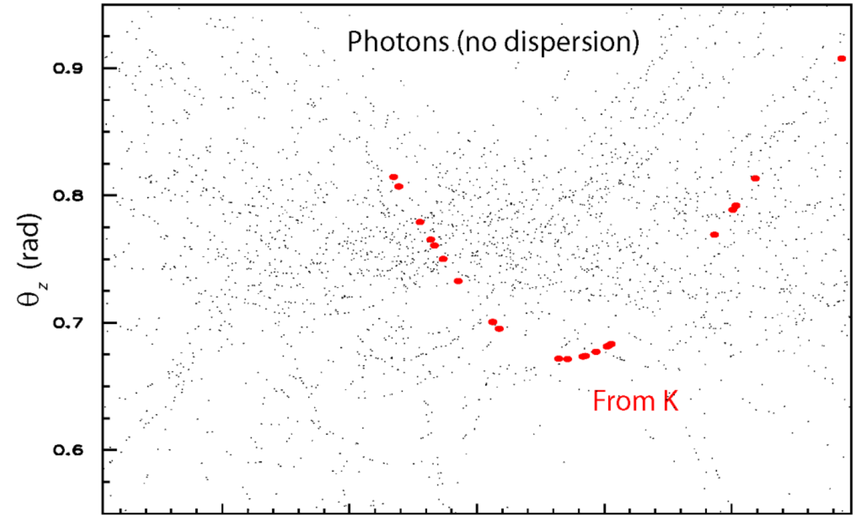
- Tracks in neutrino events mostly high momentum (> 10 GeV)
- At lower momenta (e.g. for tracks to be identified in LHCb events) other effects must be accounted for:
- Average **multiple scattering** of track in 1 cm quartz (~ 8% X_0)
  $\Delta\theta = \theta_0/2 \approx 1.8$ mrad / p [GeV]
  (i.e. small affect above a few GeV, but correlated between photons)

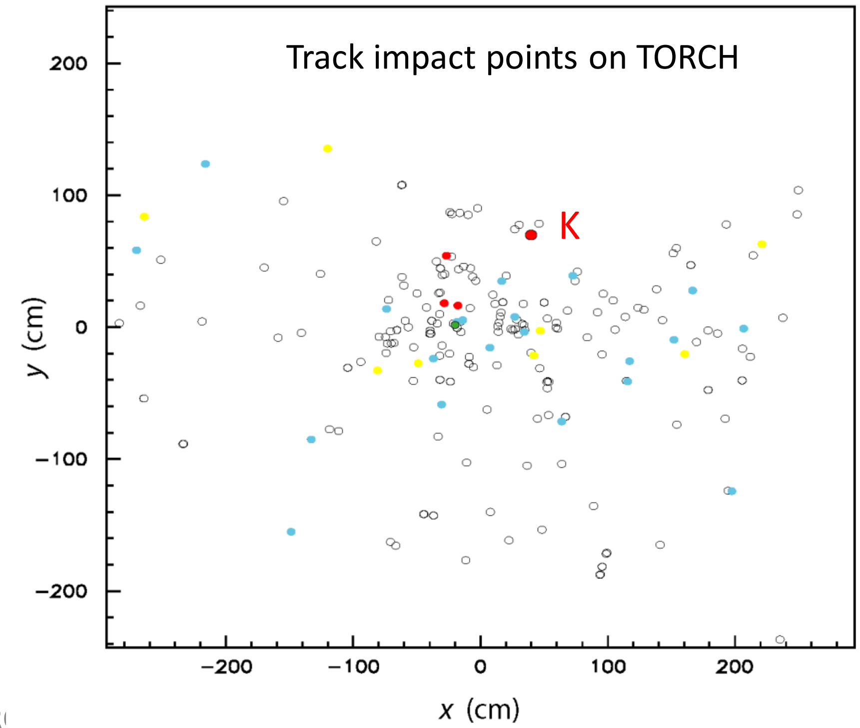


- Difference in **Cherenkov angle** between π and K becomes significant at low momentum — taken into account by comparing different mass hypotheses for each track
- Cherenkov and TOF effects are *additive* → increases low-p separation

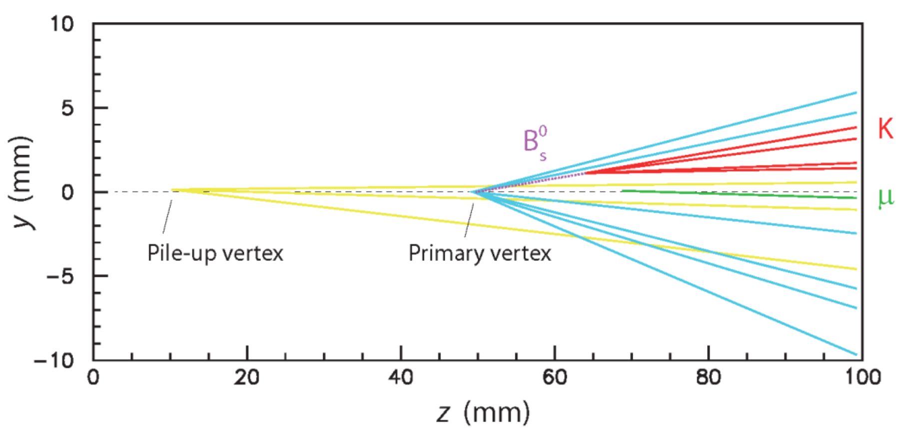
LHCb event

- Typical LHCb event, at luminosity of 10^{33} $cm^{-2} s^{-1}$ (only photons reaching the upper edge shown)
- High multiplicity! >100 tracks/event
- Tracks from vertex region colour-coded according to the vertex they come from (rest are secondaries)



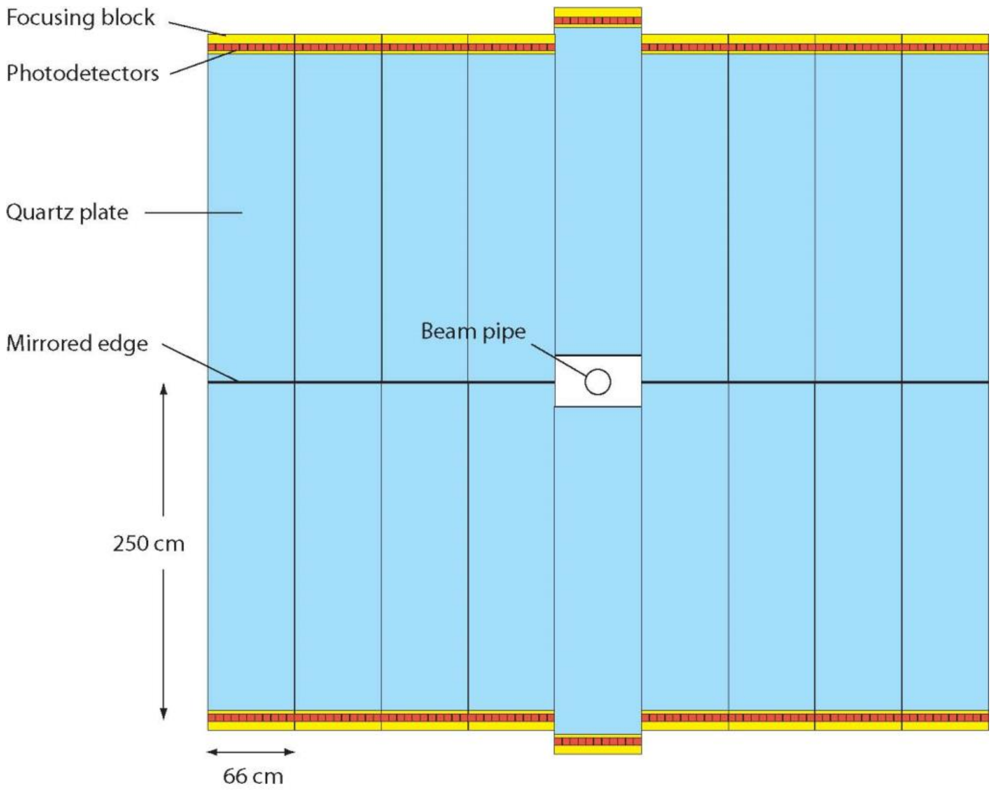


Zoom on vertex region



Modular design

- For the application in LHCb, transverse dimension of plane to be instrumented is ~ $5 \times 6\ m^2$ (at $z = 10$ m) + central hole for beam pipe
- Unrealistic to cover with a single quartz plate → develop modular layout:

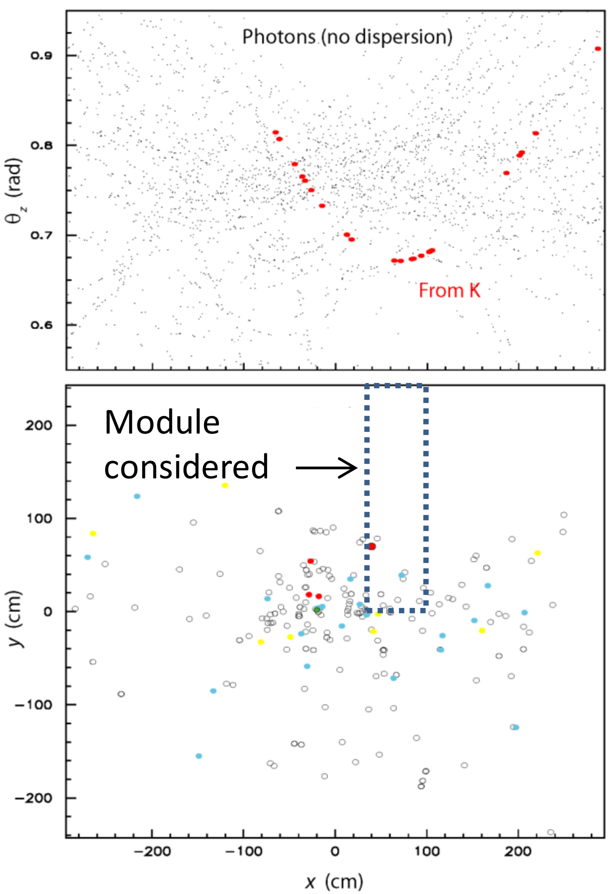


- 18 identical modules each $250 \times 66 \times 1\ cm^3$ → ~ 300 litres of quartz in total (less than BaBar)
- Reflective lower edge → photon detectors only needed on upper edge

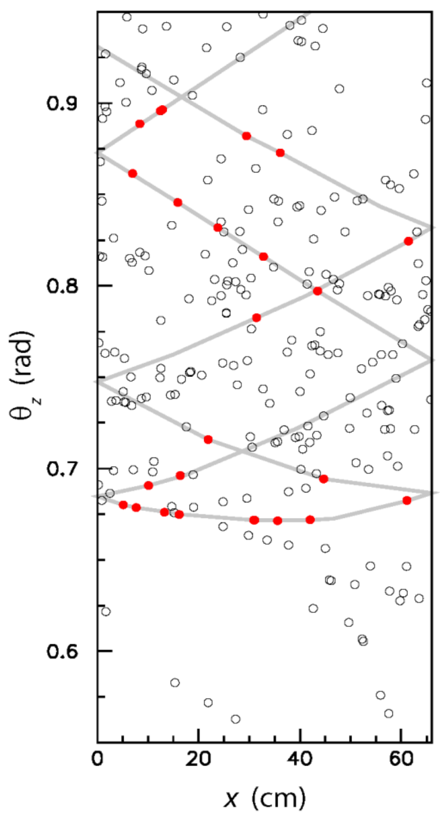
$18 \times 11 = 198$ detectors
Each with 1024 pixels
→ 200k channels total

Effect of modules

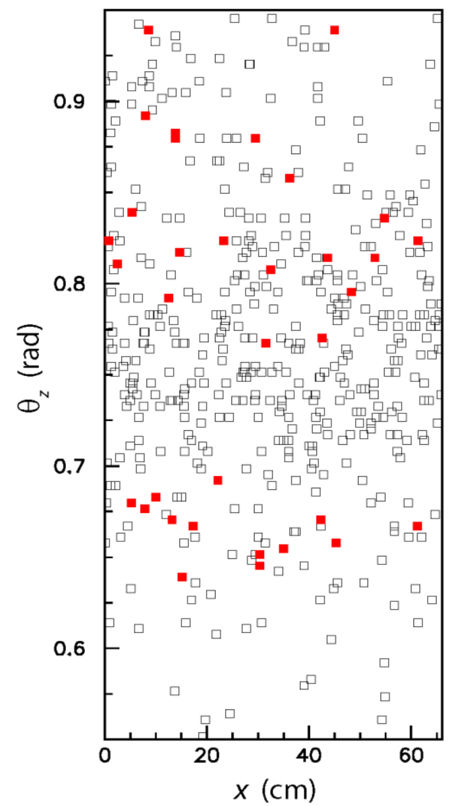
- Illustrate the effect of introducing modules, using the same LHCb event
- Far fewer hit-track combinations, but reflections from sides give ambiguities



Without dispersion or reflection off lower edge



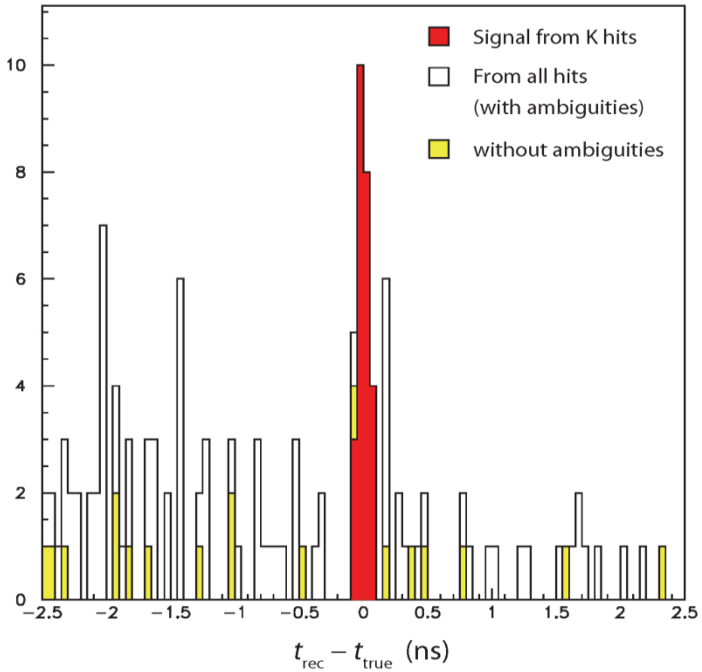
Including dispersion and reflection off lower edge



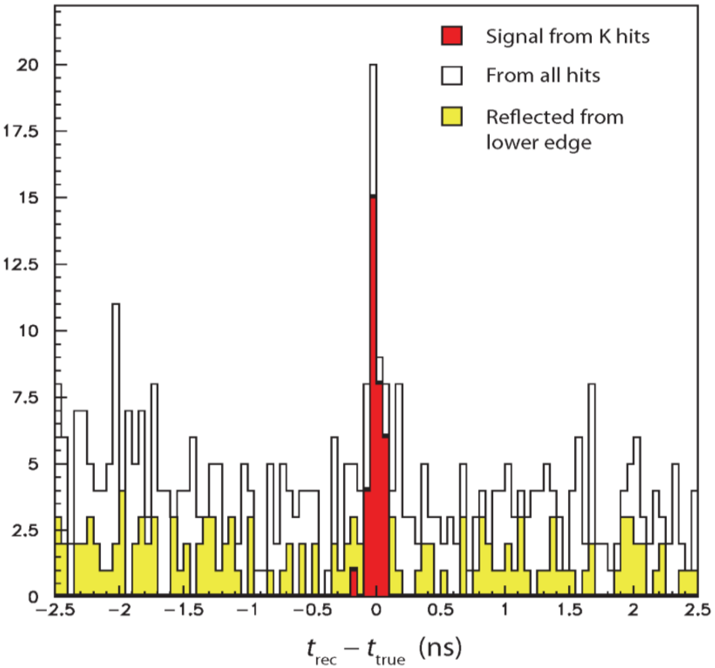
Reconstruction

- As for the previous application, signals can be isolated using the time info
  Calculate time for all hits in module with respect to the kaon track

Without reflection off lower edge



Including reflection off lower edge

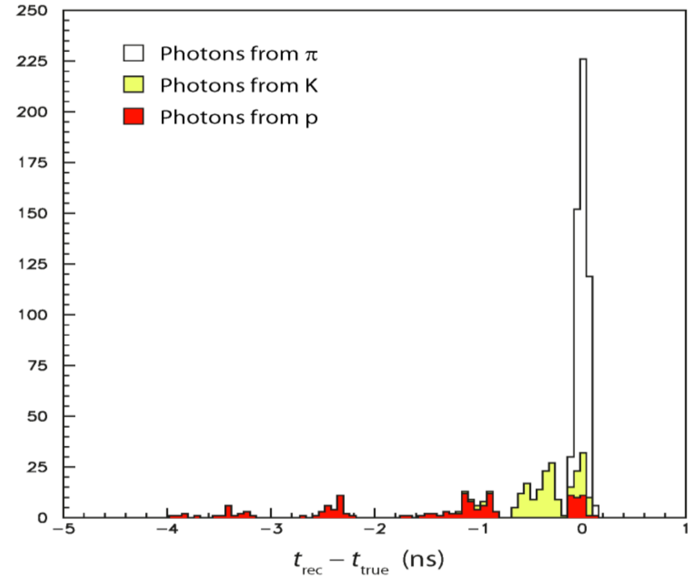


- Final choice of module width, and whether to mirror the lower edge, will be made following optimization of the performance in simulation

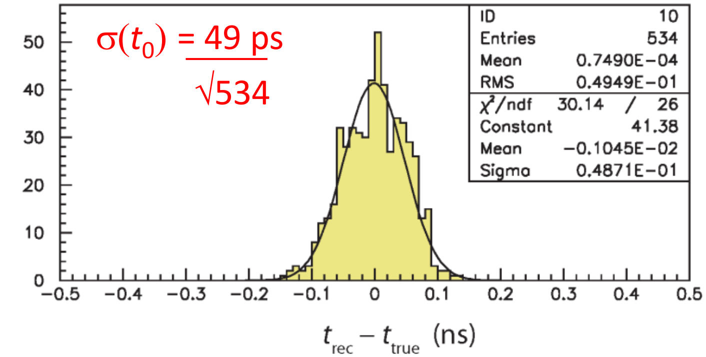
Measuring start-time

- To determine the time-of-flight, also need a start time (t_0)
- This might be achieved using timing information from the accelerator, but bunches are long (~ 20 cm) → must correct for vertex position
- Alternatively use other tracks in the event, from the primary vertex
- Most of them are pions, so the reconstruction logic can be reversed, and the start time is determined from their average *assuming* they are all π (outliers from other particles removed)
- Can achieve few-ps resolution on t_0

Example from PV of same event



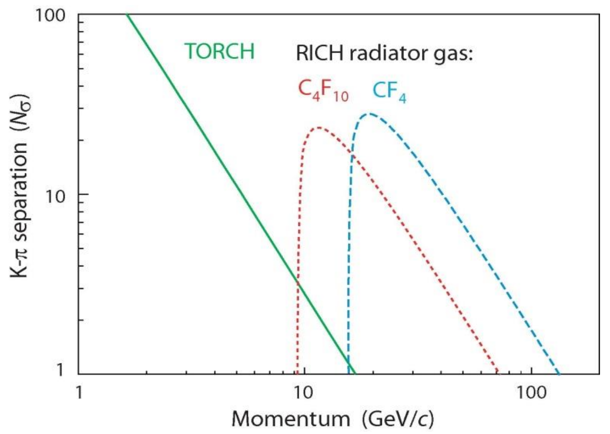
After removing outliers



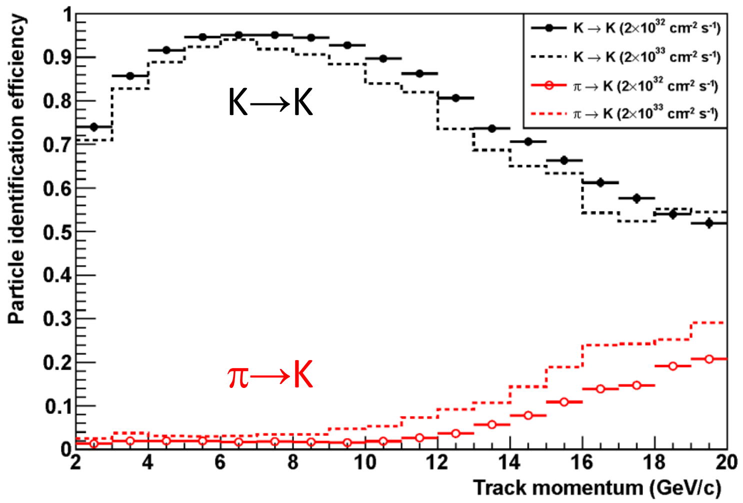
Expected performance

- Complete reconstruction studied including pattern recognition, using a simple simulation of the TORCH detector (single plate) interfaced to full LHCb simulation
- Excellent particle ID performance achieved, up to 10 GeV as required
  Robust against increased luminosity (········ after increase by ×10)
- Included in Letter of Intent for the LHCb upgrade [CERN-LHCC-2011-001]
- Full GEANT simulation of TORCH is in progress, and optimization of the modular layout

(ideal reconstruction, isolated tracks)

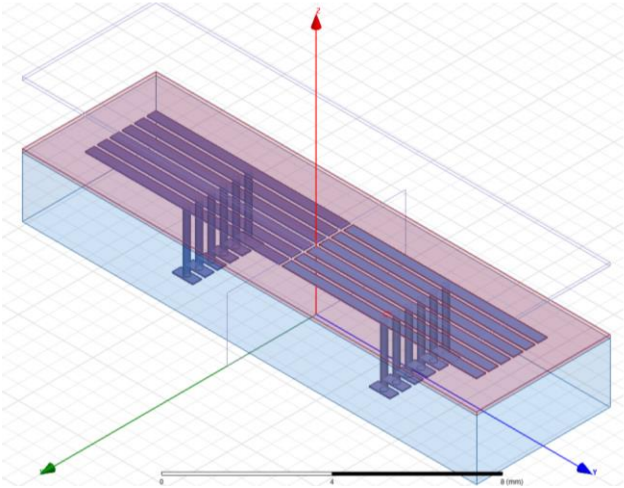


LHCb simulation: efficiency vs. *p*



4. R&D project

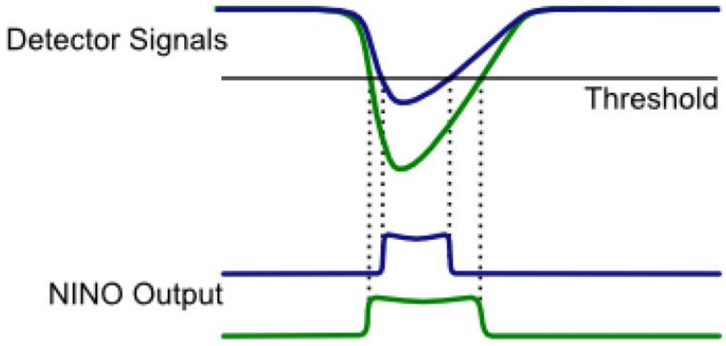
- ERC project for 4 years R&D started a year ago (collaboration between CERN, Bristol and Oxford Universities, principal investigator N. Harnew)
- Main focus is on photon detector R&D with industrial partner: Photek (UK)
- Three phases defined: 1. extended lifetime (> 5 C/cm^2 required for LHCb)
  2. high granularity (128 $\times$ 8 pixels or equivalent)
  3. square tubes with high active area (> 80%)
- Progress on lifetime using ALD coating
  [see talk of James Milnes, yesterday]
- Modelling studies under way towards achieving required granularity
  64 $\times$ 8 may be sufficient if charge-sharing between neighbouring pads can be used
- Need to survive high occupancy in LHCb
  ~ 30 hits/detector/event ($\approx$ every 25 ns…)

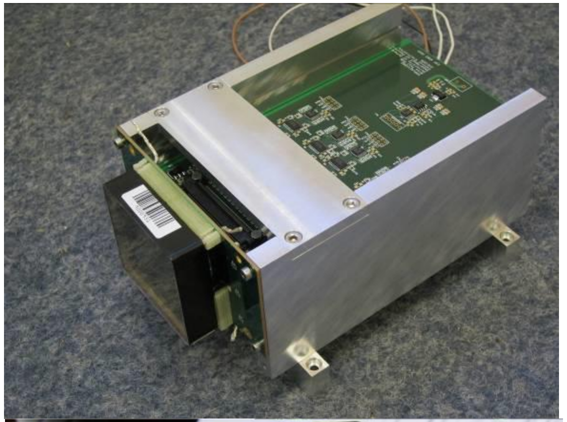


[Photek simulation]

Electronics

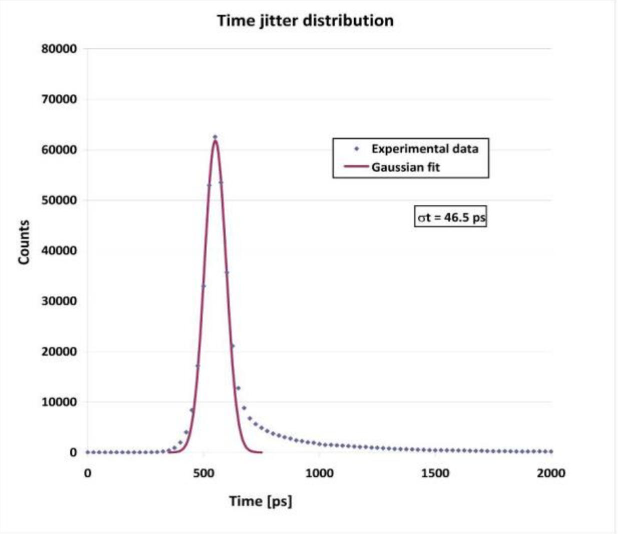
- Readout electronics is crucial component to achieve desired resolution Suitable front-end chip has been developed for the ALICE TOF system: NINO + HPTDC [F. Anghinolfi *et al.*, Nucl. Instr. and Meth. A 533, **(**2004**)**, 183]
- Currently using 8 channel versions, 32-channel available, ~ 15 fC threshold [M. Despeisse *et al.*, IEEE **58** (1011) 202]
- Provides time-over-threshold information which can be used to correct time walk (+ measure the charge, for charge-sharing)

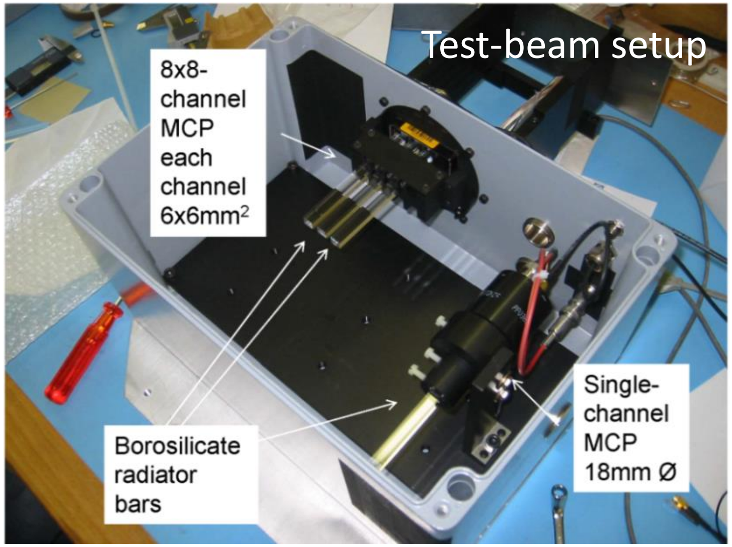


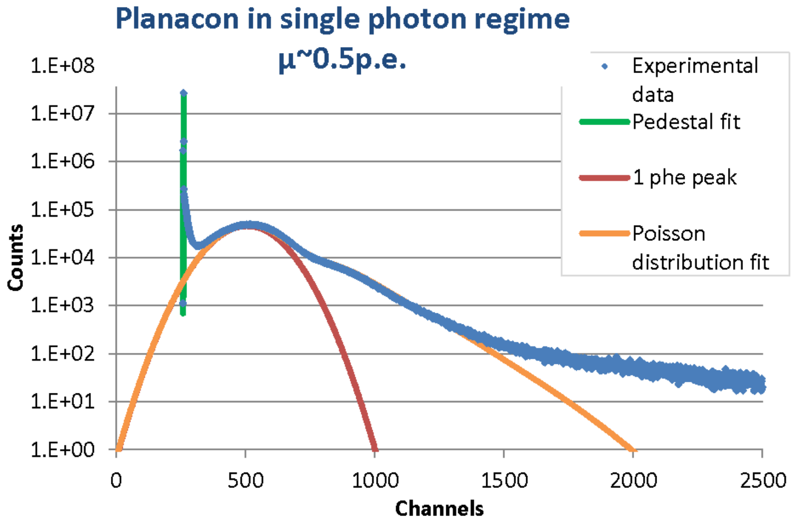


Detector studies

- Studies in progress using 8 × 8 ch. Planacon with slow or fast readout, in lab and test-beam (no time to do them justice here)
- Detection efficiency of 83% measured for NINO readout at a tube gain of 6×10^5
- Further studies planned for coming year on radiator, gluing, focusing, and Photek tubes





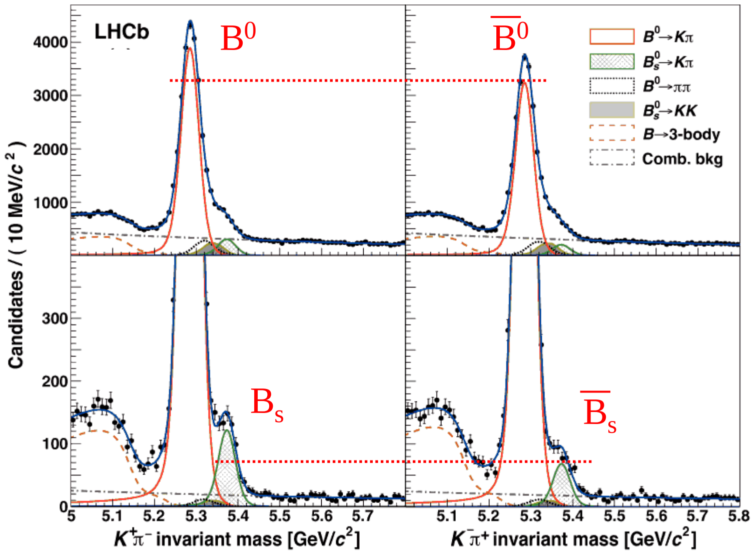


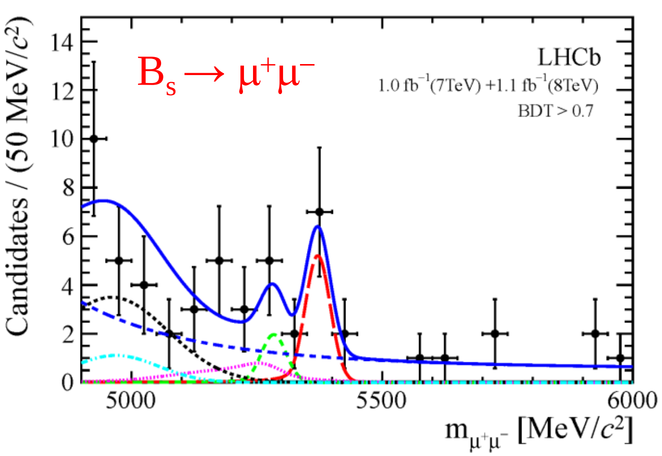
Conclusions

- TORCH is a novel concept for a DIRC-type detector
  to achieve high-precision time-of-flight over large areas
- Proposed for the upgrade of LHCb to complement the
  high-momentum particle ID provided by the RICH system
  Possible alternative application shown for sterile neutrino search
- Target resolution is 70 ps per photon to give 10–15 ps per track
  and provide clear K-π separation up to 10 GeV
- Ongoing R&D programme aims to produce suitable MCP photon
  detector within next 3 years, satisfying challenging requirements
  of lifetime, granularity, and active area
  And a prototype module to demonstrate the concept
- On successful completion of R&D, proposal for LHCb will follow

Additional slides

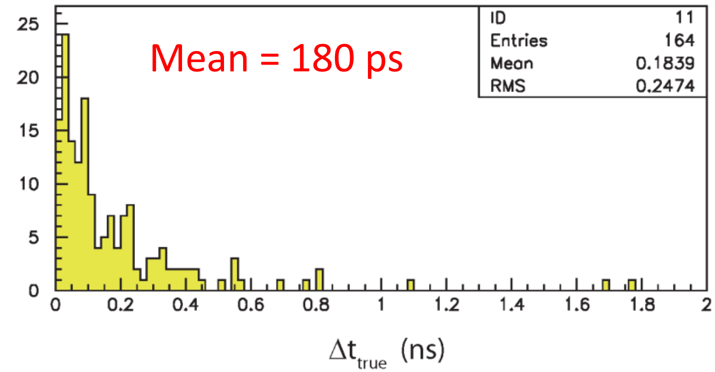
- First observation made of **CP violation** in the B_s system by LHCb
- First evidence of the very **rare decay** $B_s \rightarrow \mu^+\mu^-$ (later confirmed by CMS+LHCb)
  BR = $(2.9 \pm 0.7) \times 10^{-9}$!
- Unfortunately results are so far in overall agreement with the Standard Model expectations
- Upgrade of LHCb has been approved to increase the data rate by an order of magnitude, for installation in 2018
- TORCH is proposed for that upgrade (although it may come a little later)

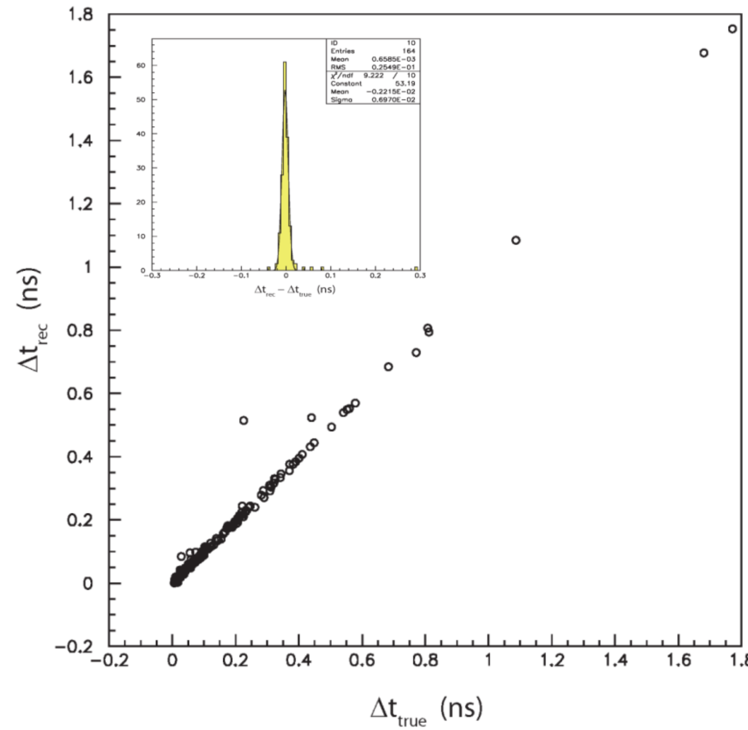




Sterile neutrino TOF

- Studied with simple simulation
  Due to its mass N would fly slower than e.g. a light Standard Model neutrino
- Plot difference of flight time (Δt_{true}) between N and massless particle over distance travelled before decay
- TOF resolution < 20 ps would be well matched to positively identify them
- Difference in time of arrival of the two muons (μ_1,μ_2) is good estimator of Δt_{true}
  Add small correction for flight distance:
  $\Delta t_{\mathrm{rec}} = t_2 - t_1 - 400\,[(d_N + d_2)/d_1 - 1]$
- Smearing due to this reconstruction technique = 7 ps (<< time resolution)





Focusing element

- Design of focusing has evolved somewhat, since the initial proposal to adjust the angular range: 0.55–0.95 instead of 0.45–0.85 rad
- Take opportunity to modify attachment to quartz plate, to reduce need for polished surfaces in focusing element (other than the mirrored surface)