Status of

The TORCH Detector

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on behalf of the TORCH Collaboration

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Outline

- Introduction to TORCH
  - TORCH principle
- Beam test analysis
  - Current time resolution and photon yield performance
- TORCH simulation and LHCb physics studies
- Summary

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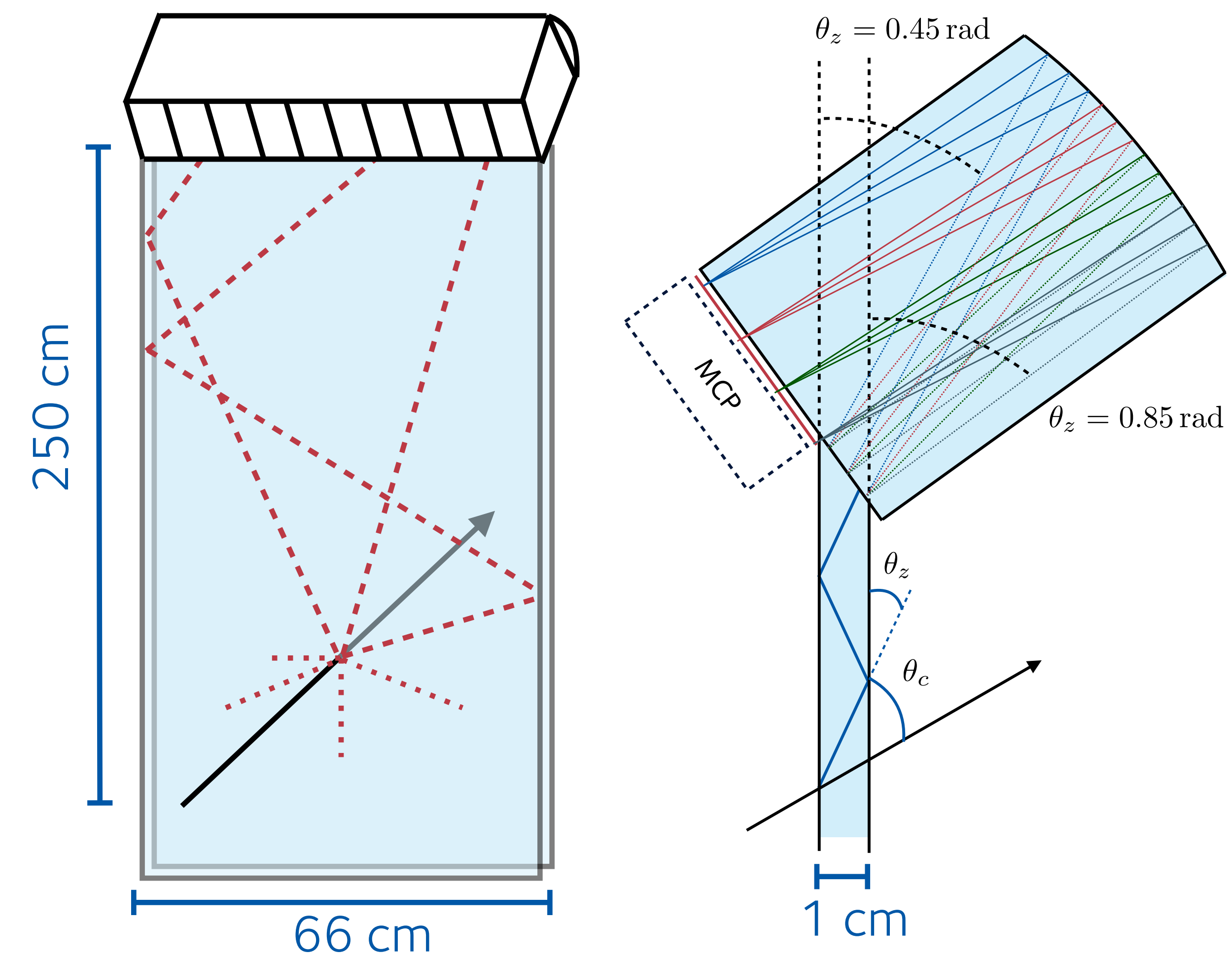
What is TORCH?

TORCH: Time of Internally Reflected CHerenkov light

- TORCH aims to provide particle identification at low momentum (P~2-10GeV/c for π/K)
- Prompt Cherenkov light emitted by charged hadrons is collected via total internal reflection in a highly polished quartz plate
- Photon arrival time and pattern allows the track species to be determined



- A hadron flight path of~10m results in a time-of-flight difference ΔToF(K-π) ~ 35 ps
- Aim to achieve 10-15ps time resolution per track
- This corresponds to a single photon resolution of **70ps** for ~30 photons per track

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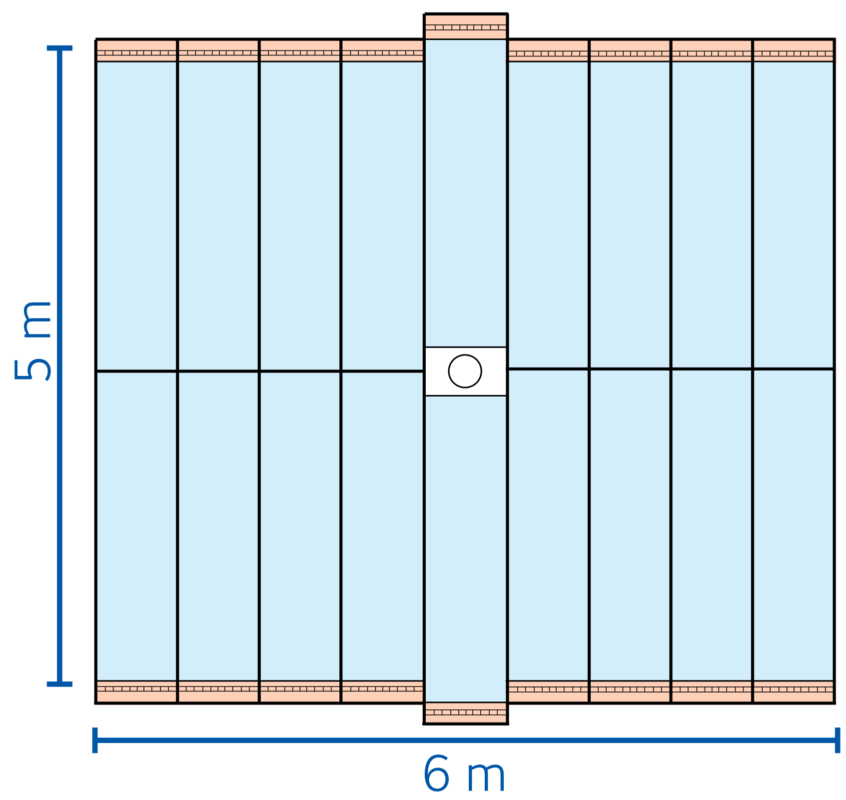
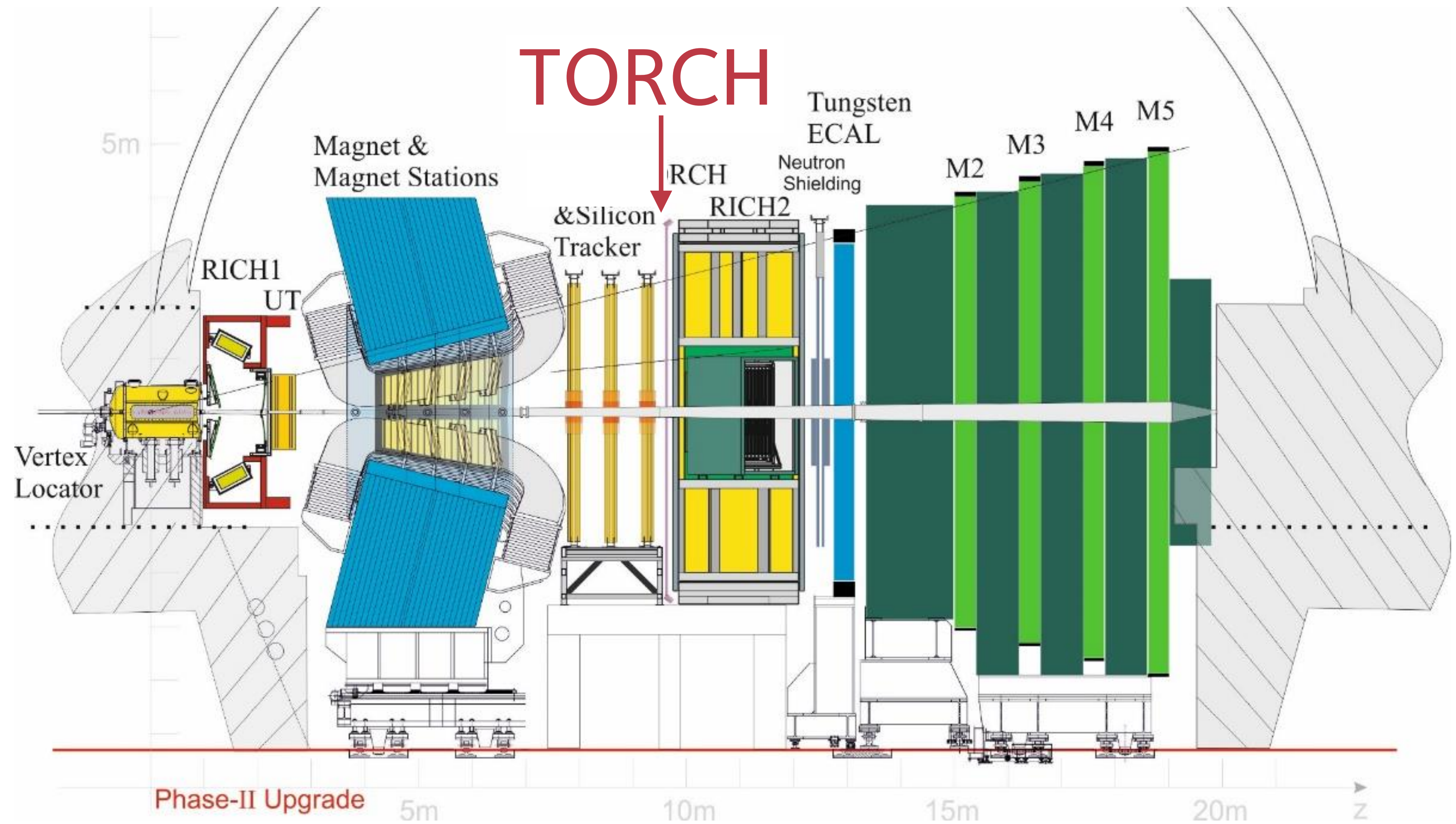
TORCH in LHCb





- The TORCH detector would provide complementary PID information to the RICH detectors in the LHCb experiment
- TORCH constitutes 18 quartz modules spanning an area of 5x6 m^2
- TORCH is proposed to be installed in LS3 (Run 4 onwards)

LHCb Phase-II Upgrade EOI

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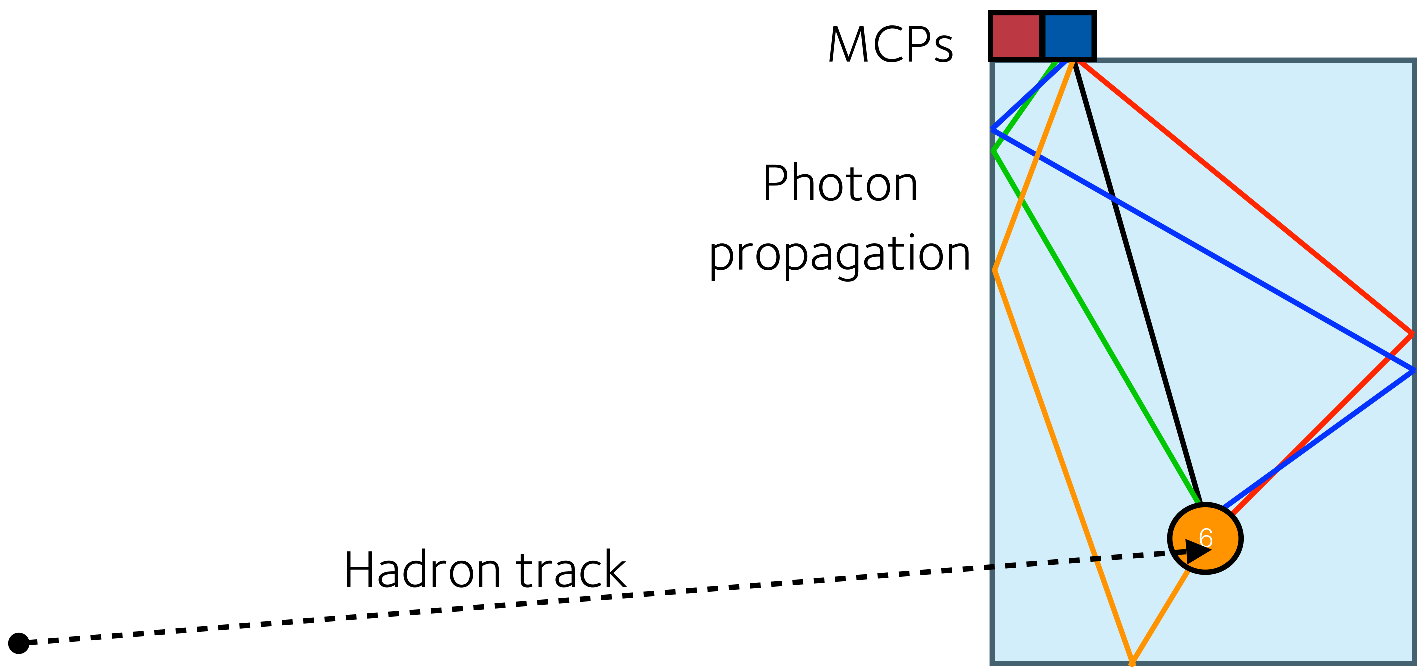
Prototypes

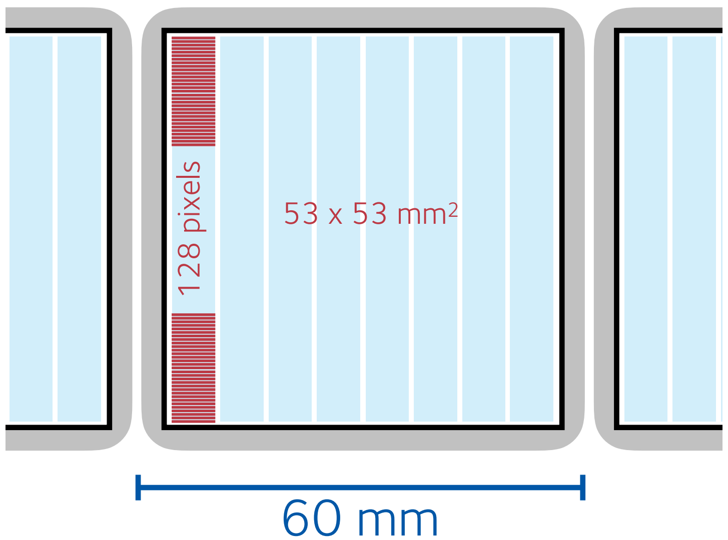
- TORCH prototypes have been tested in beam tests
- **Mini-TORCH** is a small scale module with a 12cm x 35cm x 1cm quartz plate instrumented with one MCP NIM A (2018)
- **Proto-TORCH** is a half-height, full-width module currently instrumented with 2 MCPs
- Beam tests have been performed in CERN PS 8 GeV p/π beam

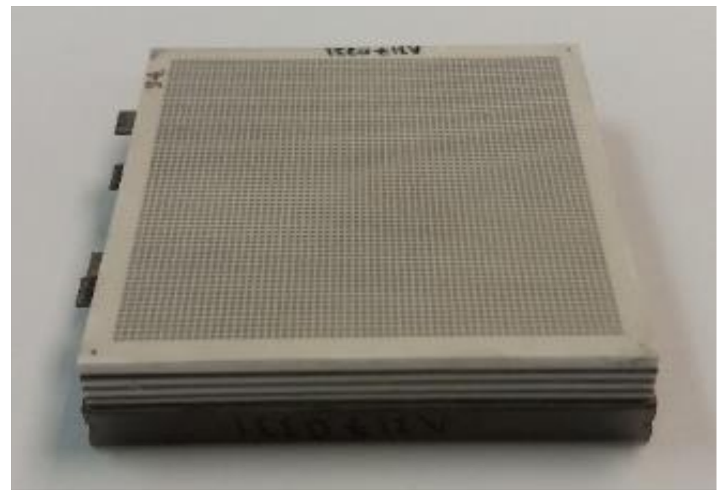


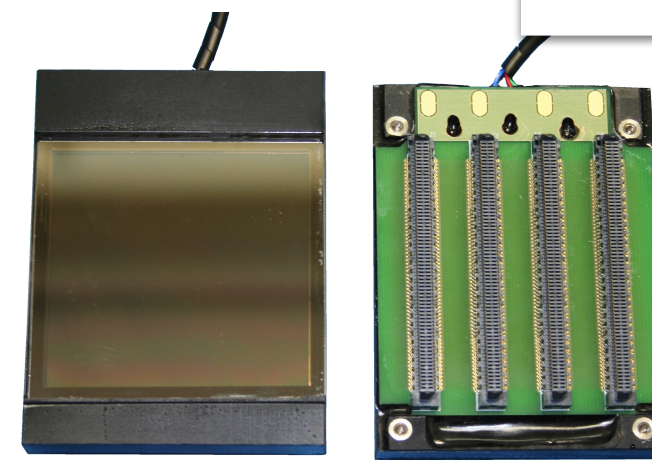
66cm x 125cm x 1cm Quartz plate

TORCH MCP-PMTs

- The Cherenkov radiation is focused onto Micro-Channel Plate PMTs
- These have been developed by industrial partner Photek UK







- Each detector has a granularity of **64x64** pixels over **53x53mm^2** active area
- Charge sharing and channel grouping is used to achieve an effective granularity of **128x8** pixels
- The MCPs are designed to withstand an integrated charge of 5 C/cm^2 (ALD coating)
- Readout electronics consists of **NINO** and **HPTDC** chipsets developed for ALICE collaboration's TOF detector

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TORCH Preliminary analysis

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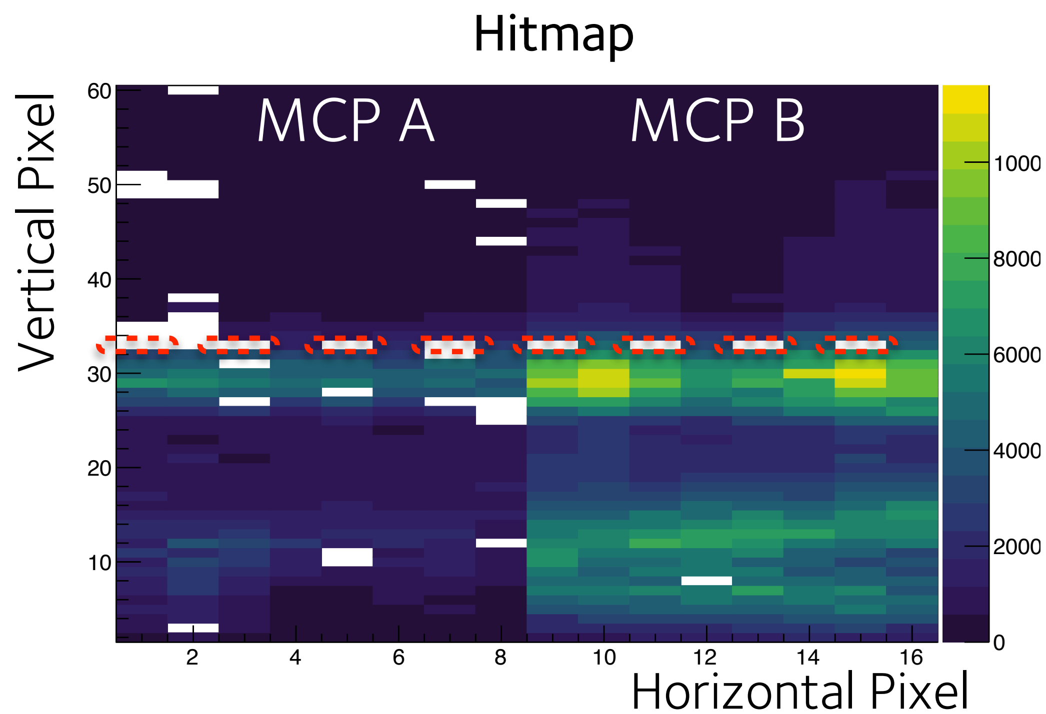
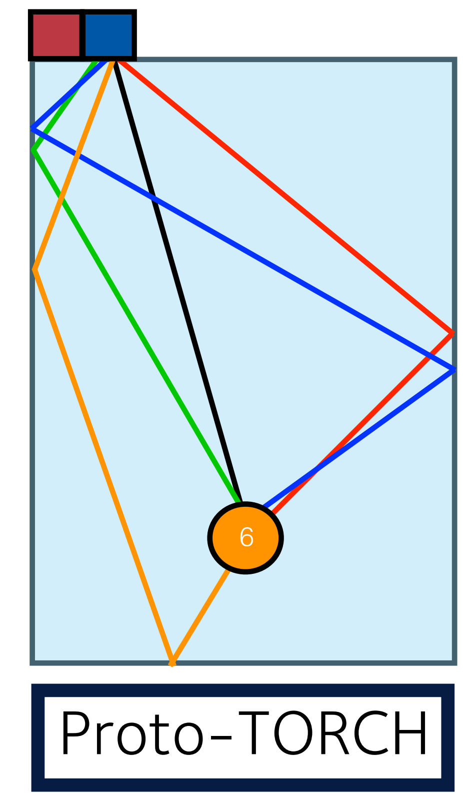
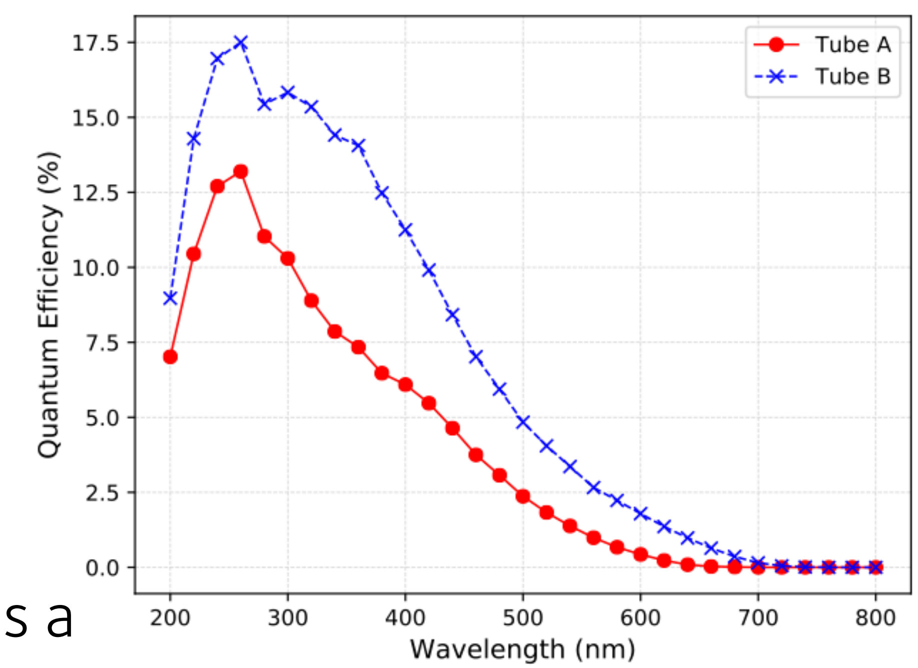
Time reference channels →

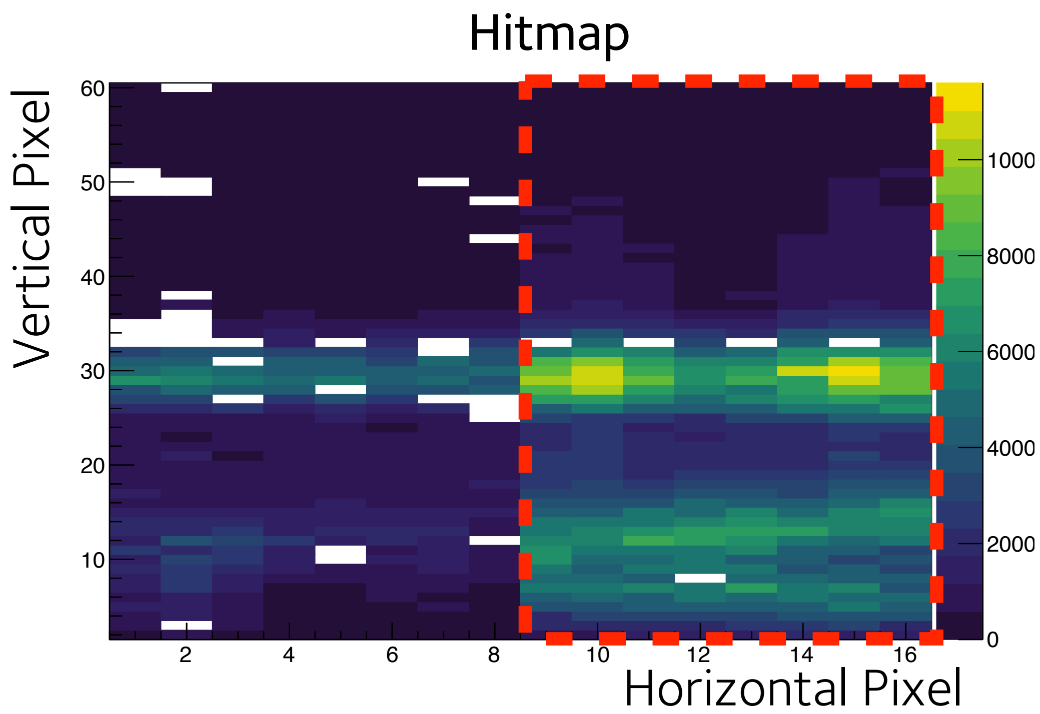


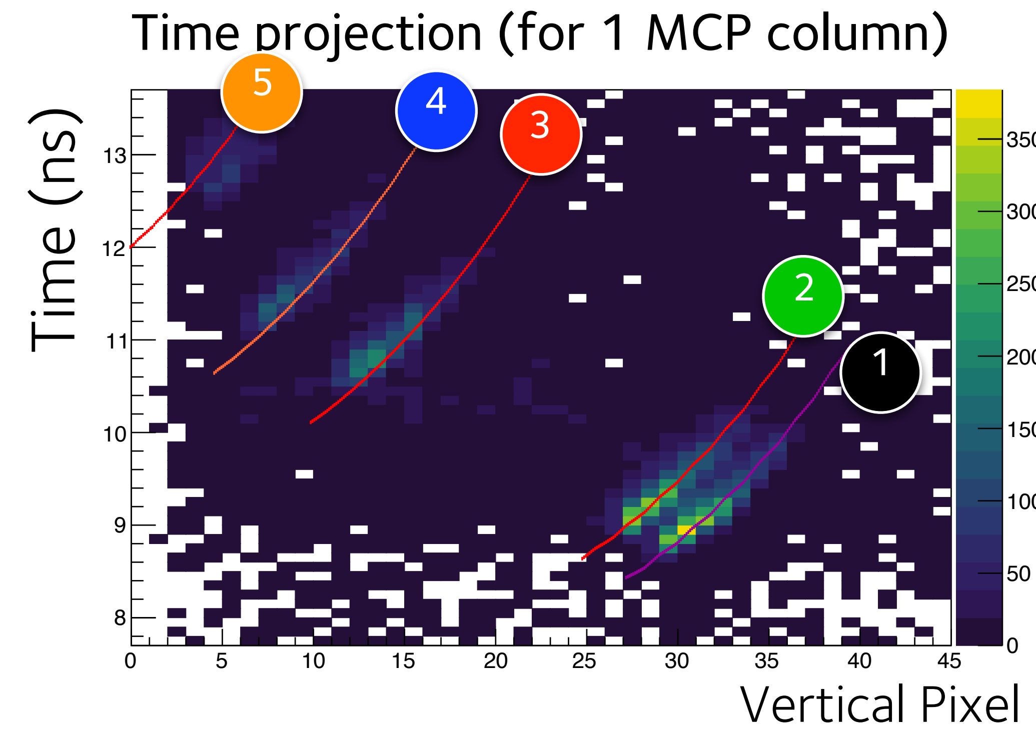


- The hitmap show various bands corresponding to light reflecting off the module sides
- The two MCPs have different quantum efficiencies
- Time reference signals are injected in the middle of the MCPs
- The number of dead pixels improved from MCP A to B as a result of improvements in NINO wire bonding procedure

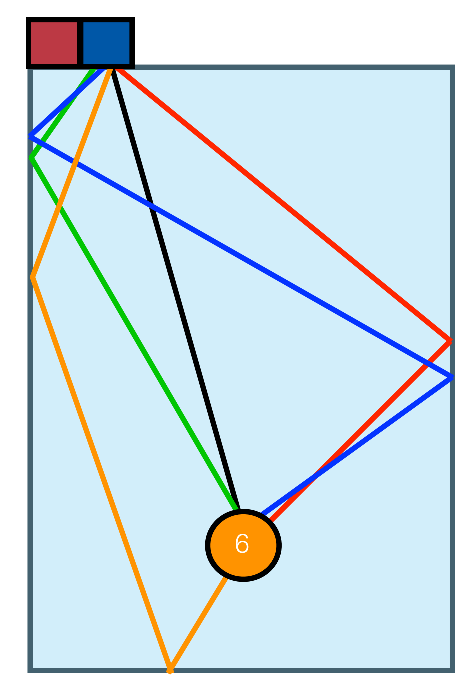


TORCH Preliminary analysis





- This analysis concentrates on MCP B with the higher quantum efficiency
- By projecting the hits in the time-of-arrival axis we can separate the different orders of side reflection
- The overlaid lines represent reconstructed predictions
- The spread in times for each order of reflection is measured to determine the single photon time resolution



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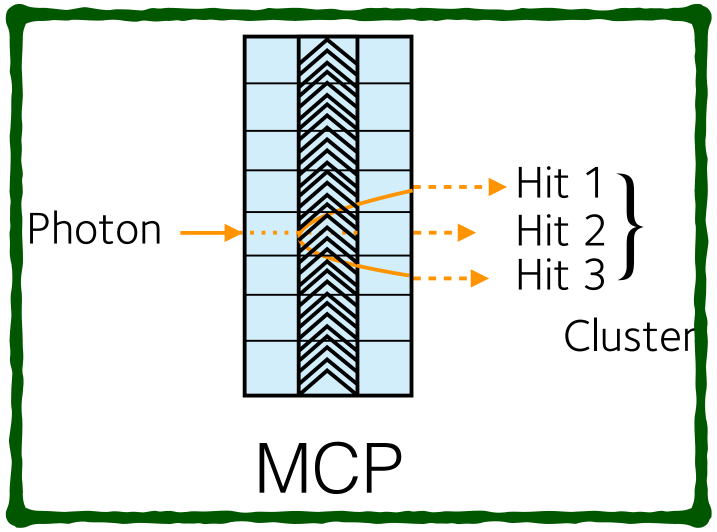
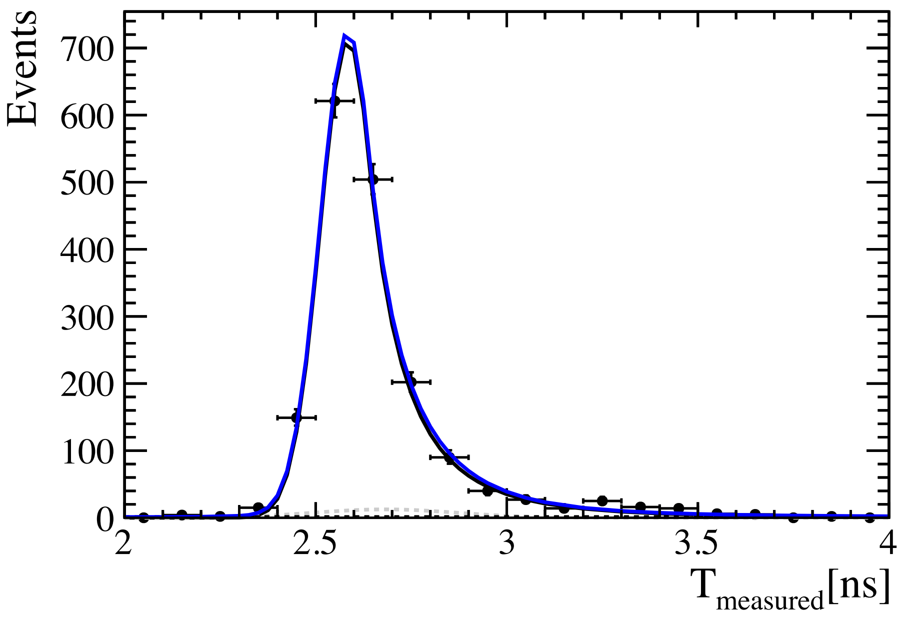
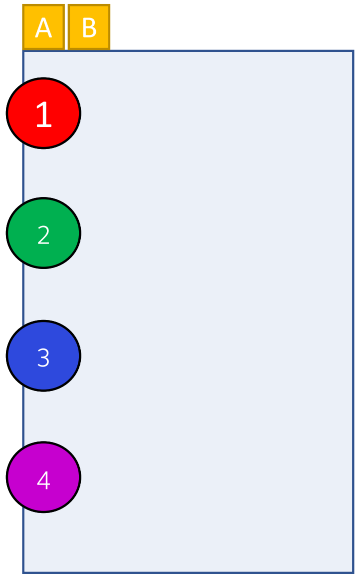
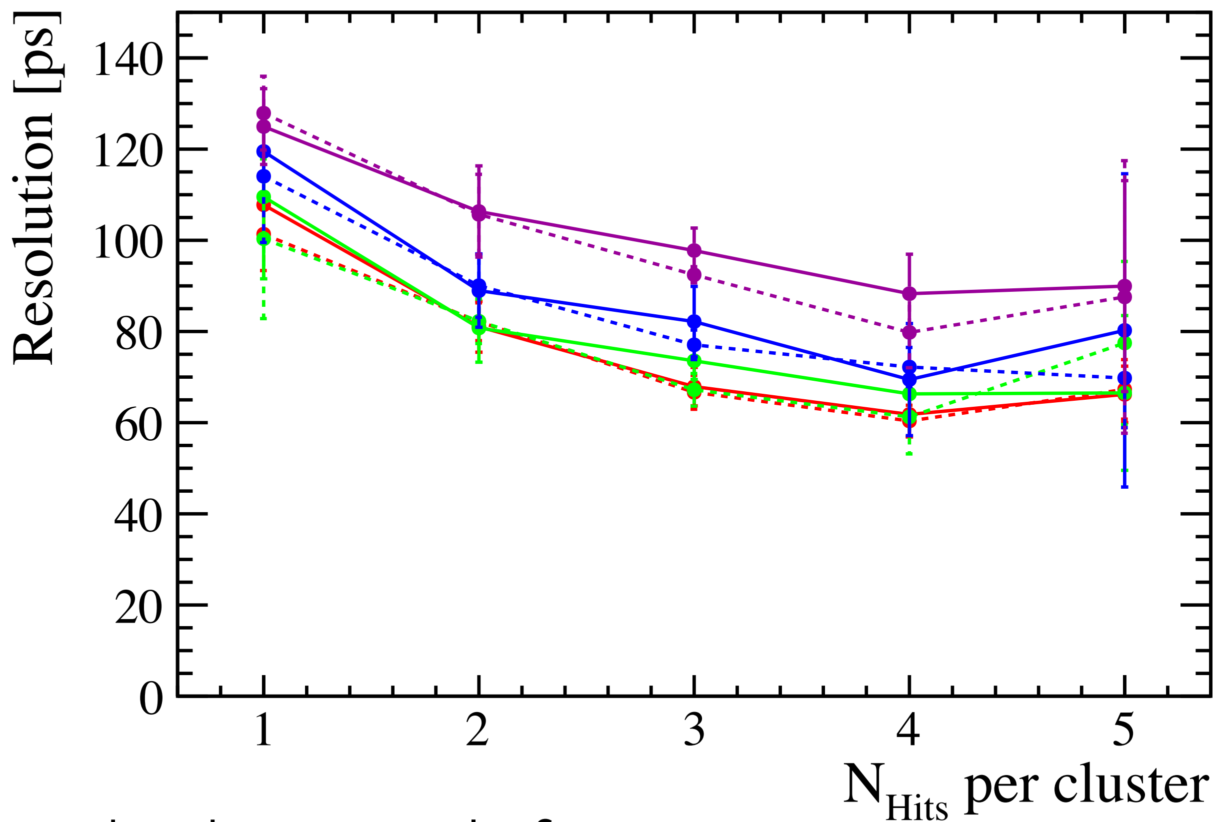
TORCH Preliminary analysis

- As a result of charge sharing in the MCP, single photons result in hits on multiple pixels
- The time resolution is measured for different sizes of clusters of hits
- A simultaneous fit determines the spread in the time of arrival at each pixel









- The time resolution is approaching or achieving the design goal of 70 ps

TORCH Preliminary analysis

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- The time resolution is parameterised into different contributions
- These various sources are under study in laboratory tests

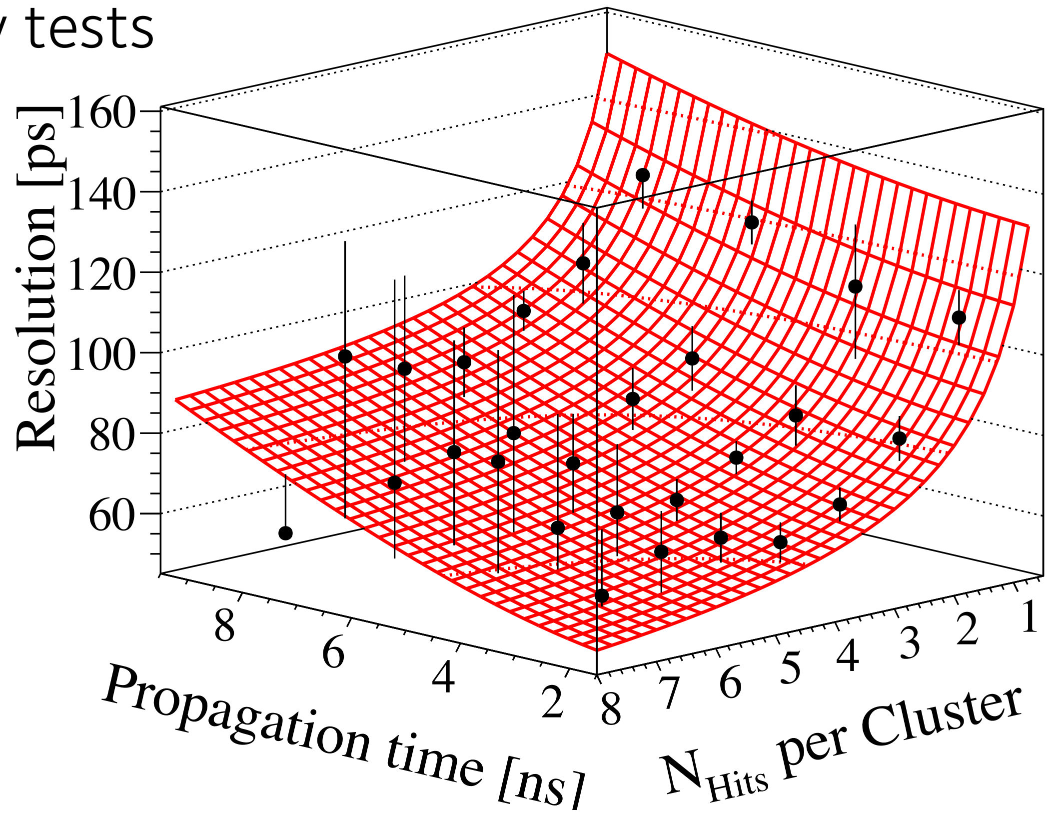
Time resolution parameterisation:

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

e.g. MCP

Propagation time (t_P) dependent effects

Electronics and readout resolution



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

t_P in ns

Further improvements from calibrations expected

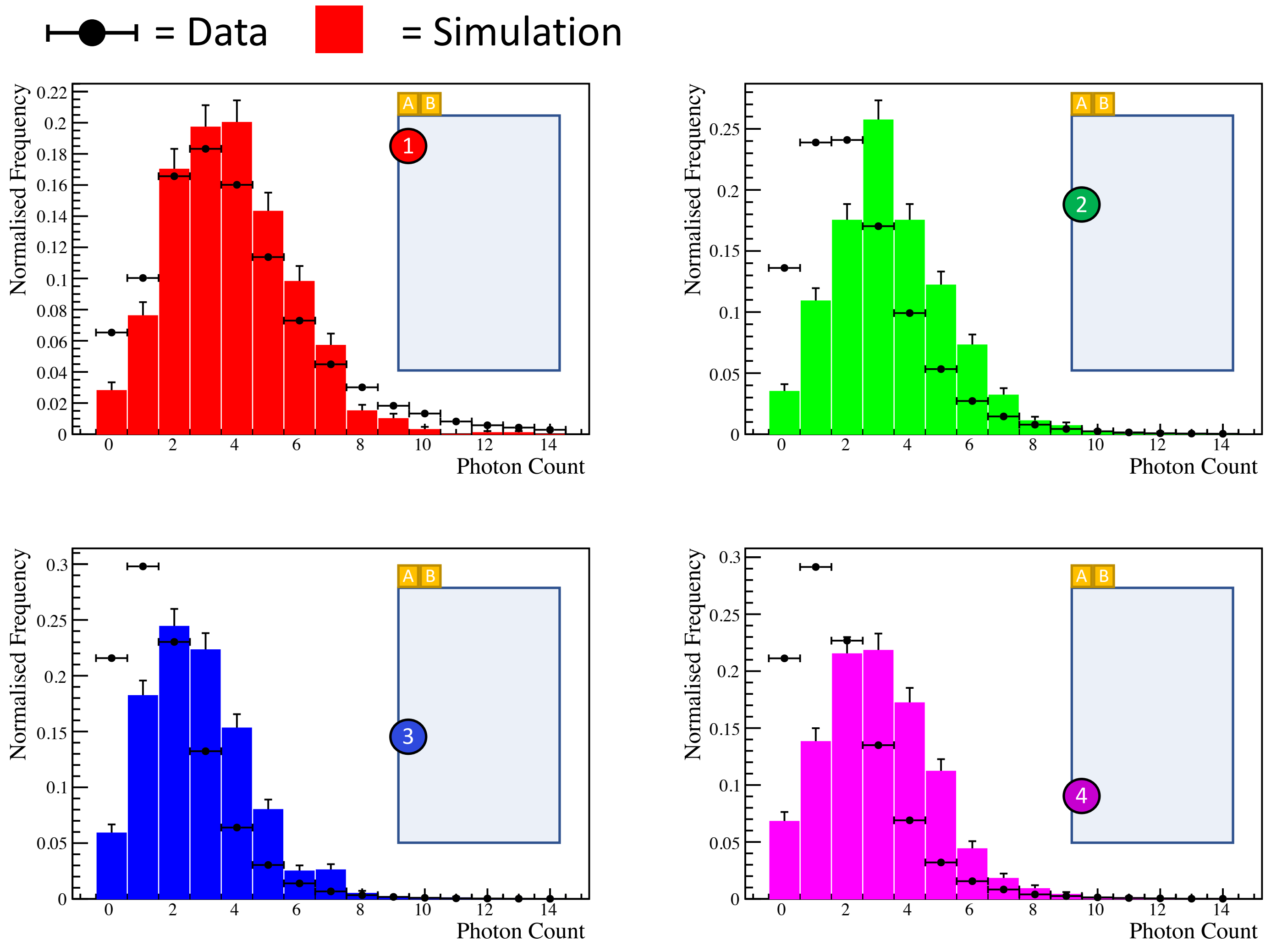
$$\sim 33\,\mathrm{ps}$$
$$\sim (3.75 \pm 0.8) \times t_P\,\mathrm{ps}$$
$$\sim \frac{60}{\sqrt{N_{\mathrm{Hits}}}}\,\mathrm{ps}$$

Ideal values from simulation

Photon yields

- In simulation, various sources of inefficiencies are accounted for, including
  - Surface roughness, MCP quantum efficiency and collection efficiency

- Discrepancies as a function of vertical position still being studied
- The current prototype only has 2 out of 11 MCPs
  - Photon yields would be ~5.5 times larger than shown here
- Final module expected to have improved quantum efficiency



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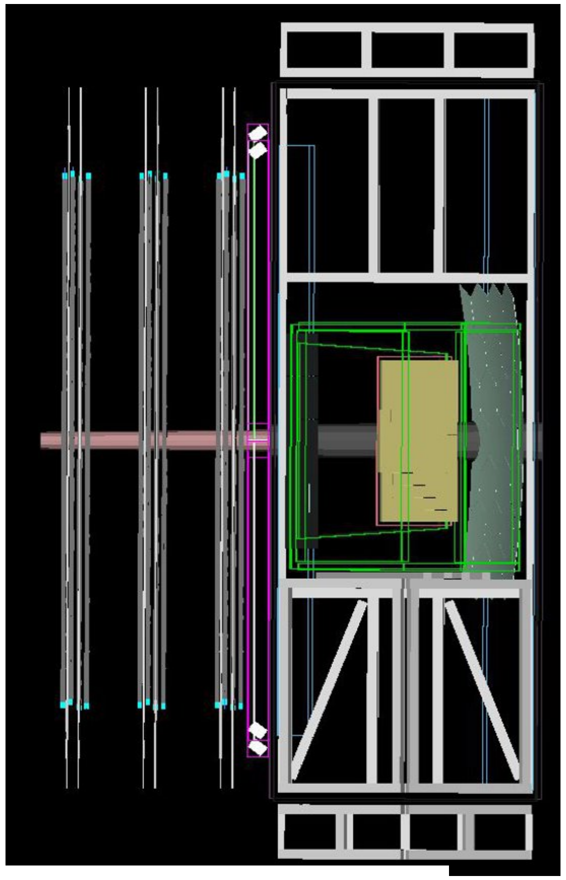
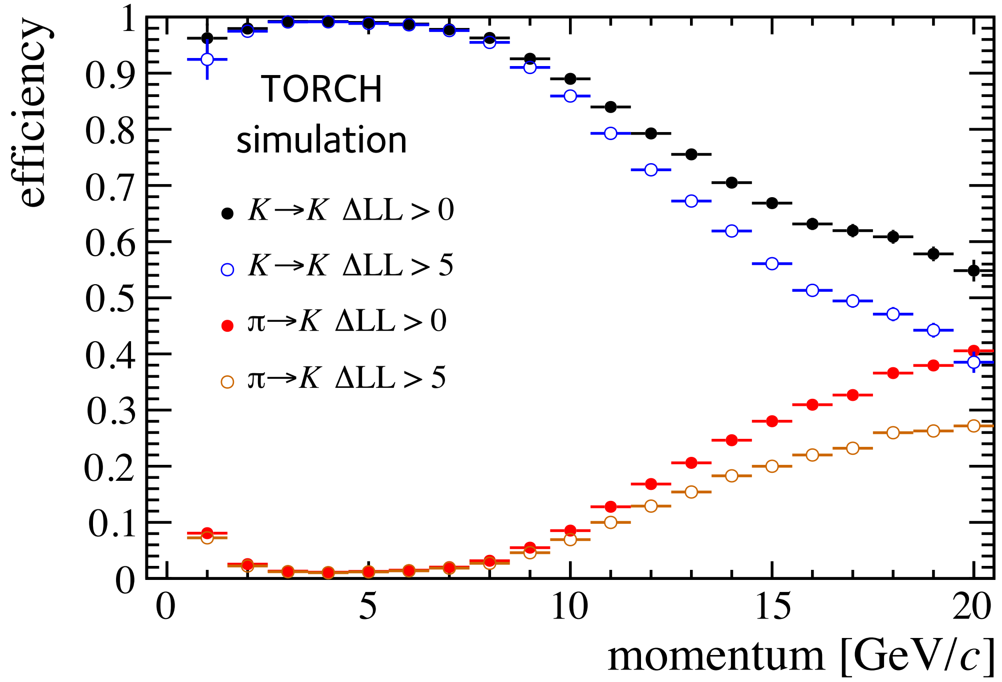
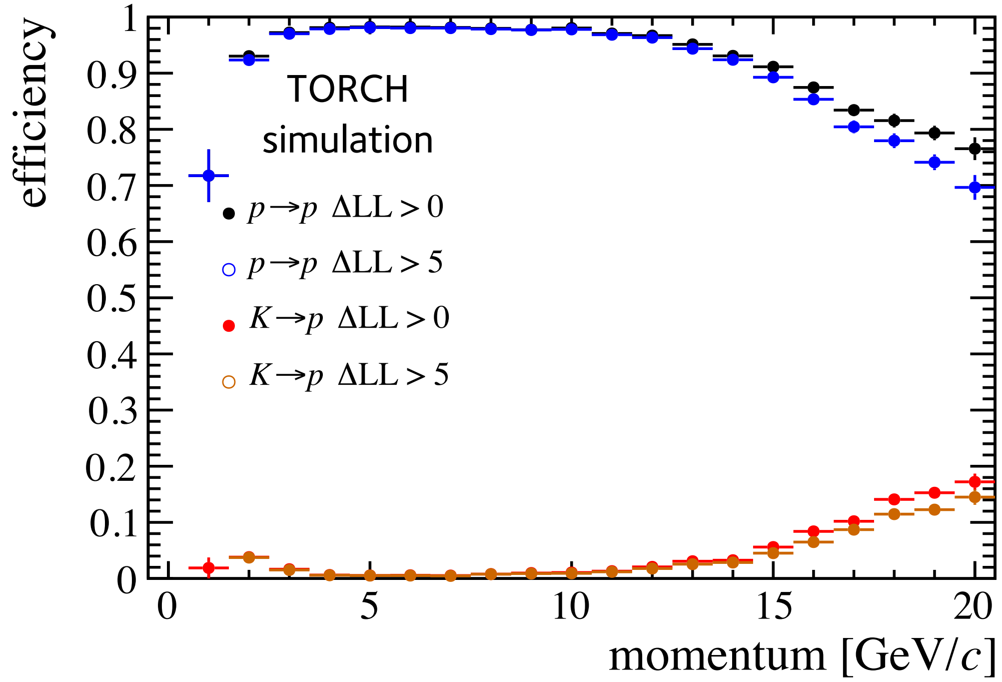
- TORCH has been simulated in the framework of the Upgraded LHCb detector
    - Optical processes are simulated in GEANT4 and sources of inefficiency from TORCH are accounted for
- The PID performance of TORCH is determined for Upgrade IB conditions (Run 4) $\mathcal{L} = 2 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$







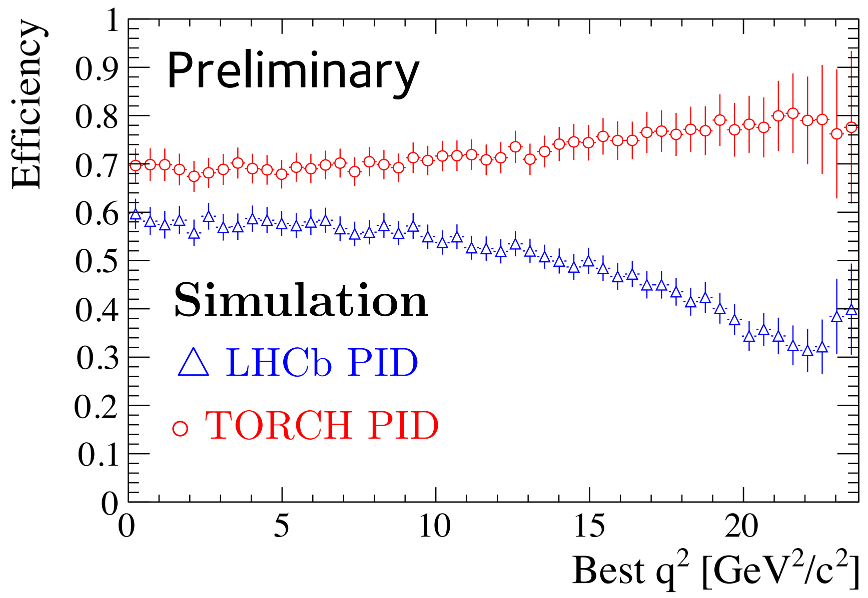
Physics studies

- The simulated PID performance is used to quantify the benefits of TORCH to the LHCb experiment in various physics channels

- As expected, modes with low-momentum kaons and protons benefit the most

- In particular TORCH could provide:
  - Increased signal efficiencies
  - Reduced particle misidentification backgrounds
  - Reduced dependence of PID efficiencies on momentum

$B_s^0 \to K^- \mu^+ \nu_\mu$



- TORCH also brings benefit to flavour tagging algorithms
  - Potential to impact a range of analyses

TORCH

Outlook

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Summary

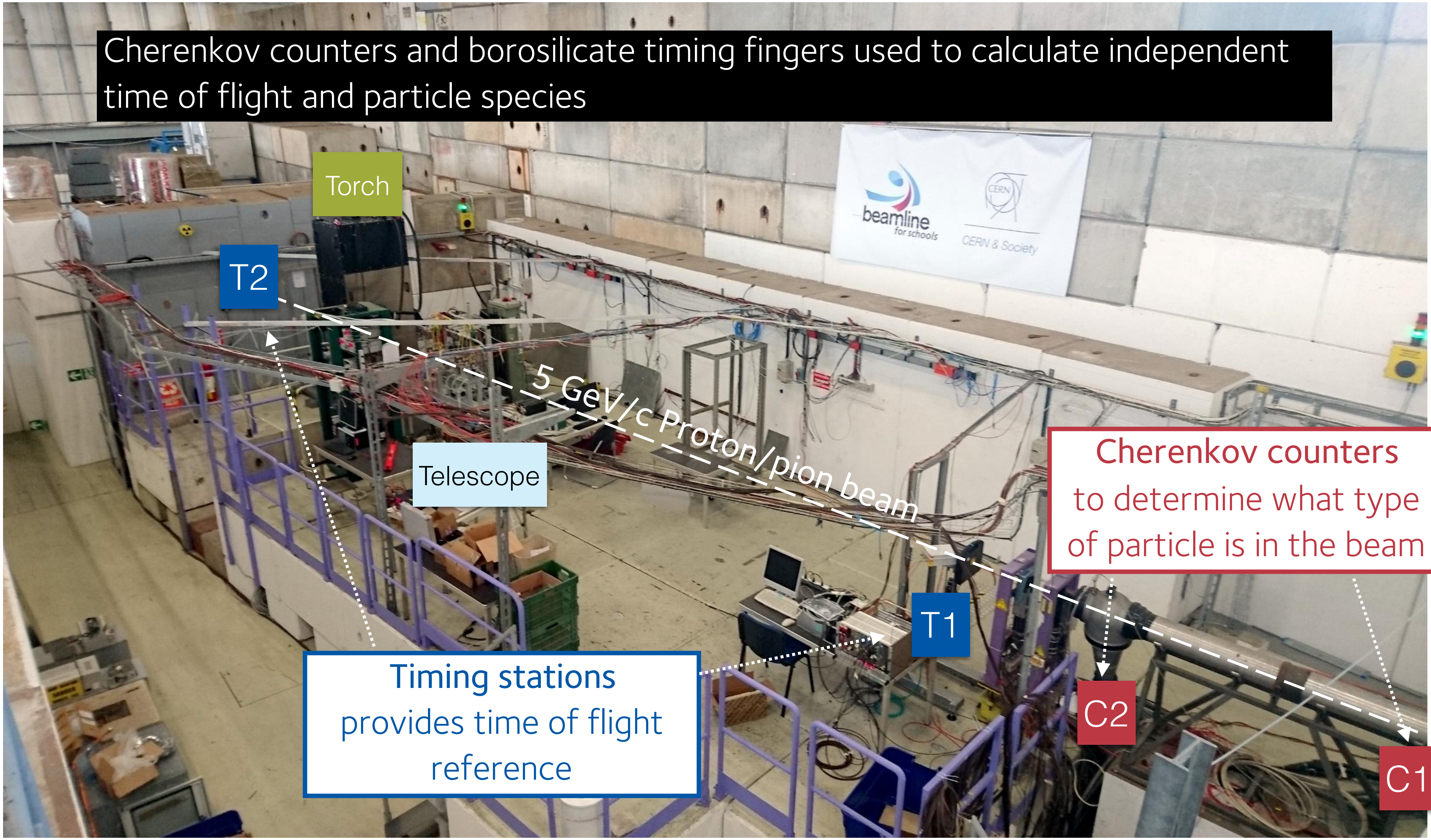
- The TORCH project is progressing well, with a successful series of beam tests
- The time resolution of the prototype is approaching the design goals
- Further lab tests and electronics calibrations are ongoing
- The device has been simulated in the LHCb experiment and studies indicate significant improvements to the LHCb physics potential

Future

- Future tests will use a fully instrumented (11 MCP) half-height TORCH module

Back up slides

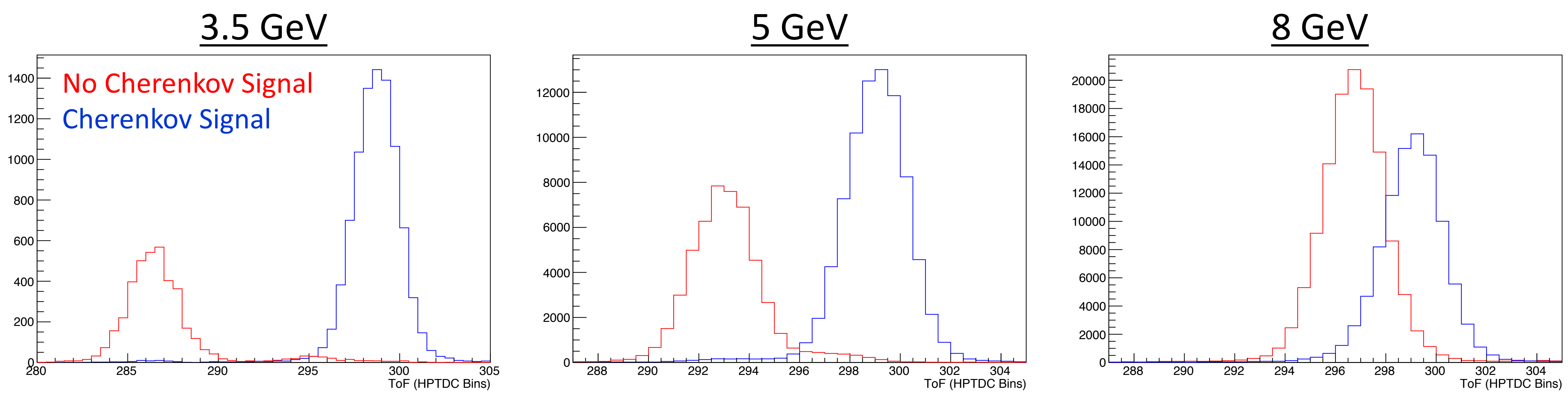
Beam test setup



Cherenkov counters

- The species of the tracks in the CERN PS beam are determined using two Cherenkov counters

- Data has also been taken with 3 GeV/c and 5 GeV/c beams



TORCH Electronics

- Readout electronics consists of **NINO** and **HPTDC** chipsets developed for ALICE collaboration's TOF detector

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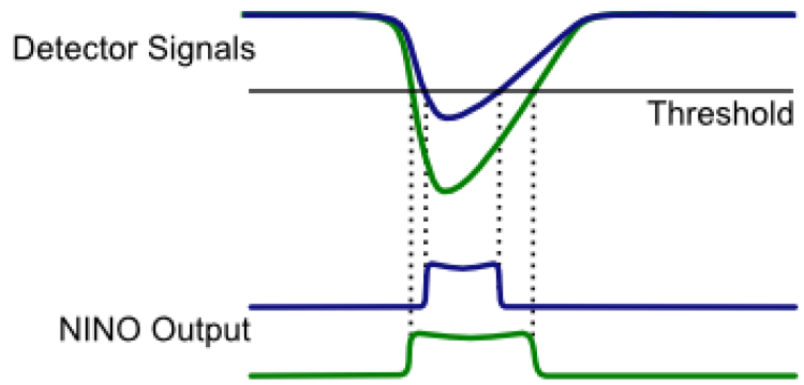
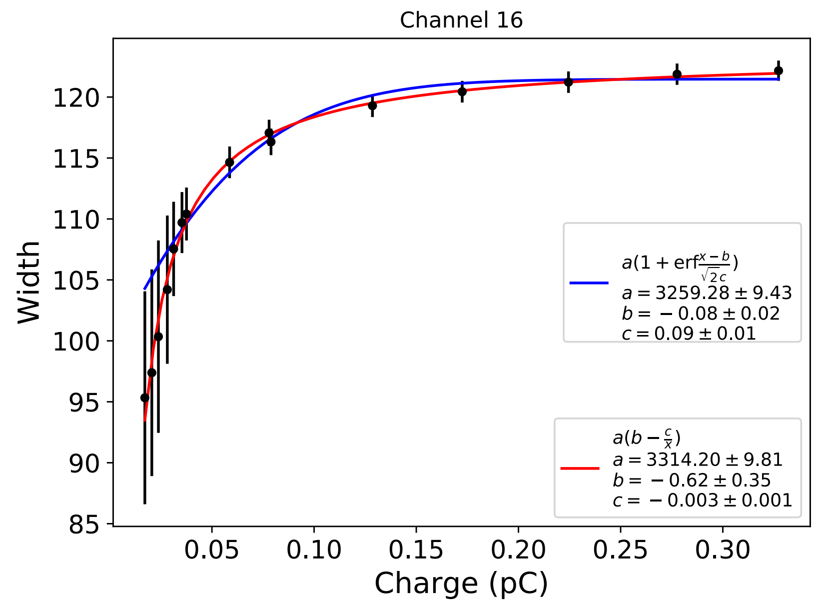
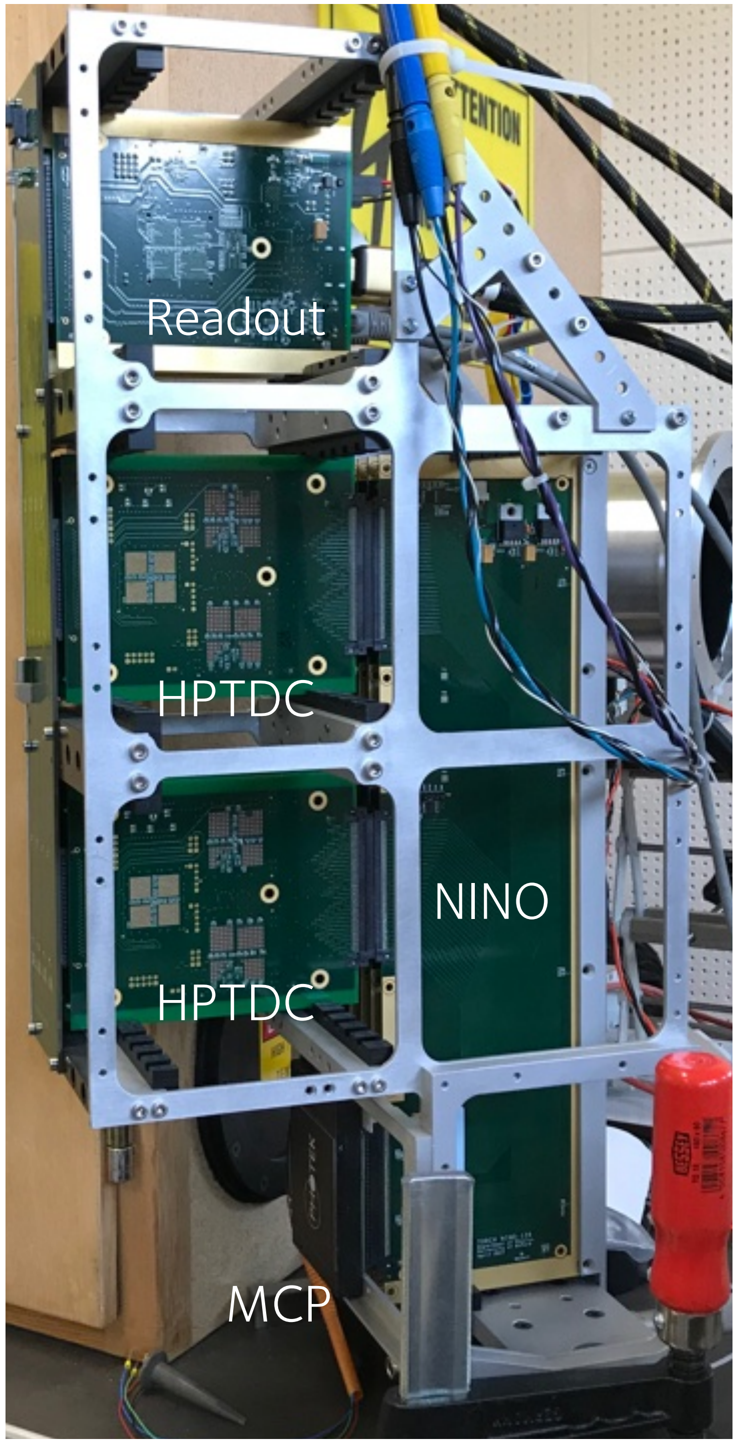
- The **NINO** provides time-over-threshold information



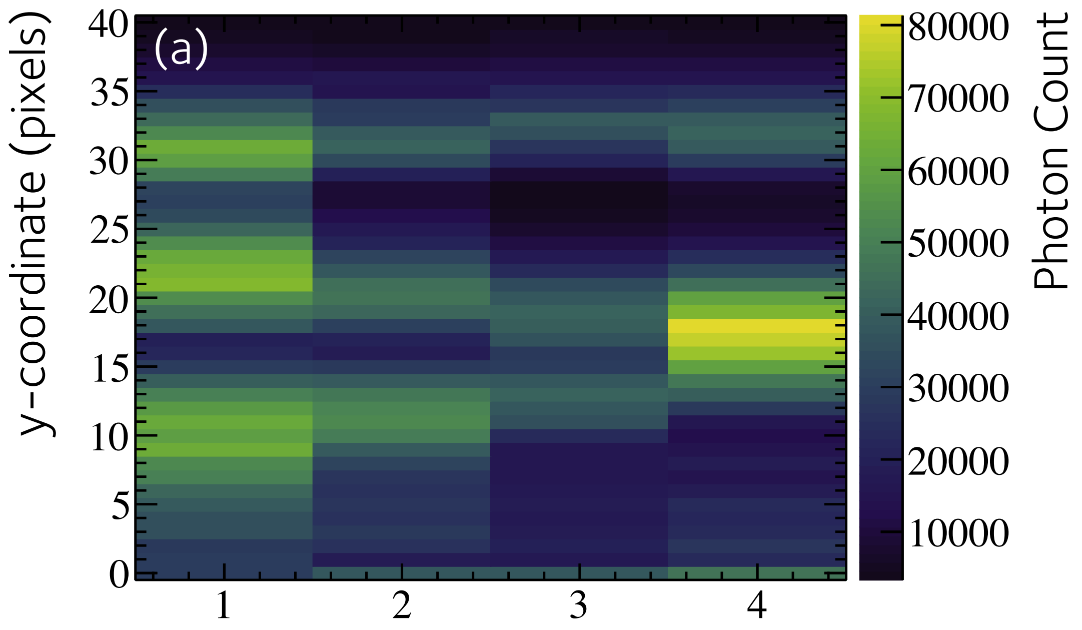
- Calibrations are performed to correct for time bin non-linearities, and pulse-shape dependent responses

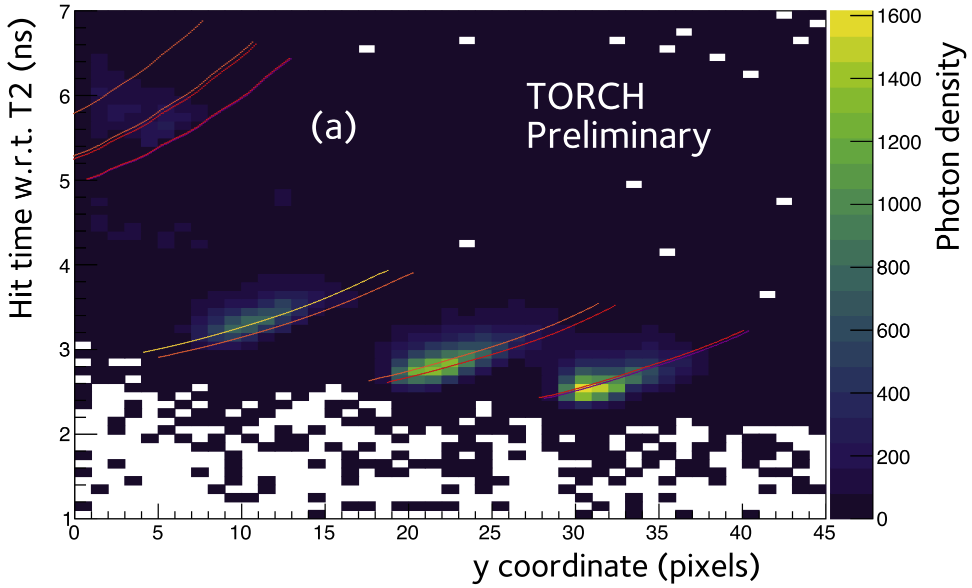


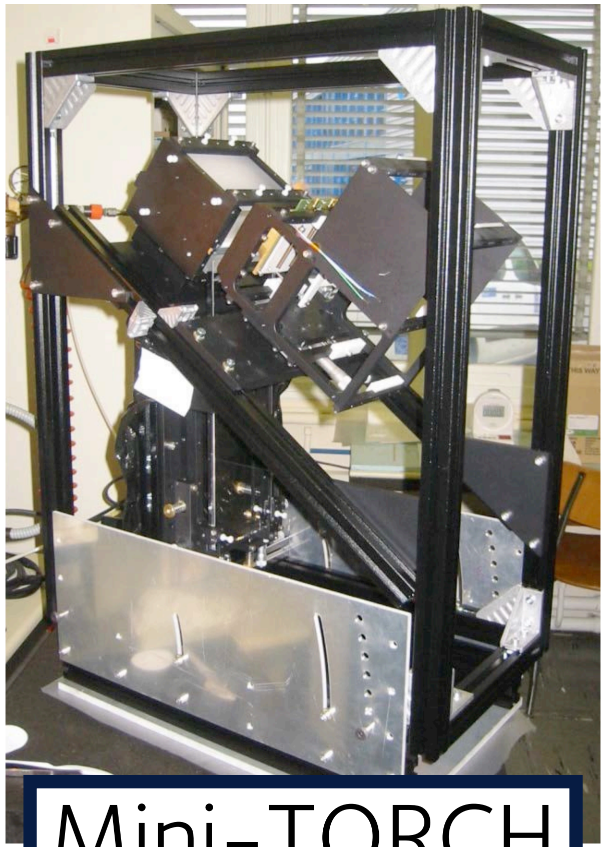


Prototypes

- Previous TORCH prototype was called **mini-Torch**
- Instrumented with two MCPs





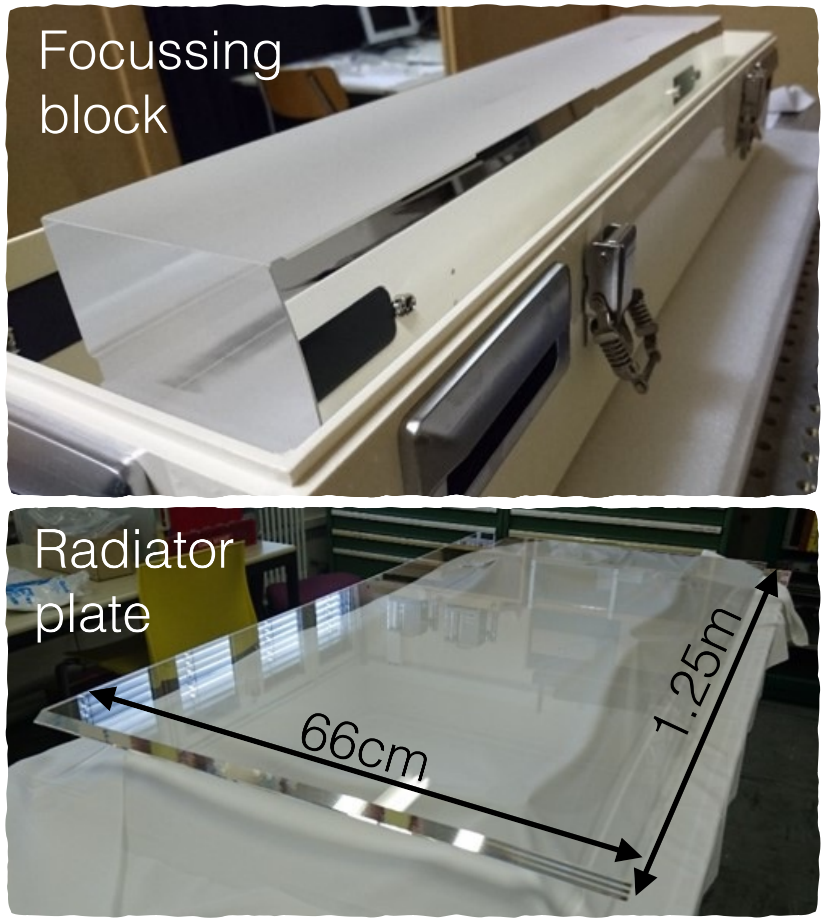


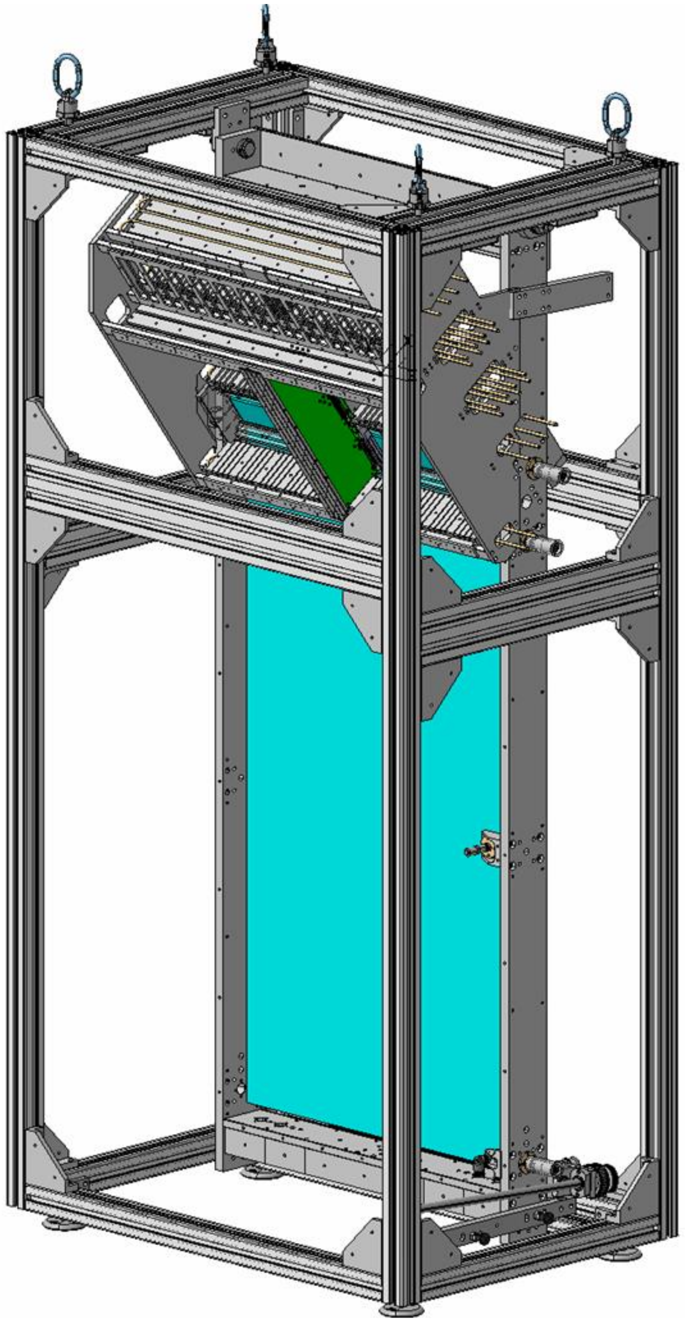
Mini-TORCH

12cm x 35cm x 1cm
Quartz plate

Prototypes

- **Proto-TORCH** is a half-height, full-width prototype



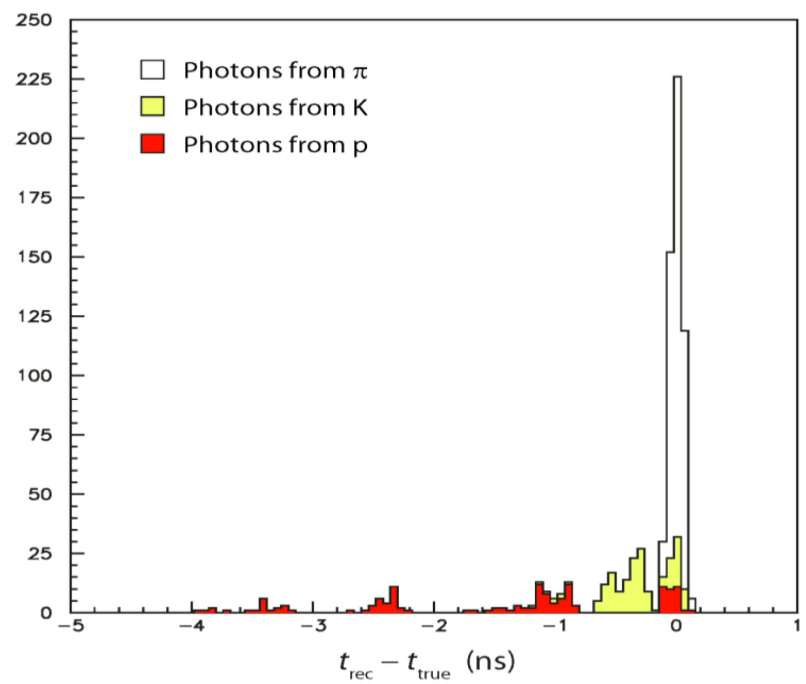


66cm x 125cm x 1cm
Quartz plate

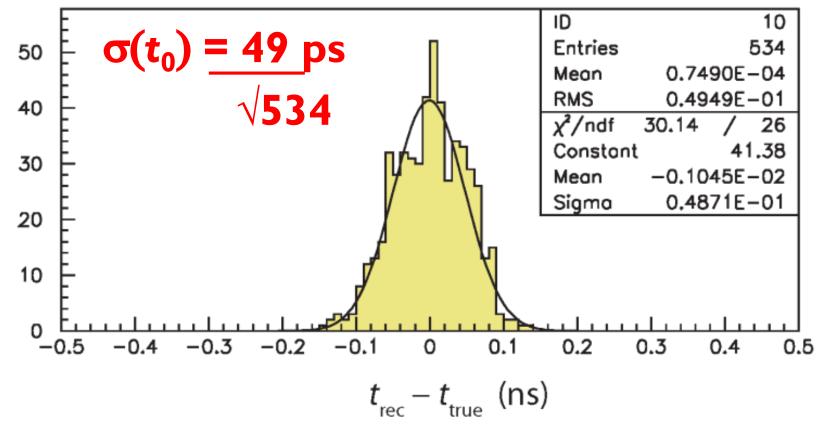
Calculating t_0

- Time of flight also requires initial time
  - Could come from timing information of accelerator, but need to account for length of bunches
- It would be possible to calculate t_0 from other tracks in event
- Reverse reconstruction logic, assuming all are pions (remove outliers)
  - Could achieve few ps resolution

Example from PV of same event



After removing outliers



PID algorithm

$$\log \mathcal{L}_h = \sum_{\text{hits}} \log P(\vec{x}_{\text{hit}}, t_{\text{hit}}, h)$$

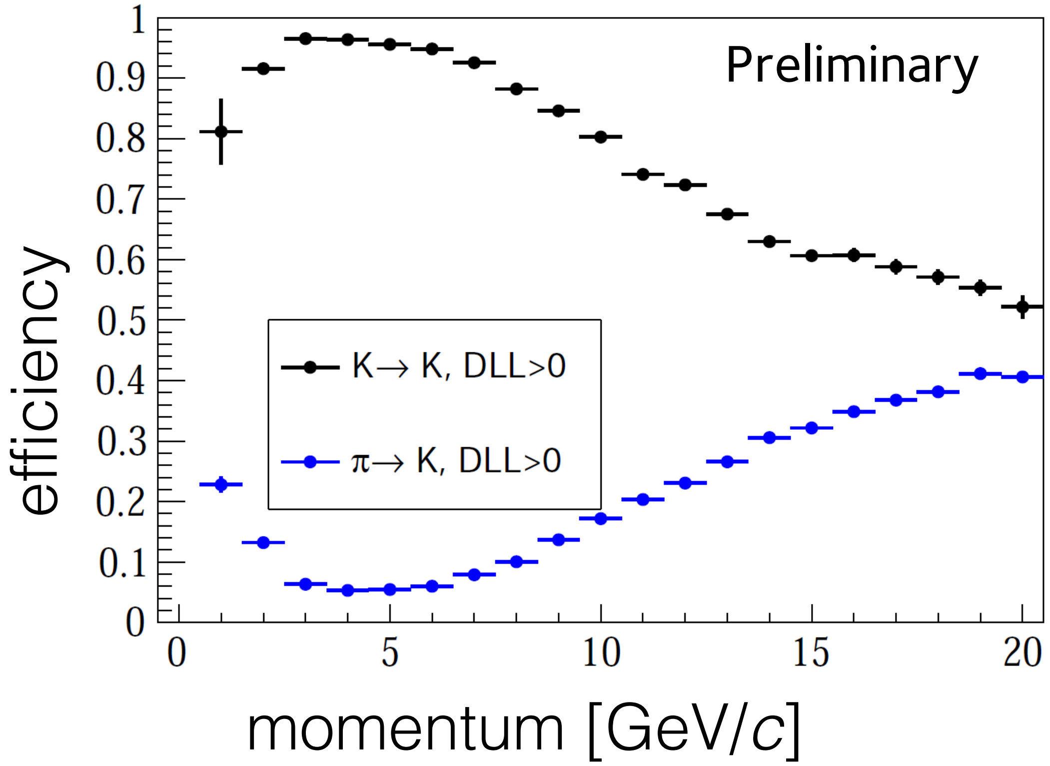
- Compare particle hypothesis using a likelihood calculation
- Performed globally for all tracks in an event

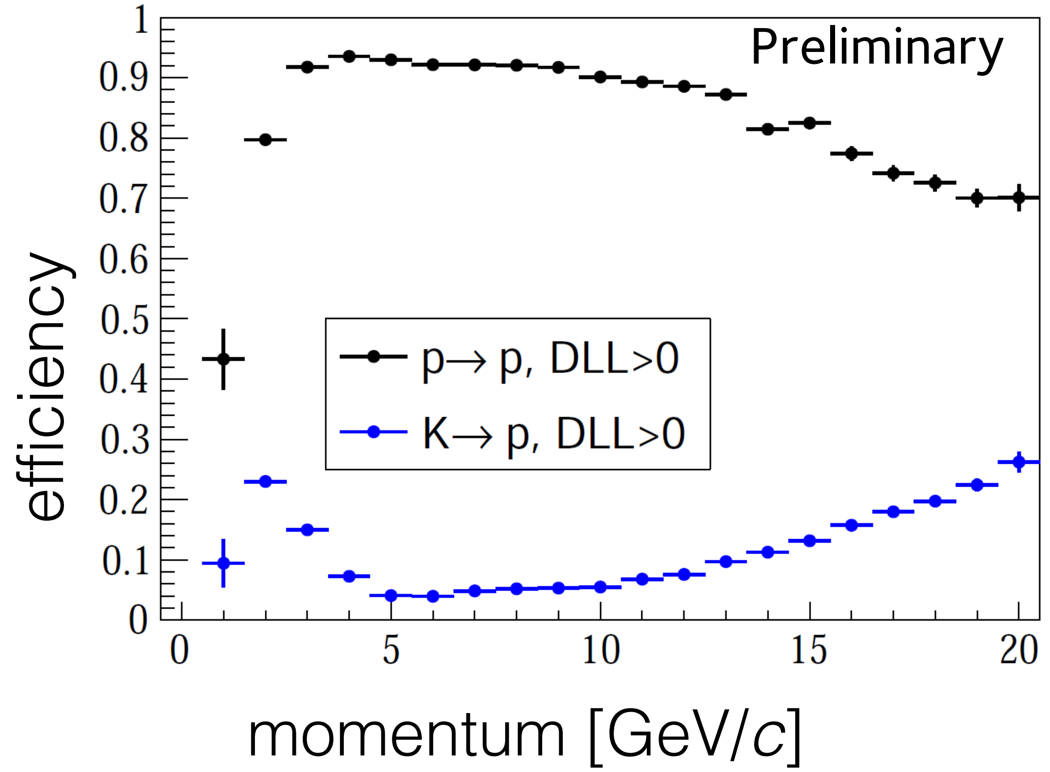
PID performance

- The PID performance has been simulated for Upgrade II conditions

$$\mathcal{L} = 2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

- Multiple events are combined to achieve the required luminosity
- Performance degrades slightly but still has significant separation power
- Further studies ongoing





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