TORCH test beam analysis and developments in MCP-PMTs and electronics

Martin Tat, on behalf of the TORCH collaboration

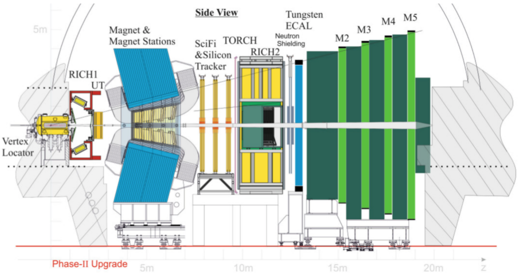
LHCb-UK annual meeting, RAL

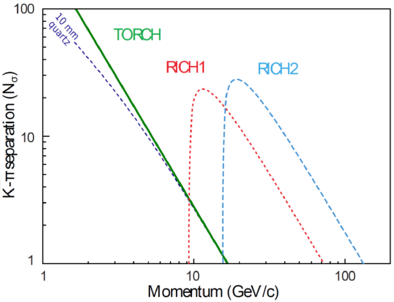
8th-10th January 2024

Introduction to TORCH

TORCH: Time Of internally Reflected CHerenkov light

- Particle identification at LHCb at low momentum (2-20 GeV)
- Ensure full coverage of LHCb's flavour physics programme
  1. Boost signal efficiencies and suppress mis-ID backgrounds
  2. Improve flavour tagging efficiency by 25-50%

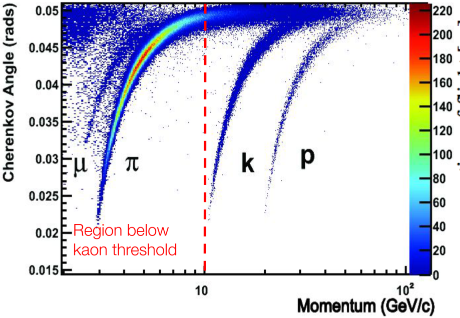


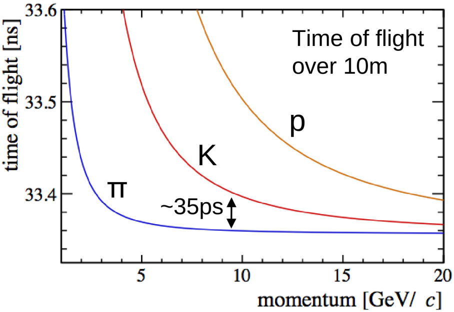


Introduction to TORCH

PID with Time-of-Flight, combined with Cherenkov information

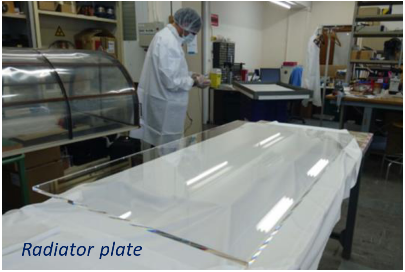
- Cover physics region inaccessible to RICH
- π-K ToF difference over 10 m $\implies$ Aim for 10-15 ps resolution
- Single-photon precision of 70 ps with $\sim$ 30 detected photons

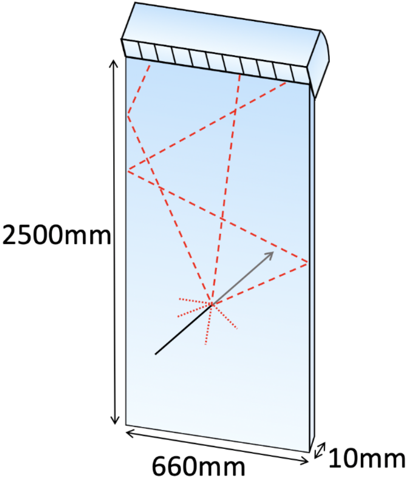




TORCH working principle

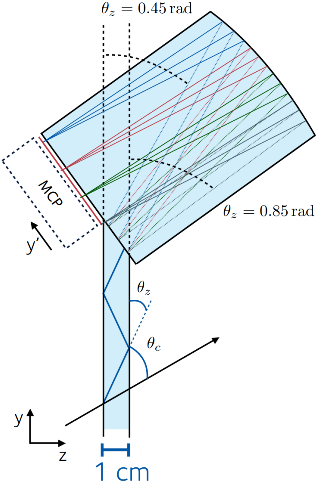
1. Charged particle enter quartz
2. Cherenkov photons emitted
3. Photons undergo internal reflection until they reach the top of the plate





TORCH working principle

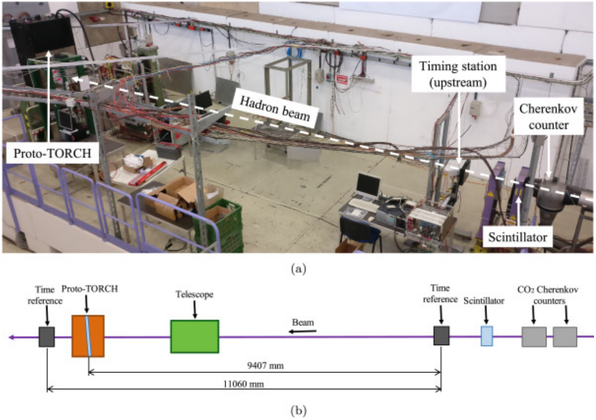
1. Focus photons with cylindrical mirrror
2. Image consists of hyperbolic “bands”
   - Compare with circular rings in RICH
3. Correct for chromatic dispersion using the Cherenkov angle obtained from y'



2018 test beam analysis

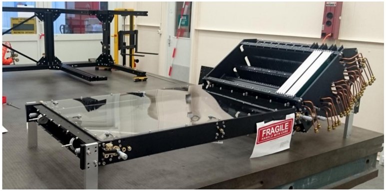
2018 test beam analysis paper published earlier this year

- 8 GeV beam of pions and protons from the CERN T9 beamline
- Single-photon resolution down to 70 ps achieved



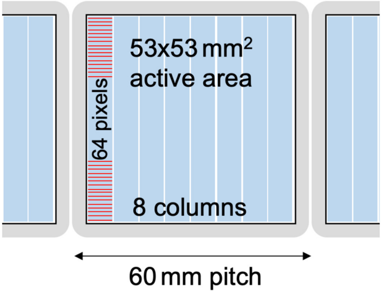
2018 test beam analysis

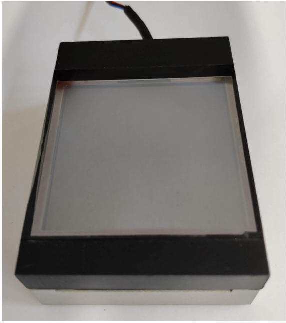
- Prototype of TORCH
- Full width, half height
- Nikon glass with polished surfaces

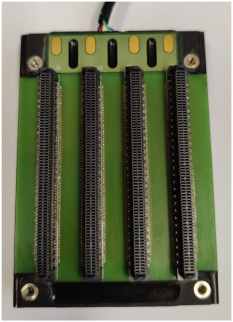


2018 test beam analysis

- Photon detector: MicroChannel Plate PhotoMultiplier Tube
- $53 \times 53\text{mm}^2$ active area
- 8 columns, each with 64 pixels
- Effectively 128 pixels with charge sharing







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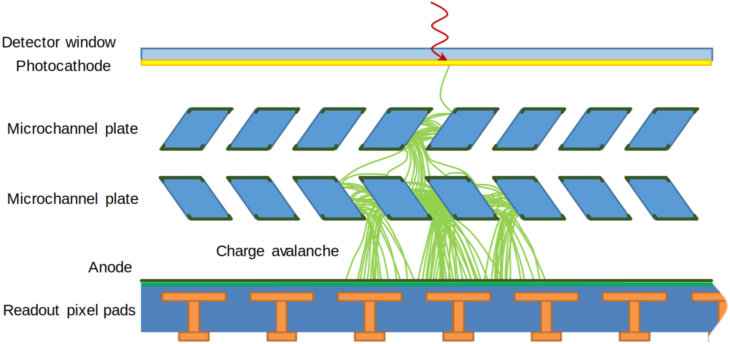
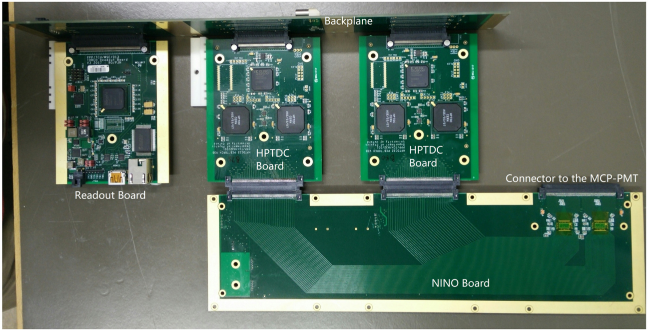


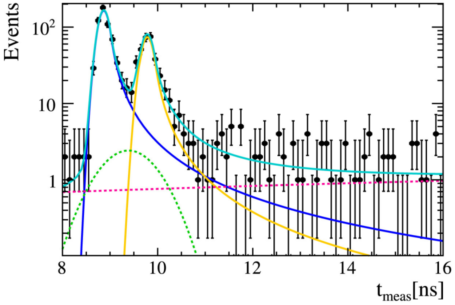
2018 test beam analysis

- NINO: Amplifier and discriminator
- High Performance Time to Digital Converter: 100 ps bins
- Legacy electronics that will be replaced, more on this later!

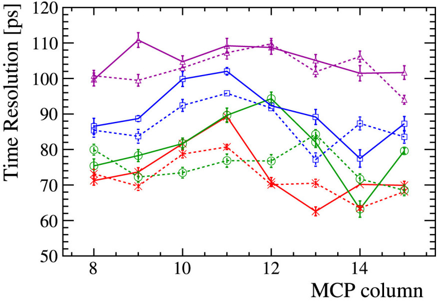


2018 test beam analysis

- Time resolution down to 70 ps
- Worse resolution for tracks entering at the bottom
  - Uncertainty in chromatic dispersion scales with photon path length
  - Improvements expected with further electronics calibrations



(a)

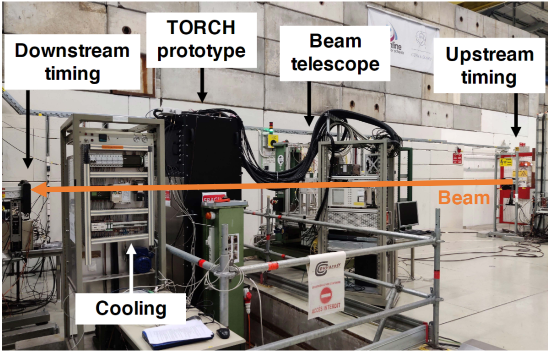


(b)

2022 test beam analysis

Back to T9, with several new goals:

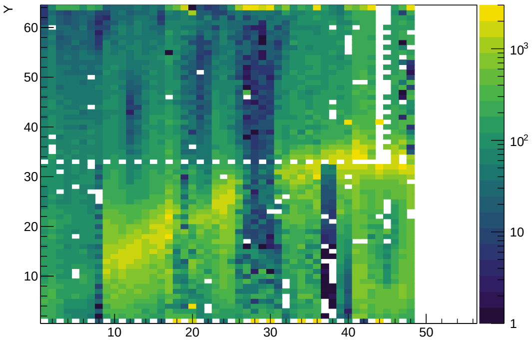
1. Additional, fully instrumented, MCP-PMT tubes (7 in total)
2. Wide range of beam momenta (3, 5, 8, 10 GeV and higher)
3. First demonstration of PID separation in TORCH



Global hit map looks very encouraging!

1. Hit pattern seen across 6 MCP-PMT tubes
2. Minimal degradation of original MCP A and B
3. Proper time reference channel present in (almost) all columns

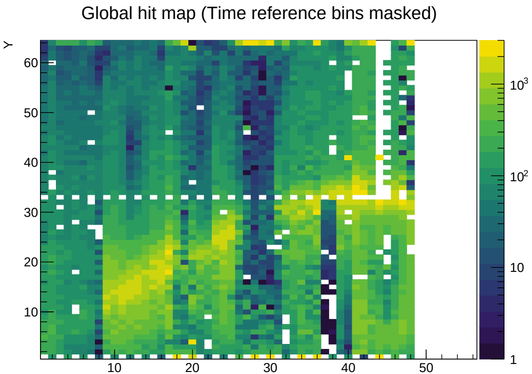
Global hit map (Time reference bins masked)



2022 test beam analysis

Additional MCP tubes work well, but focus on MCP A and B for now

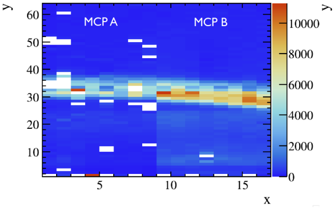
1. Electronics of new MCPs need to be understood better
    - Improve stability and reliability
    - NINO thresholds need to be optimised
2. Some non-uniformity in QE and gain seen in MCP C, D and F



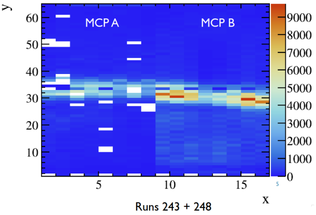
2022 test beam analysis

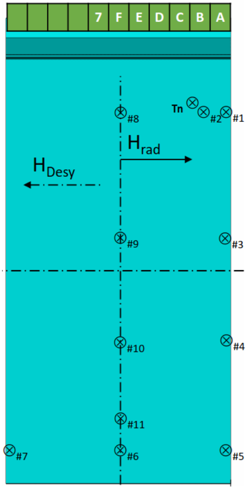
- Study positions 1, 8, 9, 10, 11, 12
- Below: Comparison of position 1 between 2018 and 2022 data $\implies$ Perfect agreement!

2018



2022

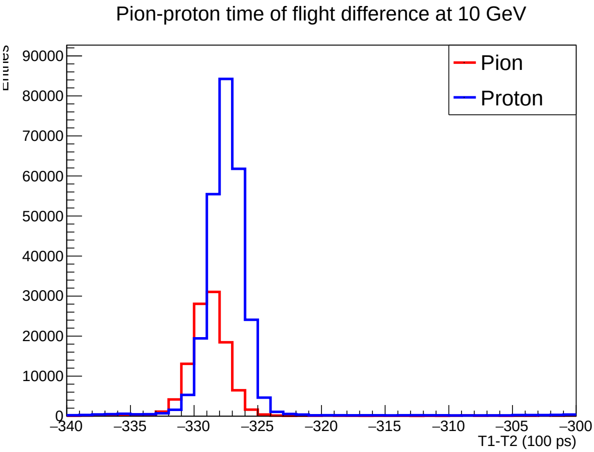




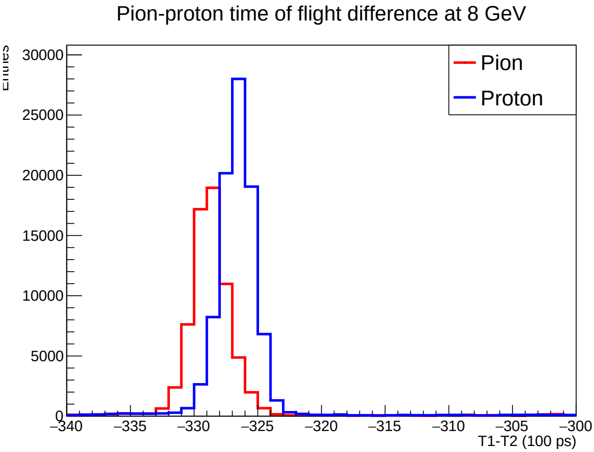
- This talk: Preliminary results from position 8
  - Never studied before!

2022 test beam analysis

Check time of flight between time references
Expected time difference at 10 GeV: 0.15 ns

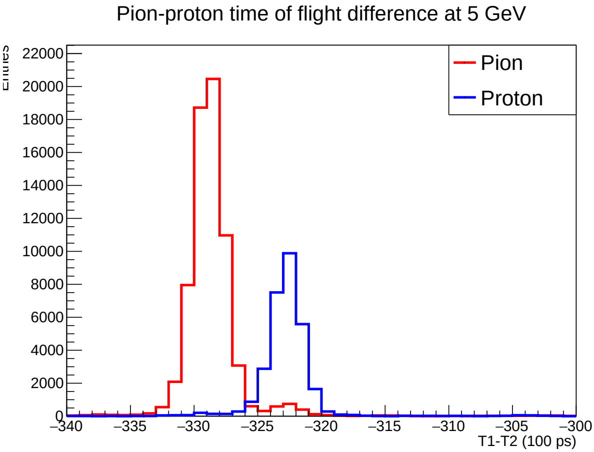


Check time of flight between time references
Expected time difference at 8 GeV: 0.23 ns

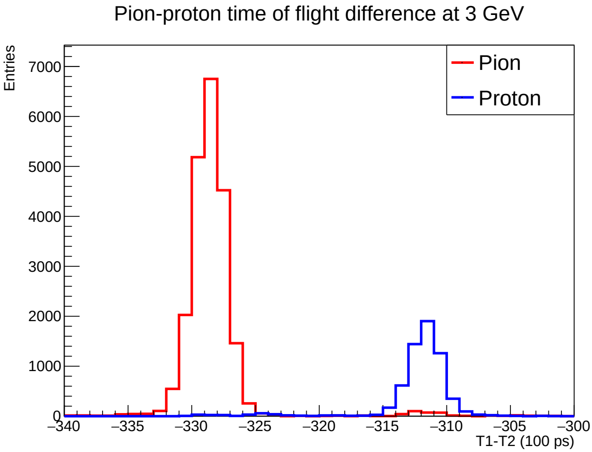


2022 test beam analysis

Check time of flight between time references
Expected time difference at 5 GeV: 0.59 ns

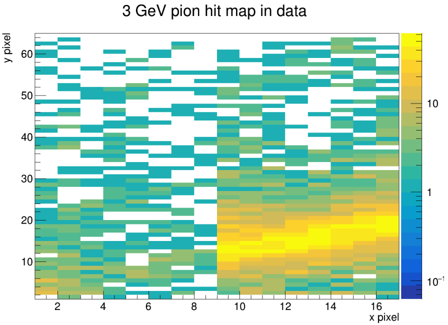


Check time of flight between time references
Expected time difference at 3 GeV: 1.6 ns

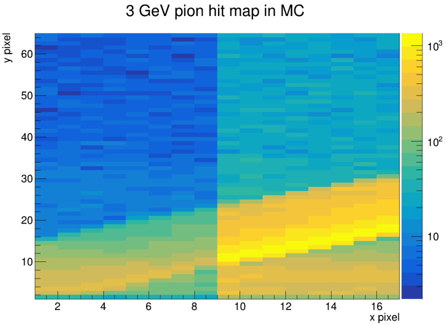


2022 test beam analysis

Let's look at hit maps of 3 GeV pions...

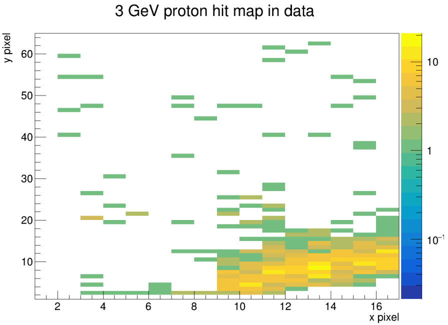


(a) Testbeam data

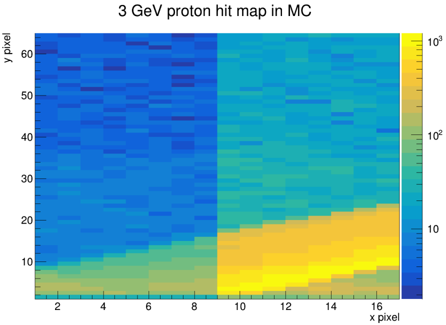


(b) Geant4 simulation

... and compare with hit maps of 3 GeV protons

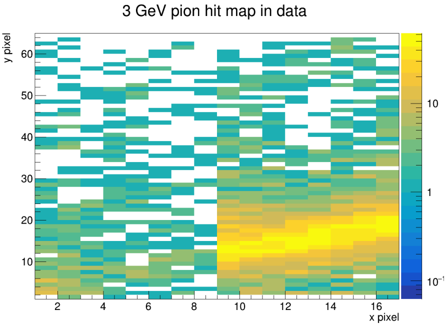


(a) Testbeam data

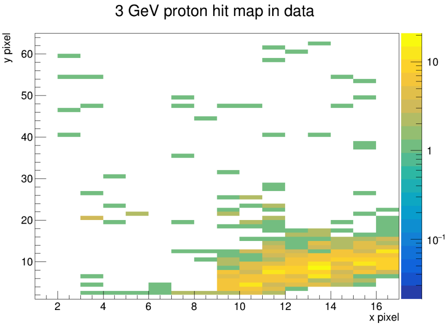


(b) Geant4 simulation

Different y-position $\Longrightarrow$ Separation in Cherenkov angle

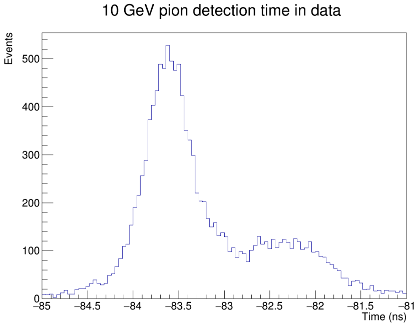


(a) Pions

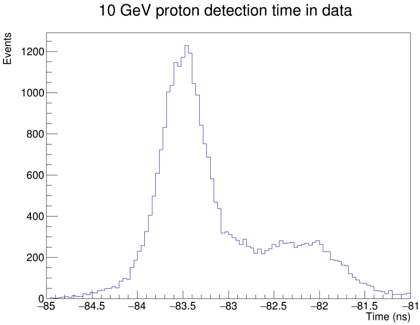


(b) Protons

What about timing information? First look at 10 GeV pions and protons



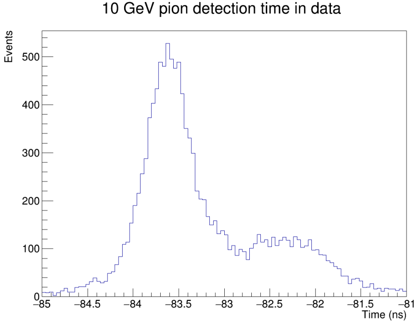
(a) Pions



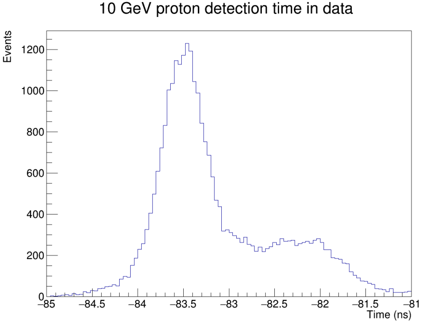
(b) Protons

Small (0.15 ns) separation, as expected

What about timing information? First look at 10 GeV pions and protons



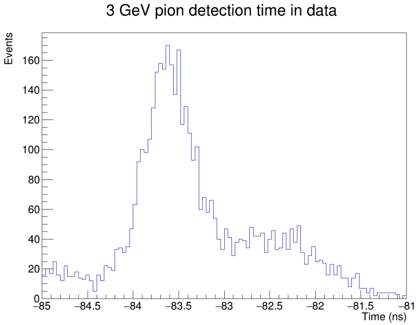
(a) Pions



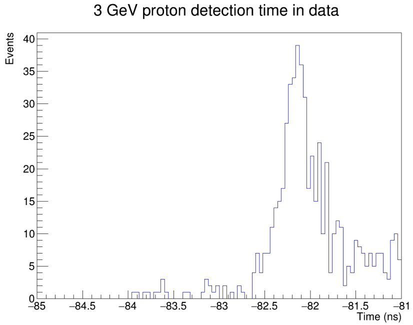
(b) Protons

Additional "reflection", which arrives ~ 1 ns later, is currently under study

Then consider the 3 GeV pions and protons, where a clear separation in arrival time is seen



(a) Pions



(b) Protons

Additional reflection also arrives later for protons

PID algorithm

- Long term goal: Demonstrate separation between pions and protons using a PID algorithm
- PID algorithm presented by Tom Jones last year:

$$P(E_\gamma, \phi_c, t_0) = P(E_\gamma) \times P(\phi_c) \times P(t_0)$$

1. $P(E_\gamma)$: Frank-Tamm distribution $\circledast$ Efficiency effects
2. $P(\phi_c)$: Uniform distribution
3. $P(t_0)$: Gaussian smearing due to electronics

PID algorithm

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- PID algorithm presented by Tom Jones last year:

$$P(E_\gamma, \phi_c, t_0) = P(E_\gamma) \times P(\phi_c) \times P(t_0)$$

- Convert (E_γ, ϕ_c) into detector hit position (x, y) using Jacobian J
- Each derivative in J is calculated by forward-propagating two photons

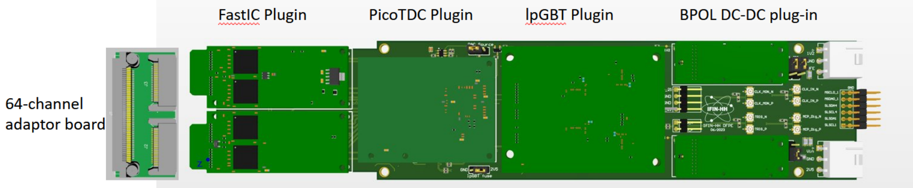
$$P(x, y, t_0) = P(E_\gamma, \phi_c, t_0)/|J|$$

2025 testbeam

- The TORCH collaboration is planning on going back to T9 in early 2025 with a full-height prototype TORCH module, which is 2.5 m tall
- Completely new mechanical support structure, which will be discussed by Adam in the next talk!
- From our experience with the 2022 testbeam, we will be much better prepared for 2025:
  - More efficient data collection
  - Better quality data
  - First demonstration with full-size prototype

Future plans: New electronics

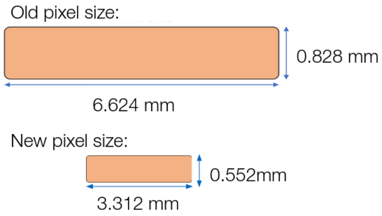
- New TORCH electronics have been aquired and is under lab testing
  - Only 2 sets available, which is insufficient for the next testbeam
- FastIC chips will replace old NINO chips
  - 250 nm → 65 nm CMOS technology
- PicoTDC replace previous HPTDC chips
  - Time binning is reduced from 100 ps to 12 ps

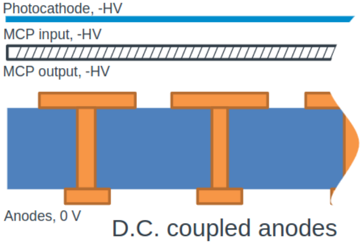


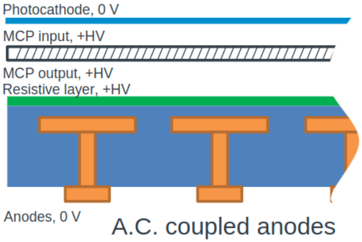
Dimensions of carrier board: 54mm X 250mm

Future plans: New MCP-PMT tubes

- Huge improvement in occupancy
- Increase granularity from 8×64 to 16×96
- Change from AC coupled to DC coupled anode







Summary and future prospects

Summary:

1. Test beam analysis progressing well, with promising results
   - Hit patterns well understood
   - More detailed analysis of time information ongoing

2. We have aquired new electronics and new MCP-PMTs
   - Lab testing ongoing
   - New electronics will replace legacy NINOs and HPTDCs
   - New MCP-MPTs have higher spatial resolution

Future prospects:

1. Finalise test beam analysis
    - Calibrations
    - Photon counting
    - Time resolution
    - PID performance
2. New test beam is planned for early 2025
    - Demonstration of full height quartz plate TORCH and mechanics

Thanks for your attention!