Developing the TORCH detector for picosecond timing of charged particles

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On behalf of the TORCH Collaboration

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Outline

What is TORCH?

- ➡ Introduction to the TORCH detector
- ➡ TORCH photon sensors (MCP-PMTs) and electronics

Analysis of TORCH prototype in Test Beam

- ➡ Time resolution

Studies in the Laboratory

- ➡ Timing measurements

TORCH simulation in LHCb

- ➡ Performance studies

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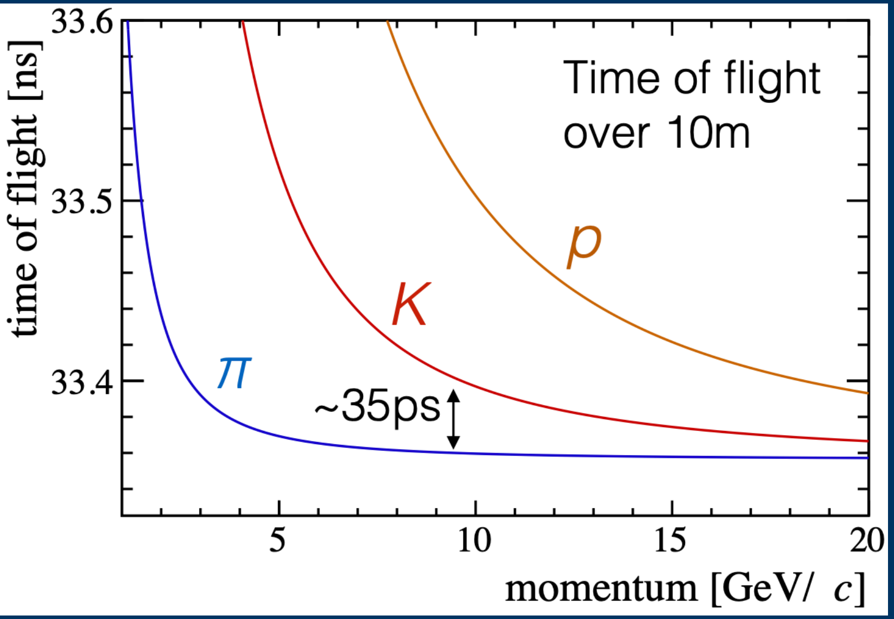
The TORCH Detector

TORCH: Time **O**f Internally **R**eflected **CH**erenkov Light

Aim:
Charged particle identification at low momentum
(K/π/p separation at $2-15$ GeV/c)

How:
- Perform a **Time of Flight measurement**
- ΔToF(K - π) ~ 35ps for a 10m flight path
- Need a time resolution of 15ps for a 3σ K/π separation



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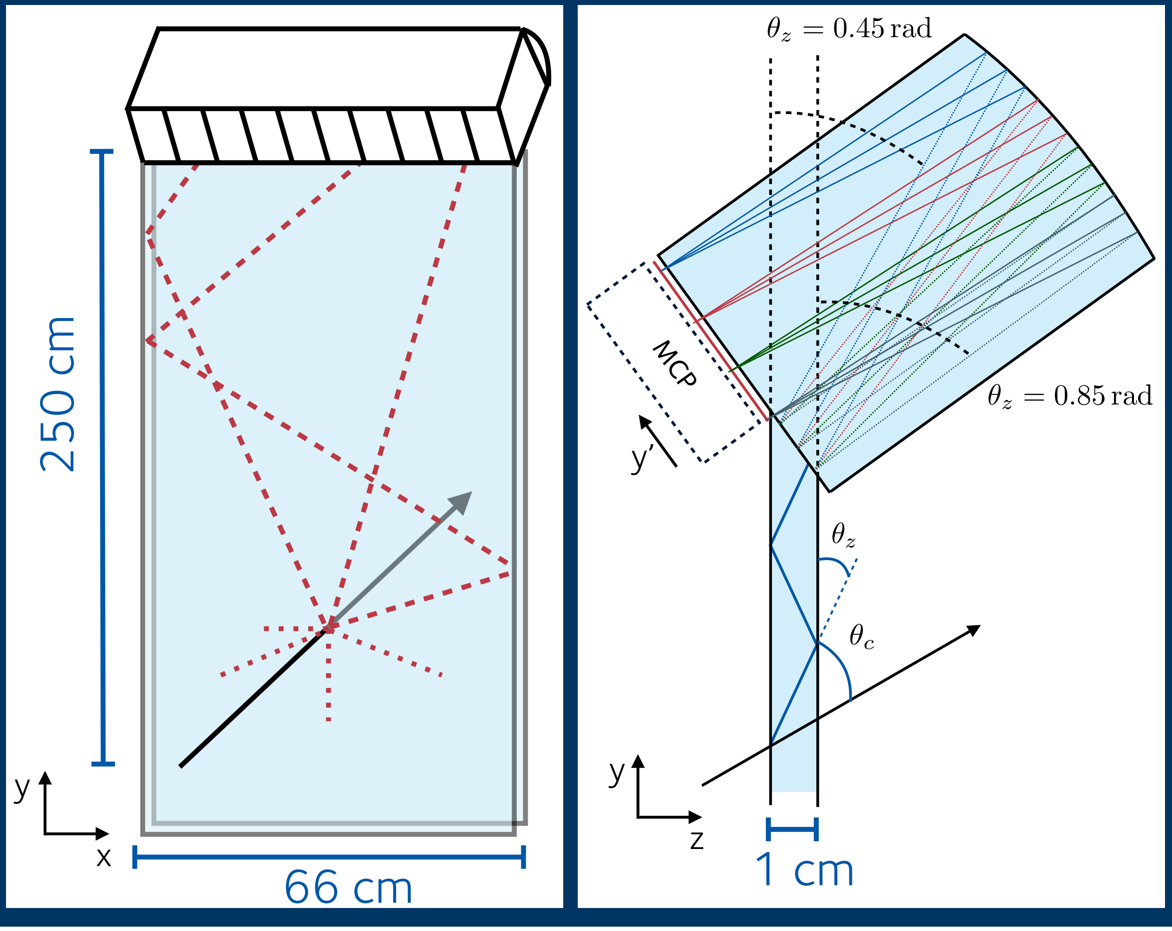
The TORCH Detector

<u>TORCH</u>: <u>T</u>ime <u>O</u>f Internally <u>R</u>eflected <u>CH</u>erenkov Light

- Quartz radiator + focusing block
- Prompt Cherenkov light emitted by charged hadrons is propagated through the quartz via total internal reflection and focused on the detector plane by a cylindrical mirror
- The photon arrival time and pattern is used to correct for chromatic dispersion effects and to identify the hadronic species
- Aim for a per-particle time resolution better than 15ps in the desired momentum range
- ~ 30 Cherenkov photons per track
- Hence 70ps resolution for a single photon is required



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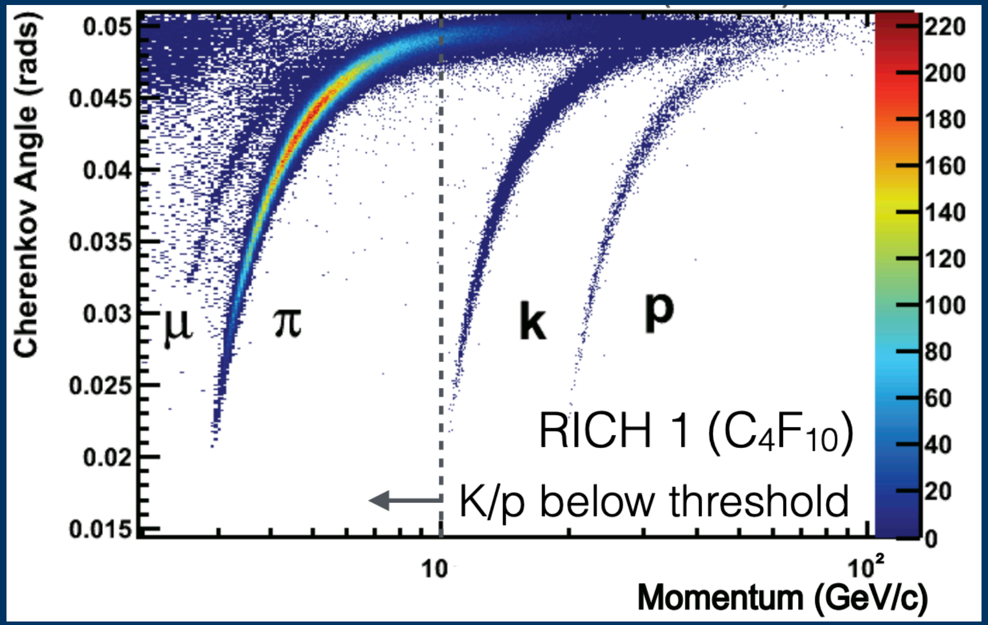
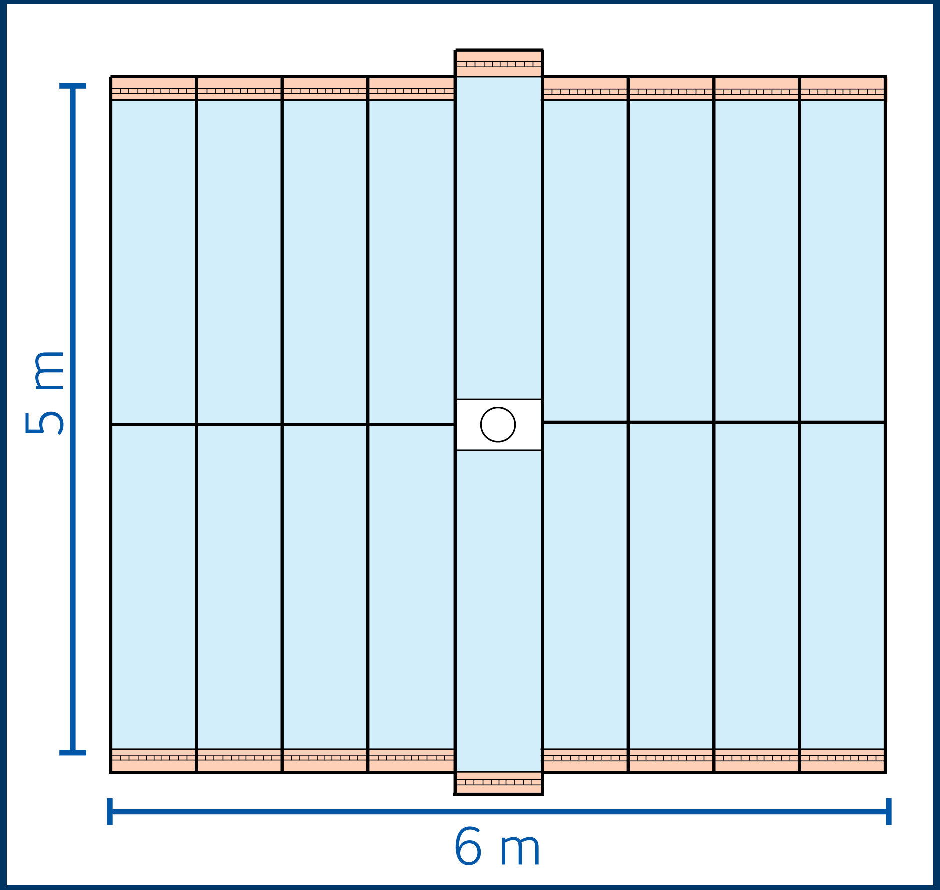
The TORCH Detector in Future Upgrade LHCb

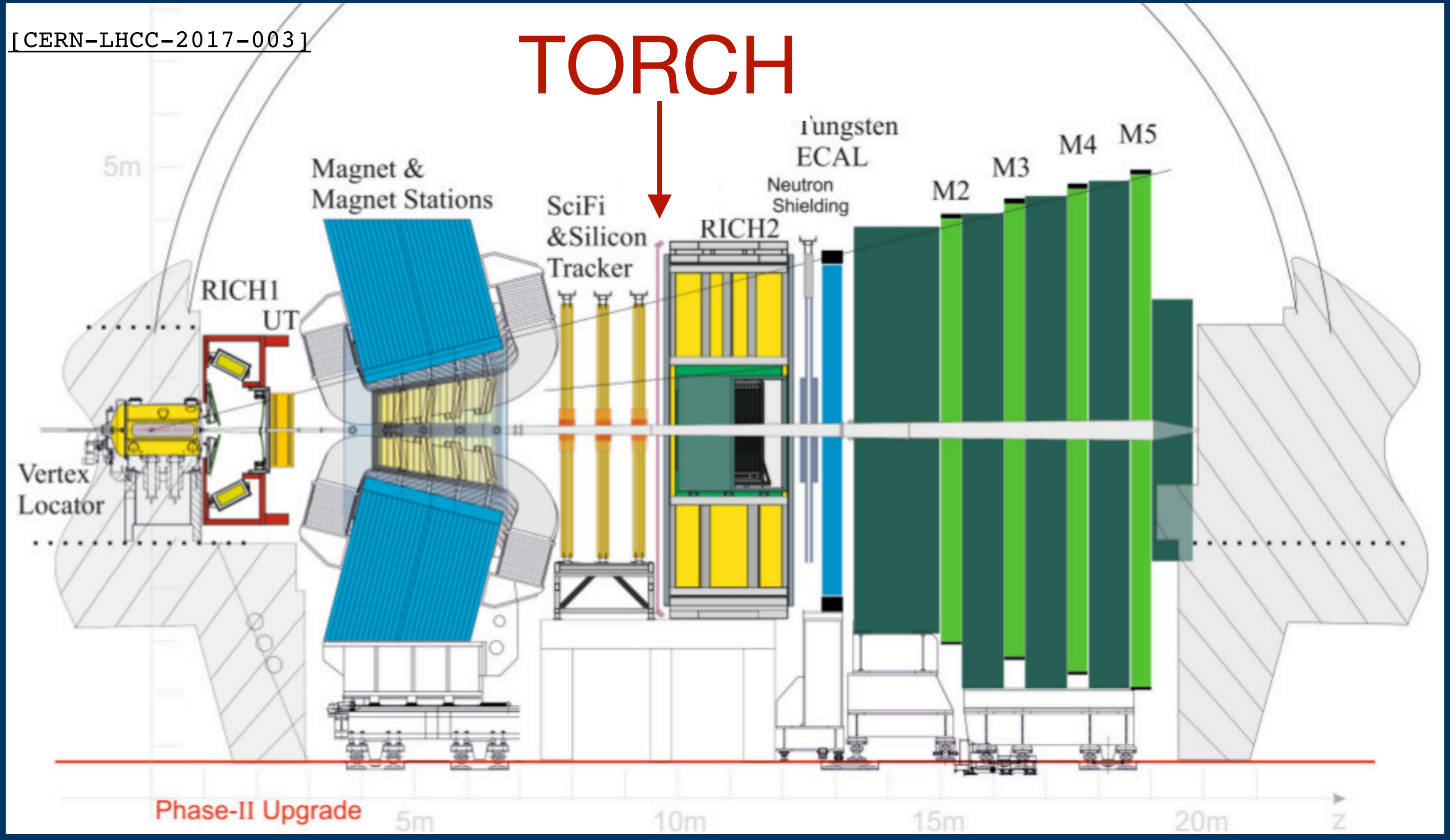
PID @ the LHCb experiment is currently provided by two RICH detectors

For HL LHC Run: Add a complementary large area ToF detector (18 TORCH modules) to probe the low momentum range

EPJC 73 (2013) 2431







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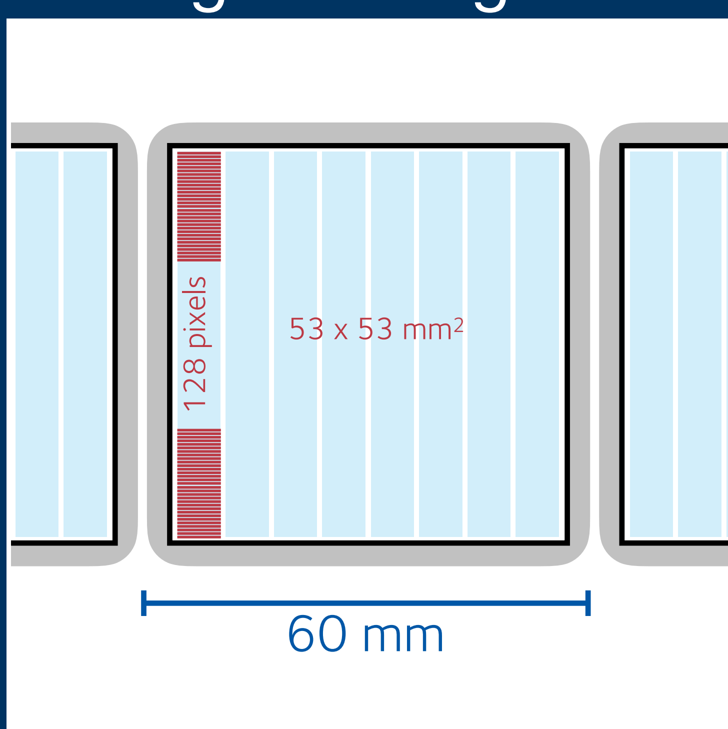
TORCH MCP-PMTs

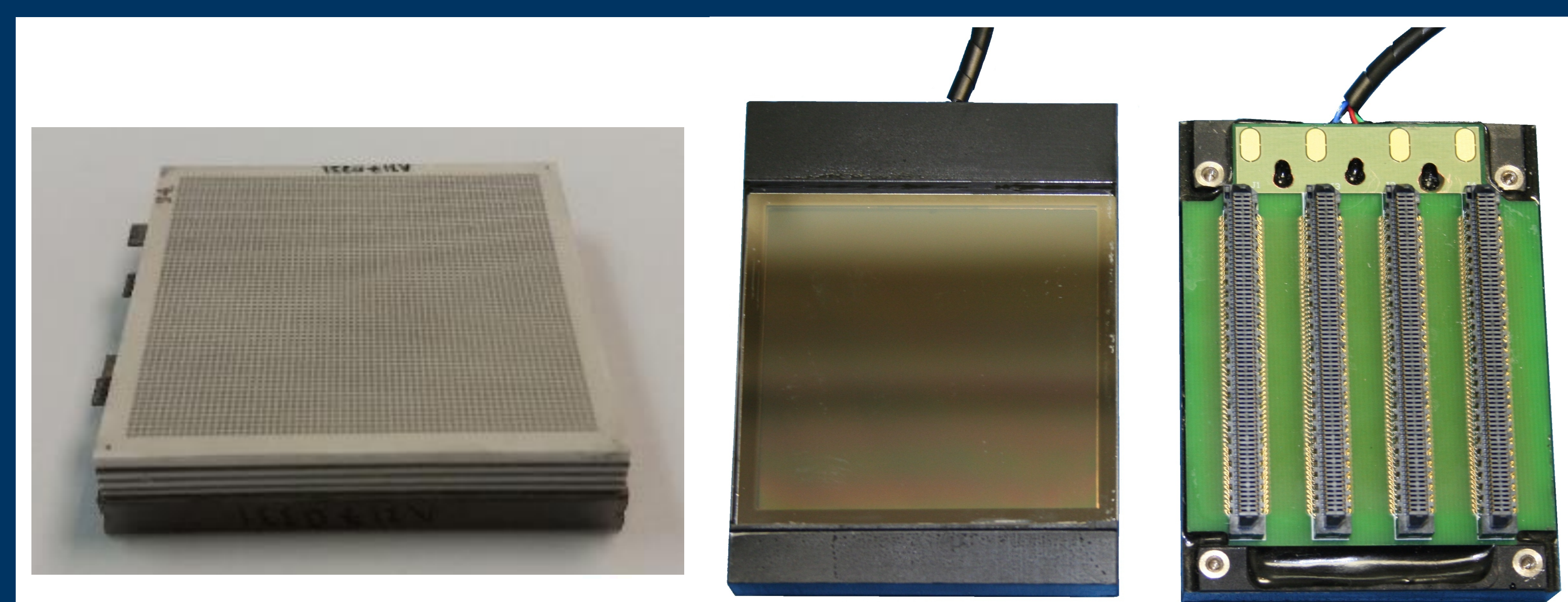
Fast timing of photons is provided by Micro-Channel Plate PMTs (11 MCP-PMT per TORCH module)

R&D program with industrial partner (PHOTEK UK) to develop tubes with extended lifetime (integrated collected charge ≥ 5C/cm^2) and high granularity [T. Conneely et al., JINST 10 (2015), no. 05: C05003]

Each MCP has a granularity of 64×64 pads (ganged into groups of 8 in one direction) over an active area of 53×53 mm^2

Effective granularity is 128×8 pixels (required for 1 mrad precision) via charge sharing





Phase-III prototype

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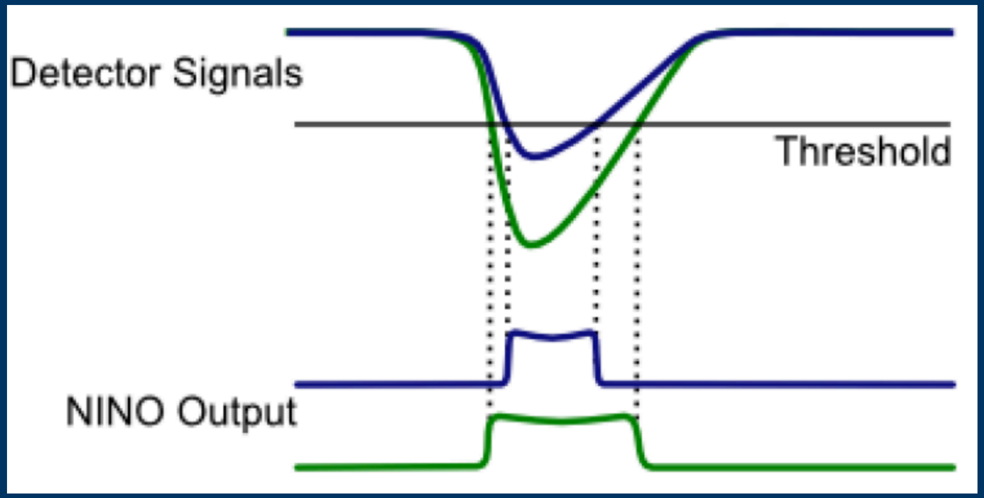
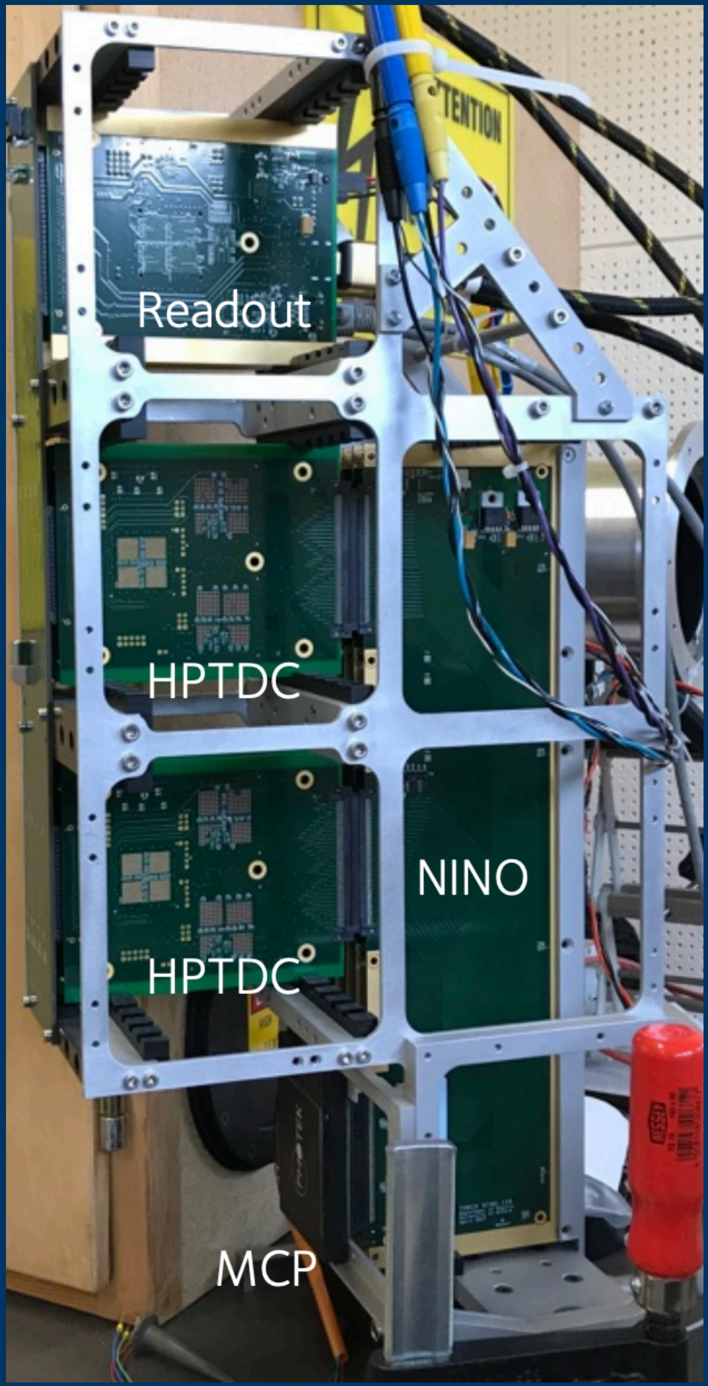
TORCH Electronics

TORCH readout electronics ([JINST 11 (2016) C04012]) consist of NINO and HPTDC chips developed for ToF at the ALICE experiment ([M. Despeisse et al., IEEE 58 (2011) 202])

NINO amplifies and discriminates charge signals that pass its threshold





HPTDC chip can be operated in high (100 ps time-bin) or very high (25 ps time-bin) resolution mode

Variable time width bins of the HPTDC introduce an integrated non-linear (INL) response

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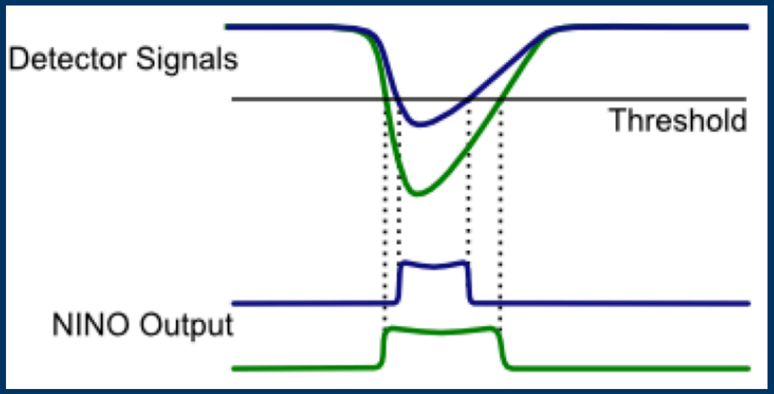
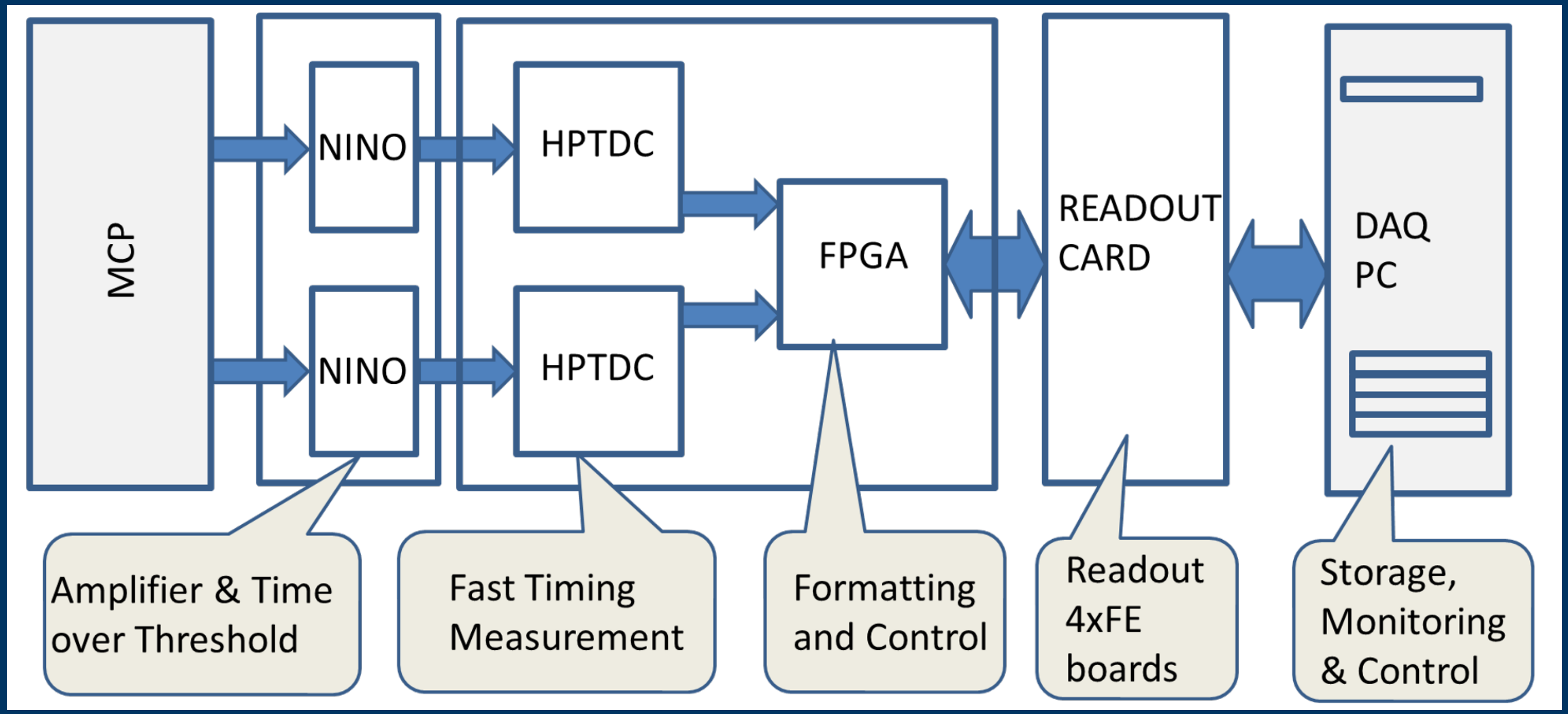
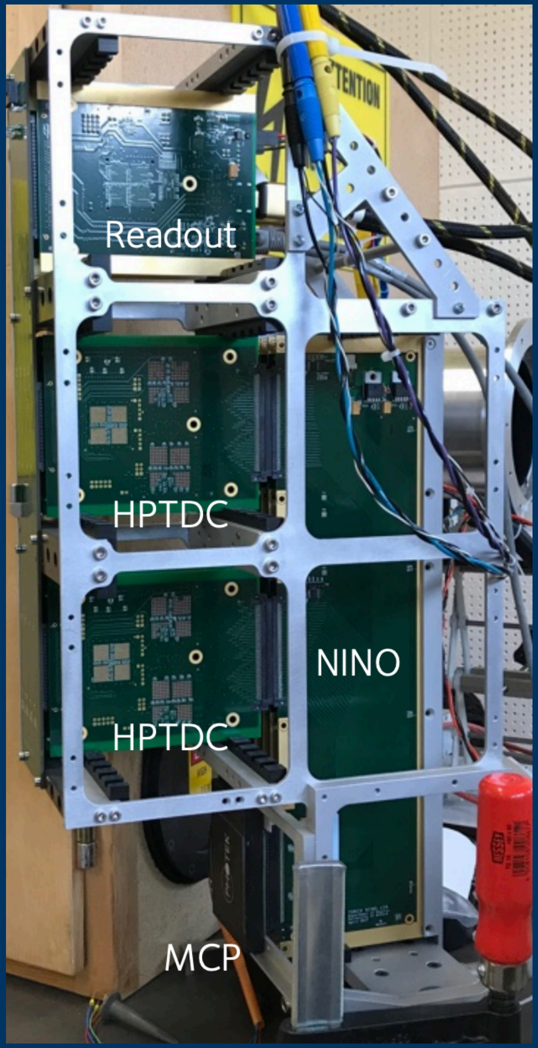
TORCH Electronics

Correct for time-walk effects by measuring the width of the NINO output signals



Performed calibration studies consisting in long diffused light exposure measurements to correct the HPTDC INL feature





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Contributions to TORCH time resolution

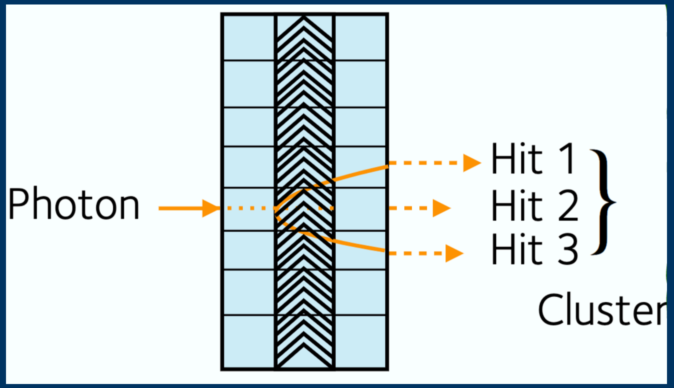
$$\sigma^2_{TORCH} = \sigma^2_{prop}(t_p) + \sigma^2_{MCP} + \sigma^2_{RO}(N_{hits})$$

Propagation time dependent effects

Electronics and readout resolution

[T. Hadavizadeh et al. PoS EPS-HEP2019 (2020) 140]

Charge sharing in the MCP-PMT causes a single photon to trigger multiple pixels, resulting in a cluster



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Contributions to TORCH time resolution

$$\sigma^2_{TORCH} = \underbrace{\sigma^2_{prop}(t_p)}^{\sim (50\mathrm{ps})^2} + \underbrace{\sigma^2_{MCP} + \sigma^2_{RO}(N_{hits})}^{\sim (50\mathrm{ps})^2} \qquad \sim (70\mathrm{ps})^2$$

[T. Hadavizadeh et al. PoS EPS-HEP2019 (2020) 140]

Propagation time dependent effects

Electronics and readout resolution

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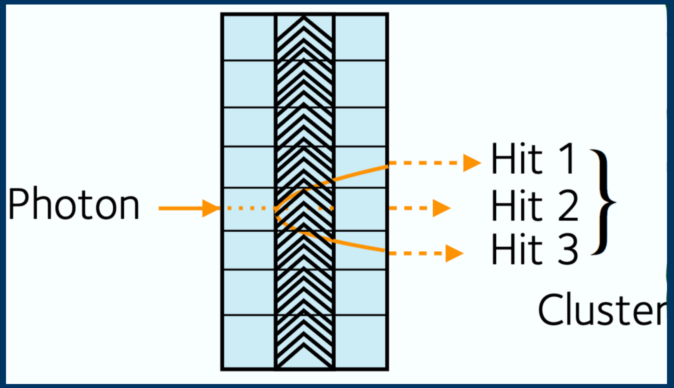
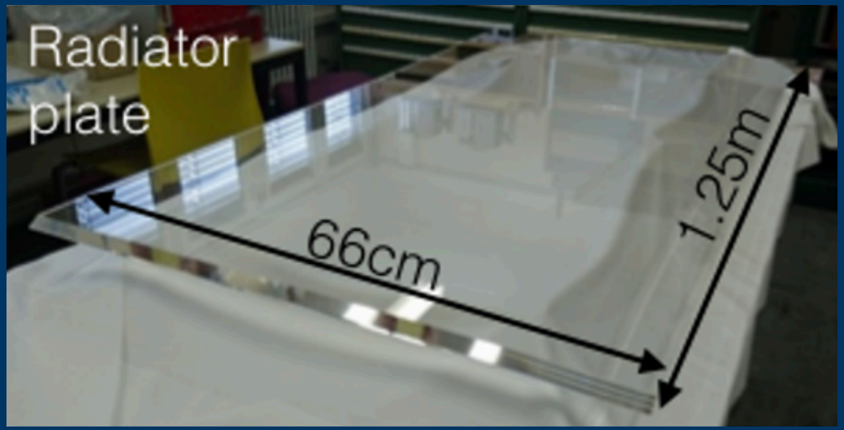


TORCH prototype in Test Beam

Proto-TORCH:

- Half height, full width TORCH module prototype
- $66 \times 125 \times 1\text{cm}^3$
- 2 MCP-PMTs mounted, labelled “A” and “B”
- HPTDC operated in 100 ps time-bin resolution mode
- Threshold Cherenkov counters to identify particle species
- Borosilicate timing fingers used as timing references
- Optical components from Nikon



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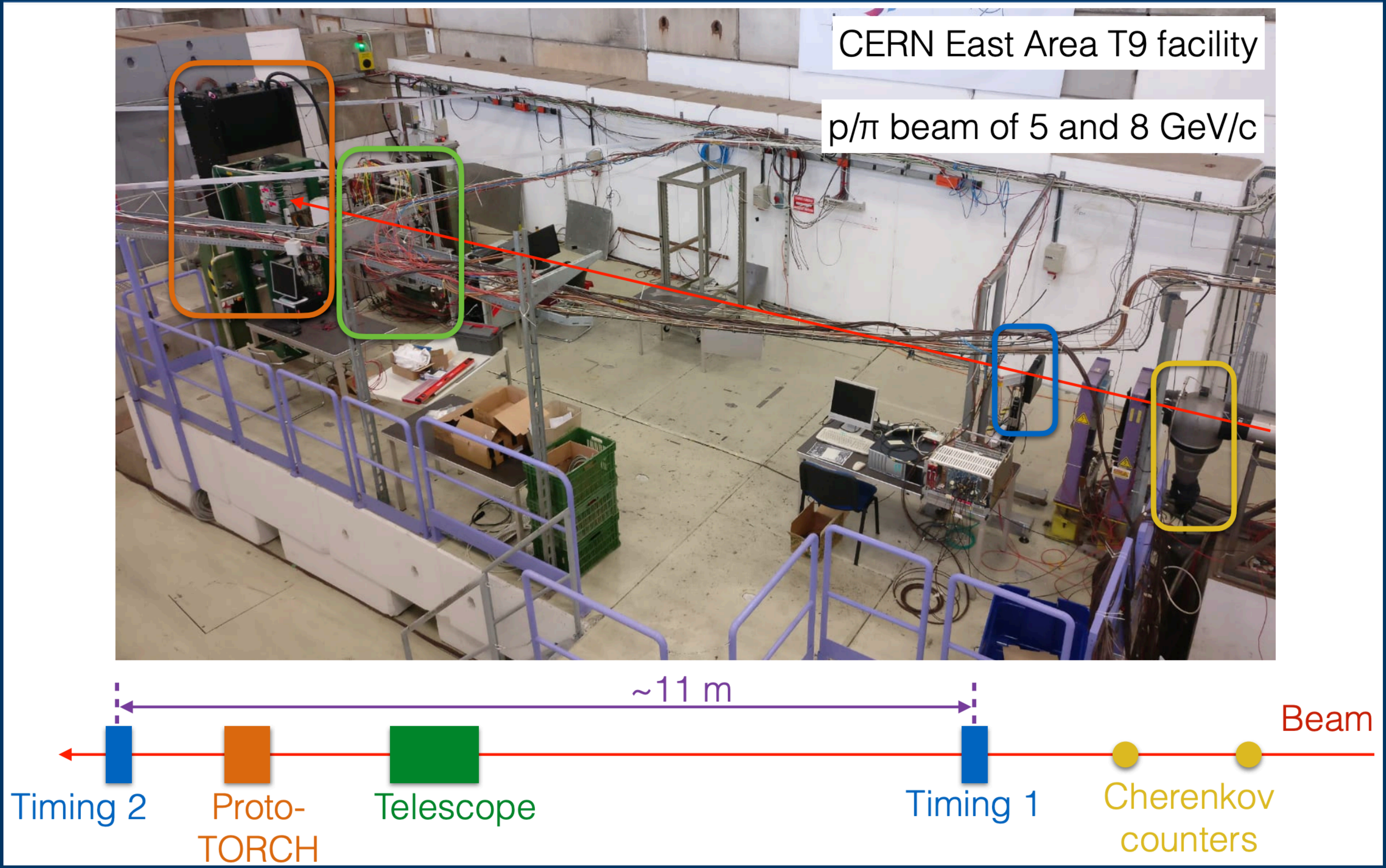
TORCH prototype in Test Beam



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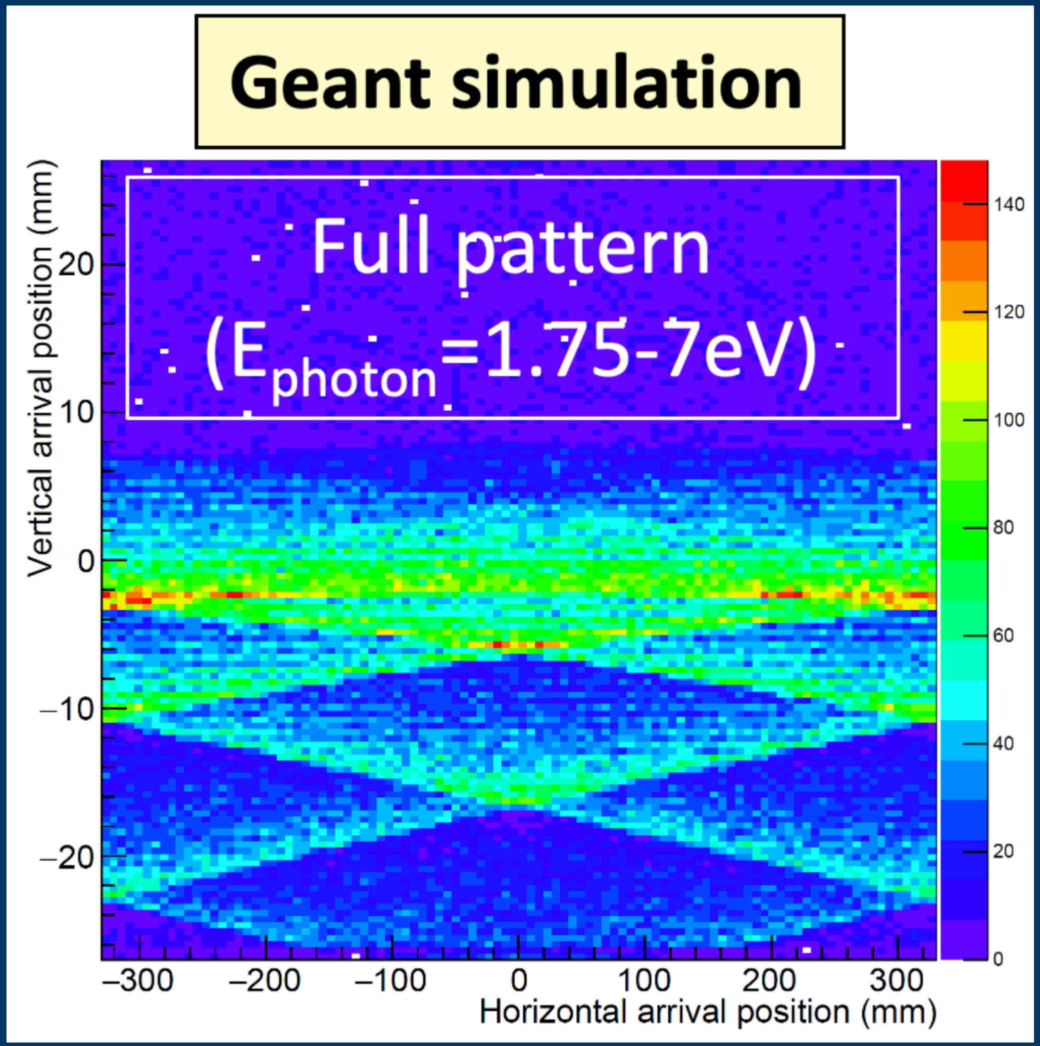
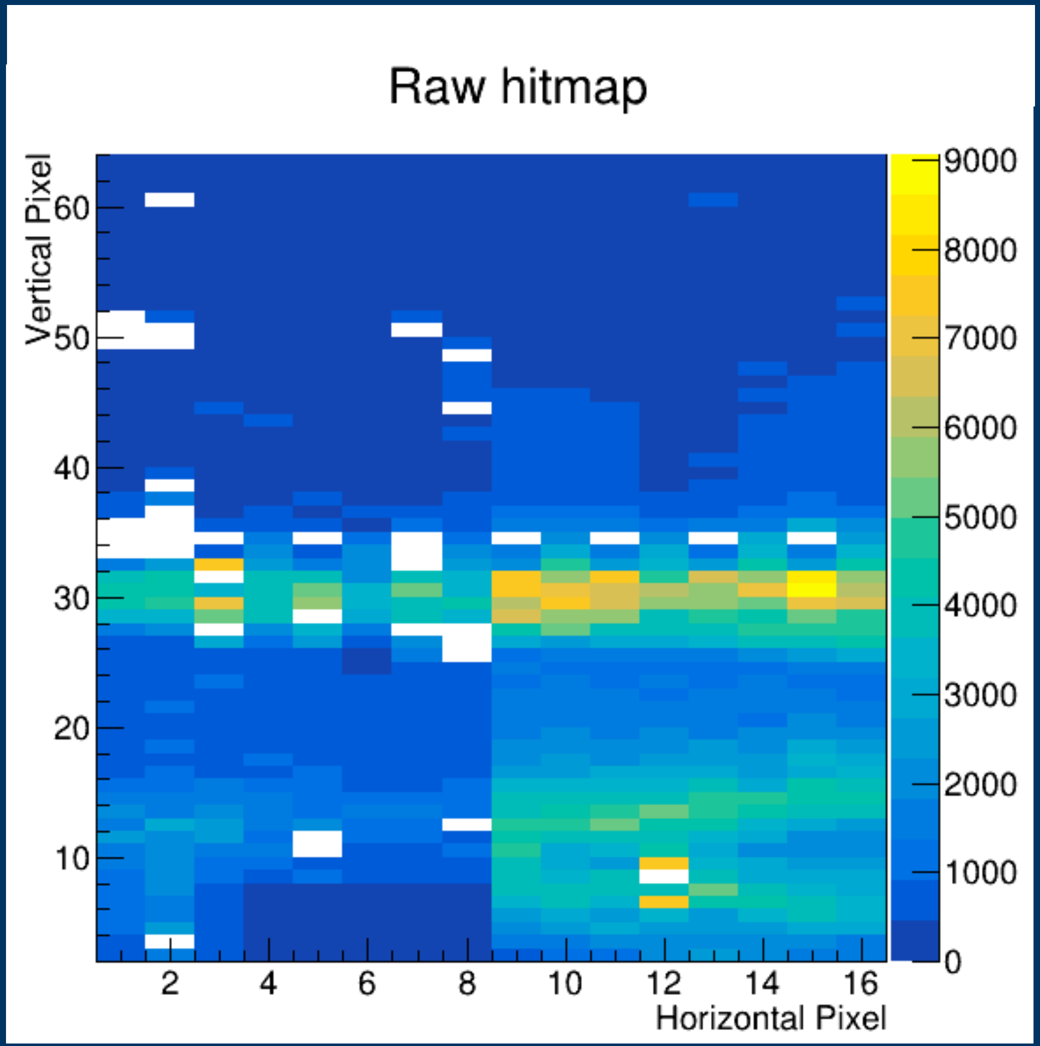
ProtoTORCH data capture

The cone of Cherenkov photons is folded into hyperbola-like patterns as the photons are reflected off the sides of the module and focused on the MCP-PMTs

Chromatic dispersion causes the smearing from a line to a band in Proto-TORCH's hitmap





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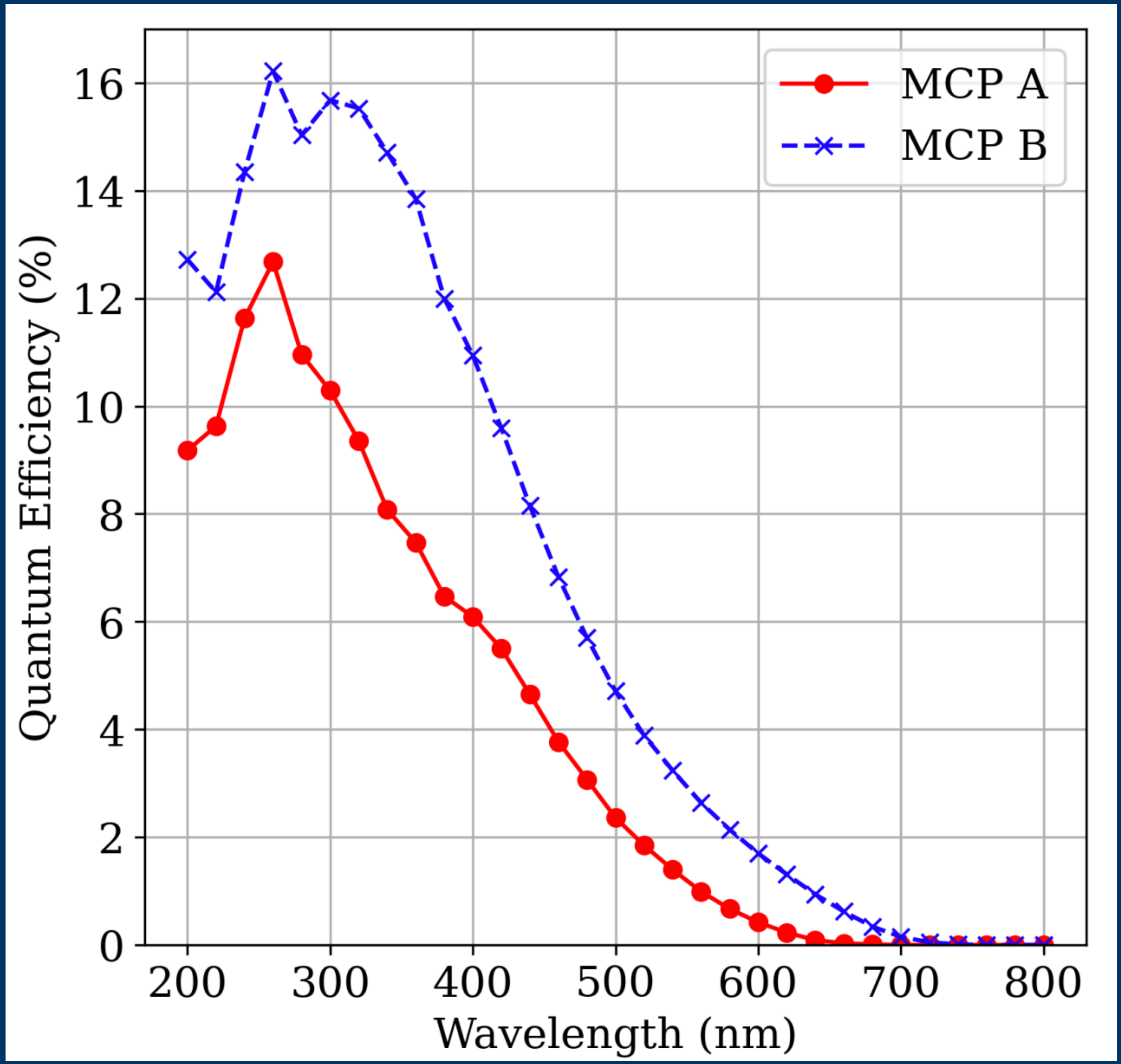
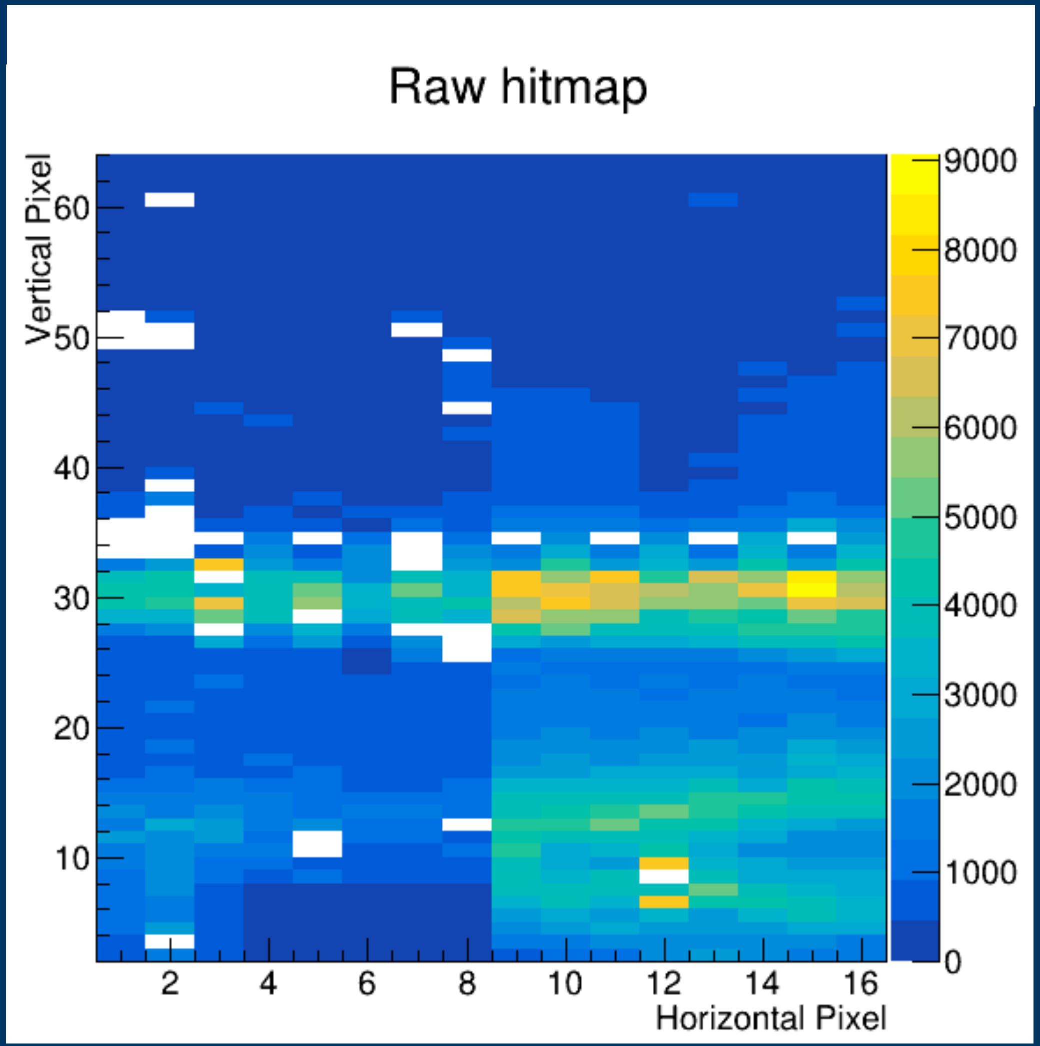
ProtoTORCH data capture

Quantum efficiency difference between MCPs: $\epsilon_Q^A < \epsilon_Q^B$





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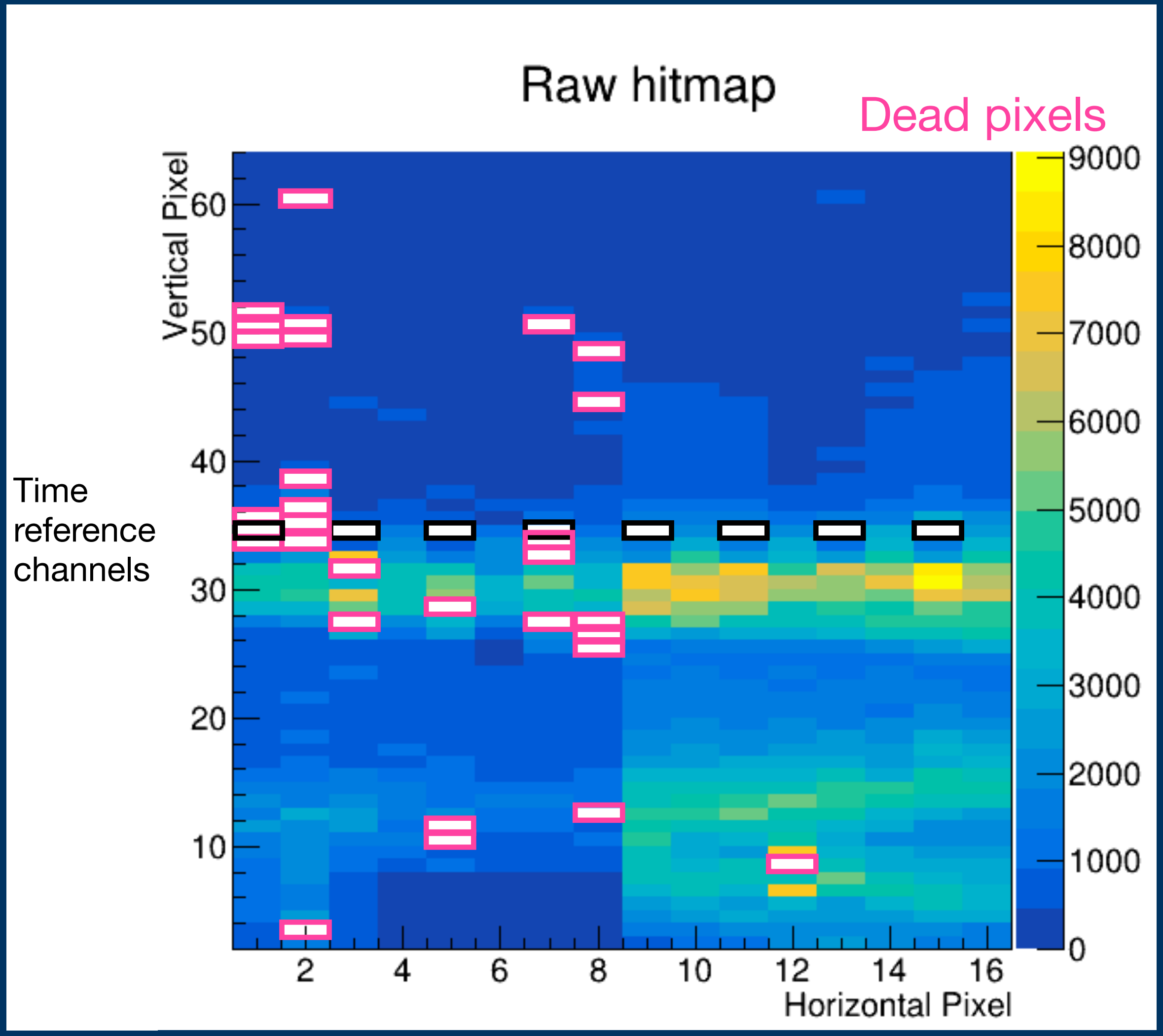

Missing pixels due to problems in wire bonding of the NINO

An improved procedure was introduced for tube B

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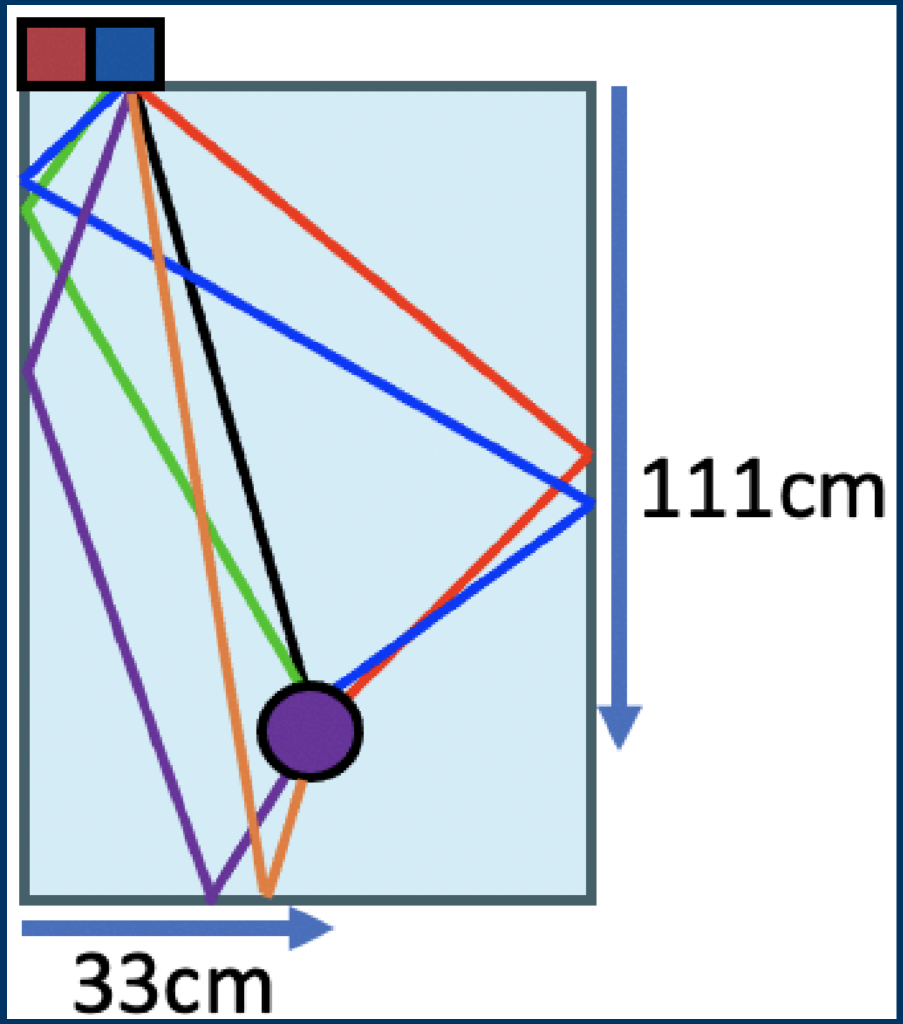
Single photon time resolution from Proto-TORCH

Path of photon path can be direct, or reflect one or more times off the sides of the module



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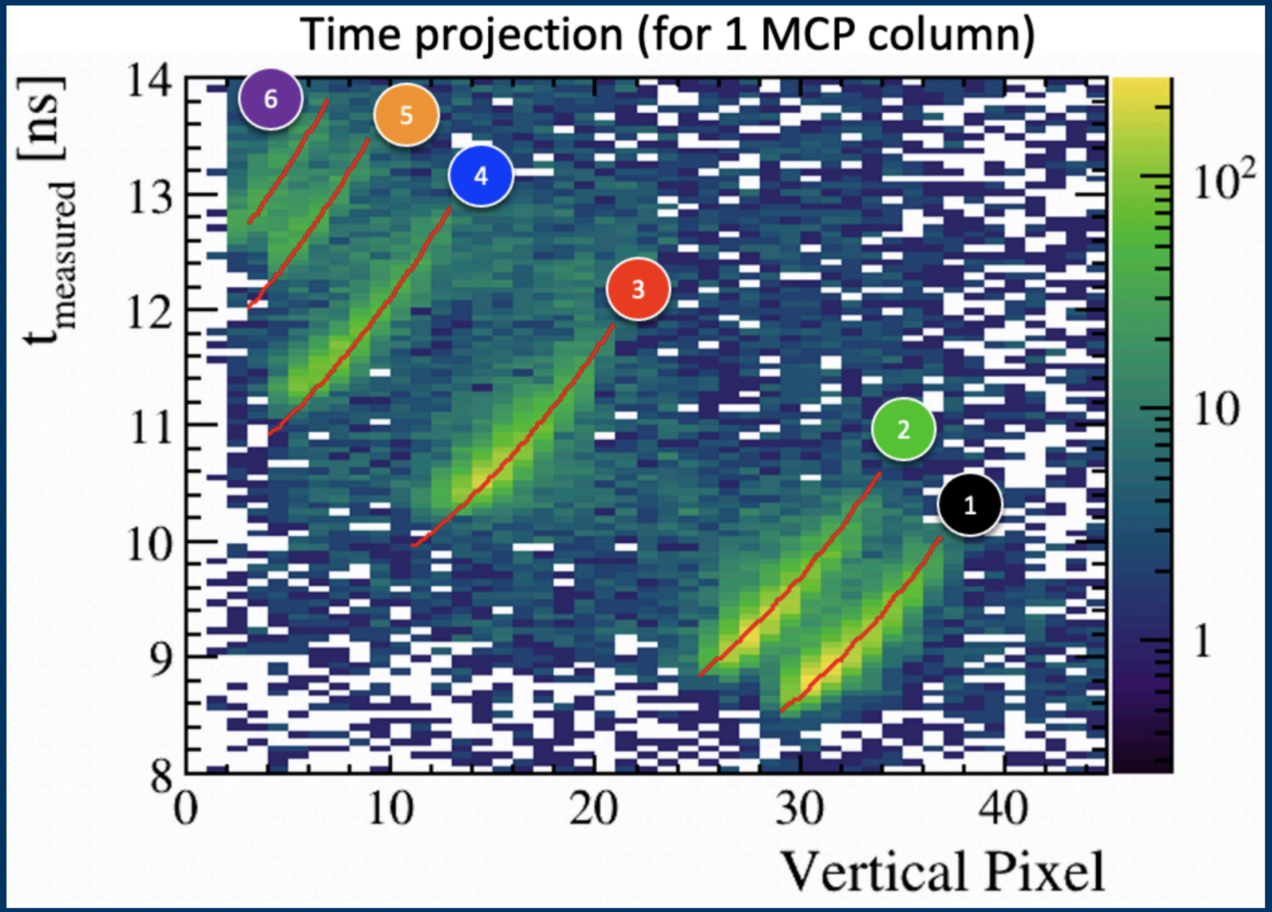
Single photon time resolution from Proto-TORCH

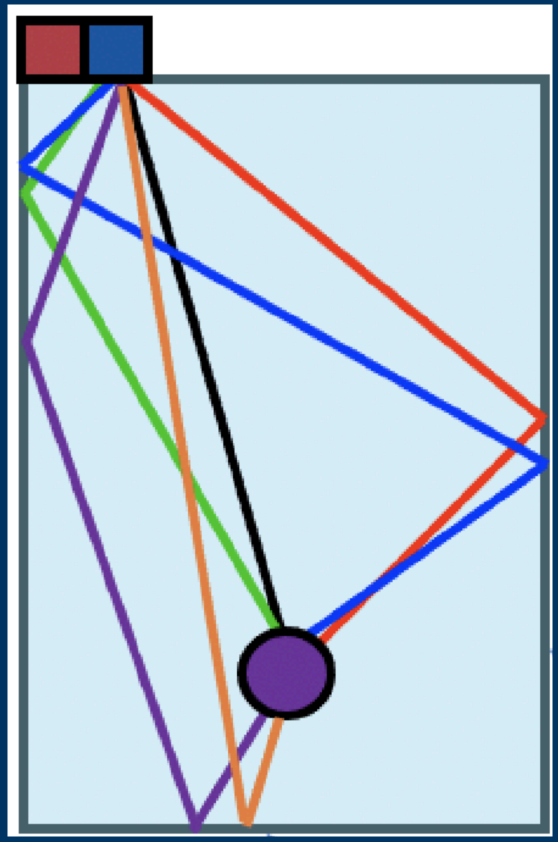
Path of photon path can be direct, or reflect one or more times off the sides of the module

Project the hits on the time-of-arrival axis to separate orders of side reflection

Hitmap of a single pixel column on the MCP overlayed with predictions from simulation

Obtain **single photon time resolution** from the width in time of the bands





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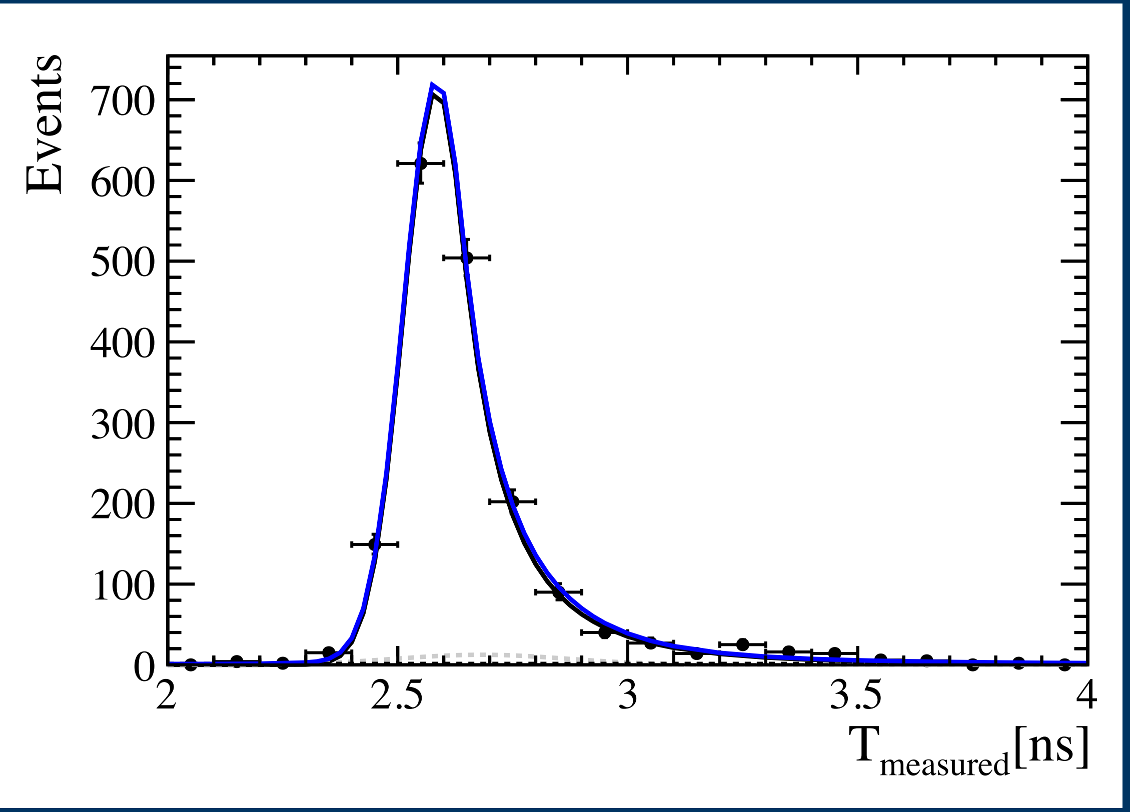
Single photon time resolution from Proto-TORCH

For first order of reflection:

- Simultaneously fit the spread in arrival time across all relevant MCP y pixels in a single MCP column



$$\sigma^2_{proto-TORCH} = \sigma^2_{measured} - \sigma^2_{time\ ref} - \sigma^2_{beam}$$

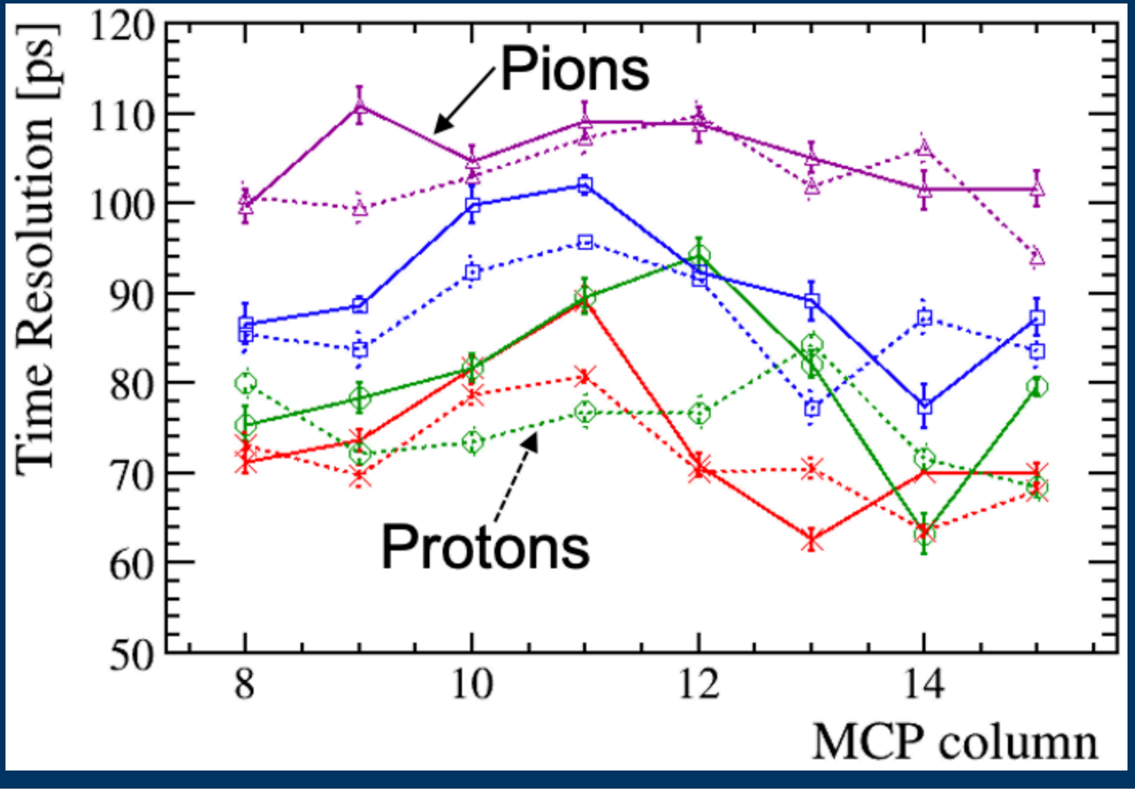
Measurement corrected for time-reference resolution and effect of beam spread

Approaching design resolution

70 ps for positions close to MCP plane

Some degradation for longer photon propagation distances (expected)

- Improvements from better calibrations ongoing



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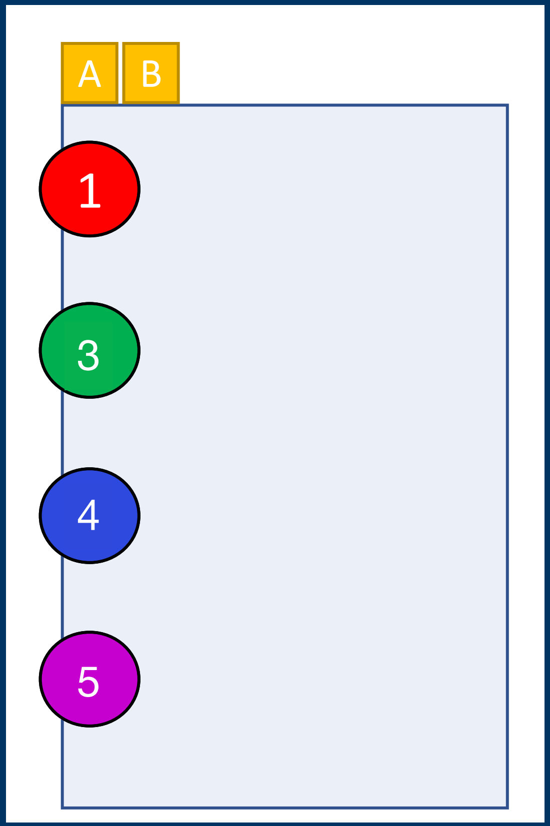
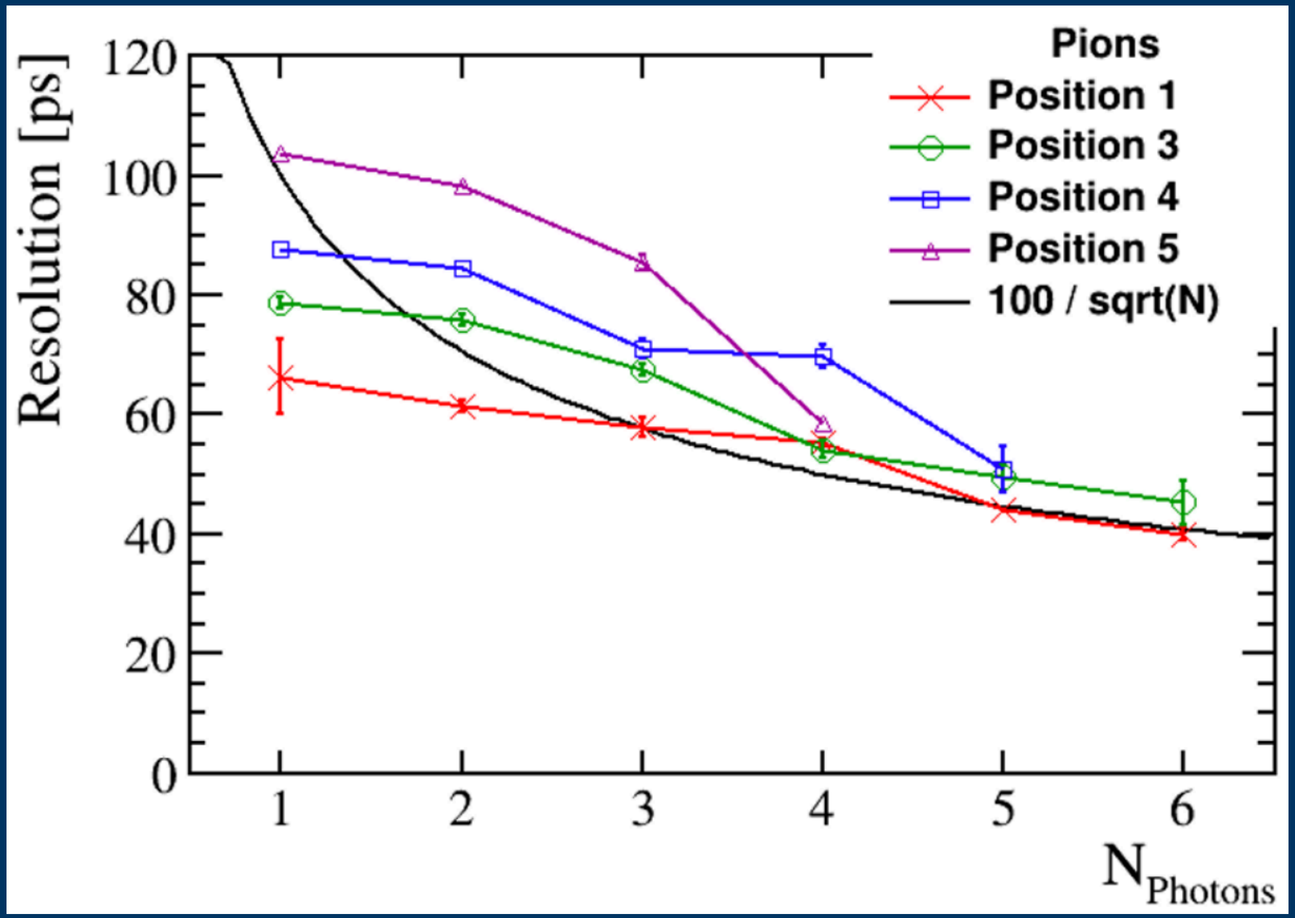
Particle track time resolution with protoTORCH

Time resolution of protoTORCH, as a function of number of detected photons per charged hadron track





Measurement corrected for time-reference resolution and effect of beam spread

Close hits could have correlations

Design goal is $\sim \dfrac{70\text{ps}}{\sqrt{N_{photons}}} \sim 15\text{ps}$ for 30 photons

Expect further improvements with ongoing calibration studies

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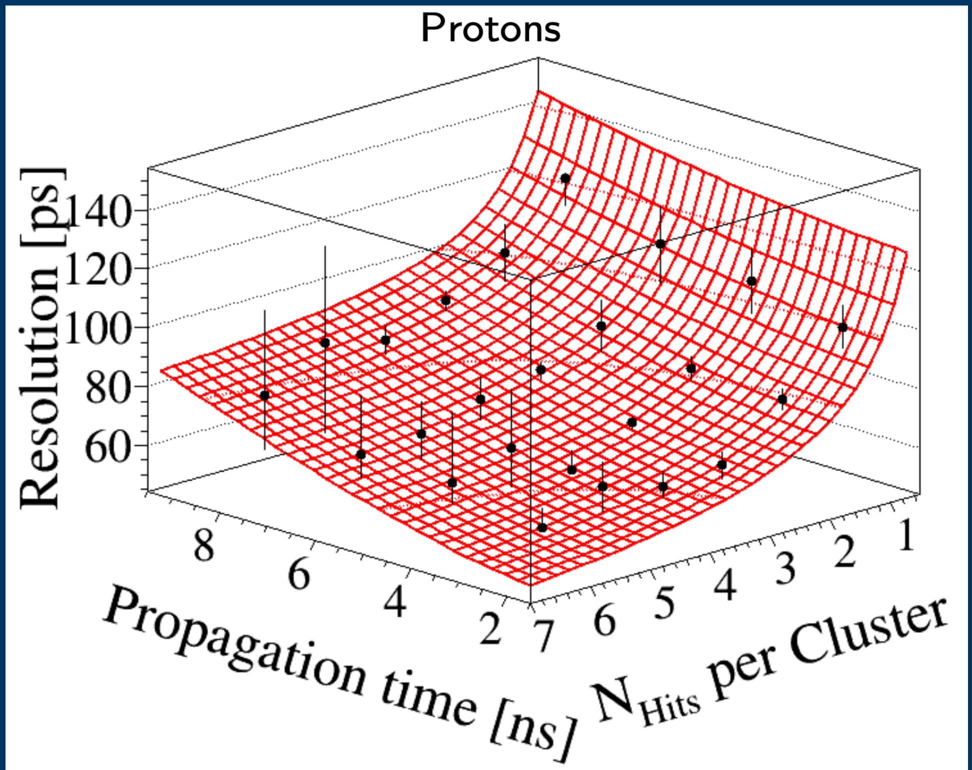
Contributions to TORCH time resolution

$$\sigma^2_{TORCH} = \underbrace{\sigma^2_{prop}(t_p)}_{\sim (50\text{ps})^2} + \underbrace{\sigma^2_{MCP} + \sigma^2_{RO}(N_{hits})}_{\sim (50\text{ps})^2}$$

Propagation time dependant effects

Electronics and readout resolution

[T. Hadavizadeh et al. PoS EPS-HEP2019 (2020) 140]



Contribution	Measured values from data (ps)	Target values from simulation (ps)
σ_{MCP}	31.0 ± 7.6	~ 33
$\sigma_{prop}(t_p)$	$(7.6 \pm 0.5) \times t_p$	$\sim (3.75 \pm 0.8) \times t_p$
$\sigma_{RO}(N_{hits})$	$\frac{95.0 \pm 6.0}{\sqrt{N_{Hits}}}$	$\sim \frac{60}{\sqrt{N_{Hits}}}$

Resolution is expected to improve with better charge to width calibration of the electronics

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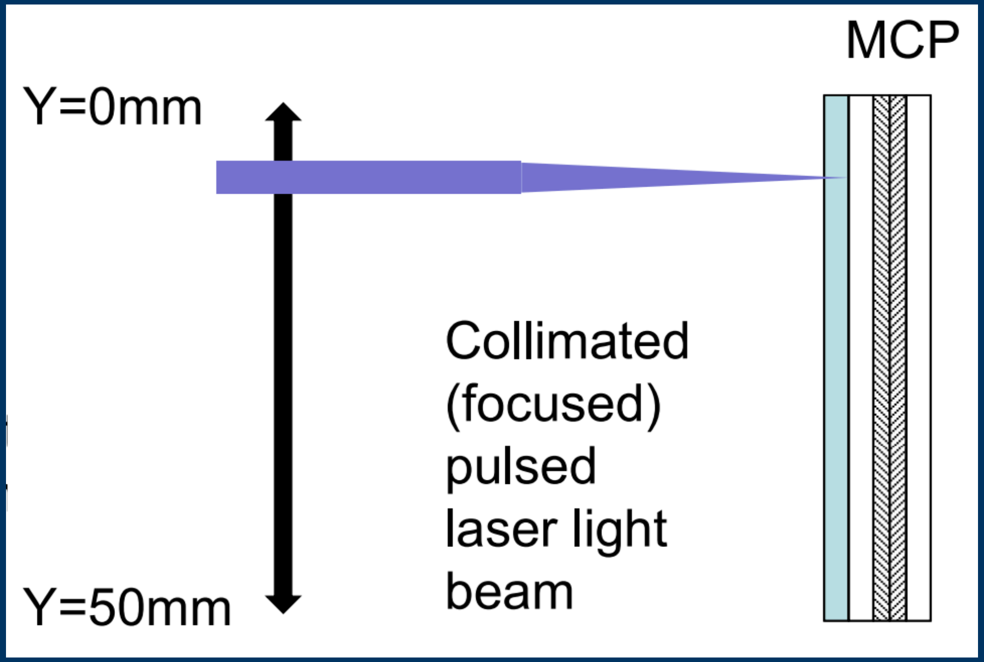
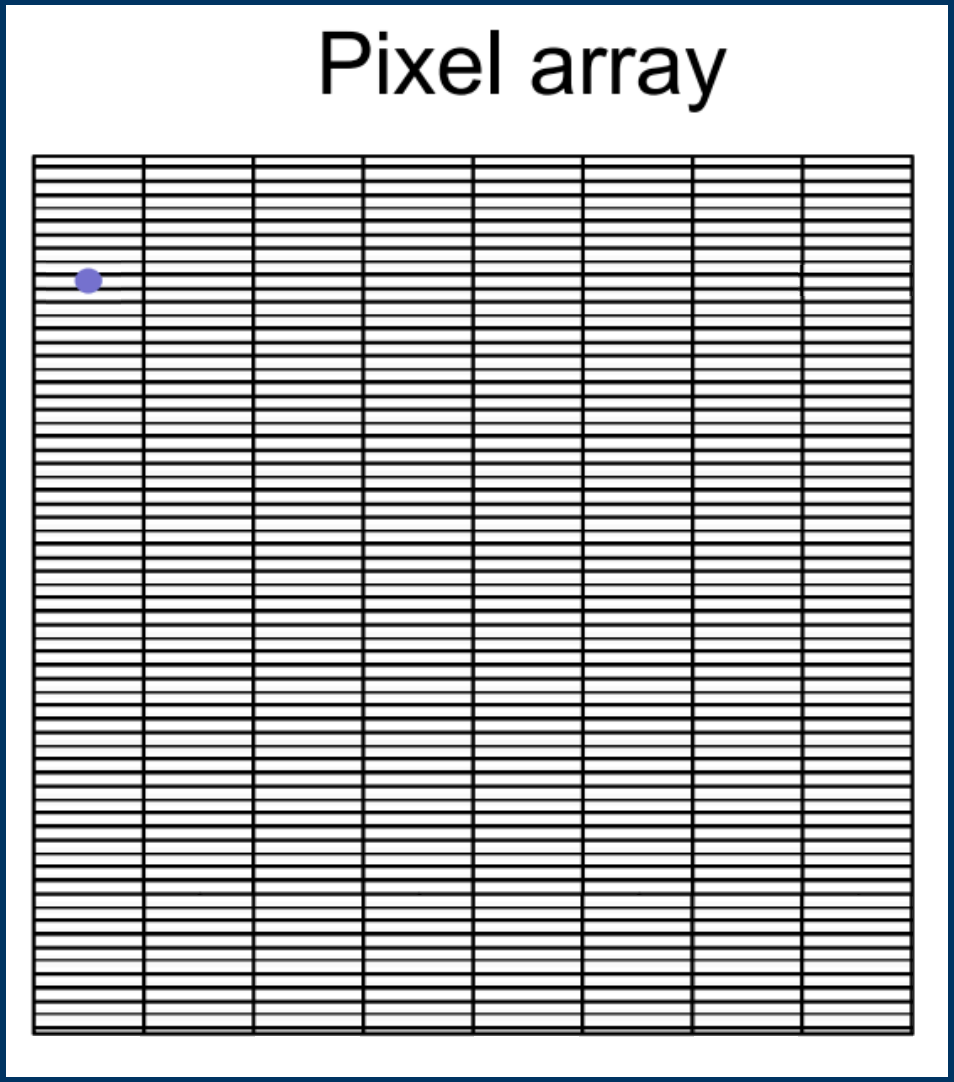
Lab based testing

Aim: measure the TORCH time resolution component attributed to one MCP-PMT combined with its readout electronics





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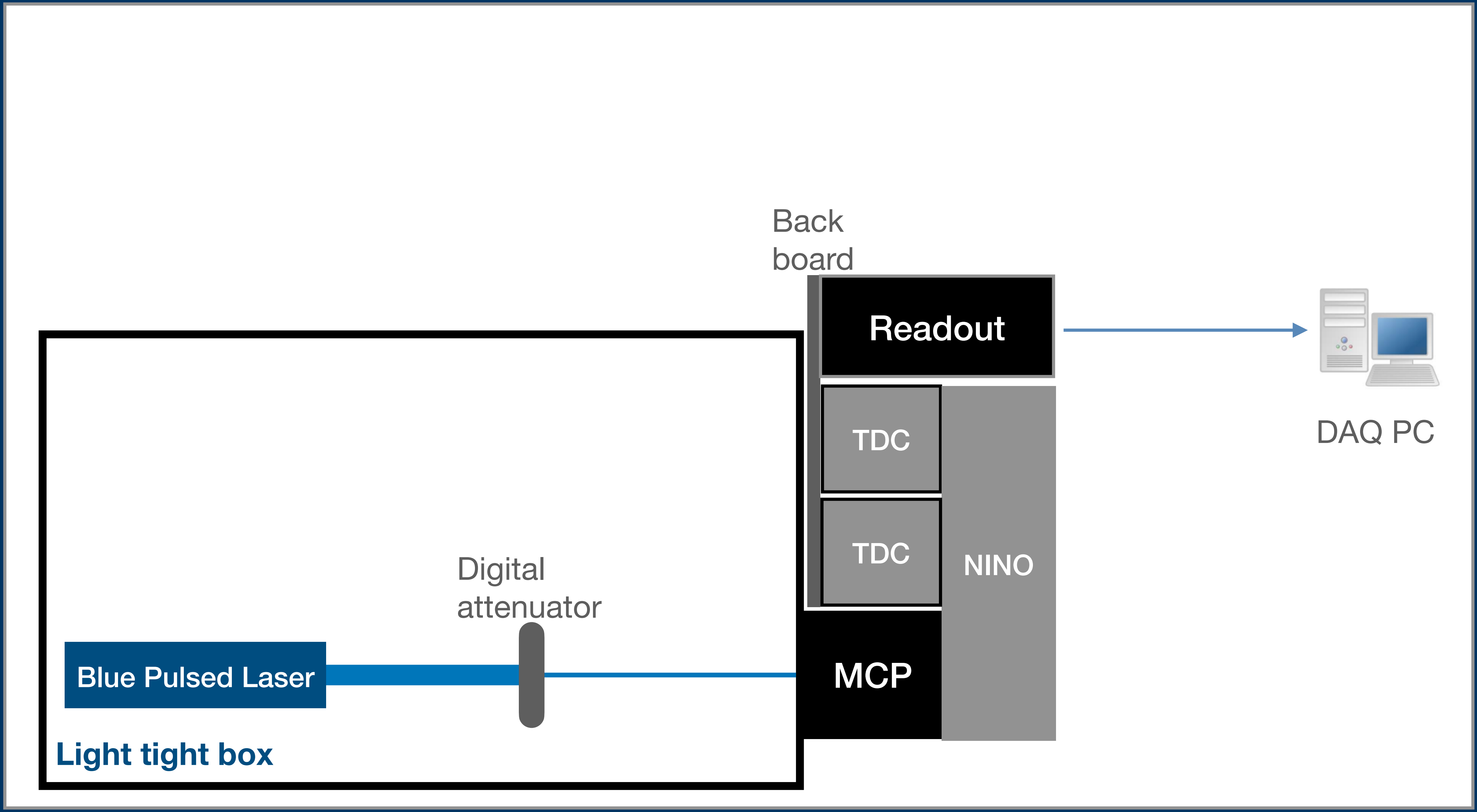

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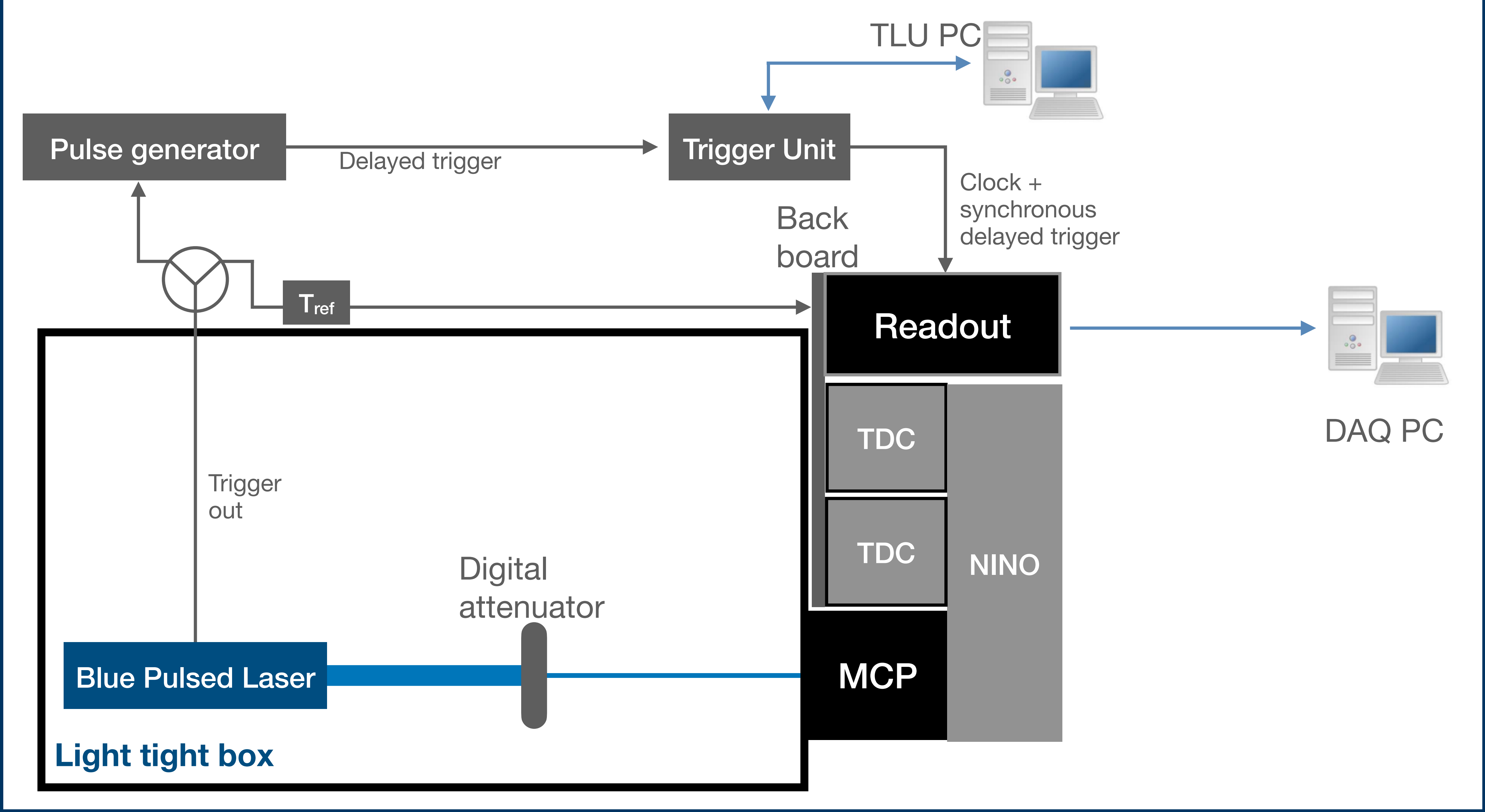

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Time resolution of MCP-PMT + electronics

Aim: measure the time resolution of one MCP-PMT combined with its readout electronics

Operate the HPTDC chip in the 25 ps time-bin resolution mode

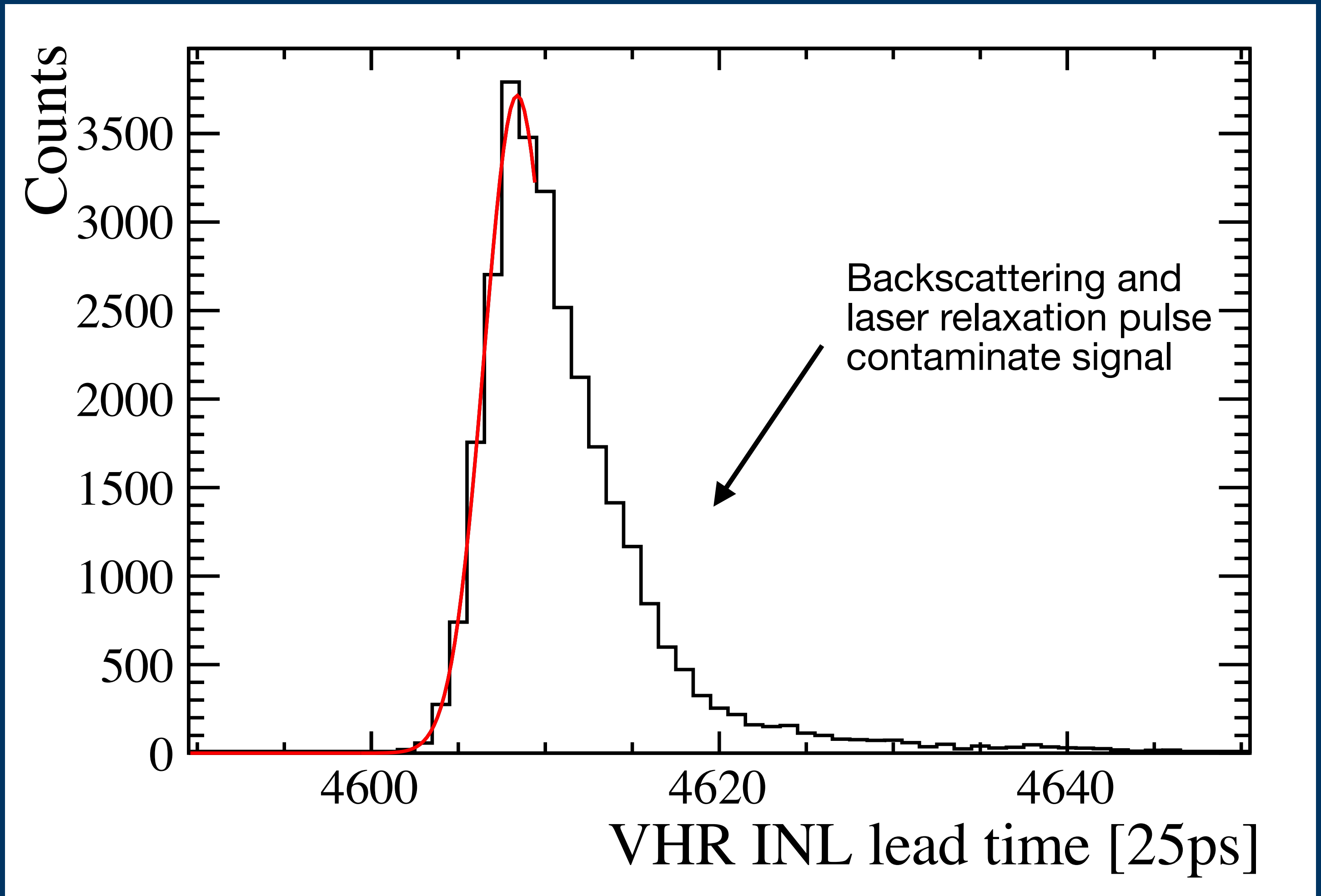
Collect 10M events at a gain of order 1Me$^-$

Select signals with constant amplitude signals to exclude time-walk effects to probe best case scenario

Measured intrinsic MCP and readout electronics resolution:

(47.5 ± 0.7) ps

Goal for MCP-PMT + readout electronics resolution: 50 ps



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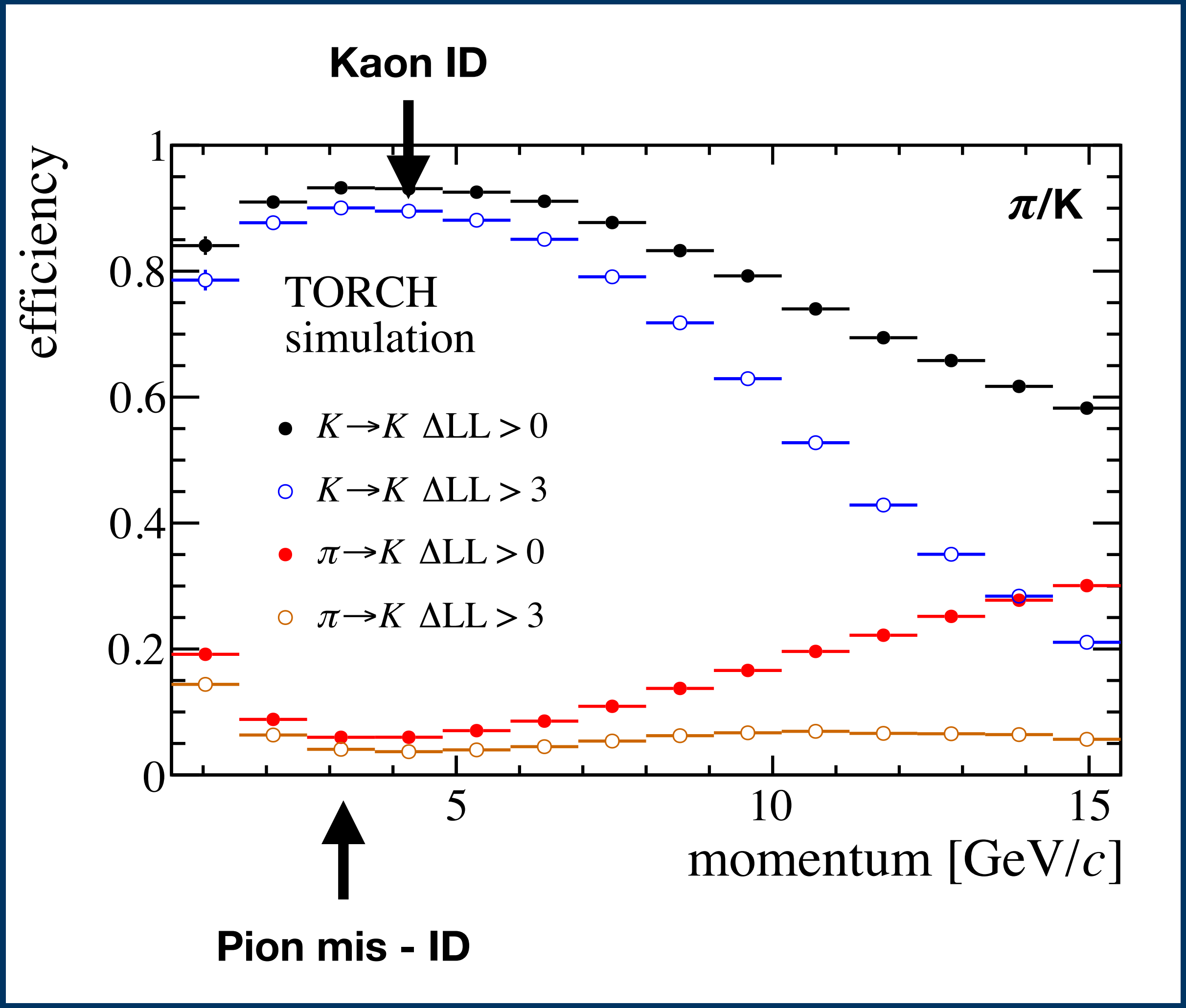
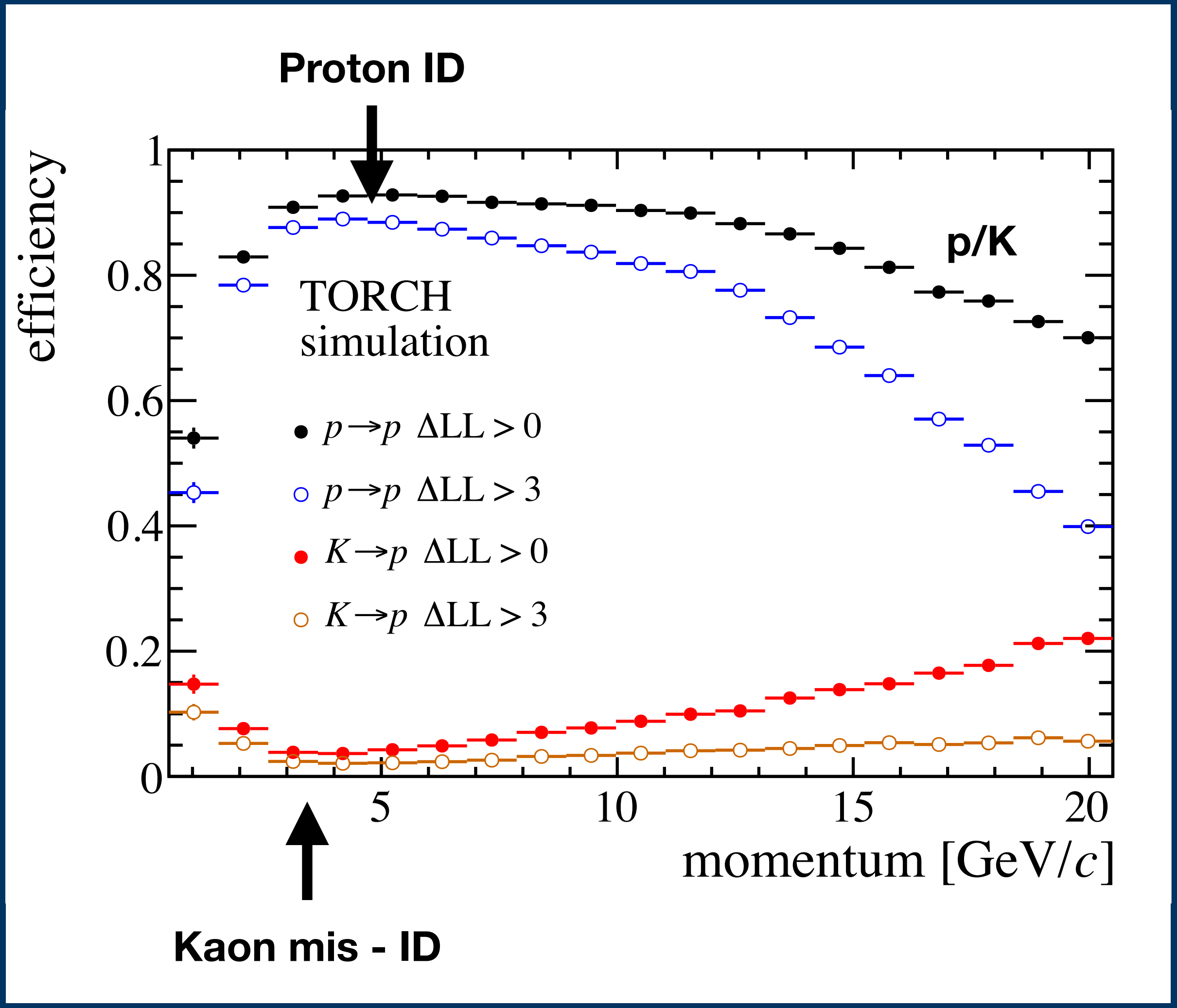
Simulation of PID Performance of TORCH in LHCb

- TORCH is simulated in Upgraded LHCb detector using GEANT4
- PID performance for LHCb Future Upgrade for HL LHC data taking conditions

$$\mathscr{L} = 1.5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$$

- Good separation expected in the $[2 - 10]$GeV/c range and beyond





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Summary and Outlook

- TORCH is a large scale time-of-flight detector aiming to provide PID at low momentum
- Successful test beam in 2018 with half-size module prototype instrumented with 2 out of 11 MCP-PMTs
- Performance is approaching the required 70ps single photon resolution for LHCb experiment
- Lab studies and controlled conditions (known signals) support test beam results and that time resolution design goals are achievable
- Simulation studies show that TORCH can significantly add to the LHCb physics program
- Plan for a new test beam campaign in 2022 with fully instrumented module

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Thank you for your attention

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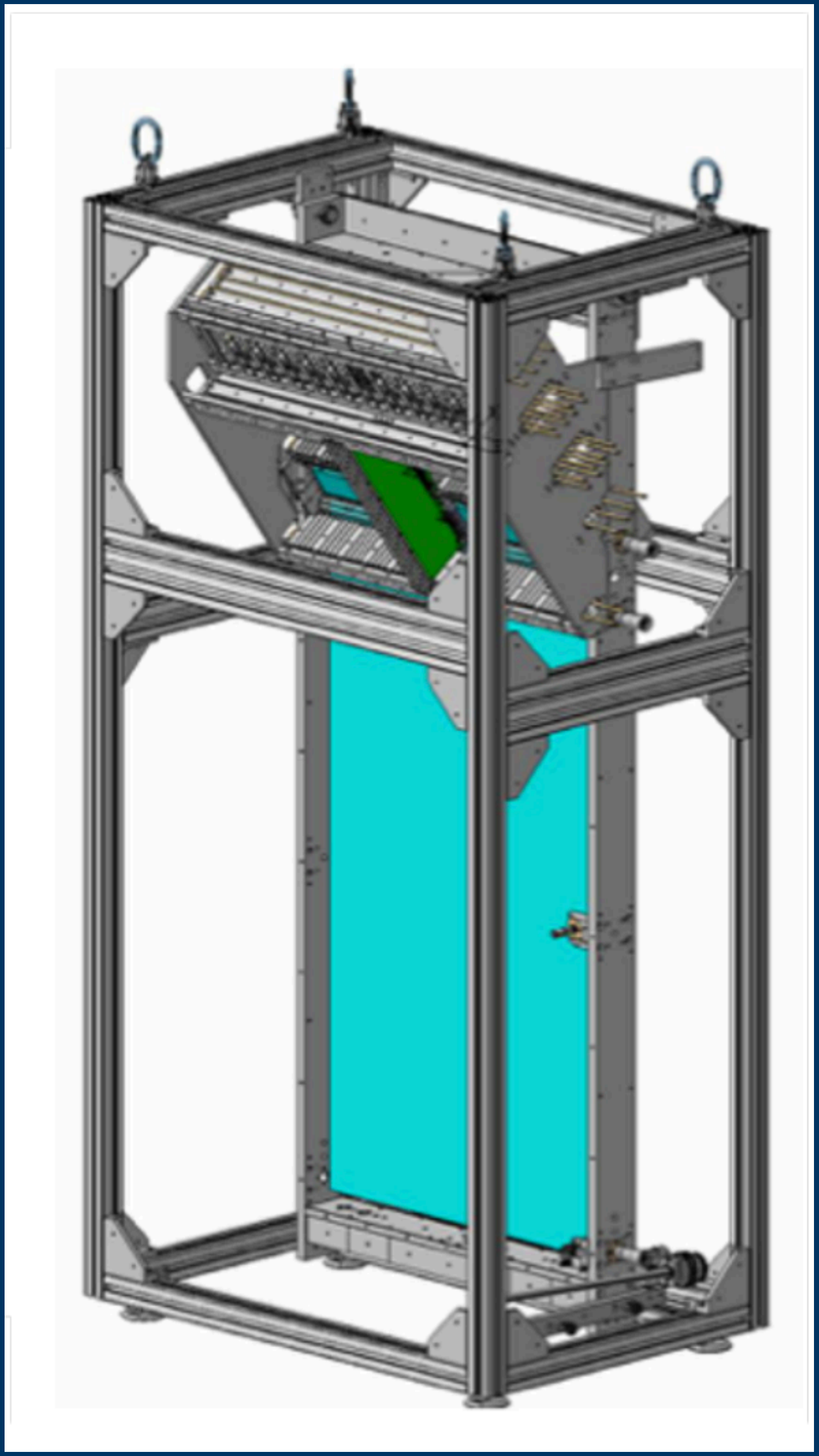
Proto-TORCH



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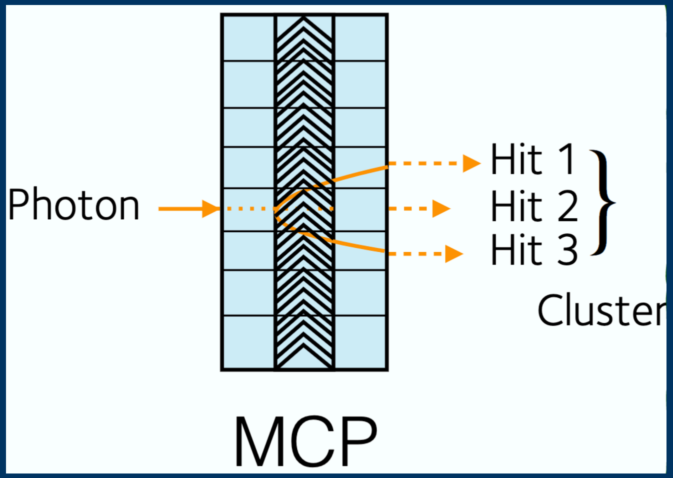
Validating photon counting with proto-TORCH

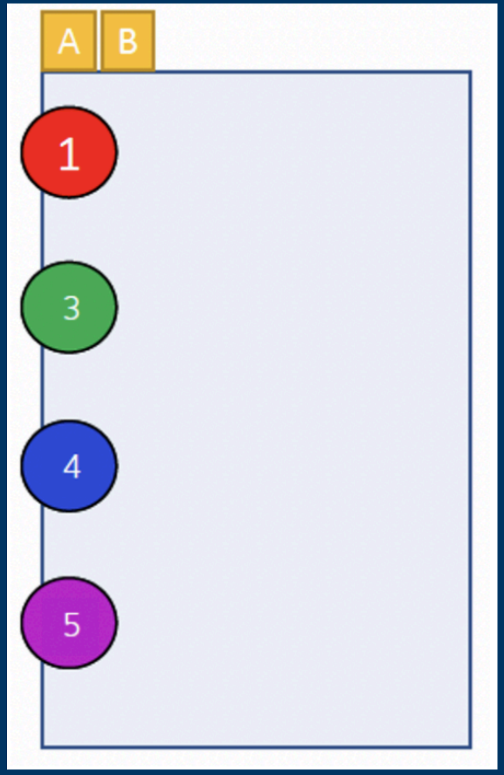
Charge sharing in the MCP-PMT causes a single photon to trigger multiple pixels, resulting in a cluster

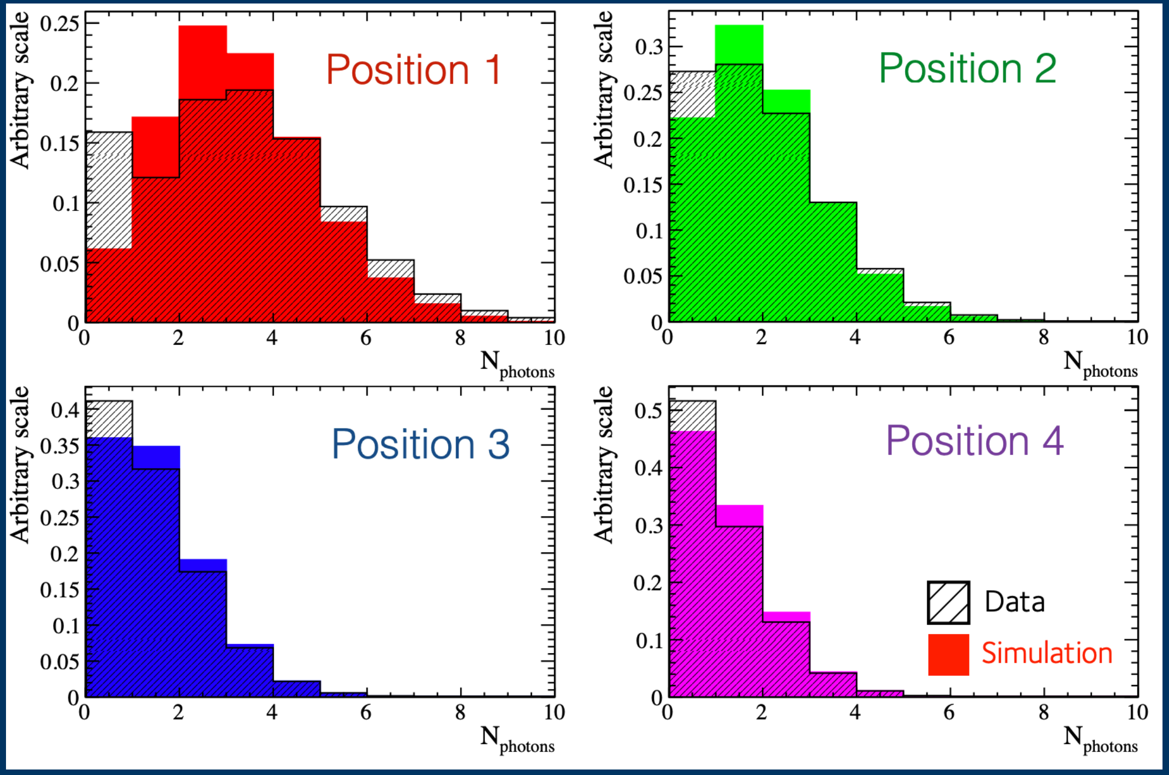


Compare clusters in data and simulation for different beam positions in a proto-TORCH module

Direct path or 1 reflection

Simulation matches the data





Mean number of photons

	Data	Sim	Ratio
Position 1	2.77	2.75	0.99
Position 2	1.53	1.54	1.01
Position 3	1.00	1.07	1.07
Position 4	0.74	0.81	1.09

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Time resolution of MCP-PMT + electronics

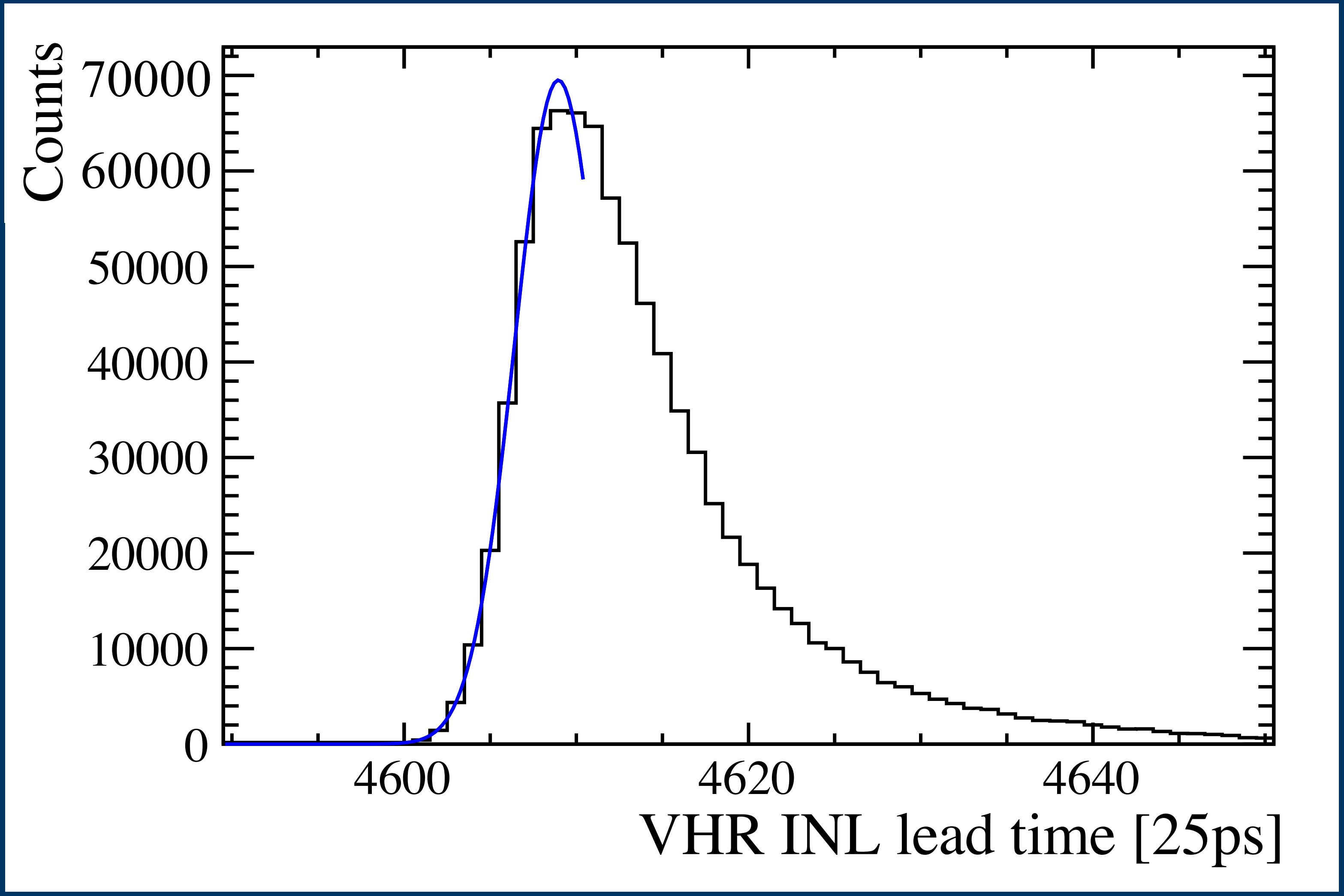
Aim: measure the time resolution of one MCP-PMT combined with its readout electronics

Operate the HPTDC chip in the 25 ps time-bin resolution mode

Collect 10M events at a gain of order 1Me$^-$

Measured resolution:

(63.23 ± 0.16) ps



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Time resolution of MCP-PMT + electronics

Aim: Measure intrinsic MCP time resolution to identify lower limit of one MCP-PMT combined with its readout electronics

Remove TORCH readout electronics

Use an analogue breakout board + constant fraction discriminator + time to amplitude converter

Collect 10M events at a gain of order 1Me$^-$

Measured resolution:

(34.2 ± 0.3) ps

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