The TORCH time-of-flight detector

Detector R&D and simulation performance

4th workshop on LHCb Upgrade II,
8th — 10th April 2019

T. Blake for the TORCH collaboration

WARWICK
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Outline

- Introduction to the TORCH concept.
- R&D towards a prototype detector.
- TORCH simulation within the LHCb software framework.
- TORCH PID performance

[LHCb-INT-2019-006]

TORCH physics performance: improving low-momentum PID performance during Upgrade IB and beyond

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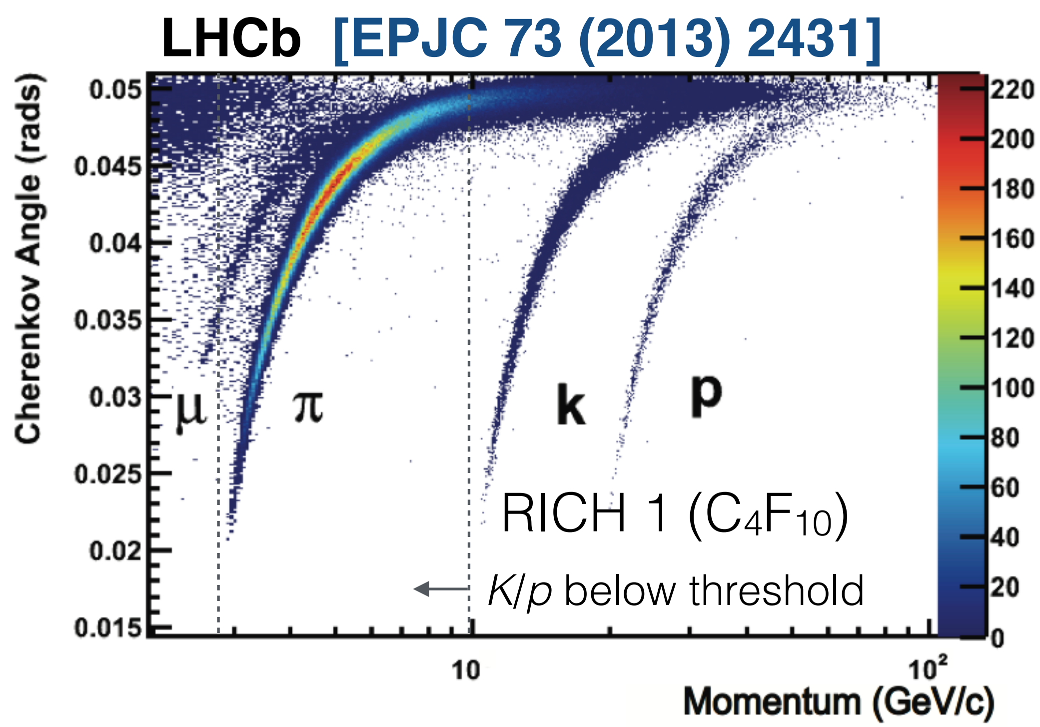
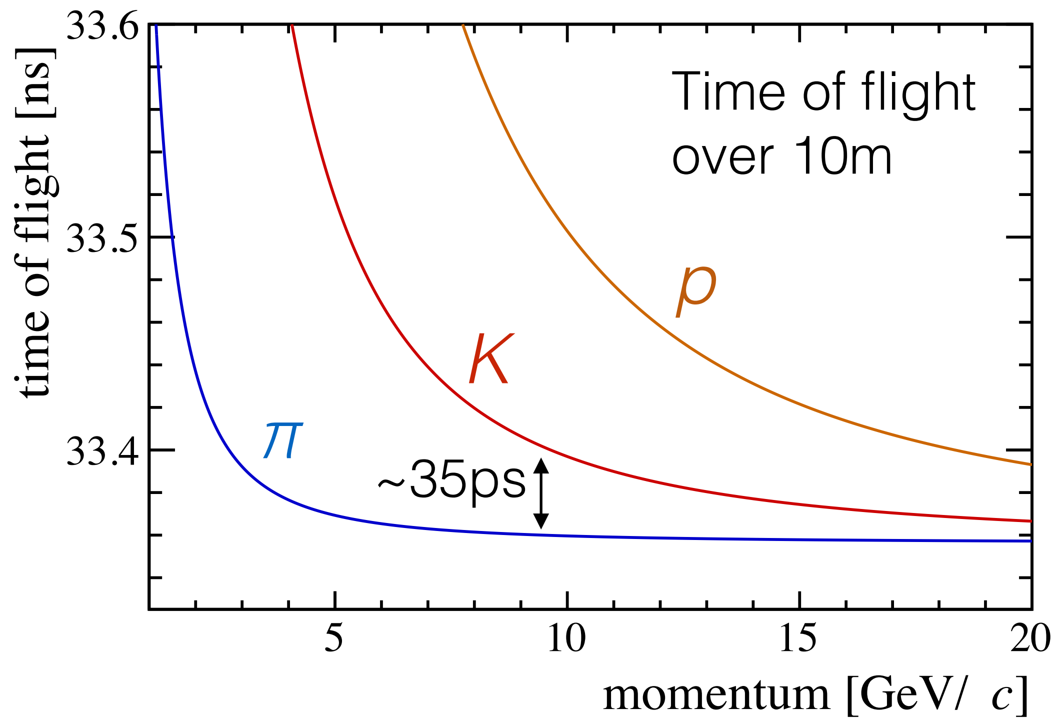
The TORCH concept

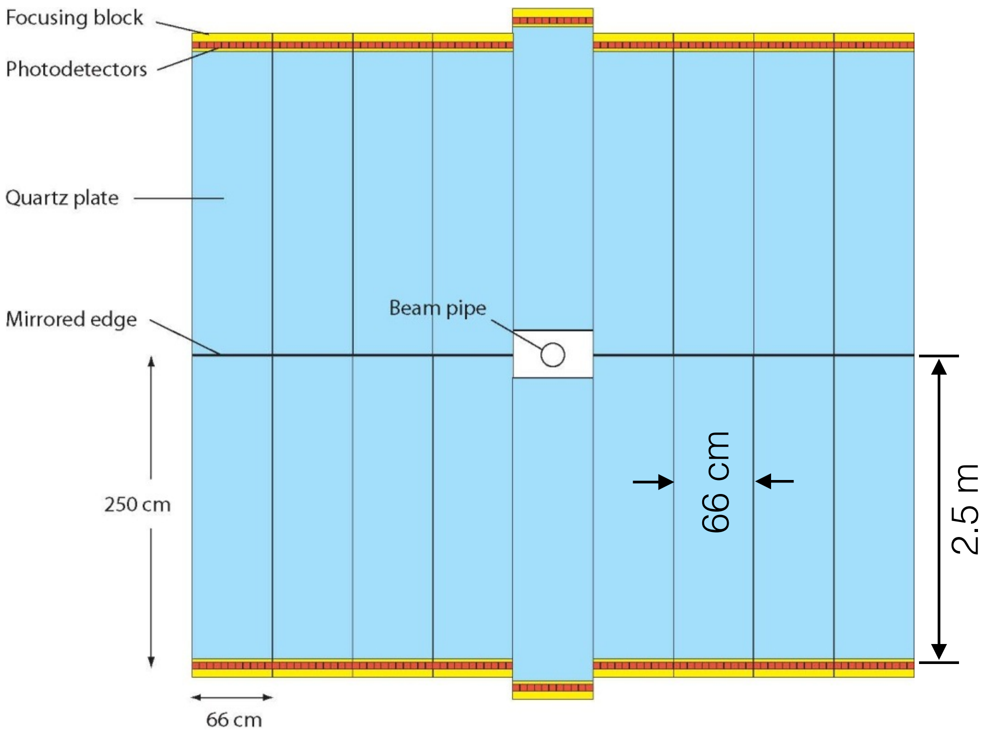
- Large area time of flight detector designed to provide PID in the 1-10 GeV/*c* momentum range.
- Exploit prompt production of Cherenkov light to determine time of flight.
- For *K* - *π* separation over 9.5m, aim for a resolution of 10-15 ps per track (requires 70 ps per photon).

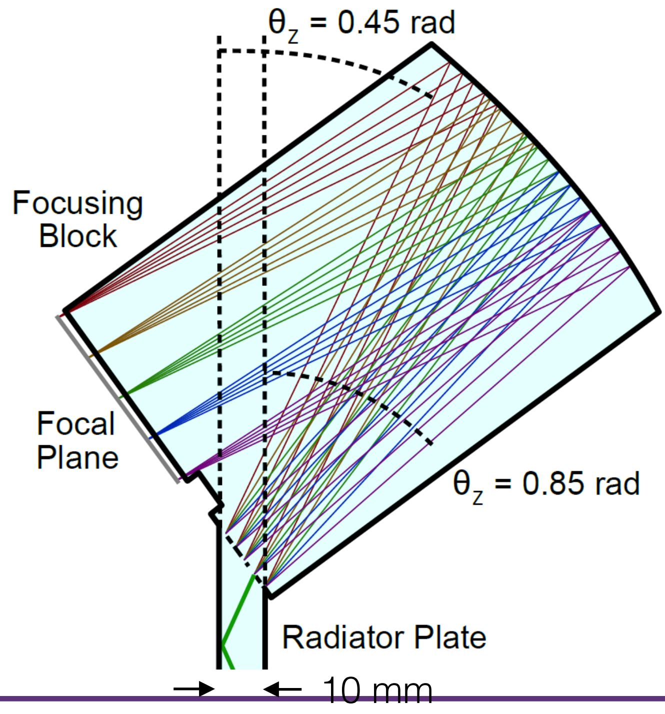




The TORCH detector

- Exploit prompt production of Cherenkov light in an array of quartz bars to determine the time of flight.
- Cherenkov photons travel to detector plane via total internal reflection from the quartz surfaces.
- Cylindrical focussing block, focusses the image onto a detector plane.
- Large area detector required to cover the LHCb acceptance (5x6m^2).
- Proposed for Upgrade Ib.

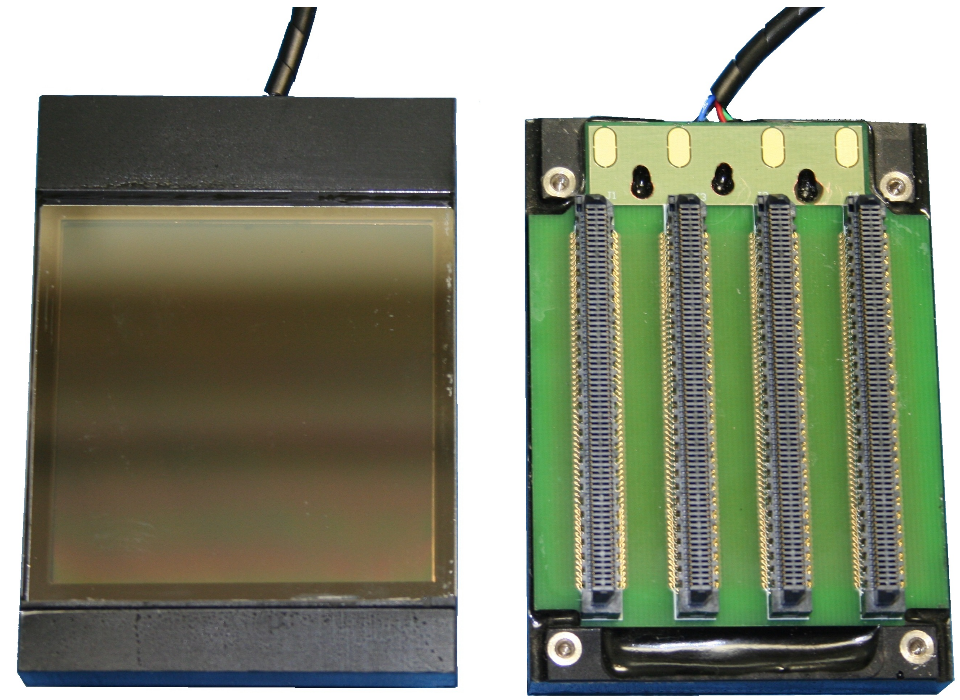




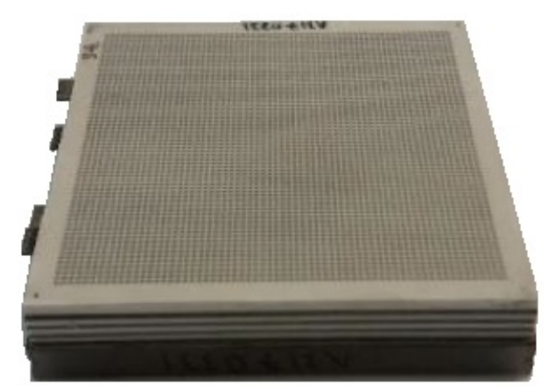
For more details on the TORCH concept see [NIM A 639 (1) (2011) 173]

Photon detectors

- Fast timing of photons is provided by microchannel plate PMTs.
- Three phase programme of R&D with a commercial partner (Photek, UK) to develop tubes with a long lifetime (>5 C cm^{-2}) and a ~35ps resolution. **[JINST 10 (2015) C05003]**
- Phase-III tube is a square tube:
  - 53x53 mm^2 active area (80% of total).
  - 64 x 8 pixels per tube, exploiting charge sharing between pixels to further improve resolution.
- Readout connectors mounted on a PCB and connected via ACF (anisotropic conductive film).



Phase-III prototype



Bare tube body

Beam tests in T9

- Series of beam tests performed in T9 (3-8 GeV/c p/π beam) to understand the potential performance of the TORCH.

November 2017/June 2018

Small scale prototype equipped with a single MCP-PMT and 120mm x 350mm radiator plate.

October 2018

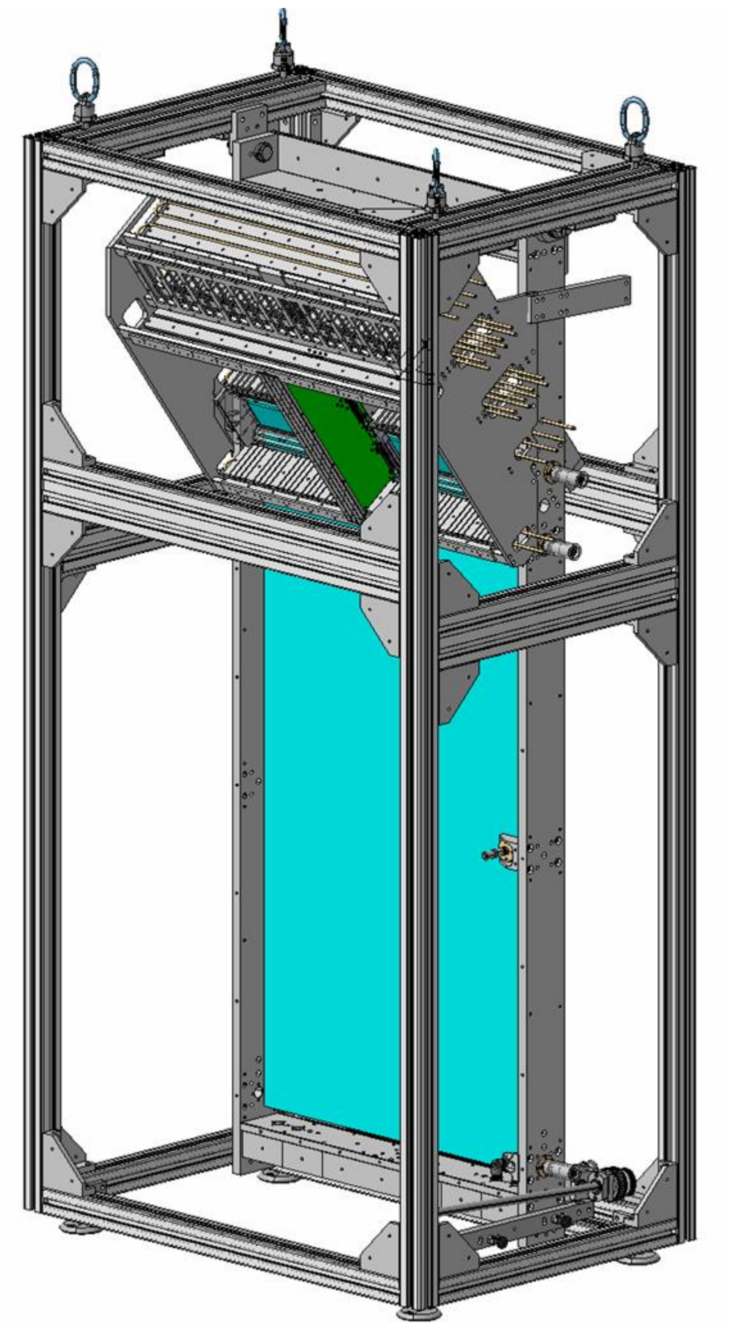
Full-width, half-length demonstrator equipped with two MCP-PMTs and 660mm x 1250mm radiator plate.

Proto-TORCH

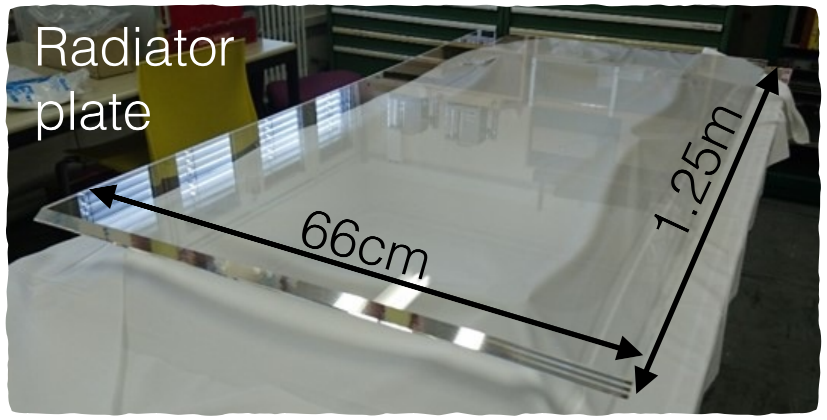
Half-scale demonstrator

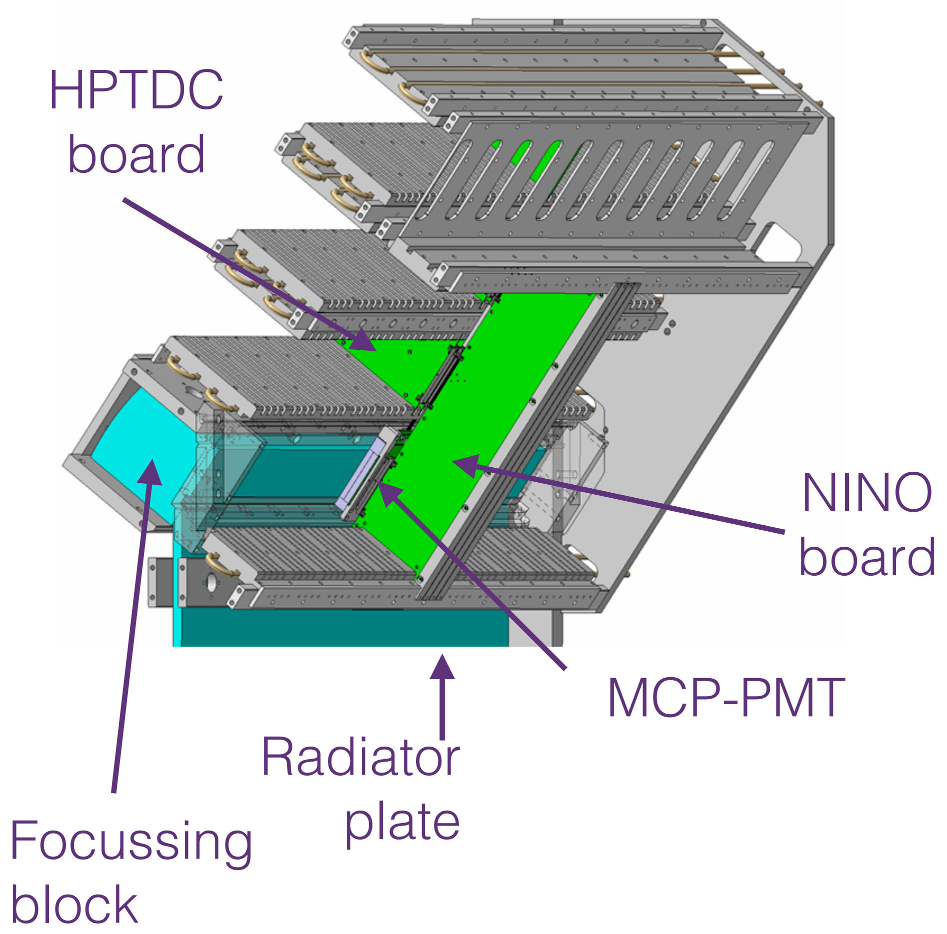
- Preliminary results from the October 2018 beam test will be shown today. For more details see [https://indico.cern.ch/event/787596/].

Half-scale prototype

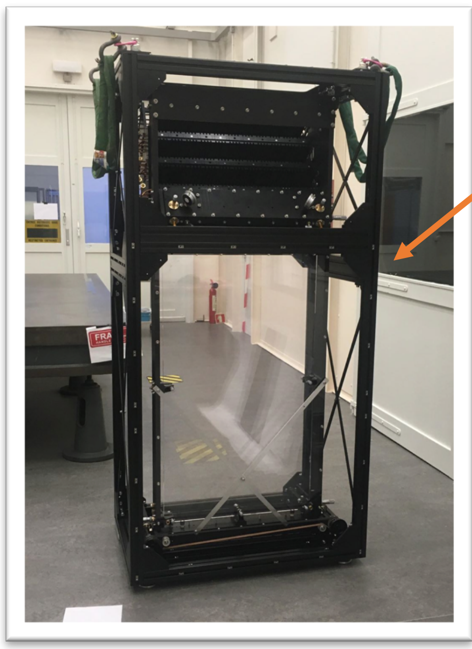


- Half-scale demonstrator module developed:
  - ➡ Currently equipped with 2 MCP-PMTs (each with 64 x 8 pixels).
  - ➡ Large scale optical components (from Nikon).

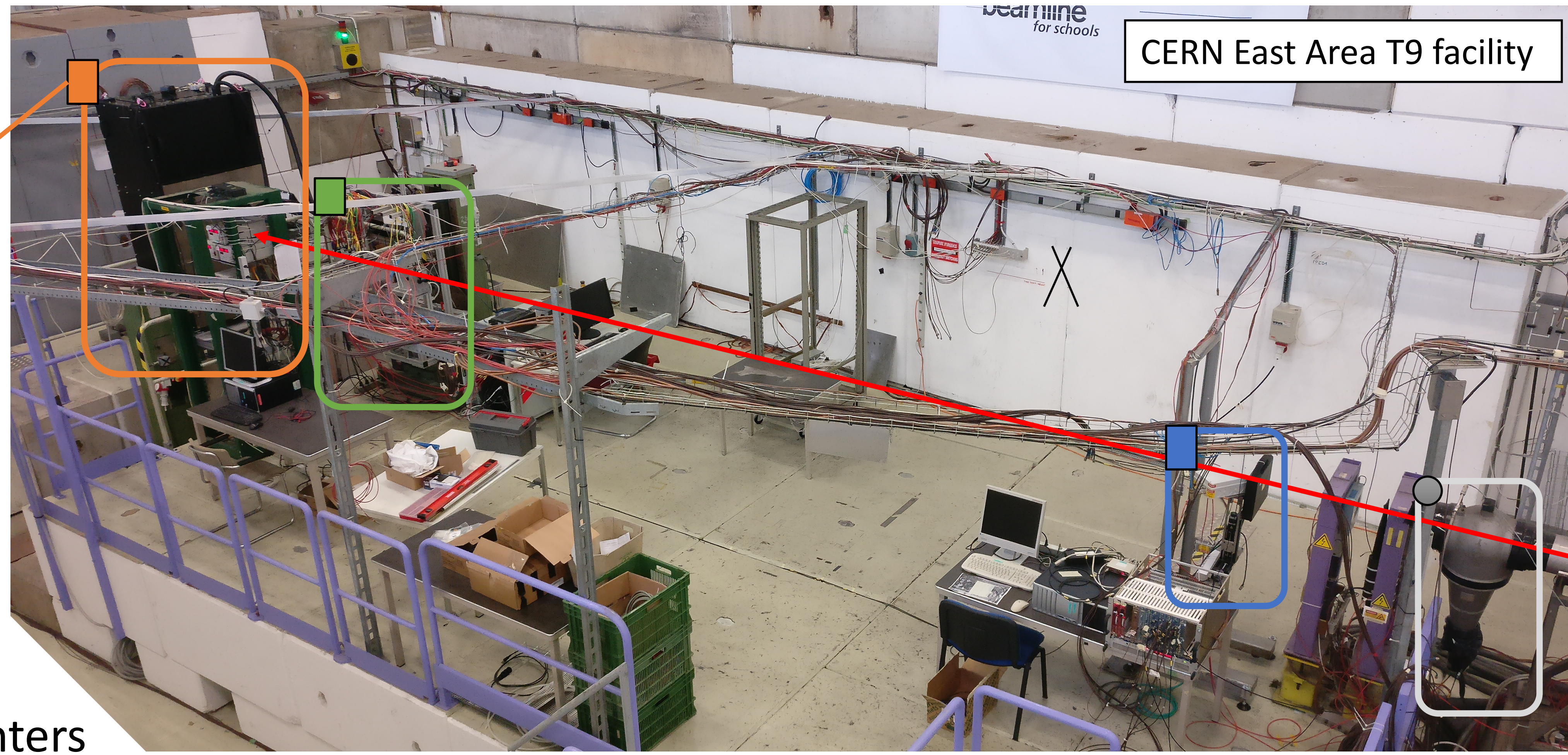




Beam tests in T9

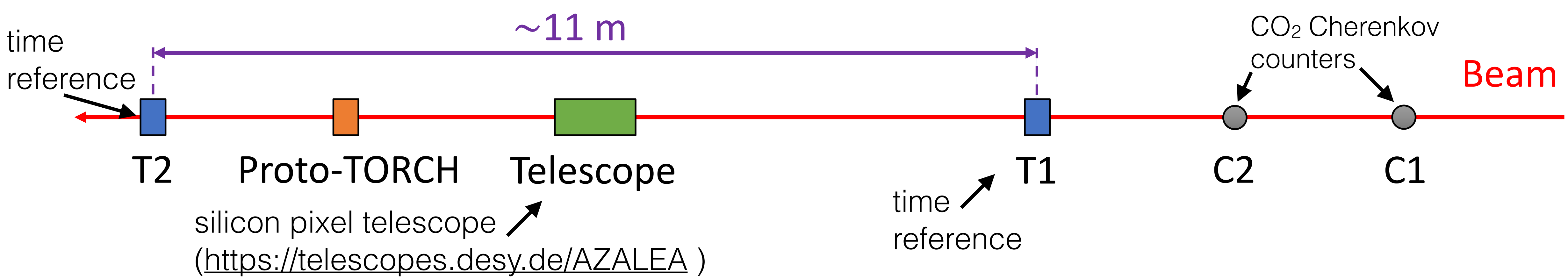


Proto-TORCH
Full-width, half-height



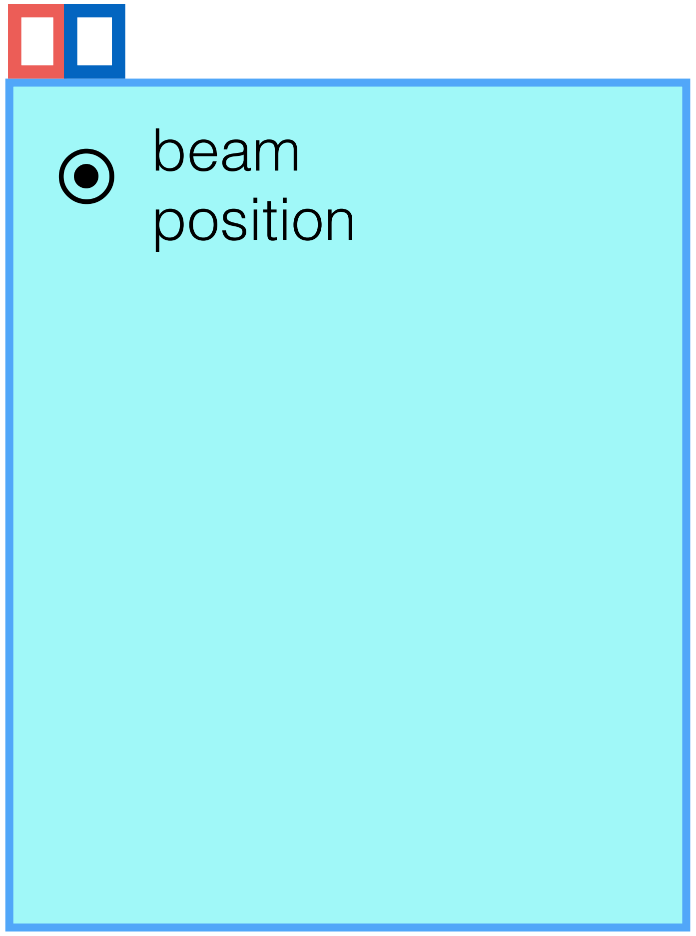
Timing Stations

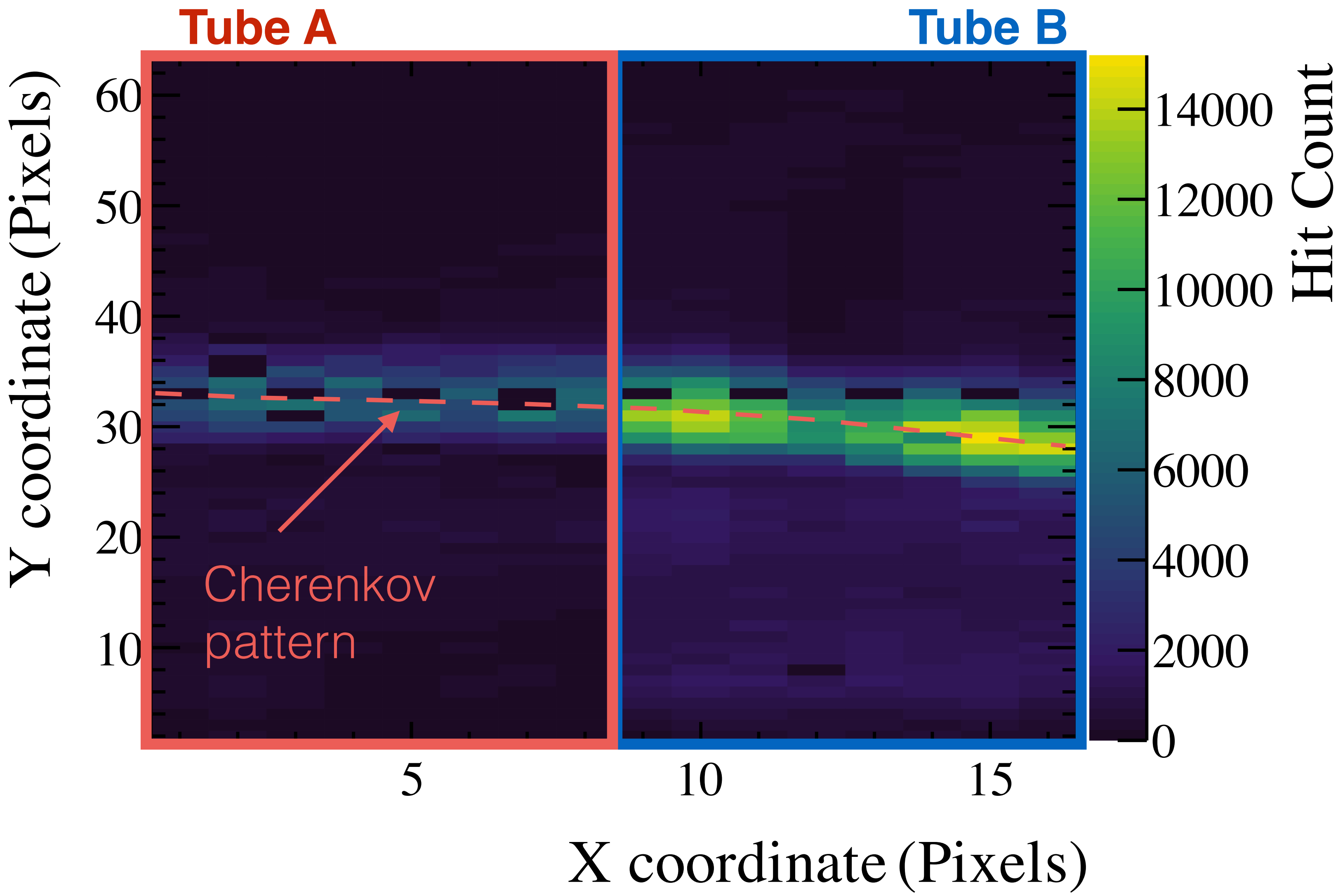
Cherenkov Counters



The TORCH pattern

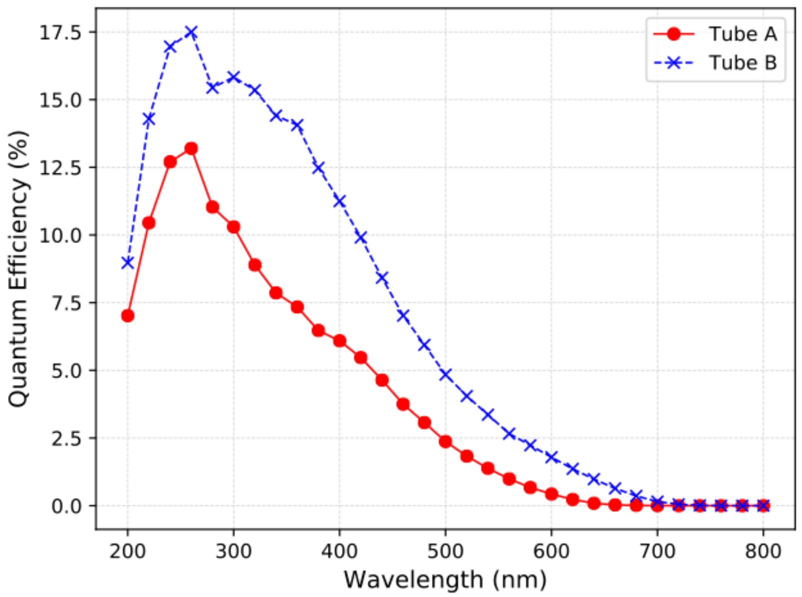
- TORCH image from October 2018 test beam with proto-TORCH:



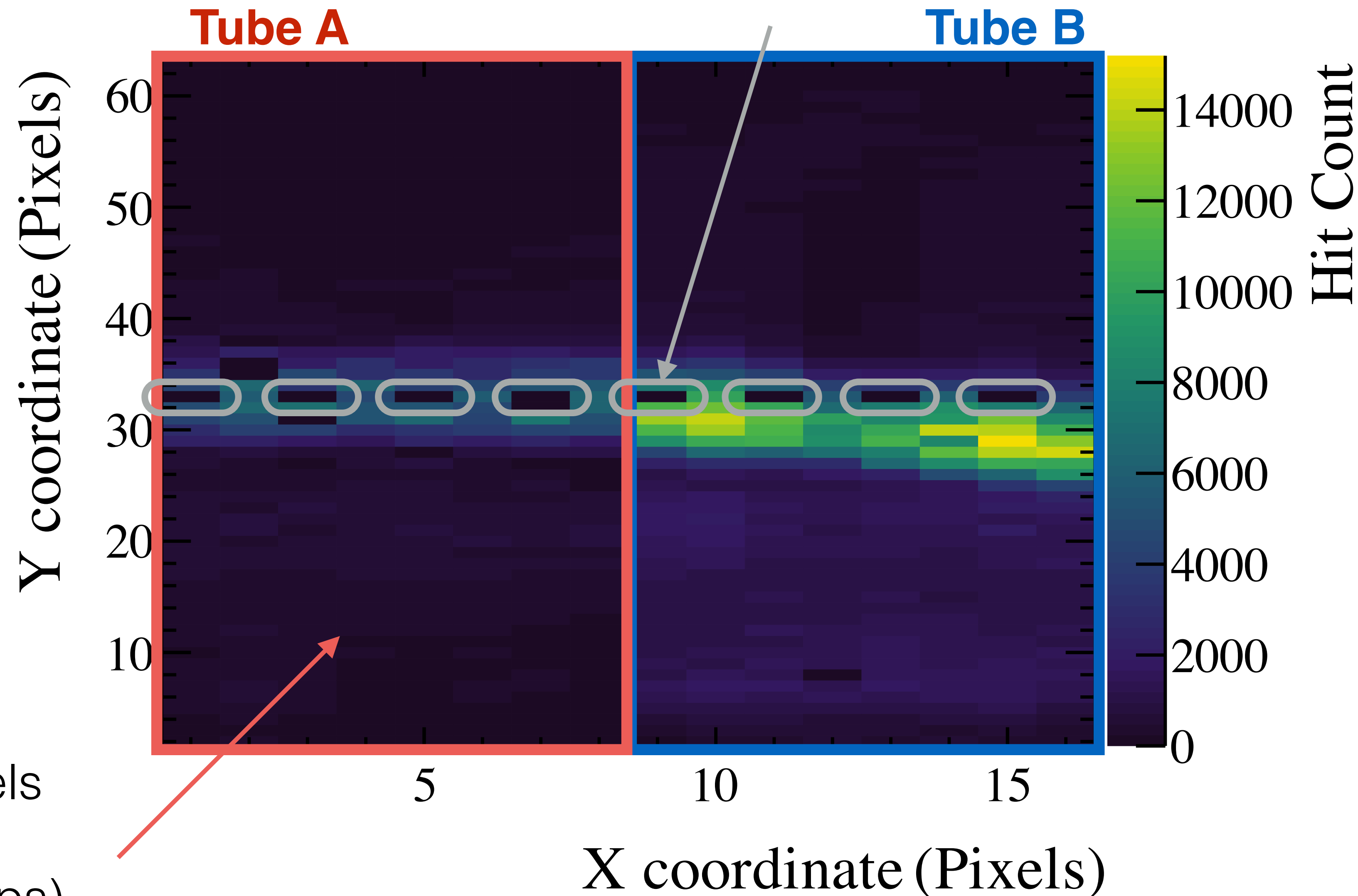


The TORCH pattern

Apparent efficiency difference between tubes due to different QE



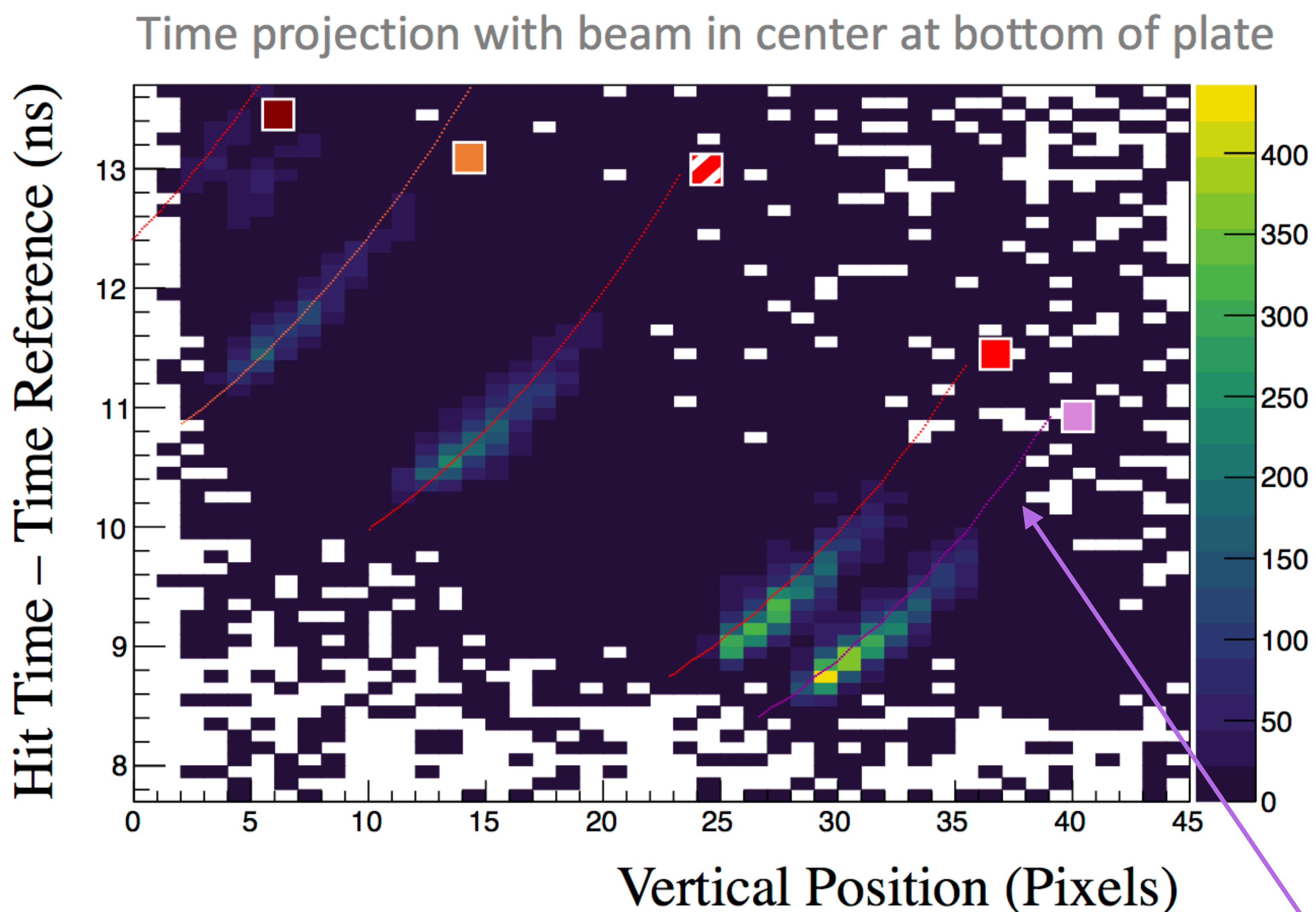
Used to inject time reference signals

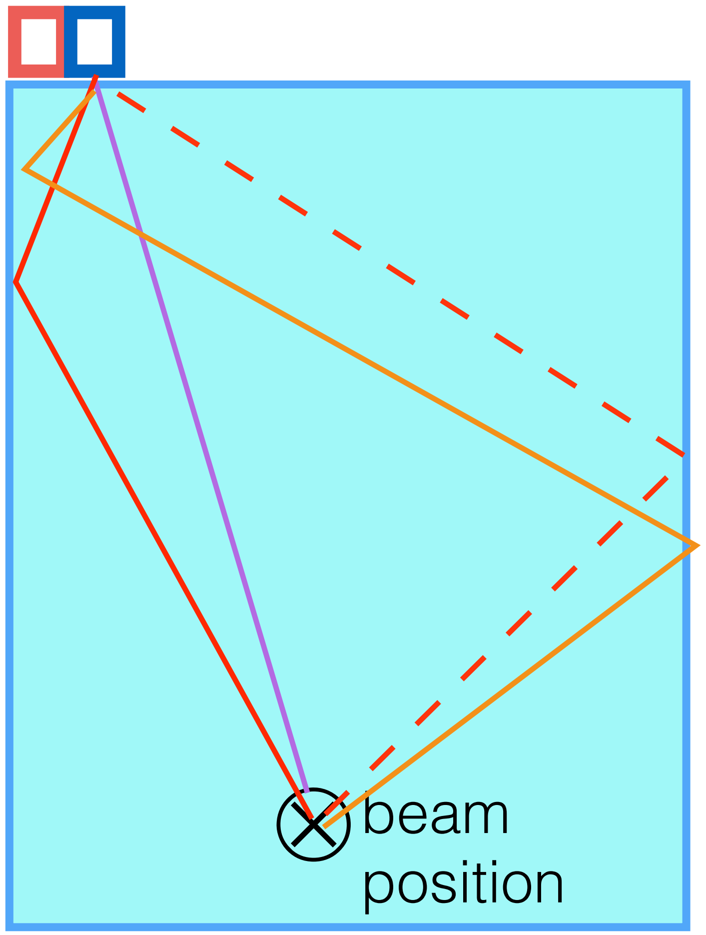


Number of dead pixels (primarily due to wire bonding of NINO chips). Resolved for the right-hand readout boards.

TORCH pattern

- Projecting time response of a single pixel column with the beam at the bottom of the plate:

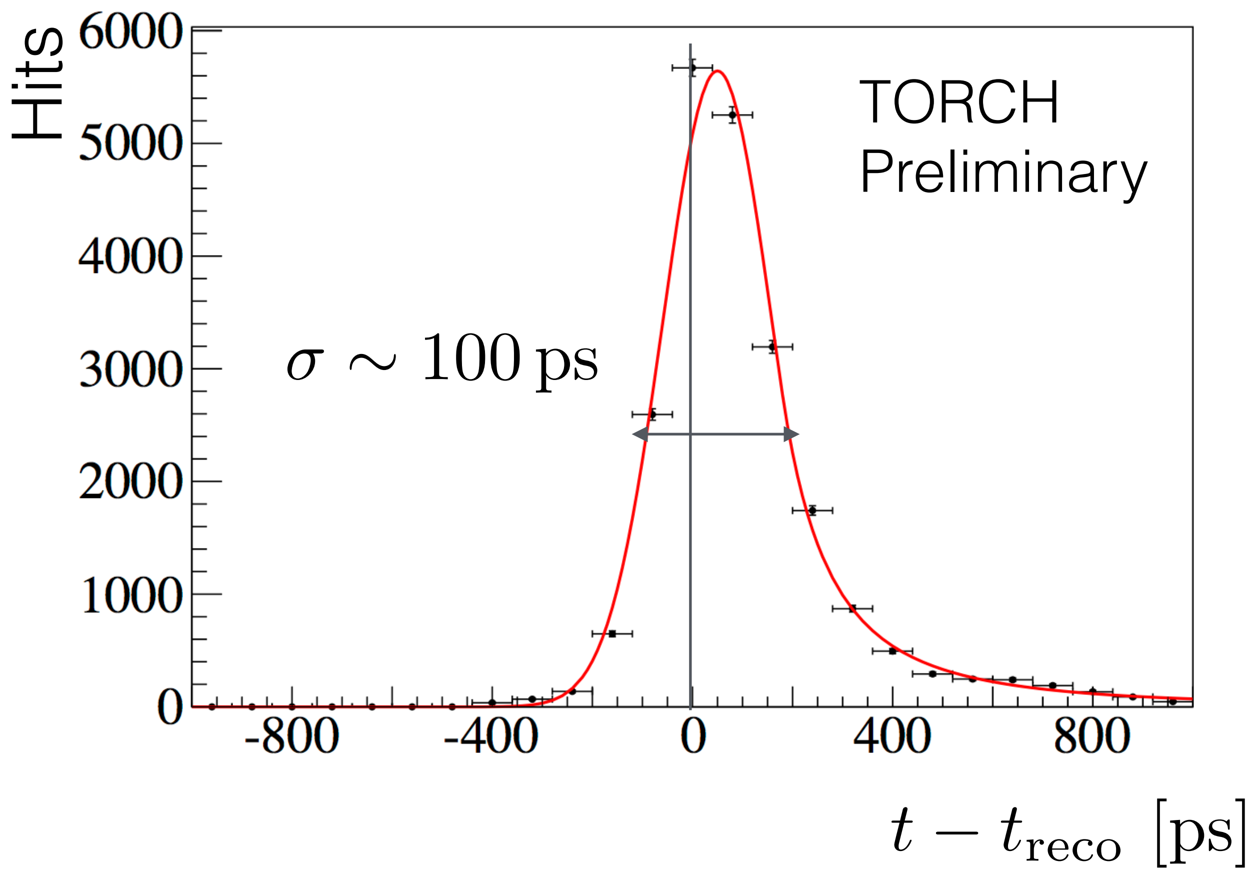




Expected arrival time/position from simulation

Time resolution

- Compare predicted time from the simulation to measured photon arrival time.
- Correct for non-linearity and time-walk in the TORCH electronics.
- Further improvements expected with improved calibration/ alignment (e.g. charge-to-width calibration of NINO).
- Resolutions of 88-130ps achieved depending on position in the radiator bar.



$$\sigma^2 = \sigma^2_{\mathrm{in.}} + \sigma^2_{\mathrm{det.}} + \sigma^2_{\mathrm{ref.}} + \sigma^2_{\mathrm{track}}$$

intrinsic (dispersion)

time reference (42±3ps)

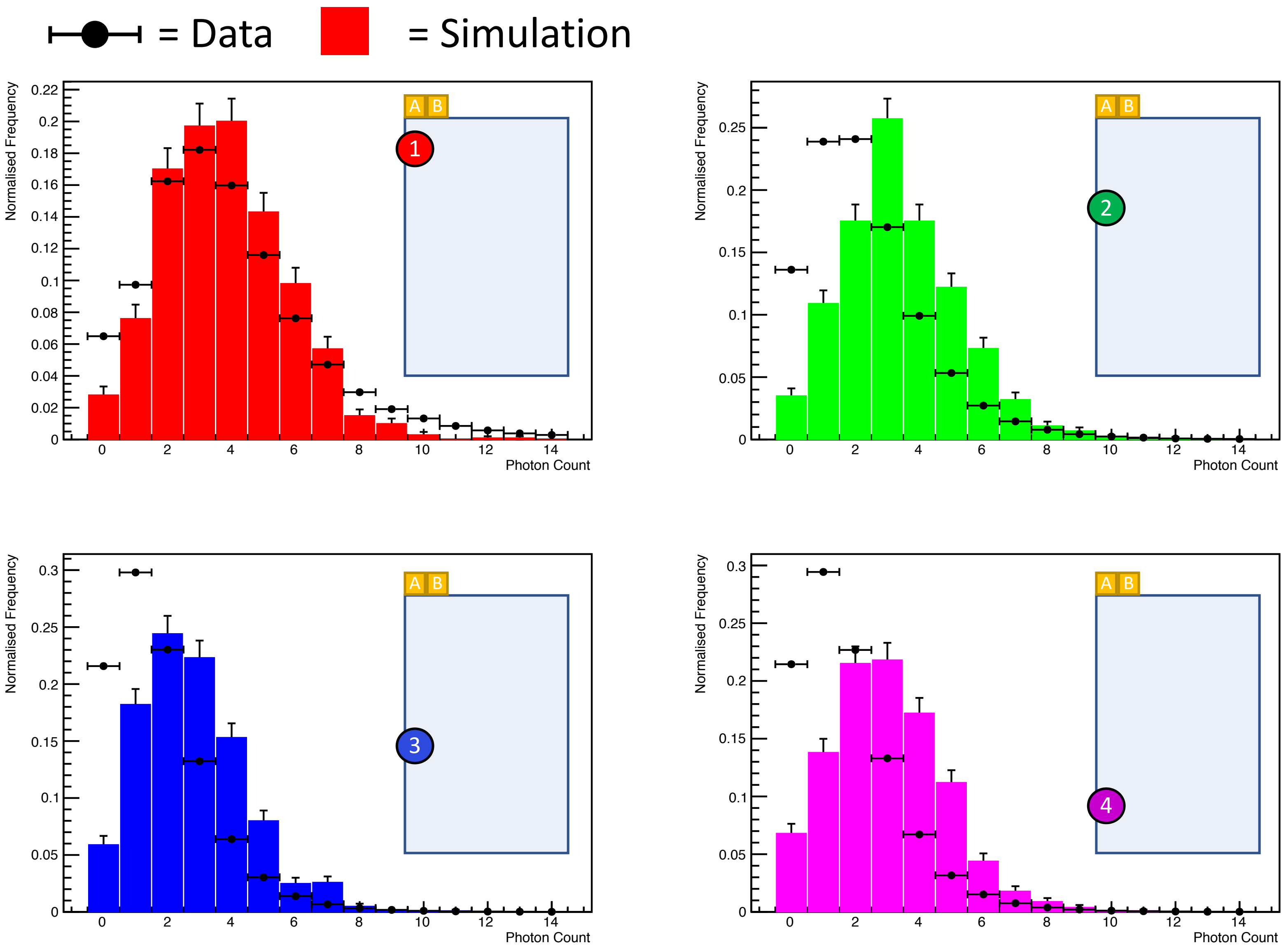
10-30 ps

Photon yield

- Can also study the photon-yield by clustering hits on the detector plane.

NB Only $^{2}/_{11}$ of the detector plane is instrumented in the proto-TORCH.

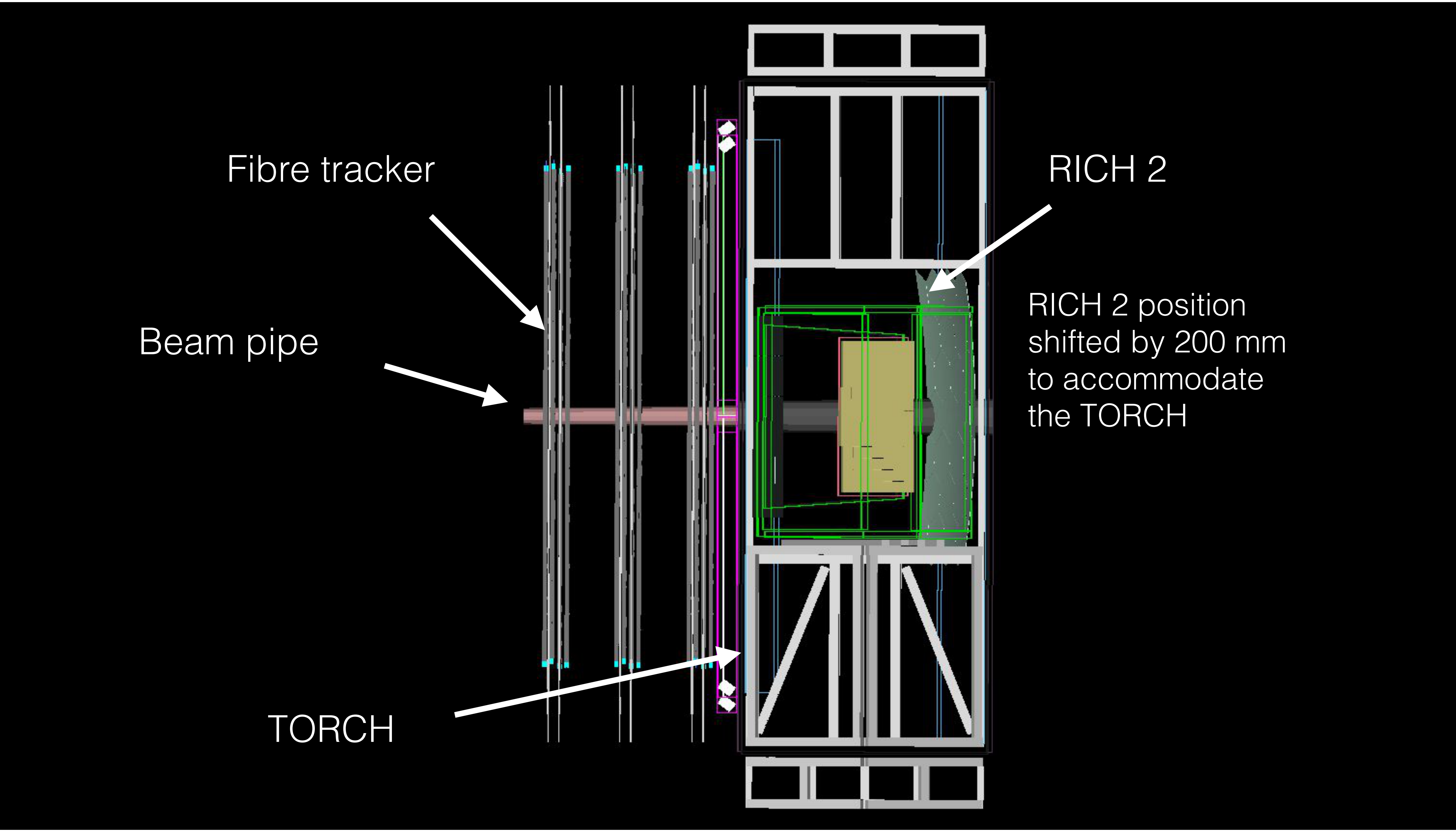
- Dependence of the yield on the position of the beam on the radiator bar is under study.



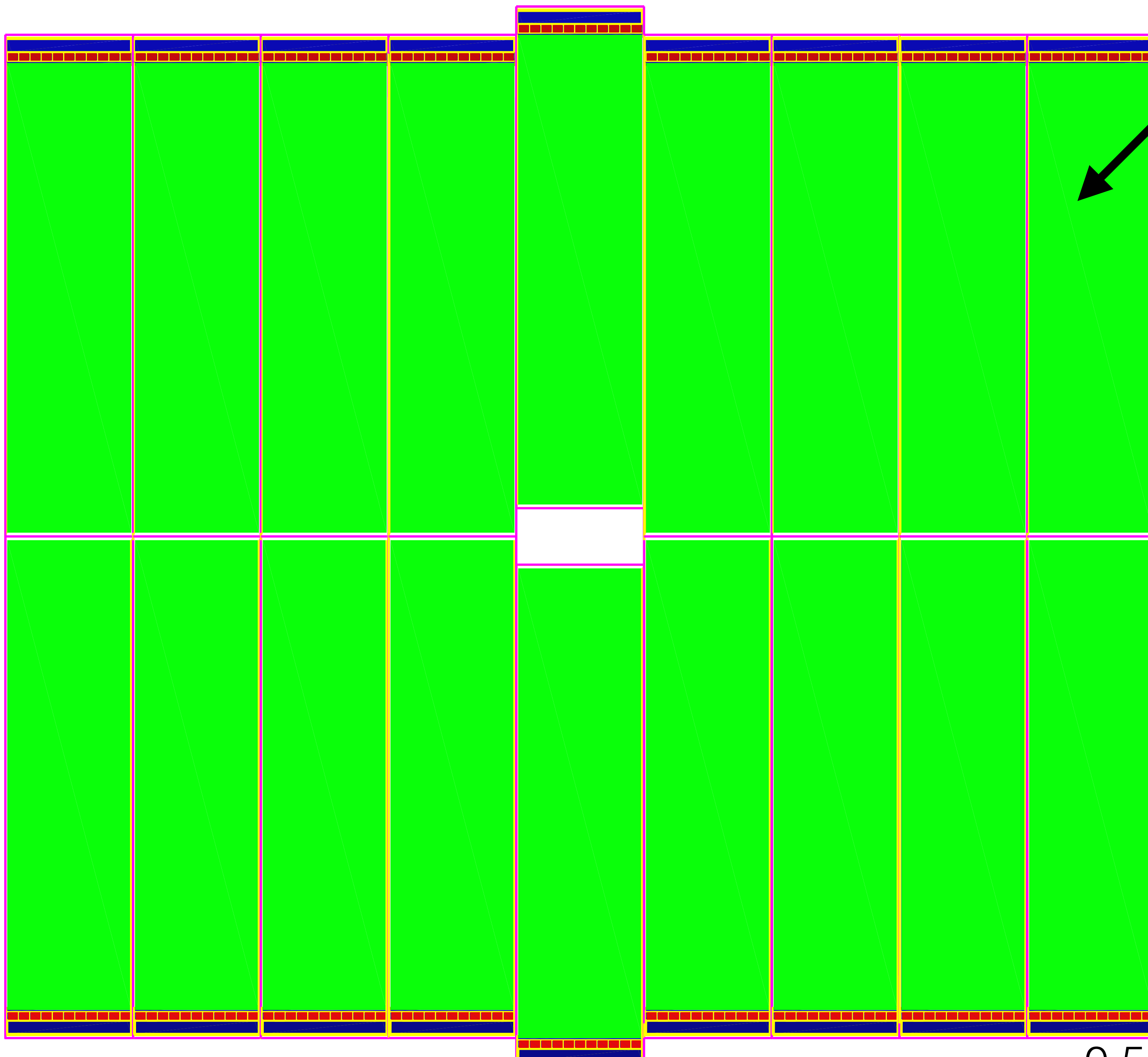
TORCH simulation

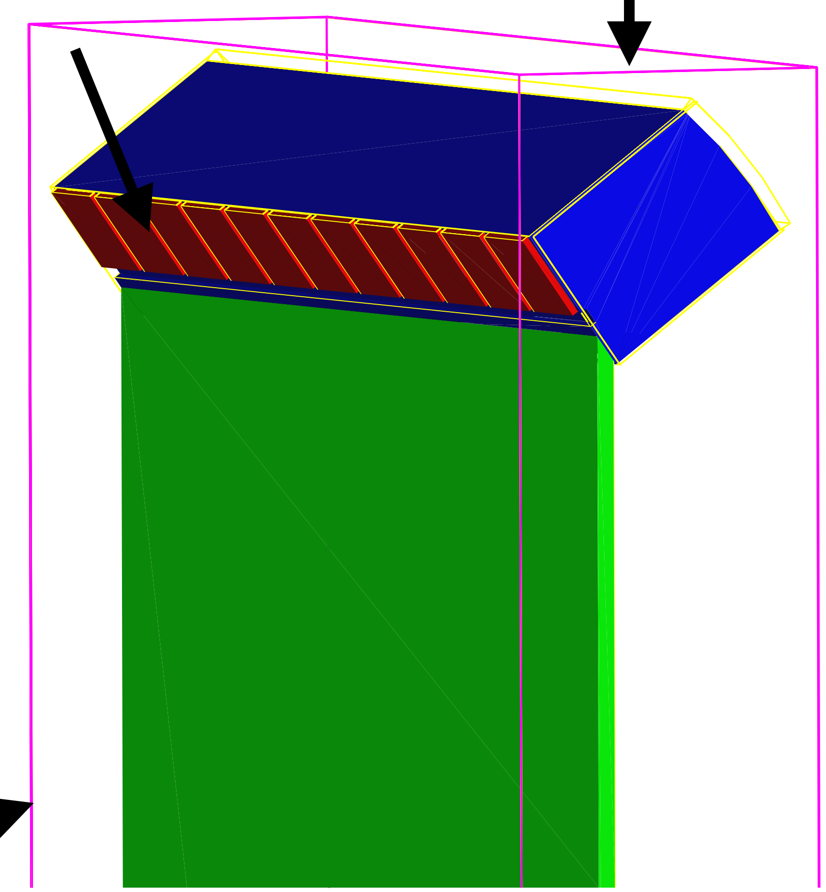
- Simulate TORCH inside LHCb:
  - ➡ XML description of detector volumes/surfaces/materials in `DDDB`.
- Physics processes simulated using `Geant4` inside `Gauss`:
  - ➡ Cherenkov process (based on `G4Cerenkov`).
  - ➡ Optical boundary effects and surface roughness (updating `G4OpBoundaryProcess` in `Gauss`).
  - ➡ Rayleigh scattering (based on `G4RayleighScattering`).
- Store MC hit container at the output of `Gauss` to be passed on to `Boole/Brunel/DaVinci`.

TORCH in LHCb



Module geometry (Panoramix)





Free-standing with no support structure.

Data taking conditions

- Simulate $b\bar{b}$ events in **Upgrade Ib** conditions, i.e. an instantaneous luminosity of $\mathscr{L}$ = 2x10^{33} cm^{-2}s^{-1} and a pile-up of $\boldsymbol{\mu}$=7.6.
- Generate spill-over from ±2 bunch-crossings.
- PID performance is determined on reconstructed tracks:
  - ➡ Run the default **Upgrade Ia** tracking sequence.
  - ➡ Extrapolate the tracks to the front of the TORCH using tracking tools.
  - ➡ Compute path length by a cubic spline interpolation between points on the tracks.
- In the **Upgrade Ib** data taking conditions the per-pixel occupancy is 5-20%, depending on the module (highest in the most central modules).

PID algorithm

- Use a similar approach to the RICH detectors and compare hypotheses directly using a likelihood calculation.

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

Determine PDF for given hypothesis by "ray-tracing"

Currently use a "local" per-track algorithm and assume the background is uniformly distributed.

- Photon arrival time can be determined from:

$$t_d = t_0 + \frac{r_{\text{track}}}{\beta c} + \frac{r_\gamma}{v_{\text{g}}}$$

detected time

production time (assumed known)

track path length to TORCH

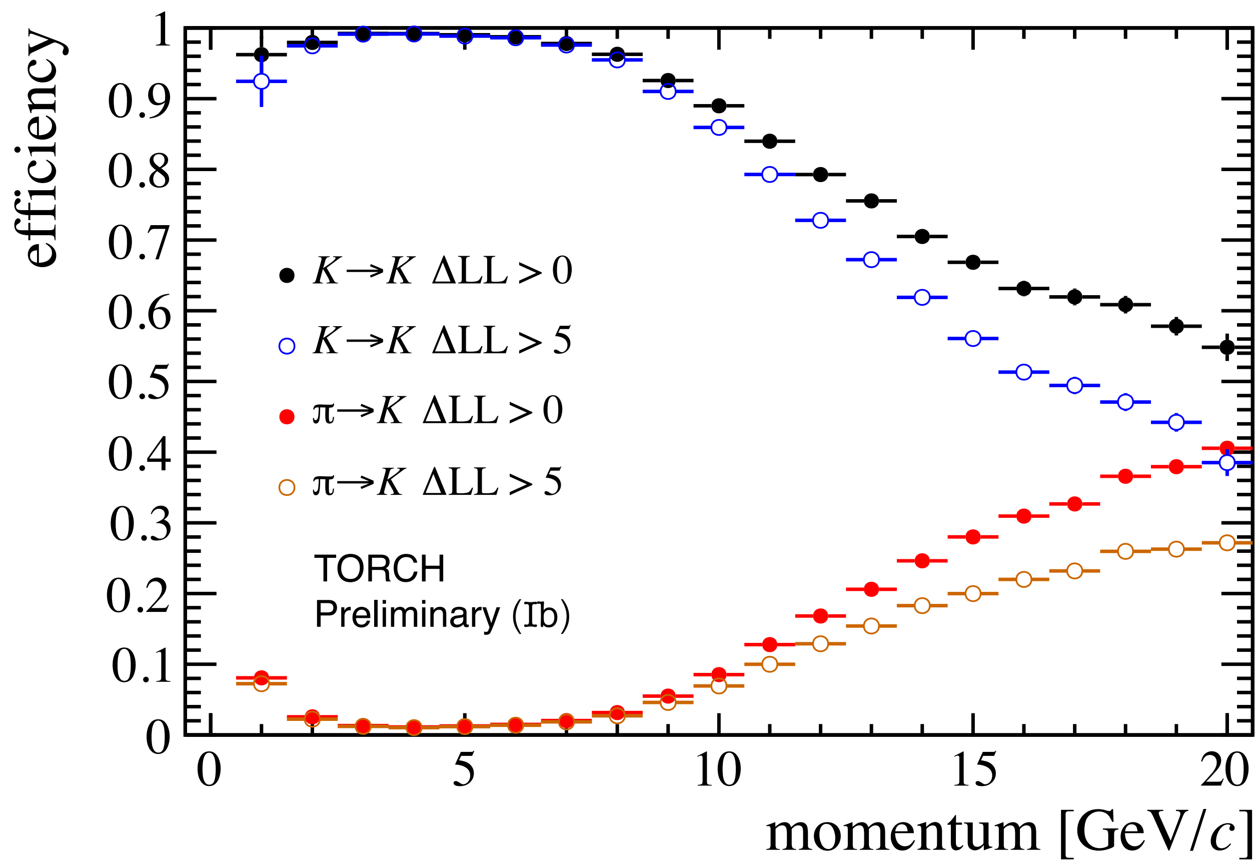
momentum and mass hypothesis

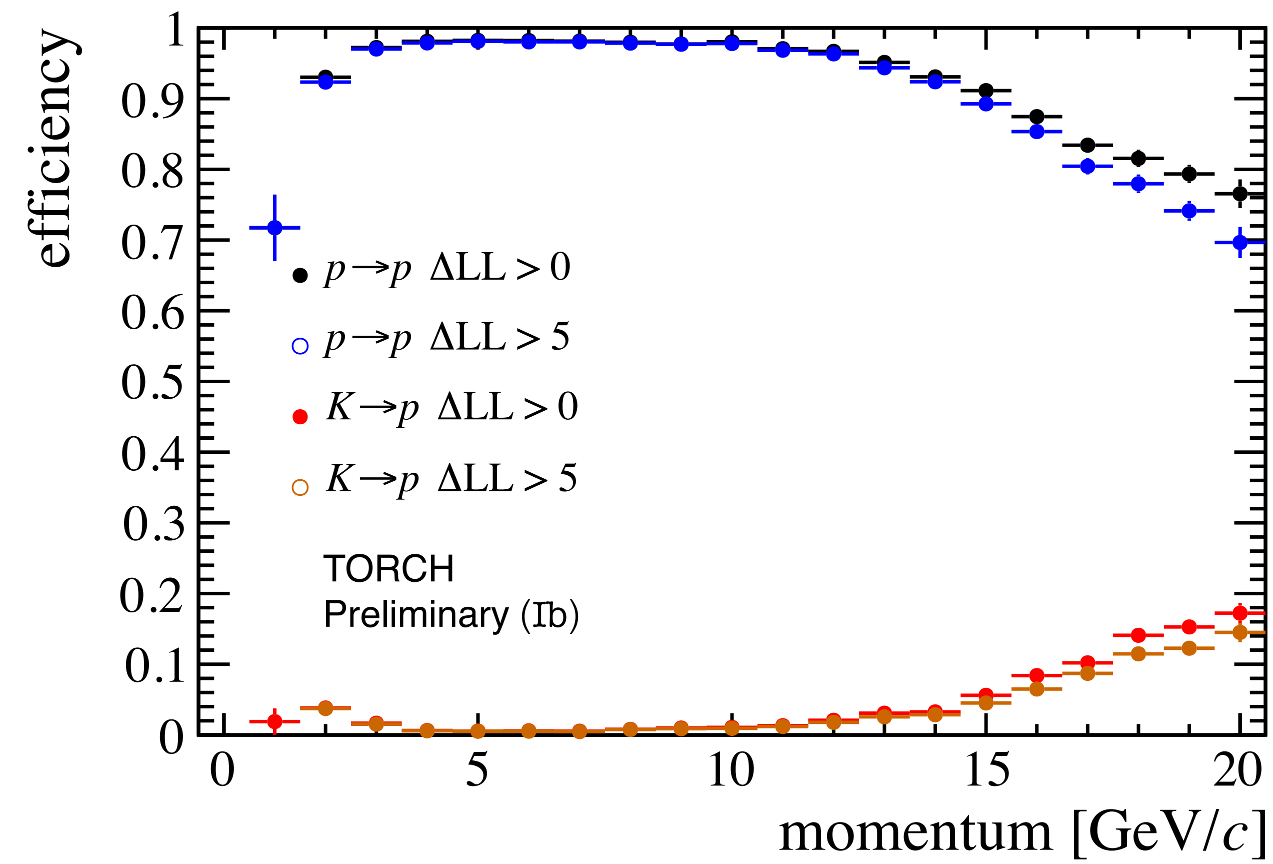
photon path length in the radiator

group velocity

PID performance

- TORCH PID performance averaged over all of the modules:

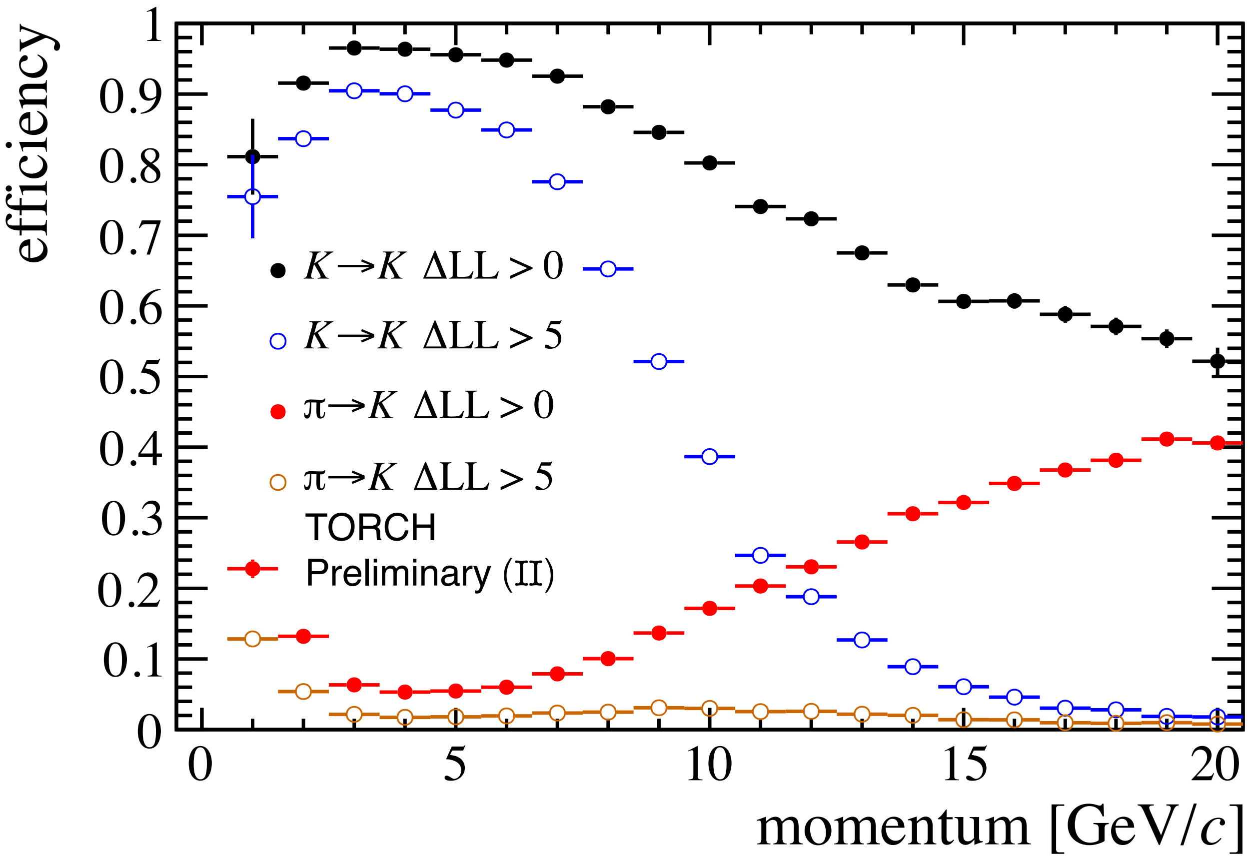


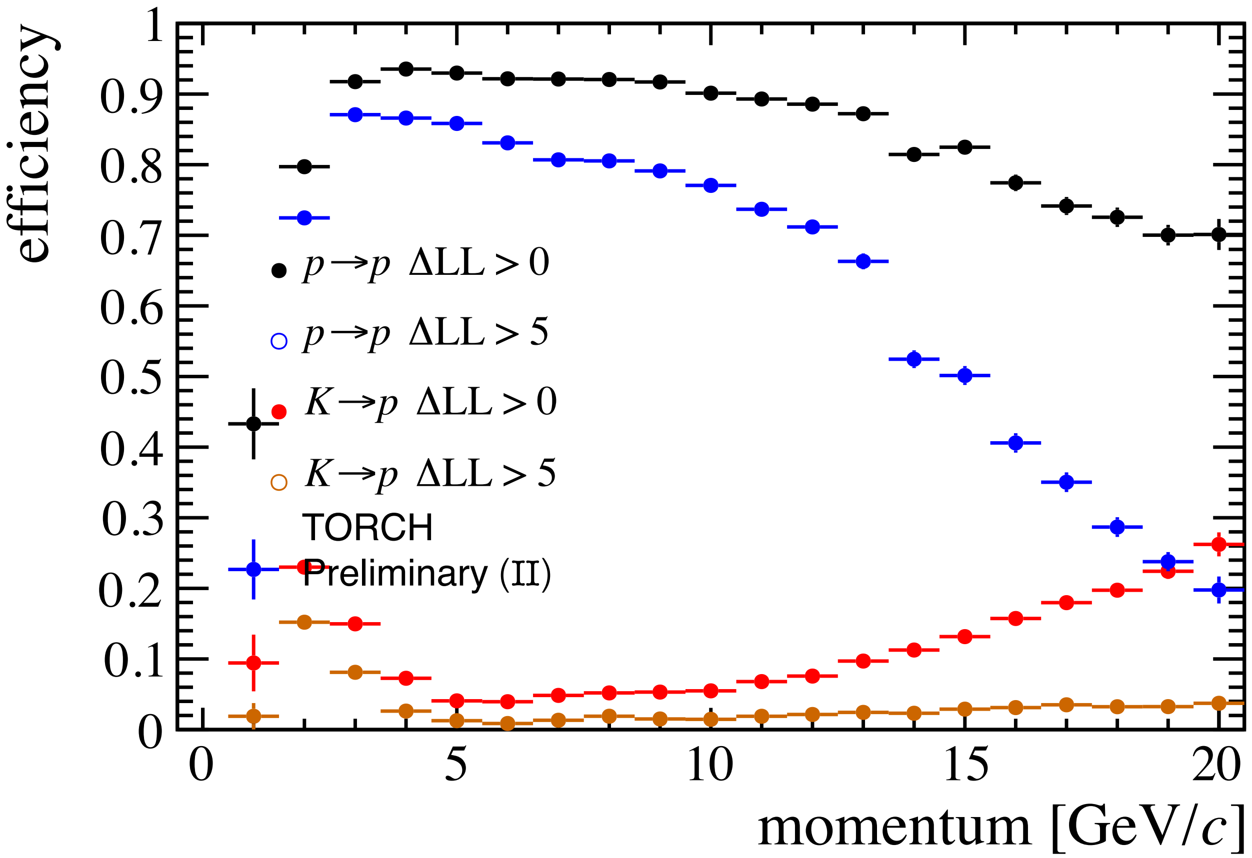


- Good separation between *π*/*K*/*p* in the 2 -10 GeV/*c* range.

PID performance (Upgrade II)

- Study the performance at 1.5x10^{34} by merging events at the input to the stand-alone PID algorithm.

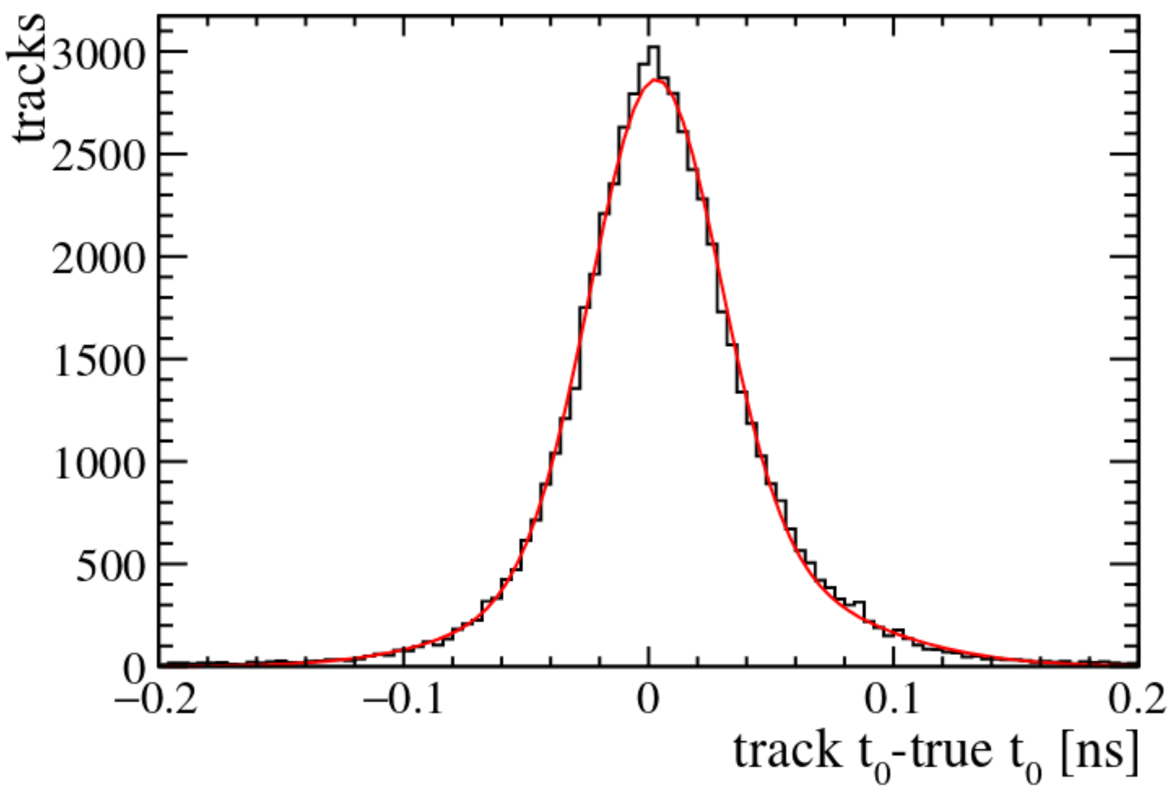




- A model for the front-end electronics (charge-sharing, deadtime etc) is required to reach a conclusion on the performance in Upgrade II conditions.

Per-track t_0 resolution

- For PID performance we are assuming a known t_0.
- It is also possible to determine t_0 for each track in the data.
  - eg for tracks with p > 15GeV/c use the pion hypothesis and vary the particle t_0.
- Determine vertex t_0 by combining t_0 from each track and rejecting outliers.



Outlook

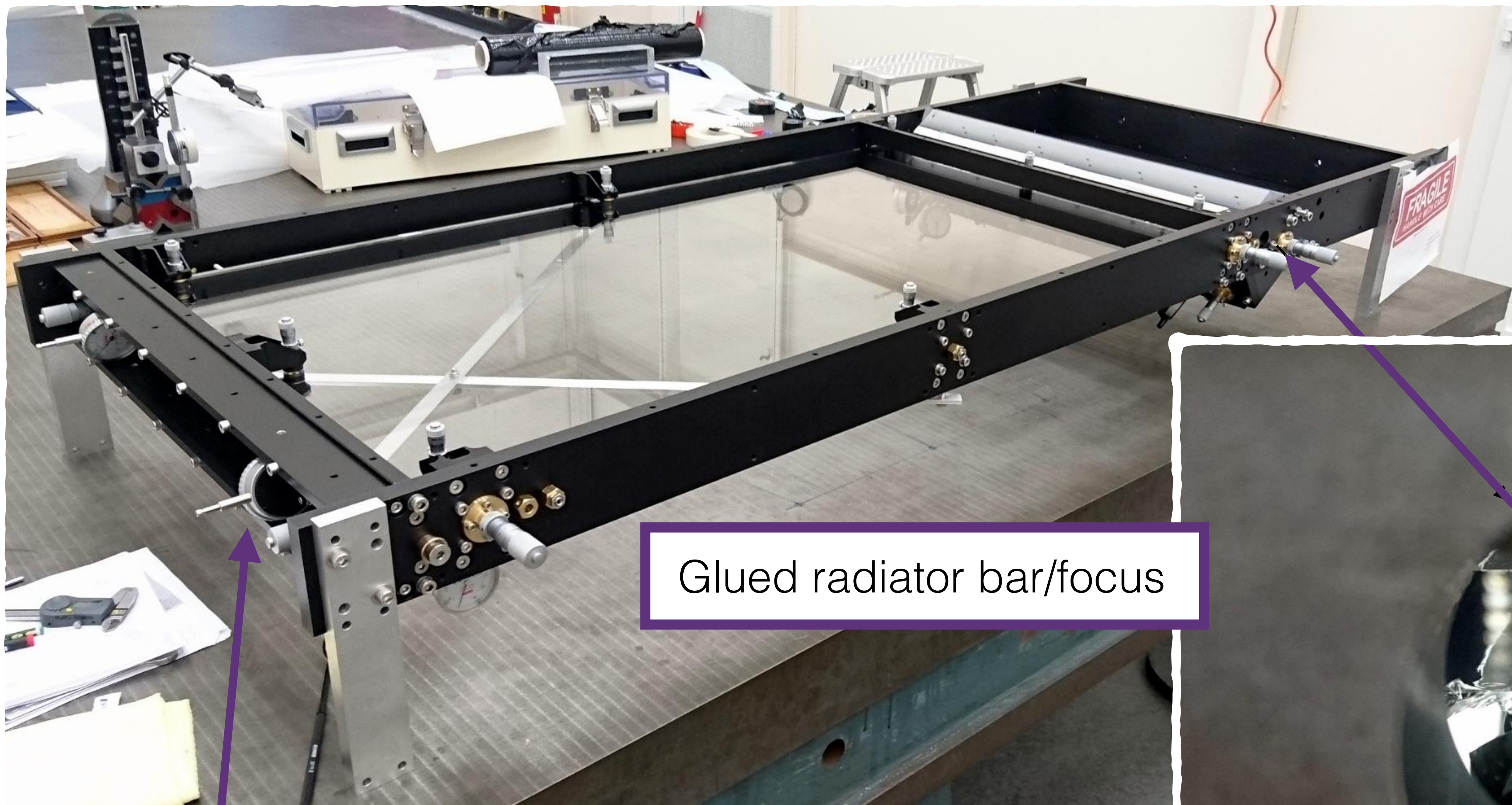
- A number of good recommendations were made during the review of the TORCH proposal at the U2PG.
- For the simulation:
  - ➡ To continue to study the TORCH PID performance and assess the performance for **`Upgrade II`** detector.
  - ➡ To test the robustness of the PID performance with occupancy and against degradations in the photon yield/time resolutions.
  - ➡ To investigate the possible track t_0 information we can get from other detectors in **`Upgrade II`** and its impact on the TORCH.
- We are also investigating ways to further improve the detector performance, e.g. treatment of background in the likelihood calculation/global likelihood calculation.

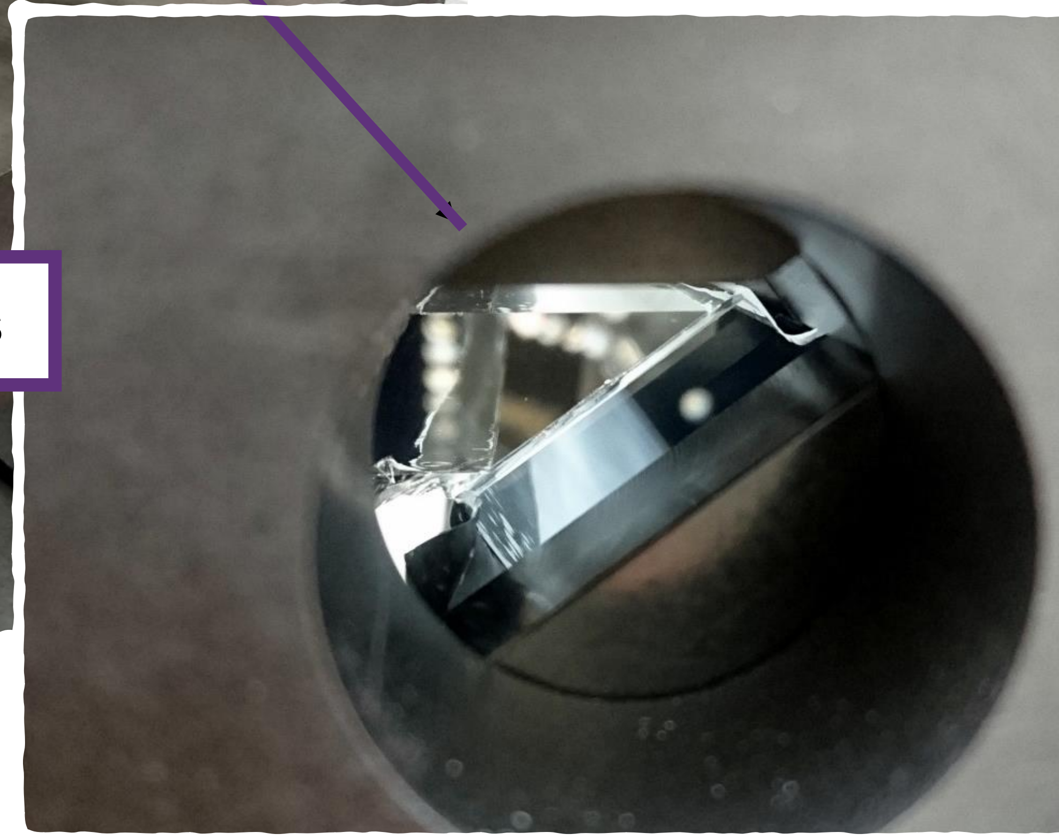
Outlook

- A number of good recommendations were made during the review of the TORCH proposal at the U2PG.
- For additional tests:
  - ➡ To improve our understanding of the different contributions to the test beam time resolution and photon yield.
  - ➡ To measure the lifetime of the phase-III MCP-PMTs and to explore future photon detector developments to cope with the large integrated charges needed for run 5 and 6.
  - ➡ To explore new chip developments as replacements for the NINO and HPTDC chips used TORCH prototype.

Finally, we would welcome interest from anyone who would like to join the TORCH project.

Holding mechanics for quartz optics



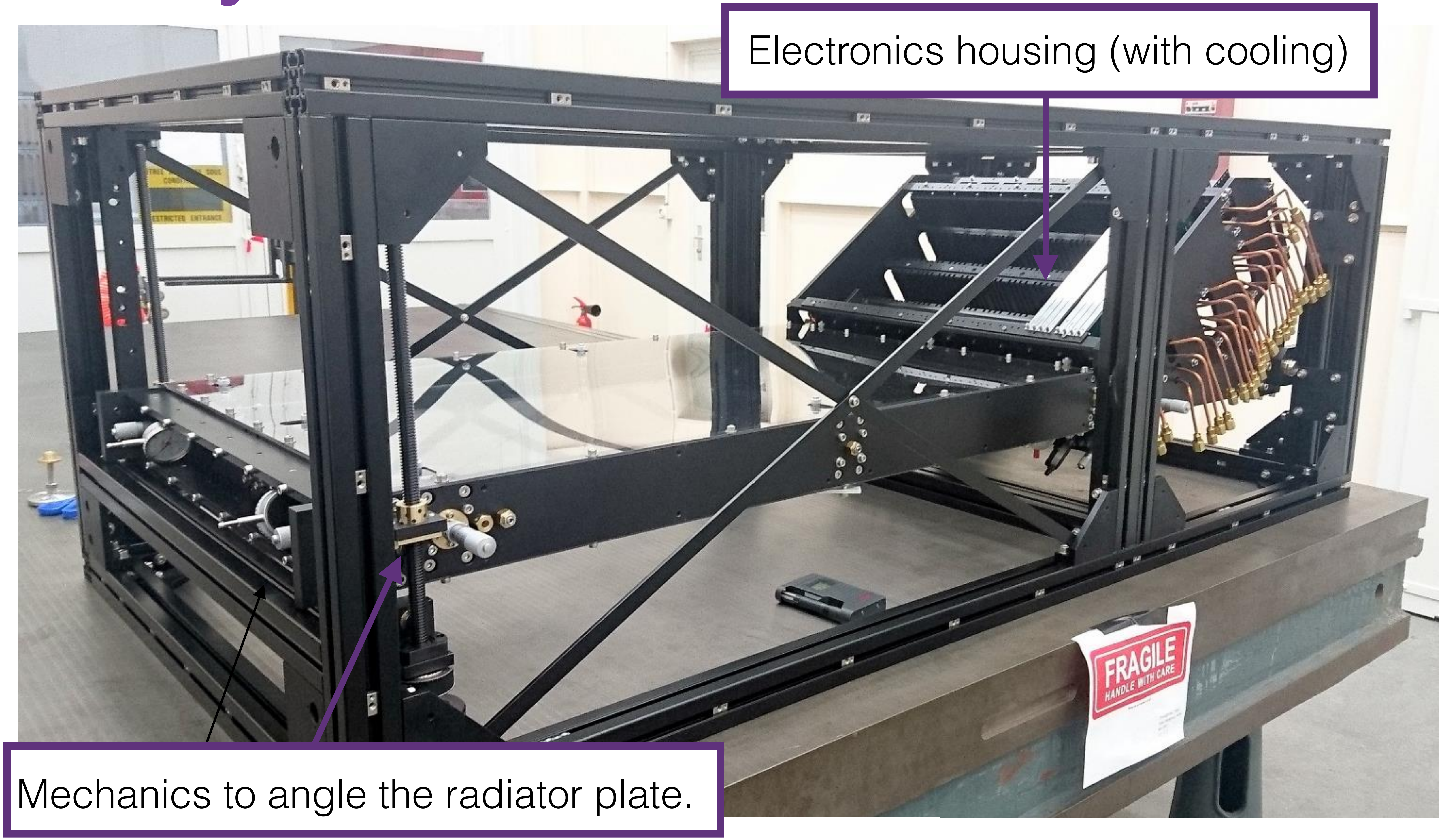


Boundary between the focus and the plate.

Glued radiator bar/focus

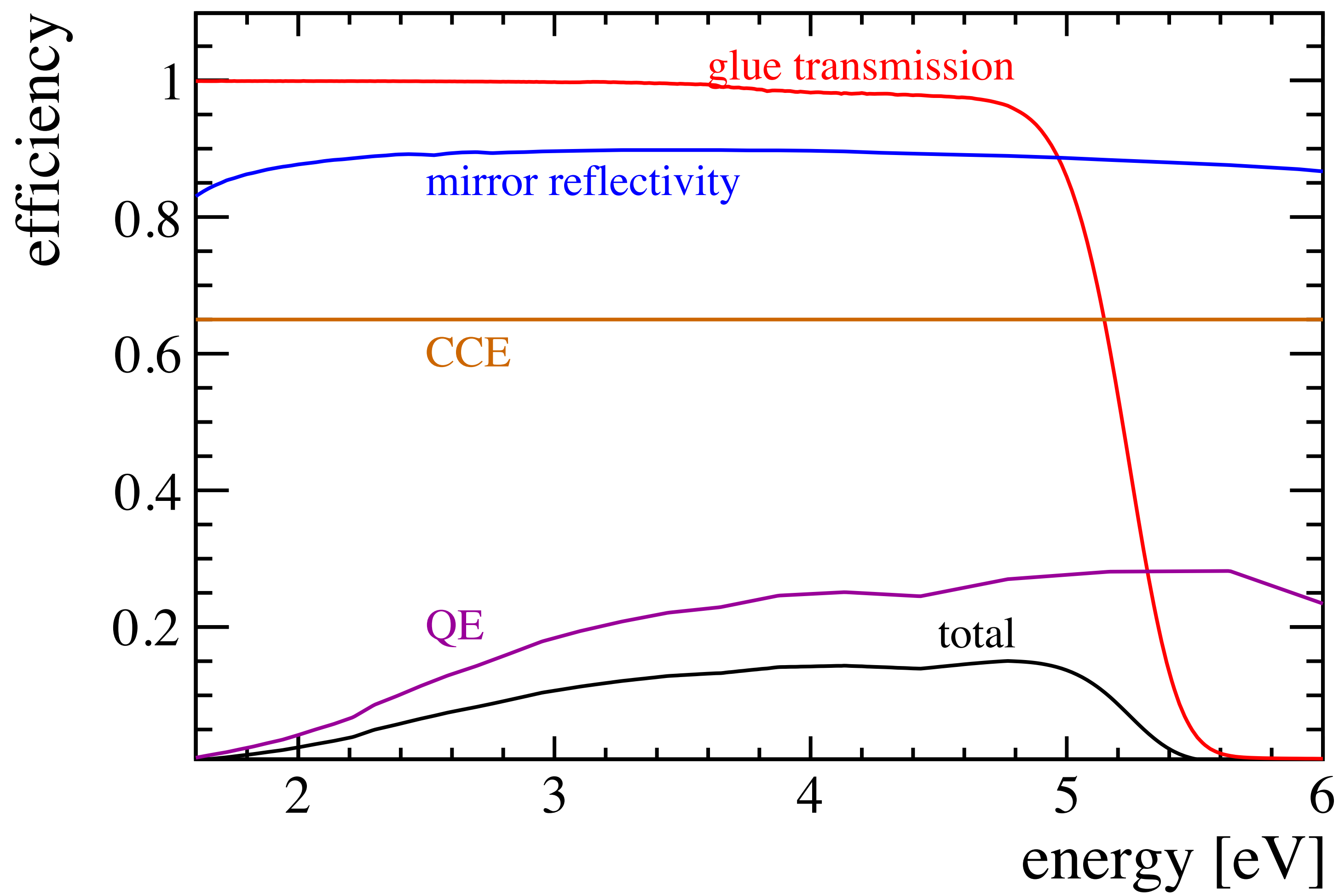
Micrometric screws used to position the radiator.

Fully assembled frame



Detector efficiency

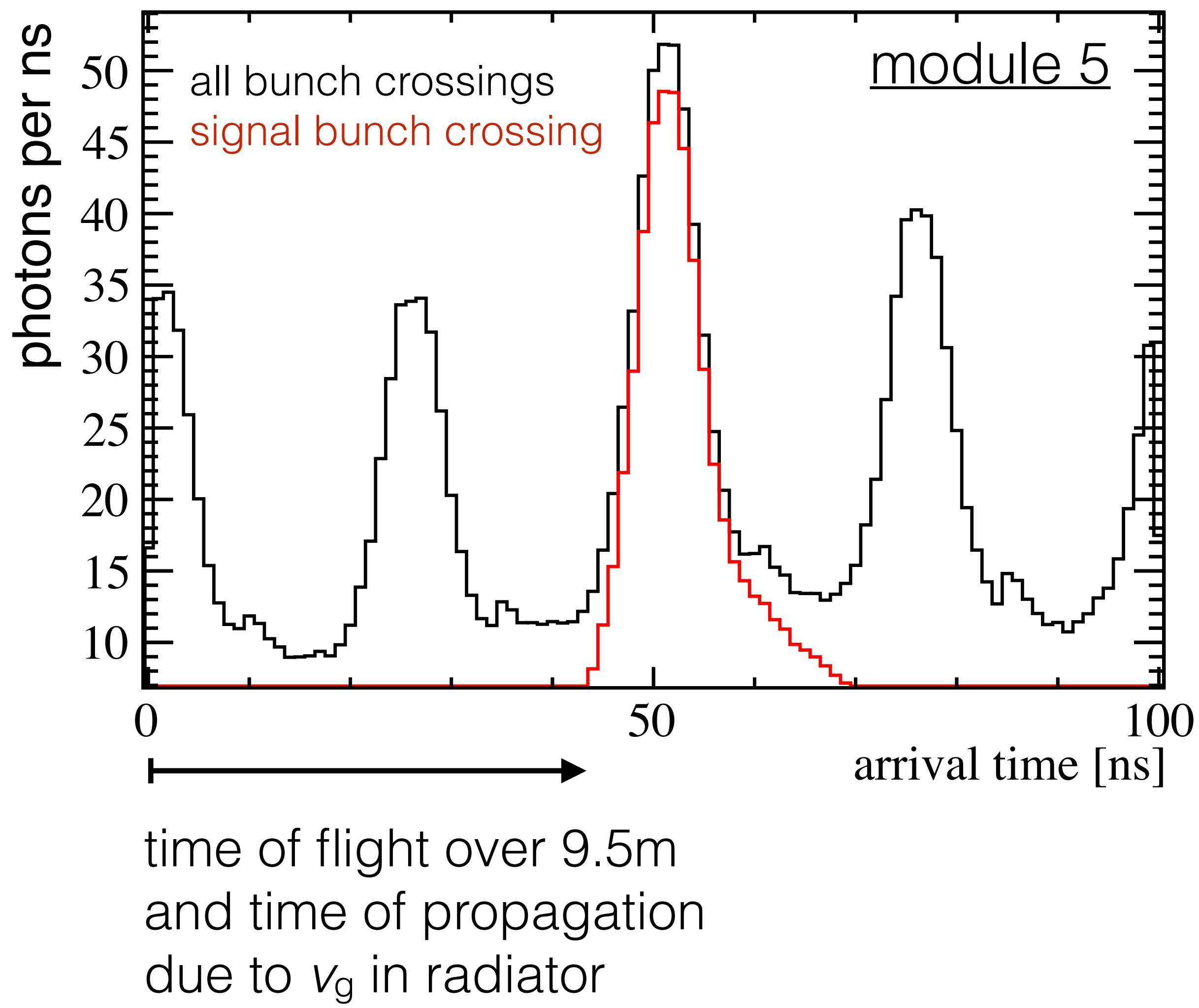
- Accept-reject photons based on measured transmission/reflection/ QE of the detector.
- Additional losses in the simulation from packing of MCP-PMTs (53/60) and the geometry of the bar and focussing optics.



- We then smear the photon arrival time (by 55ps) and pixelise hits with a 128-by-8 effective pixelisation.

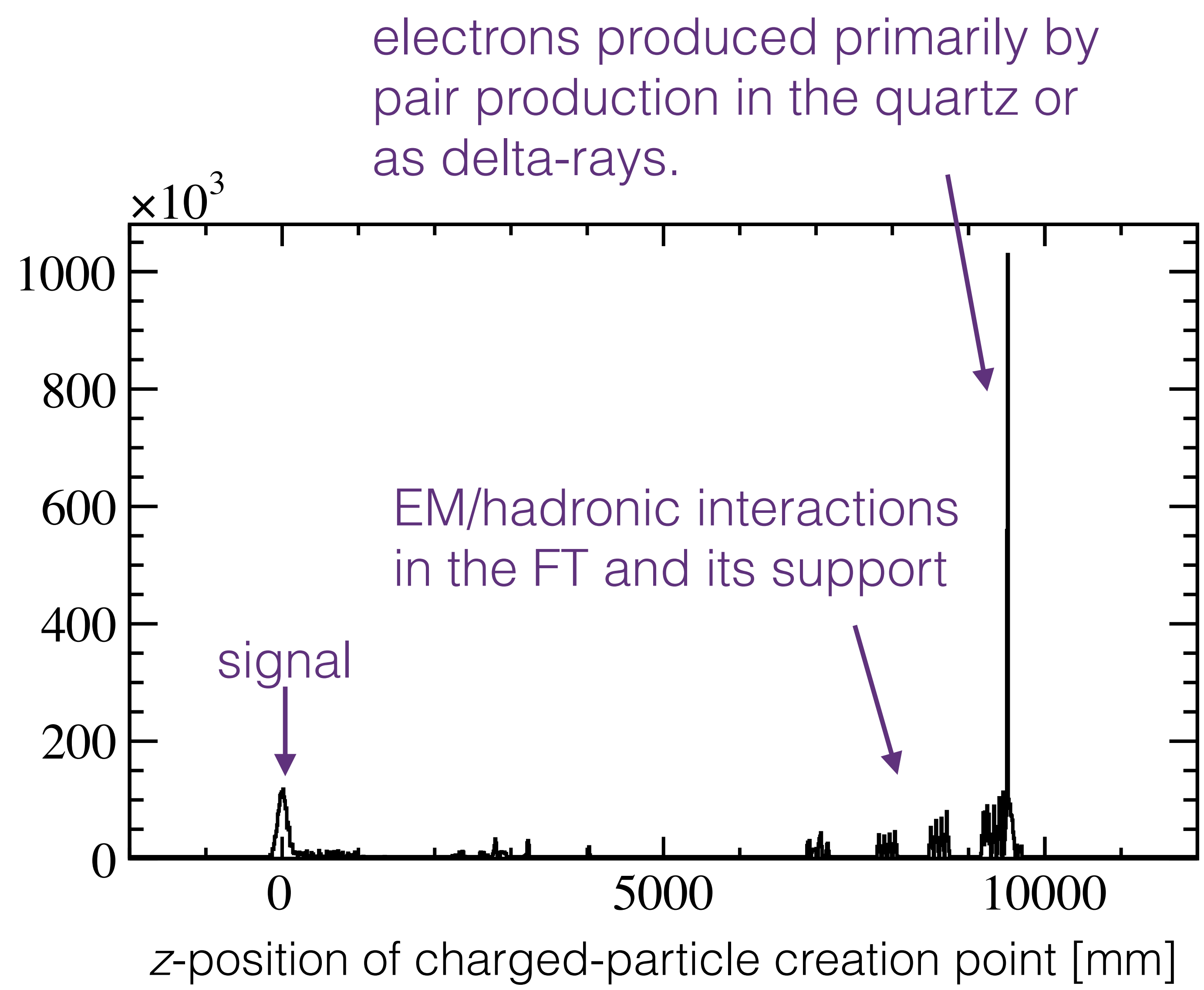
Detector occupancy

- In the **Upgrade Ib** data taking conditions the per-pixel occupancy is 5-20%, depending on the module (highest in the most central modules).



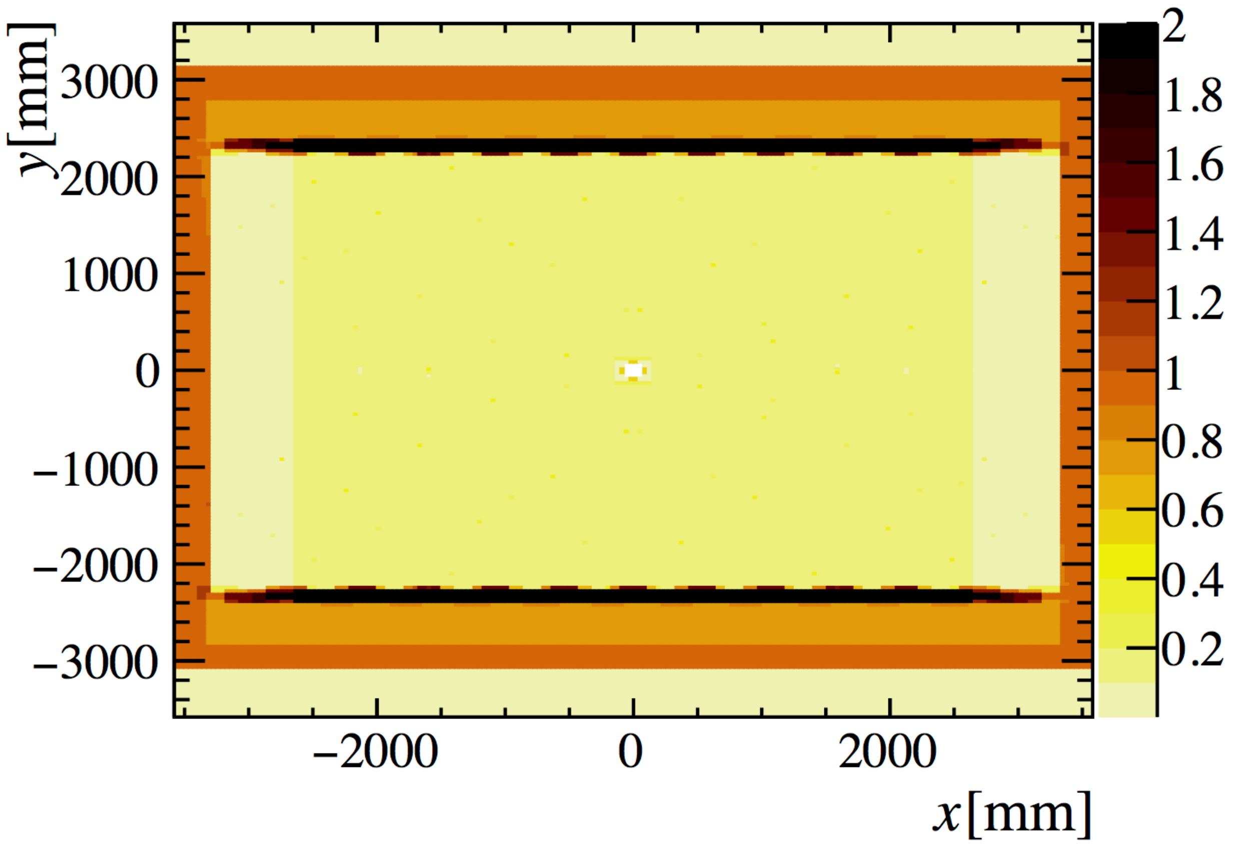
Background photons

- Large number of background photons produced by charge particles from material interactions in the detector.

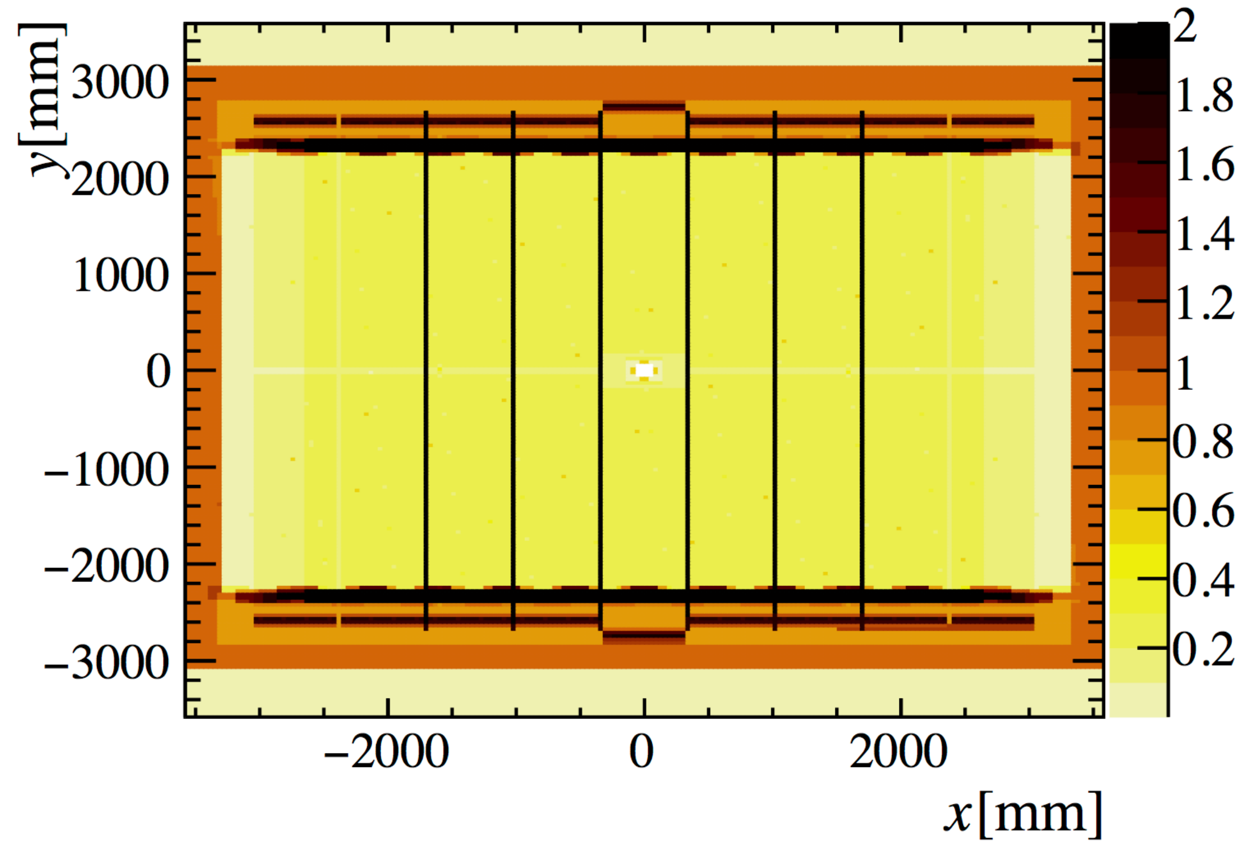


Material

- Material scan from **Gauss**:



without TORCH radiator

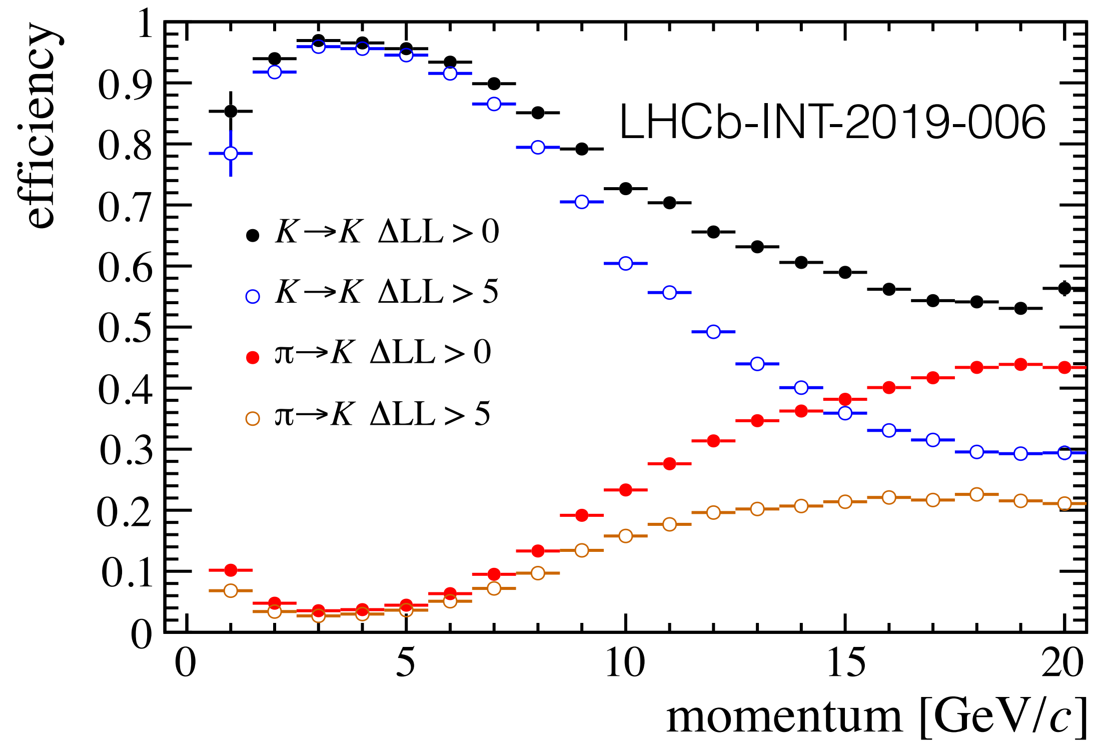


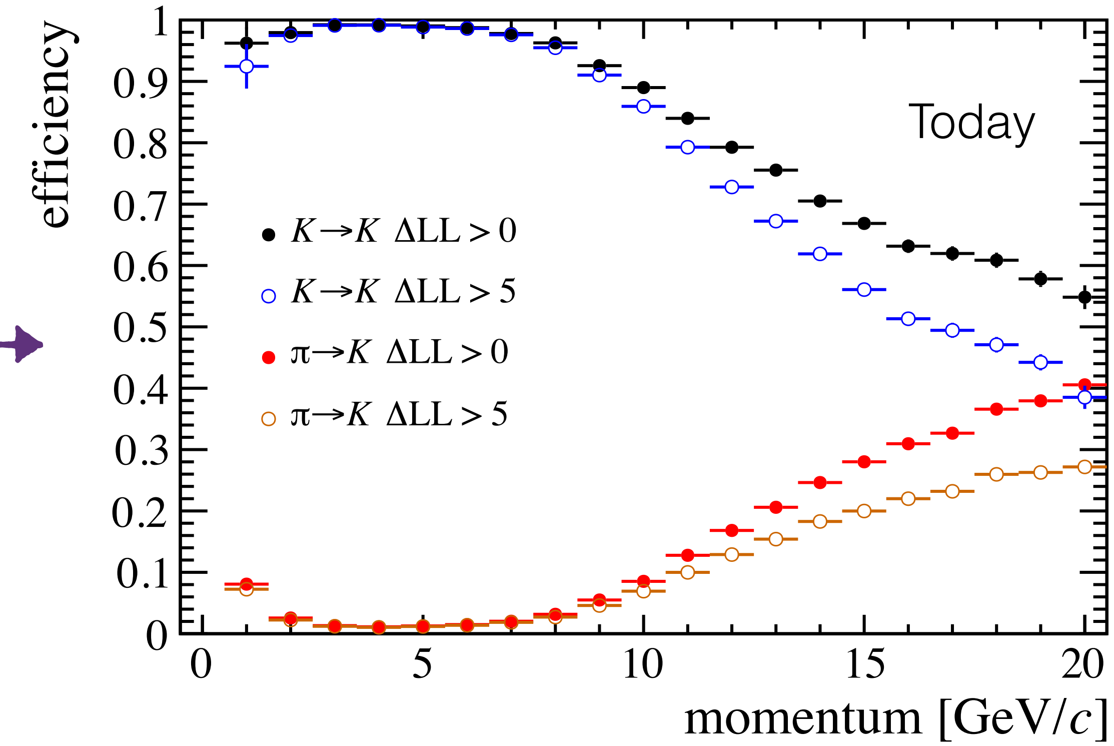
with TORCH radiator

- Increases the amount of material in the acceptance by ~0.1 X_0.
- Note, no support structure is currently included.

Performance in LHCb-INT-2019-006

NB This is a significant improvement c.f. LHCb-INT-2019-006:



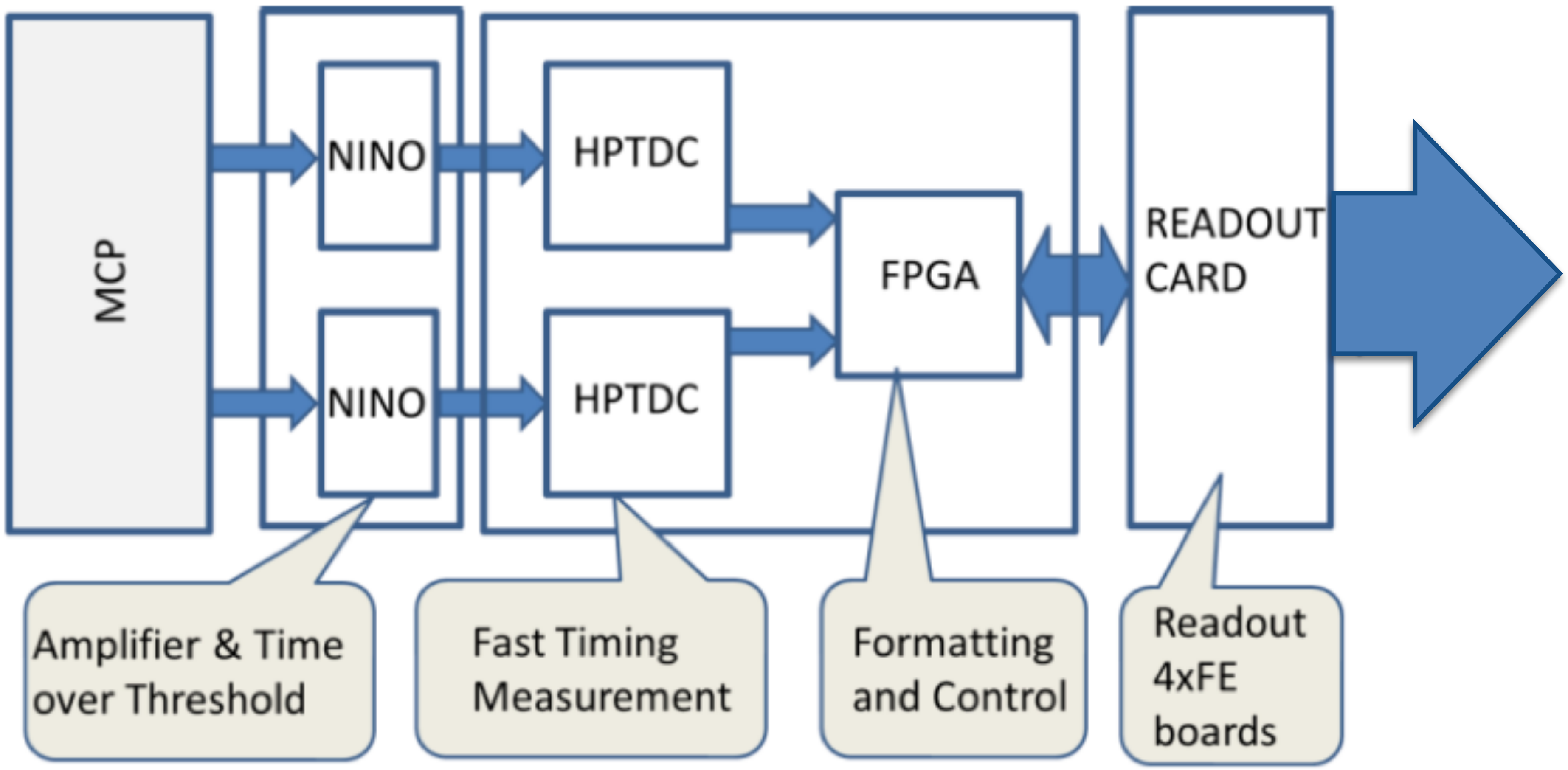


- In comparing the performance of LHCb-INT-2019-006 to a stand-alone simulation, we realised:

    1. The top/bottom of the focus were not correctly blackened in the simulation.
    2. Optical photons were randomly being removed by RICH photon tracking code, irrespective of where they were in the detector.

Data rate (preliminary)

- Schematic of the current readout electronics for the TORCH prototype:



- From each TDC we read out:
  - Header (32 bit)
  - Leading edge per measurement (32 bit)
  - Trailing edge per measurement (32 bit)
  - Trailer (32 bit)

Data rate (preliminary)

- 64-by-8 pixels per MCP, resulting in ~100k channels for the full detector.
- Estimate of the typical event size, based on the existing readout

modules

TDCs per MCP

per-pixel occupancy

$$= 18 \times 11 \times 16 \times (2 + 2 \times 10\% \times 32) \times 32\,\mathrm{bits}$$

MCPs per module

packets per TDC (header, trailer and measurements)

- Resulting data rate $= 40\,\mathrm{MHz} \times 800\,\mathrm{kbit} = 32\,\mathrm{Tbit/s}$

- Expect to reduce the rate by reading out only the leading edge and the time over threshold as a single 32 bit word. In a continuous readout we can also reduce the header/trailer sent from each TDC.