The **TORCH** Detector at the LHCb experiment

EPP Seminar, University of Warwick

13th of October 2022

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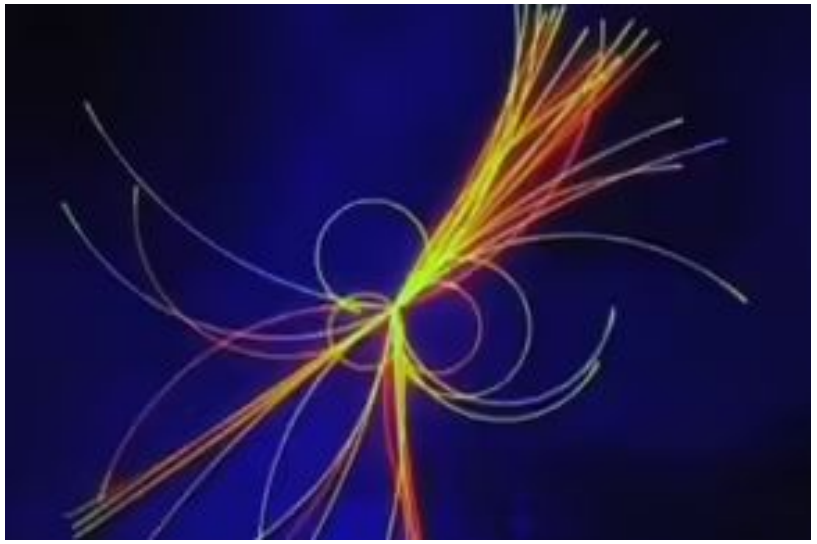
Outline

- **Introduction**
  - Importance of Particle Identification
  - Particle Identification at LHCb

- **Torch detector**
  - Principle and design
  - Pattern reconstruction
  - Performance and timing
  - Test beam

- **Summary and conclusions**

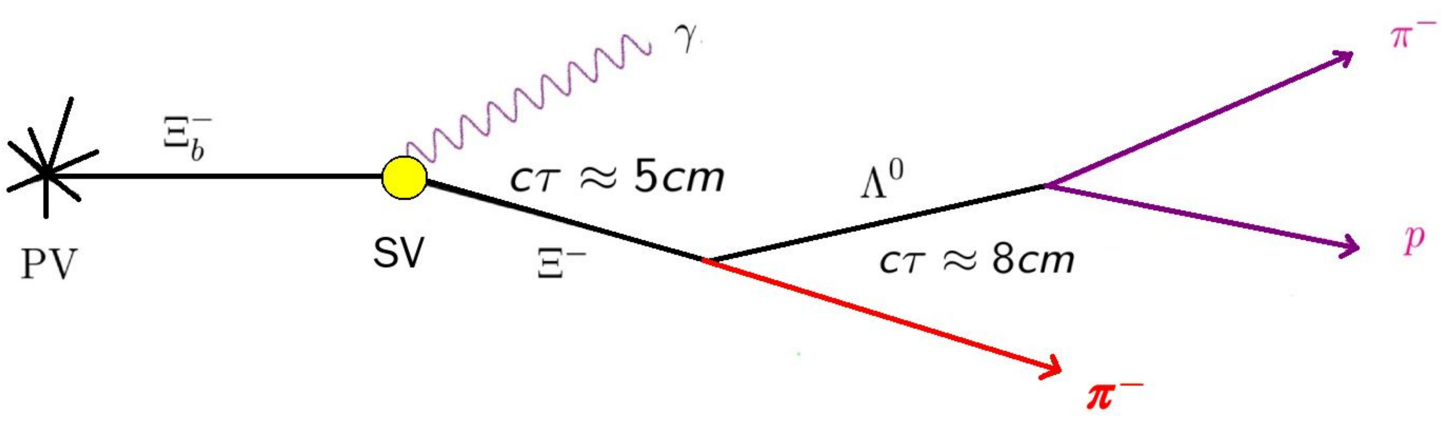


Introduction

- Searches for New Physics via the **precision study** of
  - CP violation
  - Rare decays of heavy quarks
  - …

- Particle detectors aim to measure properties of particles
  - Long-lived particles can be measured directly
  - Short-lived particles are “reconstructed” through their decay products

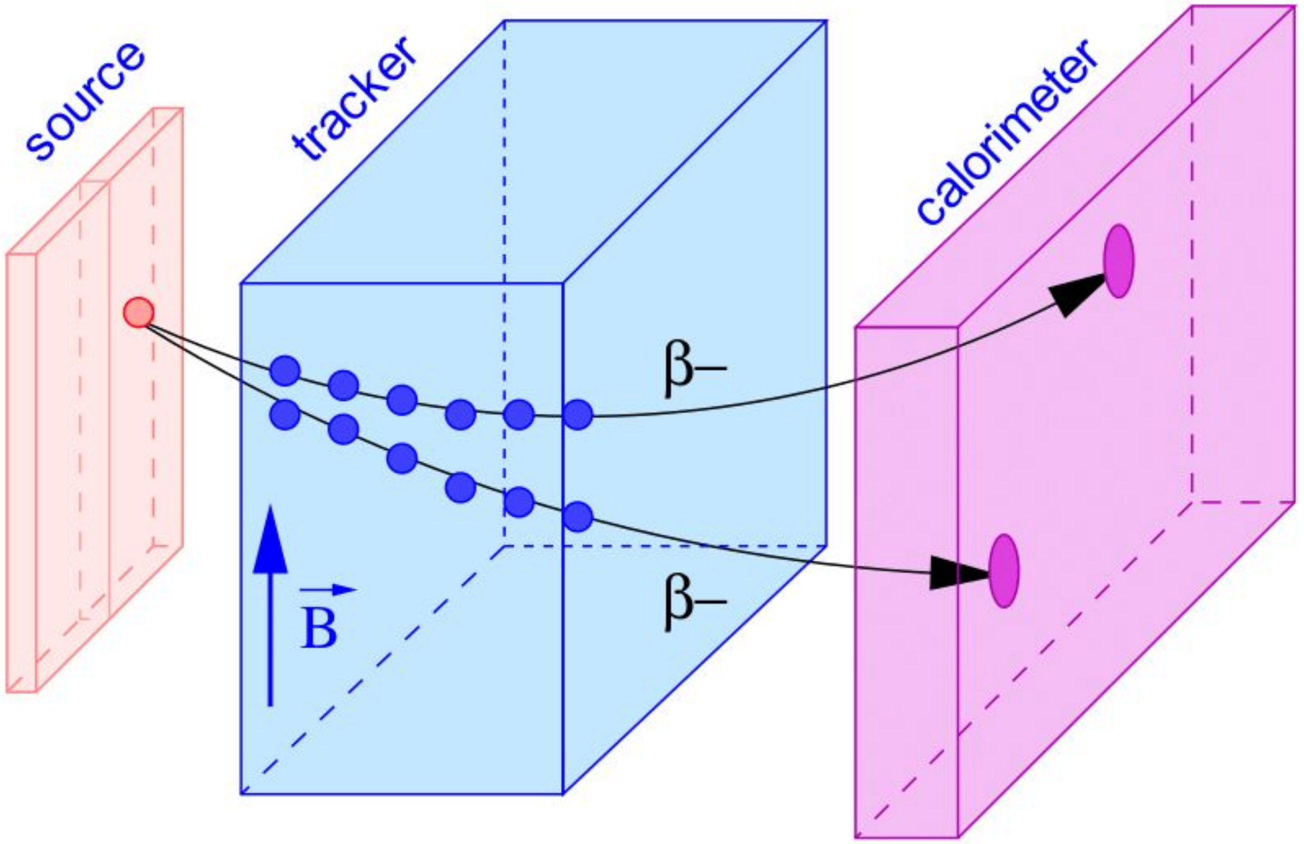
- Require accurate information about momentum, charge and mass



Introduction

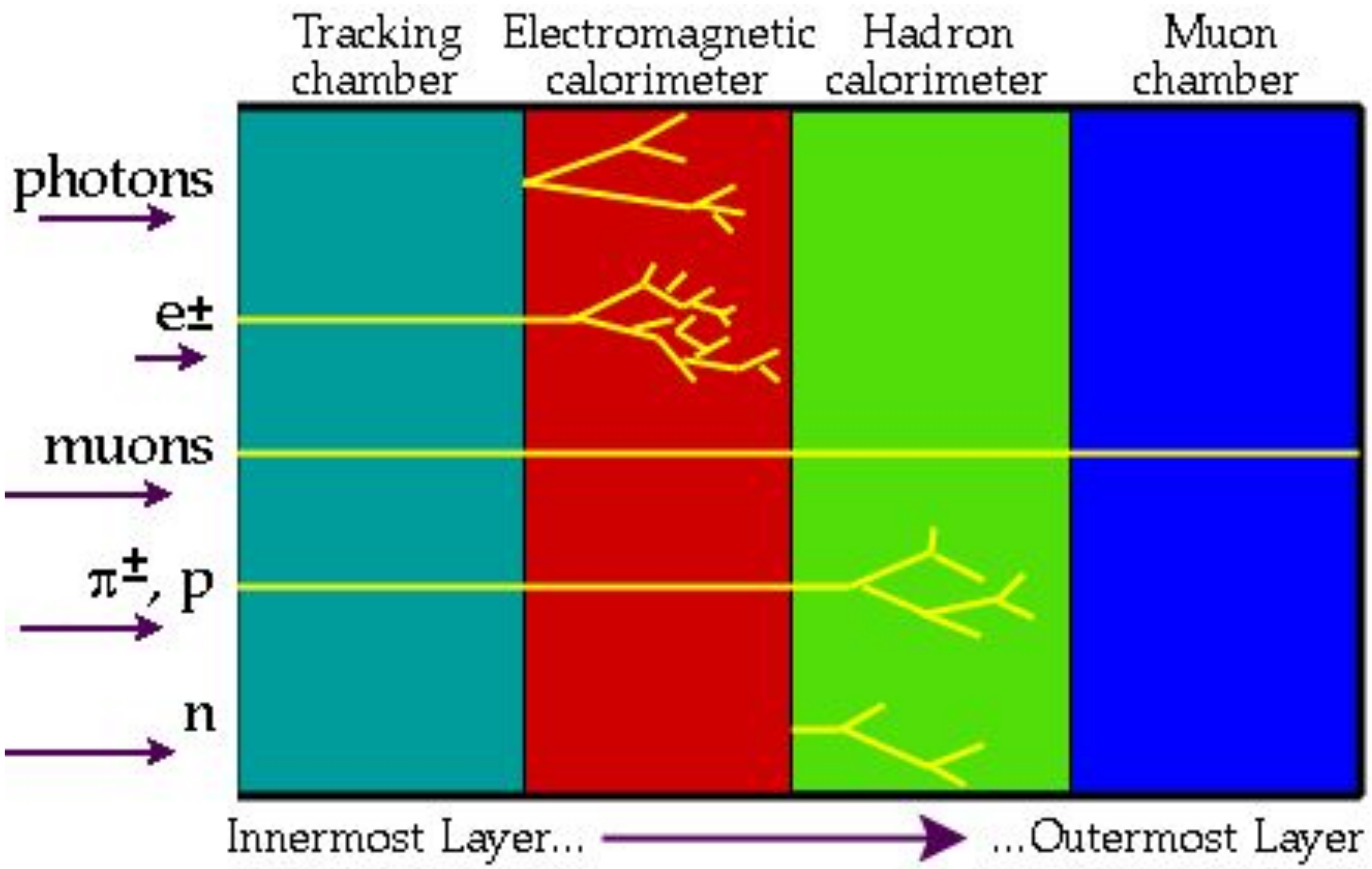
- **Tracking devices:**
  - Reveal the **paths of charged particles** as they pass through
  - Low interaction with the particles (conservative measurement)
  - Allow to measure the **momentum if used with a magnetic field**

- **Calorimeters:**
  - Measure the **energy a particle** loses as it passes through
  - Usually completely stop the (destructive measurement)



Introduction

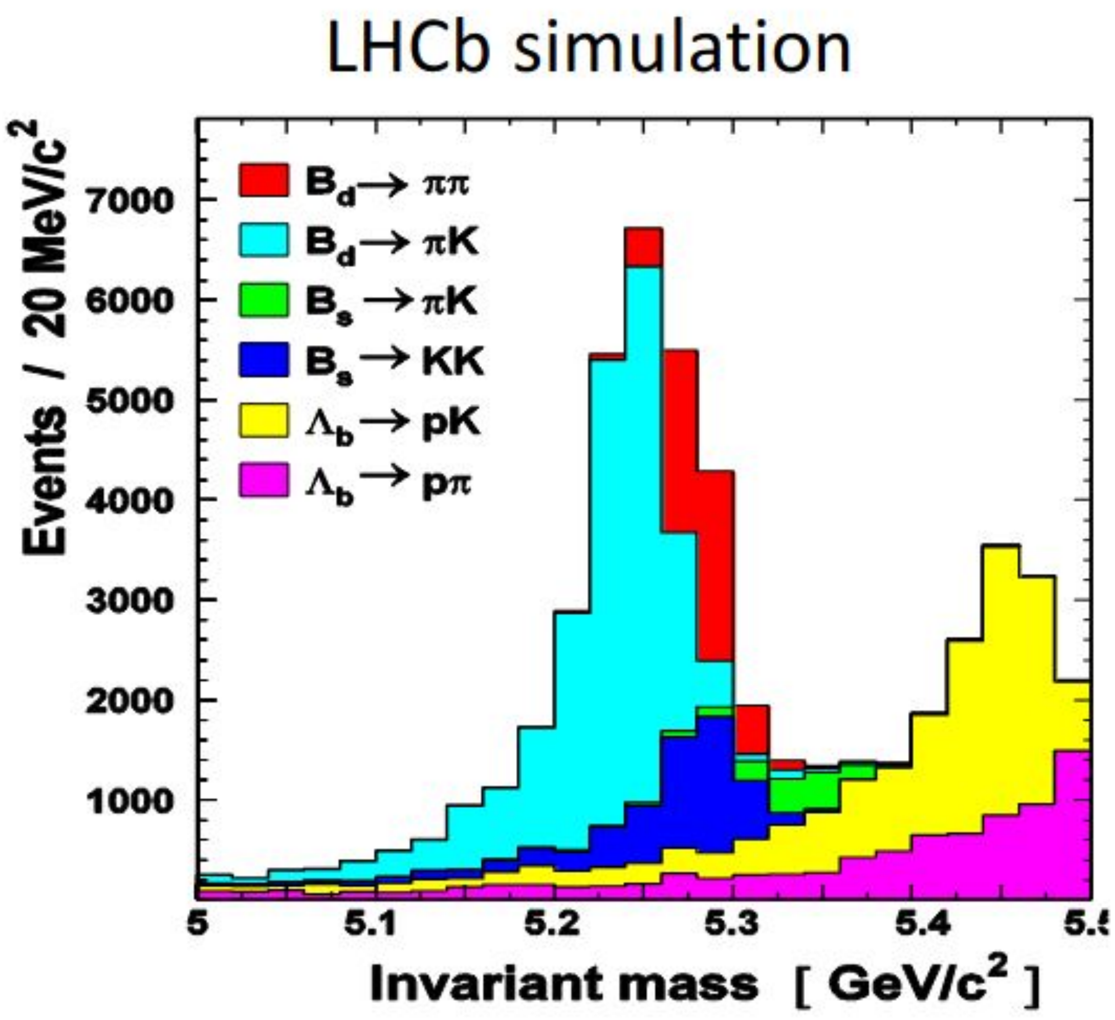
- Elementary particles give different **characteristic signatures** in detectors
- Tracking and calorimeter information provide some level of particle identification
- Allow to combine particles to “recover” their “origin” (vertexing)



Introduction

- Different charged hadrons (p, π, K) has similar signal
  track + hadronic shower
- This makes difficult distinguishing between final states with the same topology
- Making all two-track combinations in an event and calculating their invariant mass is expensive
  huge combinatoric background
- **Hadron identification is** a **key** ingredient in b-physics & hadron spectroscopy

many different modes overlap



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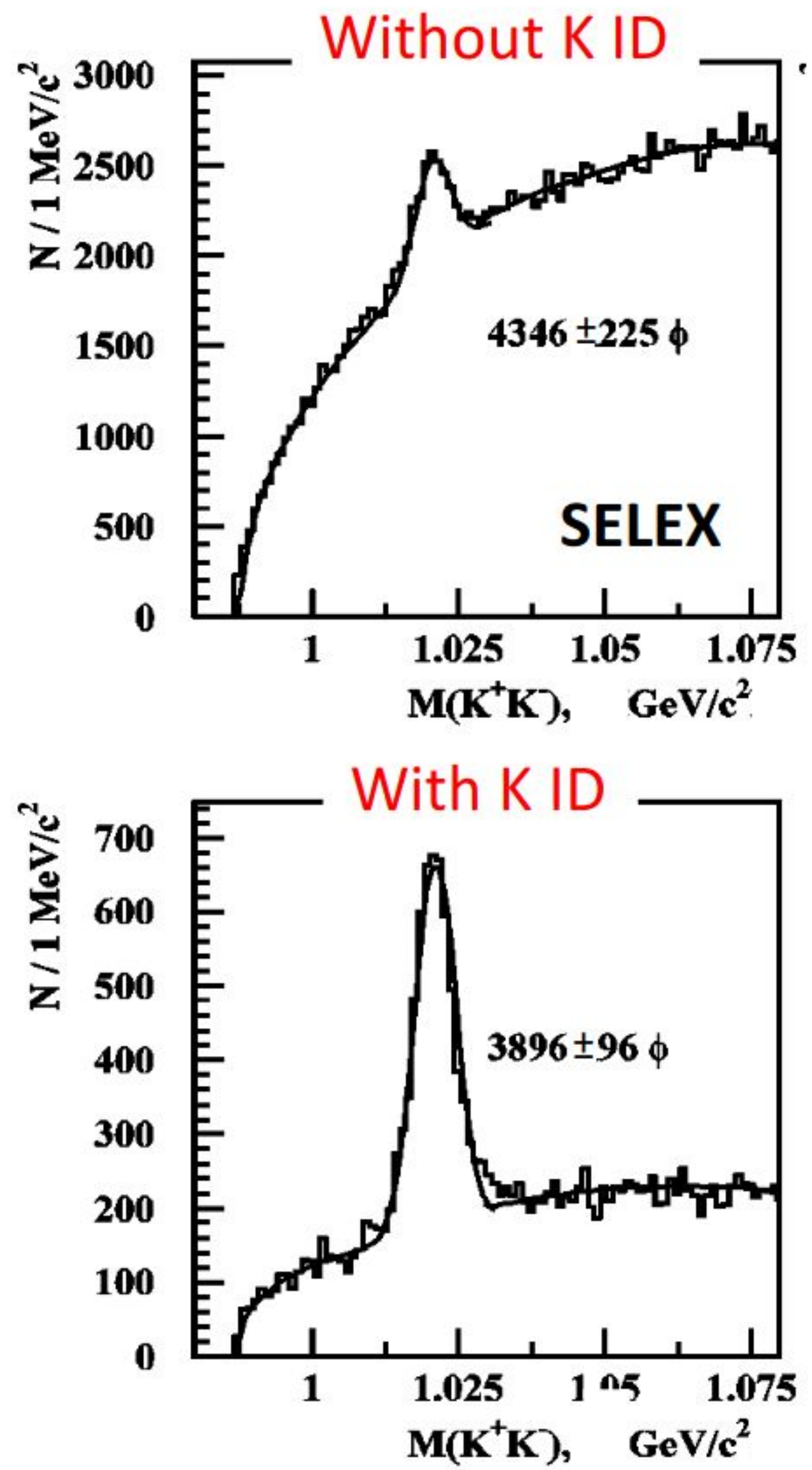
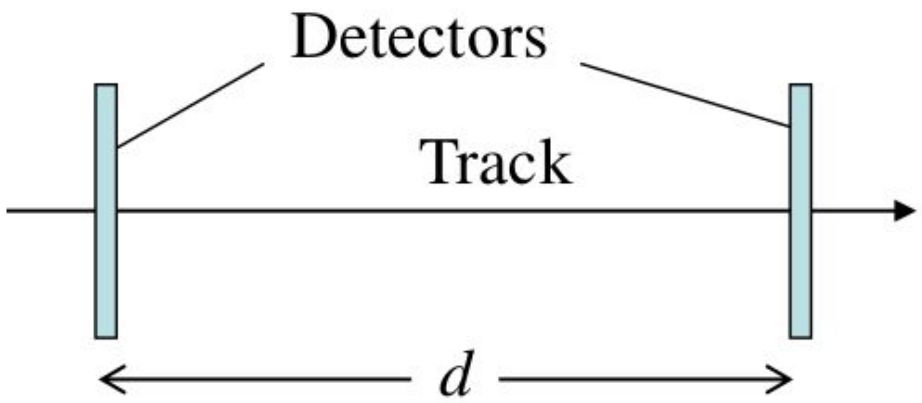


Introduction

- Exploiting charge hadron **rest mass for particle identification**
  - Momentum (p) provided by the tracking system
  - Mass (m) can be **determined from their velocity** ($p = \gamma m v$)
- Processes that depend on the particle velocity :
  - **Time Of Flight** (TOF) of the particles over a fixed distance



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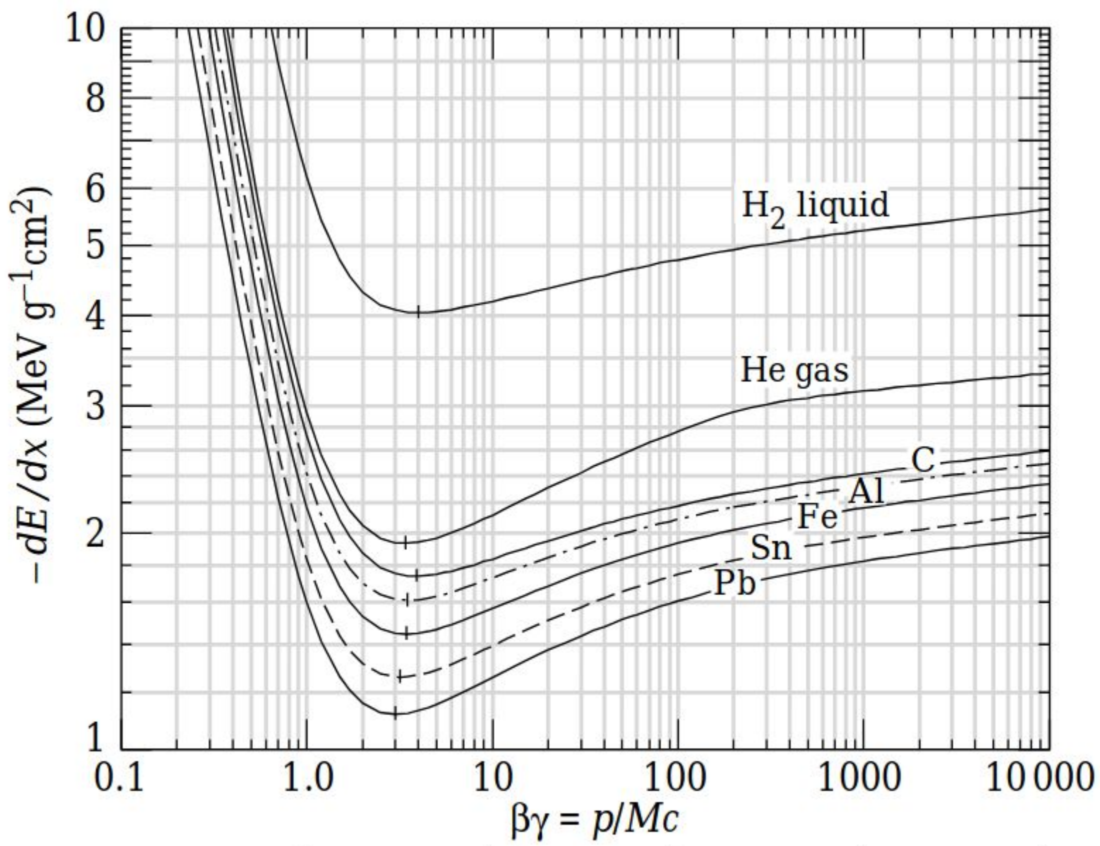

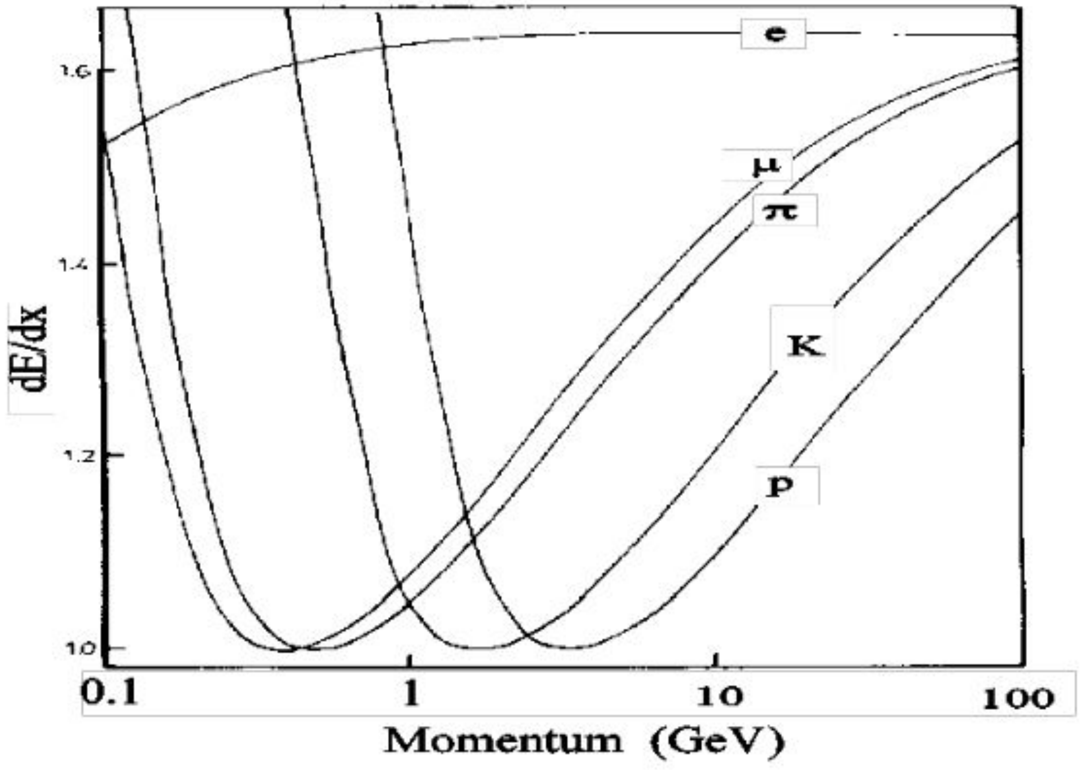

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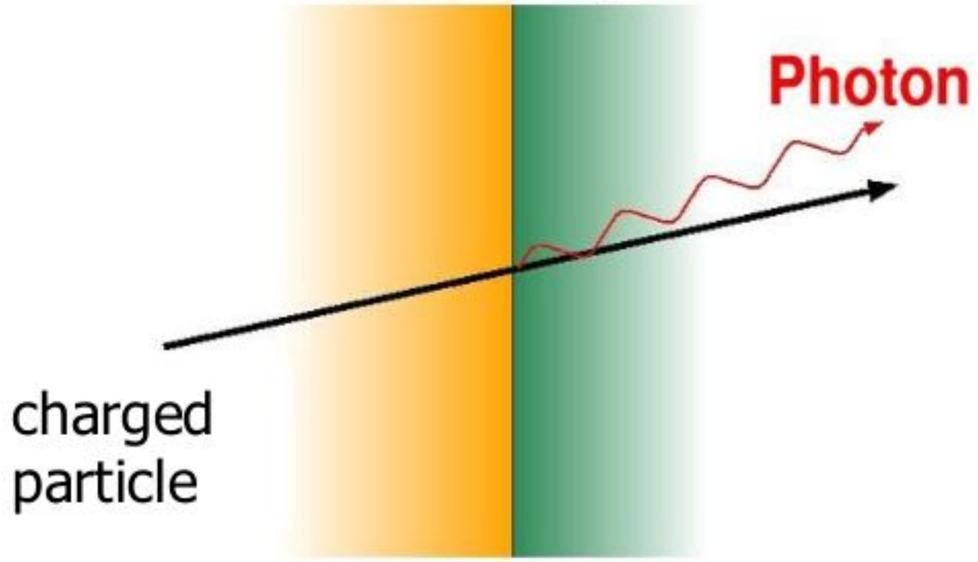
  - **Transition Radiation**: relativistic charged particle change of medium



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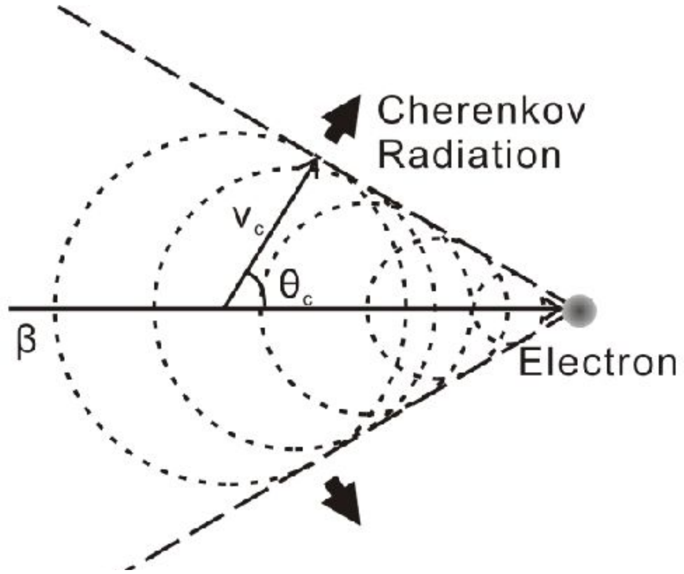
  - **Cherenkov Radiation**: particle travels faster than the local speed of light



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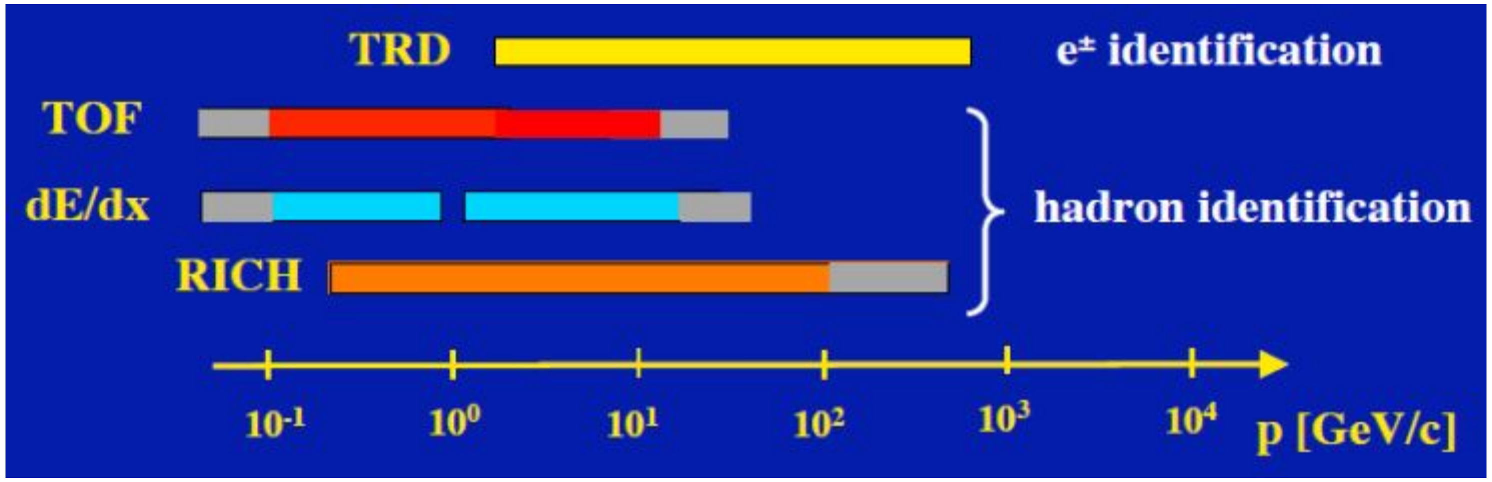
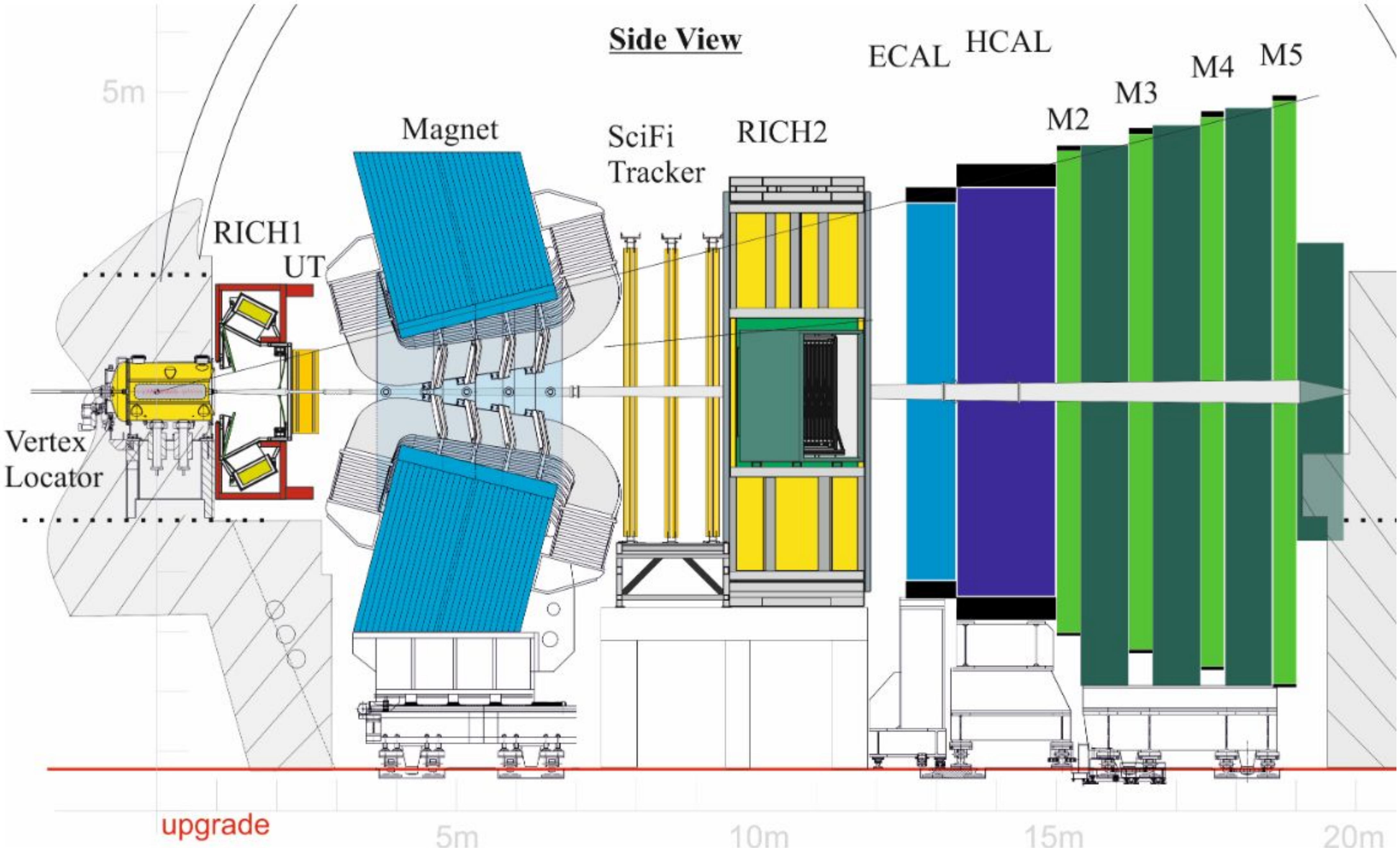


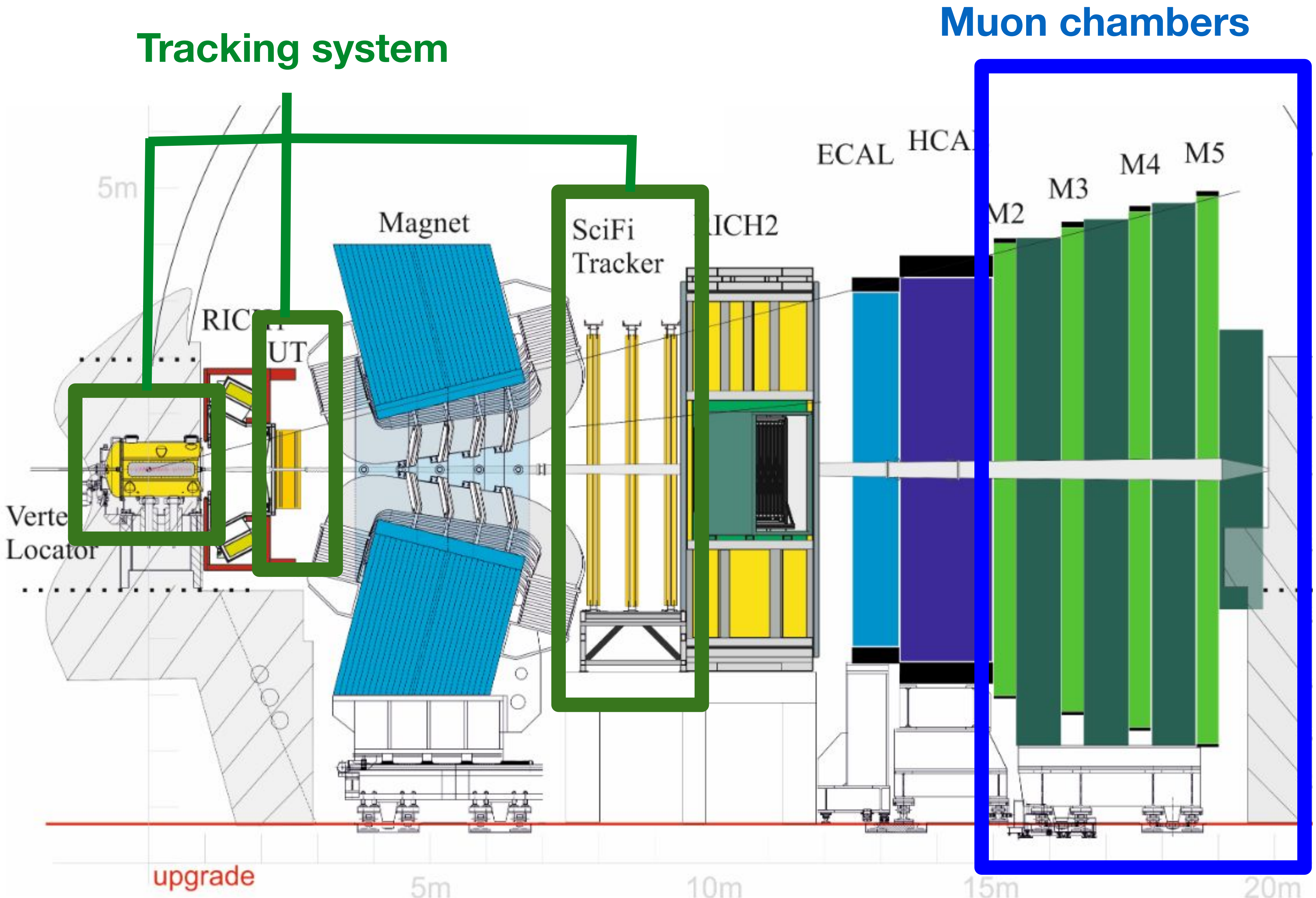
- RICH well established for hadron identification
- TRD useful for $e^{\pm}$ identification at higher momentum
- dE/dx & TOF work mainly in low momentum region
  - TOF extending upwards due to novel techniques

LHCb Detector

- Dedicated study to b- and c-hadrons (produced in the forward direction)
- Single arm forward spectrometer

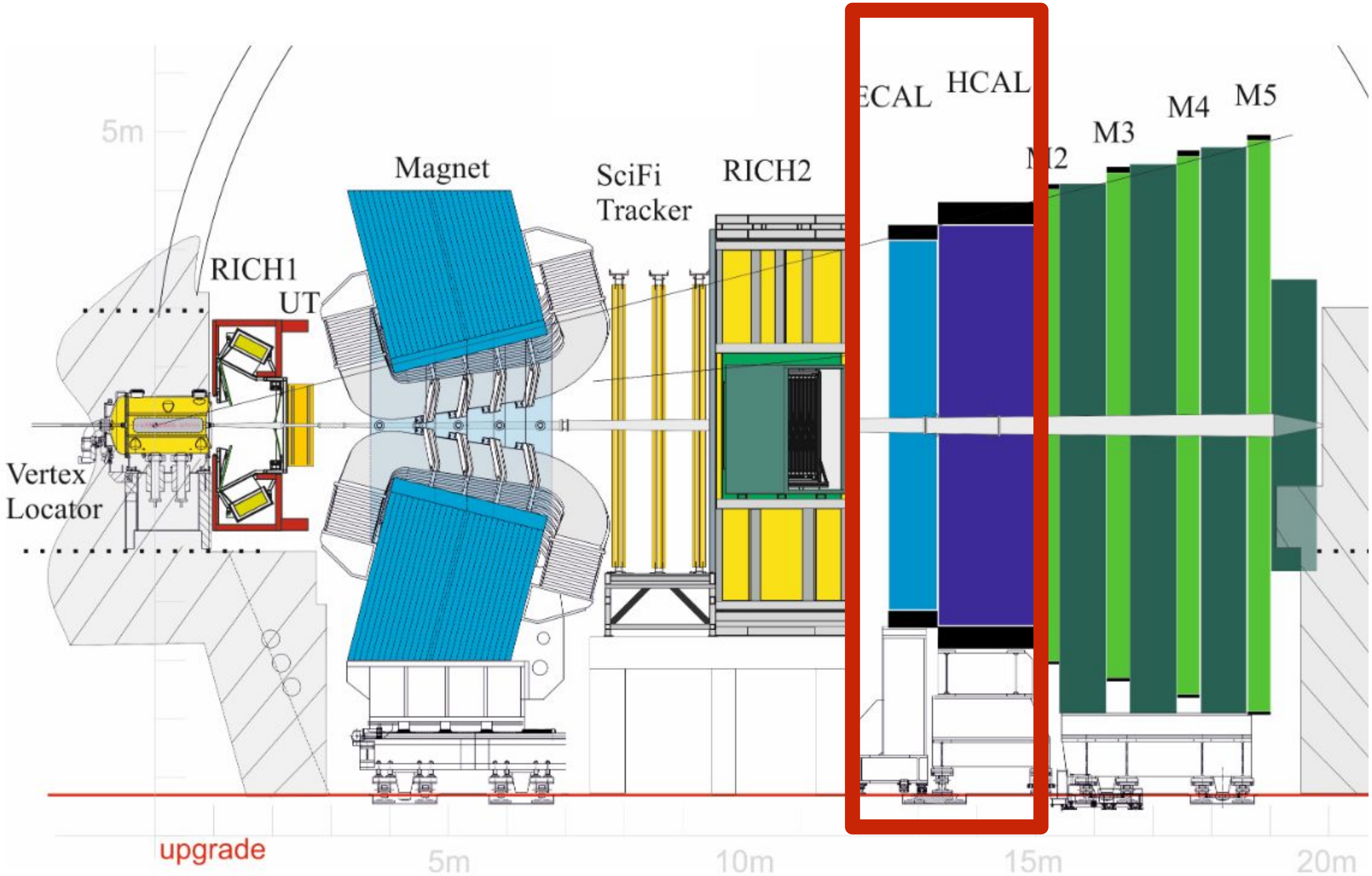


LHCb Detector



LHCb Detector

Calorimeters



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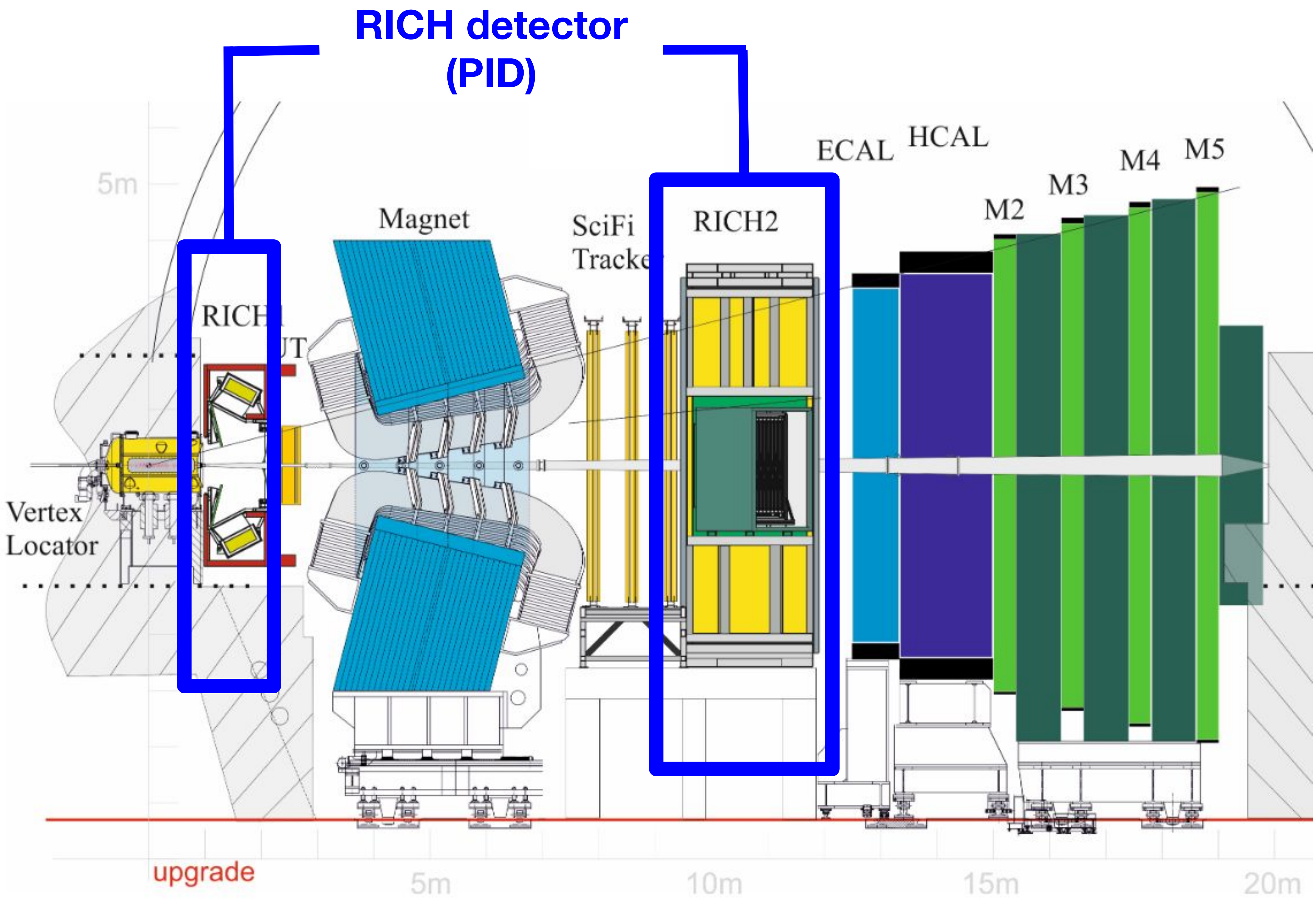


LHCb Detector

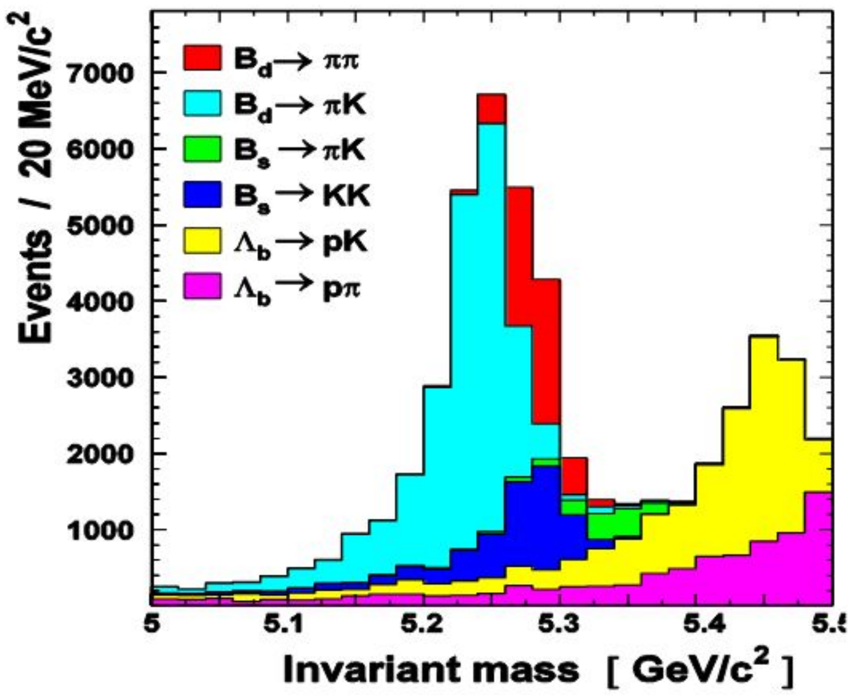
Distinguishing between final states with the same topology

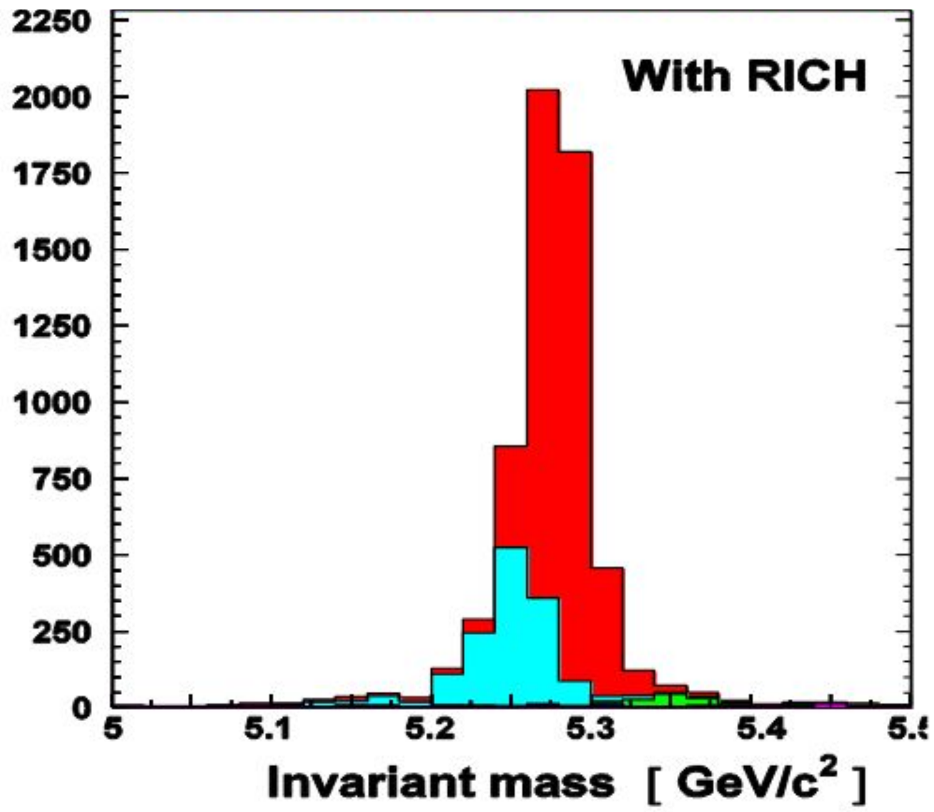
b-hadrons two-body decays into charmless charged hadrons at LHCb

→ with PID

↓ without PID

LHCb simulation





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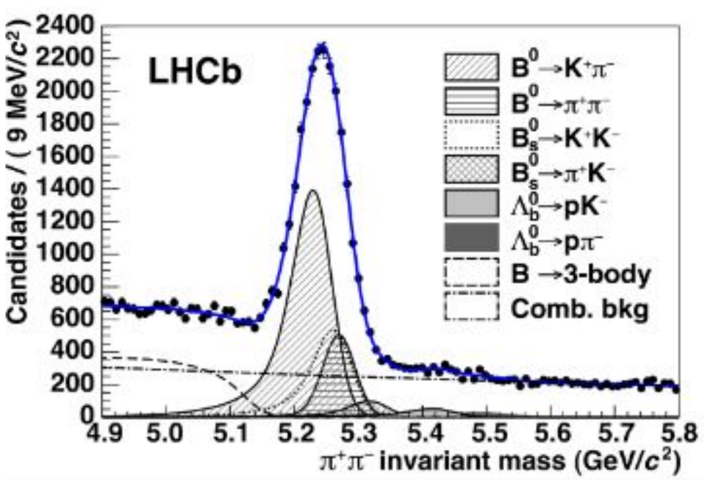
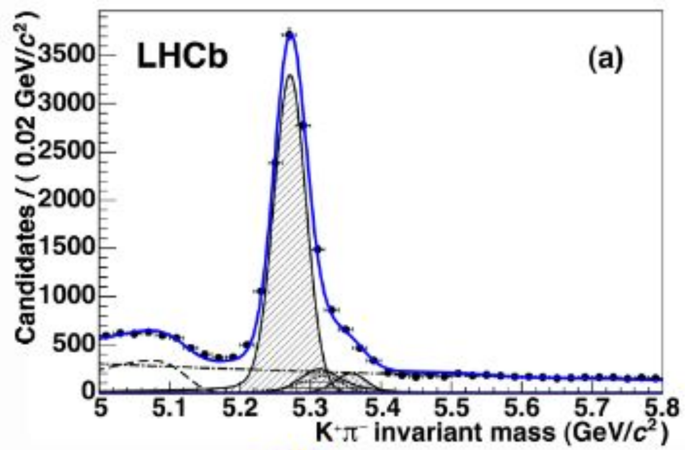
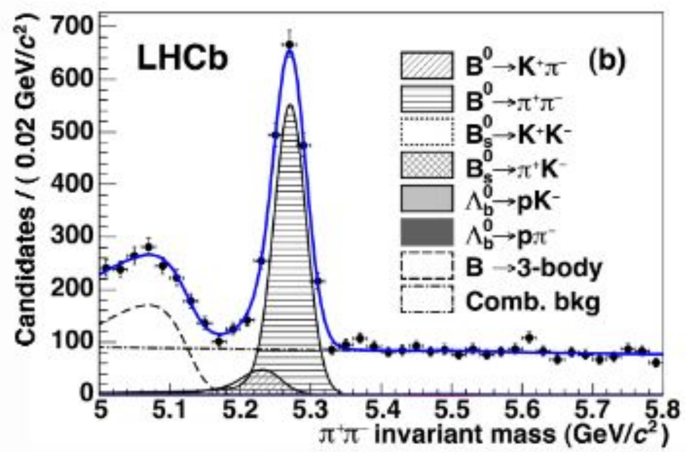


[LHCb, JHEP 10 (2012) 37]

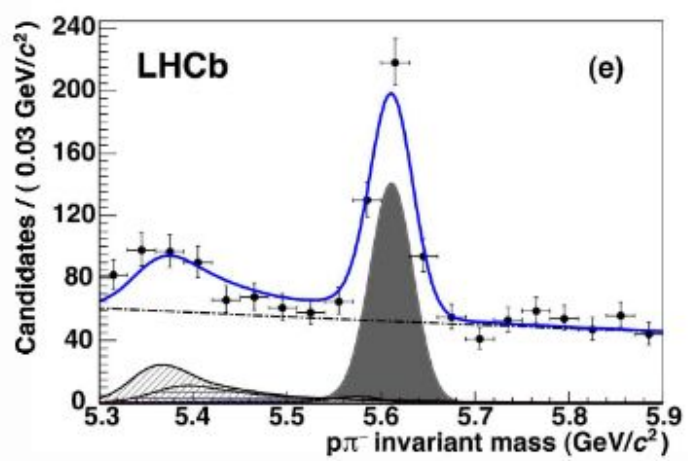
$B^0 \to K\pi$



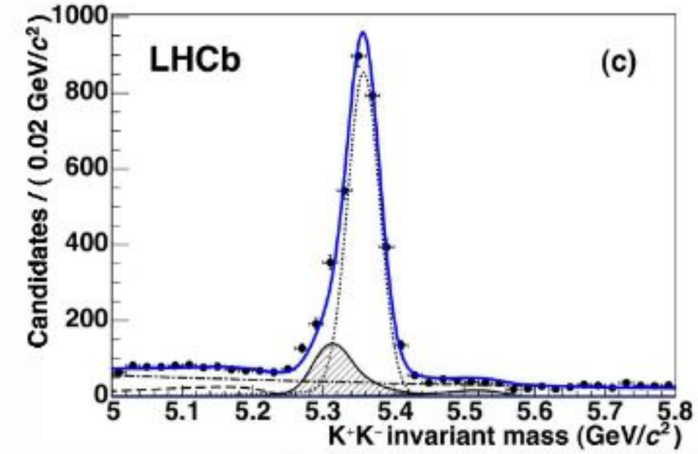
$B^0 \to \pi\pi$



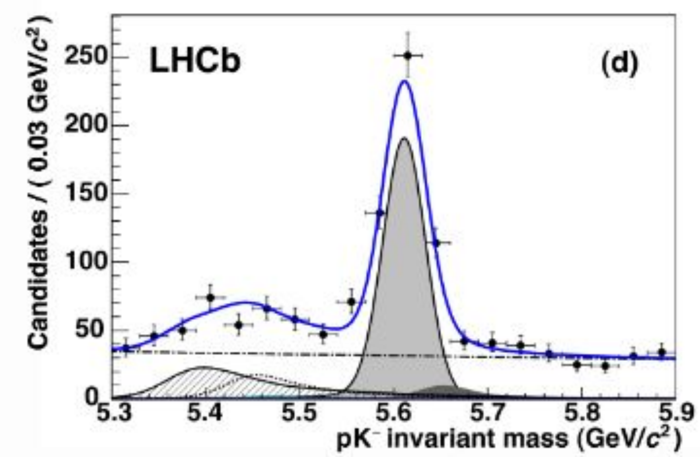
$\Lambda_b \to p\pi$



$B_s^0 \to KK$

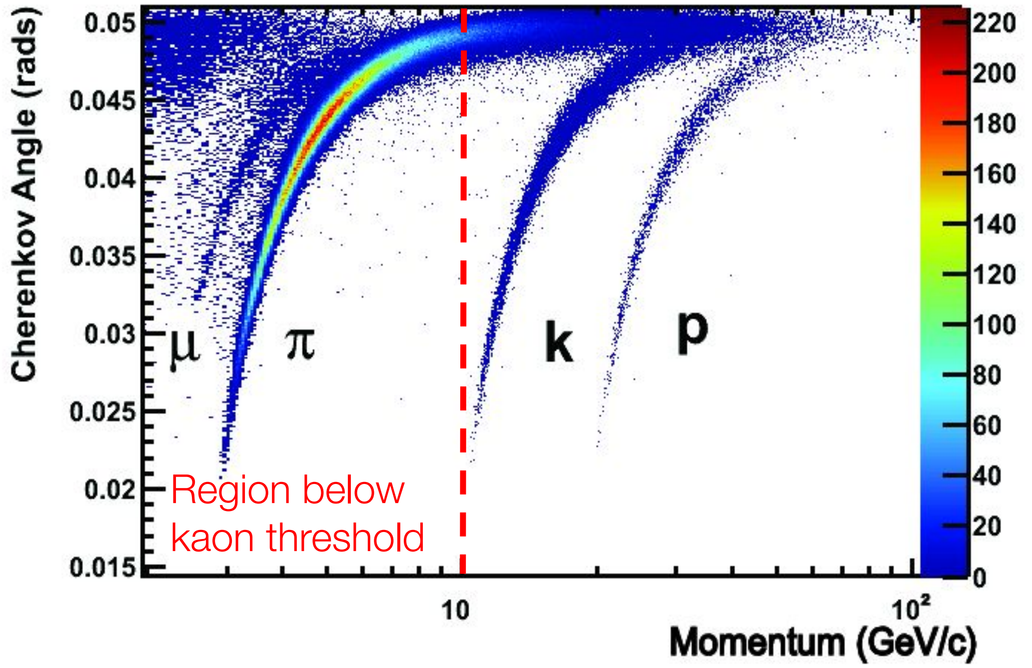


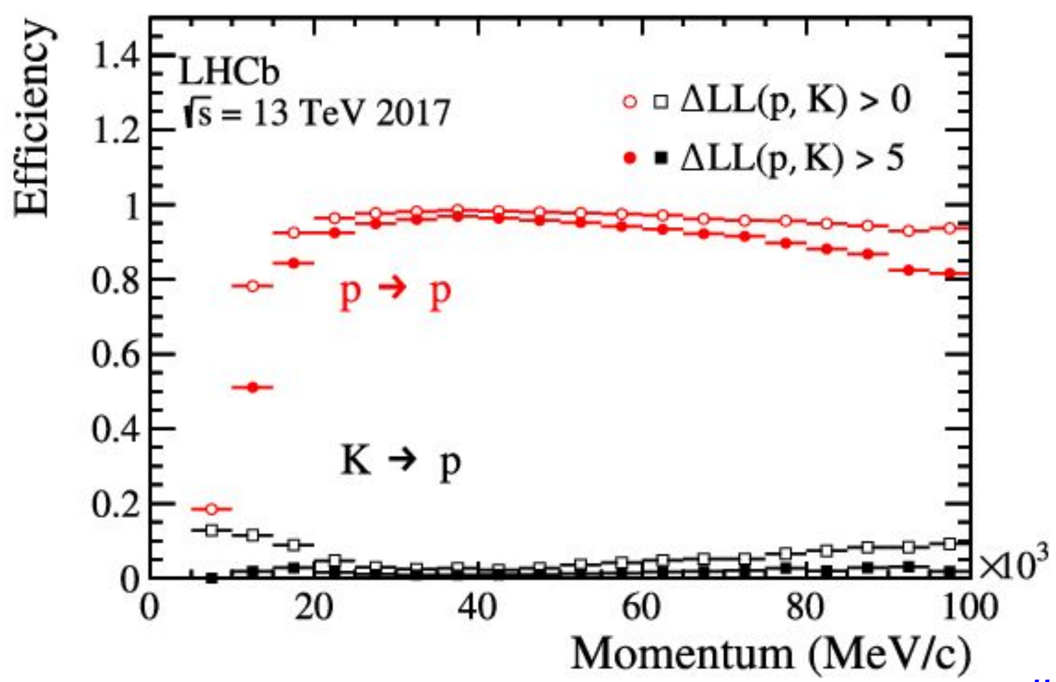
$\Lambda_b \to pK$

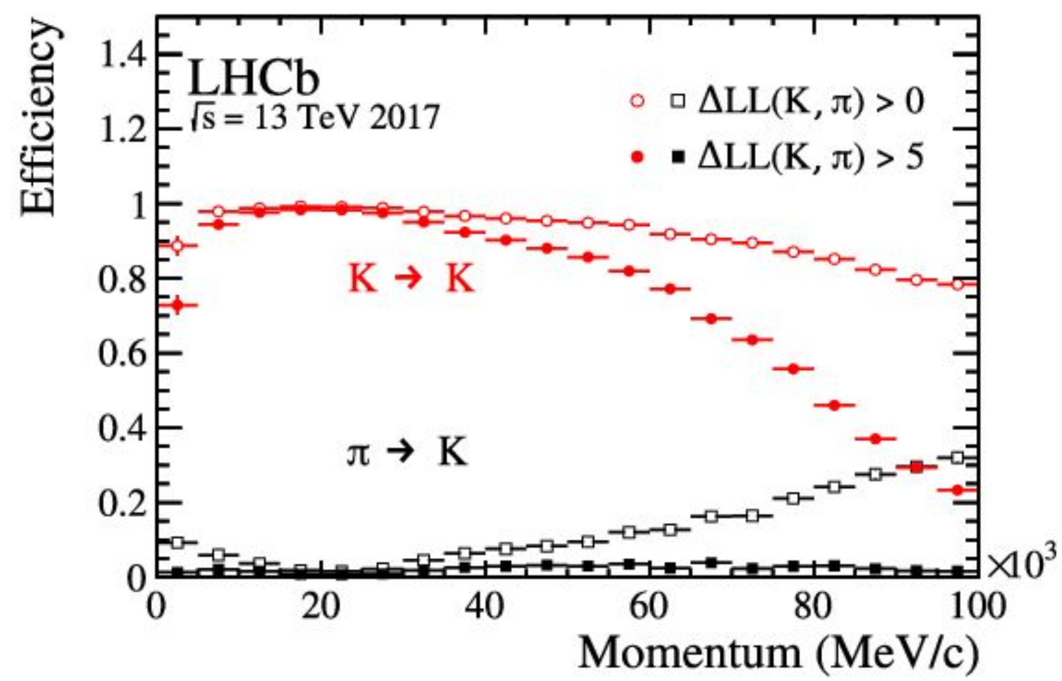


PID at LHCb

- PID at LHCb currently provided by 2 RICH detectors
- No positive kaon identification below 10 GeV/c
- No positive proton identification below 20 GeV/c





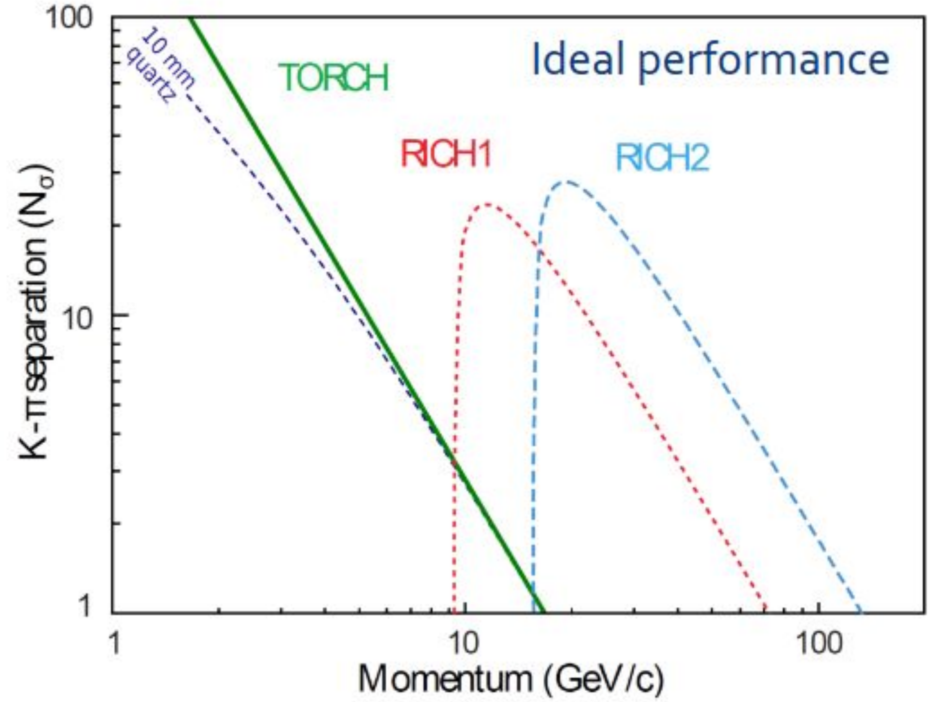


JINST 17 (2022) P07013

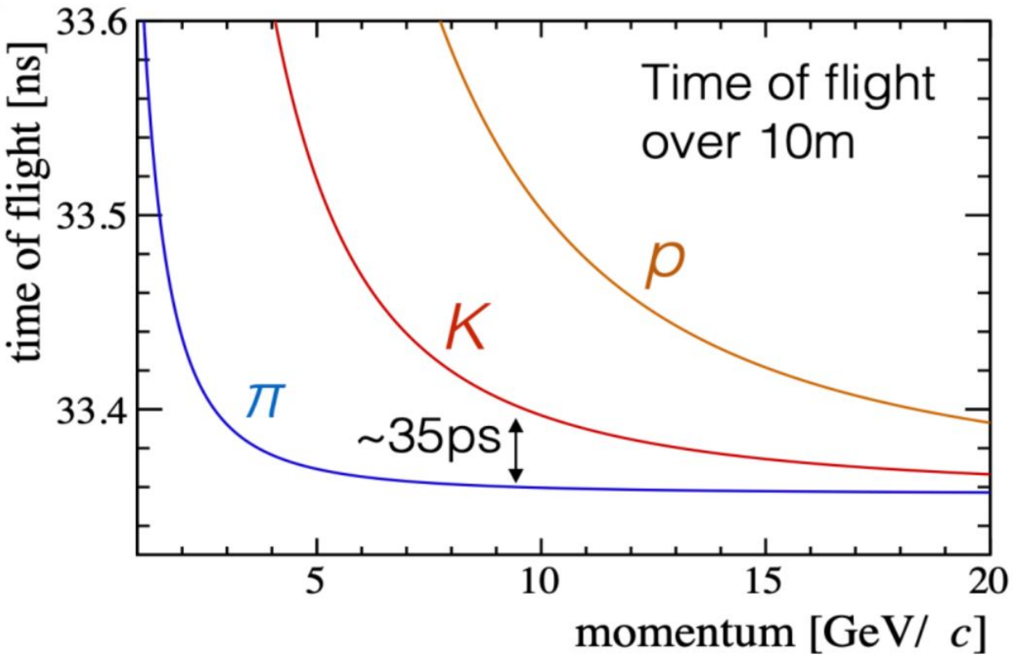
TORCH

TORCH: Time **O**f internally **R**eflected **CH**erenkov light

- Proposed solution to enhance low momentum (2-20 GeV/*c*) particle identification at LHCb:
  - Covers region where kaons are below threshold in the LHCb RICH detectors
  - Cover a large area



- **Exploit time-of-flight (ToF) for particle ID**:
  - ΔToF(K-π) ~ 35ps for a 10m flight path
  - Aim for ~10-15ps per track for 3σ K/π separation
  - Expect ~30 detected photons per track
  - Need σ_t=70ps per photon



The TORCH principle

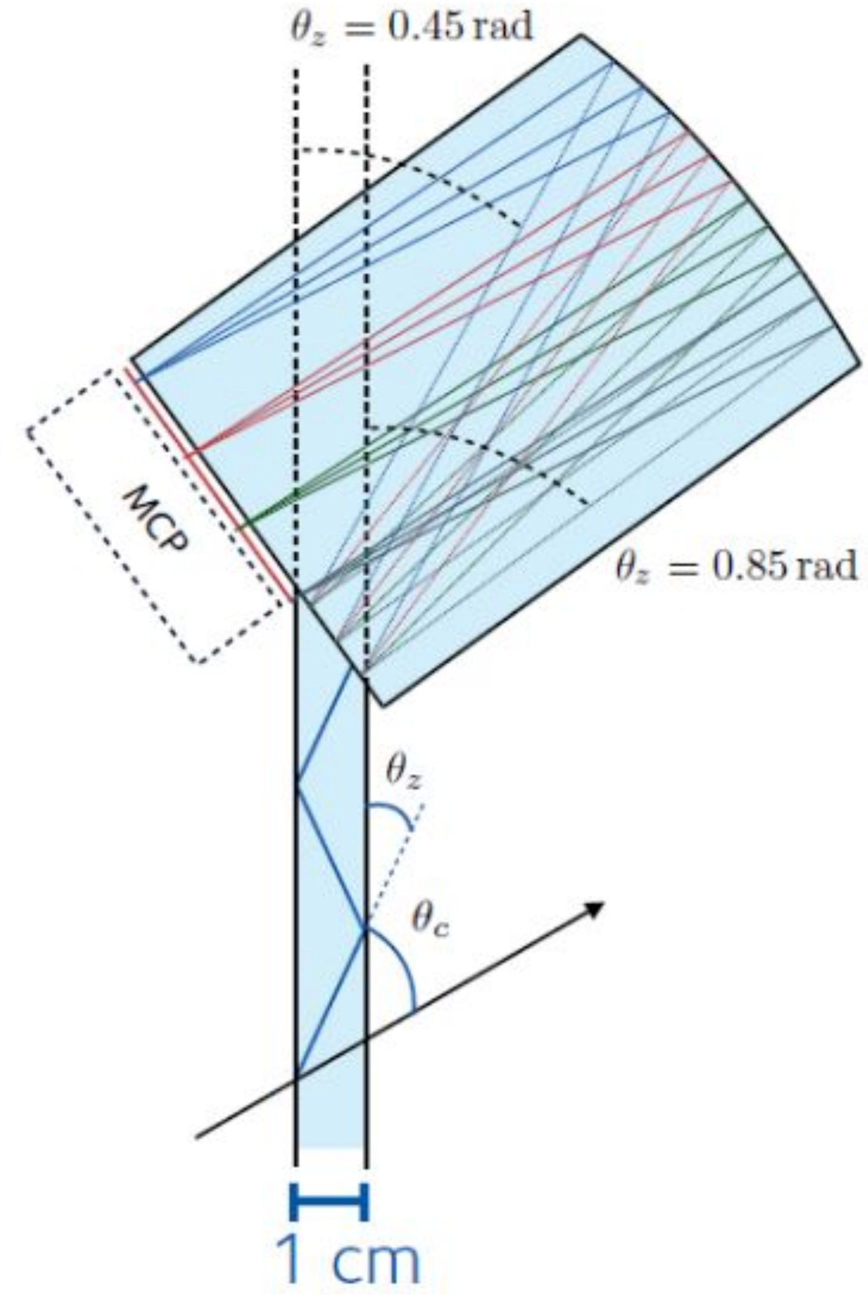
- Charged **particles** passing through a quartz plate **generate prompt Cherenkov photons**

- Photons are propagated via total internal reflection to the periphery of the detector

- A cylindrical focusing block focuses the photons onto an array of photon detectors
  - MCP position maps to θ_z

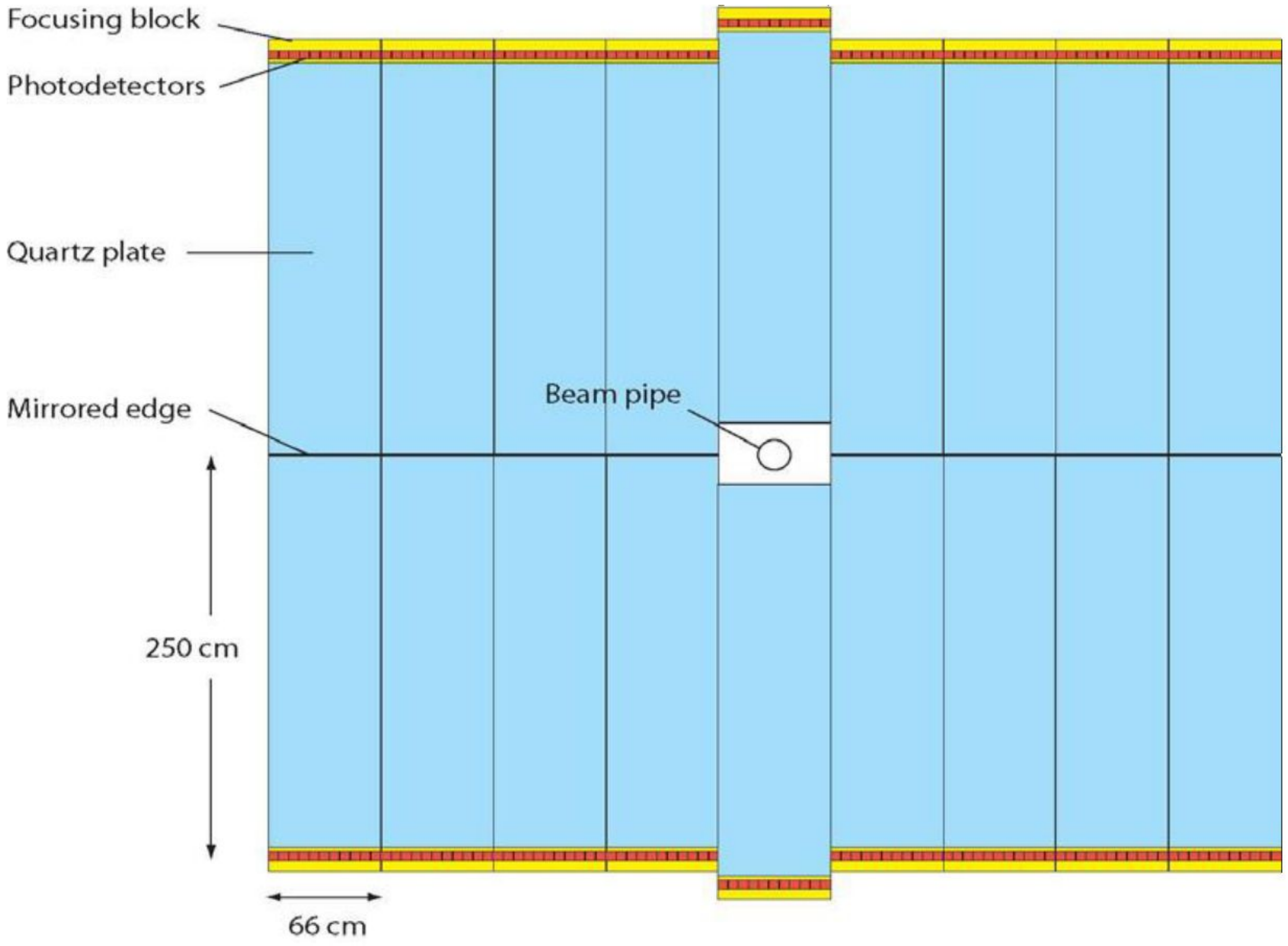
- **Photon arrival time and position is measured** to derive:
  - Cherenkov angle and path length
  - Photon propagation time

- Method is related to that used by the BaBar DIRC and Belle II TOP



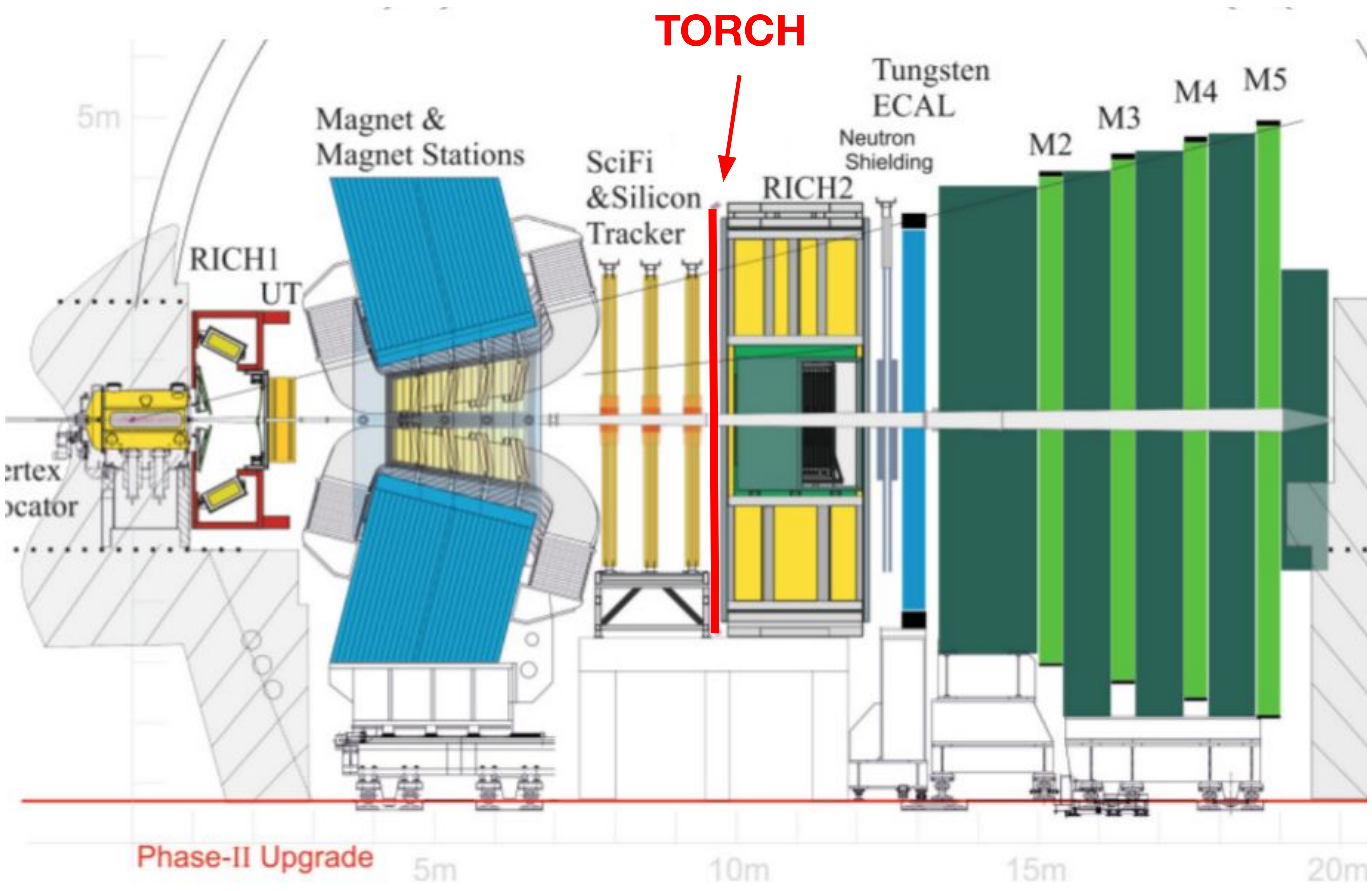
TORCH design

- 18 identical modules 250 x 66 x 1 cm^3 (covering and area of ~ 5x6 m^2)
- 11 photon detectors per module (18 x 11 = 198 photon detectors)
- Reflective lower edge (photon detector required only at top edge)
- Full TORCH implementation now planned for future LHCb upgrade at the HL-LHC (LHCb upgrade II framework TDR [LHCB-TDR-023])

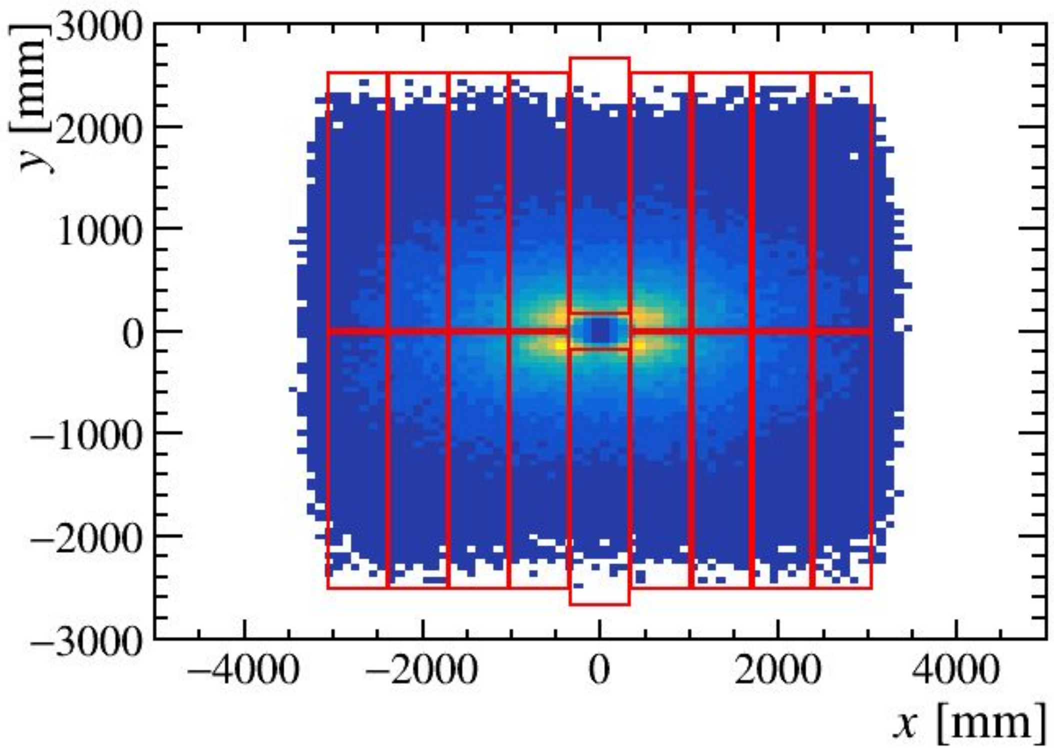


TORCH design

- Proposal to install TORCH in front of RICH2, in LS4 (for ~2033)
- TORCH will be located at 9.5m of the interaction point
- Need to cover a wide area



Extrapolated reconstructed track position of 2-20 GeV/c tracks to TORCH



The TORCH principle

- **Time-of-flight** derived from:
- Photon arrival time (measured) → $$t_{\text{arrival}} = t_0 + \frac{d_{\text{track}}}{\beta c} + \frac{d_{\text{prop}}}{v_{\text{group}}}$$

  - **Production time**: Derived from TORCH
    - Expected to have timing from VELO: Fast timing in a small region around the vertex (LHCb Upgrade II)

  - **Time-of-flight:** Test different mass hypotheses (β)
    - Determine the path length of the track by spline interpolation between track measurements
    - Extrapolate tracks to TORCH radiator (equation of motion considering mult. scat.)

  - **Photon propagation:** Affected by chromatic dispersion, $n_{\text{group}}(E_\gamma)$
    - d_{prop} is the photon path length
    - v_{group} is derived from θ_c

The TORCH principle

- **Cherenkov angle used to correct for chromatic dispersion**

- Time of propagation (ToP) in quartz depends on the photon energy:

  $t = d_{prop}/v_{group} = d_{prop}n_{group}/c$

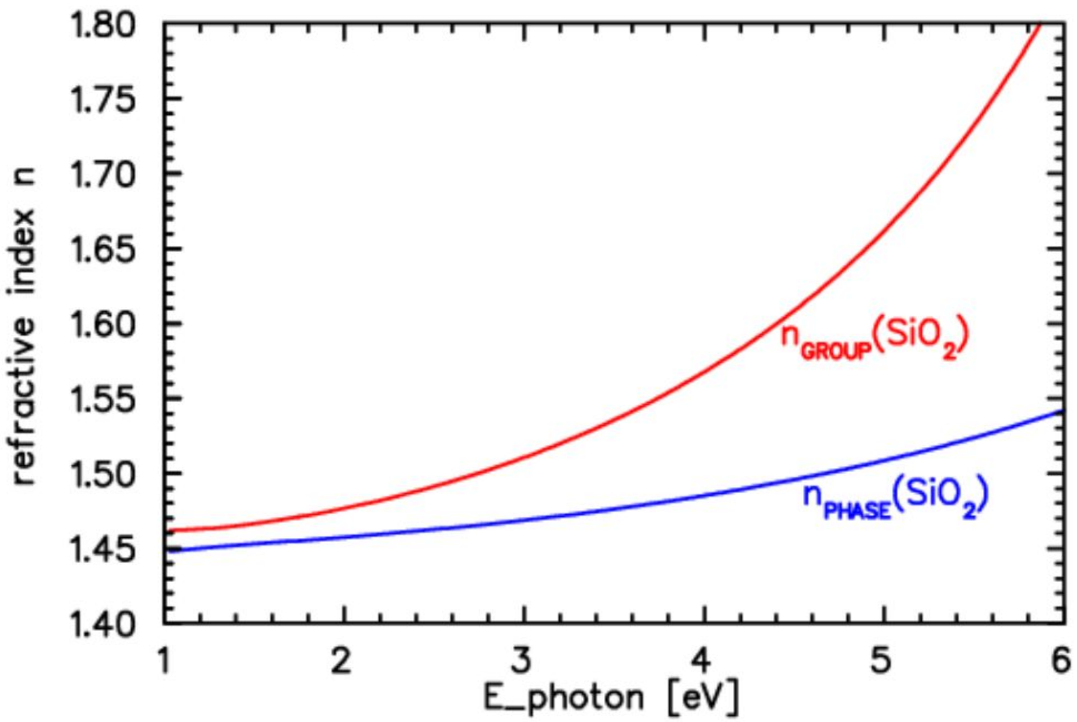
- Cherenkov angle (θ_c) and arrival time ($t_{arrival}$) measured at the top of a bar radiator

- Derive n_{phase} from θ_c for K, π, p hypotheses

  $\cos\theta_c = (\beta n_{phase})^{-1}$

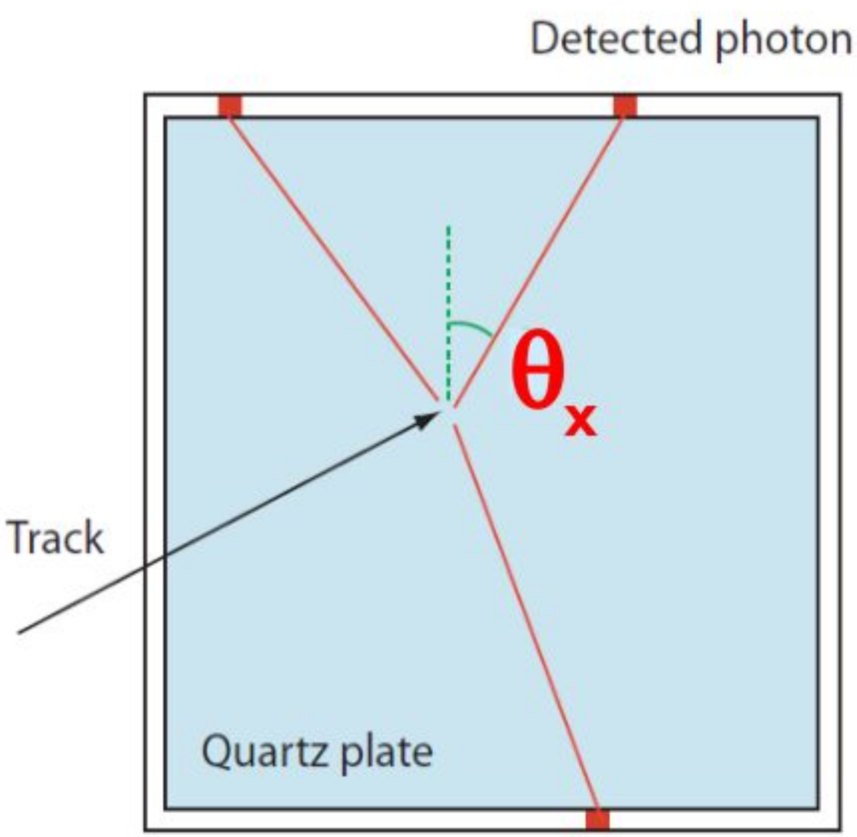
- Use dispersion relation for to get n_{group}

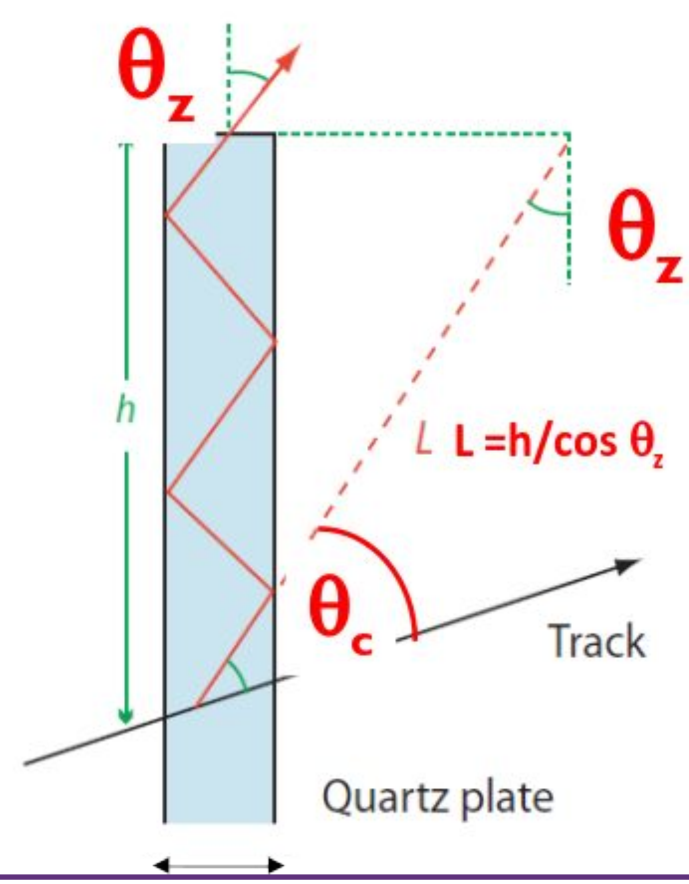
- Determine the ToP from the reconstructed photon pathlength (d_{prop}) and n_{group}



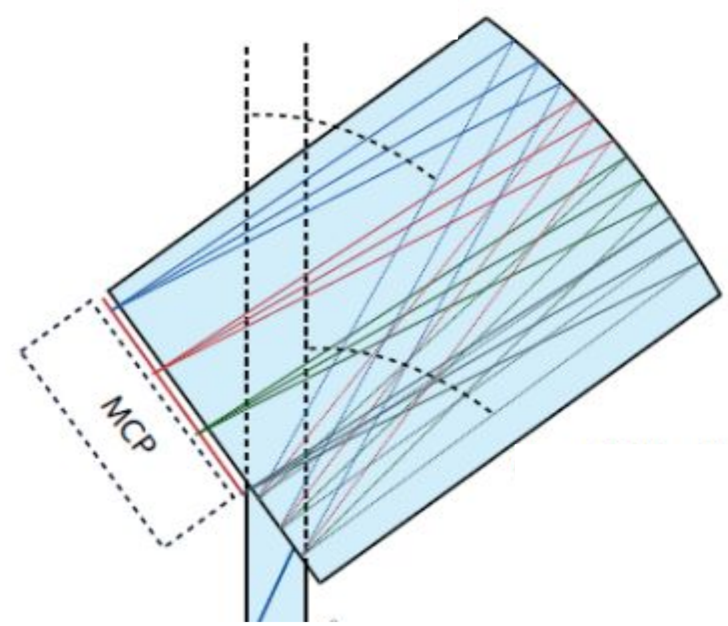
TORCH angular measurements

- Need accurate measurements of the photon to compute photon path-length (**~ 1mrad to have a 50ps** time resolution)
- θ_x typical lever arm ~ 2 m (Need 6mm pixels)
- θ_z(focusing direction): Cherenkov angular range = 0.4 rad (need 128 pixels)





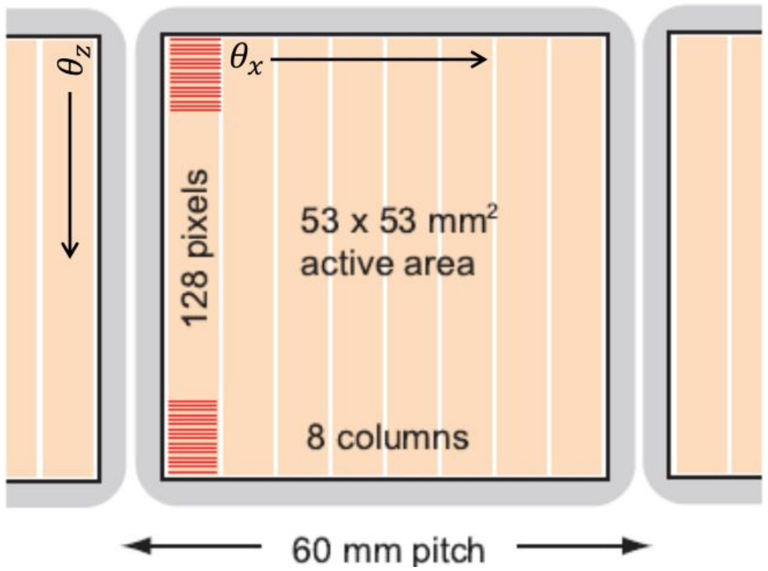
Representative photon paths:
$0.45 < \theta_z < 0.85$ rads



Photon detectors

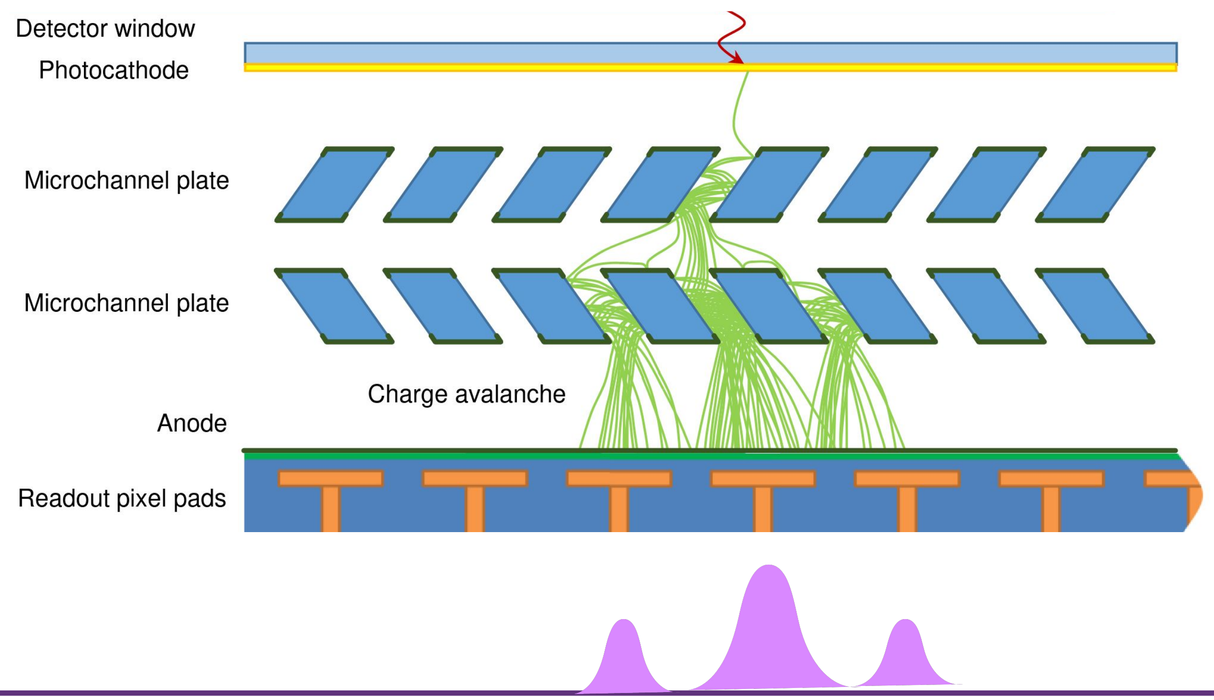
- Pads with 64x64 pixels in active area of 53x53 mm^2
  - Ganged in group of 8 for θ_x: 8 pixels of 6.4 mm
  - Exploiting charge sharing for θ_z: 128 effective pixels of 0.4 mm
  - Achieved effective **granularity of 128x8** via charge-sharing [JINST 10 (2015) C05003]

- 70ps Per-photon time resolution
  - Arrival time resolution: ~ 50ps (Electronics)
  - Propagation time precision ~ 50ps (photon detector granularity)



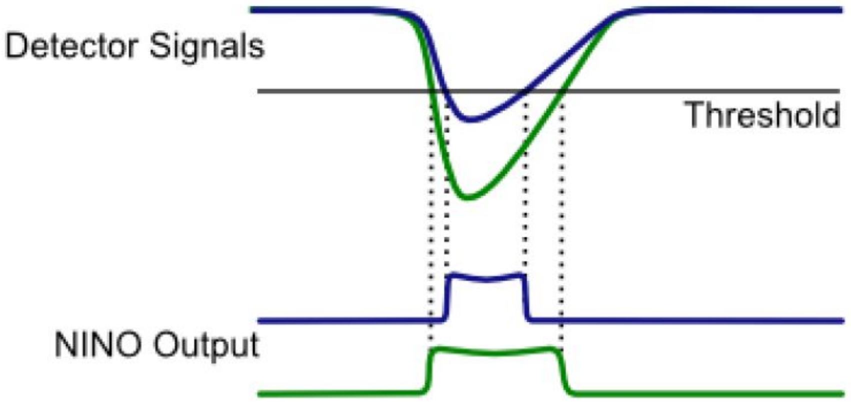
Micro-channel plate

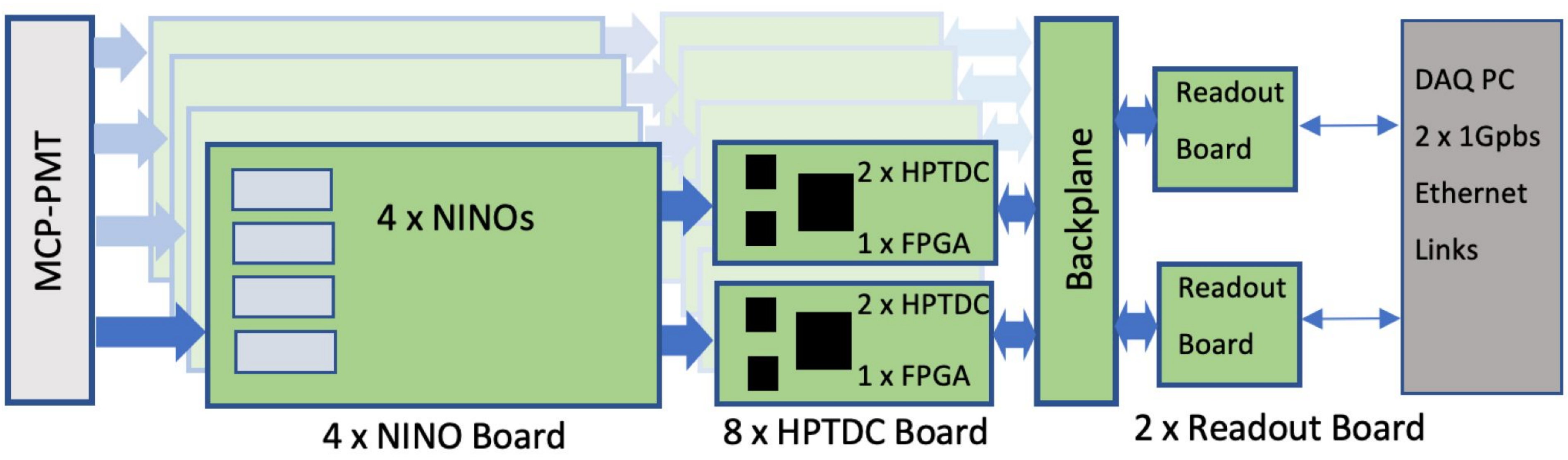
- Micro-channel plate (MCP) photon detectors used for **fast timing of single photons** in TORCH
- R&D program with a commercial partner (PHOTEK, UK) to develop tubes with a **long lifetime and high granularity**
- Charge spread over multiple pixels:
  - Can achieve **finer effective granularity** (clusters)



Read-out electronics

- Readout electronics are crucial to achieve desired resolution
- Suitable front-end chip has been developed for the ALICE TOF:
  - **NINO:**
    - Provides time-over-threshold (correct time walk)
    - Amplify the signal
  - **HPTDC:** time-tag leading edge
- Future versions based on **picoTDC** and **fastIC**





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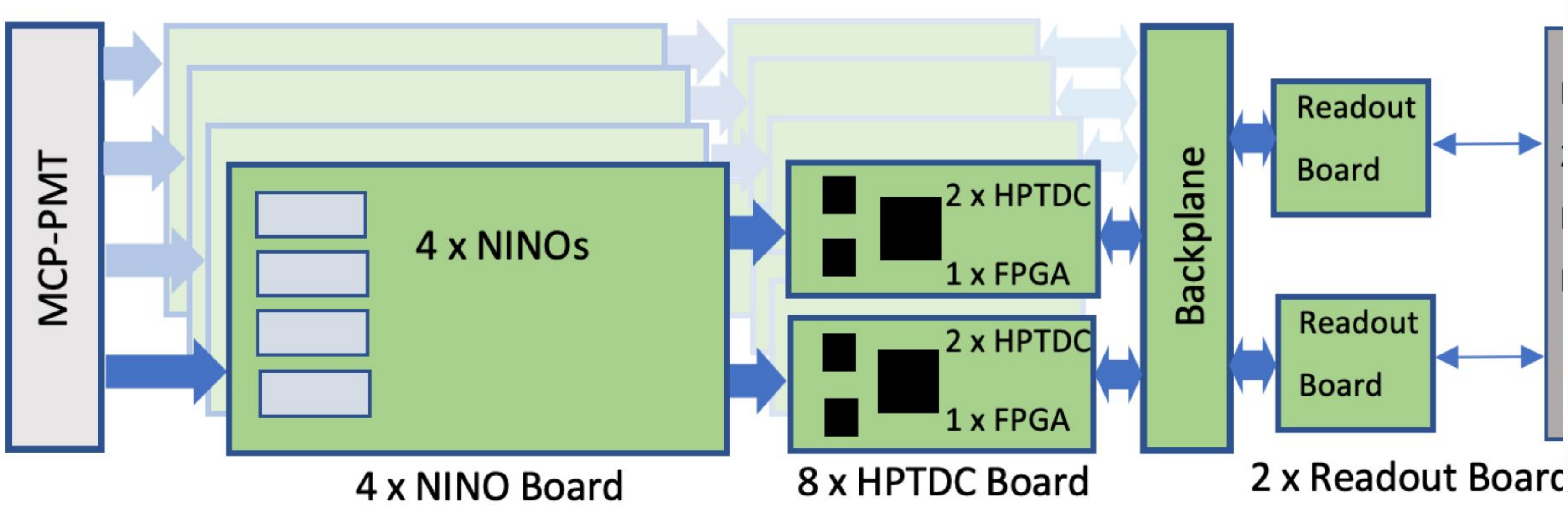
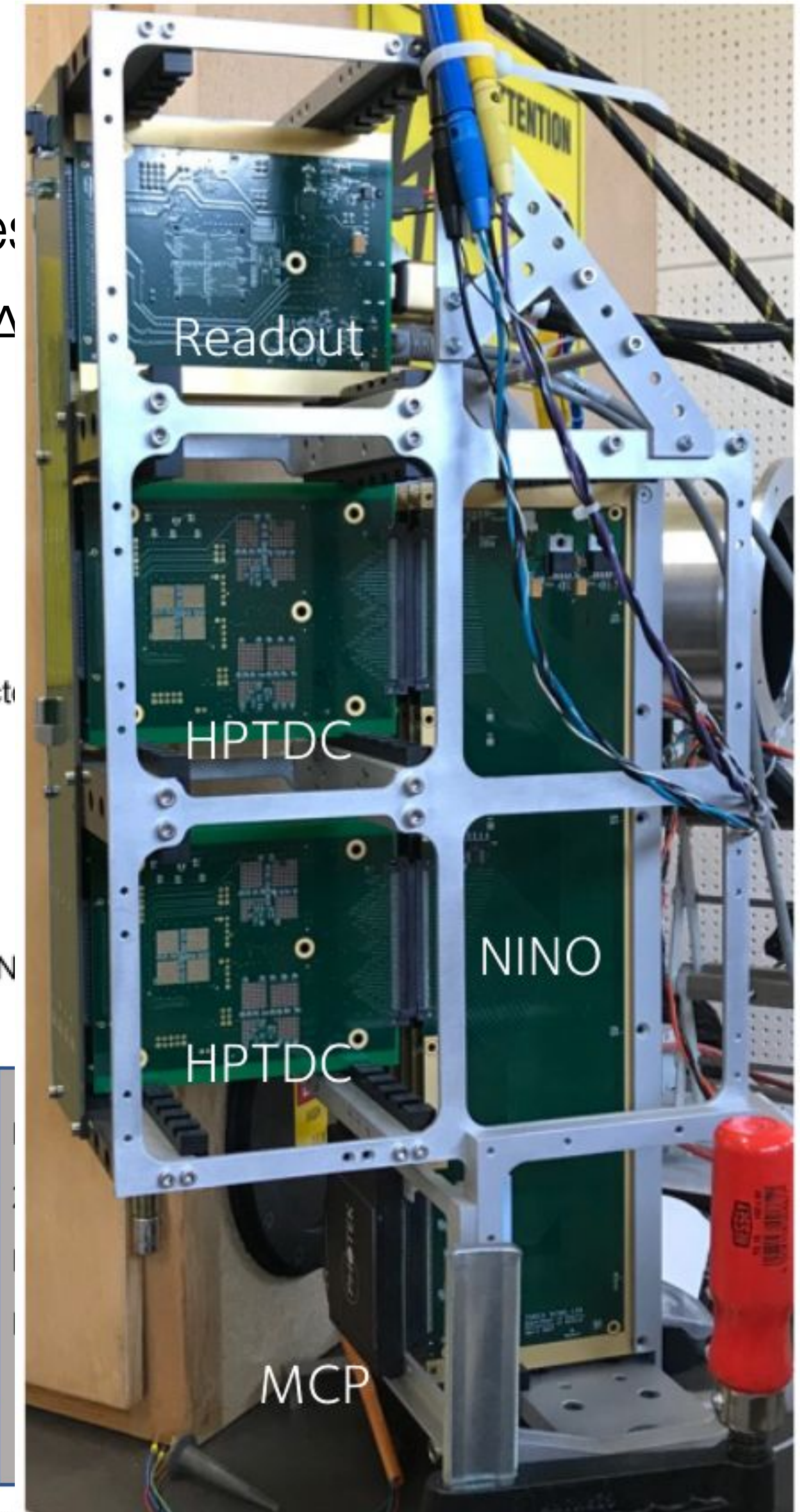


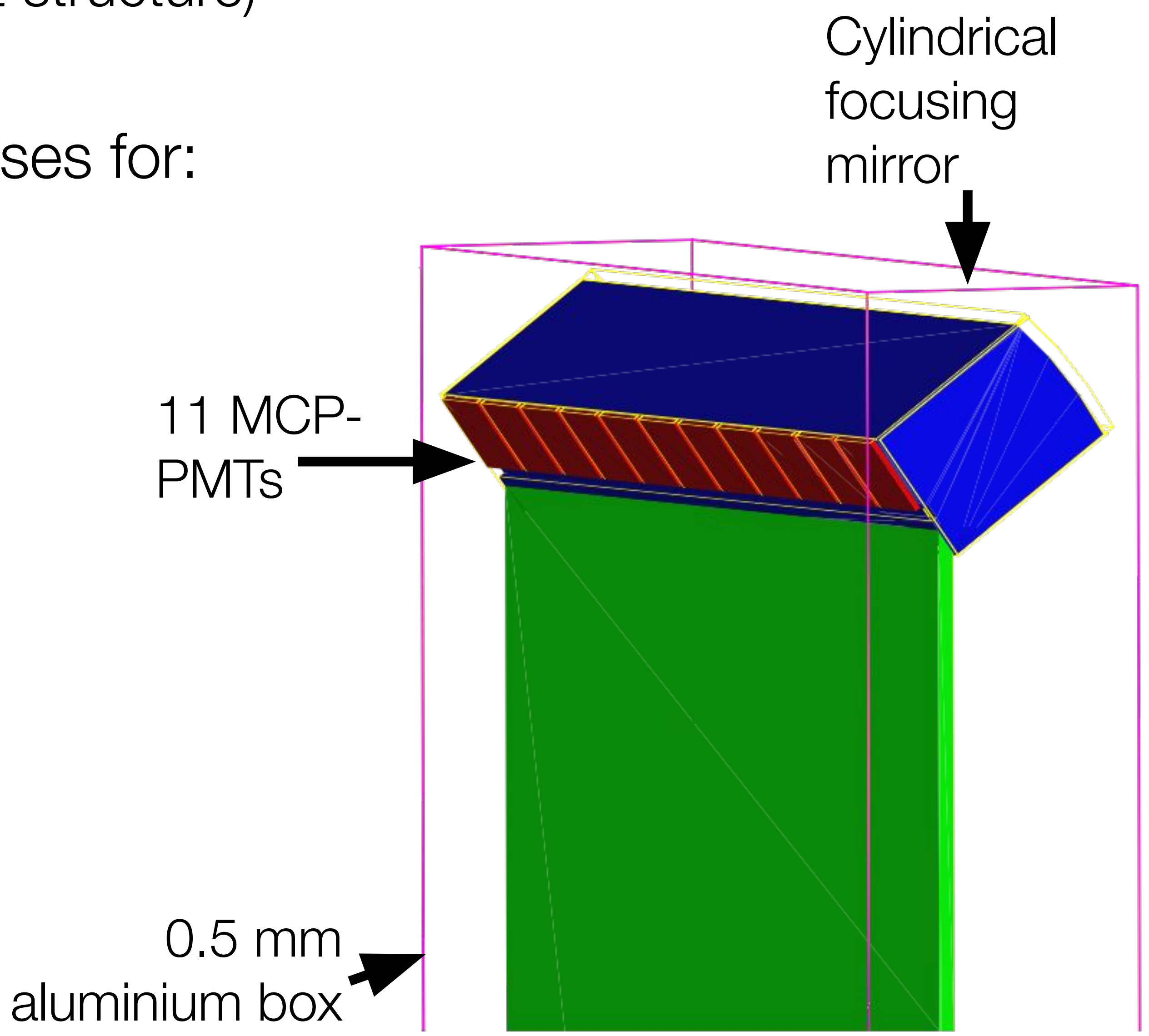


Simulation

- TORCH detector simulated using GEANT4 in the LHCb framework

- Simple simulation of the quartz radiator and focussing block:
    - Free-standing (no support structure)

- Simulation includes processes for:
    - Cherenkov emission
    - Reflection and refraction
    - Rayleigh scattering
    - Surface roughness



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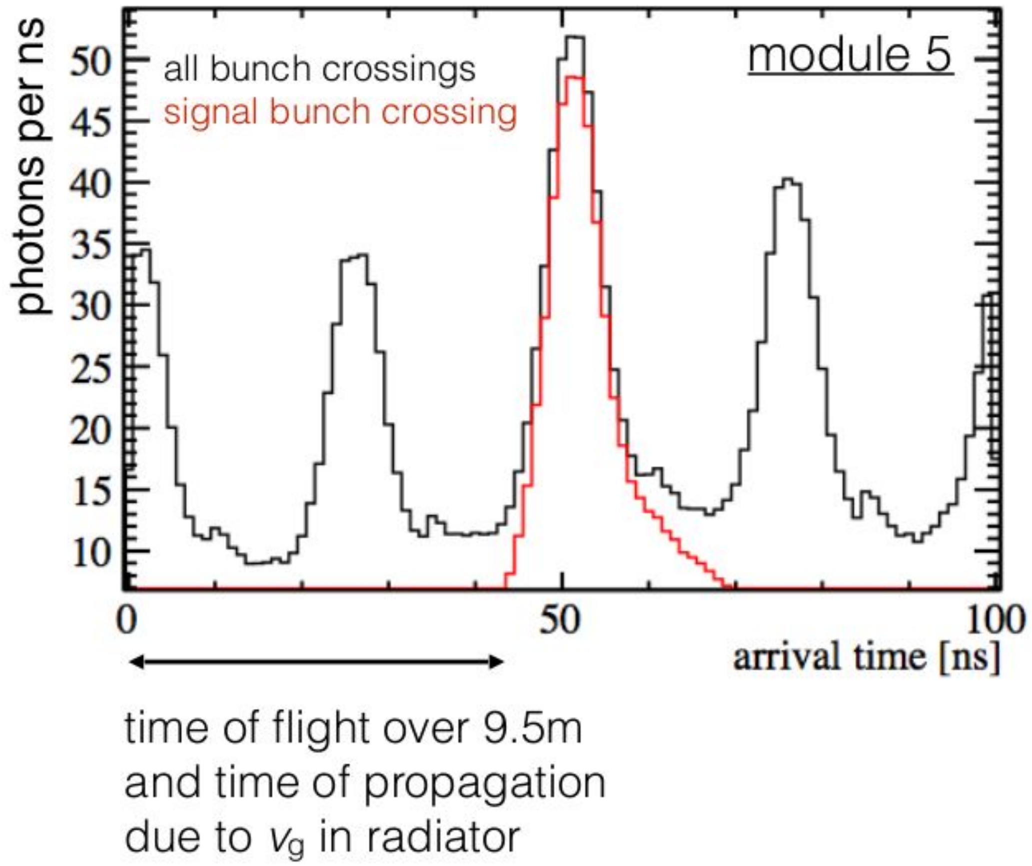
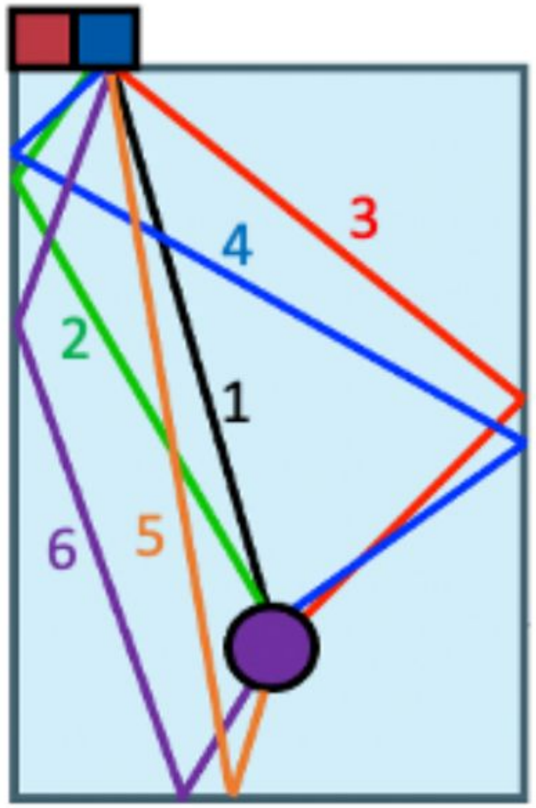


- 25ns time window
  (some photons will arrive out of time)

- Simplified model of the digitisation with charge-spread and deadtime

Reconstruction

- Each hit (photon in the MCP) is back-propagated and associated to a track
  - Analytical photon back-propagation
  - Considering several reflections (sides/bottom) ➡ ambiguity
  - Most combinations (order reflections) discarded do not give a valid solution (hit position not compatible with measured time)



front-back reflections not visible here (no ambiguity for them)

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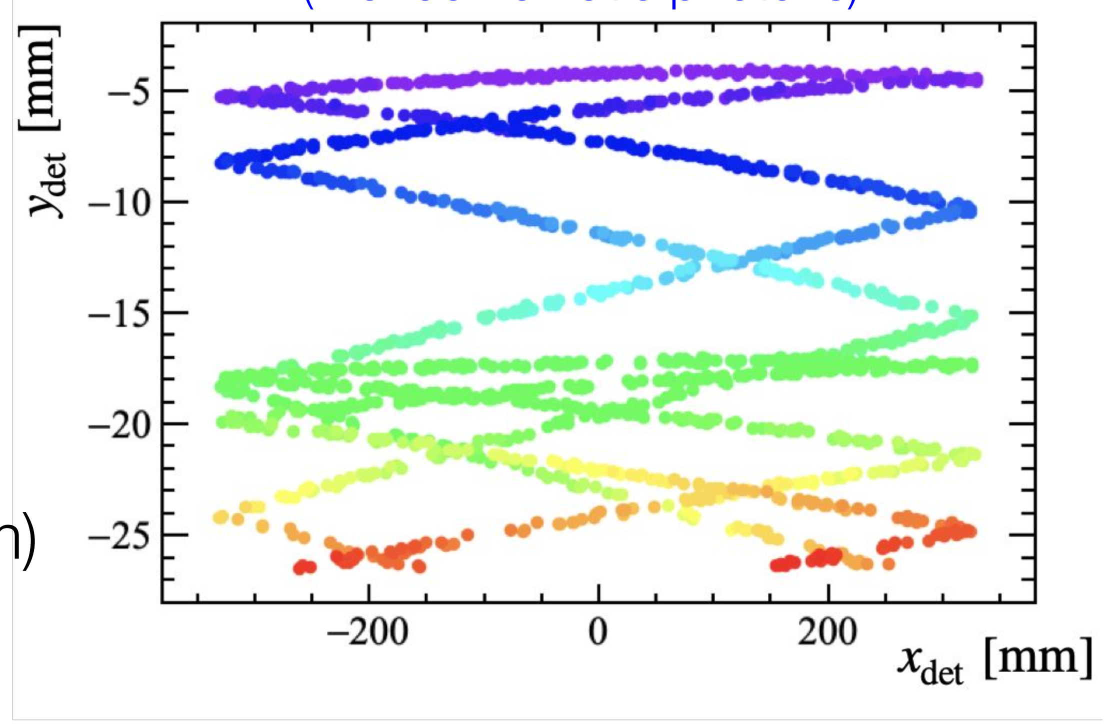
  - Most combinations (order reflections) discarded do not give a valid solution (hit position not compatible with measured time)
- Cherenkov cone results in hyperbola-like patterns (folded by reflections) in x-y plane

Photons at the MCP from a single (repeated) track (monochromatic photons)



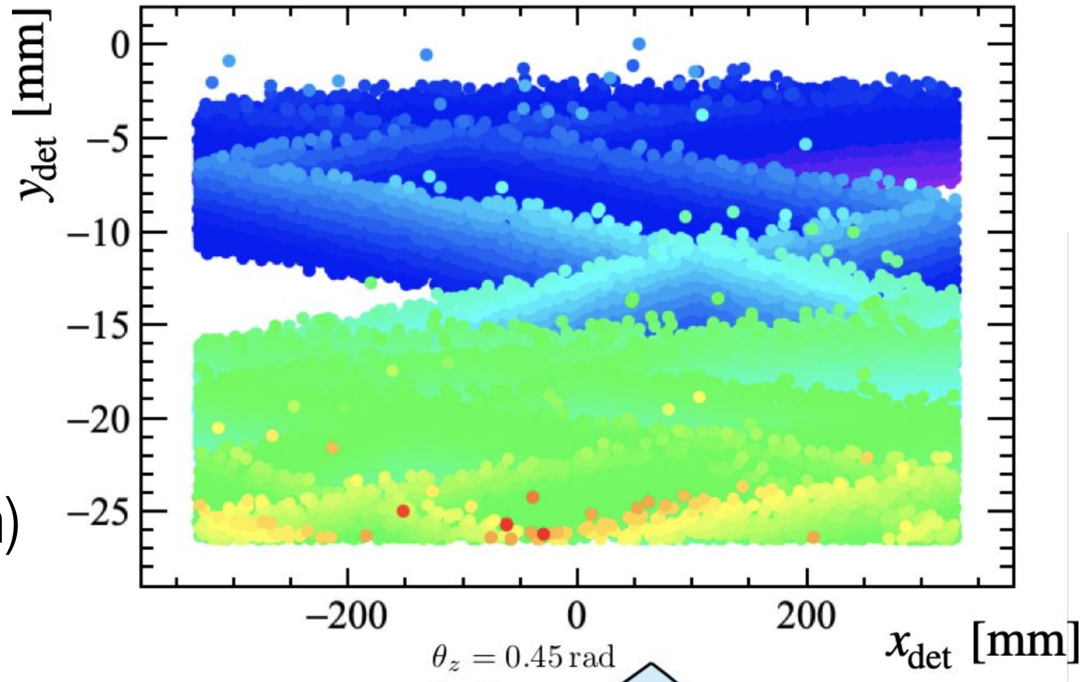
Color codes the time or arrival of the photon:

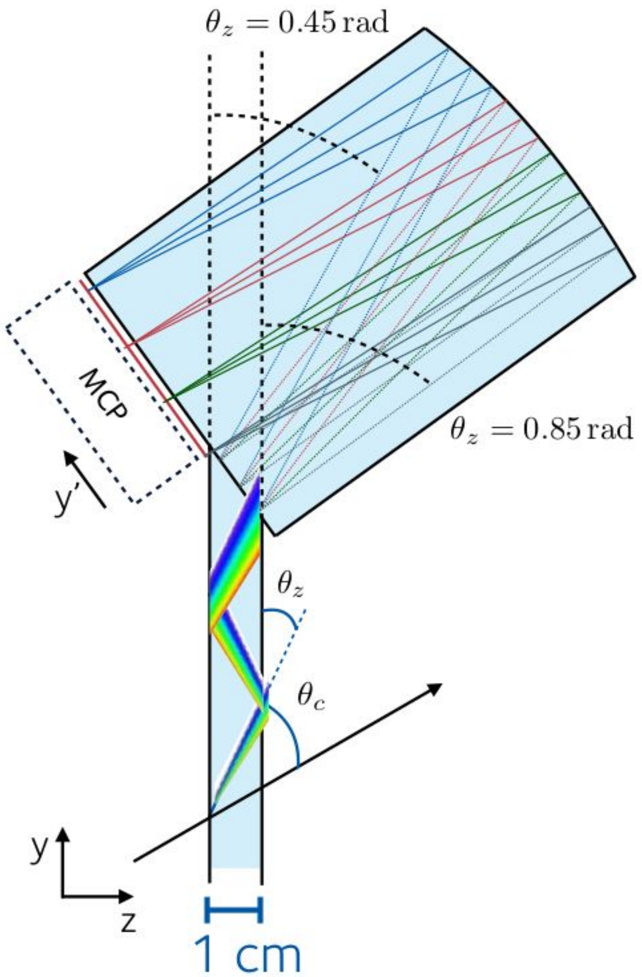
- **Early arriving (~15ns)**
- **Late arriving (~25ns)**

Reconstruction

- Each hit (photon in the MCP) is back-propagated and associated to a track
  - Analytical photon back-propagation
  - Considering several reflections (sides/bottom) ➡ ambiguity
  - Most combinations (order reflections) discarded do not give a valid solution (hit position not compatible with measured time)
- Cherenkov cone results in hyperbola-like patterns (folded by reflections) in x-y plane
- Chromatic dispersion spreads line into band

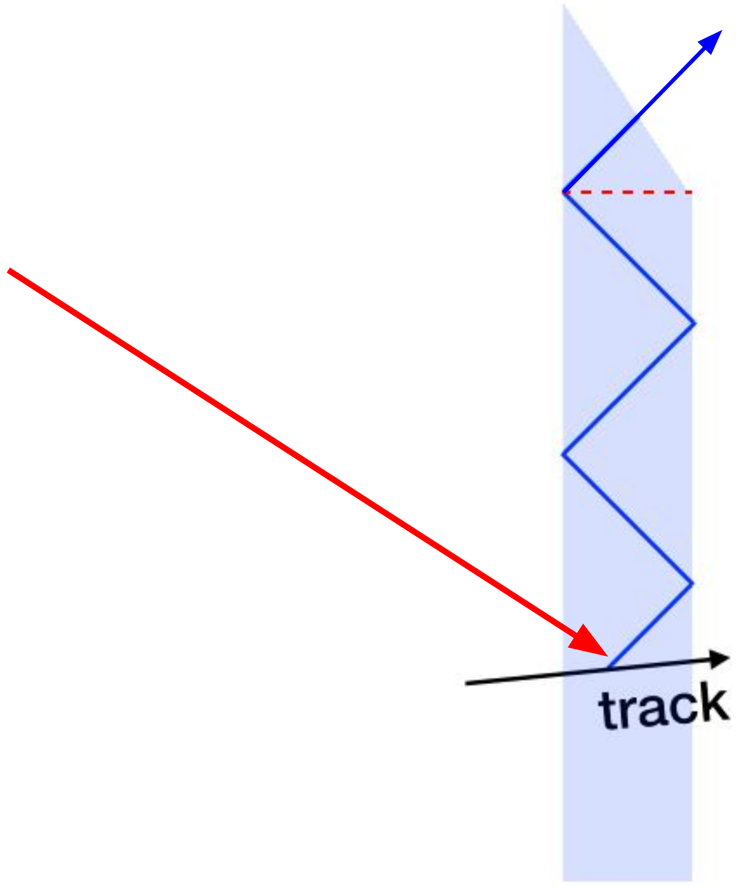
Photons at the MCP from a single (repeated) track





Reconstruction: Assumptions

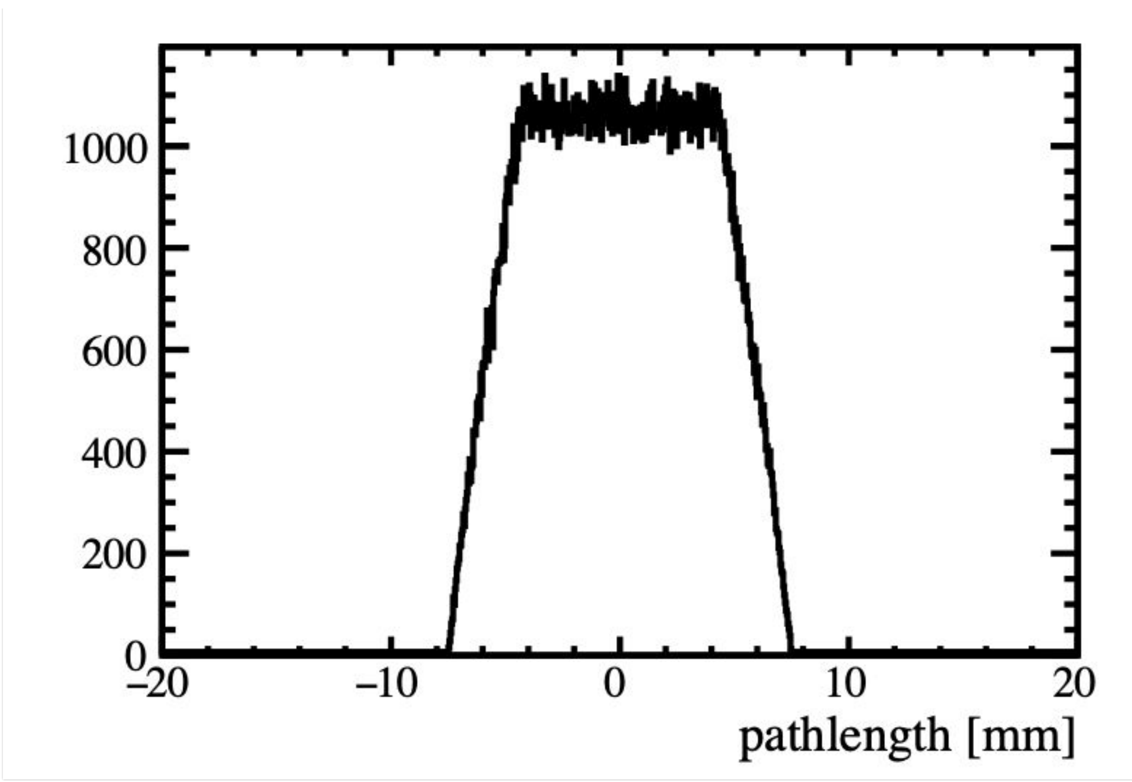
- Assume each photon:
    - Emitted in the centre of the radiator

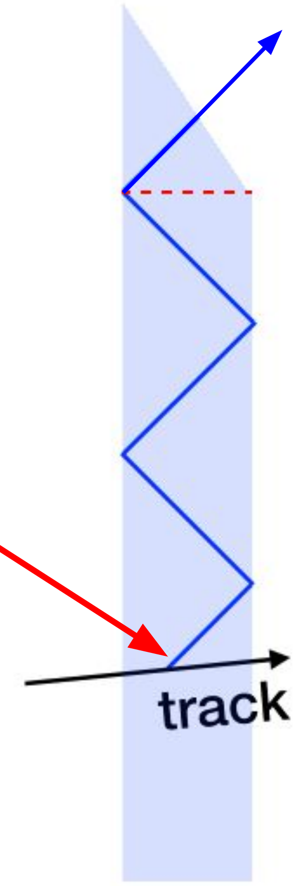


Reconstruction: Assumptions

- Assume each photon:
  - Emitted in the centre of the radiator
- Results in a smearing in time due to the incorrect path length assumptions of O(20ps)

path length difference [mm]





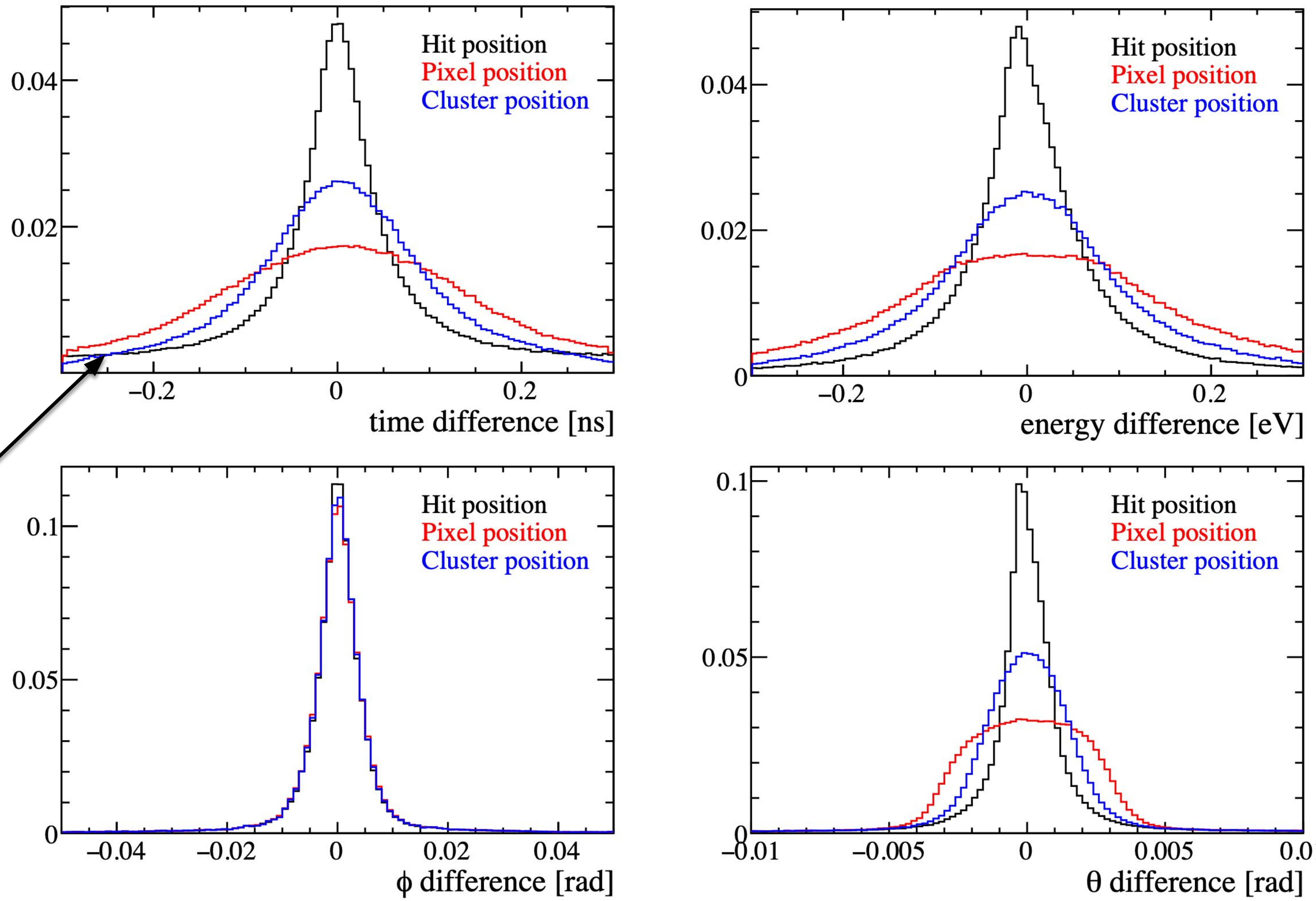
Reconstruction: Photon resolution

Hit: True photon arrival position

Pixel: Pixel hit by the photon arrival

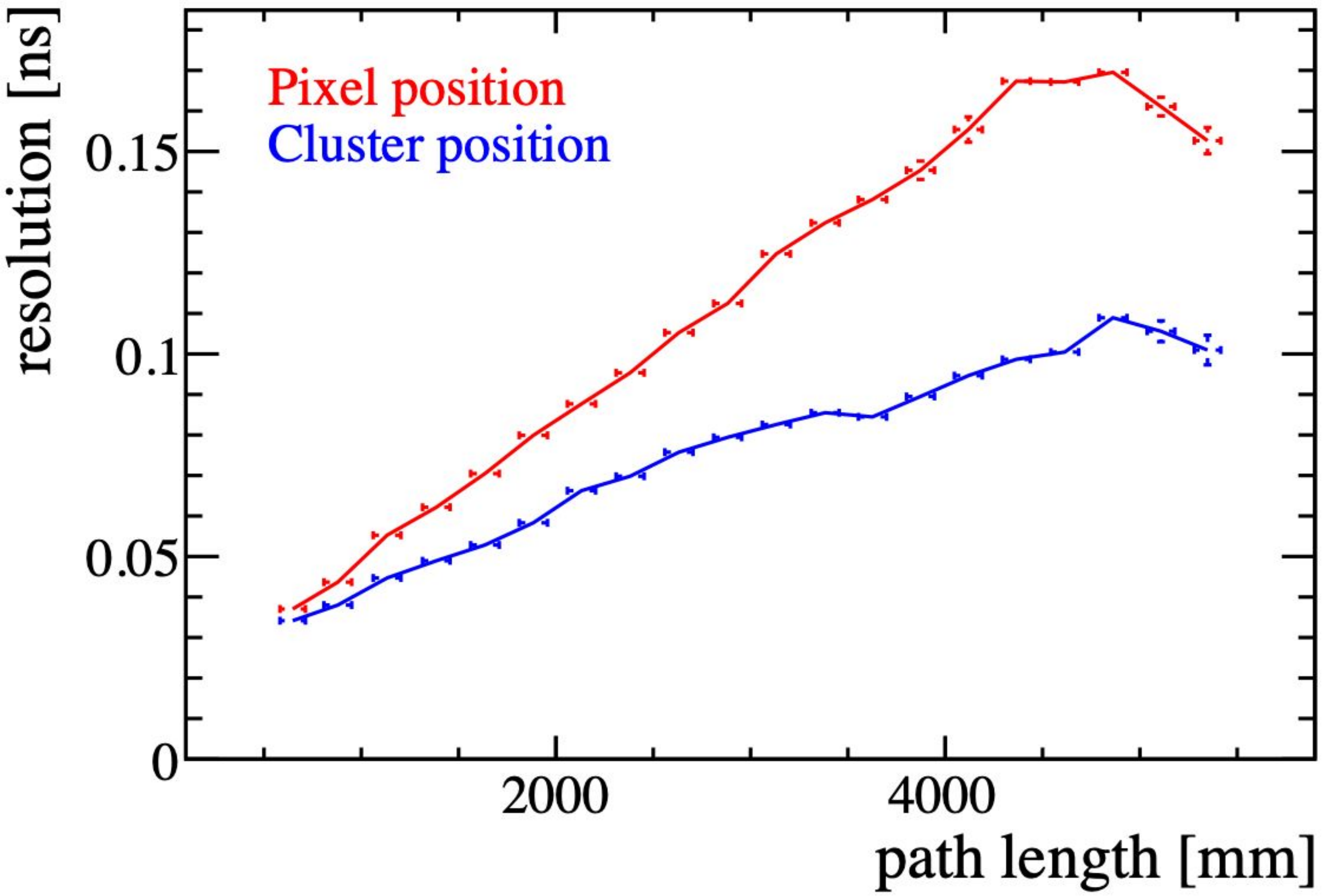
Cluster: Weighted charge-average of all pixels fired by the photon (~1-2 pixels)

Long tails due to incorrect assumption on the number of reflections



Reconstruction: resolution

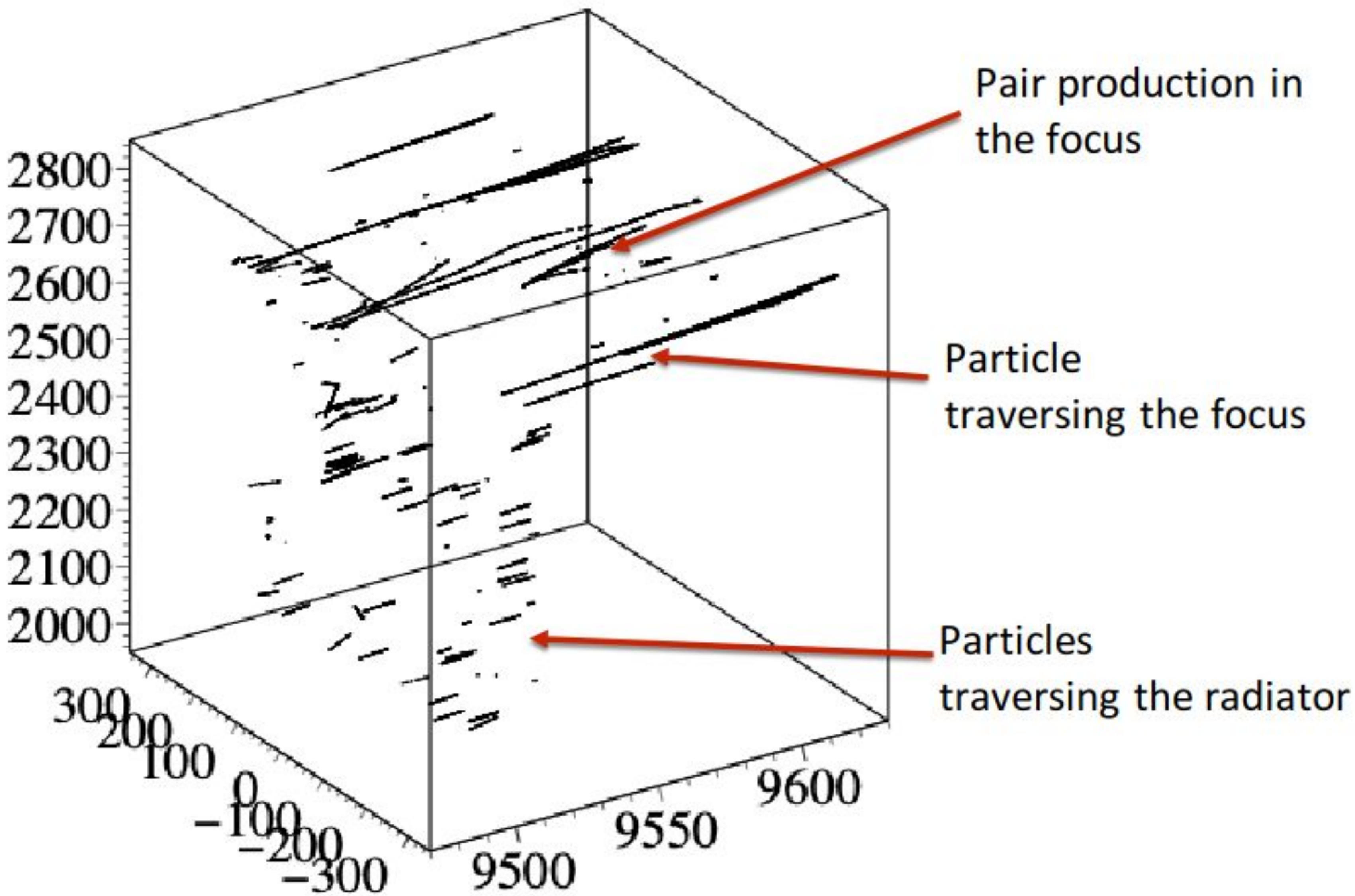
- See (expected) linear dependence on path length due to chromatic dispersion and finite pixel size.
- Limited resolution is due to:
    - The unknown emission point and entrance point to the focusing block.
    - Resolution on the track slope and multiple scattering in the radiator.



Resolution from the MCP and readout electronics is not included here

Background

- Significant fraction of photons are **not associated to reconstructible particles**



Reconstruction

- The log-likelihood for a given track/hypothesis combination is given by:

$$\log L = \sum_{\text{pixel } i} \log \left(\sum_{\substack{\text{track } j \\ j \neq t}} \frac{N_j}{N_{\text{tot}}} P_j(\vec{x}_i'' \mid h_j^{\text{best}}) + \frac{N_t}{N_{\text{tot}}} P_t(\vec{x}_i'' \mid h_t) + \frac{N_{\text{bkg}}}{N_{\text{tot}}} P_{\text{bkg}}(\vec{x}_i'') \right)$$

PDF for "best" hypothesis assignment for other tracks

PDF for considered track

Background contribution (assumed flat)

Reconstruction: Unbinned

- The log-likelihood for a given track/hypothesis combination is given by:

$$\log L = \sum_{\text{pixel } i} \log \left(\sum_{\substack{\text{track } j \\ j \neq t}} \frac{N_j}{N_{\text{tot}}} P_j(\overrightarrow{x}_i'' \,|\, h_j^{\text{best}}) + \frac{N_t}{N_{\text{tot}}} P_t(\overrightarrow{x}_i'' \,|\, h_t) + \frac{N_{\text{bkg}}}{N_{\text{tot}}} P_{\text{bkg}}(\overrightarrow{x}_i'') \right)$$

- Best hypothesis determined by iteration
  - Initially assigned the pion hypothesis
  - In n-iteration, assigned best hypothesis from (n-1)-iteration
- Converges after 3-4 iterations

Reconstruction

- The log-likelihood for a given track/hypothesis combination is given by:

$$\log L = \sum_{\text{pixel } i} \log \left(\sum_{\substack{\text{track } j \\ j \neq t}} \frac{N_j}{N_{\text{tot}}} P_j(\overrightarrow{x}_i'' \mid h_j^{\text{best}}) + \frac{N_t}{N_{\text{tot}}} P_t(\overrightarrow{x}_i'' \mid h_t) + \frac{N_{\text{bkg}}}{N_{\text{tot}}} P_{\text{bkg}}(\overrightarrow{x}_i'') \right)$$

Component fractions are fixed

- Estimate N_j by forward propagating 1000 photons through the optics
  - Position computed analytically (no need to ray-trace)
- Can't afford to find the yields in a fit (fractions fixed)
  - Need to assume $N_{\text{bkg}} = N_{\text{tot}} - \sum_j N_j$

Reconstruction

- The log-likelihood for a given track/hypothesis combination is given by:

$$\log L = \sum_{\text{pixel } i} \log \left(\sum_{\substack{\text{track } j \\ j \neq t}} \frac{N_j}{N_{\text{tot}}} P_j(\vec{x}_i'' \,|\, h_j^{\text{best}}) + \frac{N_t}{N_{\text{tot}}} P_t(\vec{x}_i'' \,|\, h_t) + \frac{N_{\text{bkg}}}{N_{\text{tot}}} P_{\text{bkg}}(\vec{x}_i'') \right)$$

- Determine the PDF for a given track/hypothesis combination from:

$$P(\vec{x}'' \,|\, h) = |J| P(E_\gamma, \phi_c, t_0)$$

- Initial PDF factorizes

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

$P(\phi) = 1/2\pi$

$P(E_\gamma)$: Frank-Tamm + efficiency

$P(t_0)$: Normal distribution with experimental time resolution

Reconstruction

- The log-likelihood for a given track/hypothesis combination is given by:

$$\log L = \sum_{\text{pixel } i} \log \left(\sum_{\substack{\text{track } j \\ j \neq t}} \frac{N_j}{N_{\text{tot}}} P_j(\overrightarrow{x}''_i \,|\, h_j^{\text{best}}) + \frac{N_t}{N_{\text{tot}}} P_t(\overrightarrow{x}''_i \,|\, h_t) + \frac{N_{\text{bkg}}}{N_{\text{tot}}} P_{\text{bkg}}(\overrightarrow{x}''_i) \right)$$

- Determine the PDF for a given track/hypothesis combination from:

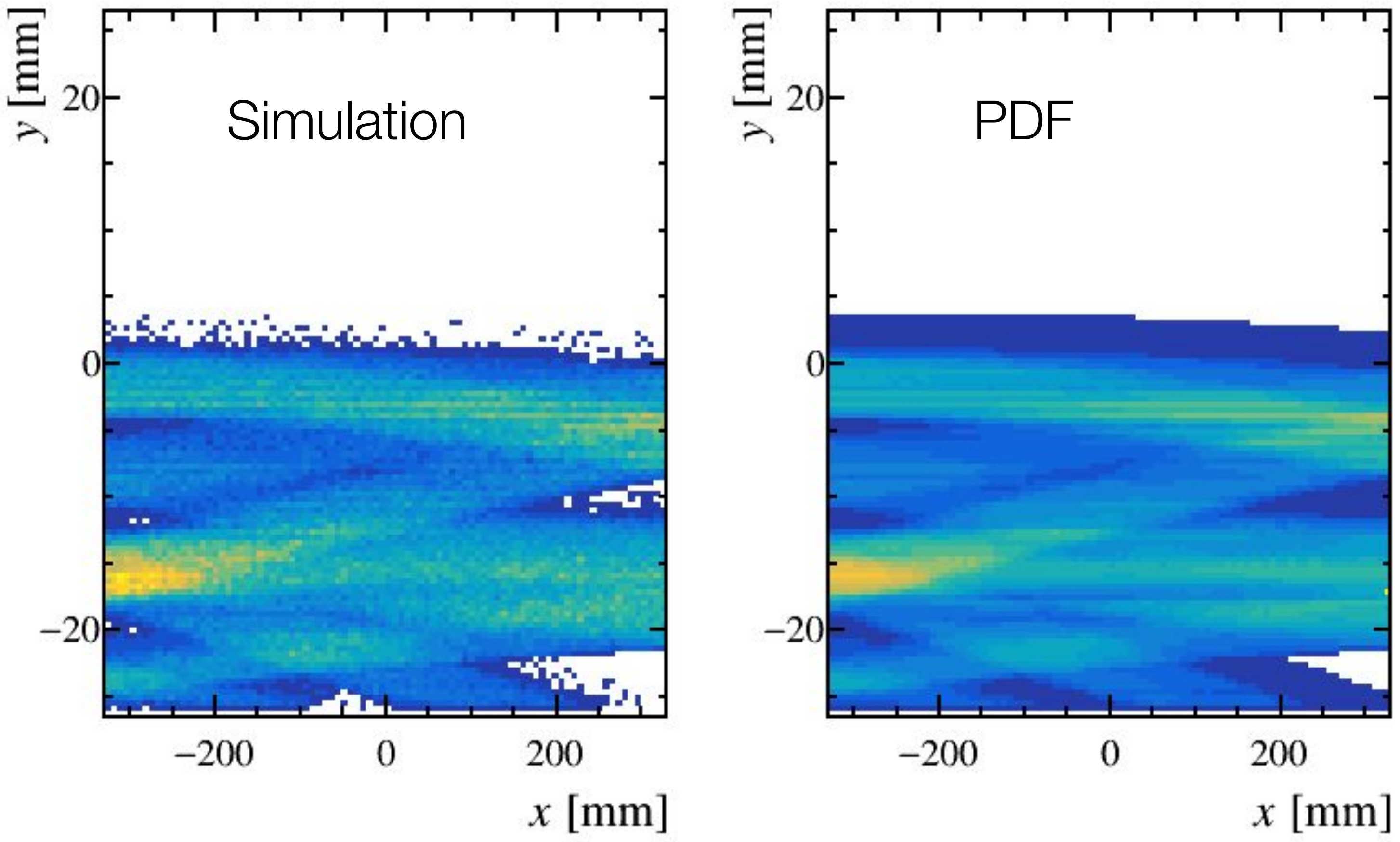
$$P(\overrightarrow{x}'' \,|\, h) = |J| \, P(E_\gamma, \phi_c, t_0)$$

with $J = \left| \frac{\partial y''_{\text{d}}}{\partial E_\gamma} \frac{\partial x''_{\text{d}}}{\partial \phi \text{c}} - \frac{\partial x''_{\text{d}}}{\partial E_\gamma} \frac{\partial y''_{\text{d}}}{\partial \phi \text{c}} \right|$

Reconstruction

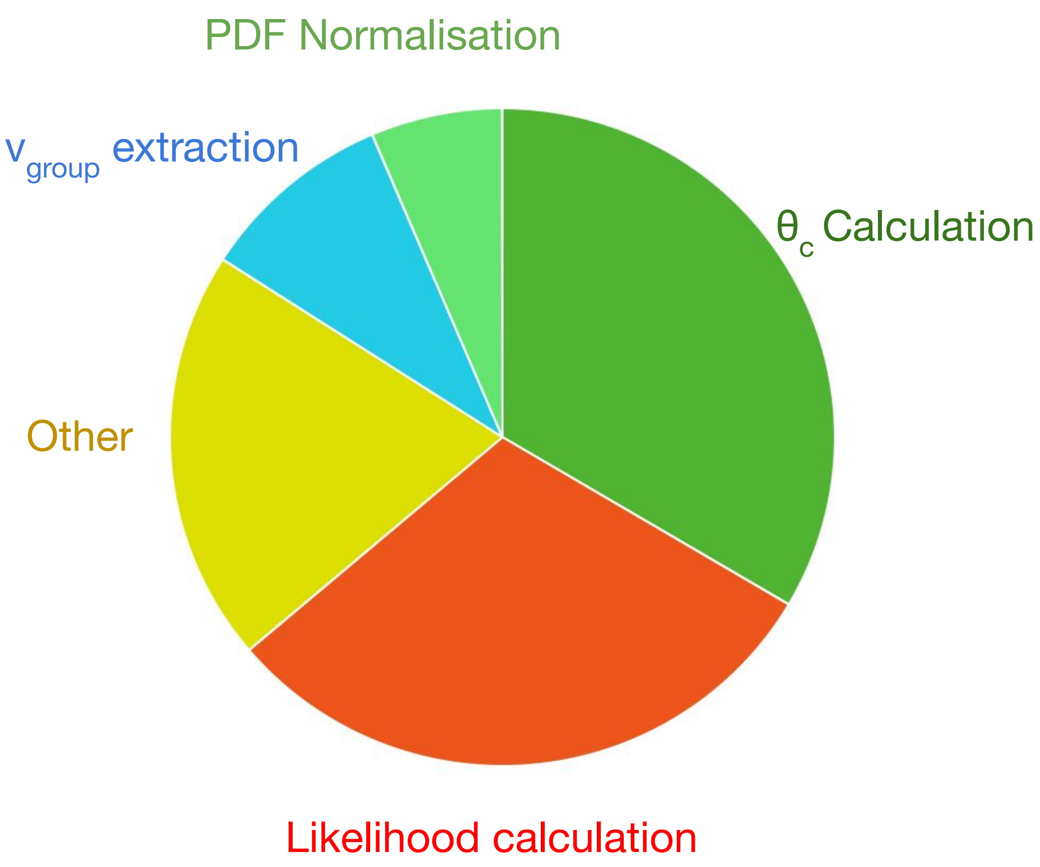
- It is possible to check the correctness of the reconstructed PDF:
  - Propagate (simulate) a large number of photons (~10^6) for each track
  - Compare simulation and analytical PDF

- **Good agreement** (even able to replicate complex structures)



CPU timing

- Current reconstruction takes ~1 second per event (Intel Core i5-10500 3.10GHz)
- Effort to optimise the algorithm:
  - Compiler optimisation options (-O).
  - Vectorisation
  - Change storage to avoid cache misses.
  - Look-up tables instead of expensive calculations
- Further optimisation can be possible
  - Using explicit SIMD data types
  - Use *const* functions and avoid control-flow (allow compiler optimisation)
  - Remove redundant calculations
  - “local” likelihood



CPU timing

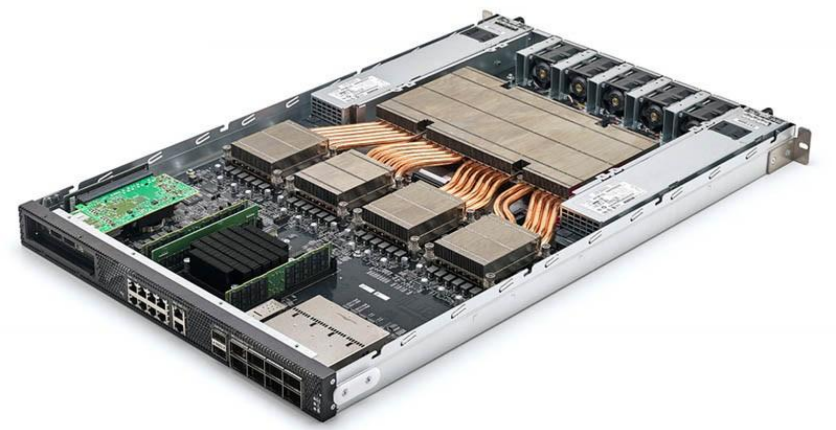
- The "local" approach of the likelihood:
  - Consider each track in isolation

$$\log L = \sum_{\text{pixel } i} \log\left(\frac{N_t}{N_{\text{tot}}} P_t(\overrightarrow{x}_i'' \,|\, h_t) + \frac{N_{\text{bkg}}}{N_{\text{tot}}} P_{\text{bkg}}(\overrightarrow{x}_i'')\right)$$

  - no need to iterate in the likelihood calculation
  - less optimal treatment of the background
    - However, performance is not significantly worse than in the global approach because there are backgrounds from e.g. γ conversions that do not have associated tracks
  - Better suited to running on hardware accelerators than the nominal approach

Developments for IPUs/GPUs

- Significant speed-up could be possible using hardware accelerators (IPUs and GPUs)
- TORCH likelihood calculation is well suited to parallelisation:
  - Modules are independent
  - Probabilities for given hit/track/hypothesis combinations could be determined independently
- Memory access could be a bottleneck
- Development of TORCH photon mapping as proof-of-principle



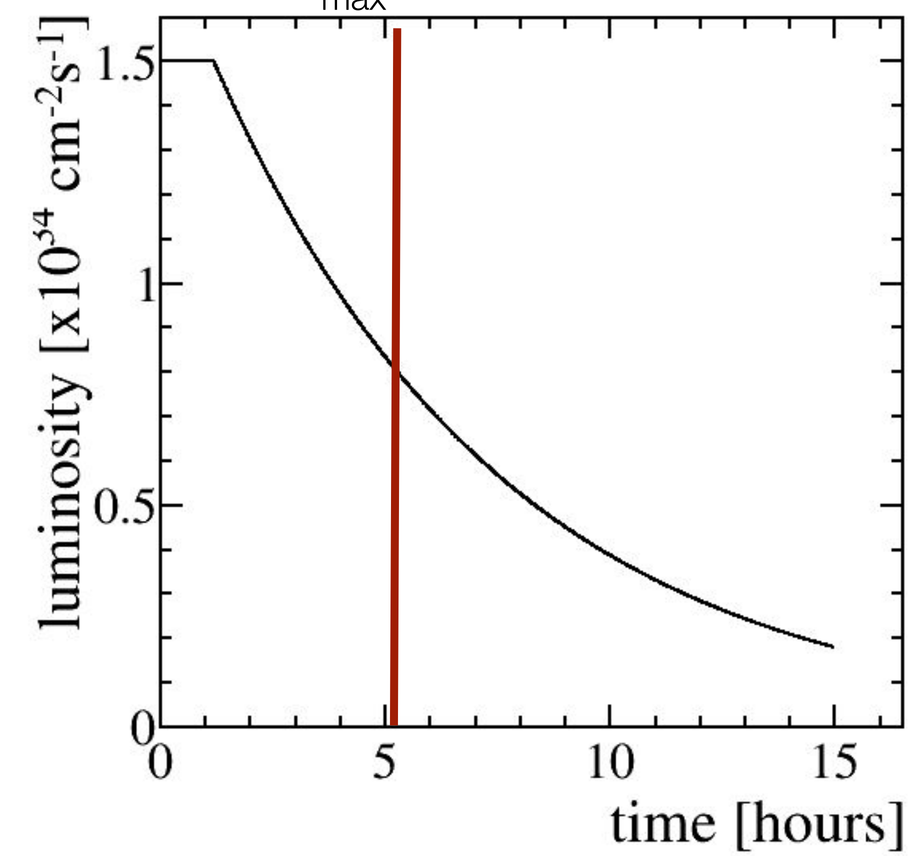
IPU: Graphcore m2000

GPU: NVIDIA RTX A5000

Instantaneous luminosity in Upgrade II

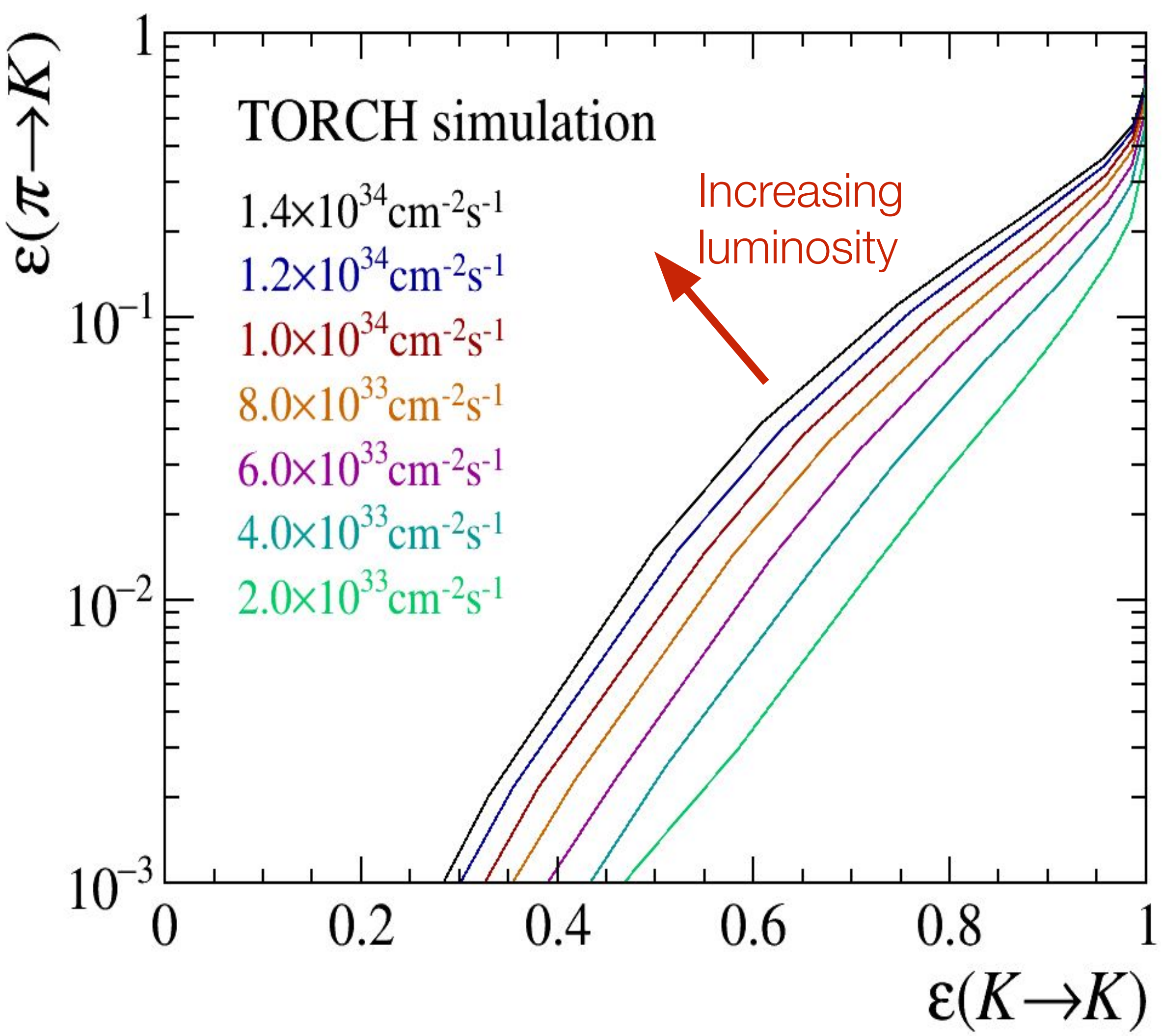
- Approximate the luminosity profile with an exponential function.
    - Luminosity decays quickly with time
- Virtual **peak luminosity: 1.8x10^{34} cm^{-2}s^{-1}**(FTDR)
- Fill duration: 8 hours (FTDR)
- **Average luminosity is 1.01x10^{34} cm^{-2}s^{-1}**
- We can only produce sample in multiples of 2.0x10^{33} cm^{2}s^{-1}
- Approximate a fill using 2.6 hours at 1.4x10^{34}, 1.6 hours at 1.0x10^{34}, 1.8 hours at 8.0x10^{33} and 1.8 hours at 6.0x10^{33} cm^{2}s^{-1}

Levelled at L_{max} = 1.5x10^{34}

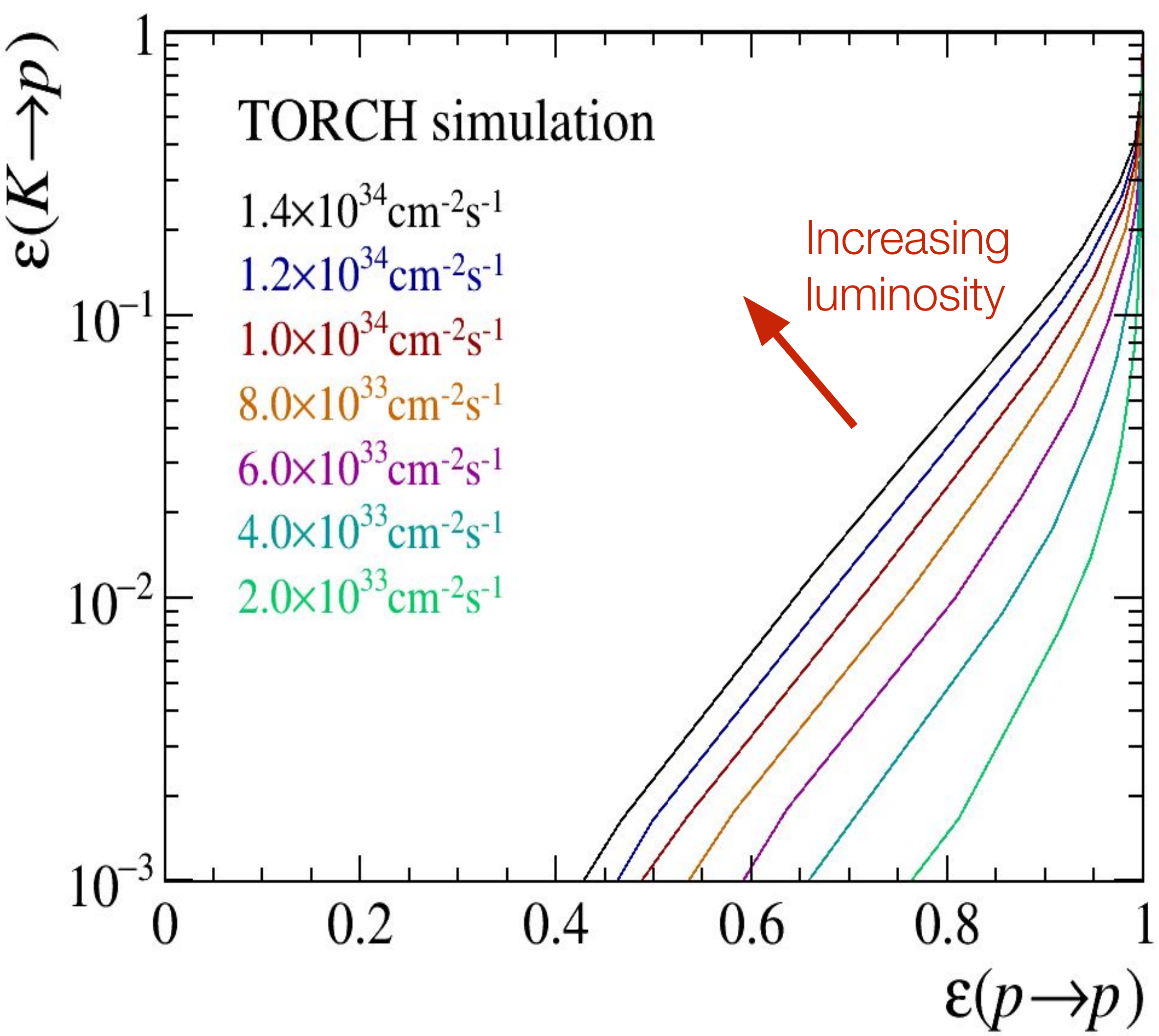


Performance versus luminosity

K-π separation

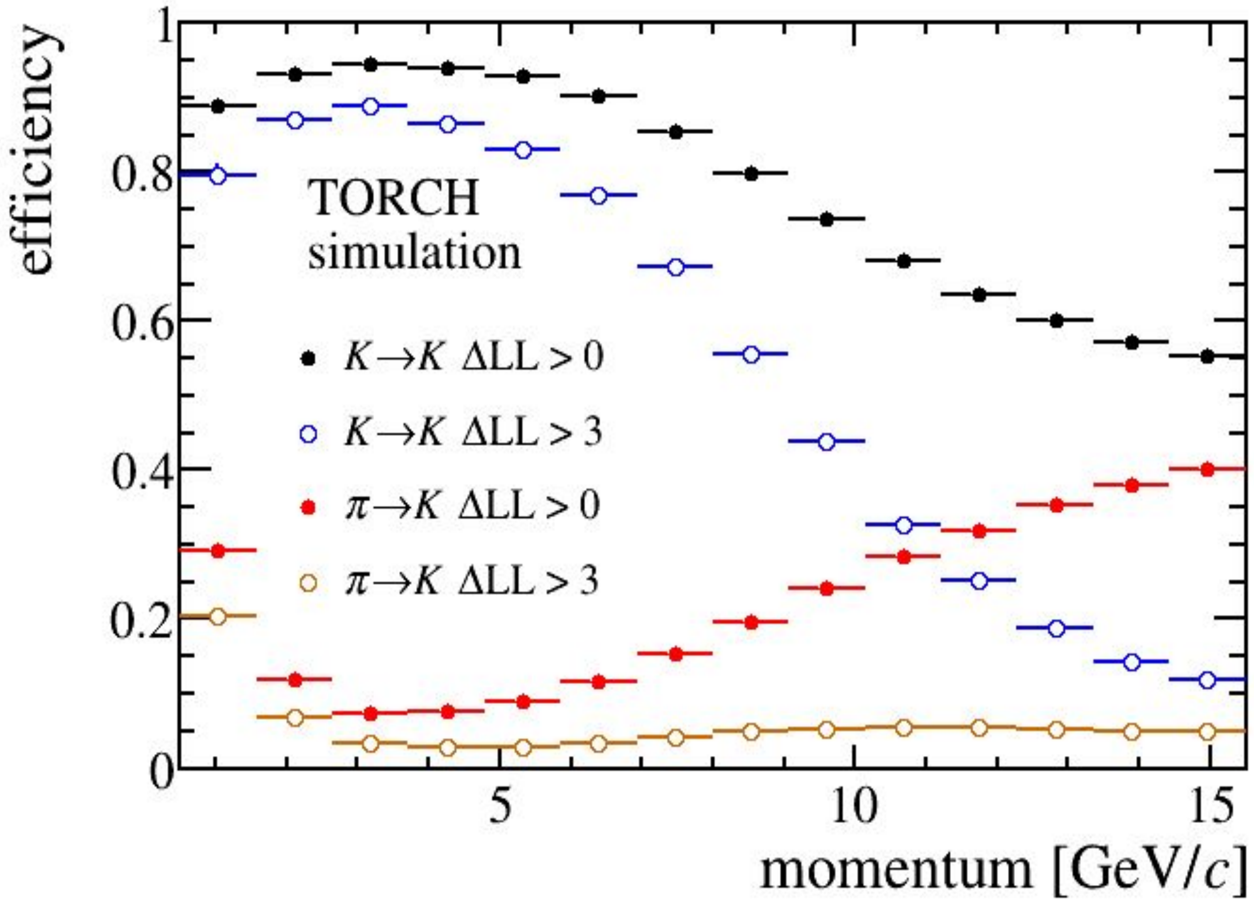


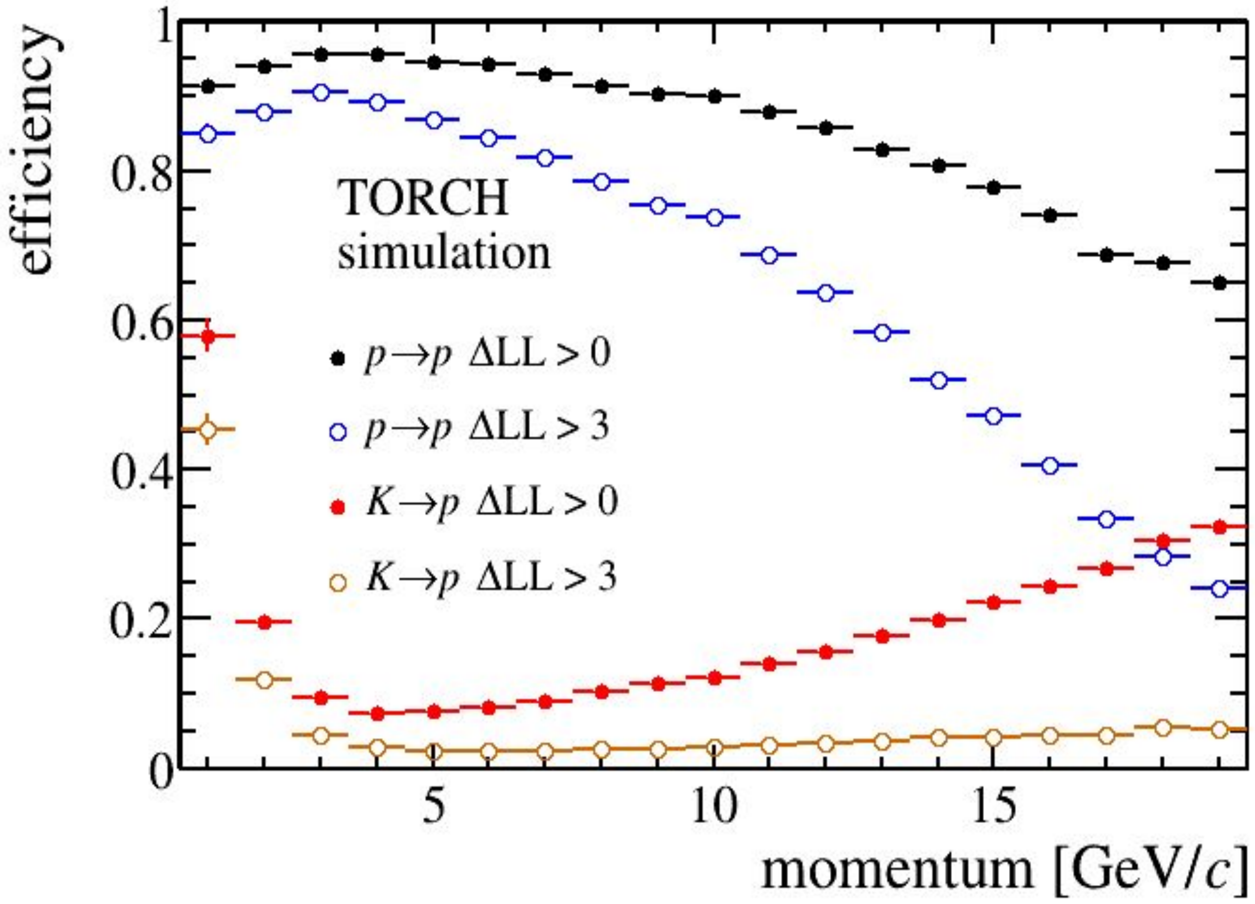
p-K separation



Performance with weighting

LHCb Upgrade II luminosity



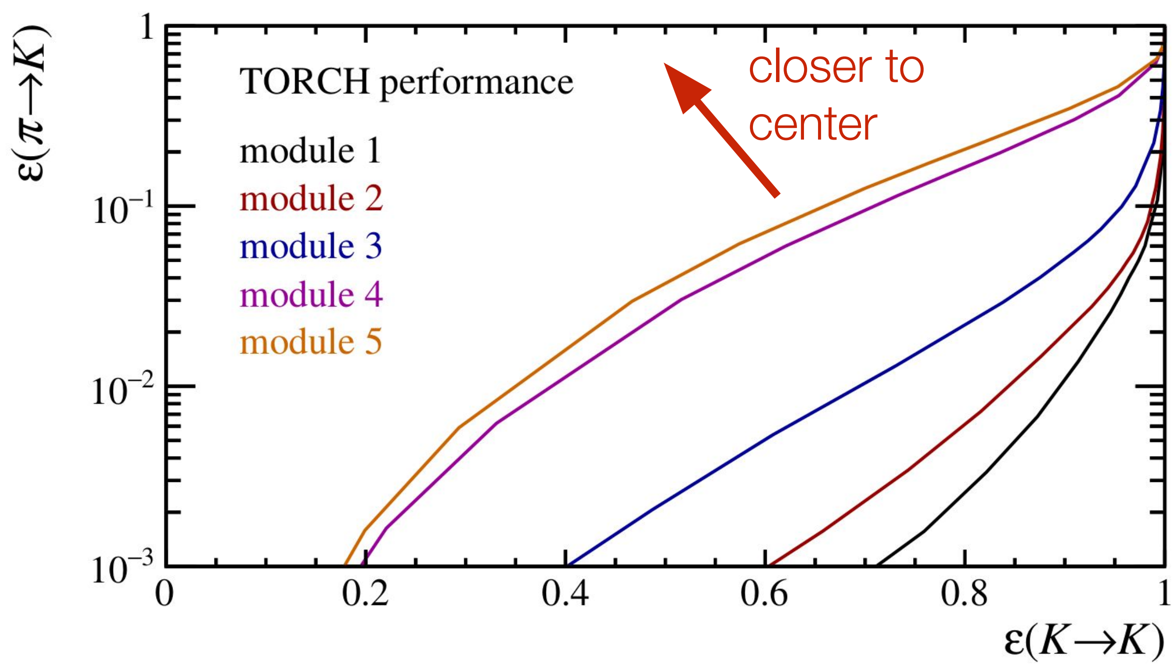


- Combining samples to realistic LHCb Upgrade II instantaneous luminosity profile

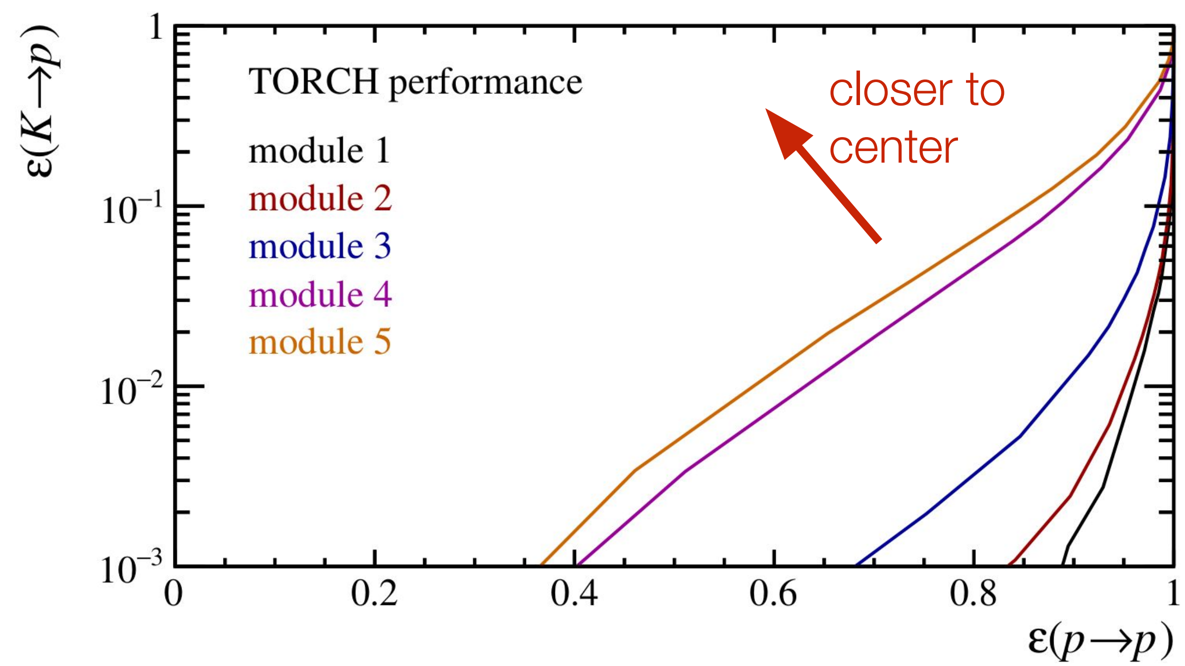
Performance versus module

- The performance is worst in **module** 5 (**central, highest occupancy**)
- Rapidly improves towards the periphery of the detector (module 1)

K-π separation

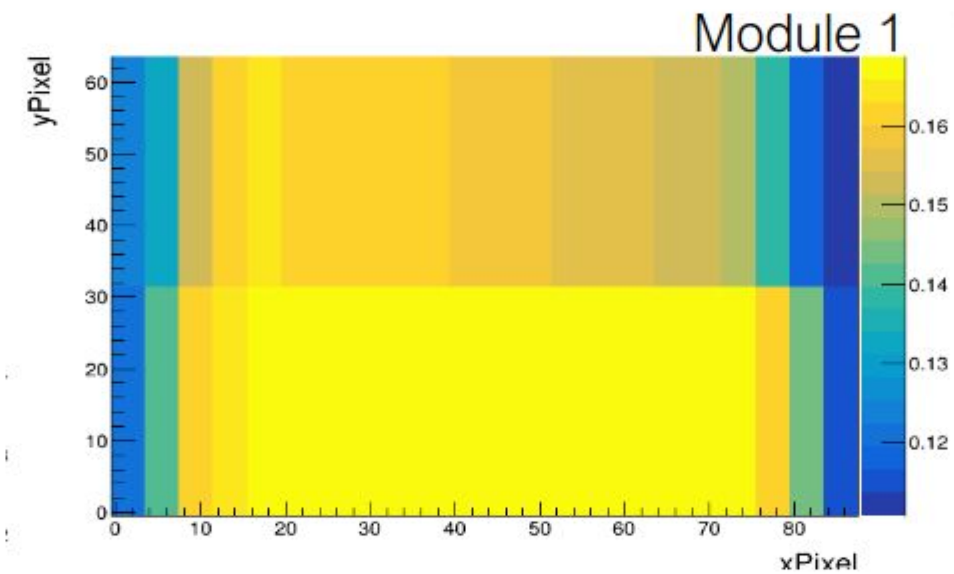


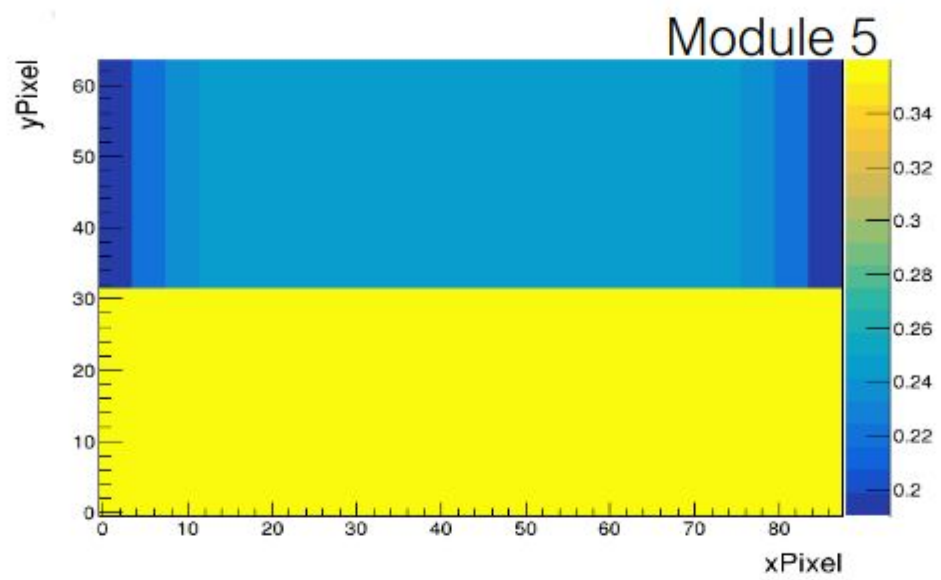
p-K separation



Performance versus module

- **Reduced performance due to high occupancy** in:
    - central modules
    - bottom region of the MCP-PMTs

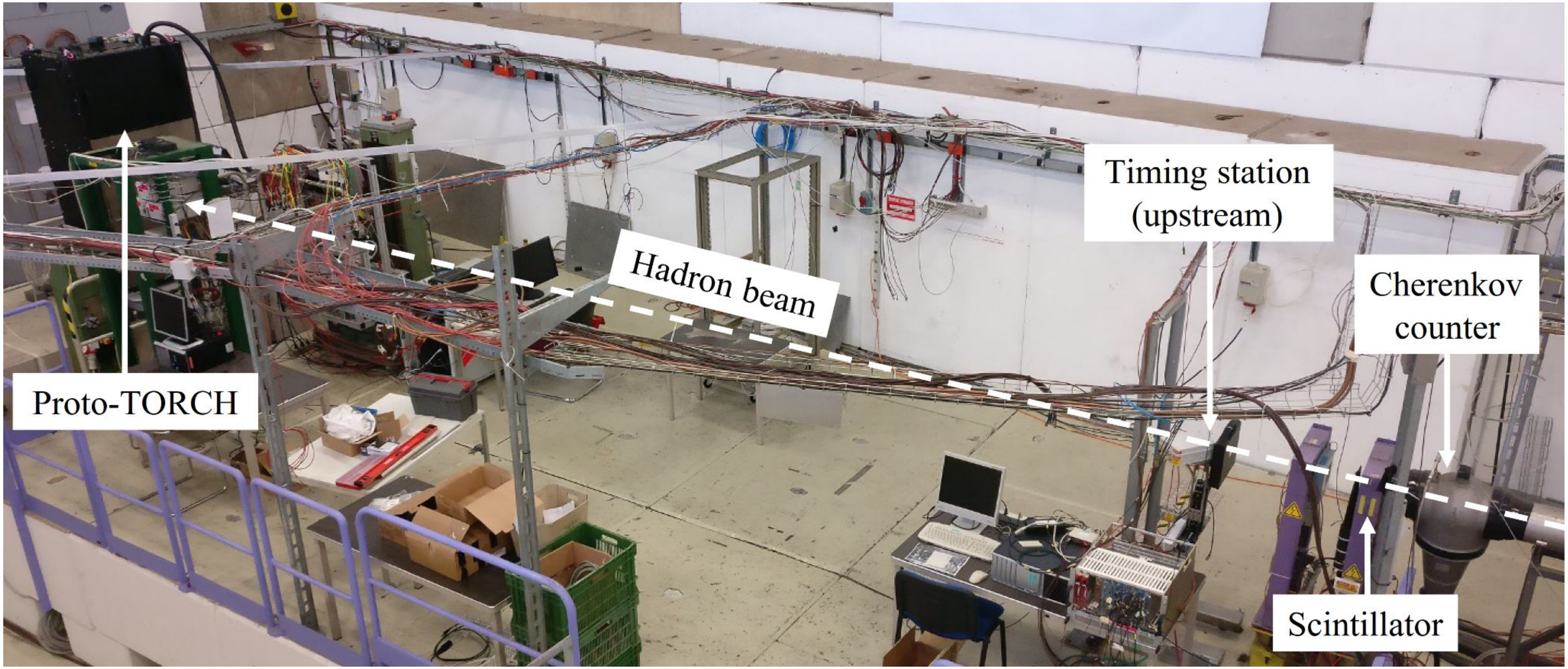


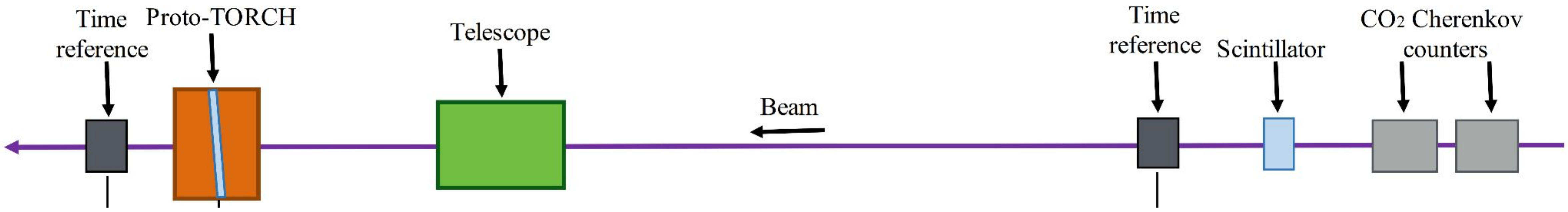


8x64, with charge sharing + 25ns dead time

- We are **trying to optimize** the optical layout **to reduce occupancy**
    - Changing focusing block's radius of curvature
    - Increasing granularity
    - Other options to be studied

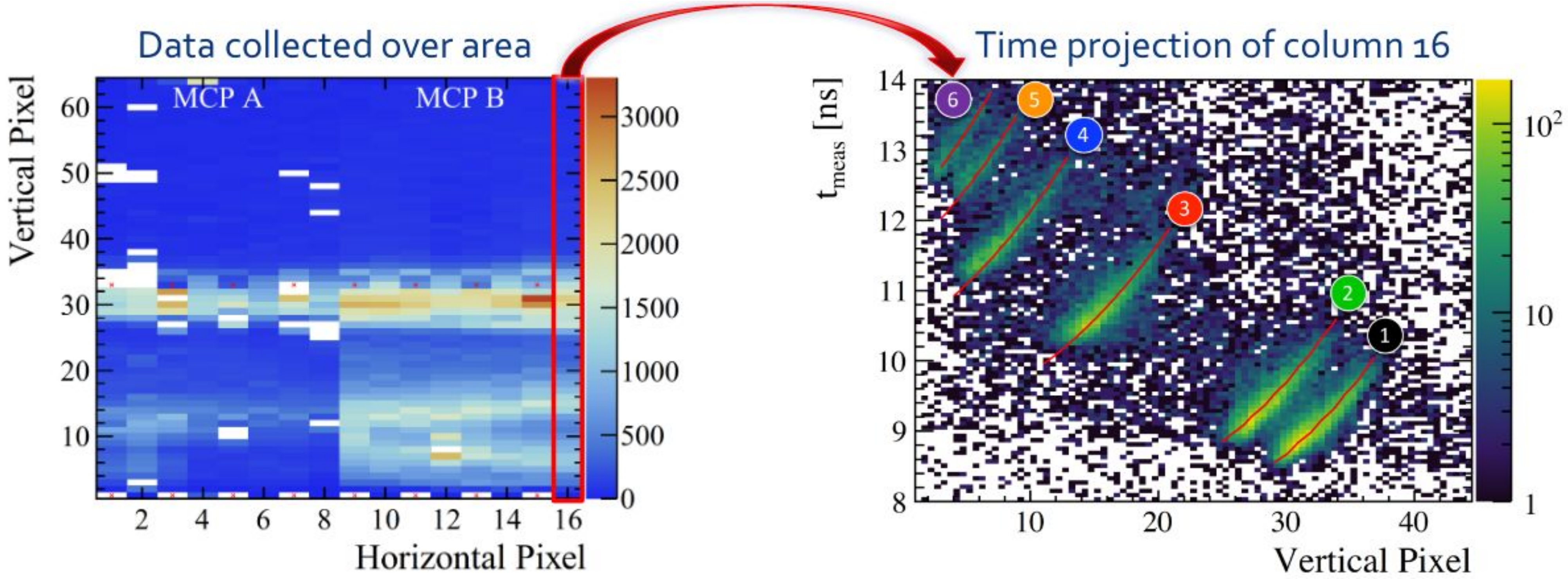
TORCH testbeam (2018)

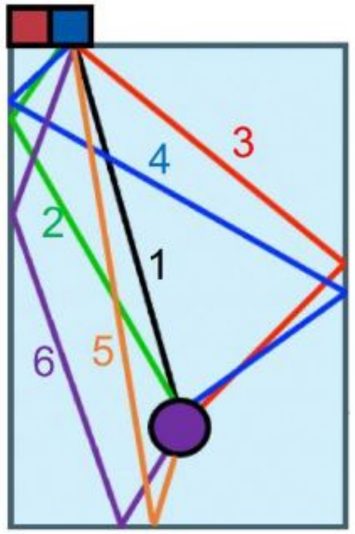




TORCH testbeam (2018)

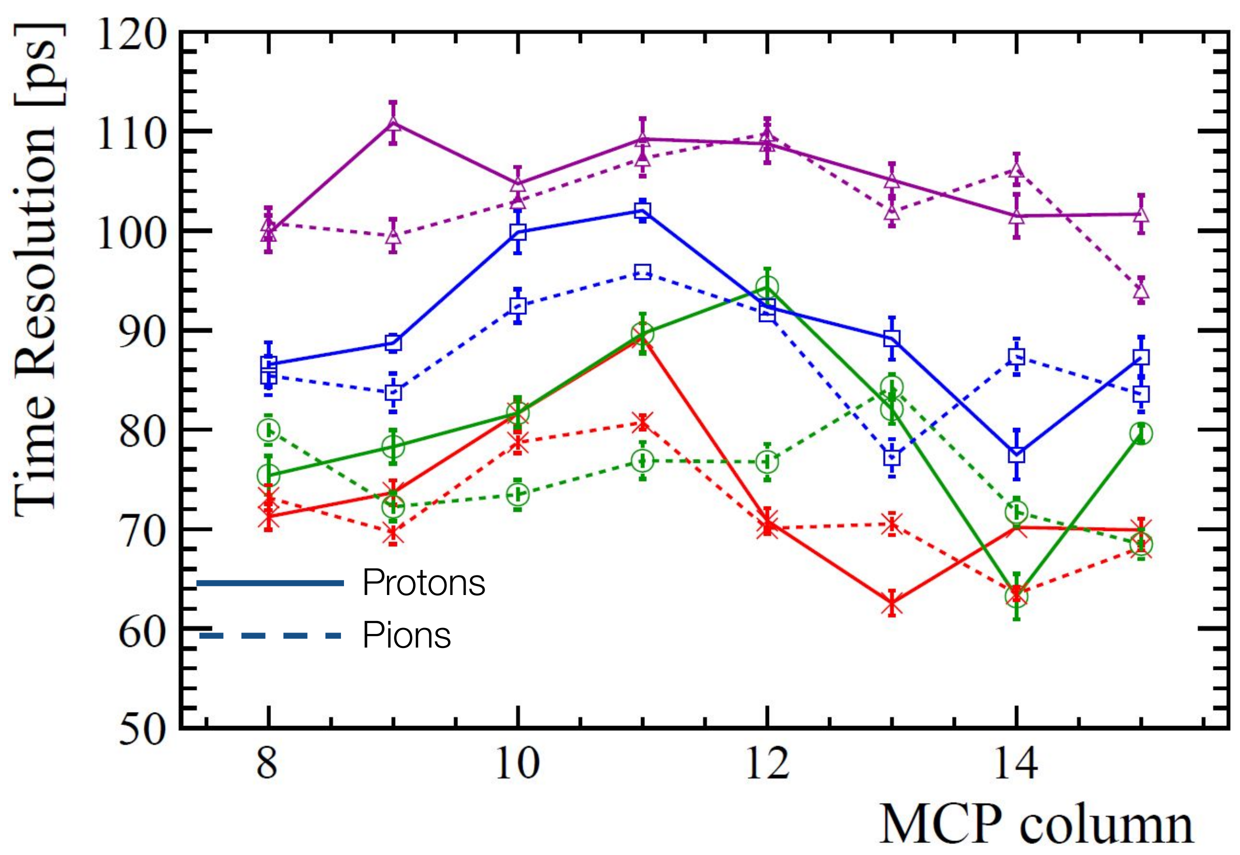
- Developed a TORCH prototype (proto-TORCH):
  - Full width, half height radiators
  - Full size focusing optics
  - Equipped with two MCP-PMTs

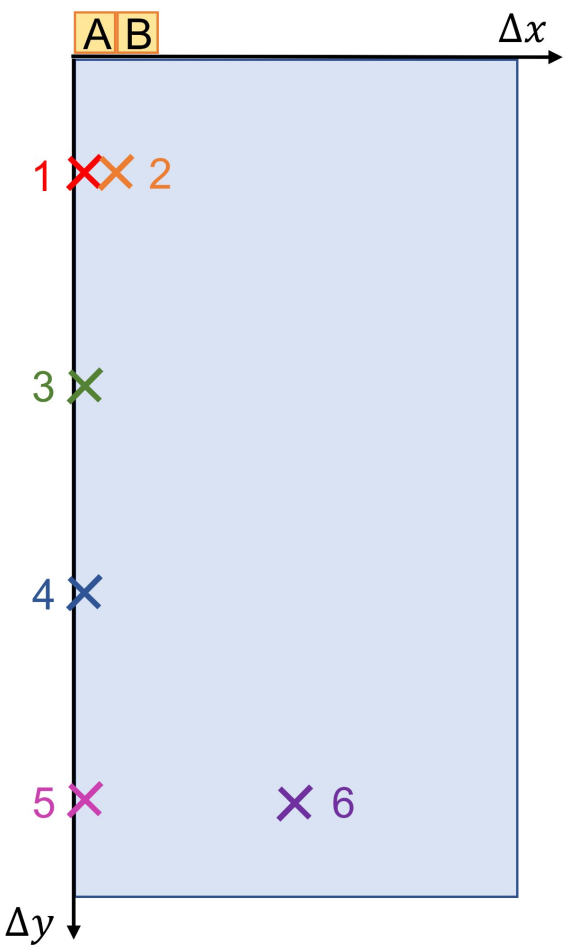




TORCH testbeam (2018)

- Exposed to **beam at six positions**
- **Reached 70ps time resolution goal** for beam position close to MCP
- Time resolution degrades with distance from MCP
- Reconstruction strongly impacted by small readout effects
- Improving calibrations further should significantly improve this issue





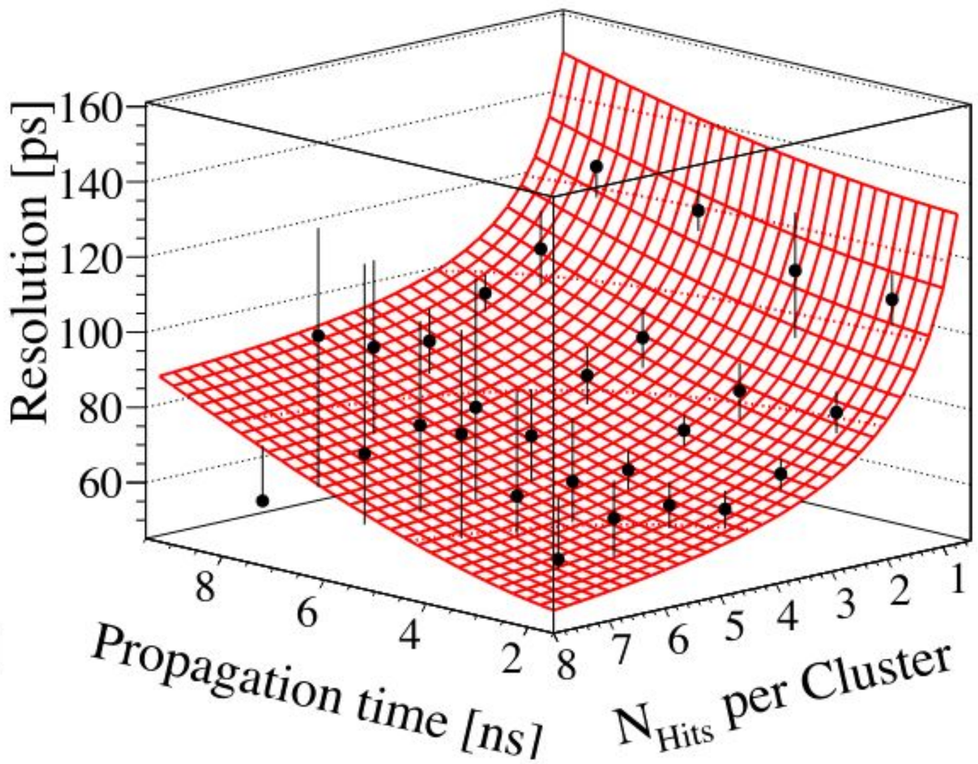
TORCH testbeam (2018)

$$\sigma^2_{\mathrm{TORCH}} = \sigma^2_{\mathrm{const}} + \sigma^2_{\mathrm{prop}}(t) + \sigma^2_{\mathrm{RO}}(N_{\mathrm{hits}})$$

MCP

Propagation time dependent effects

Cluster size and readout



Measured

$$\sigma_{\mathrm{const}} = 33.0 \pm 7.1\ \mathrm{ps}$$
$$\sigma_{\mathrm{prop}}(t) = (7.8 \pm 0.7) \times t[\mathrm{ns}]\ \mathrm{ps}$$
$$\sigma_{\mathrm{RO}}(N_{\mathrm{hits}}) = \frac{100.5 \pm 5.7}{\sqrt{N_{\mathrm{hits}}}}\ \mathrm{ps}$$

Expected

$$\sigma_{\mathrm{const}} \approx 33\ \mathrm{ps}$$
$$\sigma_{\mathrm{prop}}(t) \approx (3.75 \pm 0.8) \times t[\mathrm{ns}]\ \mathrm{ps}$$
$$\sigma_{\mathrm{RO}}(N_{\mathrm{hits}}) \approx \frac{60}{\sqrt{N_{\mathrm{hits}}}}\ \mathrm{ps}$$

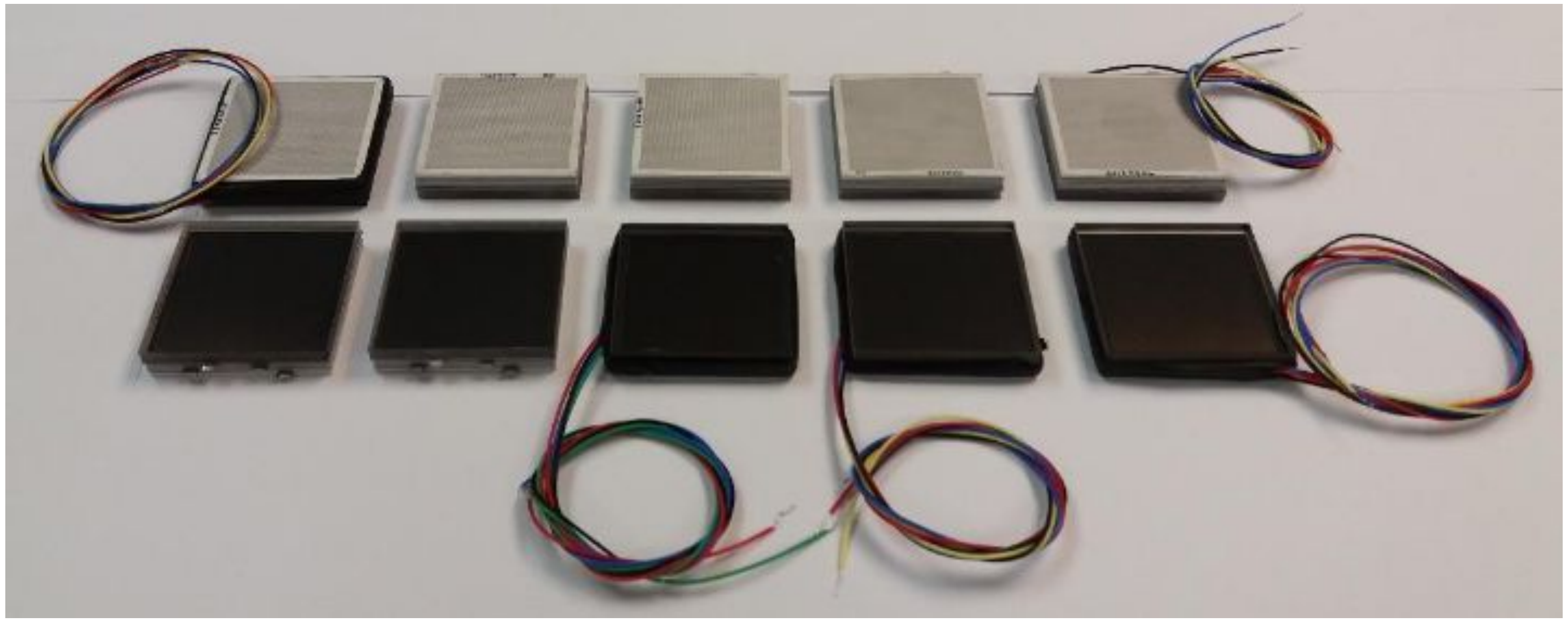
Resolution expected to improve with better electronics calibration

TORCH testbeam (2022)

- Testbeam planned on 31 October – 28 November

TORCH testbeam (2022)

- Testbeam planned on 31 October – 28 November
- Fully instrumented detector
  - 10 MCP-PMTs with 8x64 channels
  - Fully equipped with NINO + HPTDC
- Calibration of boards ongoing in dedicated test setup
- New DAQ for streamlined data taking



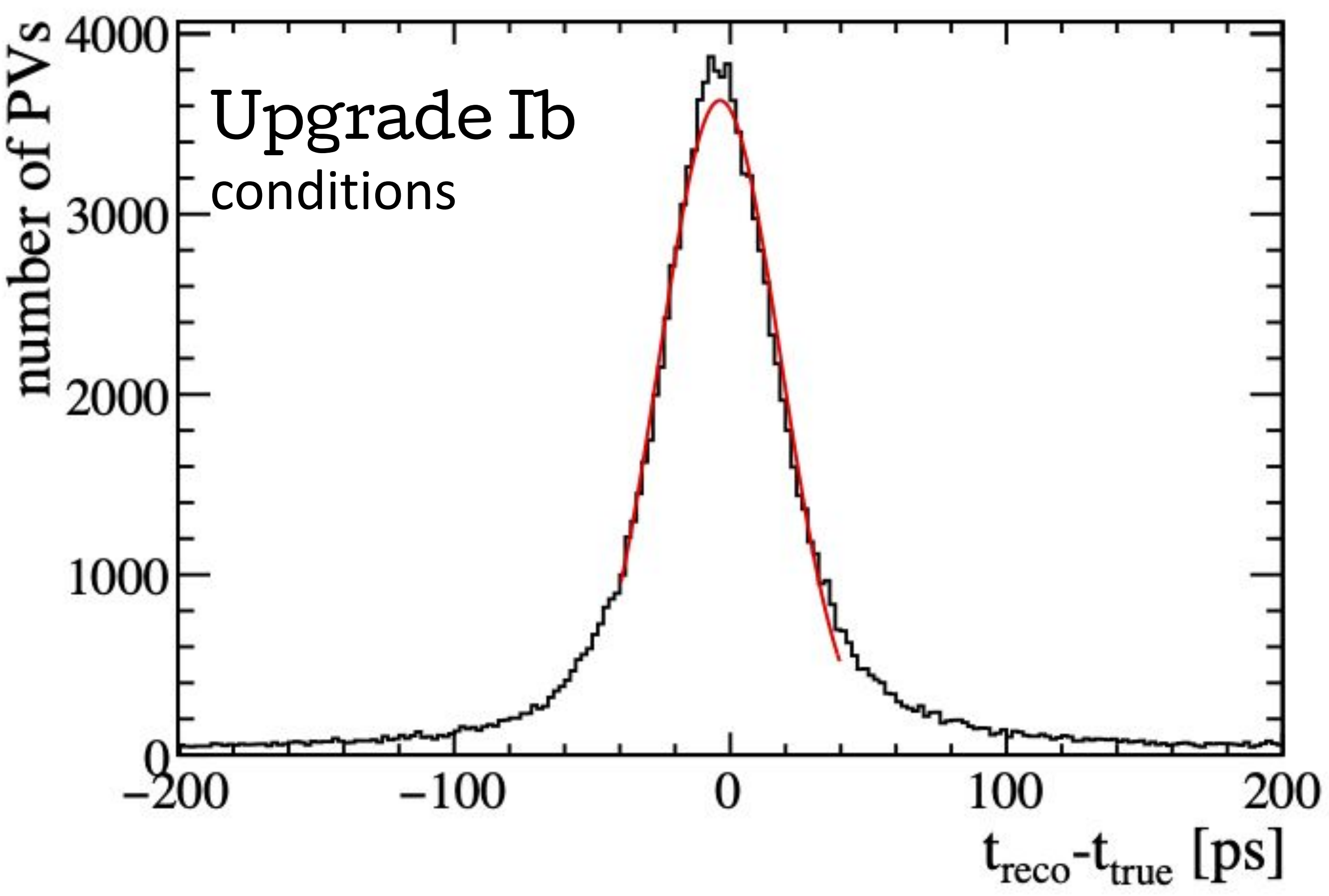
Outlook

- TORCH is a novel concept for a DIRC-type detector to achieve high-precision time-of-flight over large areas.
- The TORCH detector provides particle identification in the 2-20 GeV/c momentum range
- Good performance is seen for LHCb Upgrade II conditions [CERN-LHCb-PUB-2022-006]
- Reconstruction algorithms developed and tested [CERN-LHCb-PUB-2022-004] [CERN-LHCb-PUB-2022-007]
- Testbeam results very promising (~100ps time resolution)
- New Testbeam planned this November

Thanks for your attention

t_0 reconstruction

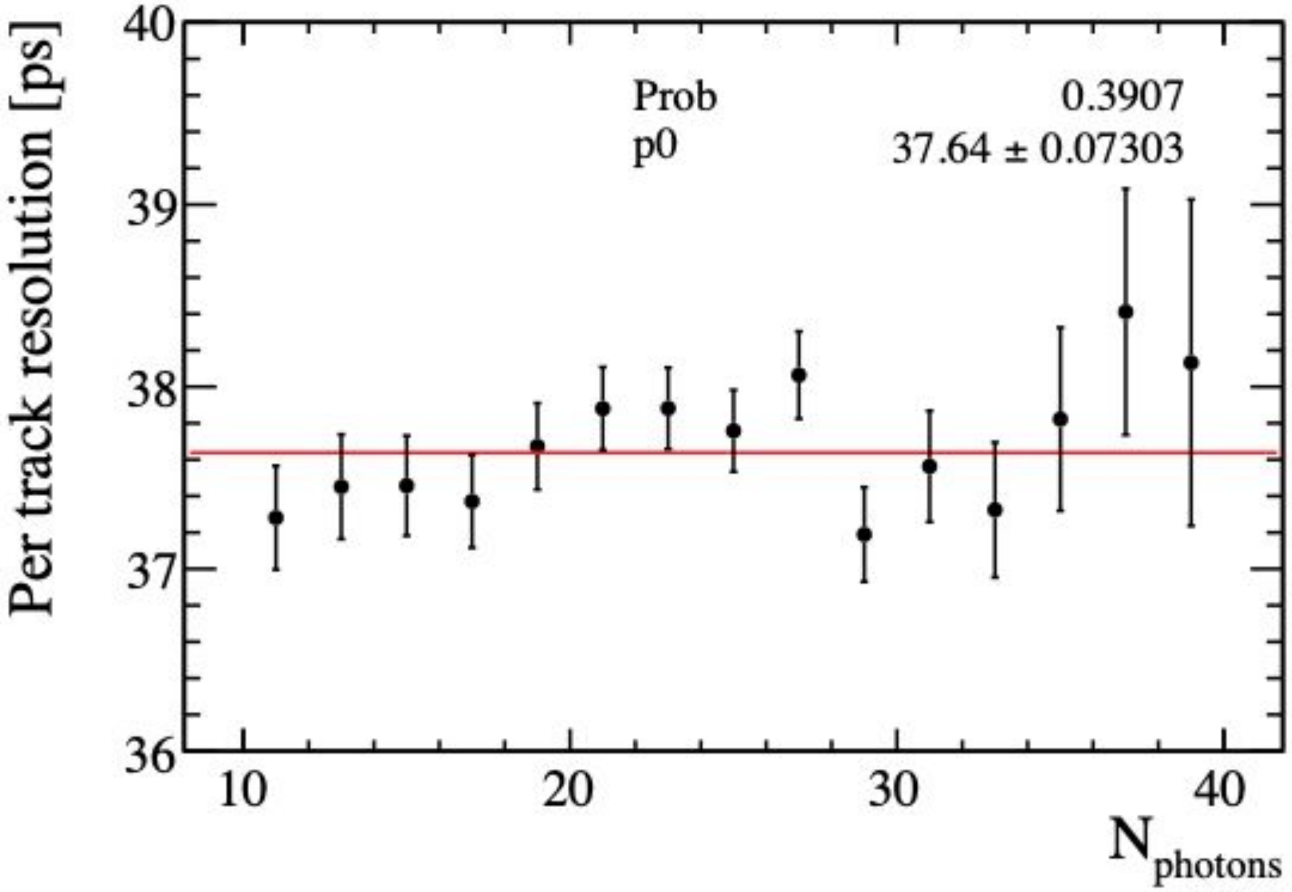
- Obtain likelihood profile for each track (under different PID hypothesis) as a function of t_0.
- Combine likelihoods for all tracks assigned to vertex.
  - ➡ Choose the hypothesis for each track which fits best with the other tracks.
- Core of the distribution has width of about 22 ps.
- Time resolution of 70 ps per photon should translate to 10-15 ps per track with 20-30 photons.



Per track t_0 resolution

Upgrade Ib conditions

- Determine track level t_0 using true PID hypothesis.
- Resolution of 37.6 ps with little dependence on $N_{photons}$.
- Significant variation seen across modules. Suggests that:
  - ➡ Likelihood is dominated by background hits.
  - ➡ Occupancy is driving t_0 resolution.

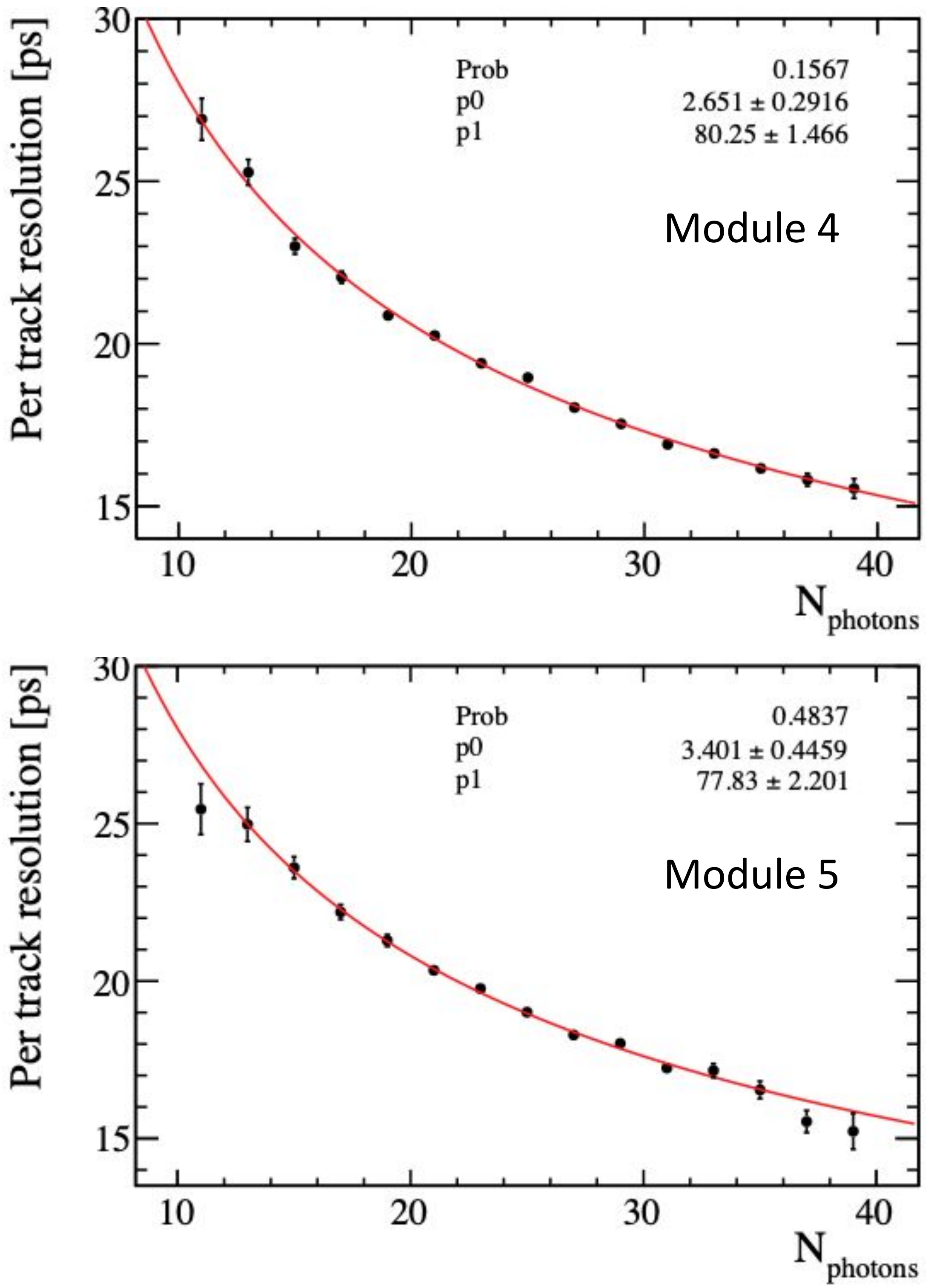


Per track t_0 resolution

- Test occupancy issue by reconstructing t_0 when removing all photons except those from given track.
- Use true track entry position/angle.
- Use correct PID hypothesis.
- Fit with Gaussian in ±3*expected resolution.
- Dependence of per-track resolution described by:

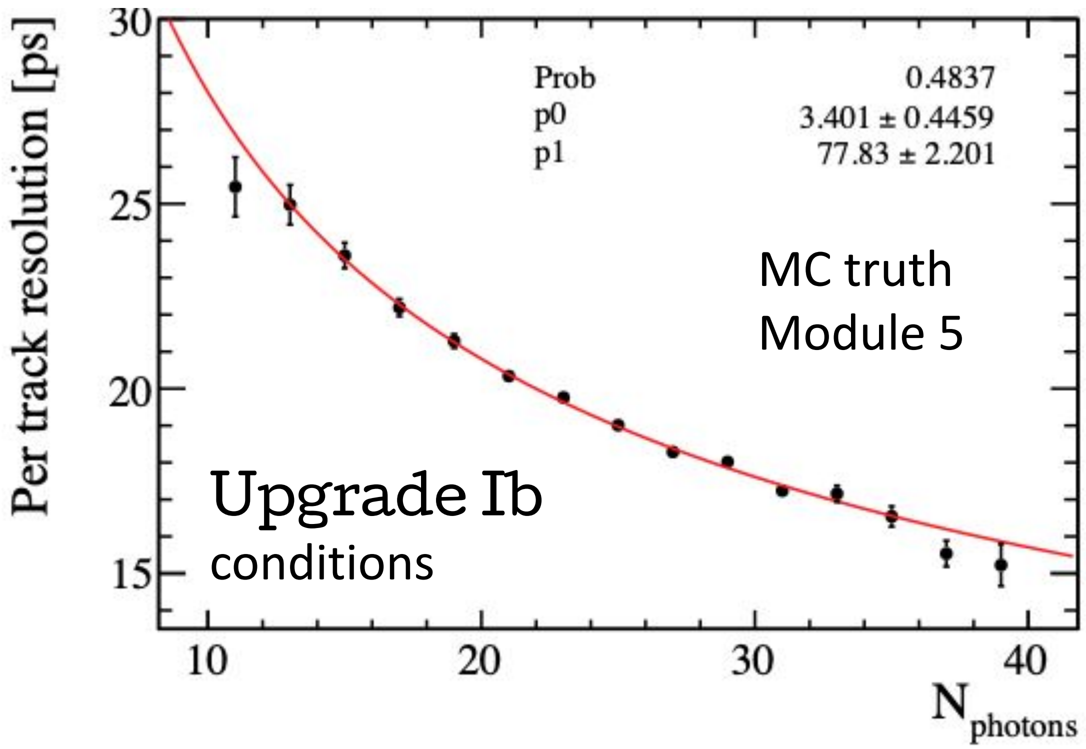
$$p_0 + p_1/\sqrt{N}_{\mathrm{photons}}$$

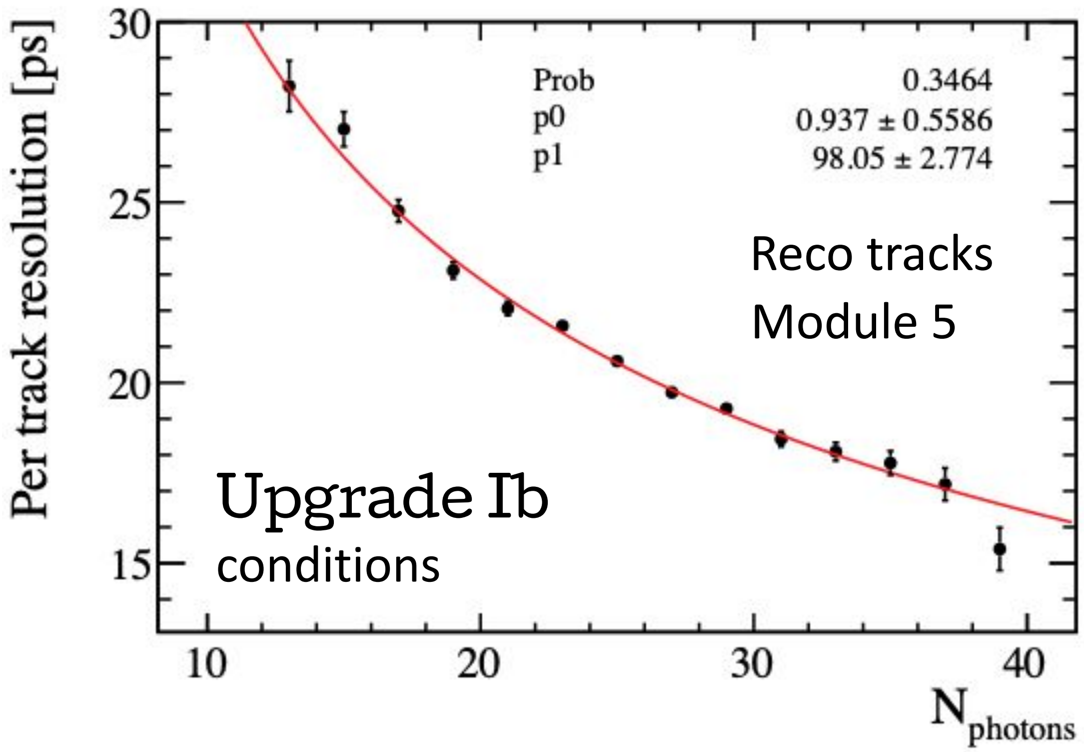
Upgrade Ib conditions



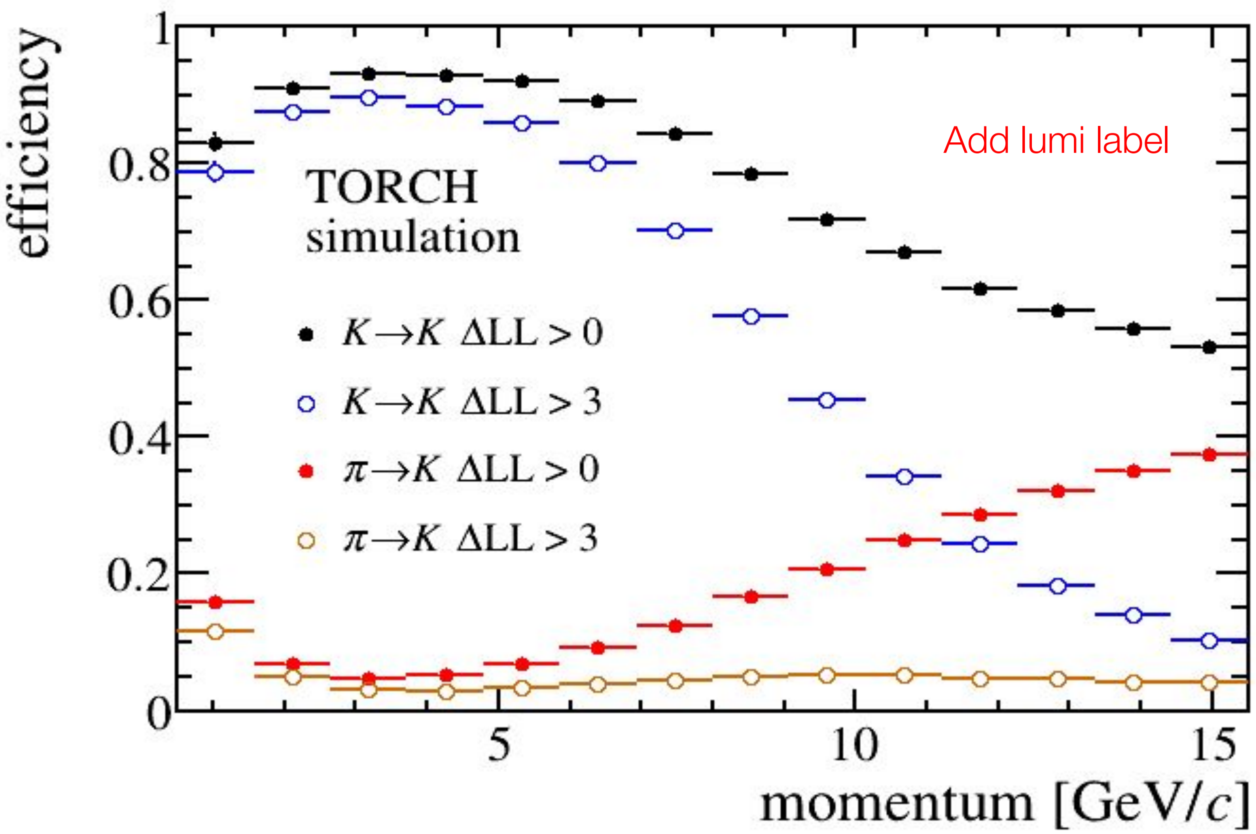
Track reconstruction effect on t_0

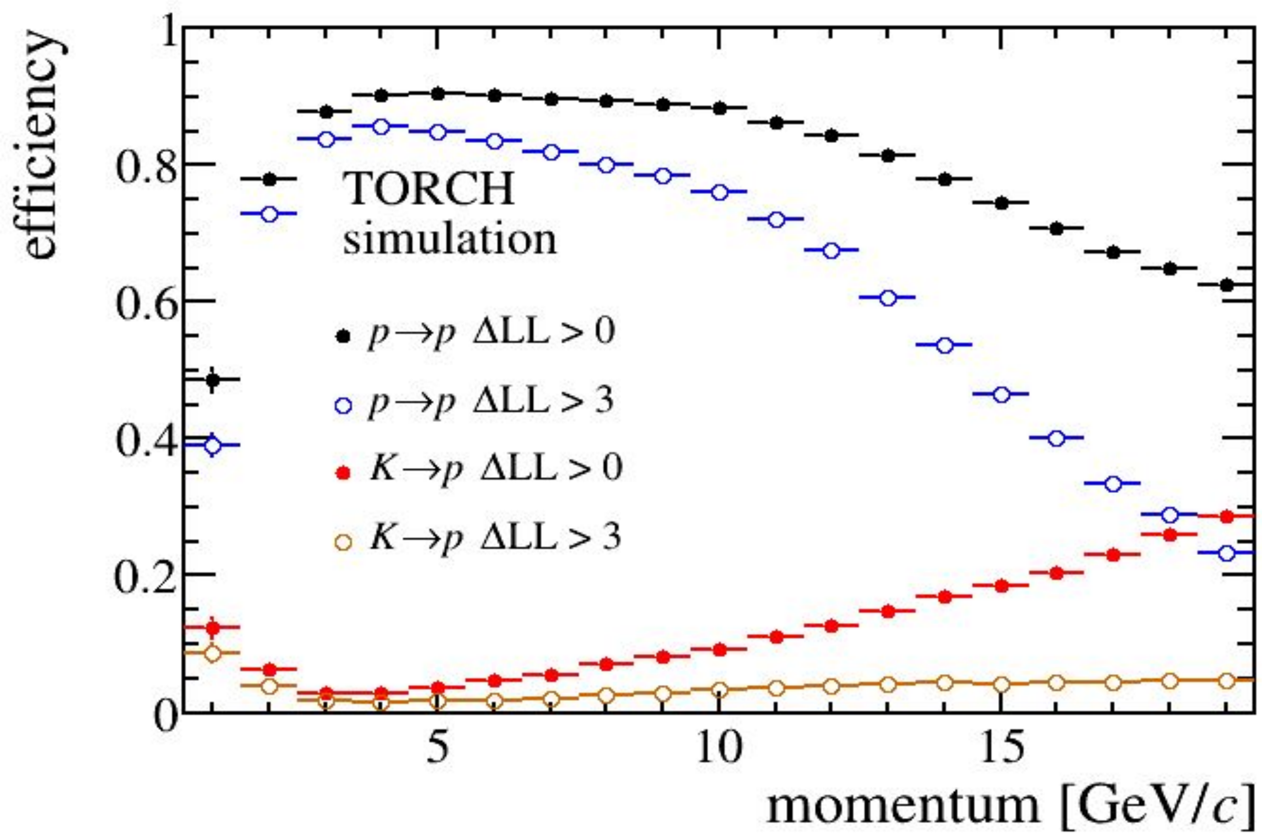
- When using the reconstructed track entry position and angle, the resolution gets worse:
  - ➡ Precision on the track parameters decreases the resolution by about 20 ps per photon.
- The MC true tracking is still affected by:
  - ➡ Multiple scattering in the radiator bar.
  - ➡ Surface scattering due to surface roughness.
  - ➡ Photon pathlength dependence/pixel size.





Performance in the FTDR



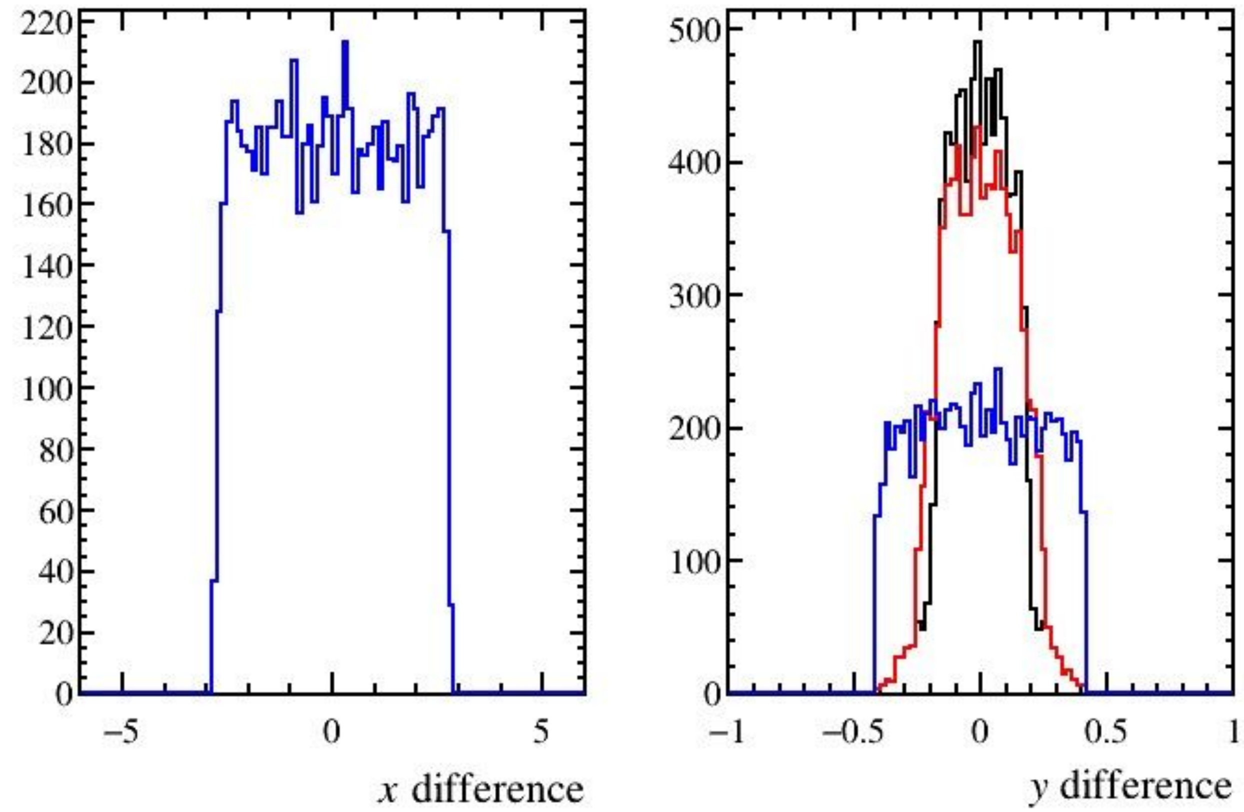


- Uses an 8-by-128 effective pixelation in outer modules and 16-by-128 effective pixelation in the central region.
- No charge-sharing or deadtime is used.

Pixelisation

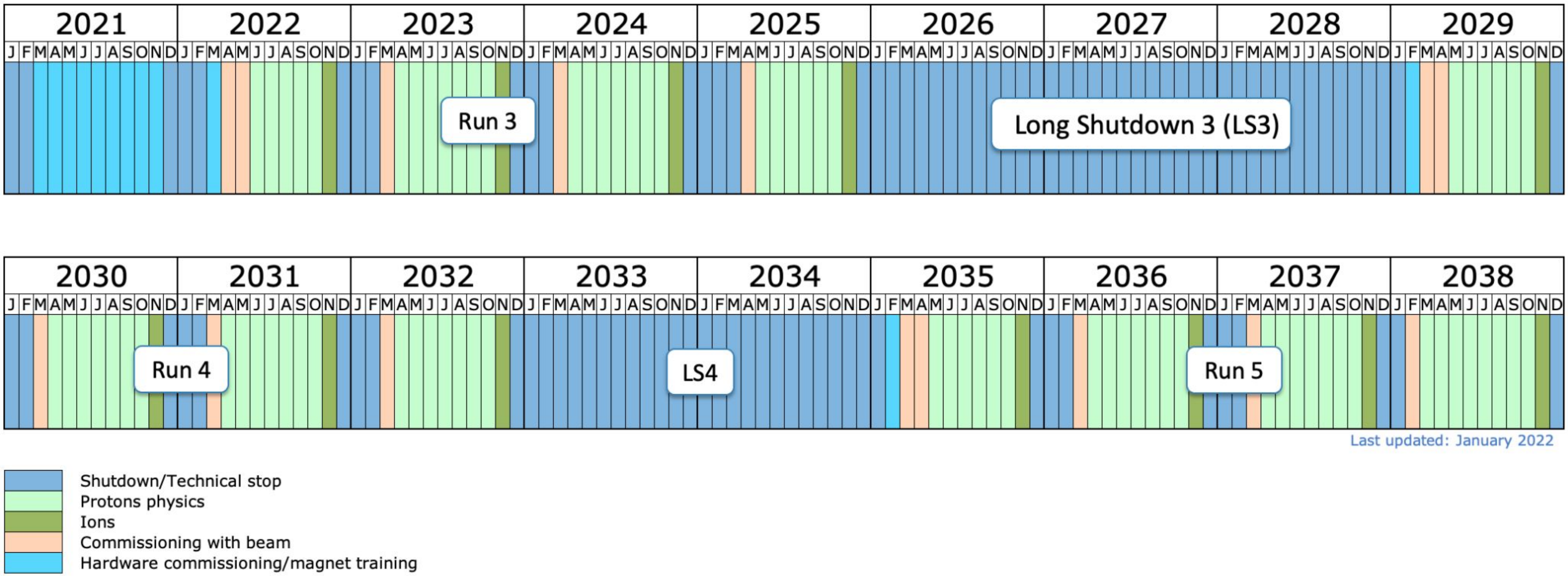
- Also checked to see if we can go beyond the 8-by-128 by using charge weighting.
- The conclusion strongly depends on the gain-to-threshold ratio and the point spread.

Using standard 650k gain, 30fC threshold and 0.8mm point spread.



8-by-64 pixel
Naive cluster centre
Charge weighted cluster centre

LHC Schedule



Test beam results

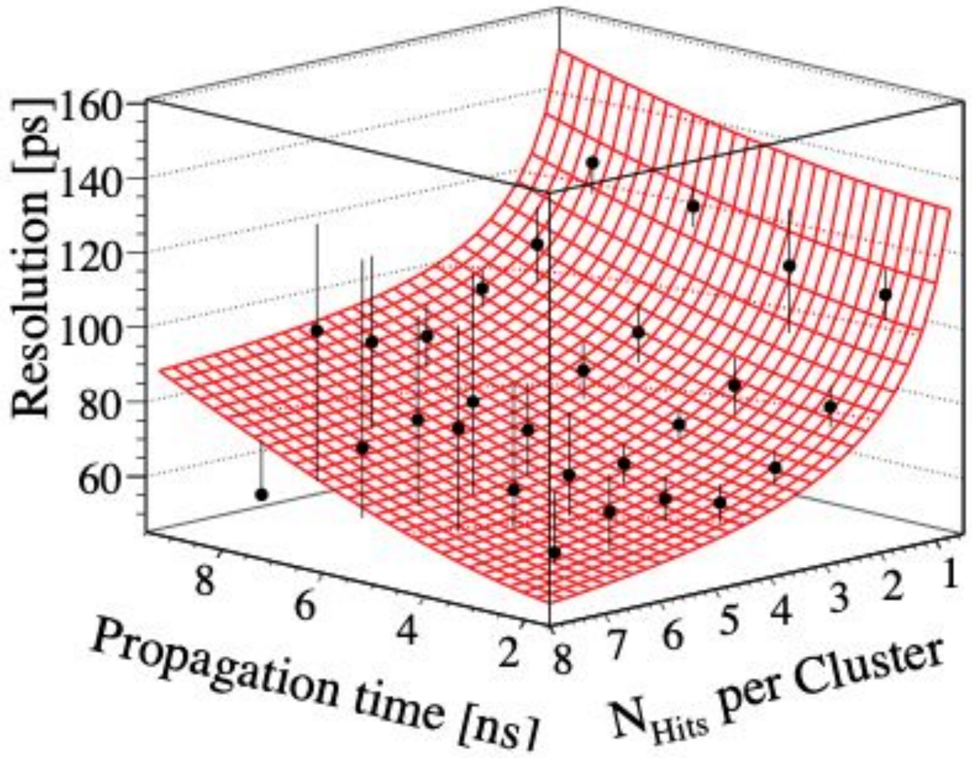
- Can parametrise resolution in 2D

$$\sigma^2_{\mathrm{TORCH}} = \sigma^2_{\mathrm{const}} + \sigma^2_{\mathrm{prop}}(t) + \sigma^2_{\mathrm{RO}}(N_{\mathrm{hits}})$$

MCP

Propagation time dependent effects

Cluster size and readout



Measured

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$$\sigma_{\mathrm{RO}}(N_{\mathrm{hits}}) = \frac{100.5 \pm 5.7}{\sqrt{N_{\mathrm{hits}}}} \text{ ps}$$

Expected

$$\sigma_{\mathrm{const}} \approx 33 \text{ ps}$$

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$$\sigma_{\mathrm{RO}}(N_{\mathrm{hits}}) \approx \frac{60}{\sqrt{N_{\mathrm{hits}}}} \text{ ps}$$

Resolution expected to improve with better electronics calibration

Comparison with RICH

Similarities:

- Reconstruction uses a similar approach to the RICH detectors
    - Optimisation from RICH reconstruction can be imported to TORCH
- A 3D image (x,y,t) image is measured
    - Ring (RICH) and Hyperbola (TORCH)

Differences:

- Photons from a track spread over 25ns window in TORCH
    - Narrow time window for RICH

Reconstruction

- Use two different algorithms to compute hit/track/hypothesis probabilities:
  - **Binned**: Based on simulating large numbers of photons (ray-tracing)
  - **Unbinned**: Semi-analytic approach based on back-propagation
- The semi-analytic approach is faster and works with either pixel hits (integrating over the pixel size) or clusters.

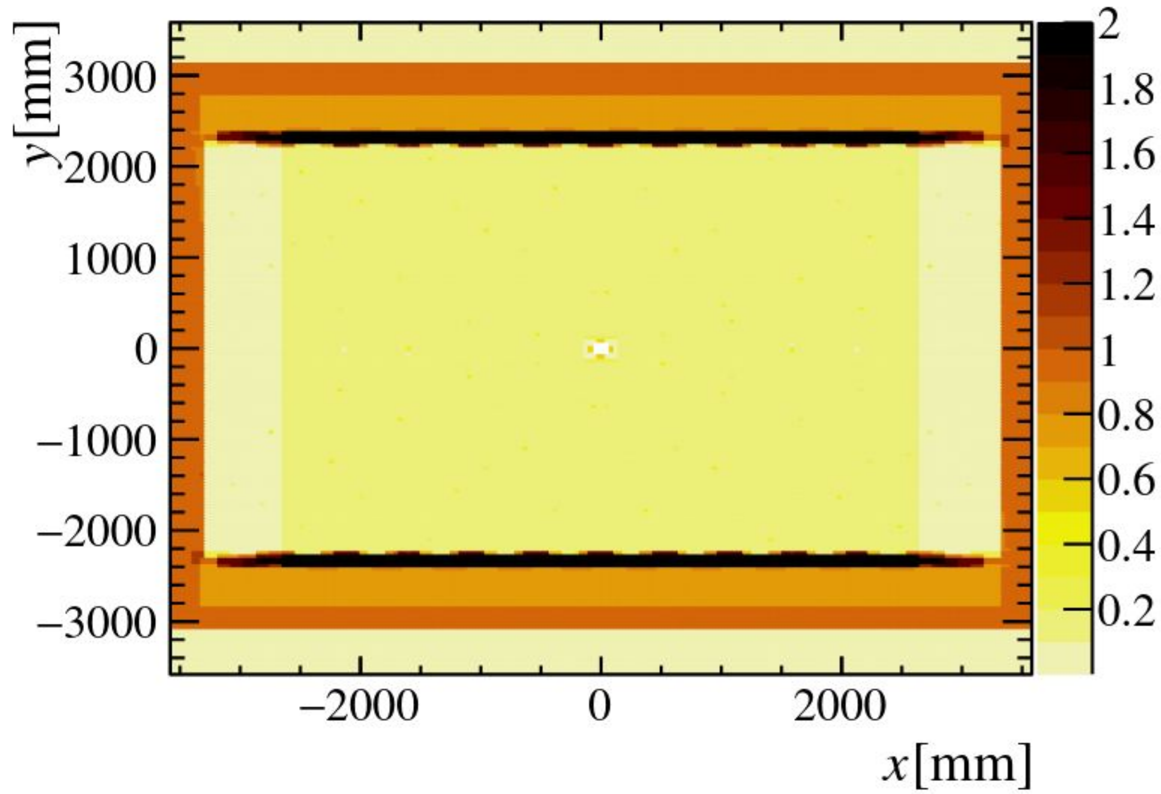
- Two different approaches to consider the likelihood:
  - **Local**: Consider each track in isolation
  - **Global**: Consider all track hypothesis together

Impact of TORCH material

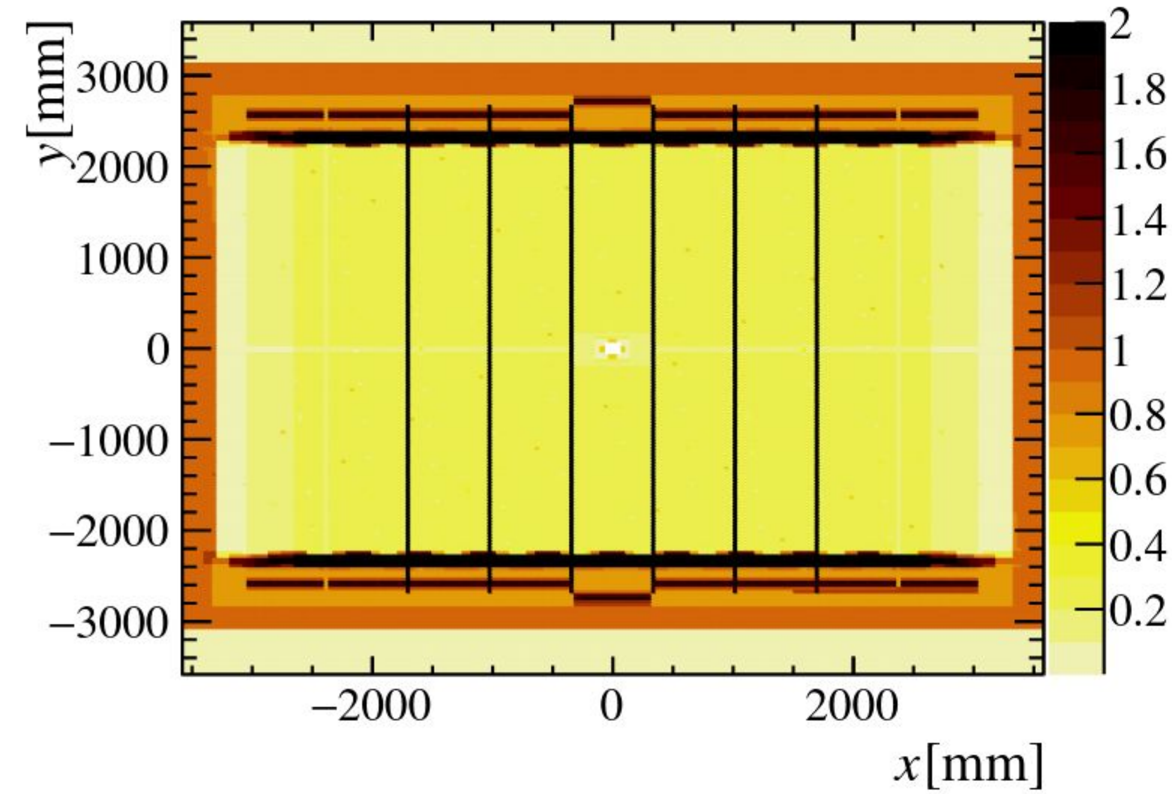
- Placing TORCH in front of RICH 2 slightly increases the material budget

Material in terms of radiation length from start of FT to entry to RICH2 volume:

without TORCH



with TORCH

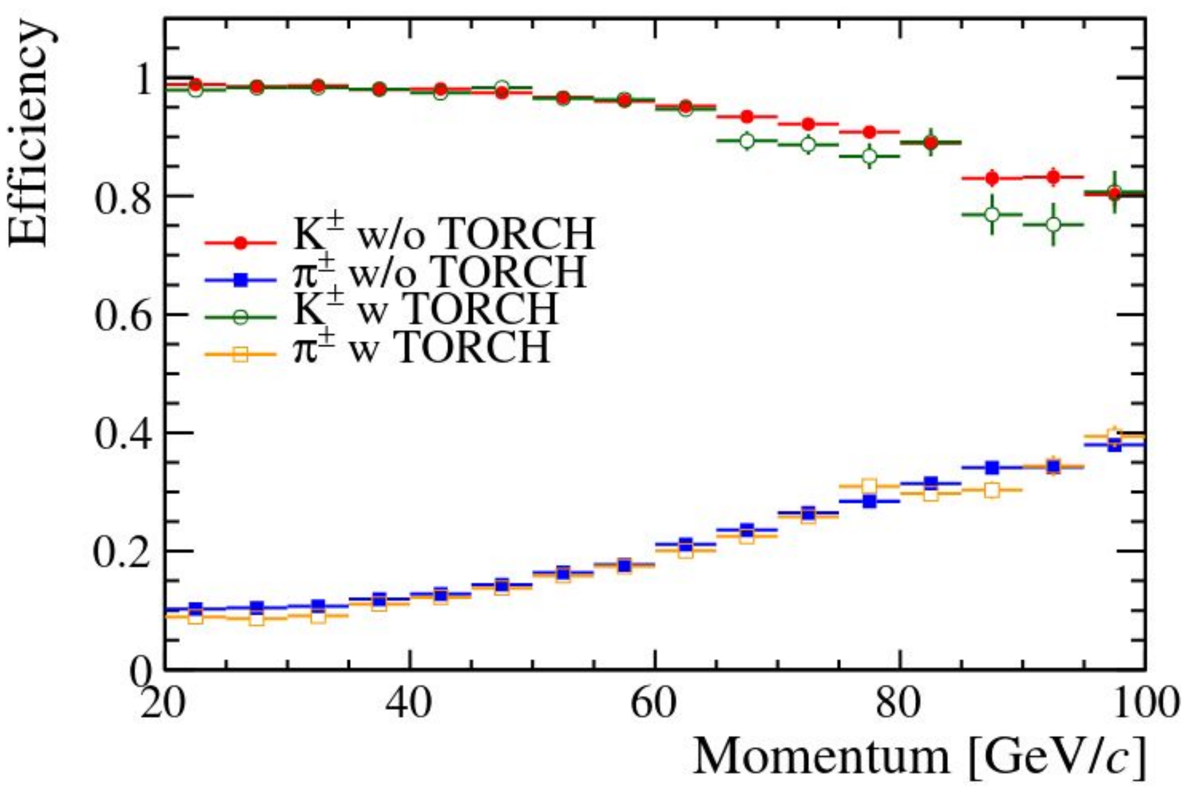


Impact of TORCH material

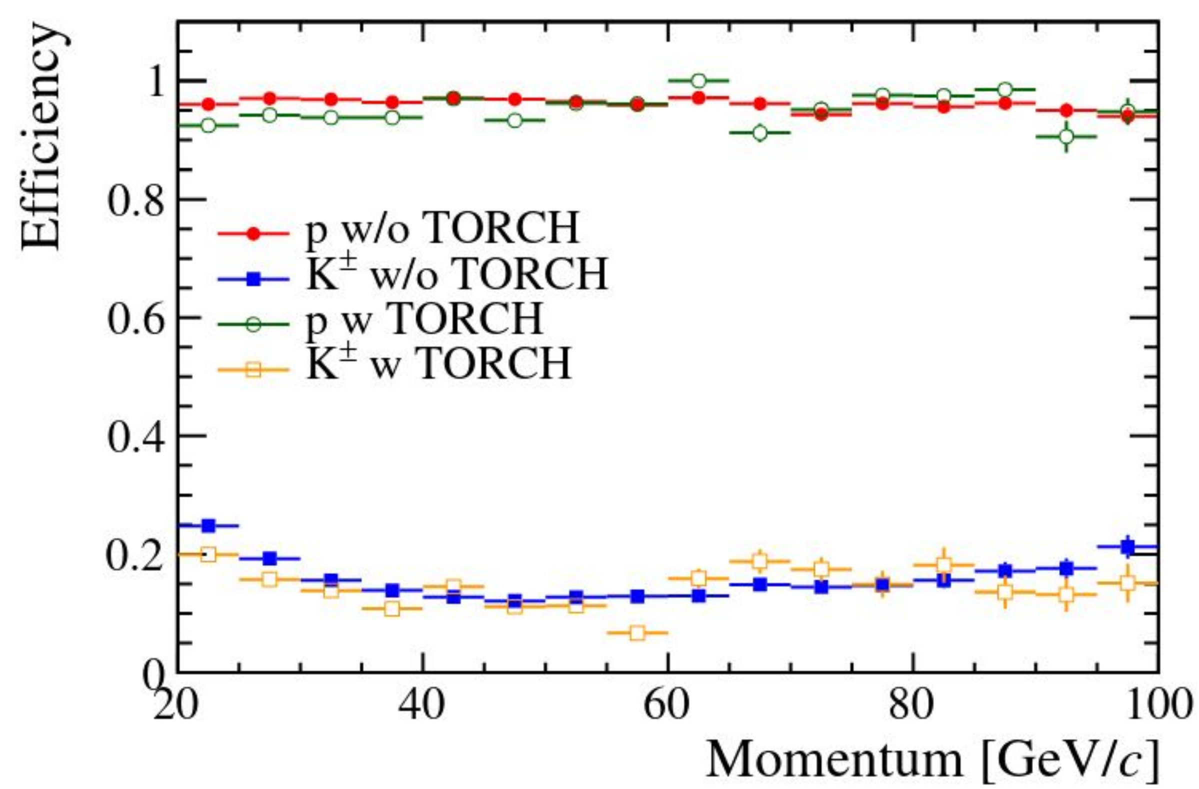
- Placing TORCH in front of RICH 2 slightly increases the material budget
- Effect on RICH2 PID performance is negligible

RICH2 PID performance with and without TORCH

DLLK > 0

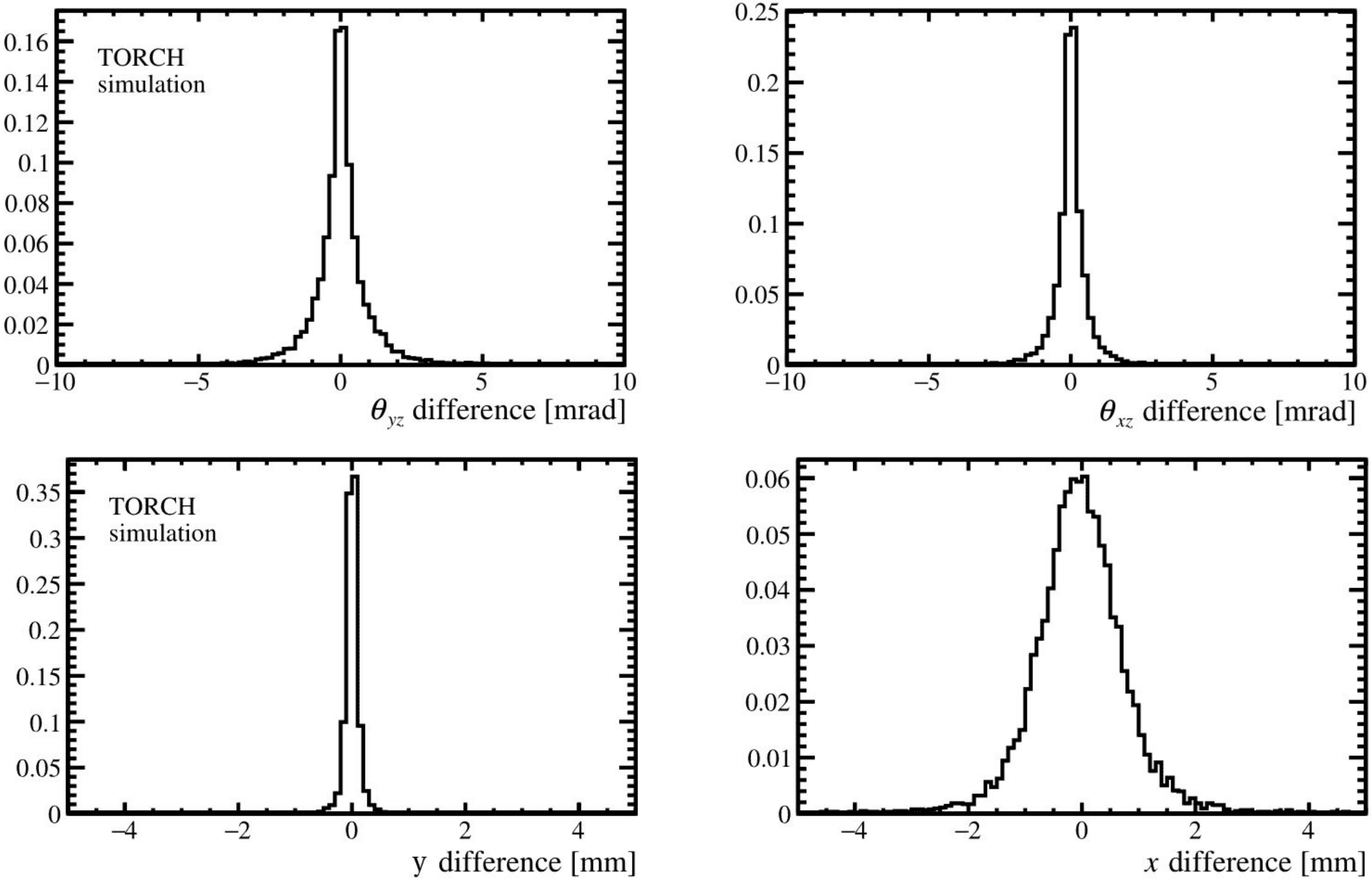


DLLp - DLLK > 0



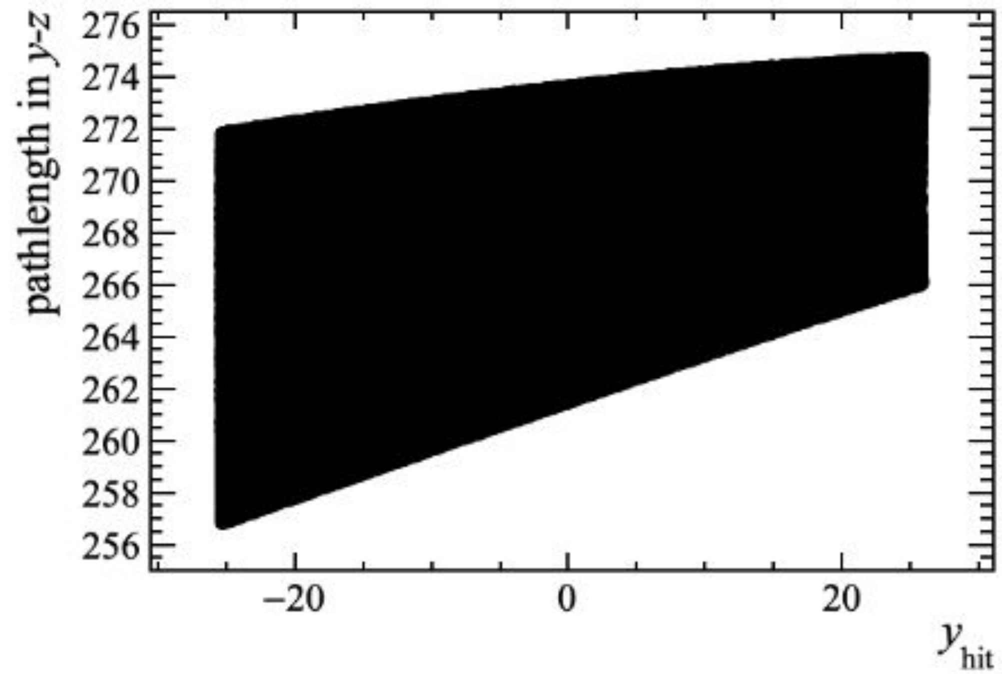
Track resolution

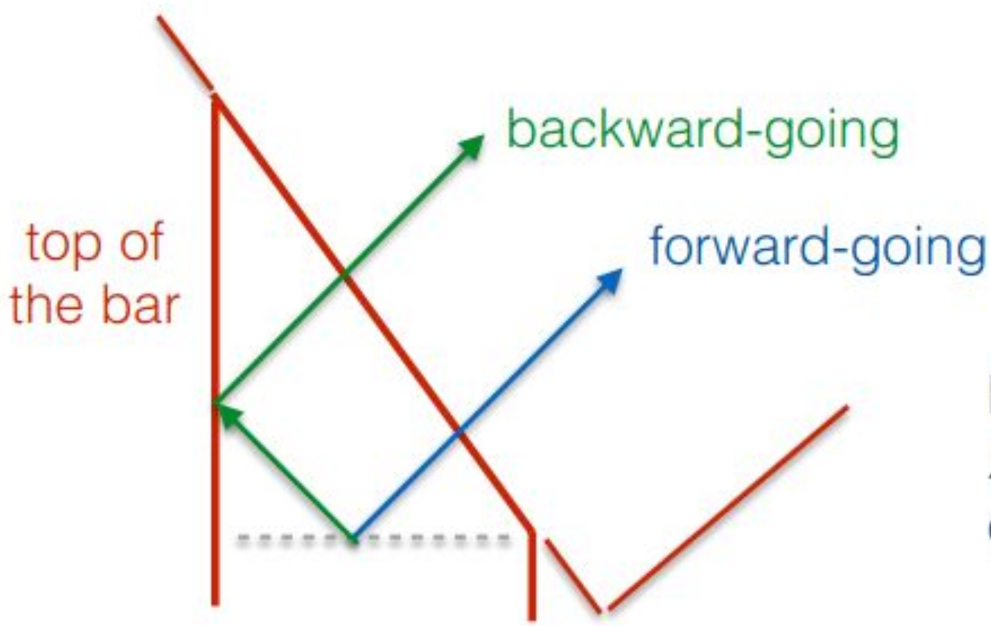
Track resolution using LHCb Upgrade I

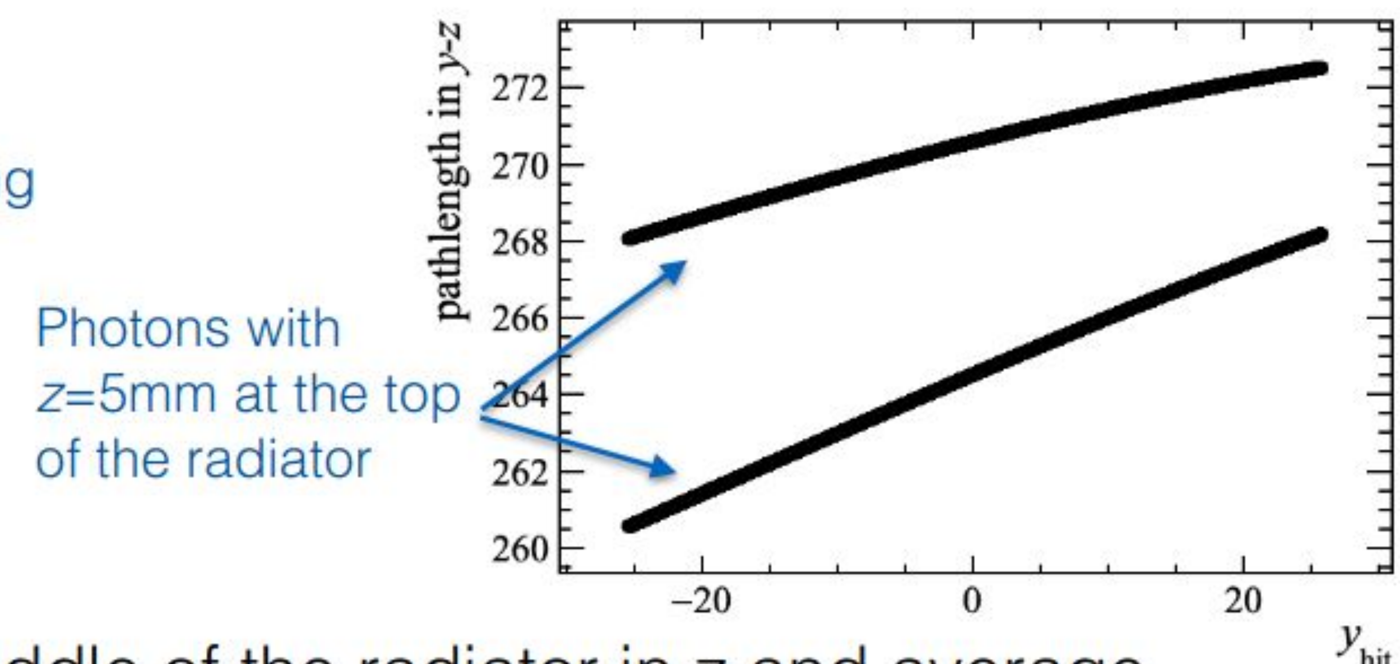


Effect of the focussing block

- However, the path length in the focus is not unique for a given hit position.
- The path length depends on the photon position in *z* at the top of the bar and whether or not the photon is forward or backward going.







- Assume photons are at the middle of the radiator in z and average the forward- and backward-going path lengths.