TORCH: Pattern recognition and particle identification performance

11th International Workshop on Ring Imaging Cherenkov Detectors

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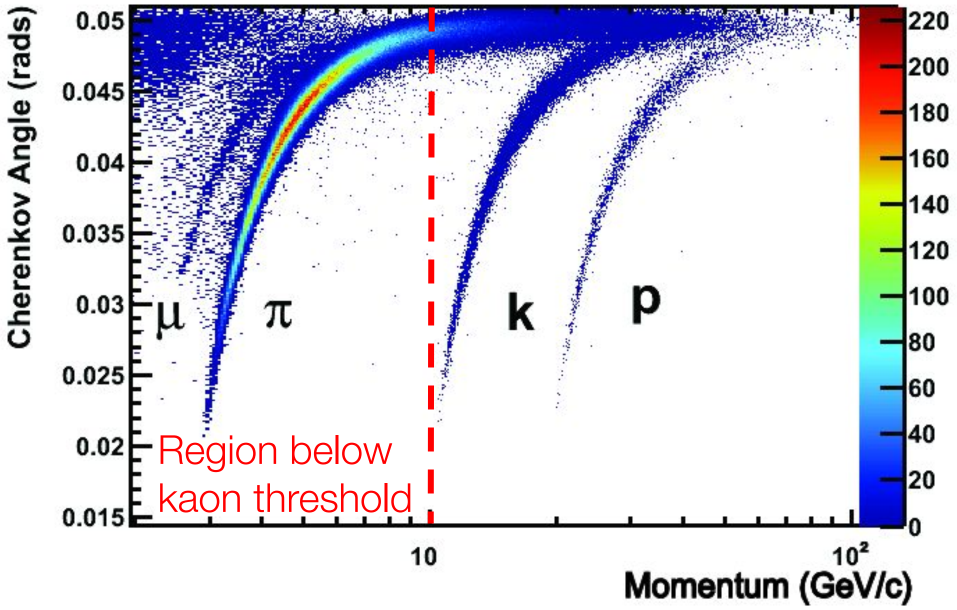
On behalf of the TORCH collaboration

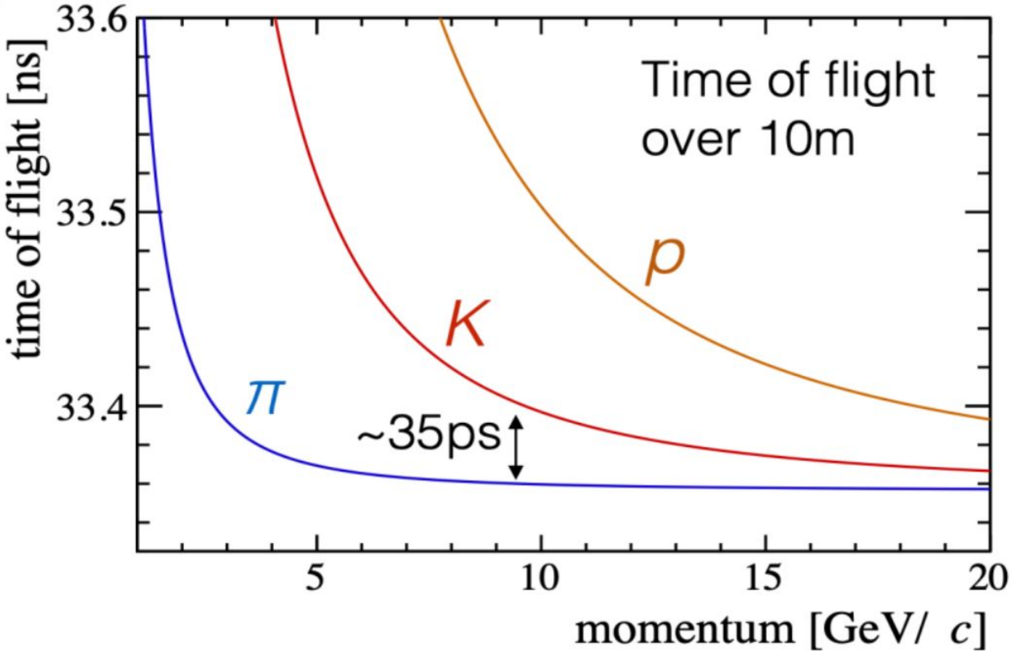
Introduction

- PID at LHCb currently provided by 2 RICH detectors

- **TORCH:** 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

- **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





The TORCH principle

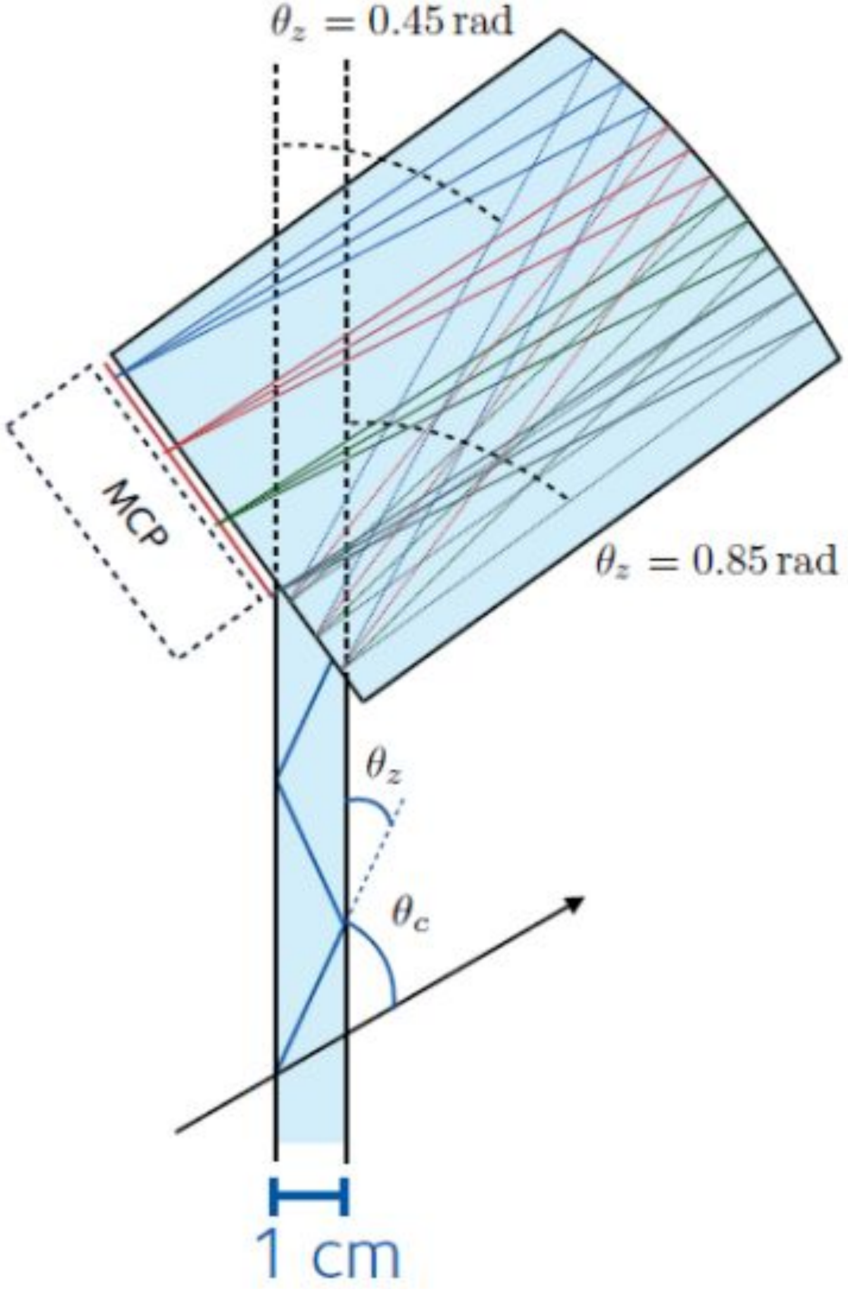
- Charged particles passing through a quartz plate generate prompt Cherenkov photons

- 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

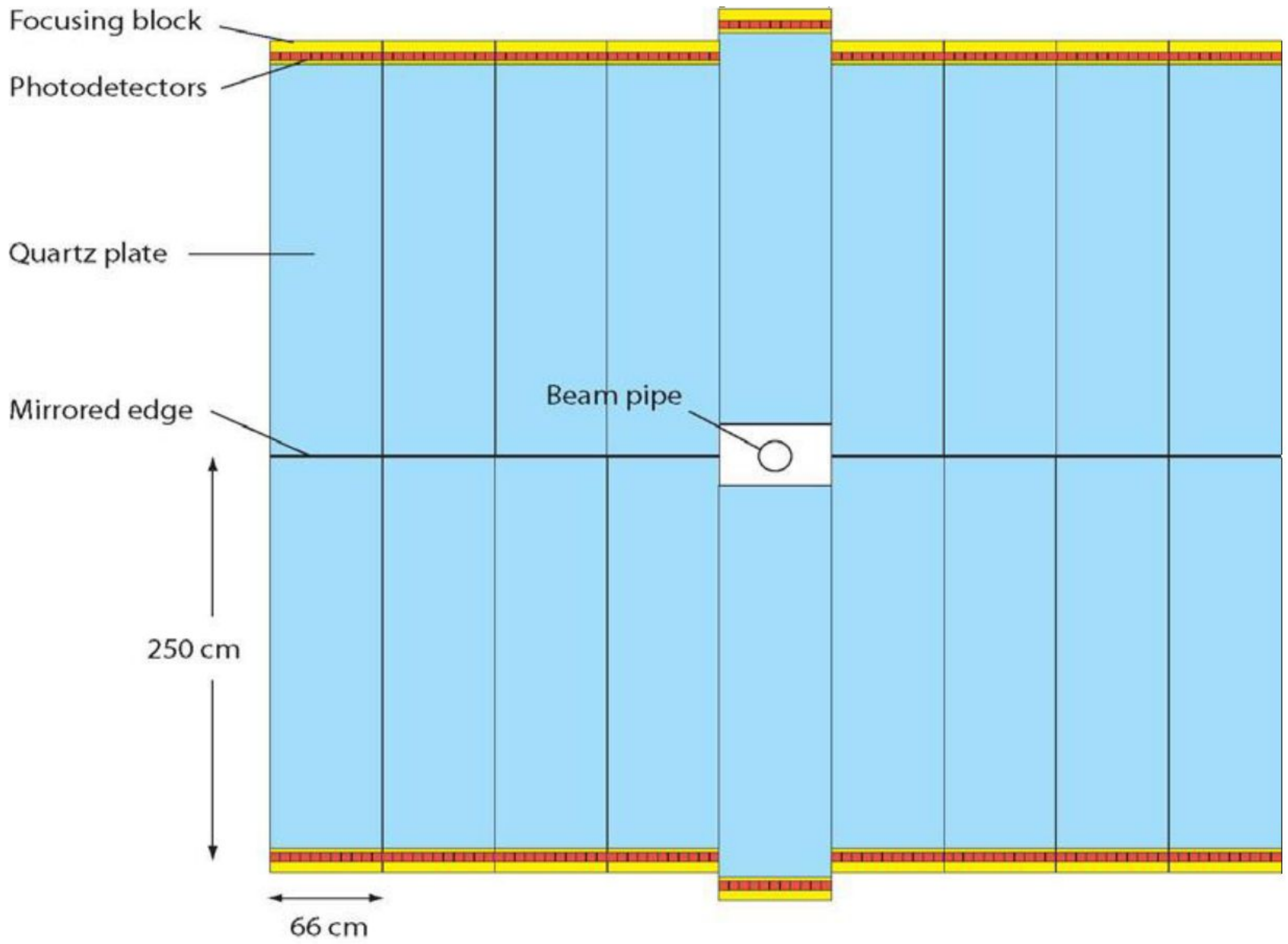
- Photon arrival time and position is measured to derive:
  - Cherenkov angle and path length
  - Photon propagation time
  - Expect ~30 detected photons per track (σ_t=70ps)

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



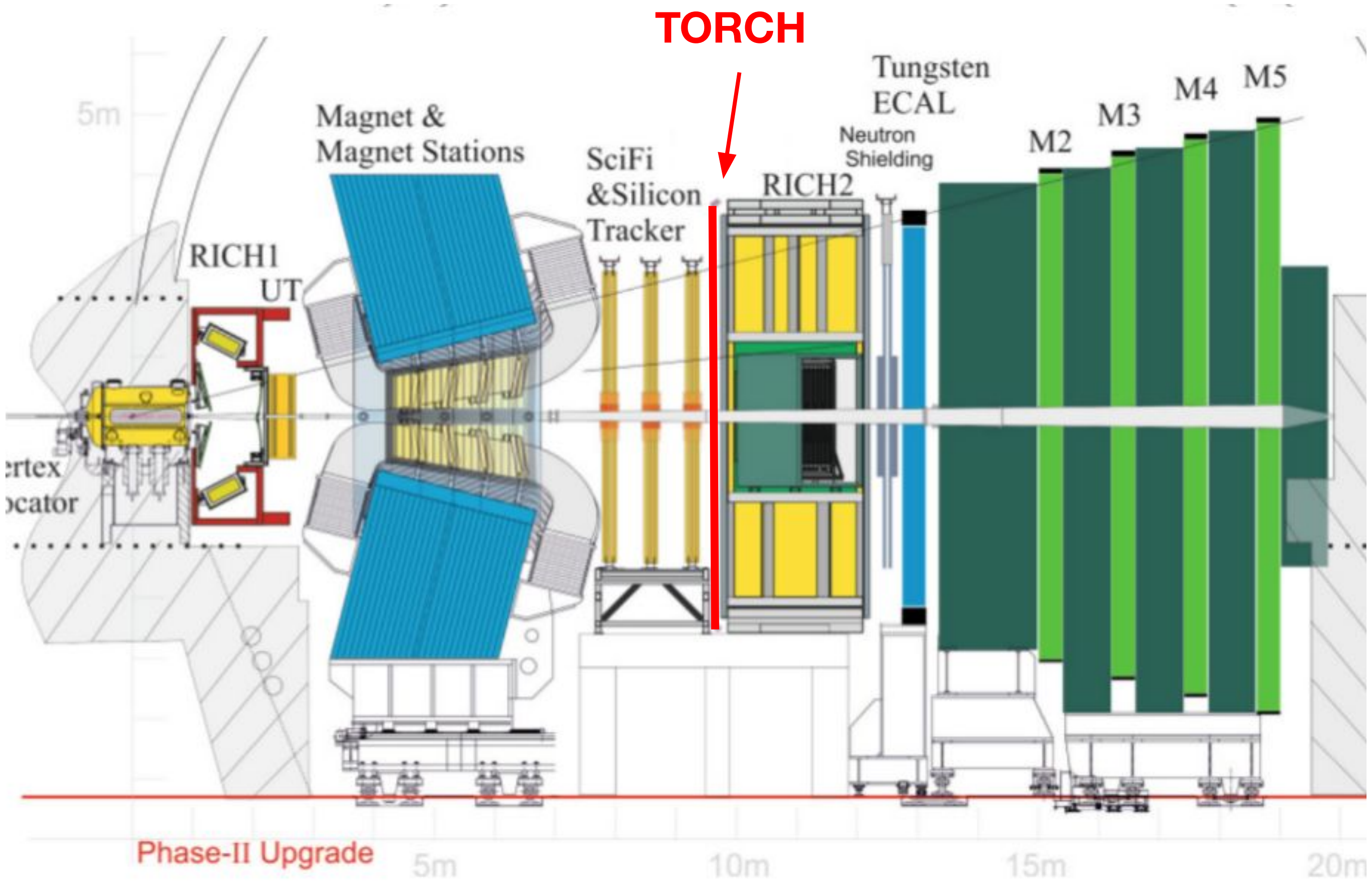
TORCH design

- 18 identical modules 250 x 66 x 1 cm^3 (covering and area of ~ 5x6 m^2)
- Full TORCH implementation now planned for future LHCb upgrade at the HL-LHC (LHCb upgrade II framework TDR [LHCB-TDR-023])
- See Maarten Van Dijk’s talk tomorrow for more details on design and photon detectors

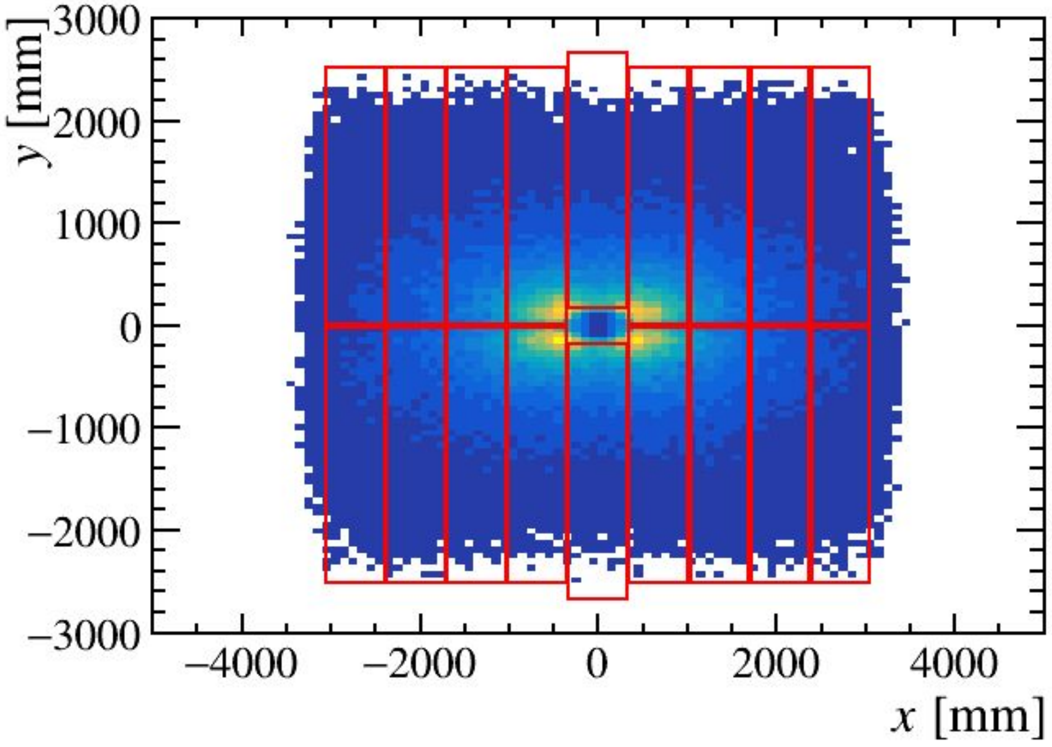


TORCH design

- 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

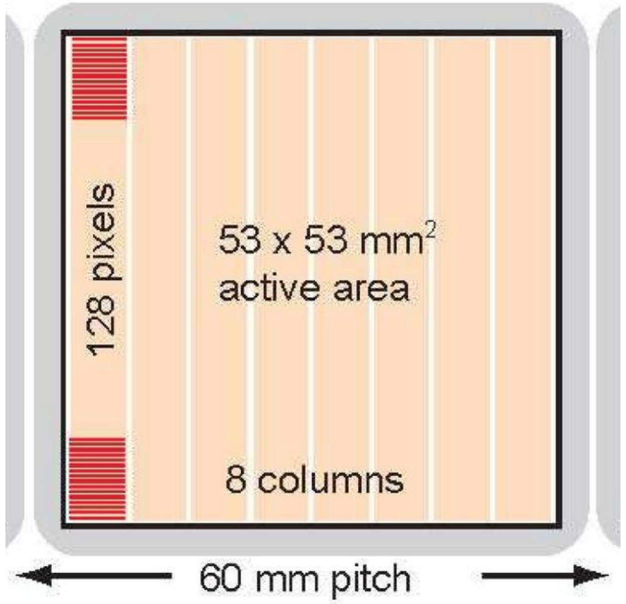


Simulation

- 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



- Simplified model of the digitisation with charge-spread and deadtime
  - 64x8 pixels of 0.8 x 6.4 mm^2
  - Achieved effective granularity of 128x8 via charge-sharing [JINST 10 (2015) C05003]

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

Reconstruction

- **Time-of-flight** derived from:

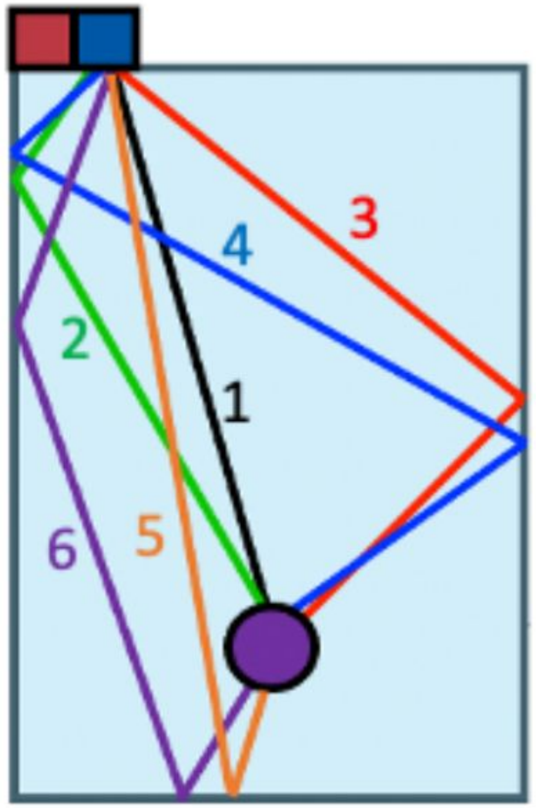
Photon arrival time
(measured)

$$t_{\mathrm{arrival}} = t_0 + \frac{d_{\mathrm{track}}}{\beta c} + \frac{d_{\mathrm{prop}}}{v_{\mathrm{group}}}$$

  - **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, $n_{\mathrm{group}}(E_\gamma)$
    - d_{prop} is the photon path length
    - v_{group} is derived from θ_c

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)

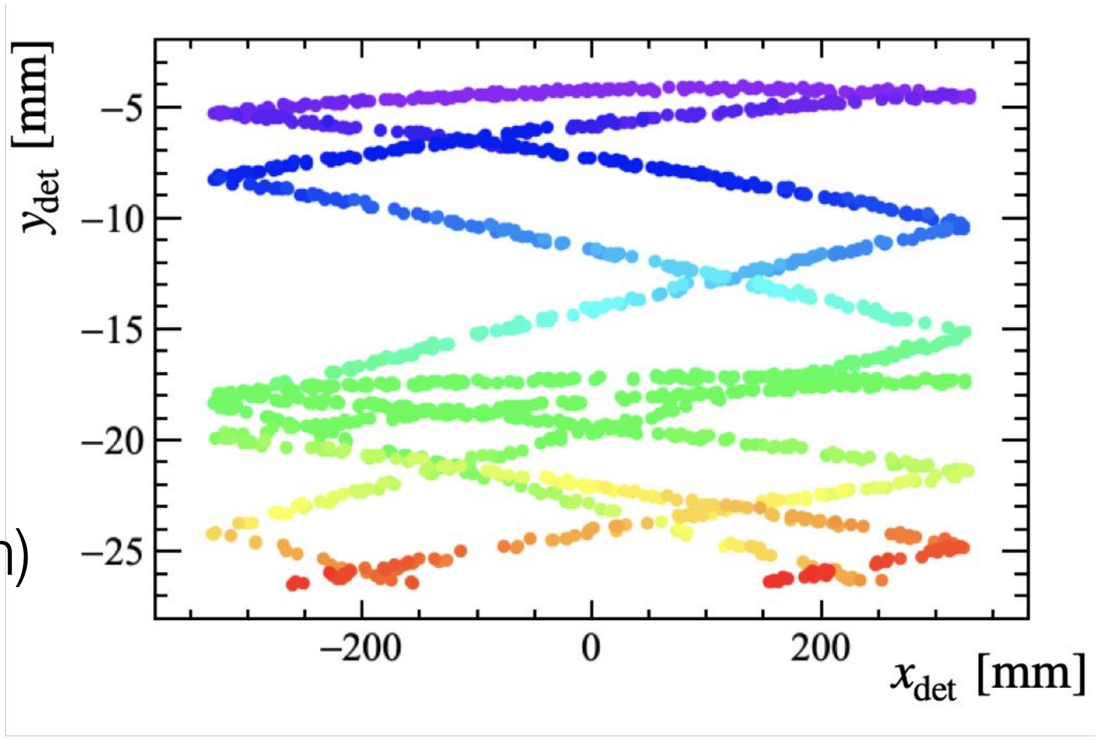


front-back reflections not visible here (no ambiguity for them)

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

Photons at the MCP from a single (repeated) track



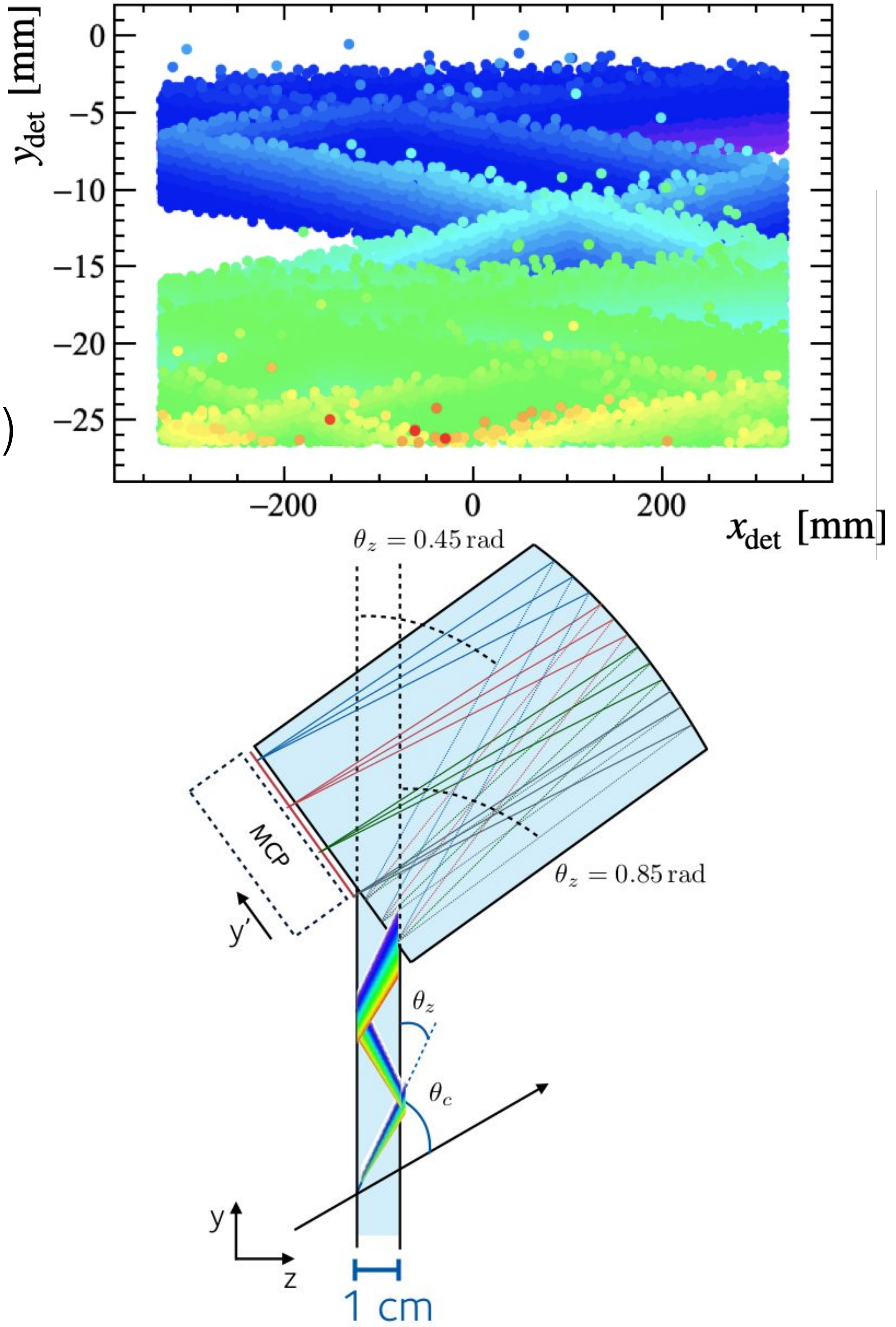
Color codes the time or arrival of the photon:

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

Reconstruction

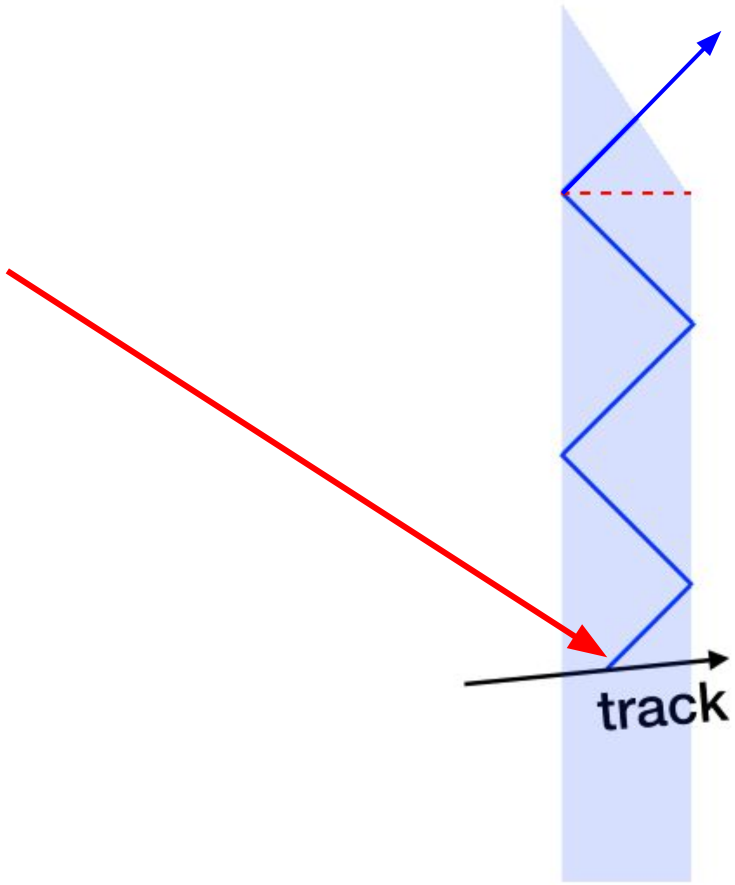
- Each hit (photon in the MCP) is back-propagated and associated to a track
    - Analytical photon back-propagation
    - Considering several reflections (sides/bottom) ➡ ambiguity
    - Most combinations (order reflections) discarded do not give a valid solution (hit position not compatible with measured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



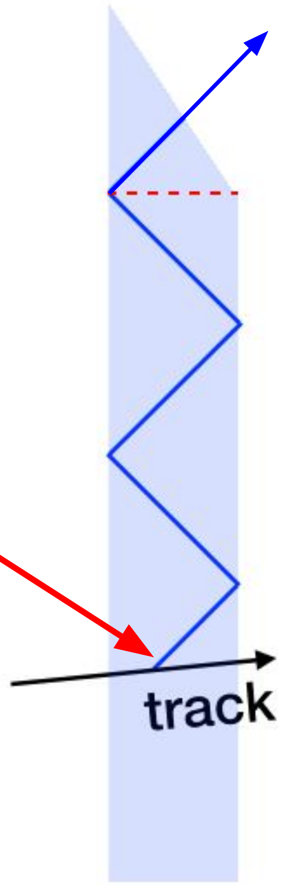
Reconstruction: Assumptions

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

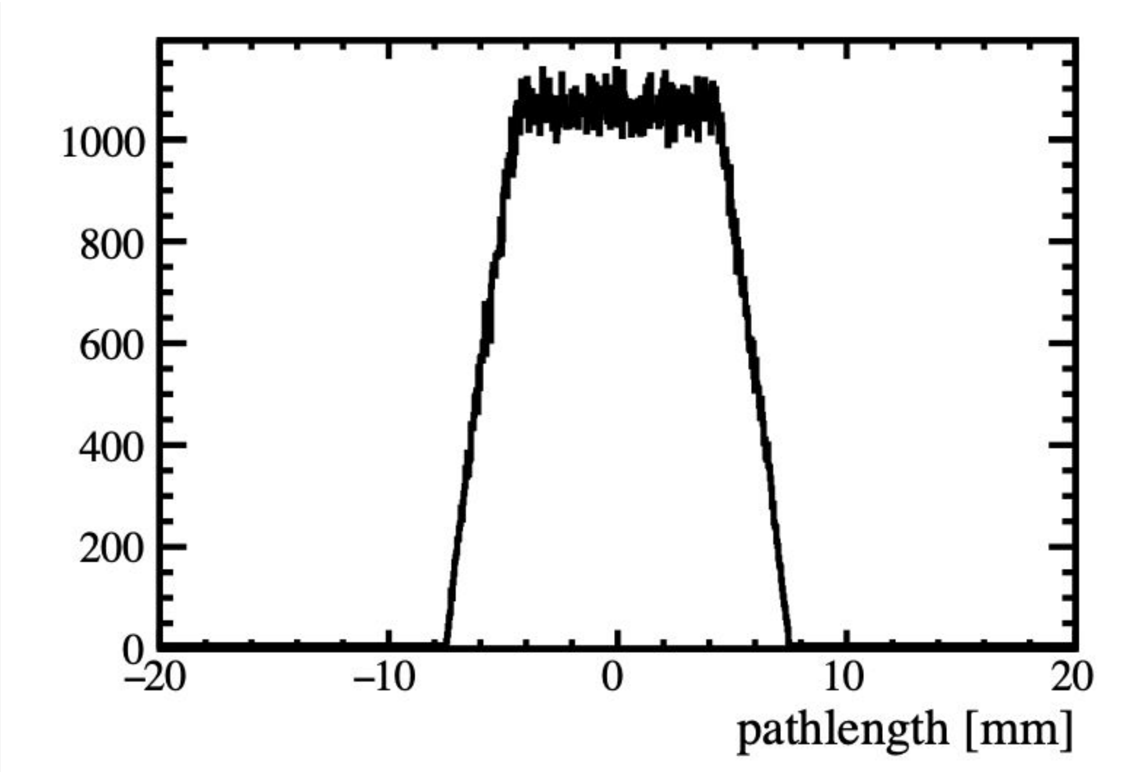


Reconstruction: Assumptions

- 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]

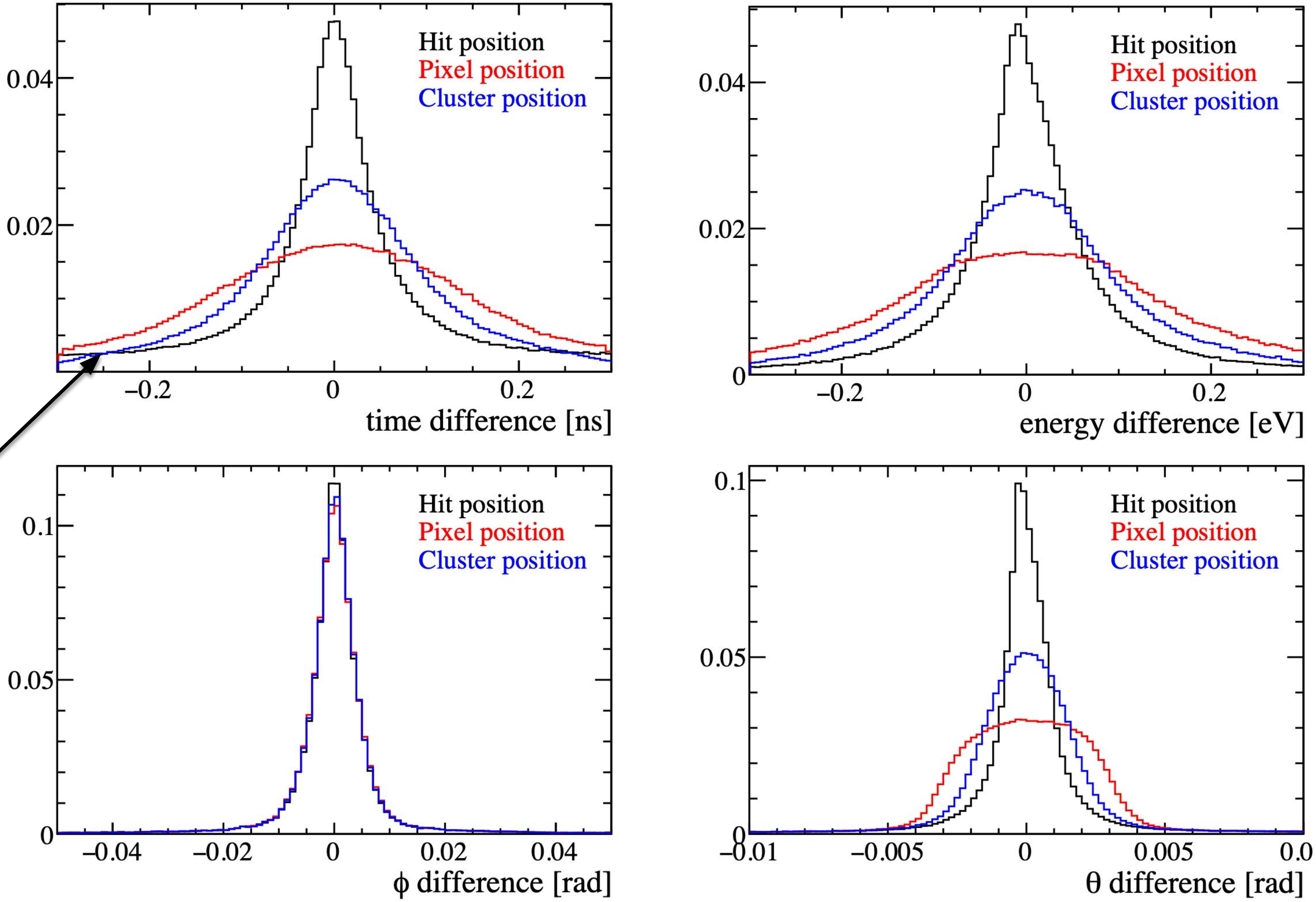


Reconstruction: Photon resolution

Hit: True photon arrival position

Pixel: Pixel hit by the photon arrival

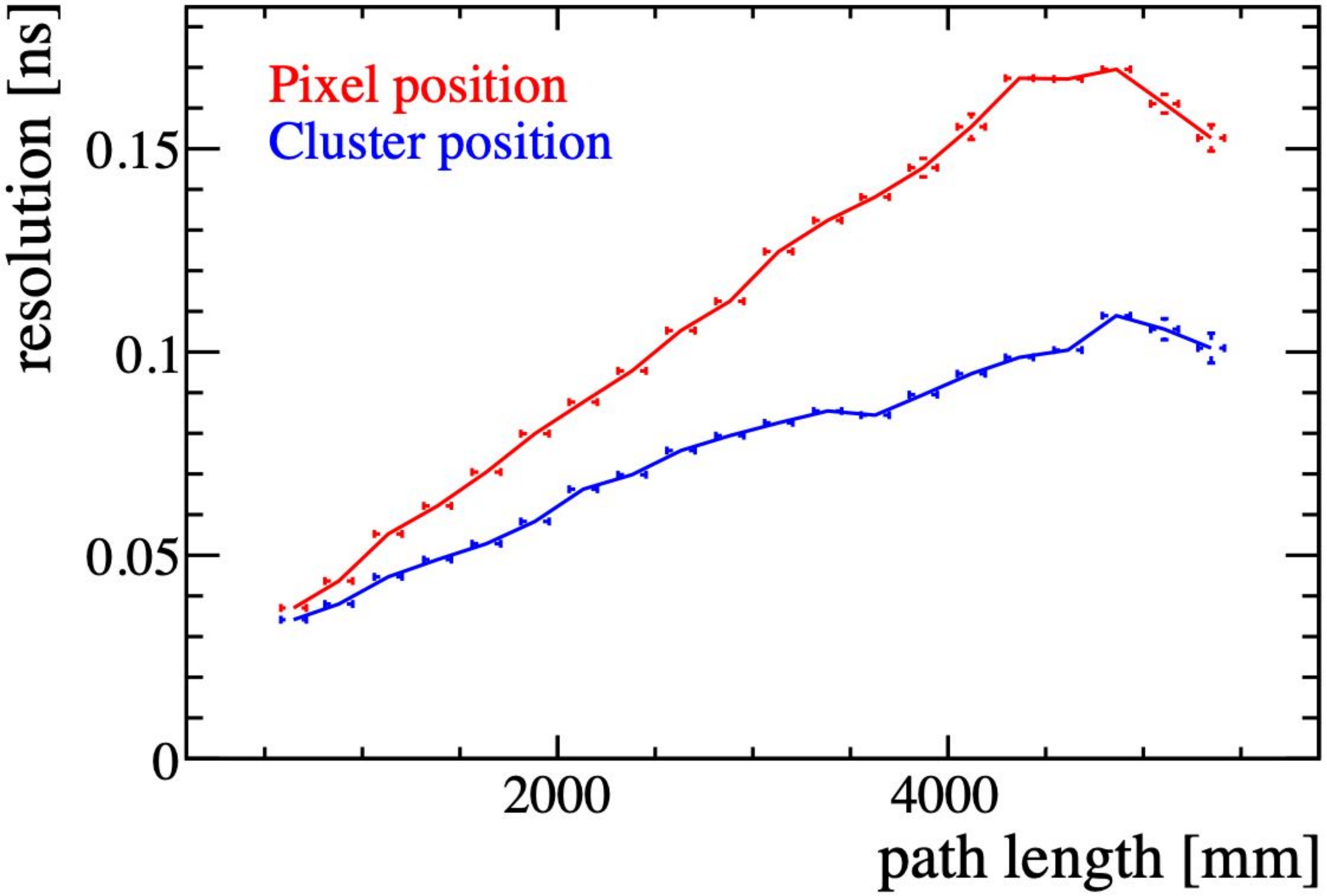
Cluster: Weighted charge-average of all pixels fired by the photon (~1-2 pixels)



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

Reconstruction

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

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

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:

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

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

$$P(E_\gamma, \phi_c, t_0) = P(E_\gamma) \overset{1/2\pi}{P(\phi)} P(t_0)$$

Frank-Tamm + efficiency

Normal distribution with experimental time resolution

Reconstruction

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

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

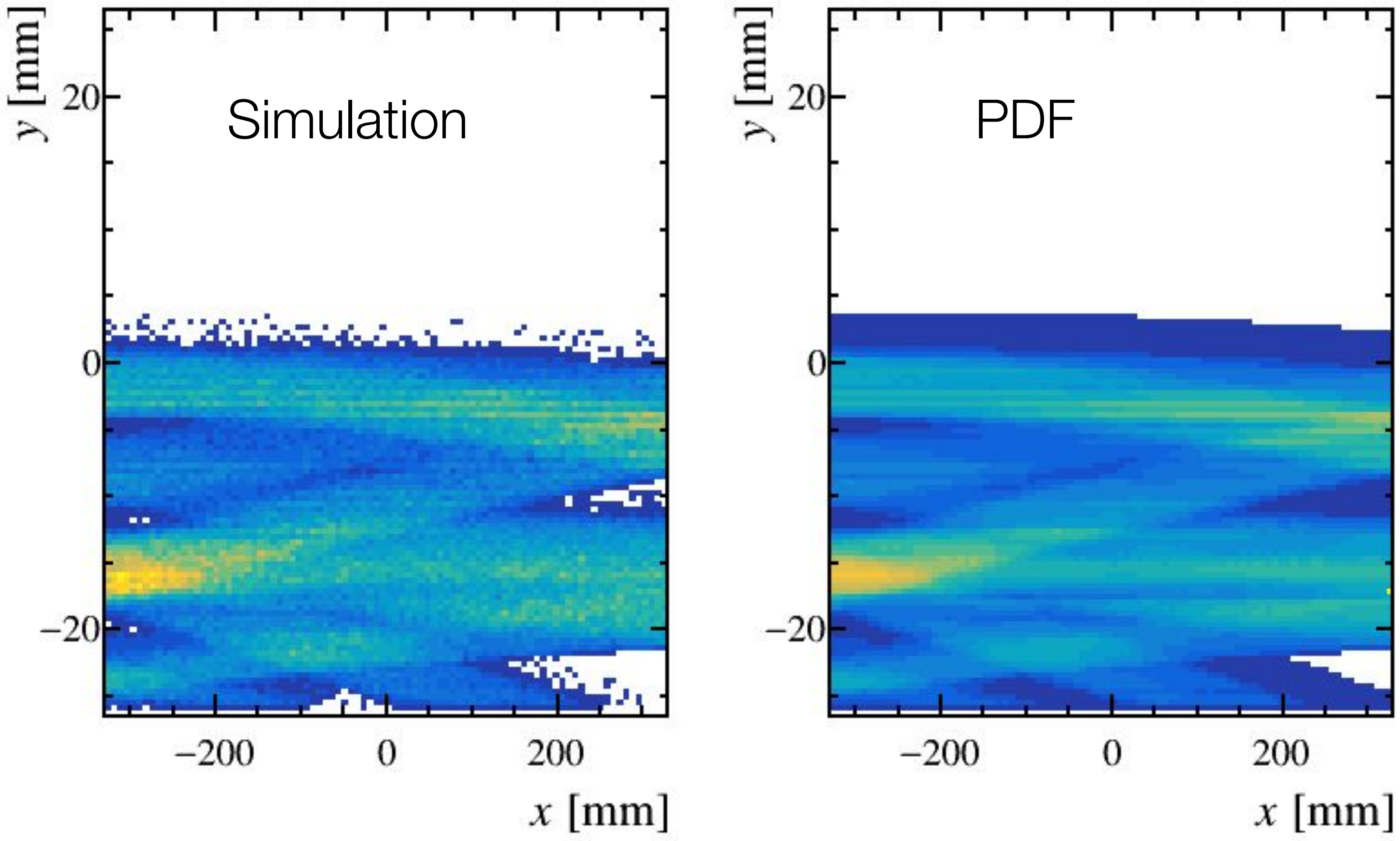
- Determine the PDF for a given track/hypothesis combination from:

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

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

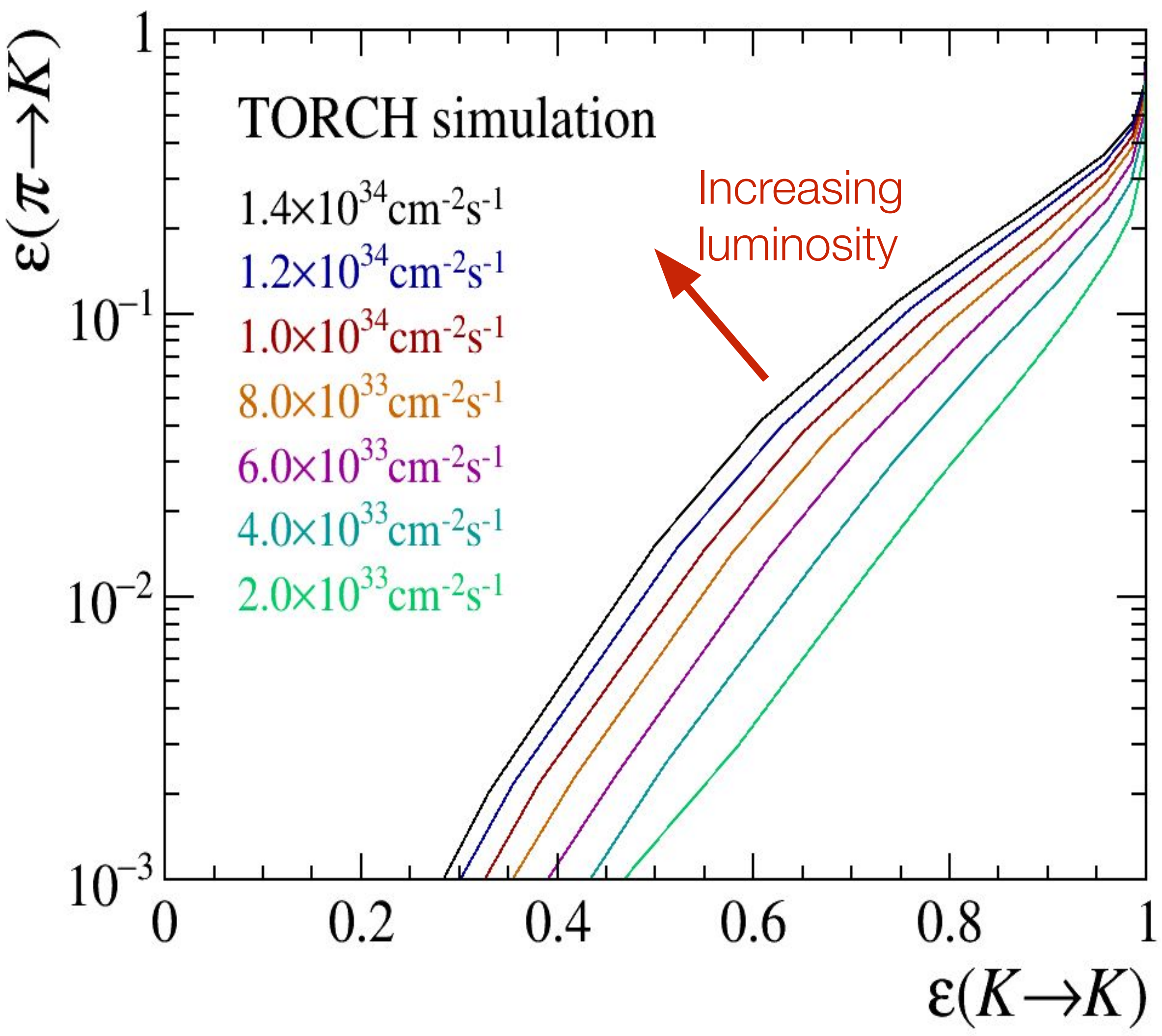
Reconstruction

- 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)



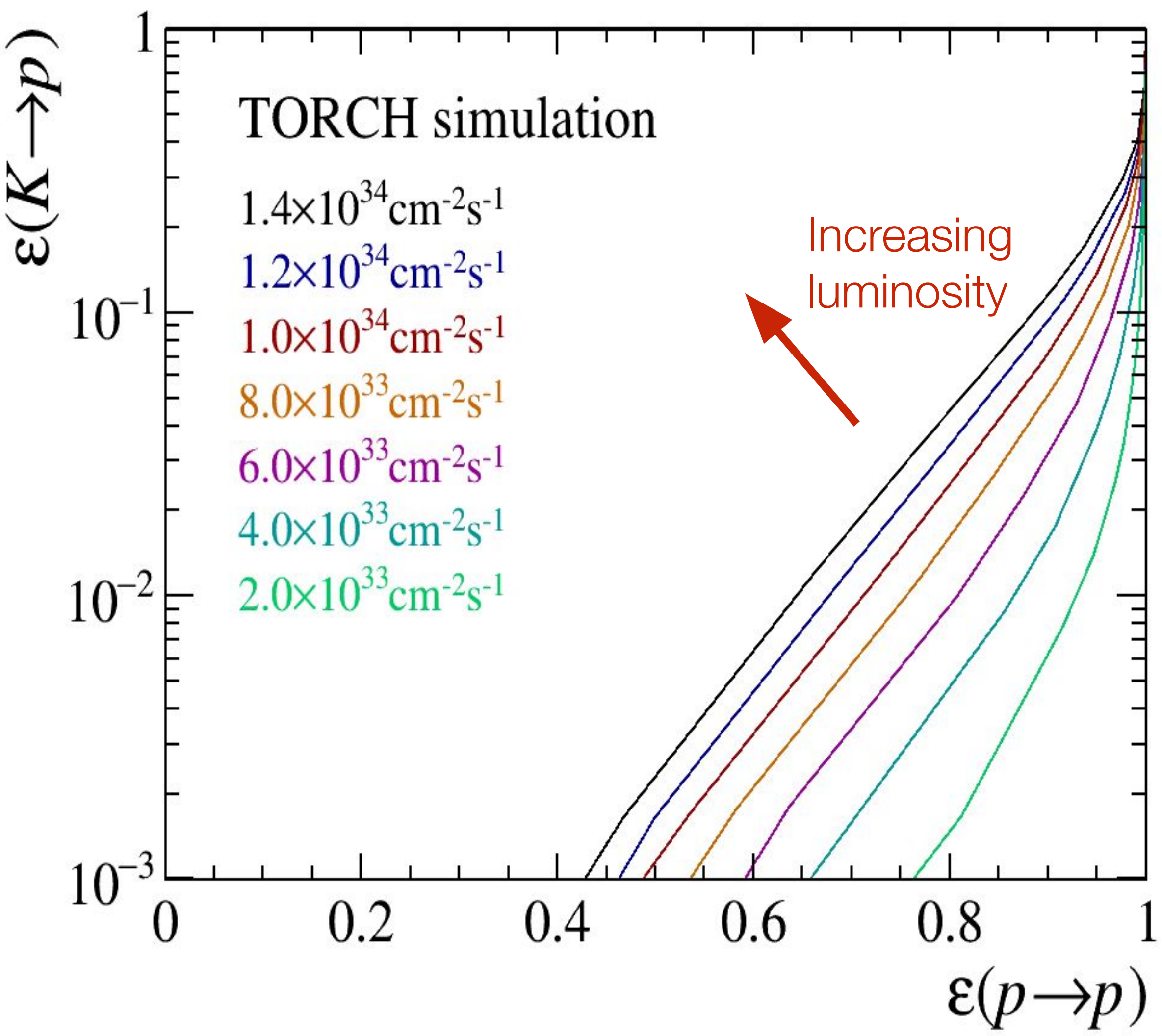
Performance versus luminosity

K-π separation



Increasing luminosity

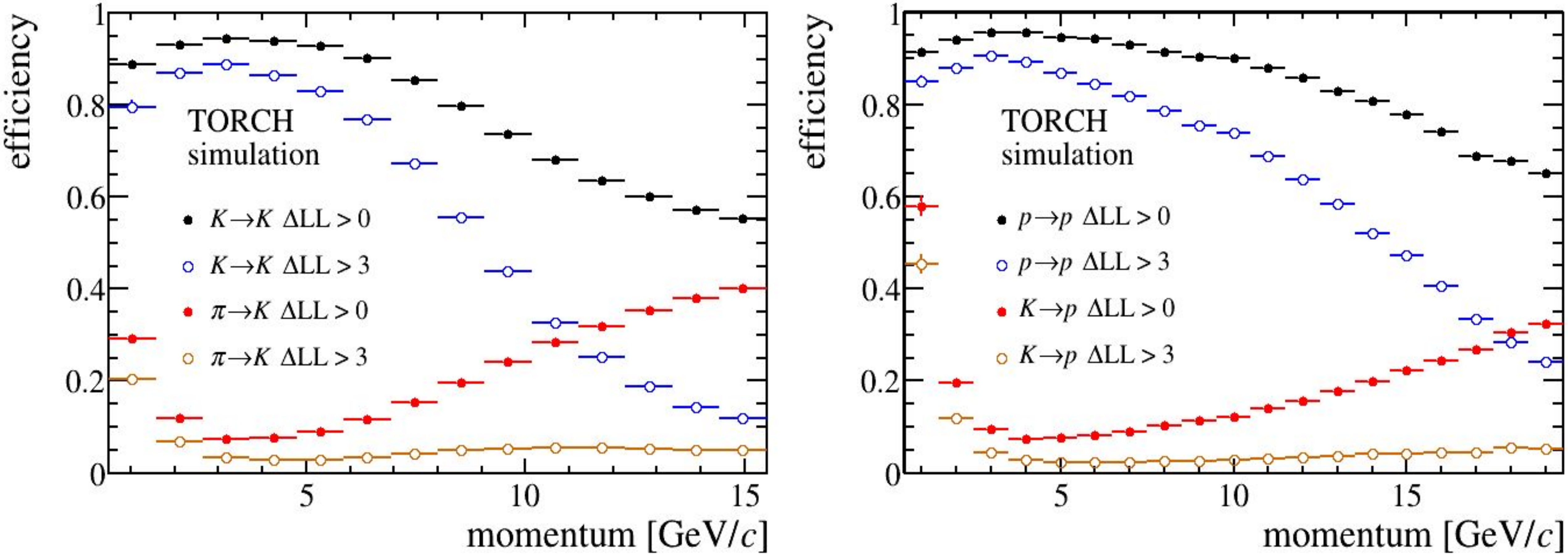
p-K separation



Increasing luminosity

Performance with weighting

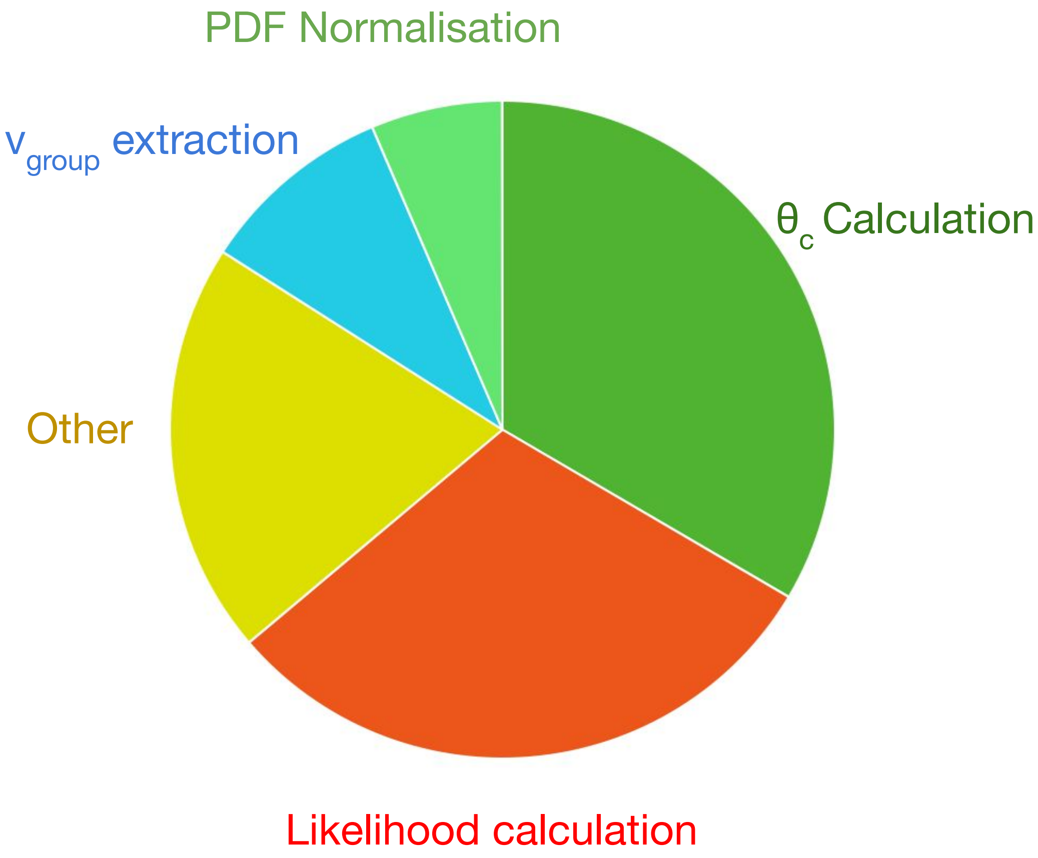
LHCb Upgrade II luminosity



- Combining samples to realistic LHCb Upgrade II instantaneous luminosity profile

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

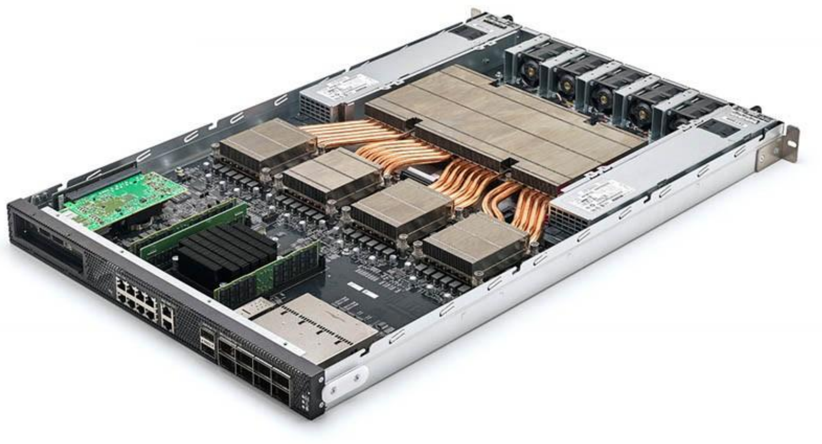
- The “local” approach of the likelihood:
  - Consider each track in isolation

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

  - 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

Outlook

- 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]
- Plan to submit documentation to journals
- Further improvements (speed-up) are on the way

Thanks for your attention

Photon time of propagation

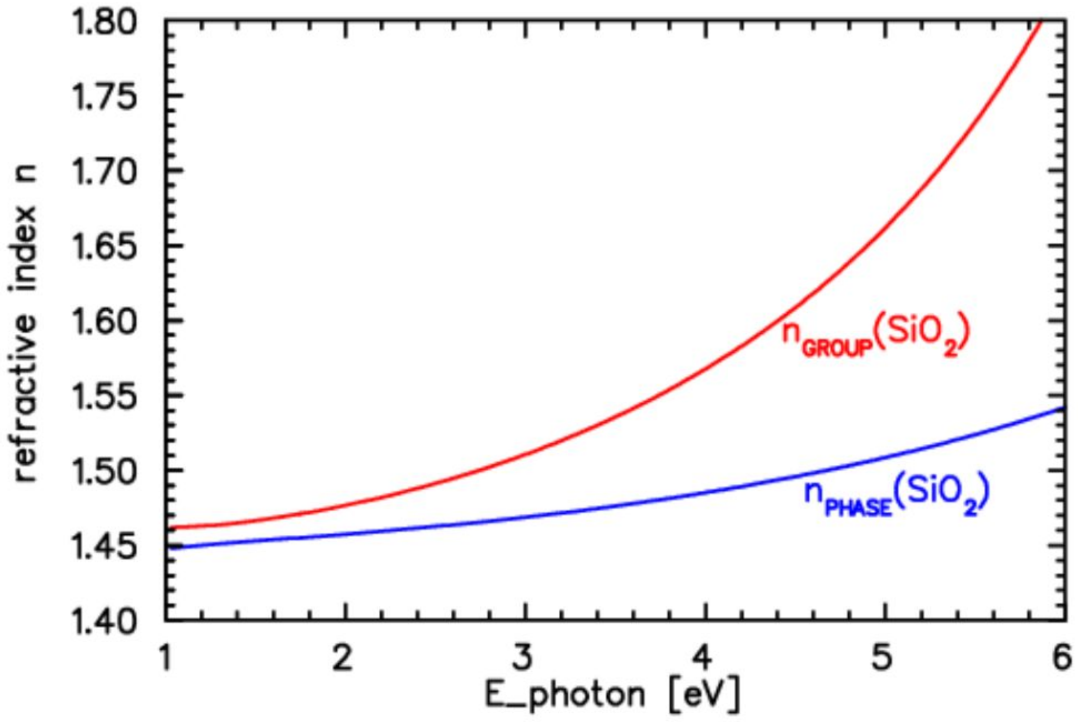
- Time of propagation (ToP) in quartz depends on the photon energy:

$$t = L/v_{group} = Ln_{group}/c$$

- 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

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

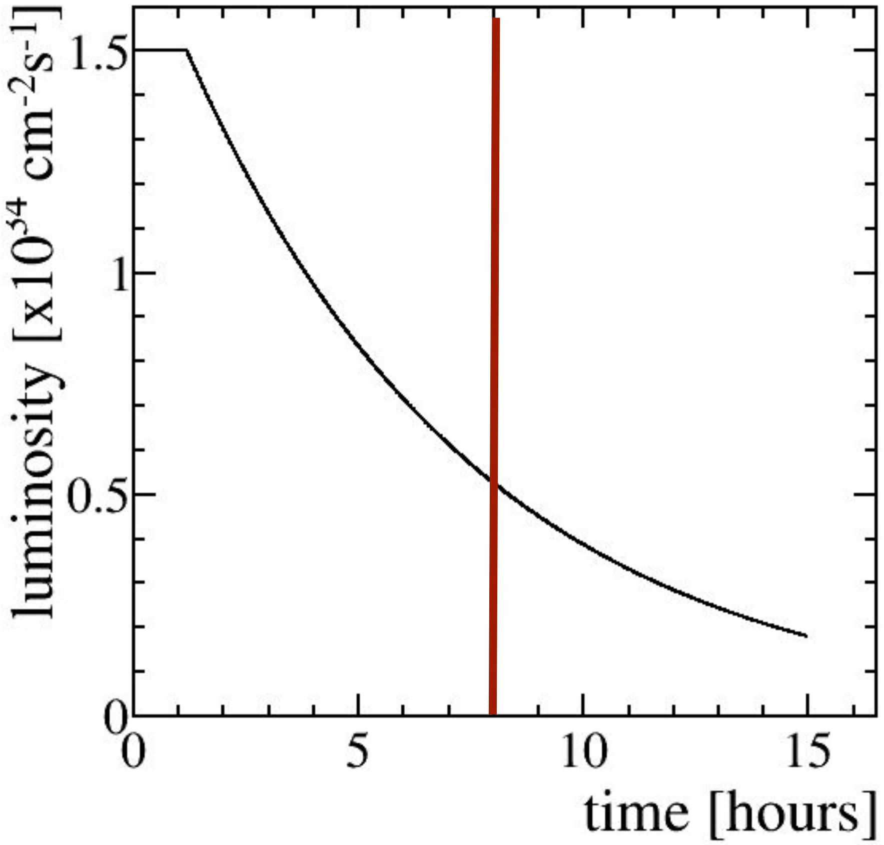
- Use dispersion relation for to get n_{group}
- Determine the ToP from the reconstructed photon path length and n_{group}



Instantaneous luminosity in Upgrade II

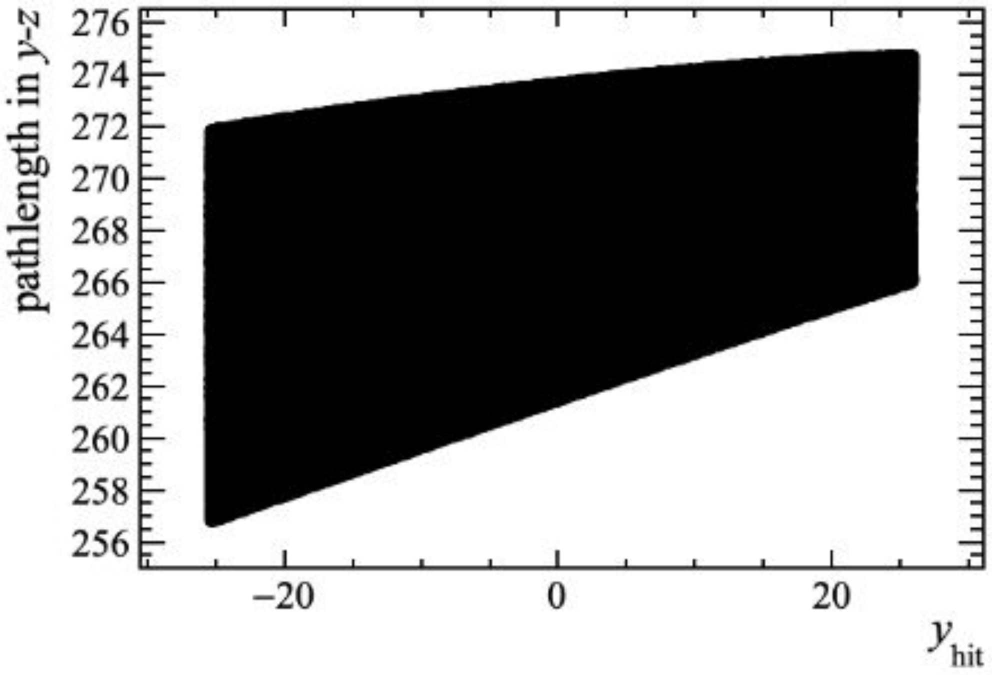
- Approximate the luminosity profile with an exponential function.
  - ➡ Luminosity decays quickly with time.
- From the FTDR, the virtual peak luminosity is 1.8x10^{34} and the fill duration is 8 hours.
- Average luminosity is 1.01x10^{34} $cm^{-2}s^{-1}$.
- We can only produce sample in multiples of 2.0x10^{33} cm^2s^{-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^2s^{-1}.

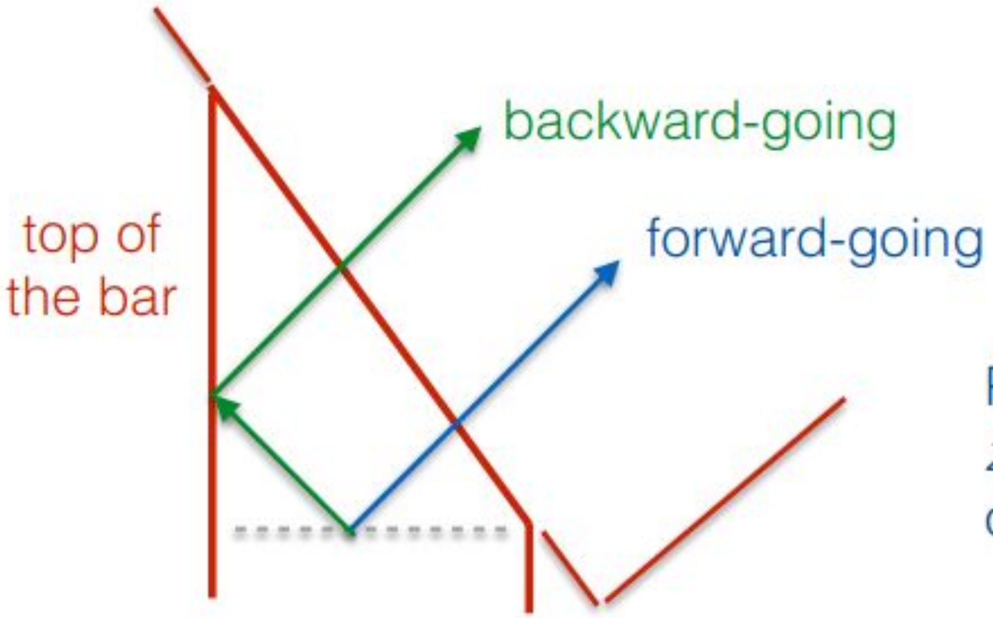
Levelled at L_{max} = 1.5x10^{34}

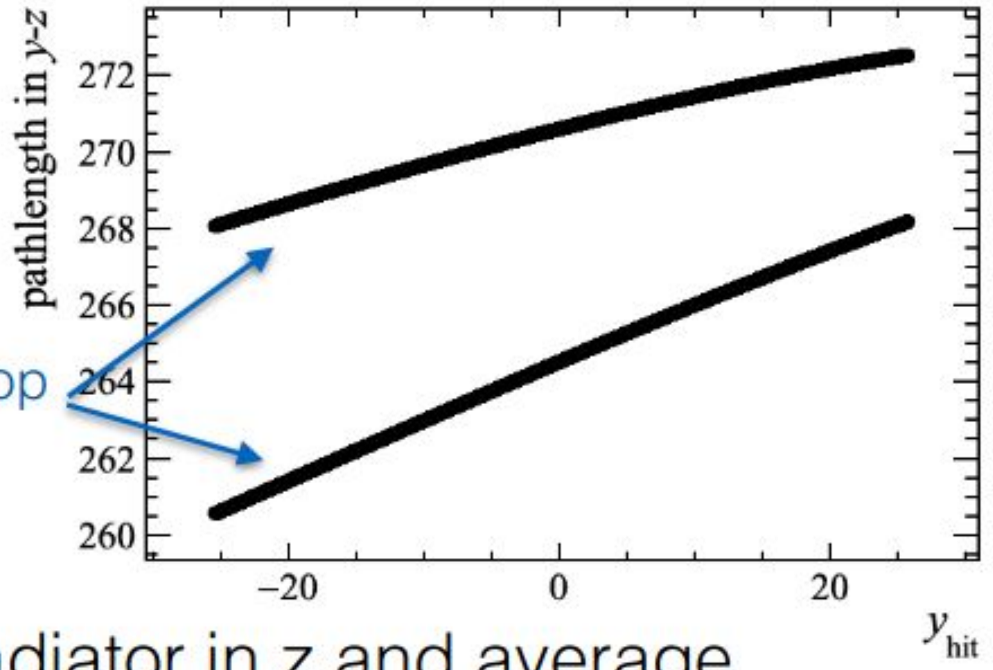


Effect of the focussing block

- 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.







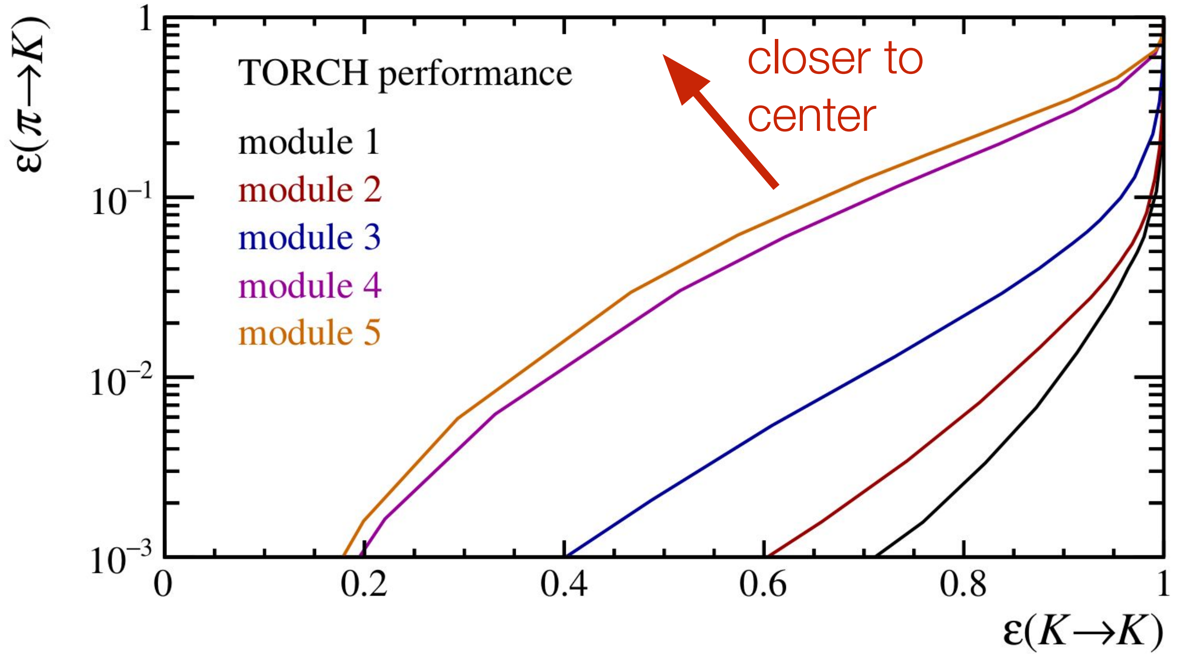
Photons with z=5mm at the top of the radiator

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

Performance versus module

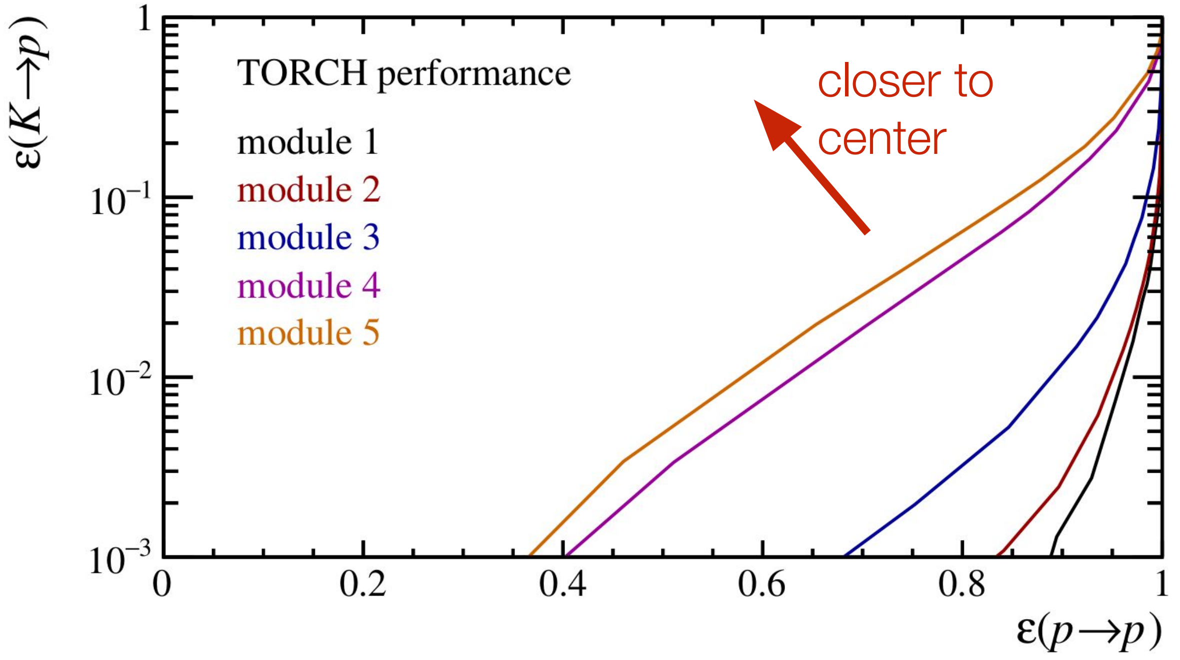
- The performance is worst in module 5 (central, highest occupancy)
- Rapidly improves towards the periphery of the detector (module 1)

K-π separation



closer to center

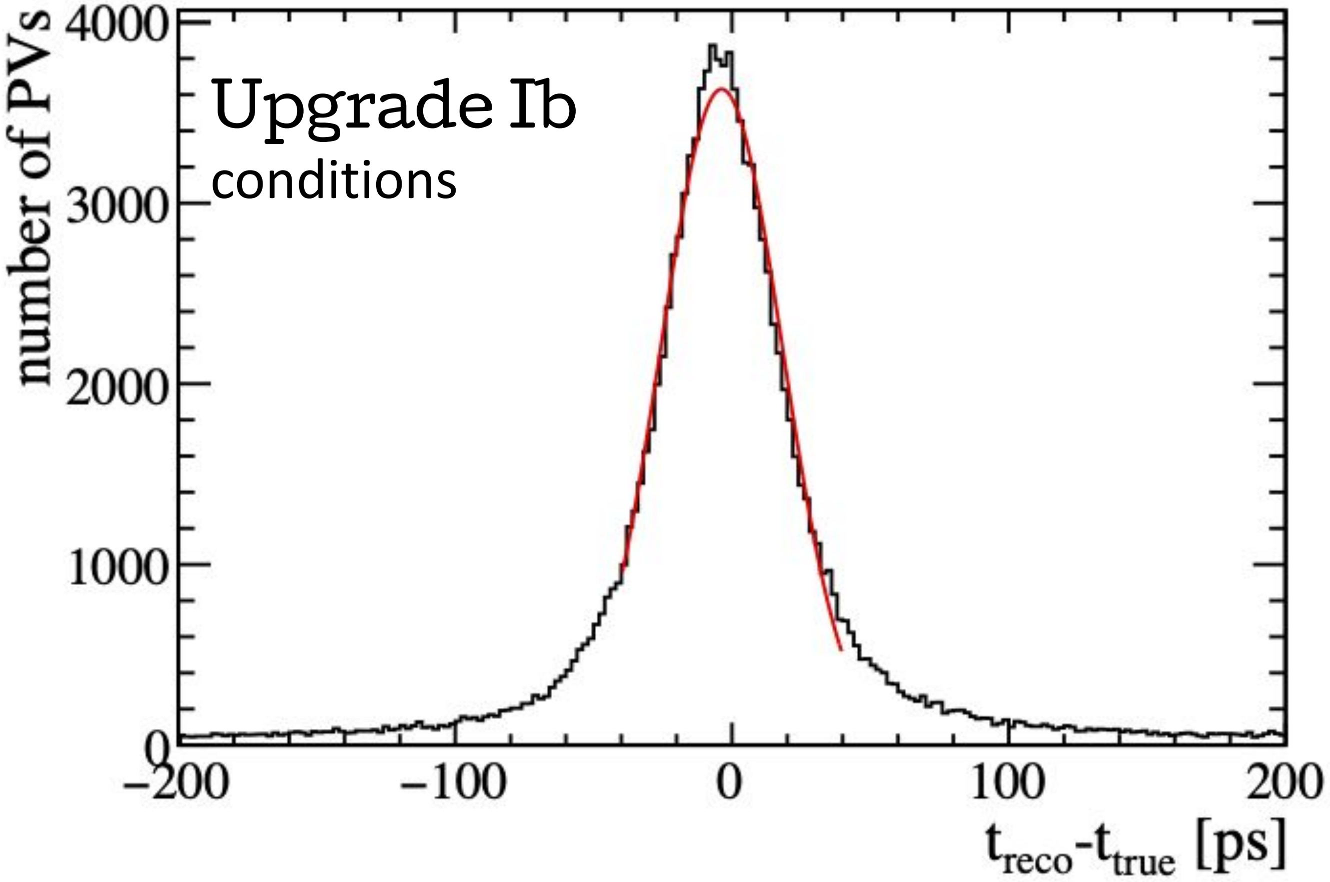
p-K separation



closer to center

t_0 reconstruction

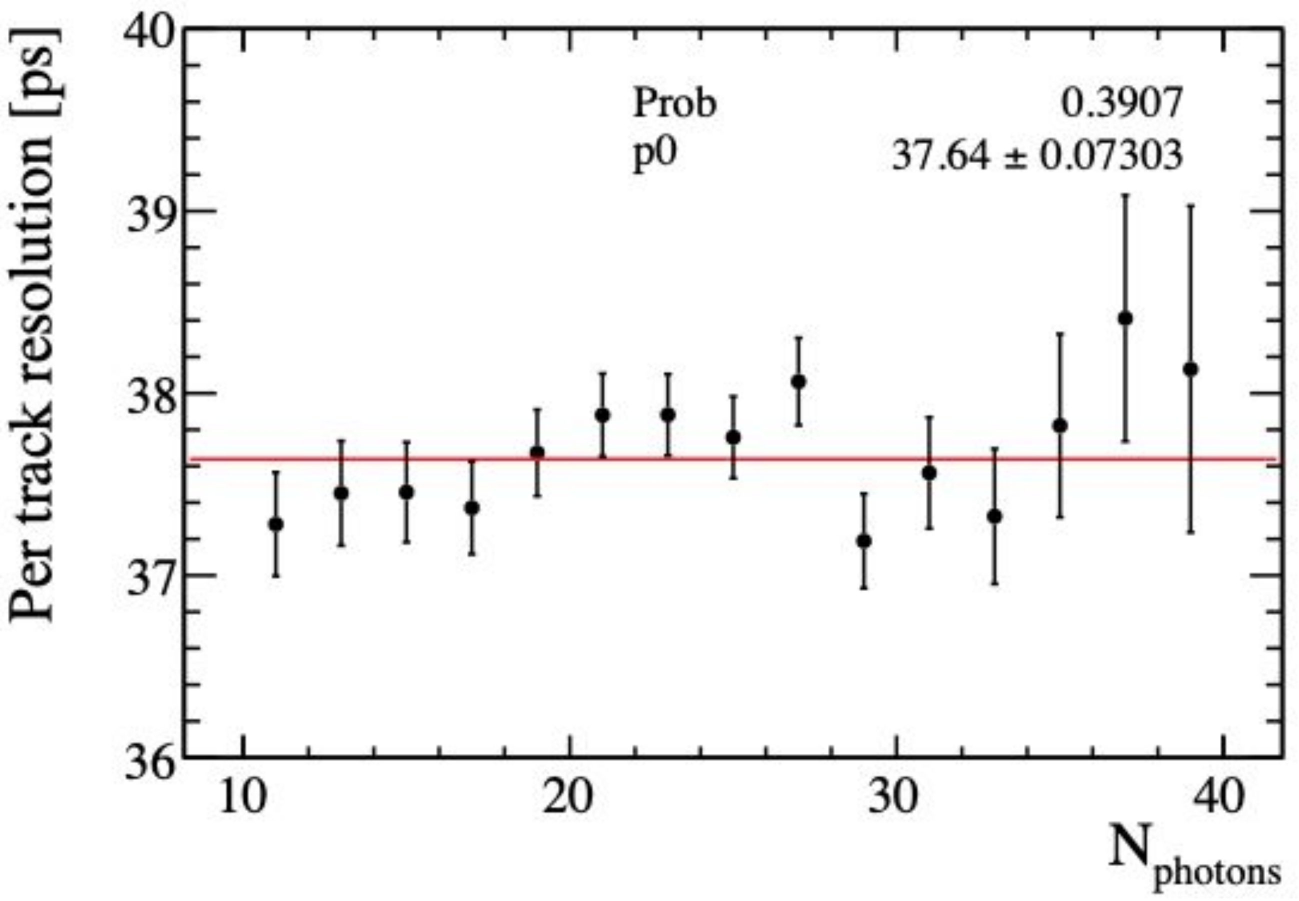
- Obtain likelihood profile for each track (under different PID hypothesis) as a function of t_0.
- Combine likelihoods for all tracks assigned to vertex.
  - ➡ Choose the hypothesis for each track which fits best with the other tracks.
- Core of the distribution has width of about 22 ps.
- Time resolution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



Per track t_0 resolution

- 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.

Upgrade Ib conditions

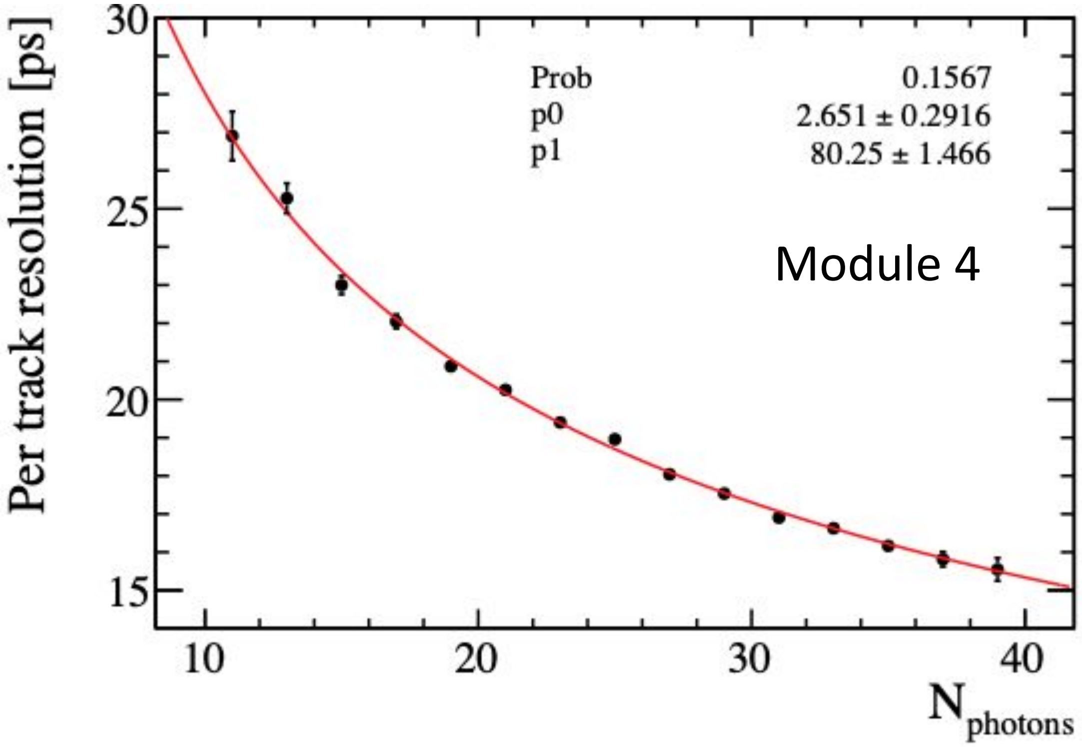


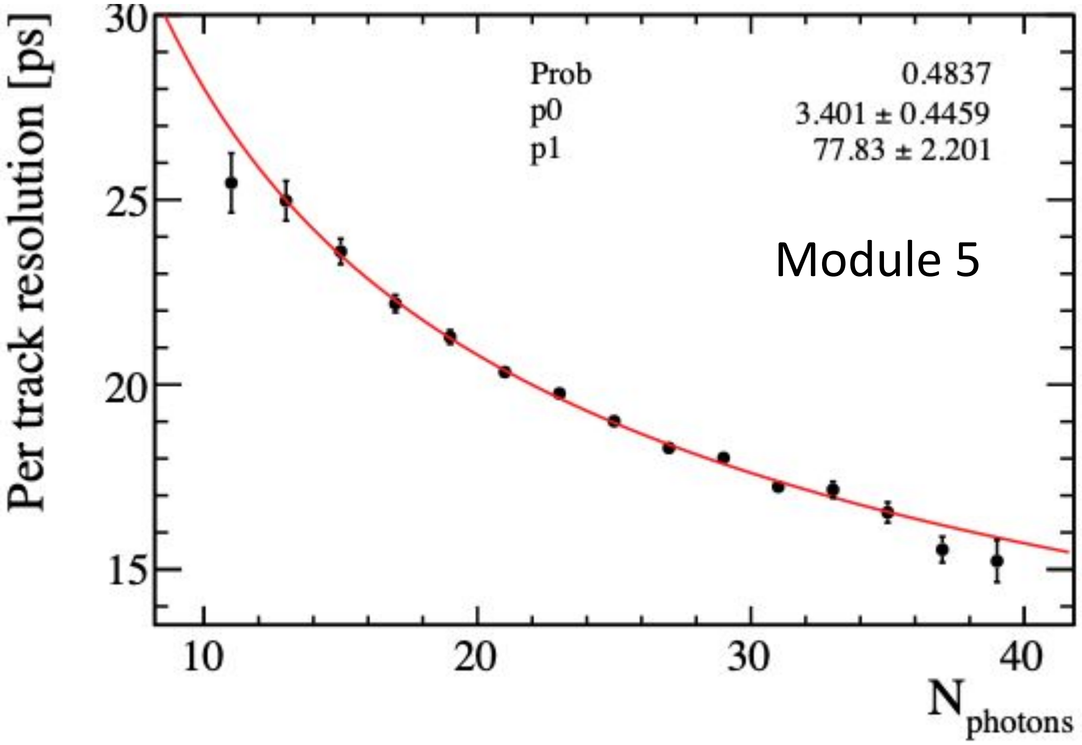
Per track t_0 resolution

- 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:

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

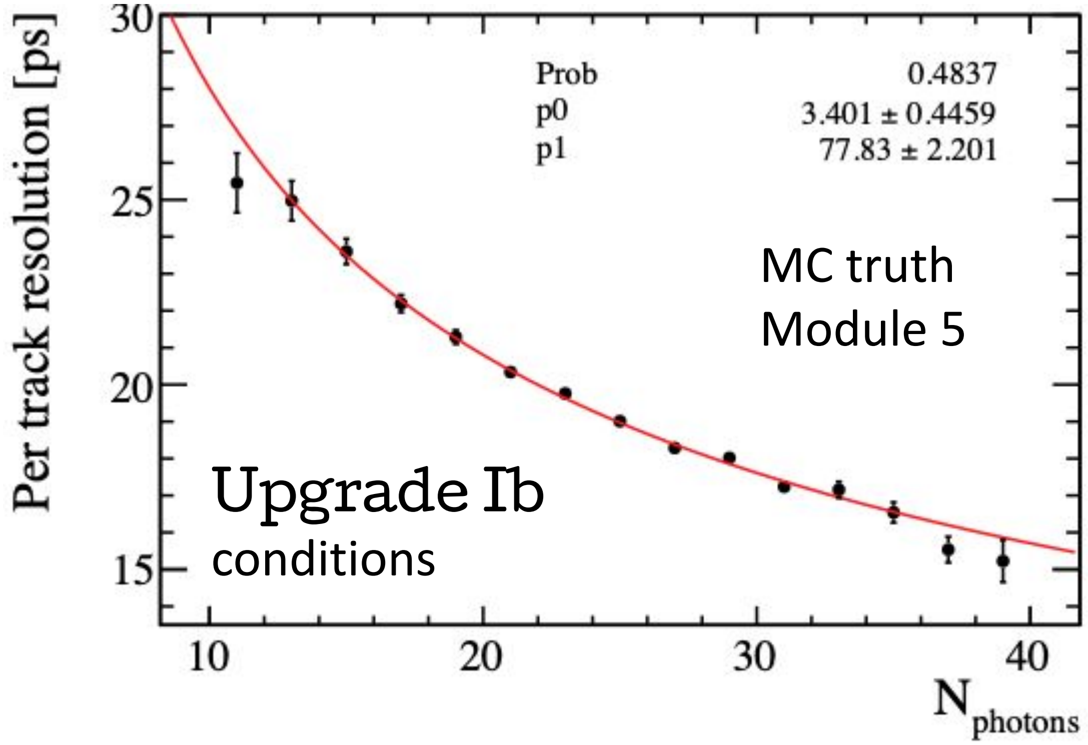
Upgrade Ib conditions

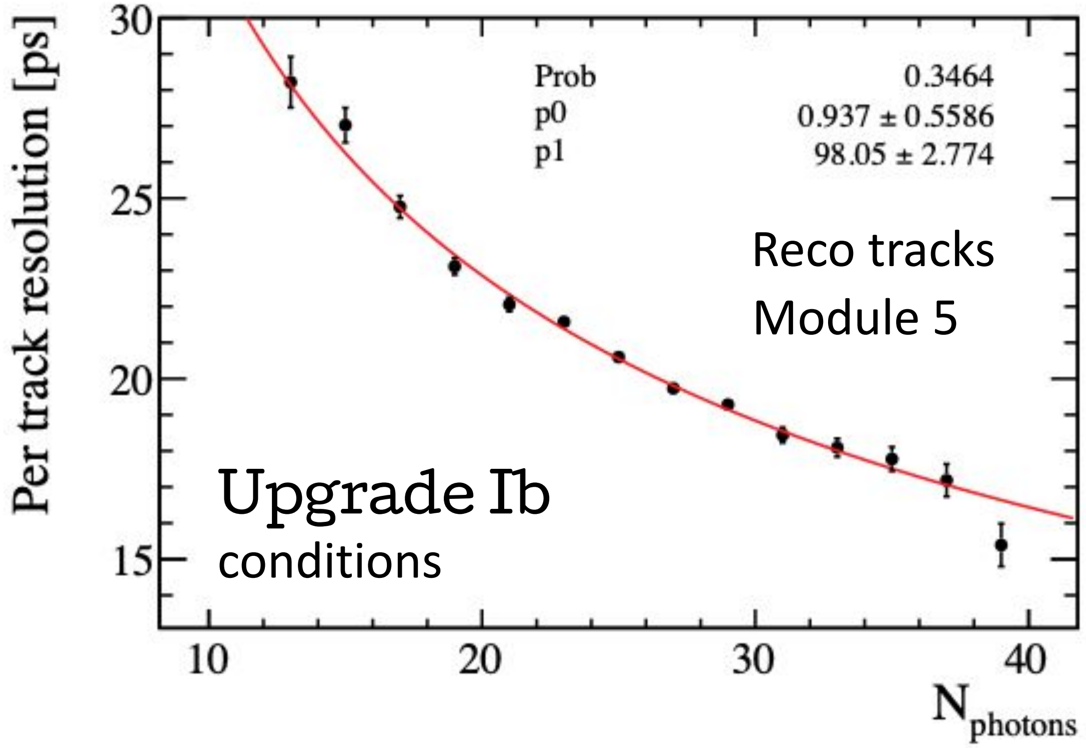




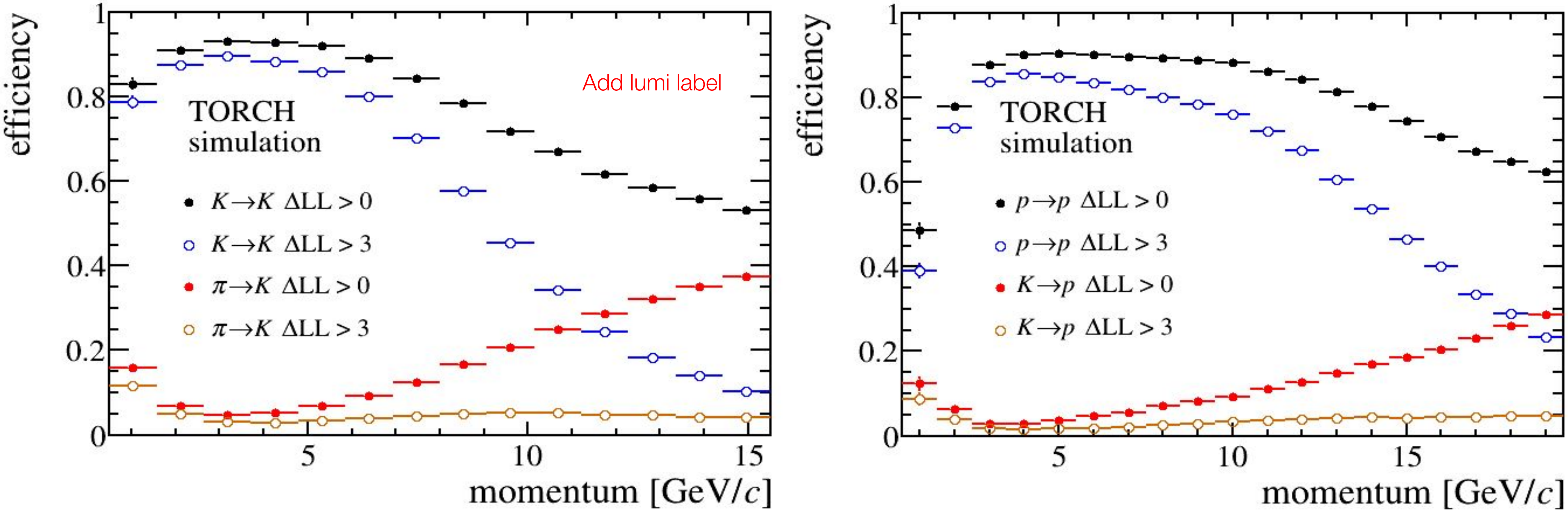
Track reconstruction effect on t_0

- 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



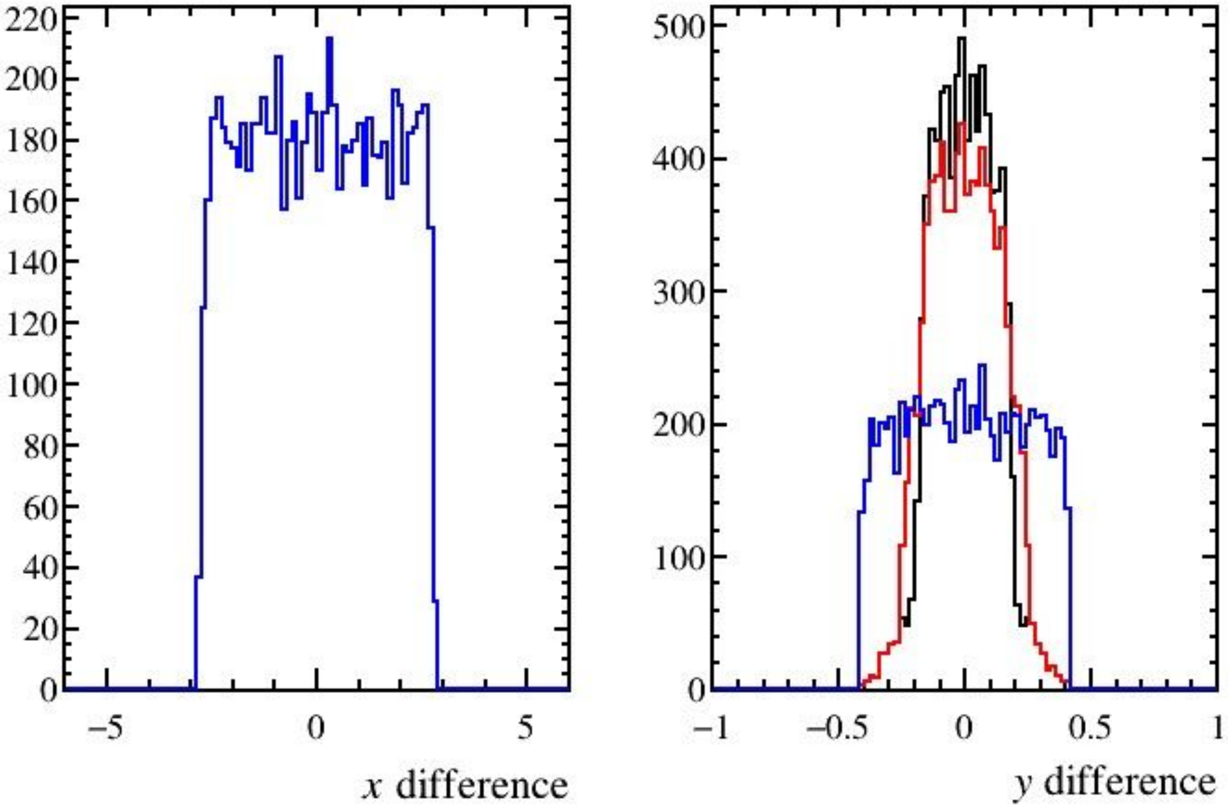
Add lumi label

- 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.

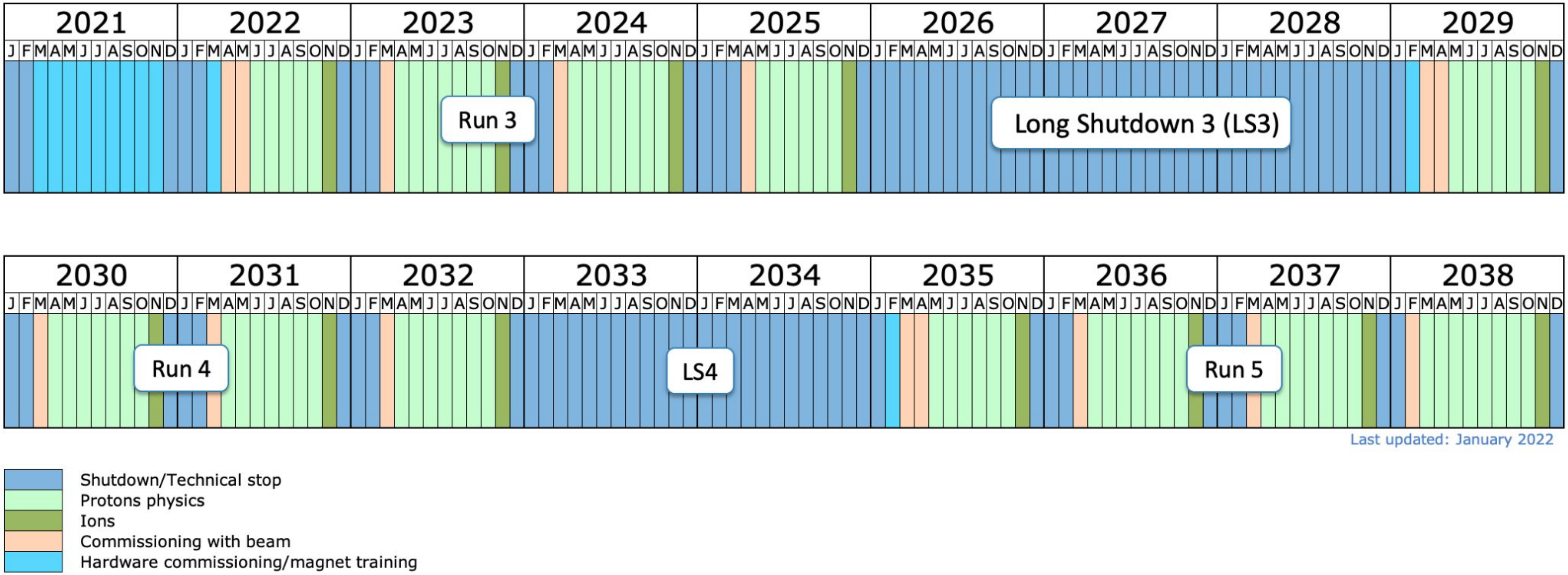


8-by-64 pixel

Naive cluster centre

Charge weighted cluster centre

LHC Schedule



Last updated: January 2022

Test beam results

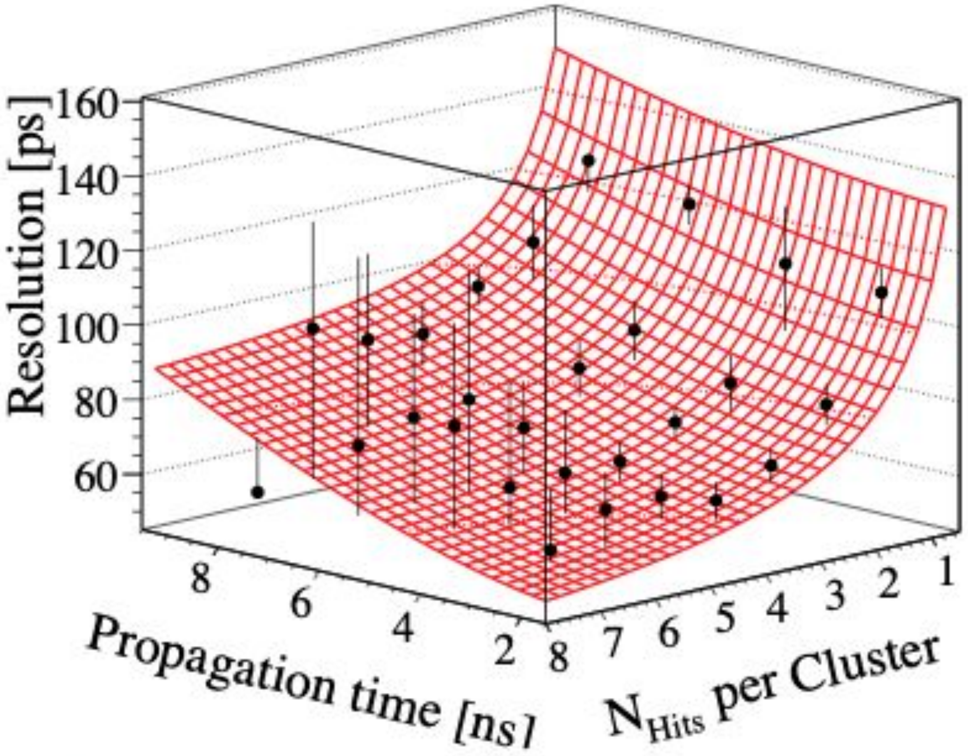
- Can parametrise resolution in 2D

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

MCP

Propagation time dependent effects

Cluster size and readout



Measured

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

Expected

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

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)

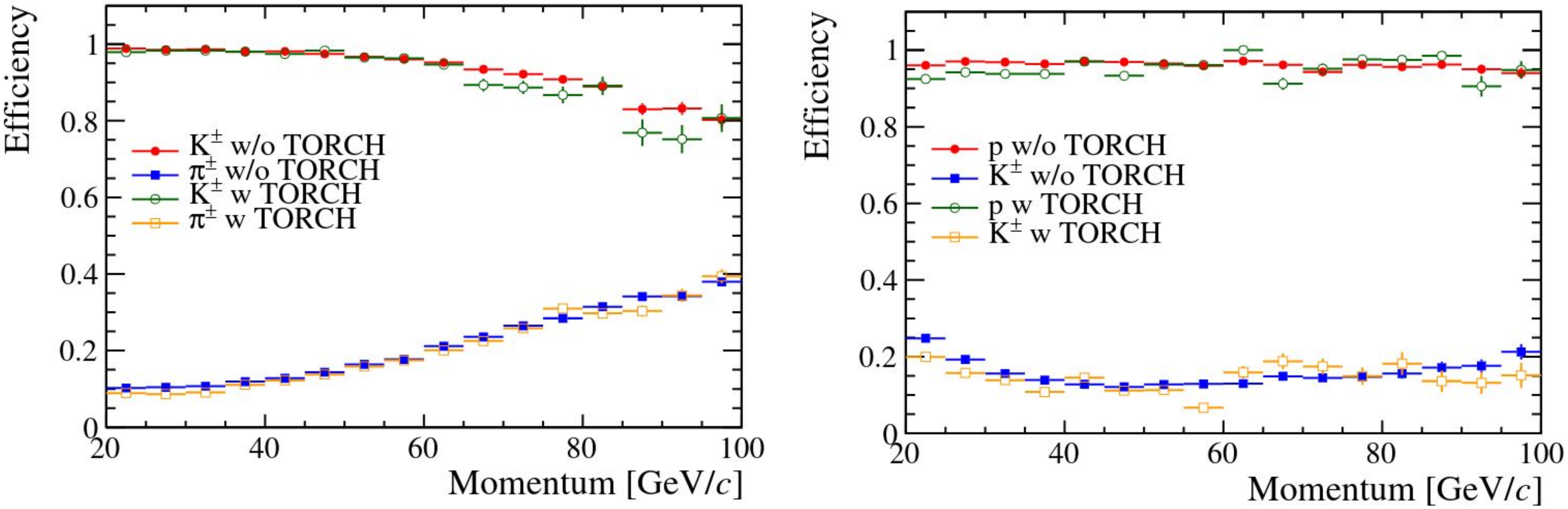
Differences:

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

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

Reconstruction

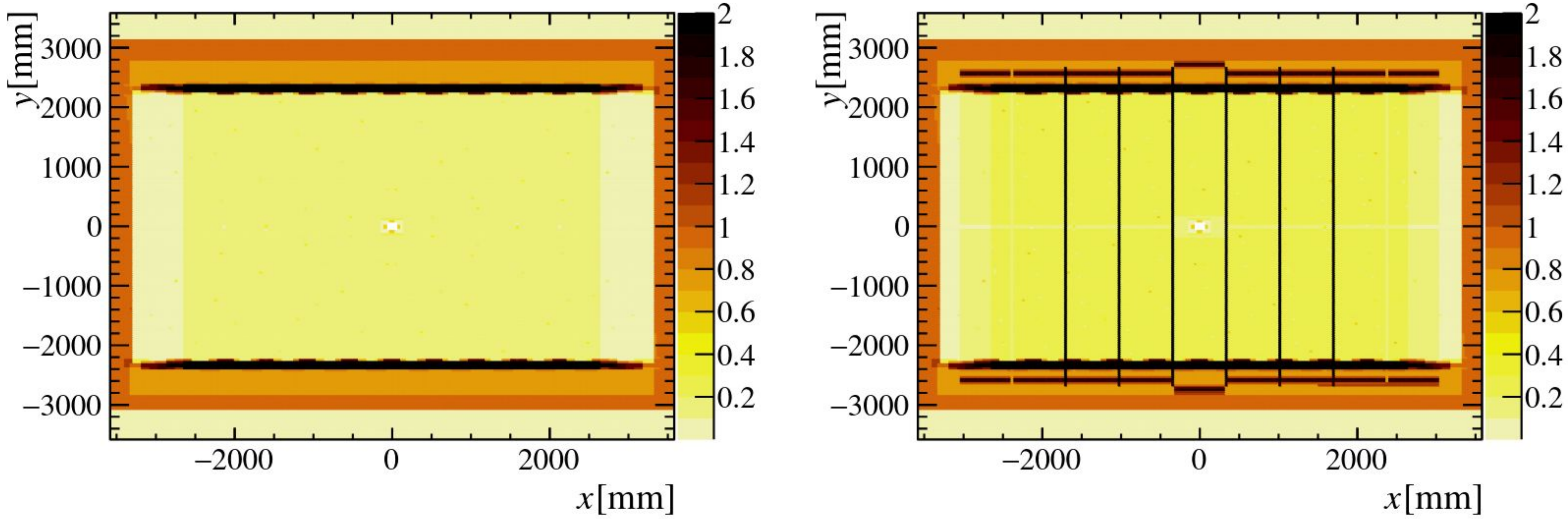
- Use two different algorithms to compute hit/track/hypothesis probabilities:
  - **Binned**: Based on simulating large numbers of photons (ray-tracing)
  - **Unbinned**: Semi-analytic approach based on back-propagation
- The semi-analytic approach is faster and works with either pixel hits (integrating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

Track resolution

Track resolution using LHCb Upgrade I