TORCH — simulation and reconstruction

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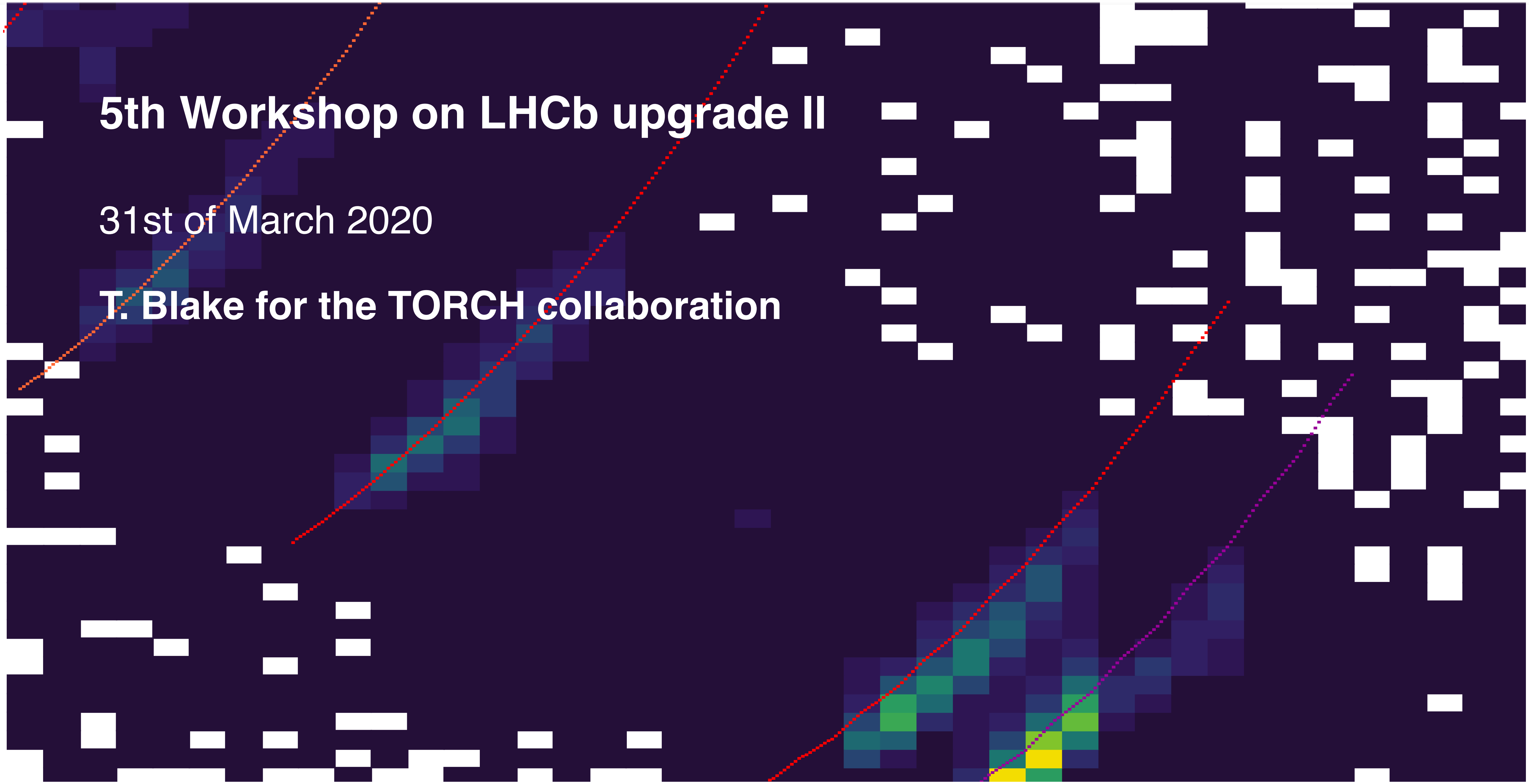

5th Workshop on LHCb upgrade II

31st of March 2020

T. Blake for the TORCH collaboration

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Outline

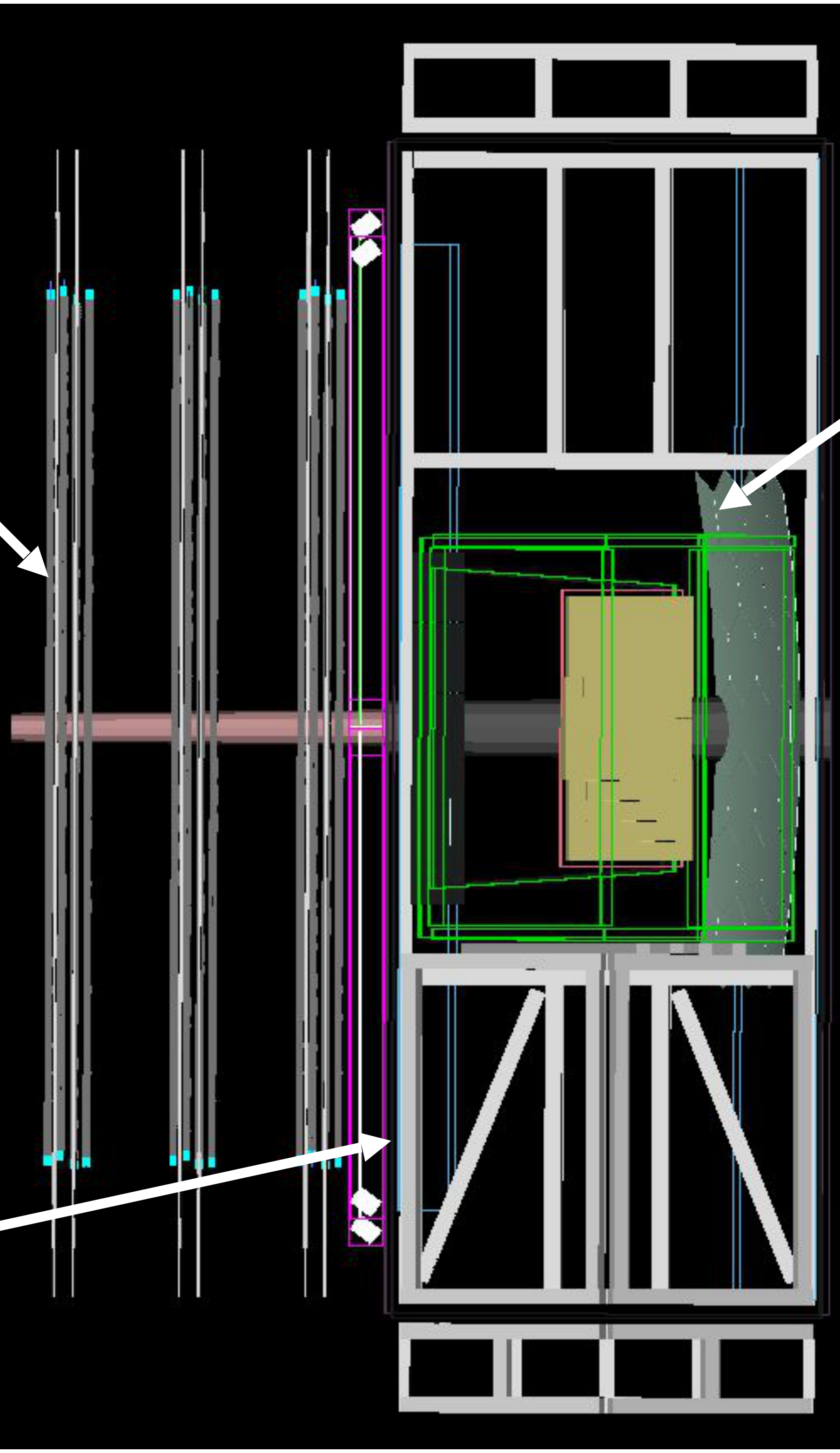
- TORCH simulation and reconstruction
- Performance in **Upgrade Ib** conditions.
- Performance in **Upgrade II** conditions.
- Primary-vertex timing.
- Physics studies.

TORCH simulation

- A simulation of the TORCH has been developed in the LHCb software framework:
  - An `XML` detector geometry has been implemented in `DDDB` to describe the TORCH optical elements.
  - Code has been ported from `Geant 4` to `GaussRICH` to implement surface roughness effects.
- We then persist photons reaching the MCP-PMTs at the output of `Gauss` and use a standalone reconstruction.

TORCH in LHCb

Default position in front of RICH 2



Fibre tracker

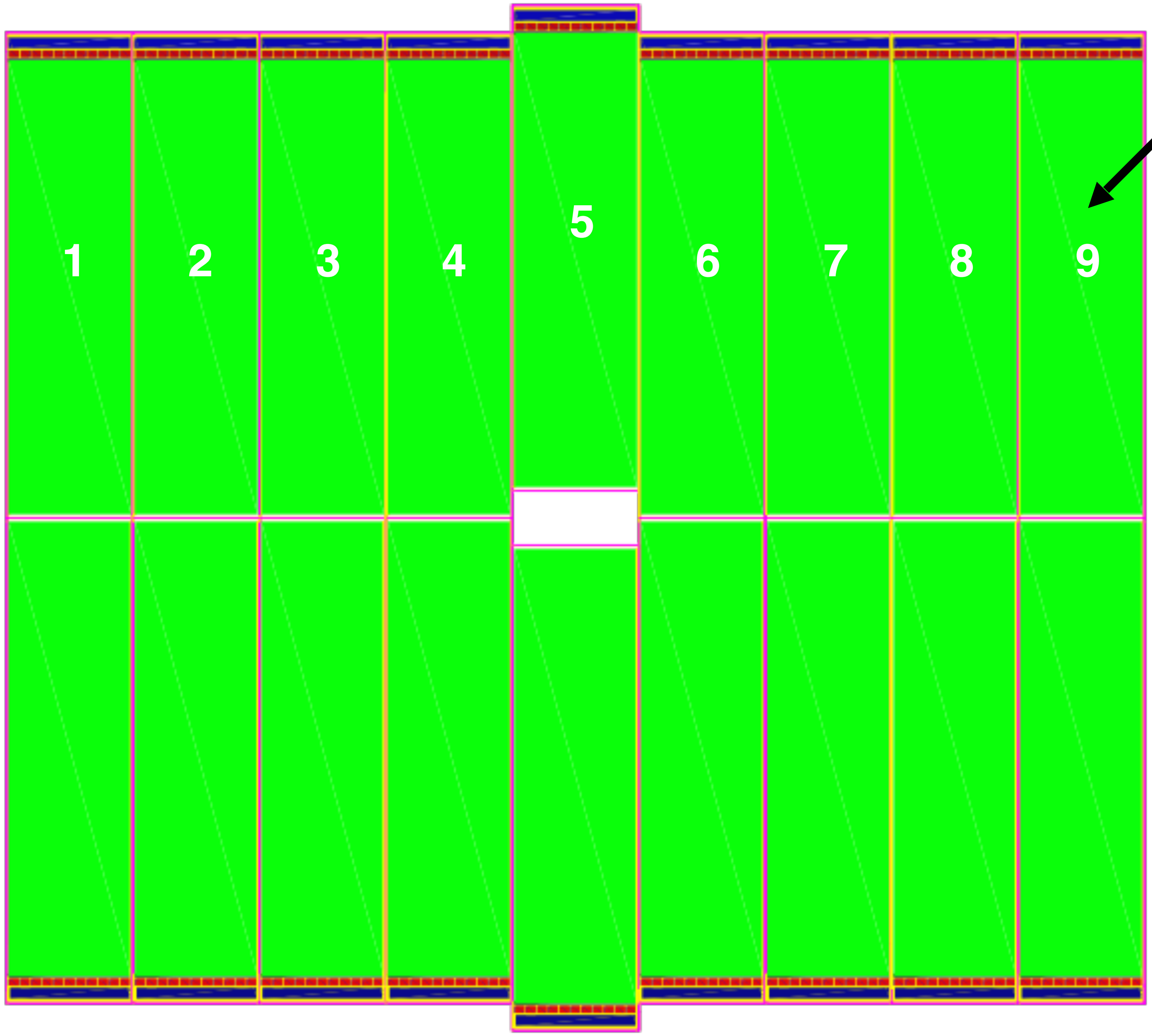
Beam pipe

TORCH

RICH 2

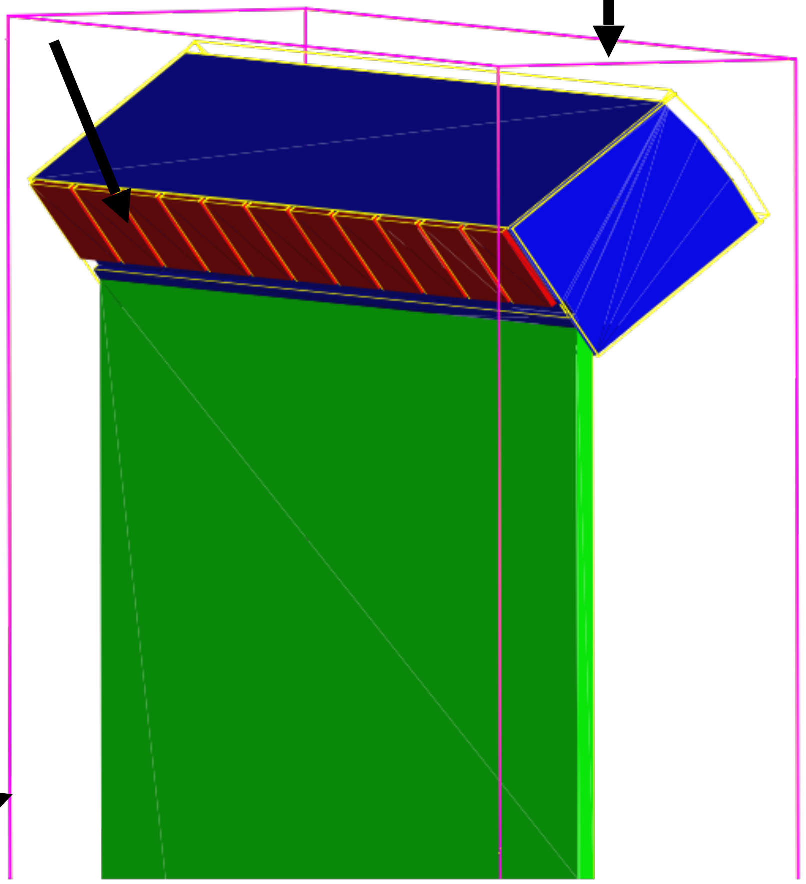
RICH 2 position shifted by 200 mm to accommodate the TORCH

Module geometry



660 x 2500 x 10 mm radiator bar

Free-standing with no support structure.



11 MCP-PMTs

Cylindrical focusing mirror

0.5 mm aluminium box

Data taking conditions

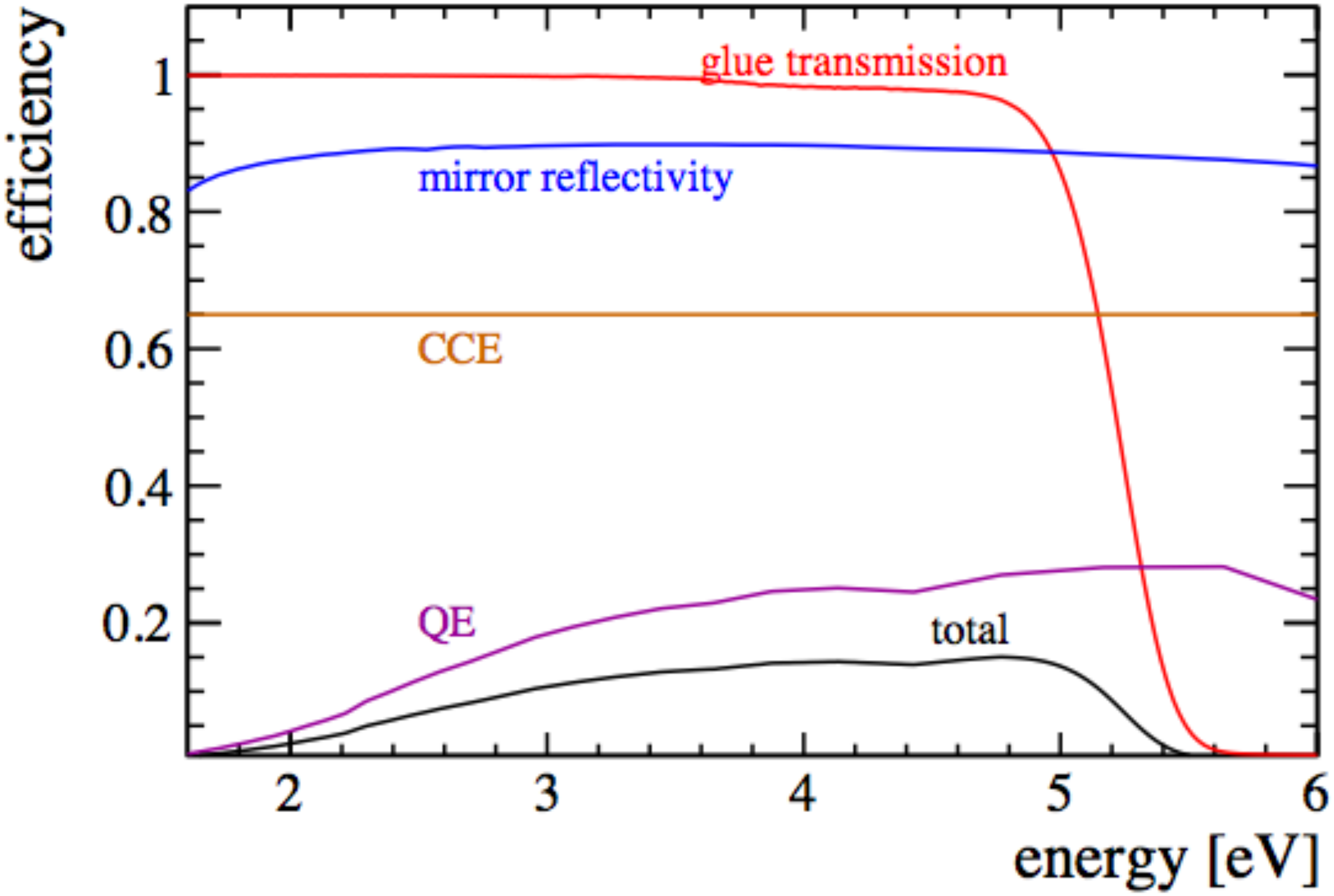
- Simulate $b\bar{b}$ events in **Upgrade Ib** conditions, i.e. an instantaneous luminosity of $\mathscr{L}$ = 2x10^{33} cm^{-2}s^{-1} and a pile-up of μ=7.6.
  - ➡ Generate spill-over from ±2 bunch-crossings.
- Preliminaries studies have also been performed for the **Upgrade II** luminosity of $\mathscr{L}$ = 1.5x10^{34} cm^{-2}s^{-1}.
  - ➡ Merge events from **Upgrade Ib** studies to simulate the conditions, assuming the tracking performance is unchanged.

Reconstruction

- Extrapolate tracks using the `Upgrade Ia` tracking to the front of the TORCH detectors.
    - ➡ Compute path length by a cubic spline interpolation between points on the tracks.
    - ➡ Assume we have input on the track t_0 from elsewhere (although this can be determined using the TORCH).

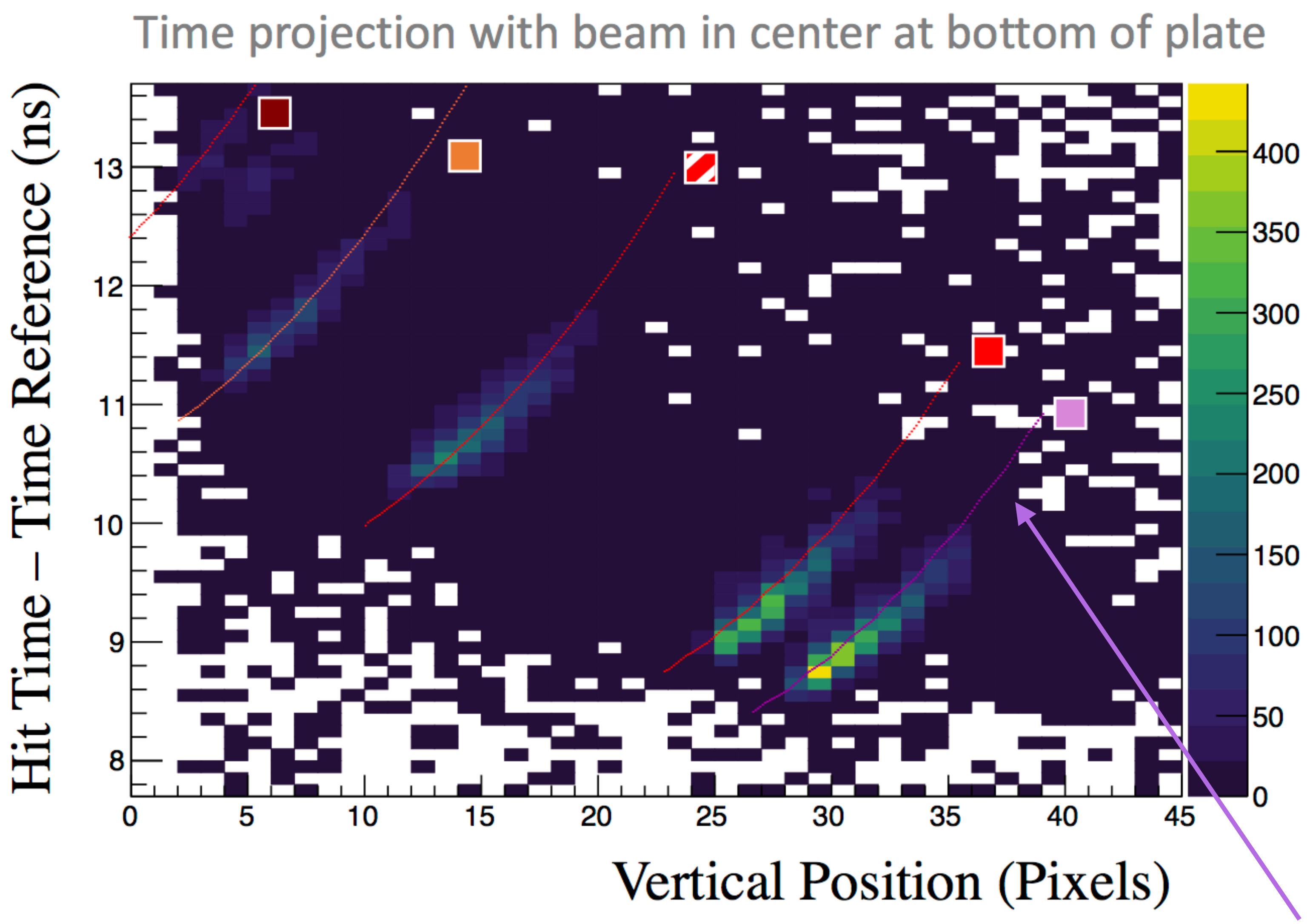
Detector performance

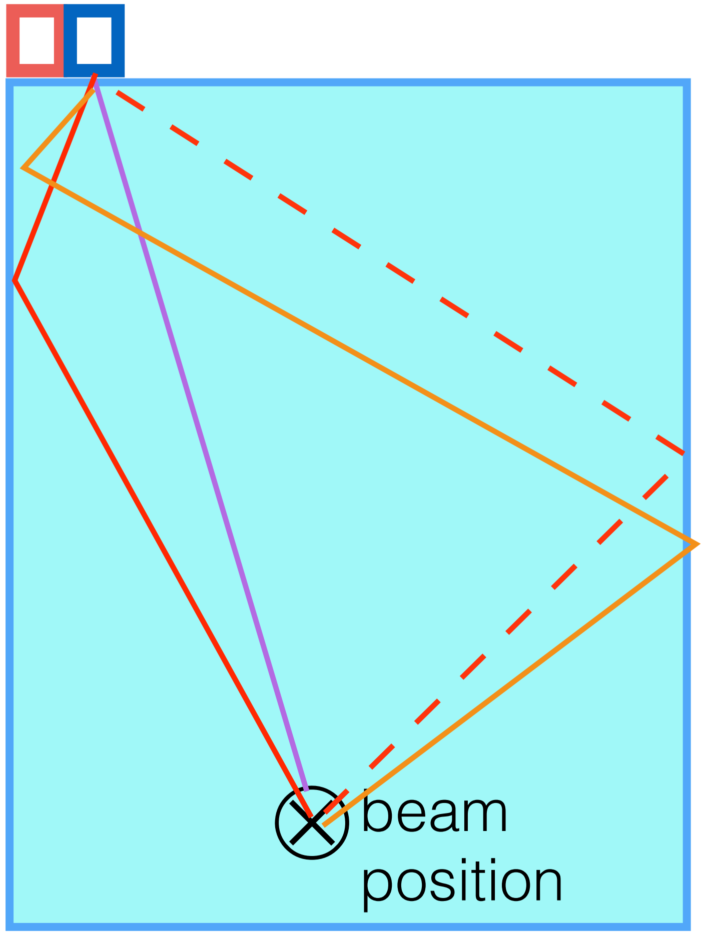
- Assume an 8-by-128 effective pixelisation with with 10ps TDC bins.
- Photon arrival time is smeared by an additional 55ps resolution to account for the MCP response and the effect of the readout electronics.
- Apply known efficiency losses, *e.g.* due to QE.



Reminder: pattern in a beam test

- Each track produces a three dimensional image in space and time, *e.g.* from beam test results:





Expected arrival time/position from simulation

PID algorithm

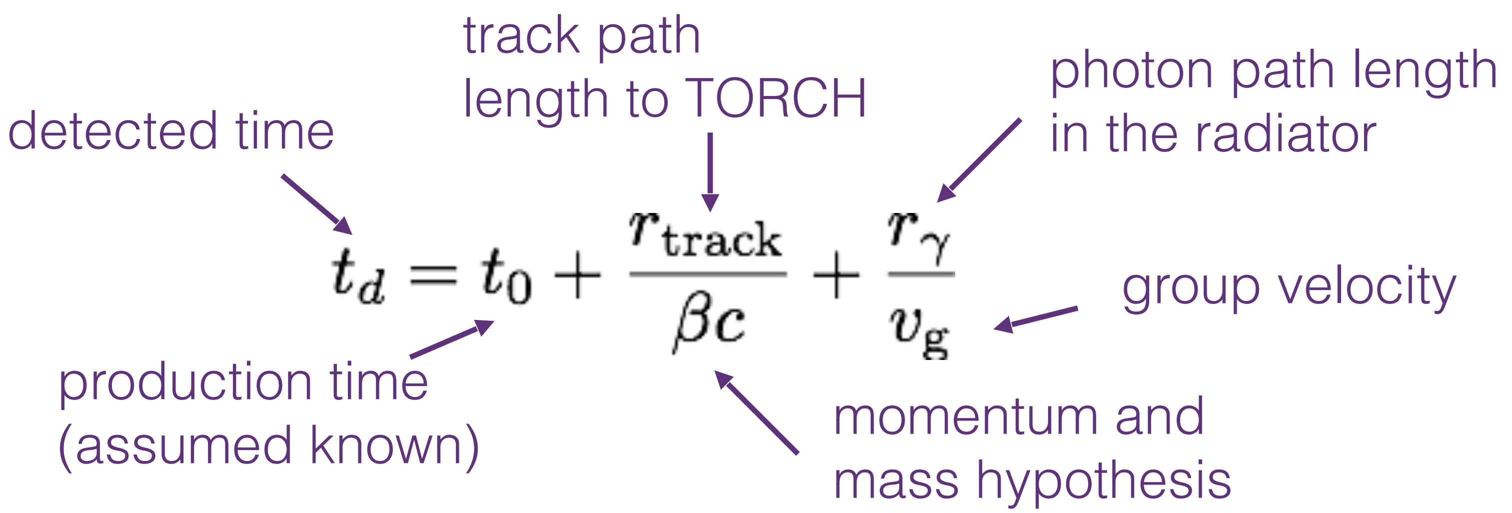
- Use a similar approach to the RICH detectors and compare hypotheses directly using a likelihood calculation.

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

Determine PDF for given hypothesis by “ray-tracing”

Currently use a “local” per-track algorithm.

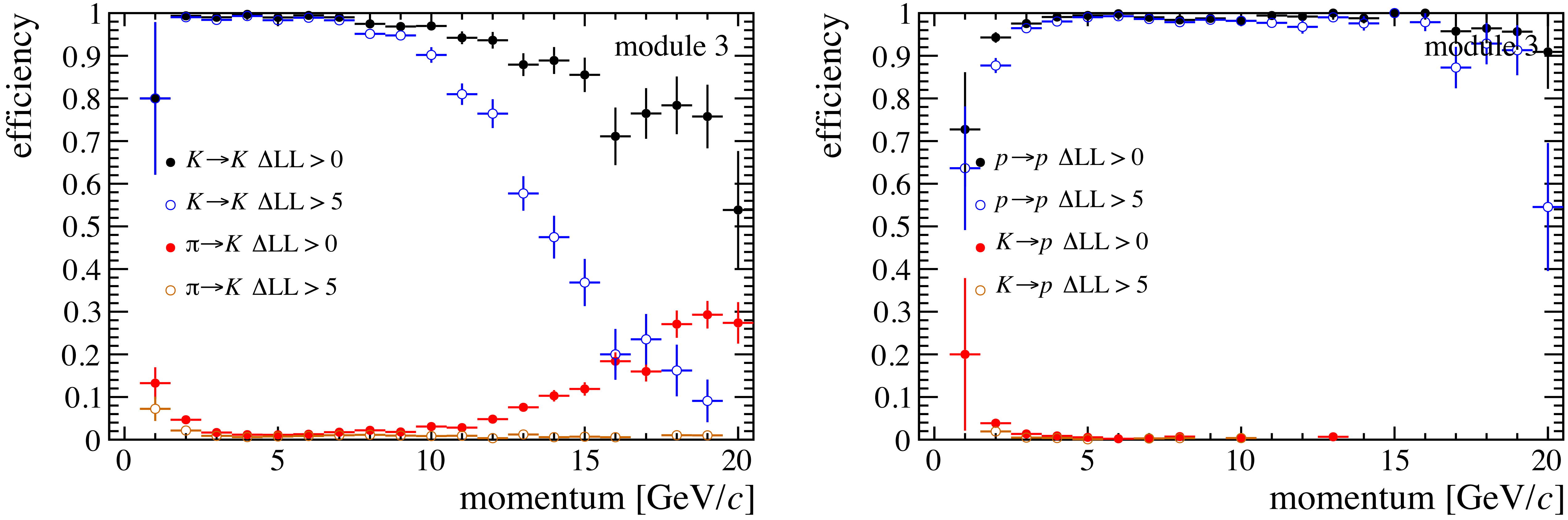
- Photon arrival time depends on the track t_0 and particle hypothesis:



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

Upgrade Ib performance

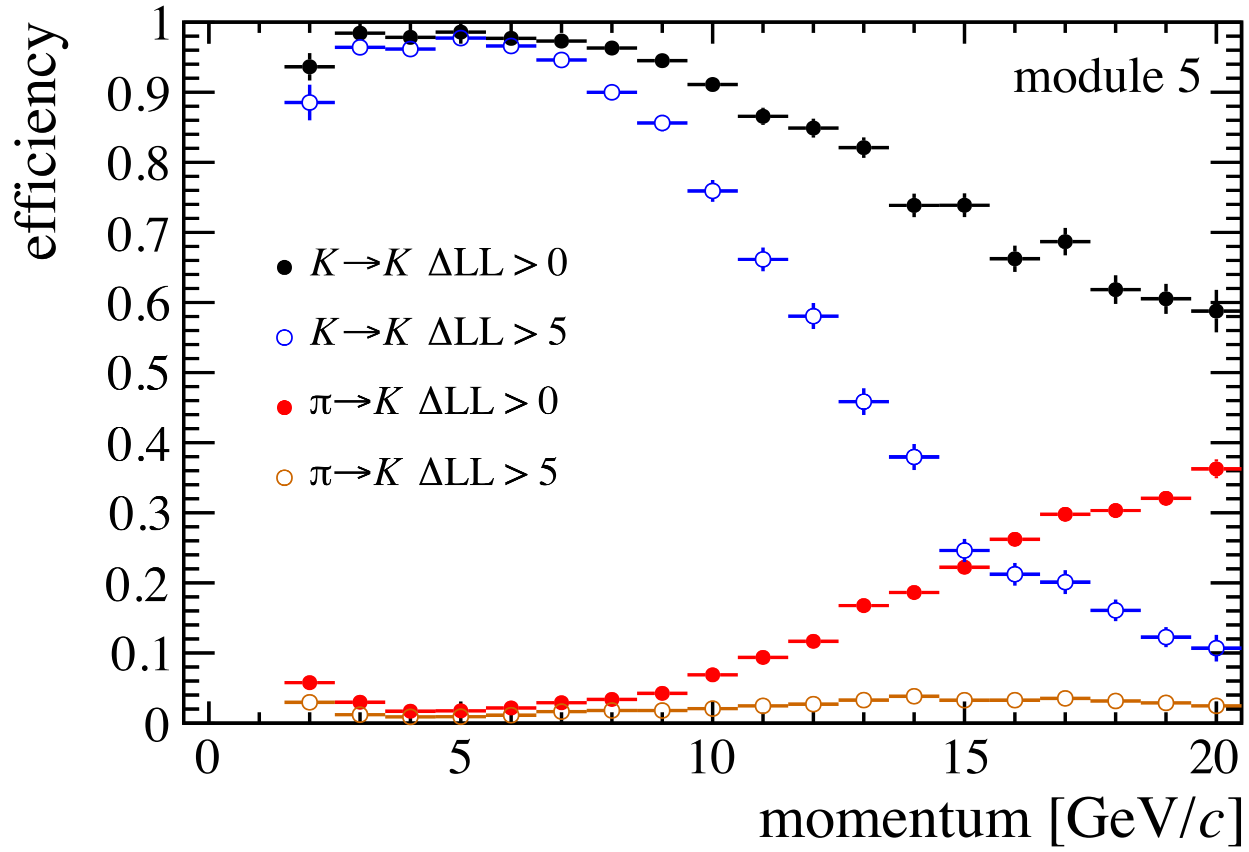
- TORCH PID performance for module 3 at $\mathscr{L} = 2\times10^{33}\ \mathrm{cm^{-2}s^{-1}}$:

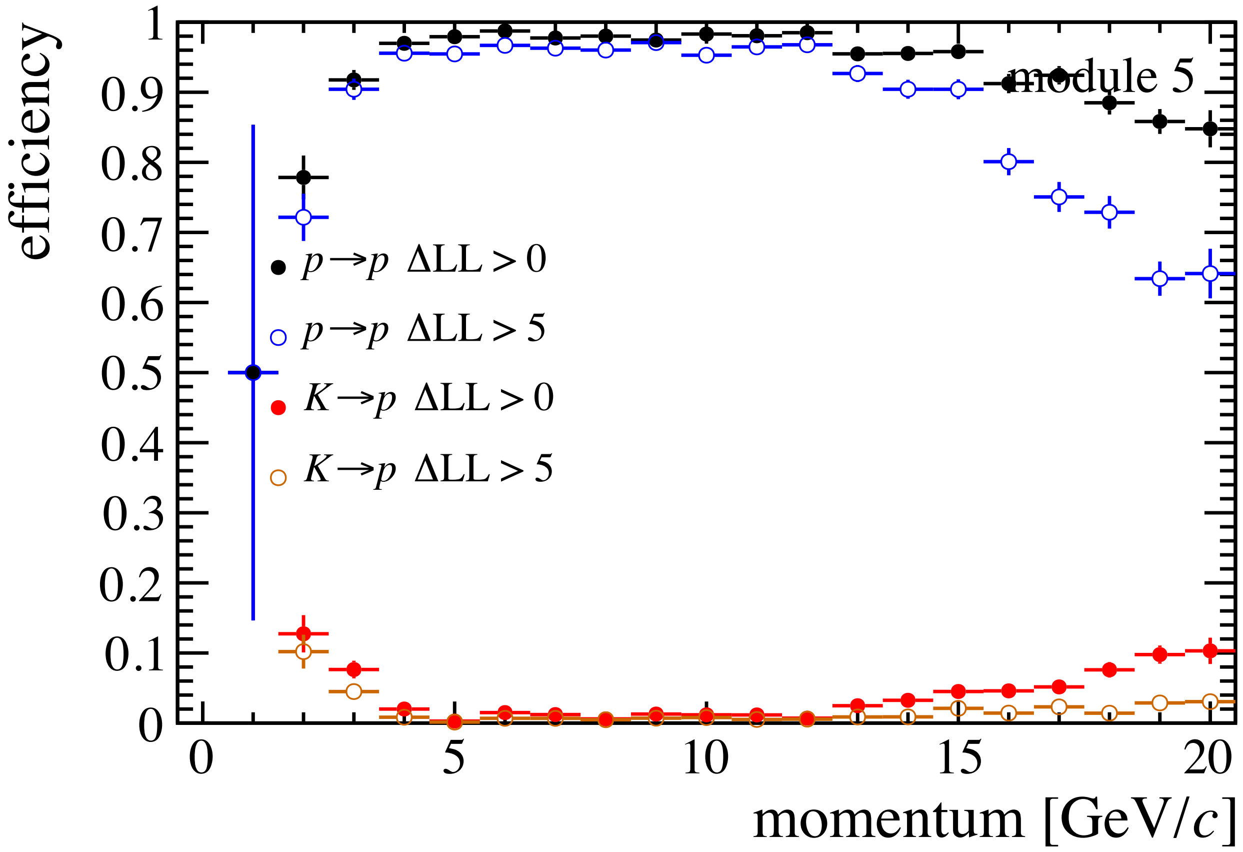


- Excellent separation between *π*/*K*/*p* in the 2 -10 GeV/*c* range.

Upgrade Ib performance

- TORCH PID performance for the **highest occupancy** module (module 5) at $\mathscr{L}$ = 2x10^{33} cm^{-2}s^{-1}:

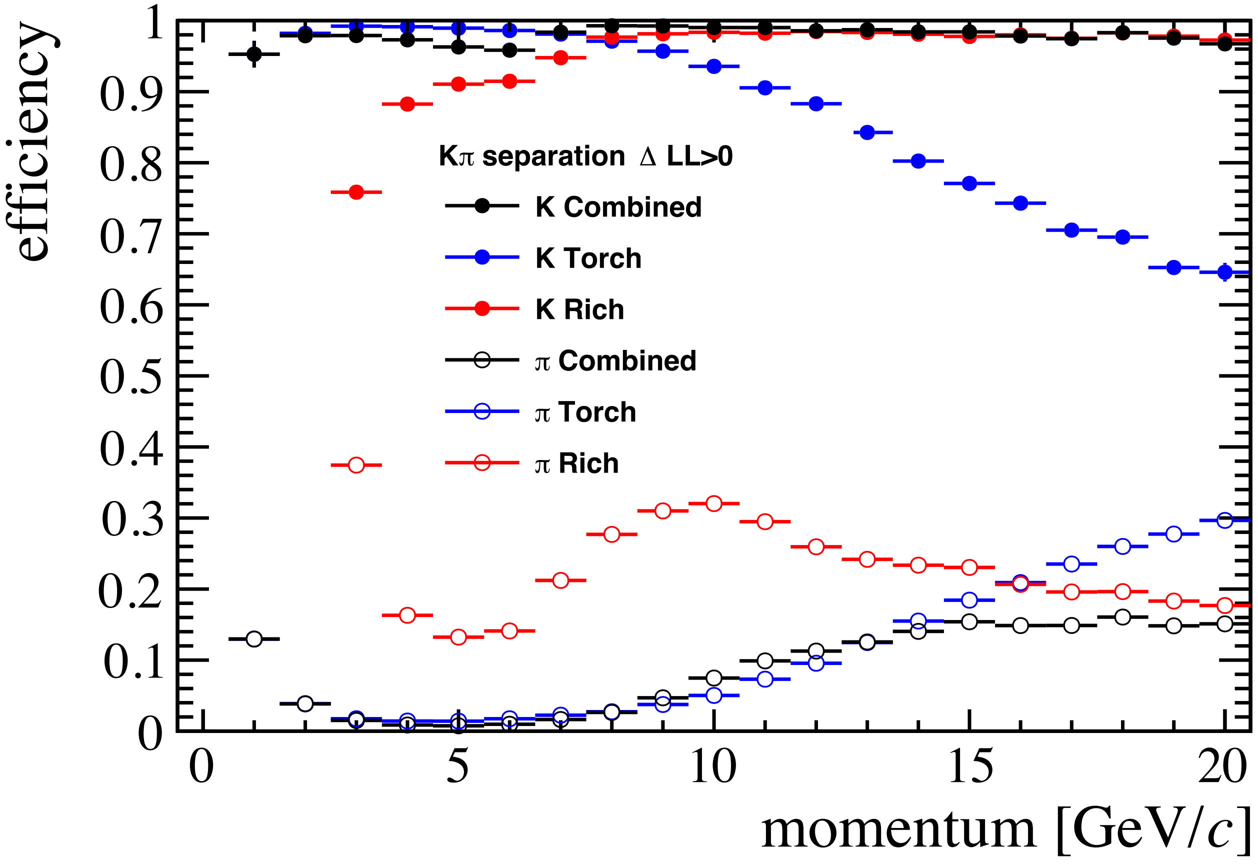


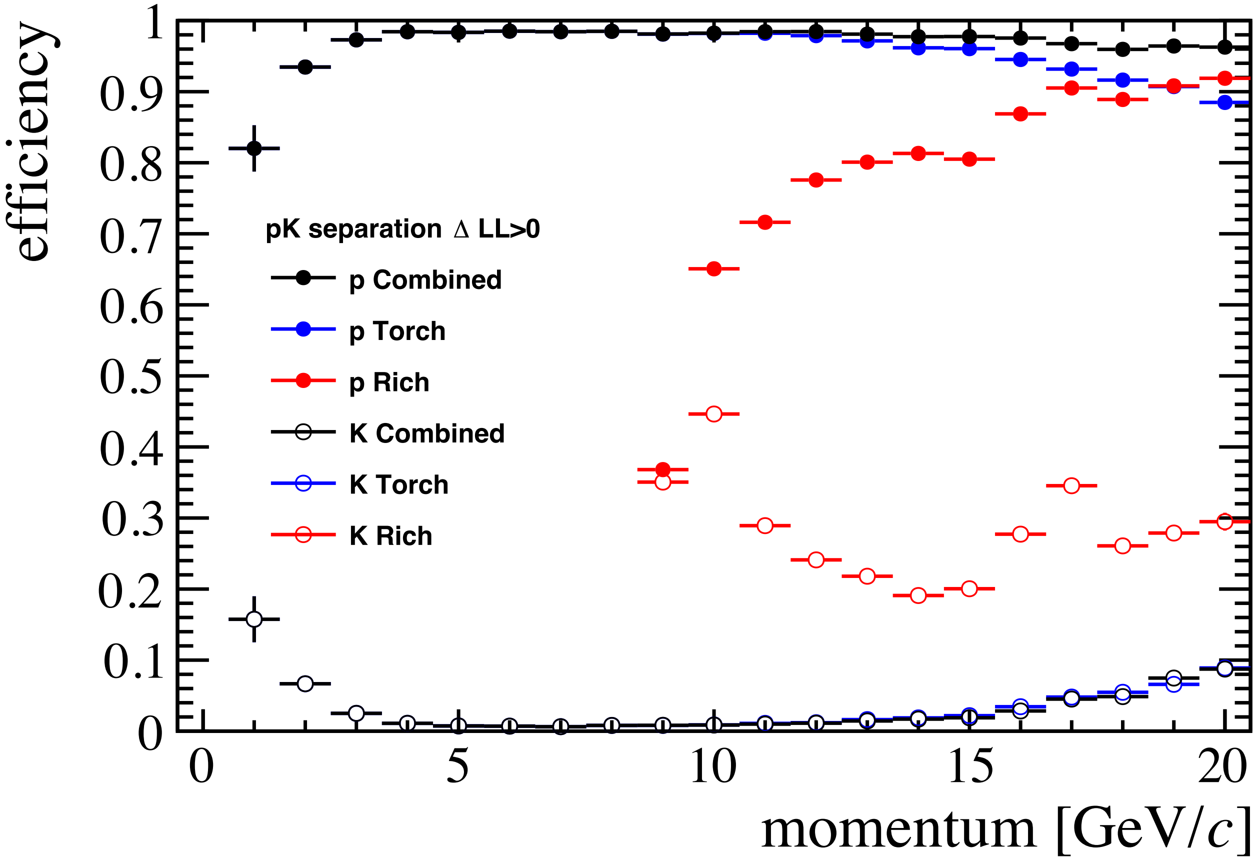


- Good separation between *π*/*K*/*p* in the 2 -10 GeV/*c* range.

Combined PID performance

- Combining TORCH and RICH performance in `Upgrade Ib` scenario:

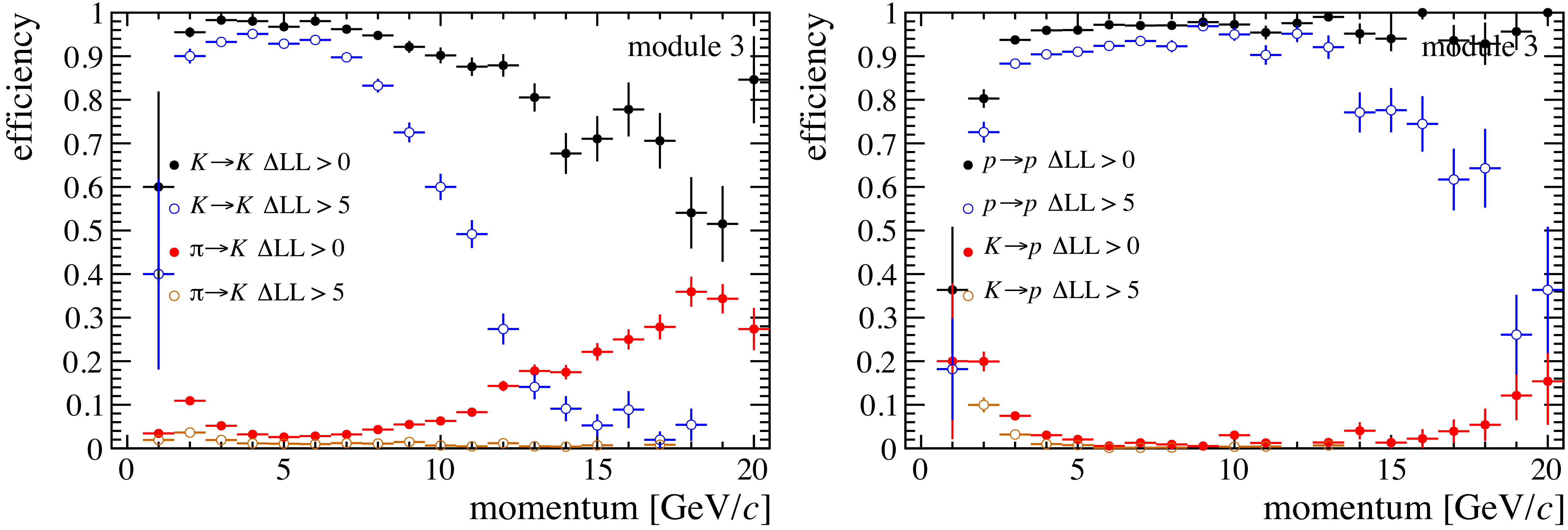




- TORCH performance dominates at low momentum ($p \lesssim 10$ GeV/c) but we gain from combining TORCH and RICH 2 information at intermediate momentum.

Upgrade II performance

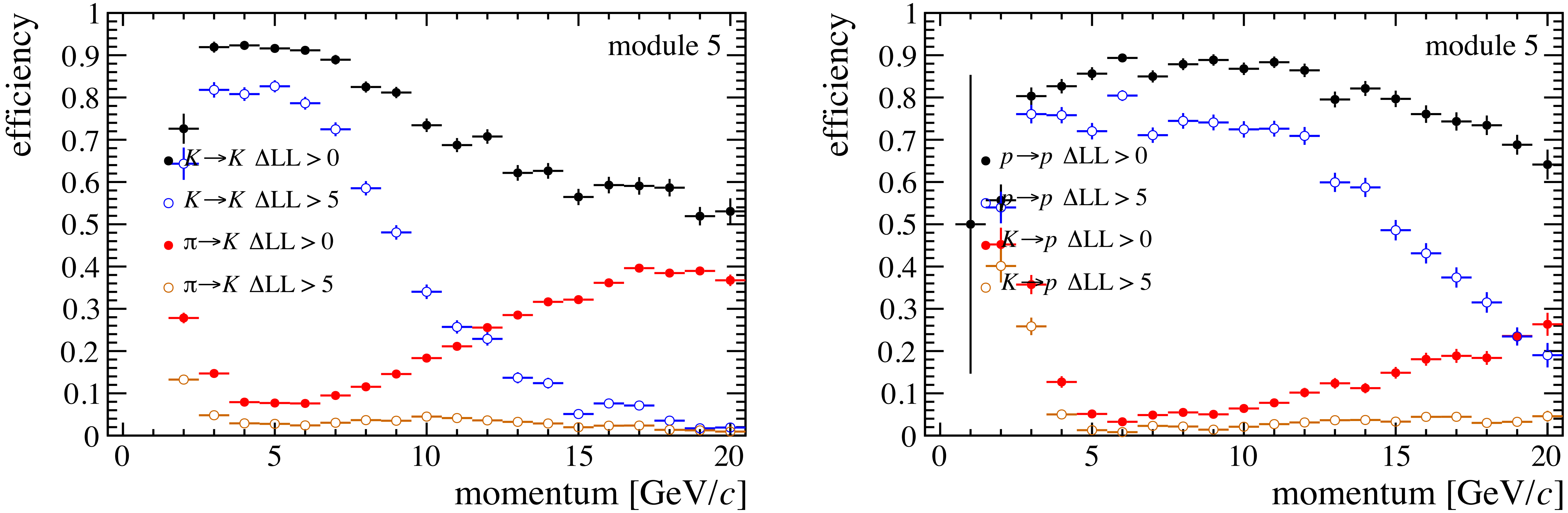
- TORCH PID performance for module 3 at $\mathscr{L} = 1.5\times10^{34}\ \mathrm{cm^{-2}s^{-1}}$:



- **Performance is robust against higher detector occupancies**. See only a small drop-off in performance in Upgrade II conditions.

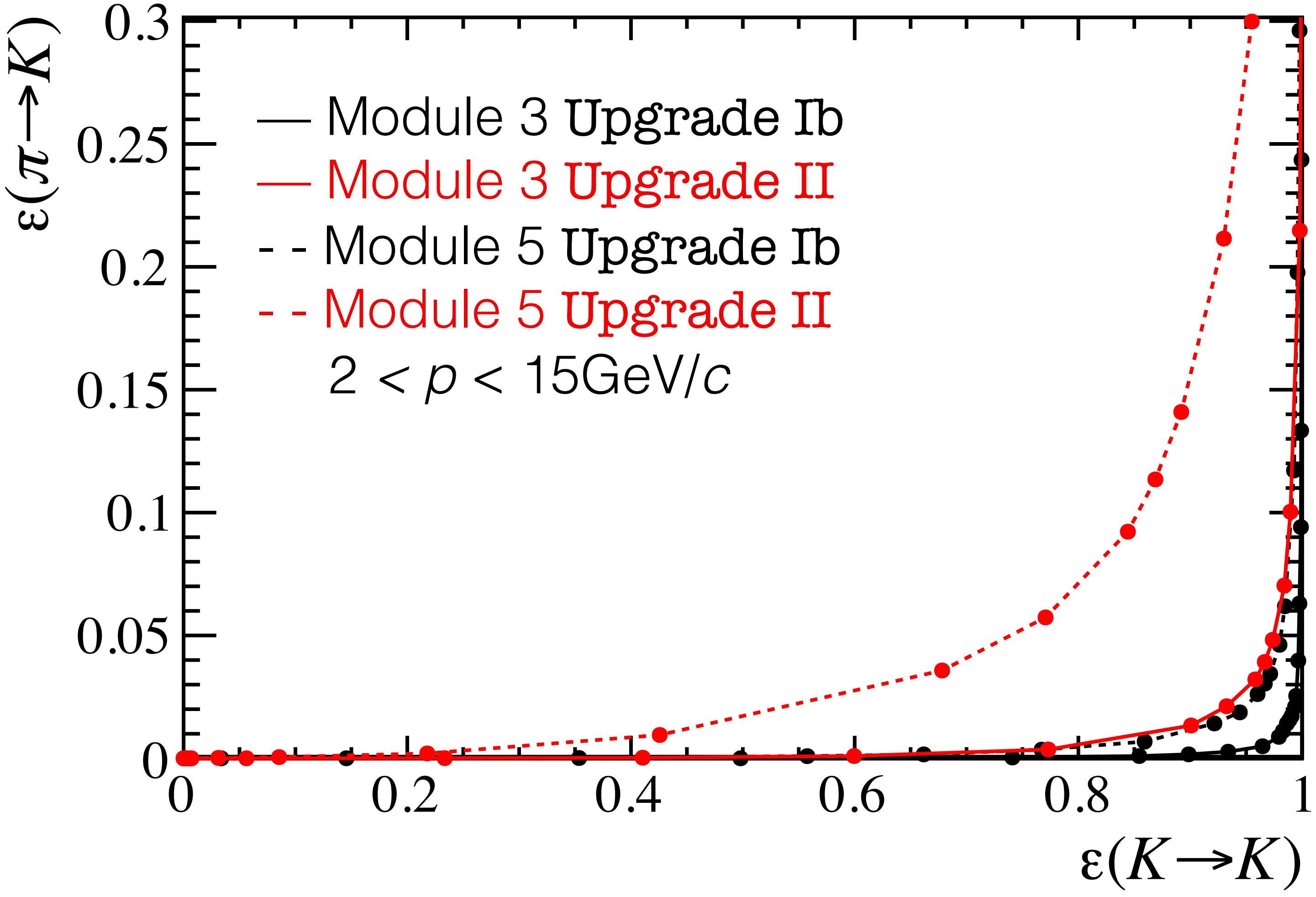
Upgrade II performance

- TORCH PID performance for the **highest occupancy** module (module 5) at $\mathscr{L}$ = 1.5x10^{34} cm^{-2}s^{-1}:



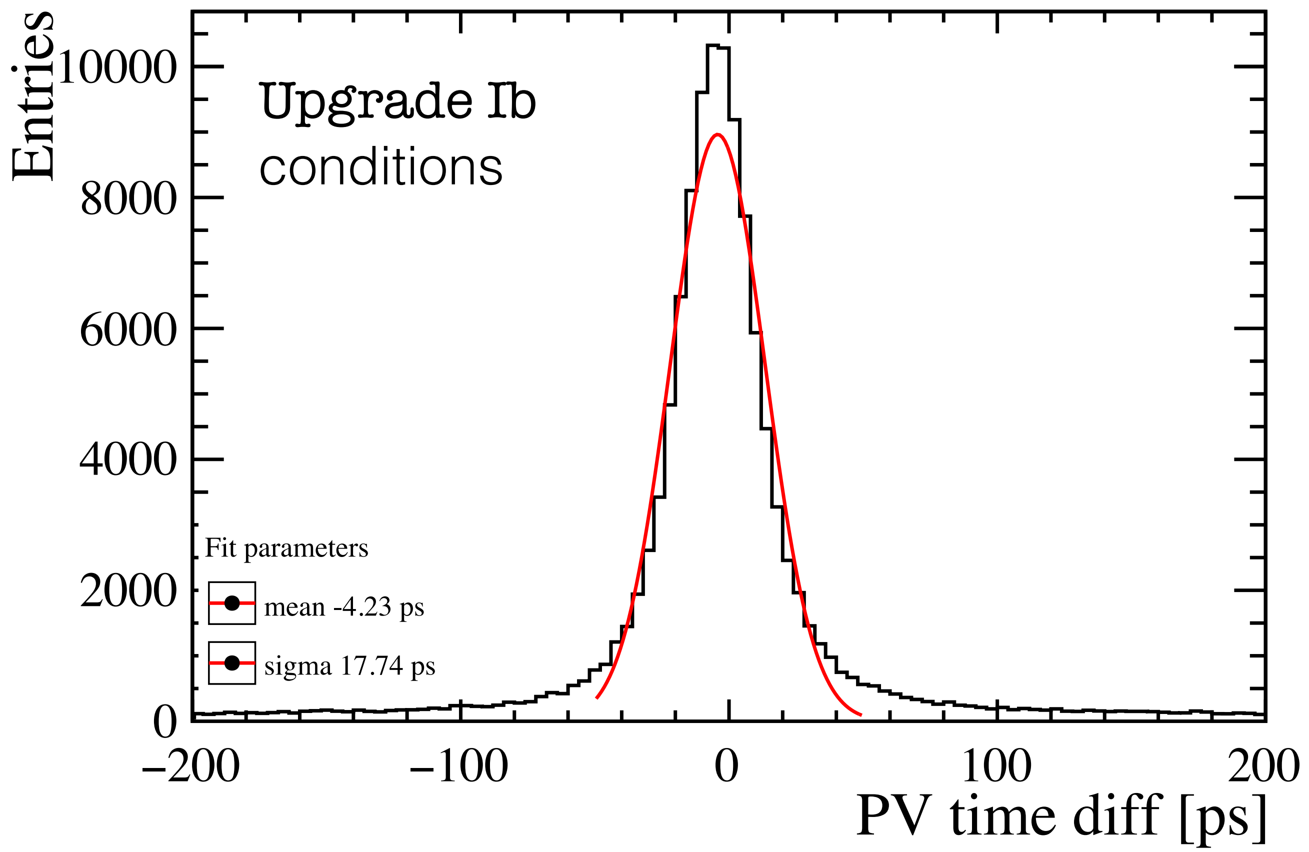
Performance comparison

- Comparison of performance between **Upgrade Ib** and **Upgrade II** scenarios.
- We are able to modify the pixelisation in the central region of the detector to recover the performance in **Upgrade II**. The optics would remain unchanged.



Primary vertex timing

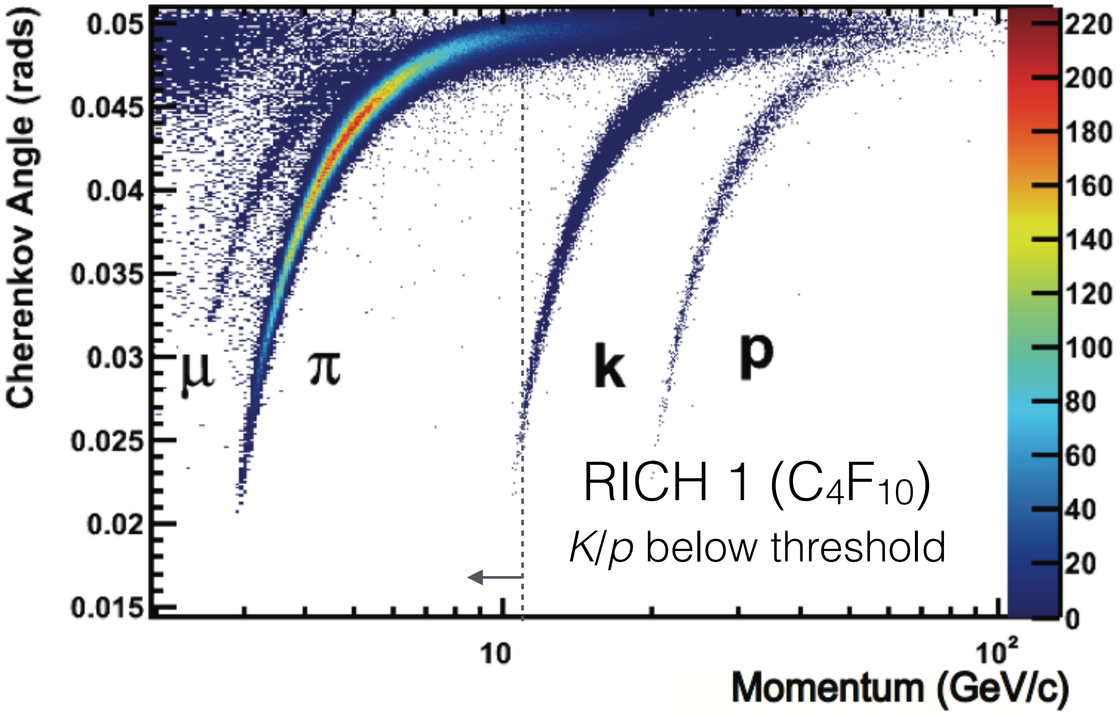
- Per-track likelihood depends on the assumed particle hypothesis t_0.
- For a given hypothesis, can maximise the likelihood to determine t_0.
- Can combine individual track likelihoods to determine vertex level t_0:
  - ➡ Try each particle hypothesis in turn and pick the best hypothesis for each track.
- Combined resolution is ~15ps.



Physics studies

- Two benefits from TORCH:
  1. Get improved π-K separation at low momentum due to positive kaon identification.
  2. Gain p-K separation below 10 GeV/*c*.
- Illustrate performance in the `Upgrade Ib` scenario using:
  1. Baryonic decays.
  2. Semileptonic decays.
  3. Flavour tagging.

LHCb [EPJC 73 (2013) 2431]

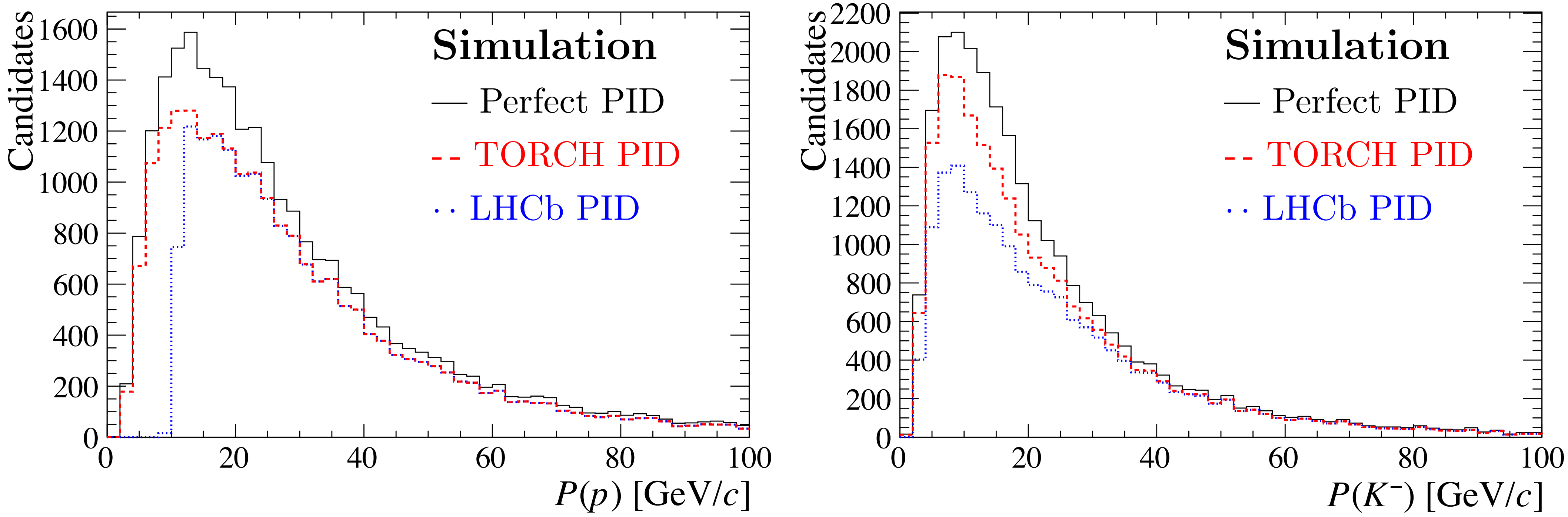


RICH 1 (C_4F_{10})

K/*p* below threshold

$\Lambda_b \rightarrow J/\psi pK$

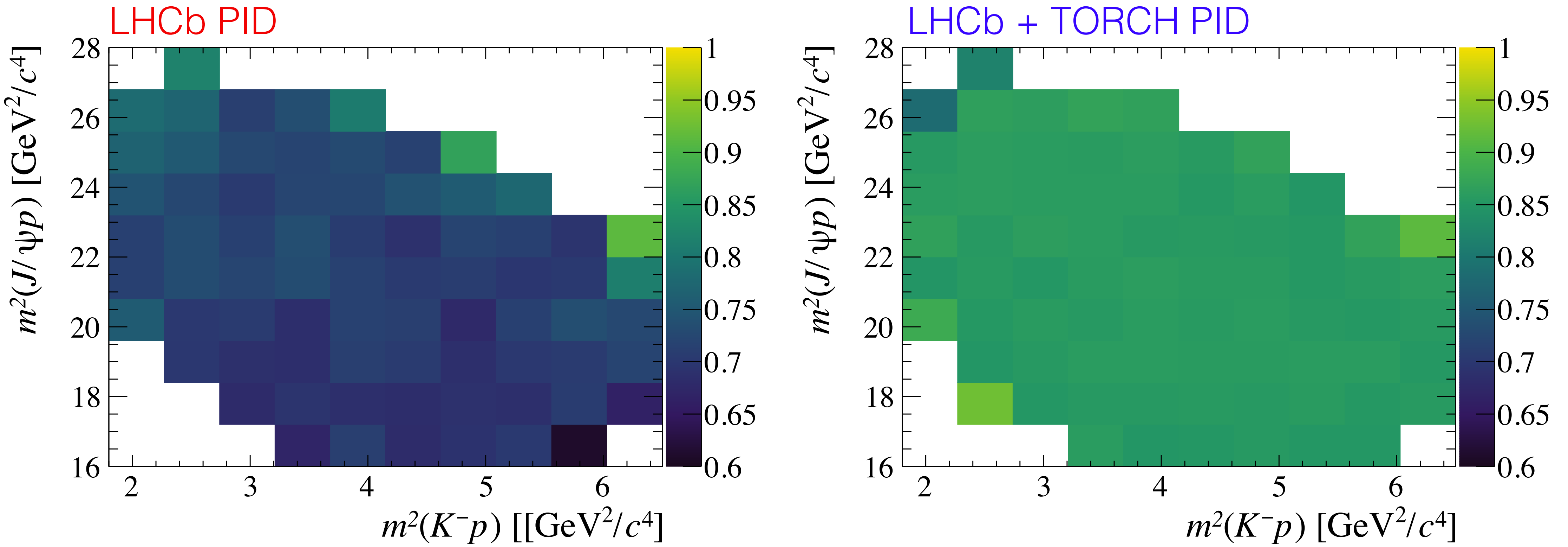
- Momentum distribution of stripped candidates in simulated $\Lambda_b \rightarrow J/\psi pK$ decays:



- Can increase efficiency by about 25% using RICH+TORCH PID rather than the PID requirements used in the current analysis.

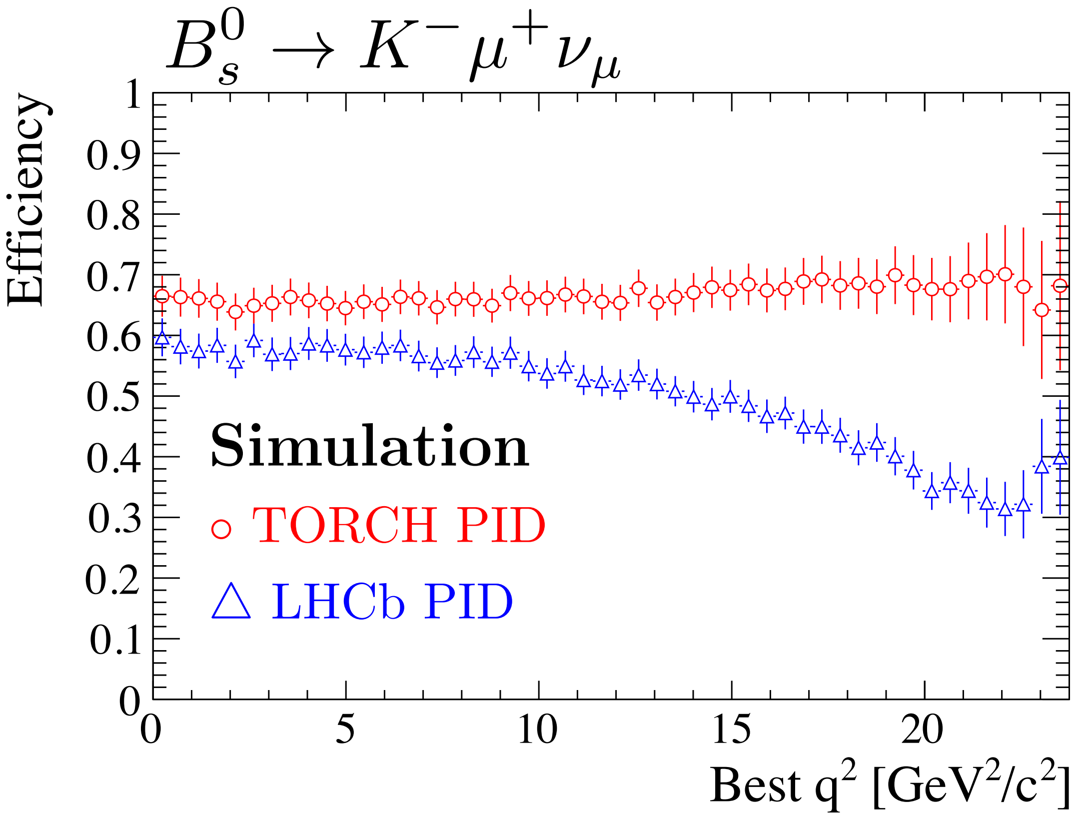
$\Lambda_b \rightarrow J/\psi pK$

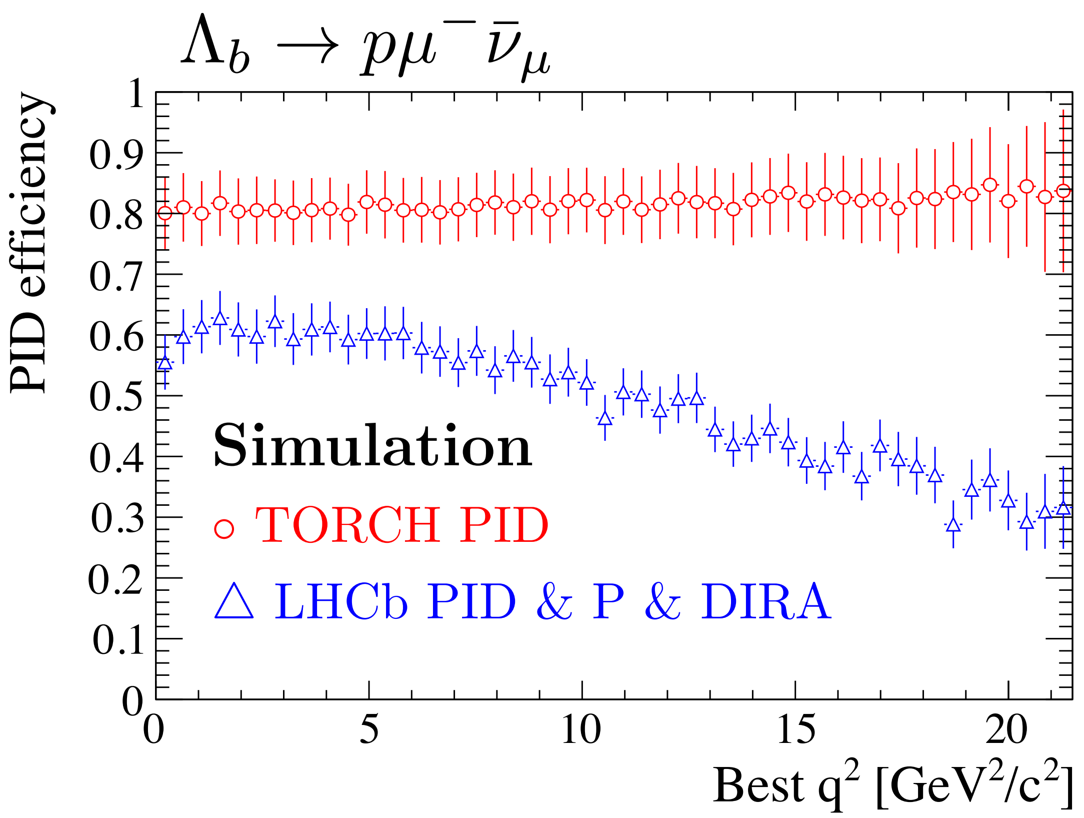
- Gains at low-momentum improve the uniformity of Dalitz observables.



Semileptonic decays

- Also expect to see significant gains at high *q*² in semileptonic decays, where the energy of the hadronic system is small:





- This is the *q*² range where the most precise theoretical predictions are available (from Lattice QCD).

Flavour tagging

- Develop simple cut-based tagging algorithms to test performance of the TORCH:
  - ➡ Taggers use momentum requirements, RICH and TORCH PID.
- Effective tagging power:

$B_s^0 \to D_s^+\pi^-$

	Nominal	with TORCH	Perfect
`SS Kaon`	$1.20 \pm 0.05\%$	$1.52 \pm 0.05\%$	$1.61 \pm 0.05\%$
`OS Kaon`	$1.29 \pm 0.05\%$	$1.73 \pm 0.05\%$	$1.80 \pm 0.05\%$

$B^+ \to J/\psi K^+$

	Nominal	with TORCH	Perfect
`SS Kaon`	$1.06 \pm 0.05\%$	$1.51 \pm 0.05\%$	$1.61 \pm 0.05\%$

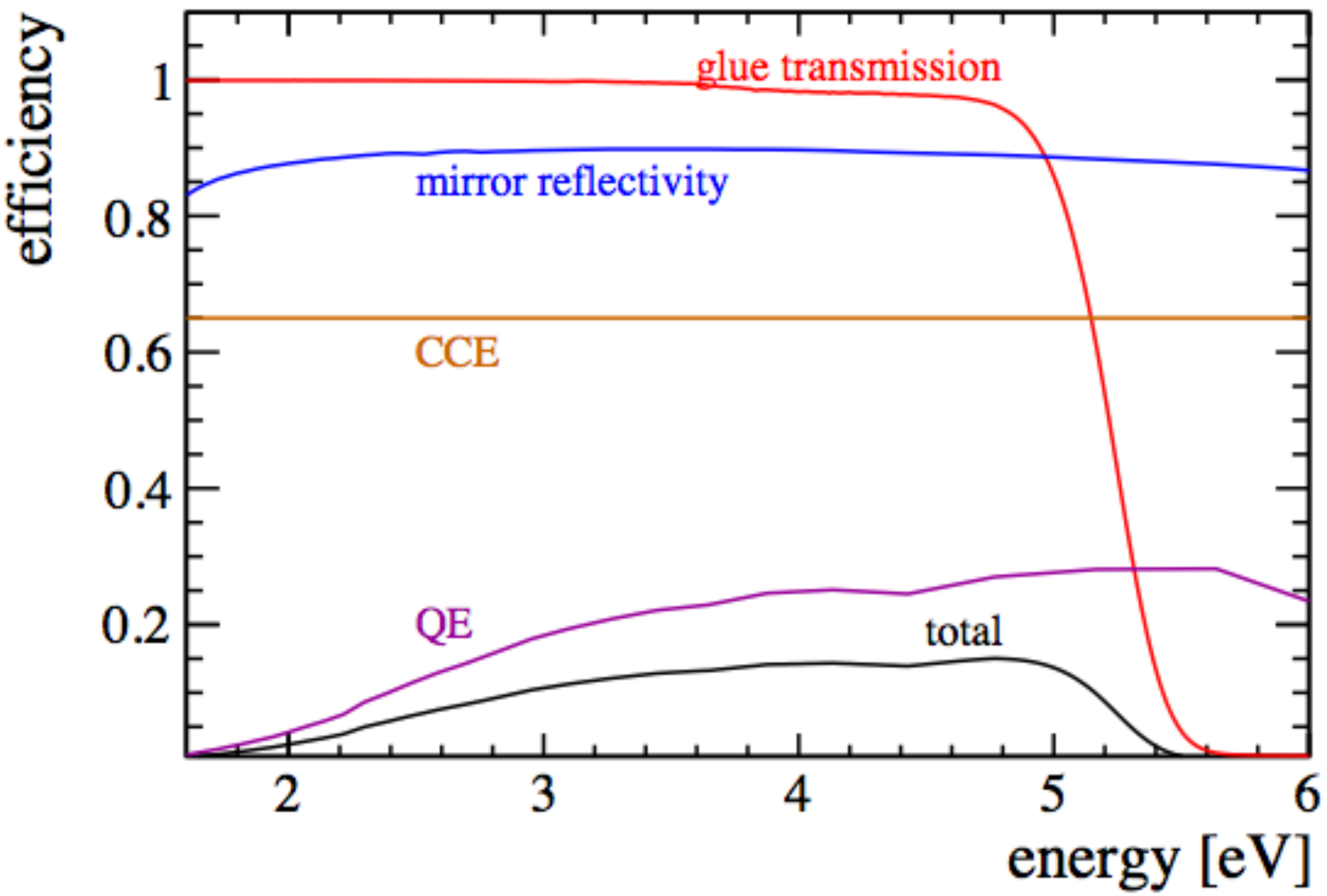
Summary

- The TORCH detector provides particle identification in the 2-20 GeV/*c* momentum range.
- A simulation of the TORCH has been developed in the LHCb framework.
- Good performance is seen in `Upgrade Ib` and `Upgrade II` conditions.
- Work is ongoing to make the simulation more realistic and to understand what detector configuration is needed for `Upgrade II`.

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

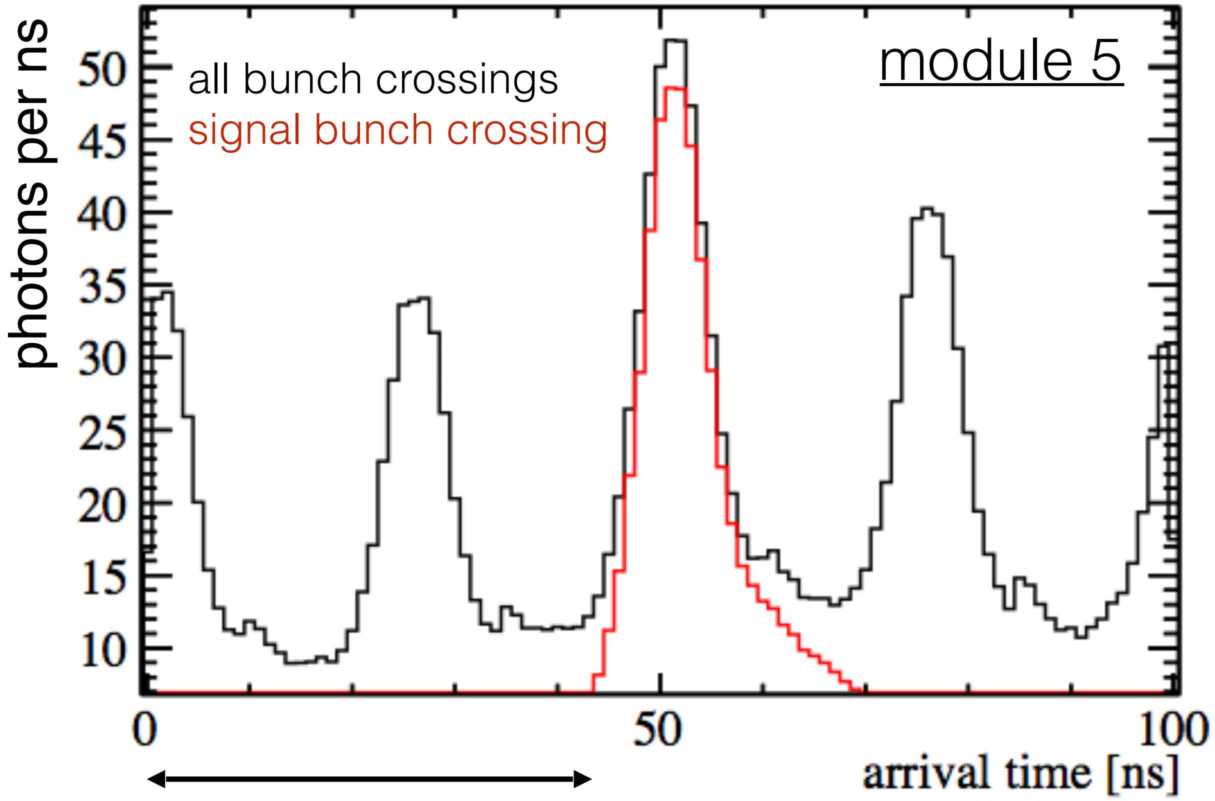
Detector efficiency

- 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.



Detector occupancy

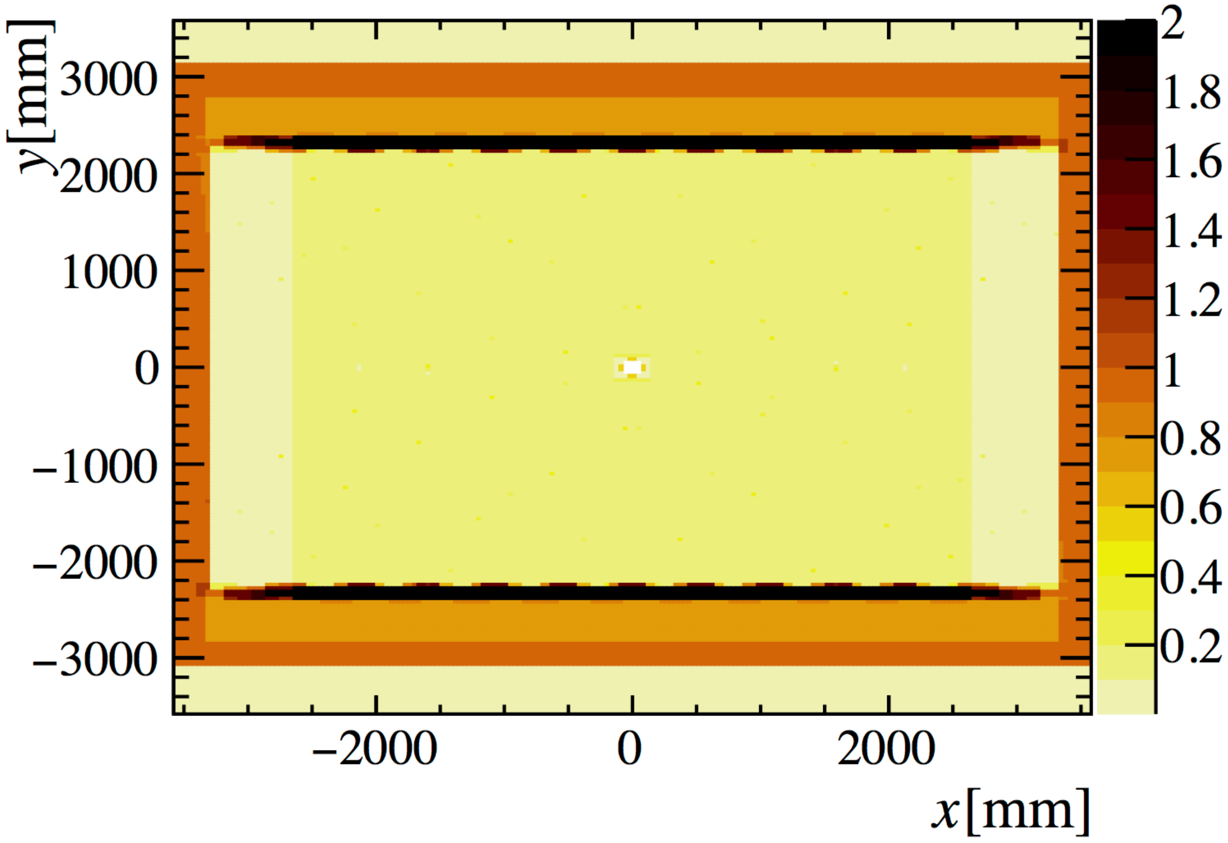
- In the **Upgrade Ib** data taking conditions the per-pixel occupancy is 5-20%, depending on the module (highest in the most central modules).



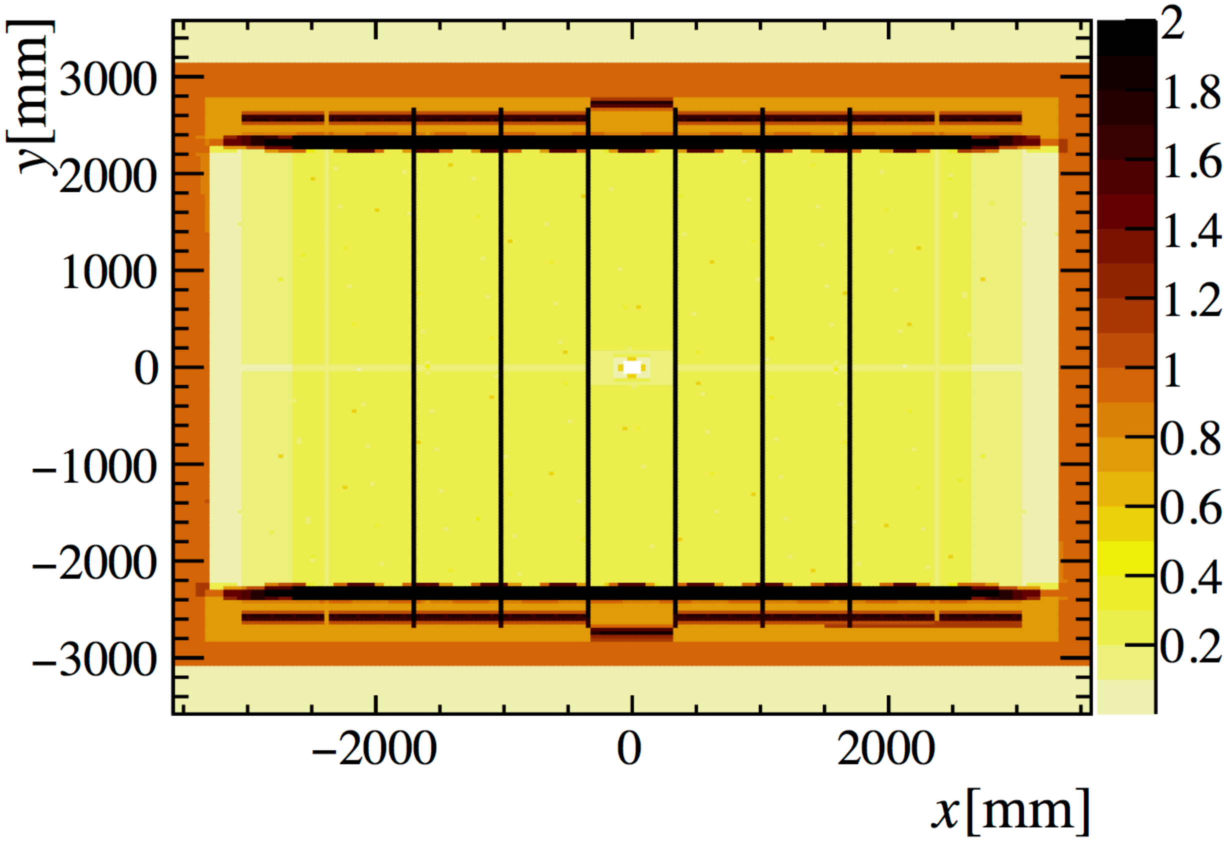
time of flight over 9.5m and time of propagation due to v_g in radiator

Material

- Material scan from **Gauss:**



without TORCH radiator

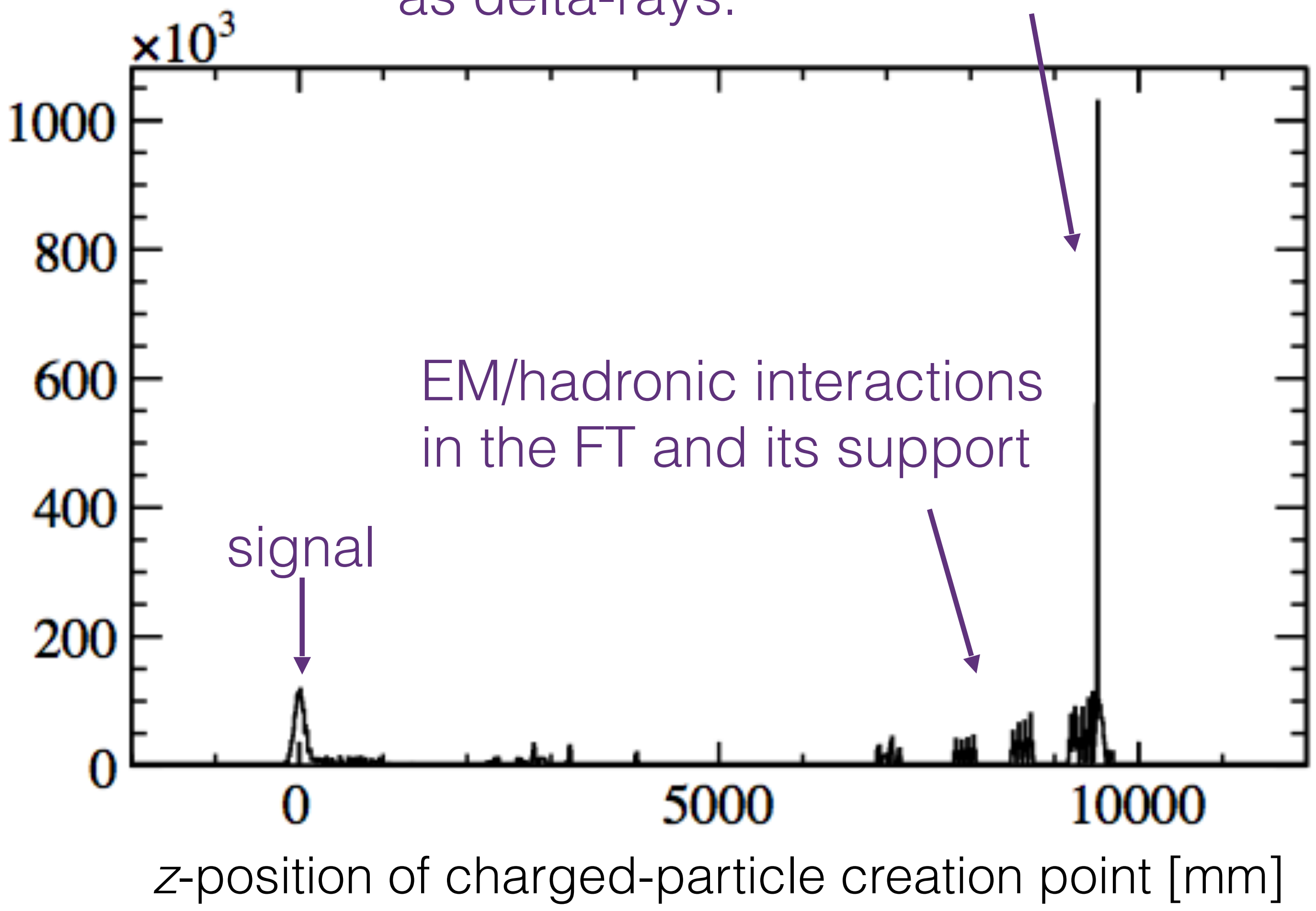


with TORCH radiator

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

Background photons

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



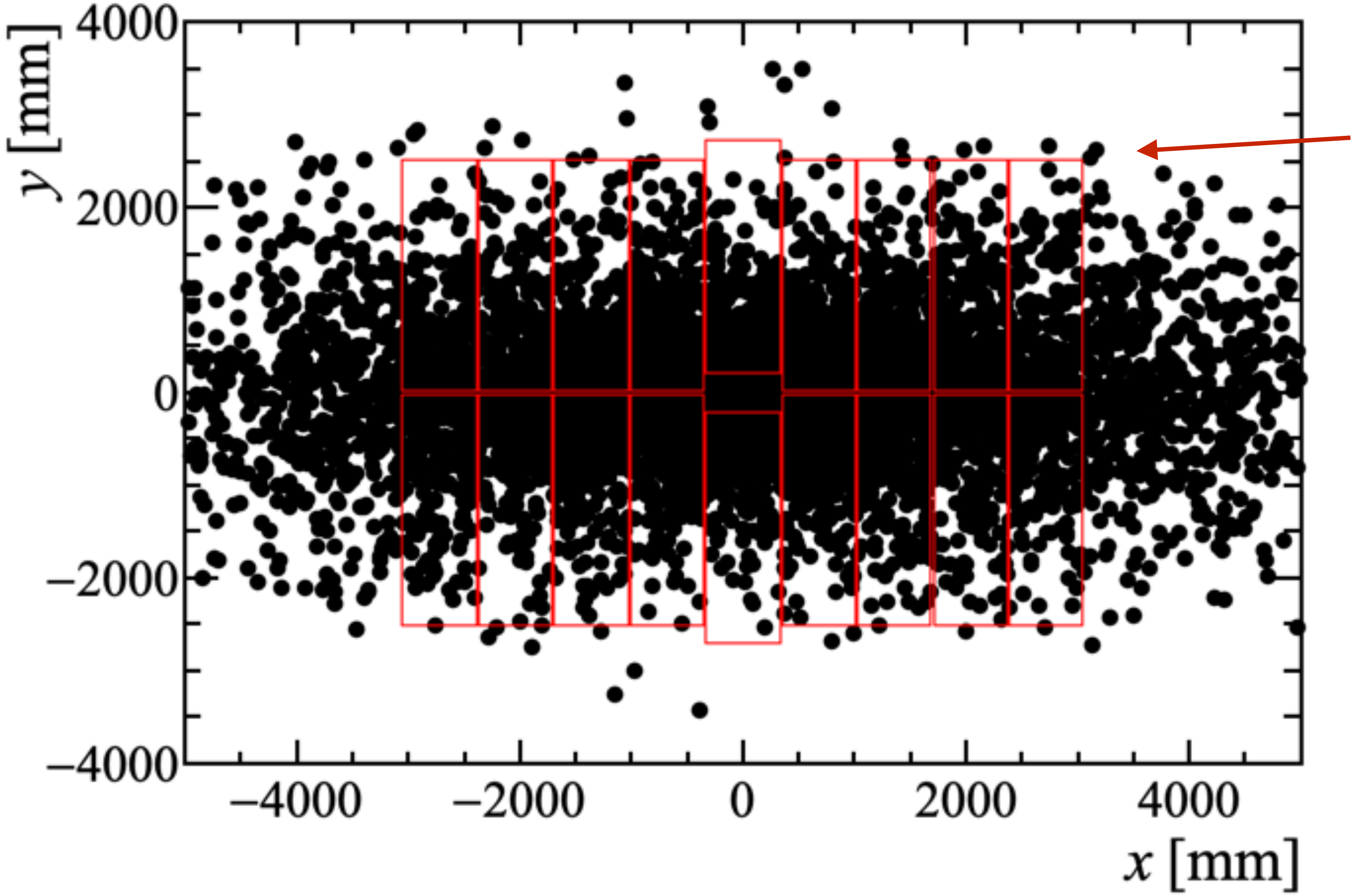
electrons produced primarily by pair production in the quartz or as delta-rays.

EM/hadronic interactions in the FT and its support

signal

Acceptance behind RICH 2

- Extrapolated track position behind RICH 2:

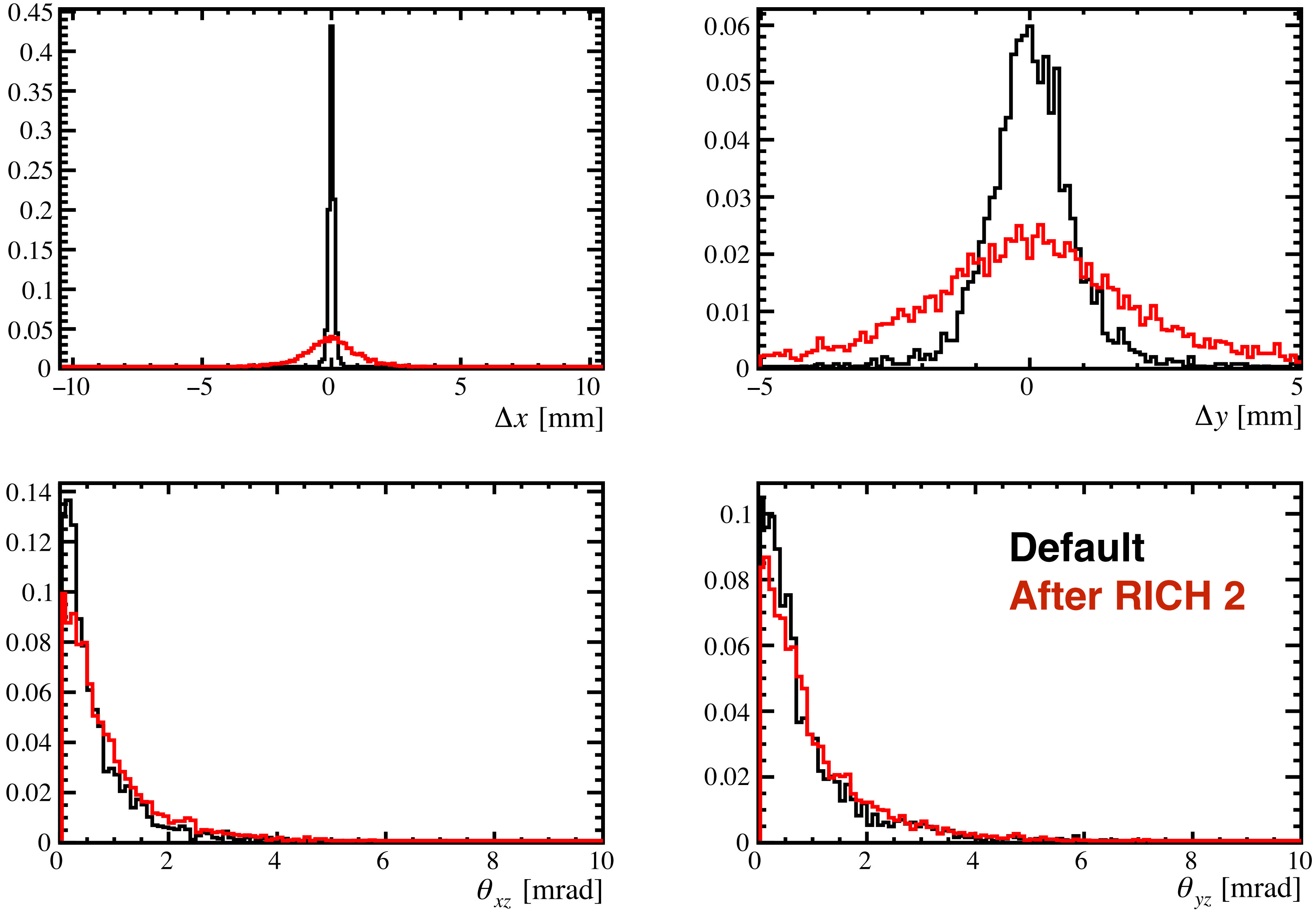


Regular TORCH module arrangement

- At least two additional modules per half needed to cover acceptance. Increase module height by 25% to accommodate detector.

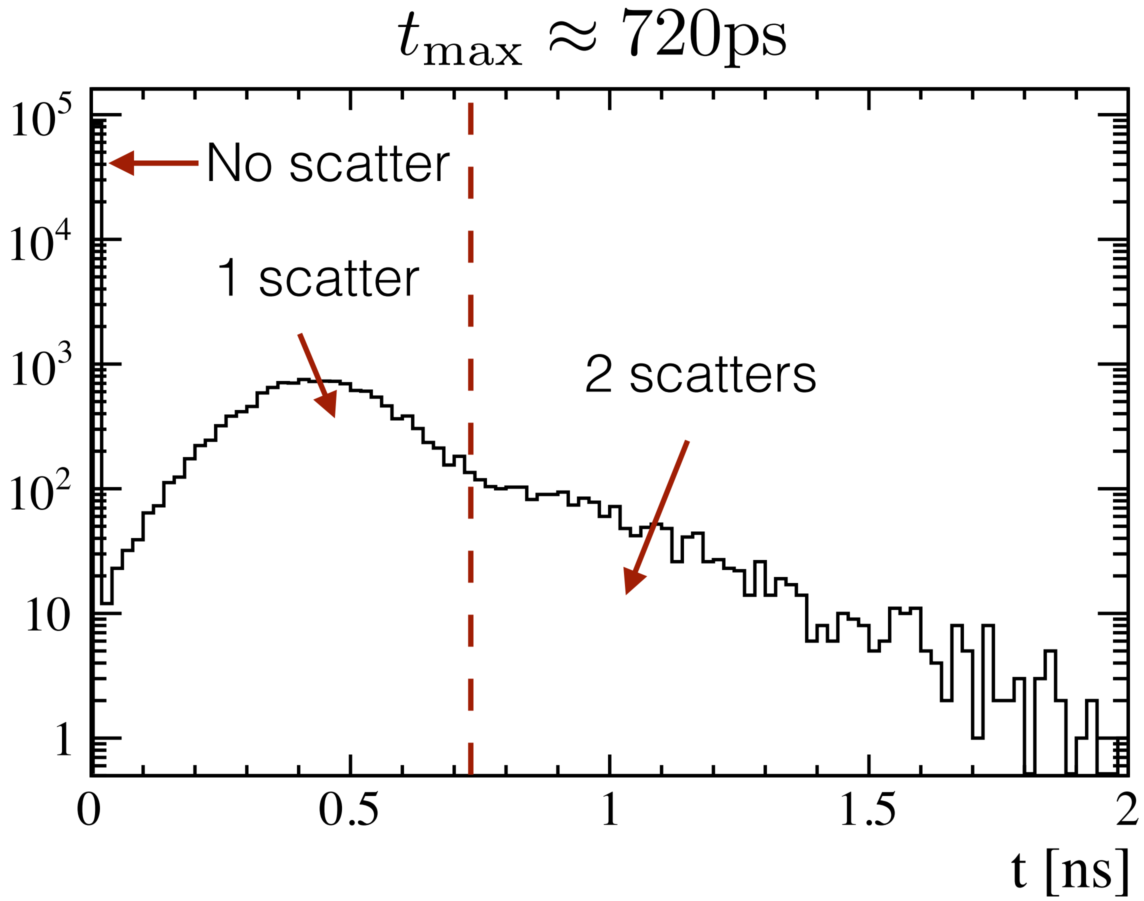
TORCH behind RICH 2

- Comparison of true and reconstructed track entry position/angle.



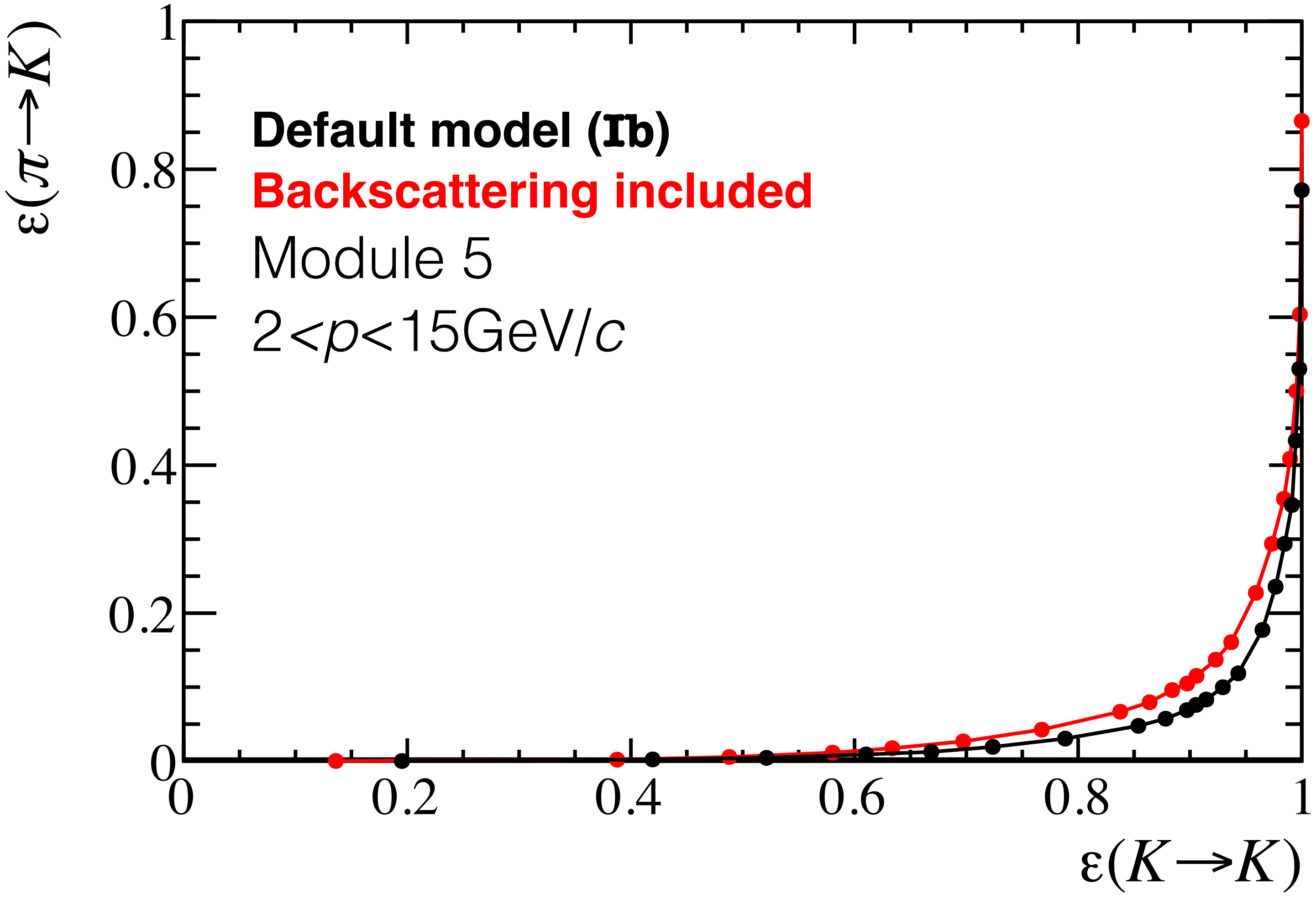
Backscattering

- Implemented an ad-hoc model of photoelectron backscattering:
    1. Assume an MCP gap of 1.5mm and voltage of 200V between the photocathode and MCP foil to determine t_{max}.
    2. Smeared resulting time distribution with Gaussian.
    3. Assume a backscatter probability of 15% from the foil.
- Can also consider producing a more complete simulation of this effect in `GEANT4`.



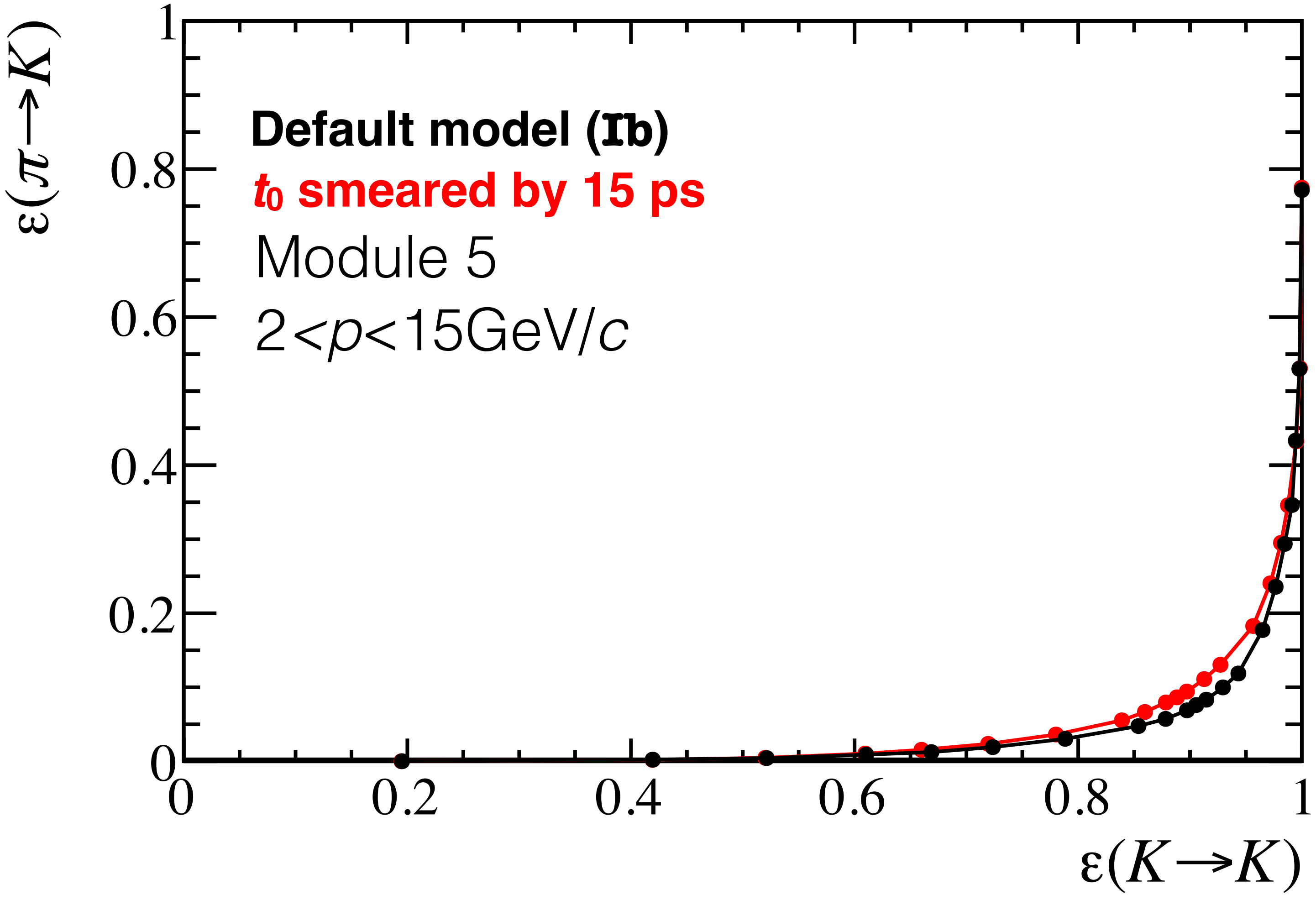
PID performance: backscattering

- Backscattering model is applied to simulated photons but ignored in the likelihood calculation.
- Results in a small degradation of the PID performance.



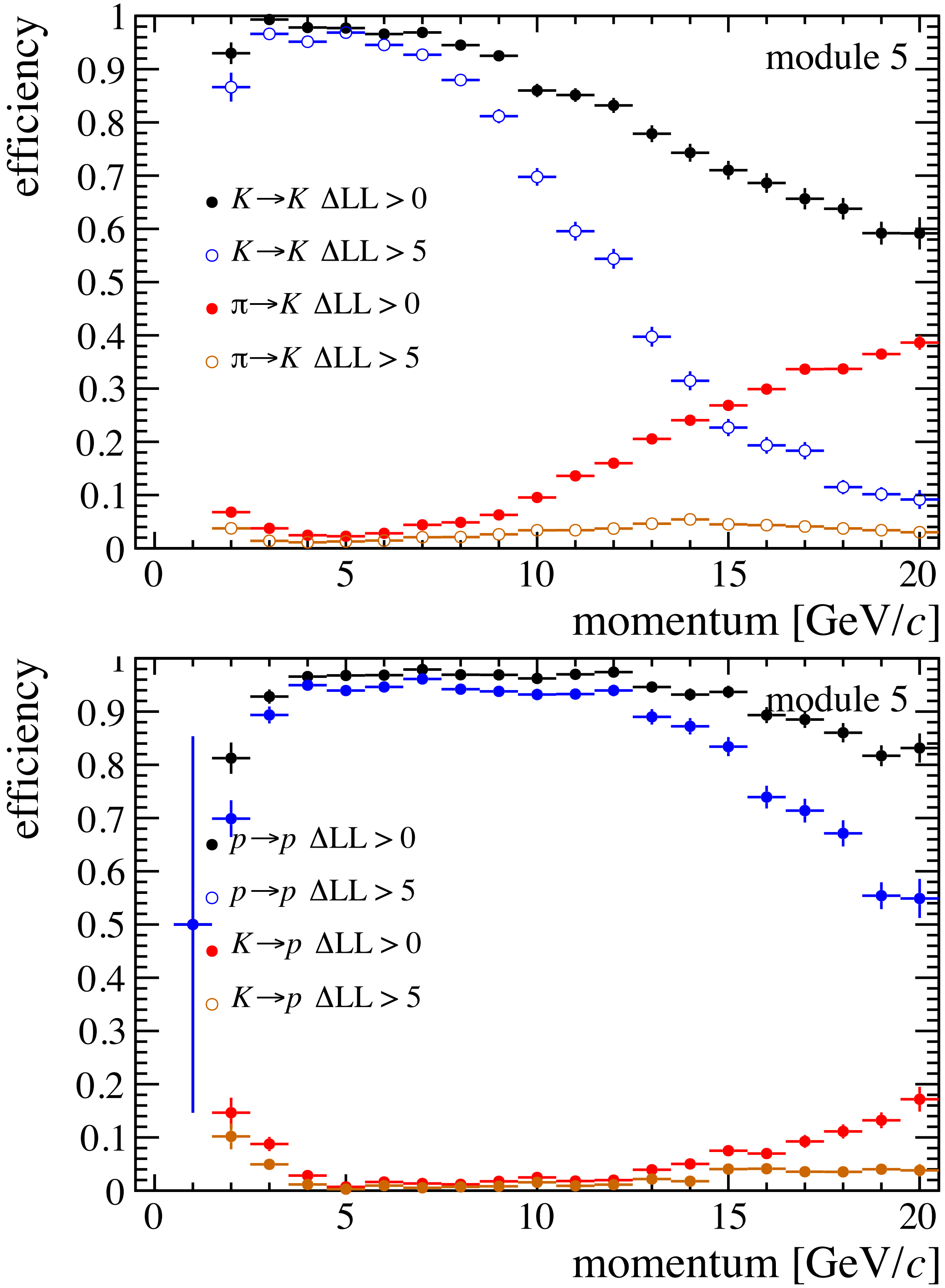
PID performance: t_0 smearing

- Re-evaluate performance smearing track t_0 by 15ps.



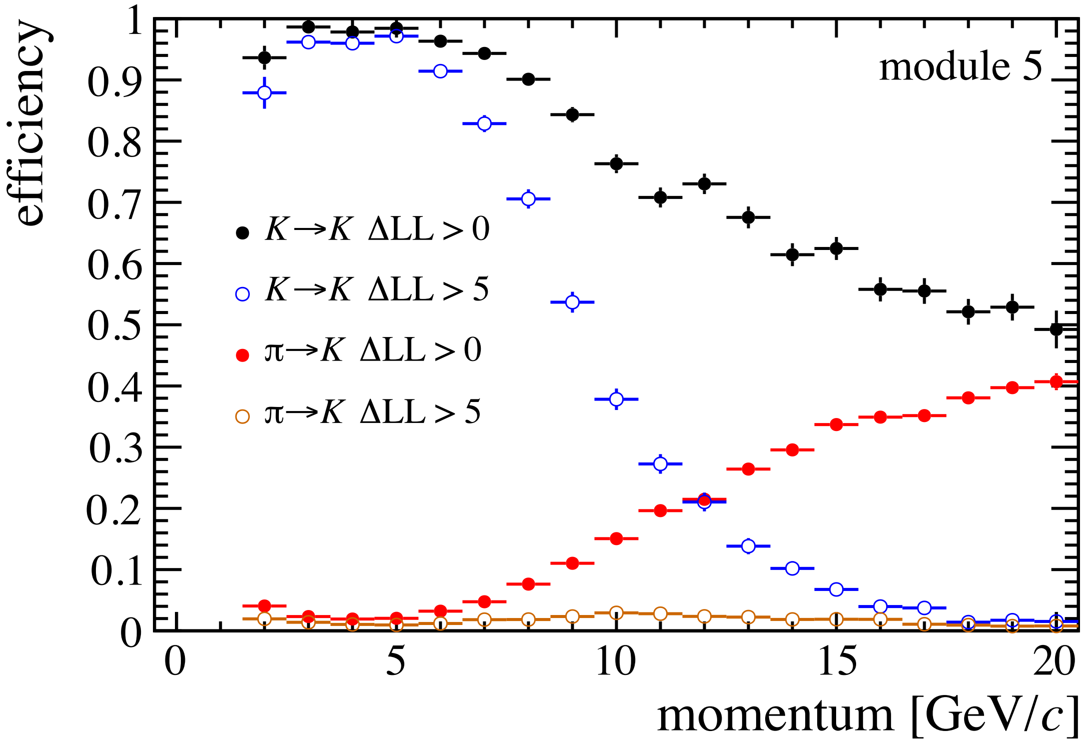
Dependence on photon yield

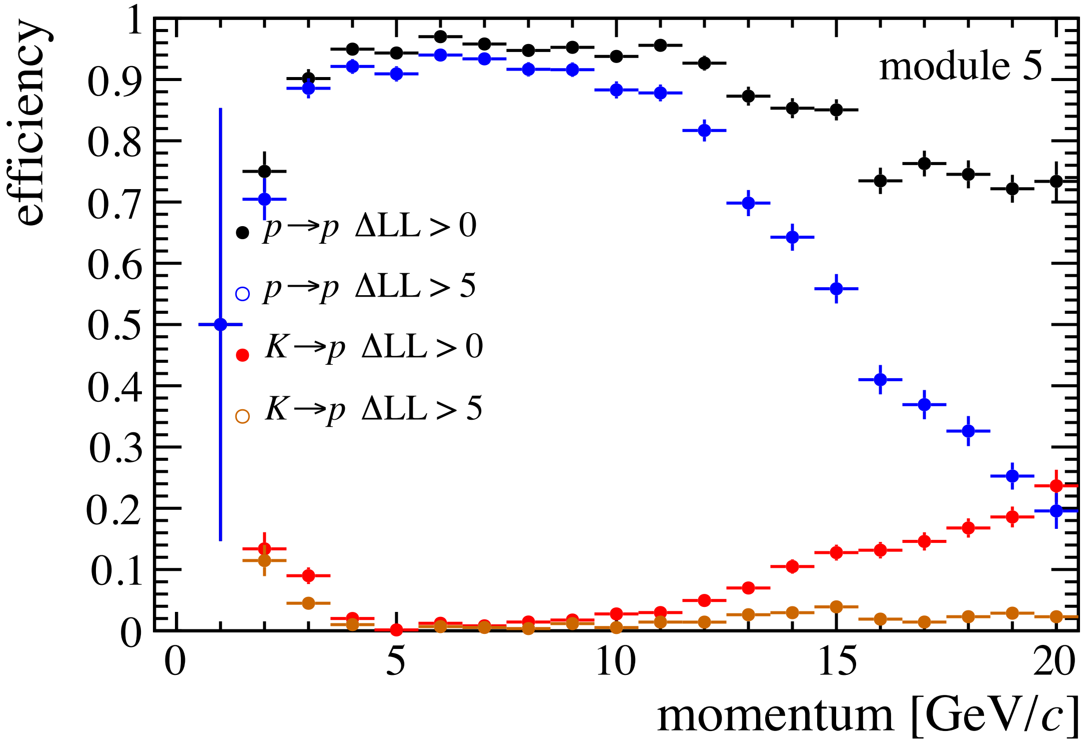
- Scaling the photon yield by 2/3 reduces slightly the separation.
- Still have a good *π*/*K*/*p* separation at low momentum.



Dependence on resolution

- Performance is also robust against changing from 55ps to 70ps smearing (of the hits and the pattern).





Front-end emulation

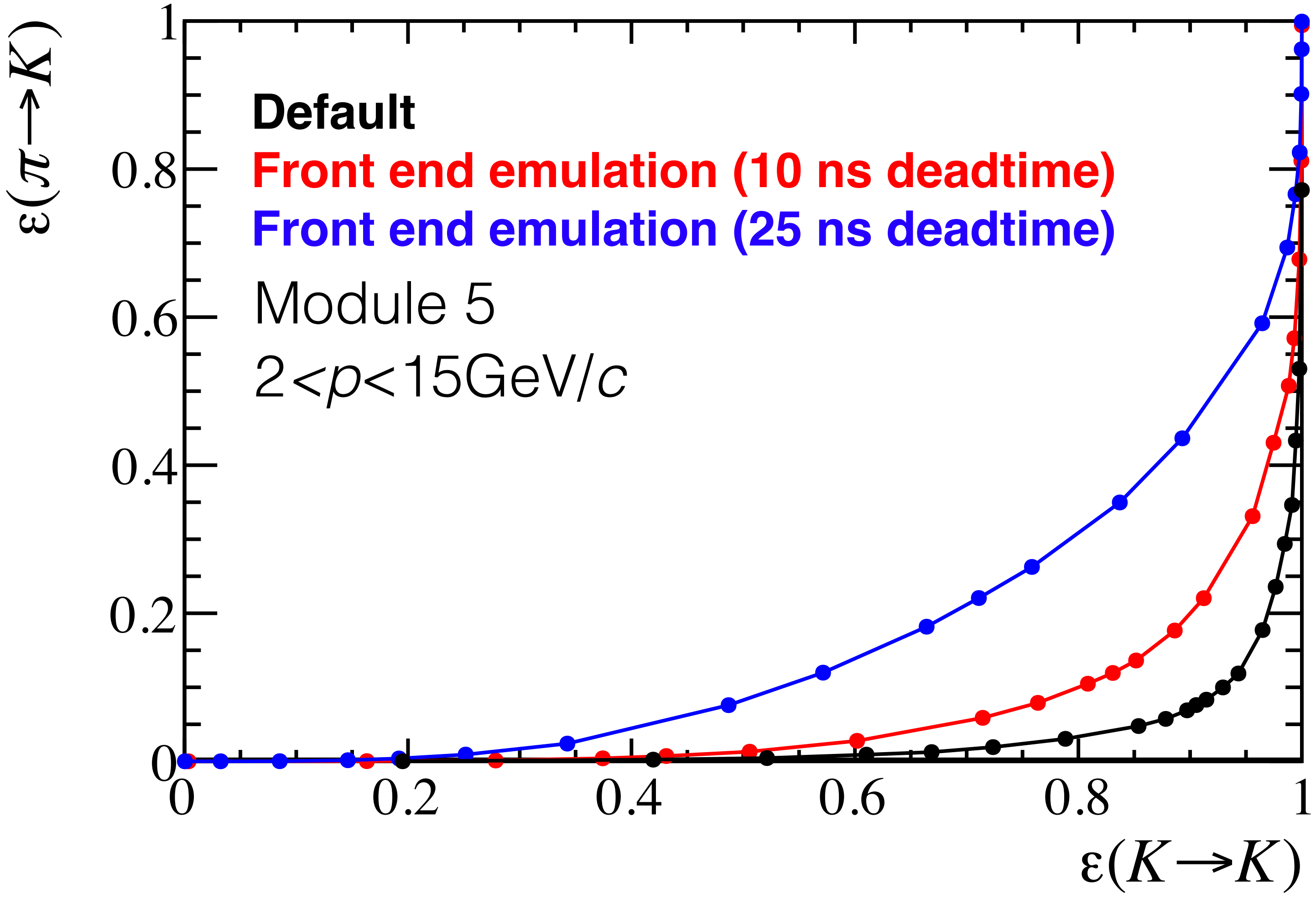
- For pixel hit creation:
  1. Evaluate charge sharing (creates 0, 1 or 2 pixel hits).
  2. Smear each hit (independently) by 55ps.

Should we also consider a correlated component?

- For deadtime:
  1. Consider hit pixels only if they are within desired 25ns window.
  2. Reject hits if the pixel was hit by another photon in range [$t - t_{\text{deadtime}}$, t].
- For clustering follow similar approach to test beam:
  1. Loop through hits and create 1 pixel clusters.
  2. Merged clusters if hits are within 200ps.
  3. Repeat step (2.) until no more clusters can be merged.
  4. Take an (unweighted) average of the cluster position/time.

Front-end emulation

- Significant degradation in performance with a 25ns deadtime in high occupancy modules.
- There are several reasons for degraded performance:



1. Clustering merges photons together, biasing photon hit positions.
2. Deadtime reduces per-photon signal efficiency (and can bias photon position).
3. Effect of dead time is much worse at 25ns since hits from previous bunch-crossing can cause dead time in current bunch crossing.