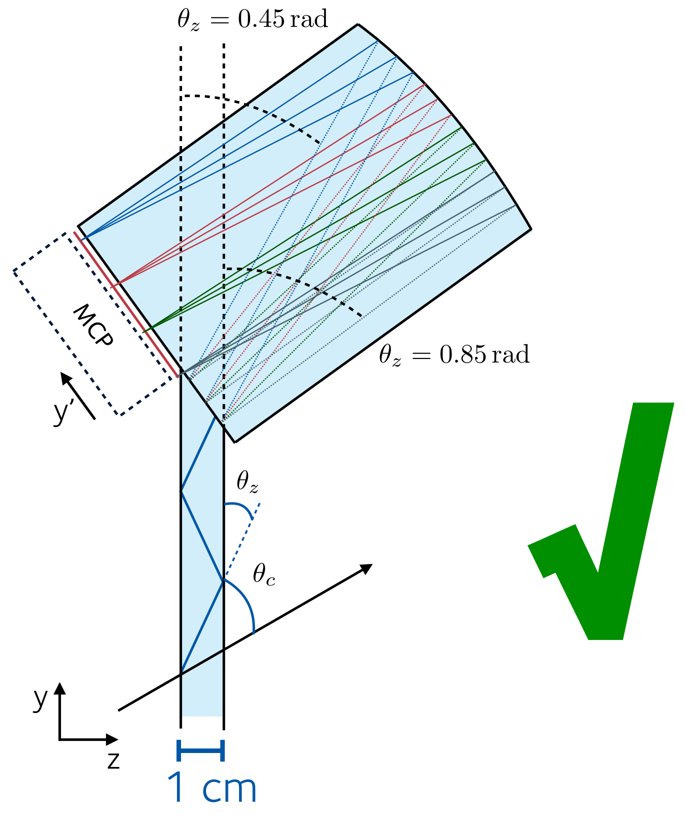
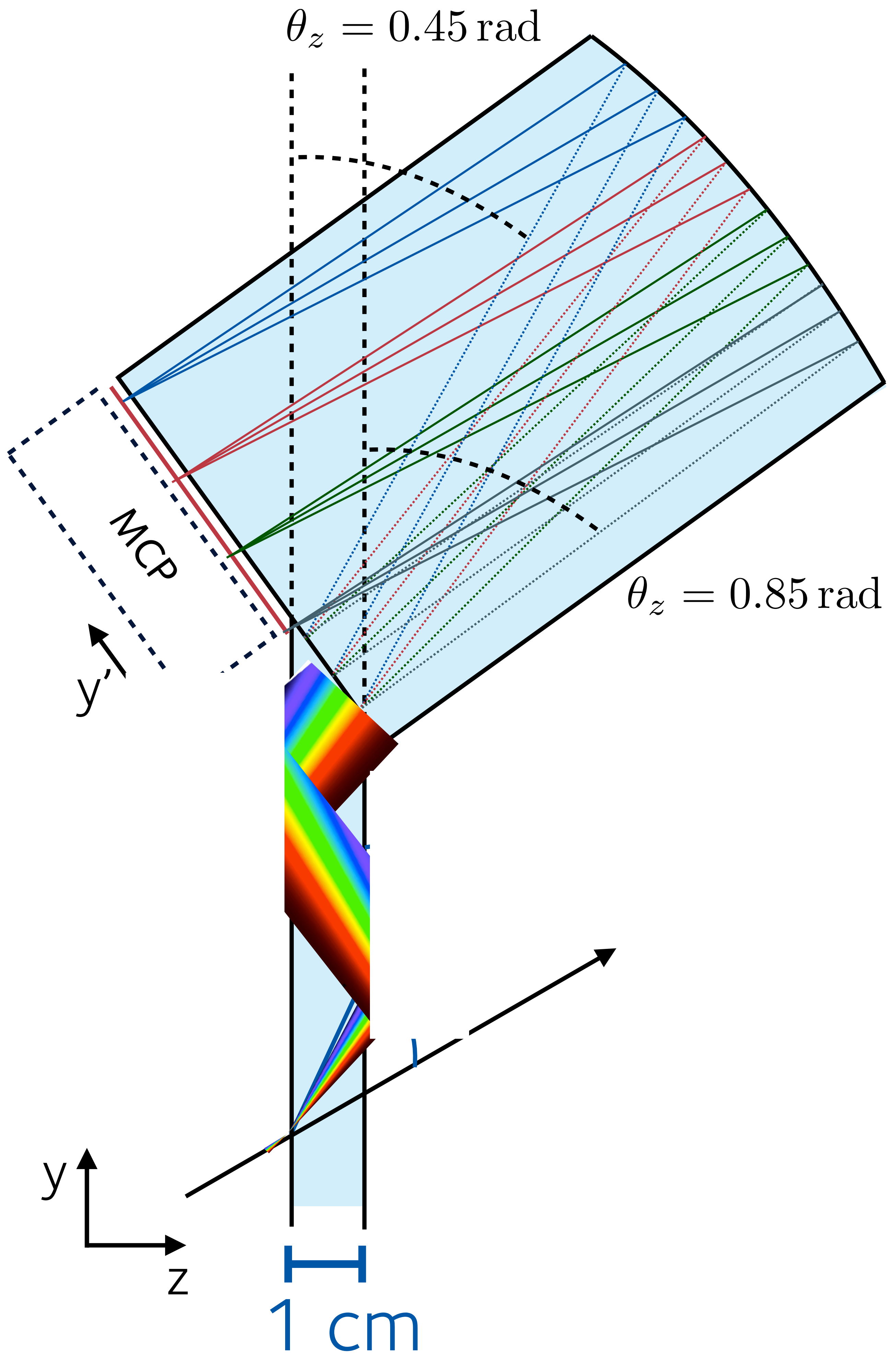
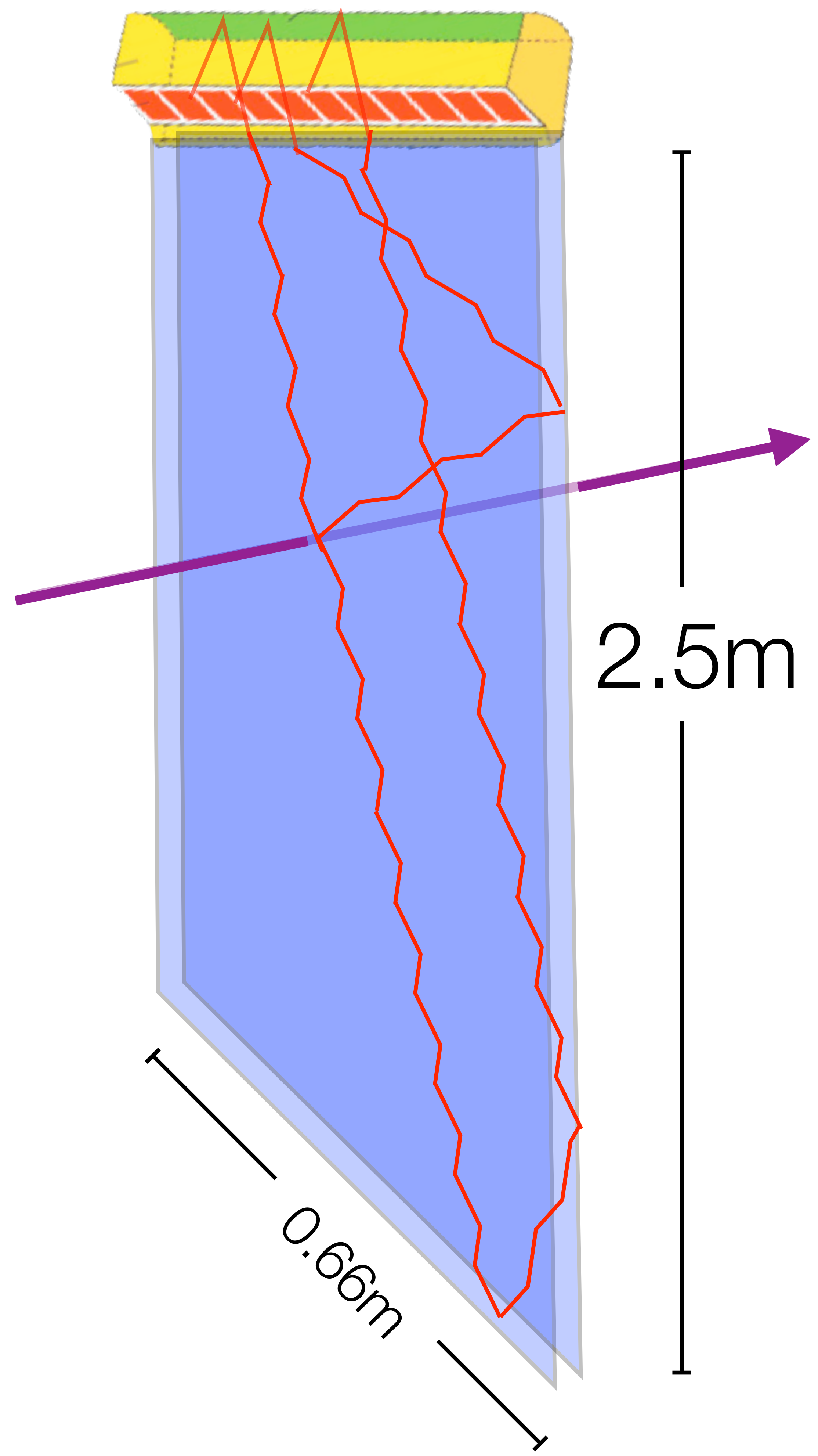
TORCH

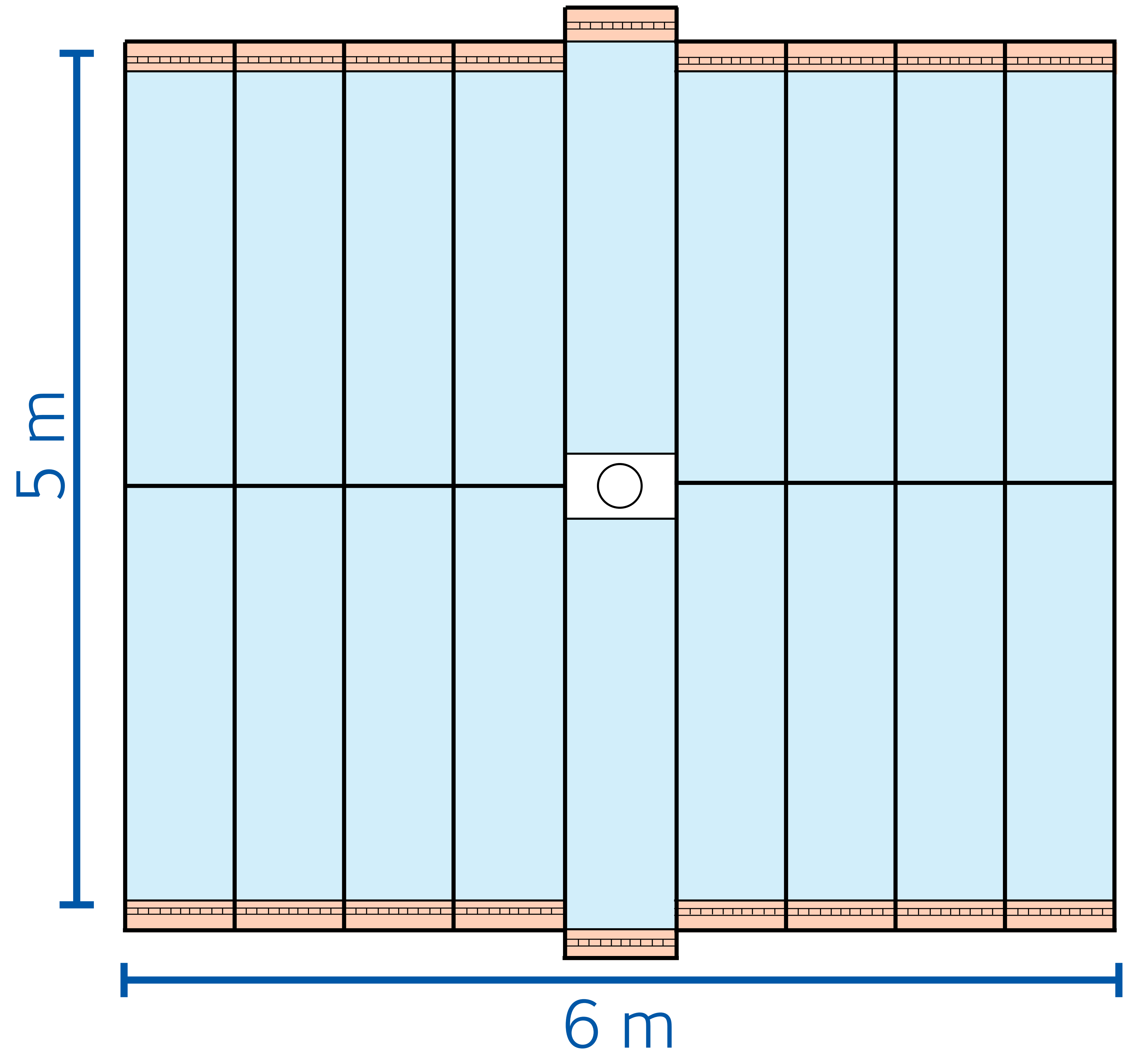
Jonas Rademacker (University of Bristol) on behalf of the TORCH collaboration.



TORCH (**T**ime **O**f internally **R**eflected **CH**erenkov light) principle



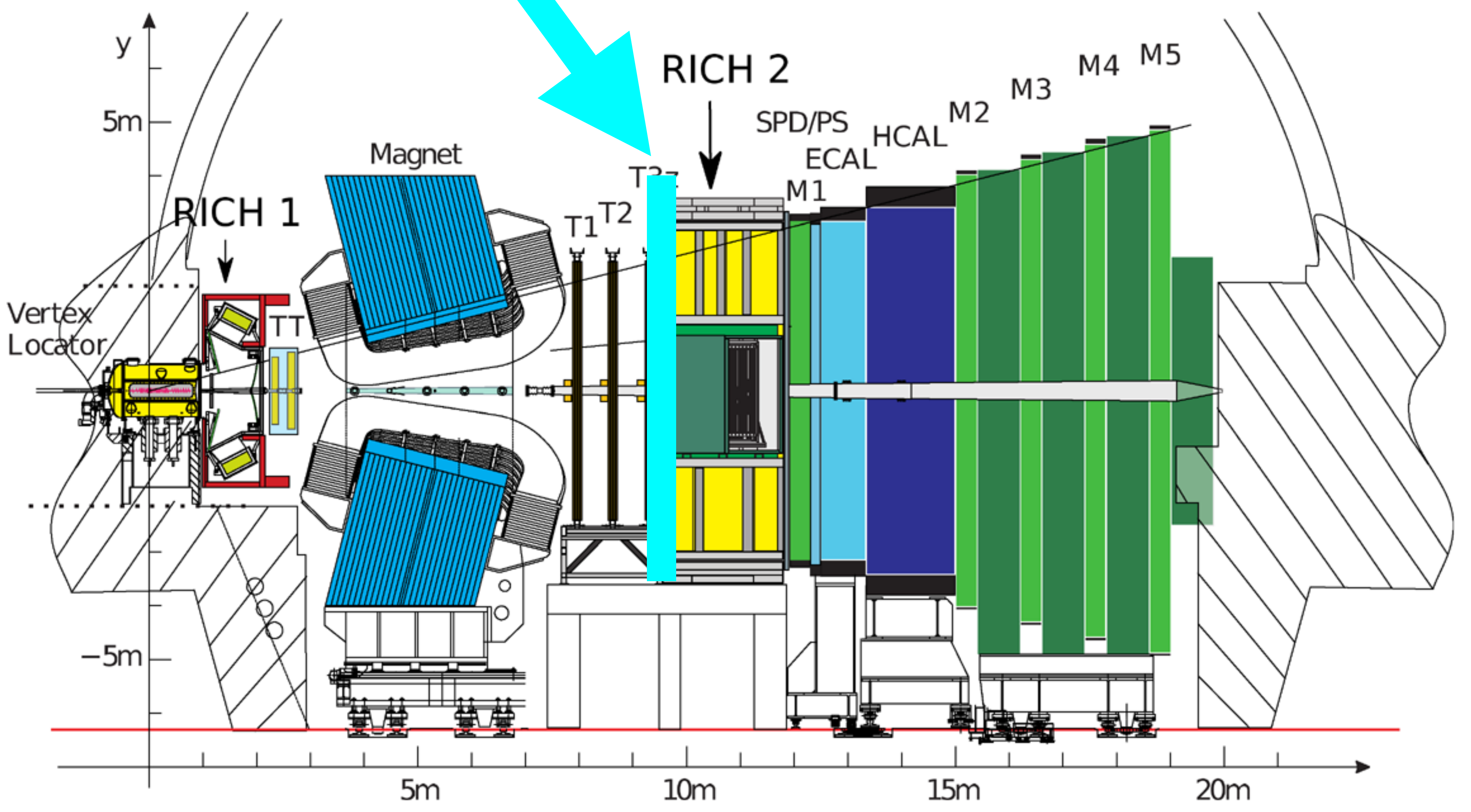




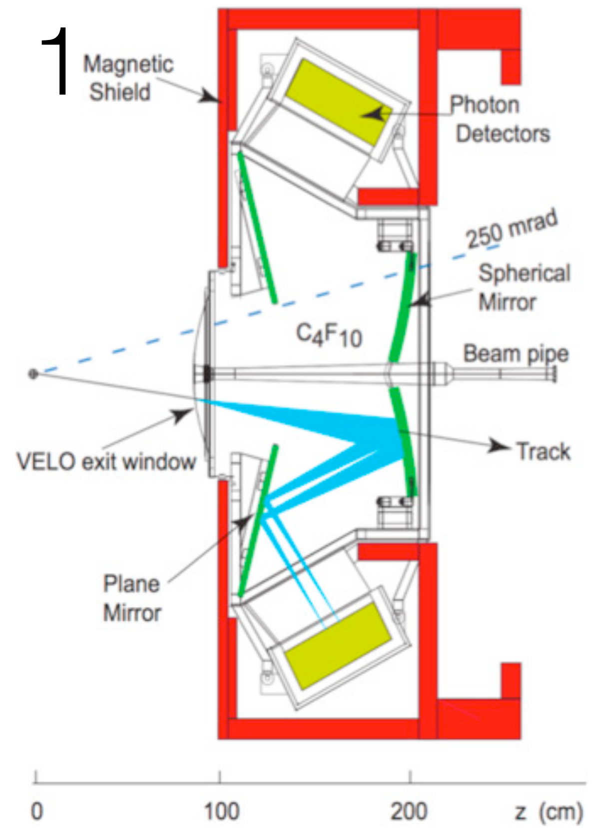
See Jianchun Wang's talk on LHCb UG II last Thursday, and Frédéric Blanc's plenary talk on LHCb on Monday

LHCb particle ID with RICH + TORCH (planned for Upgrade II)

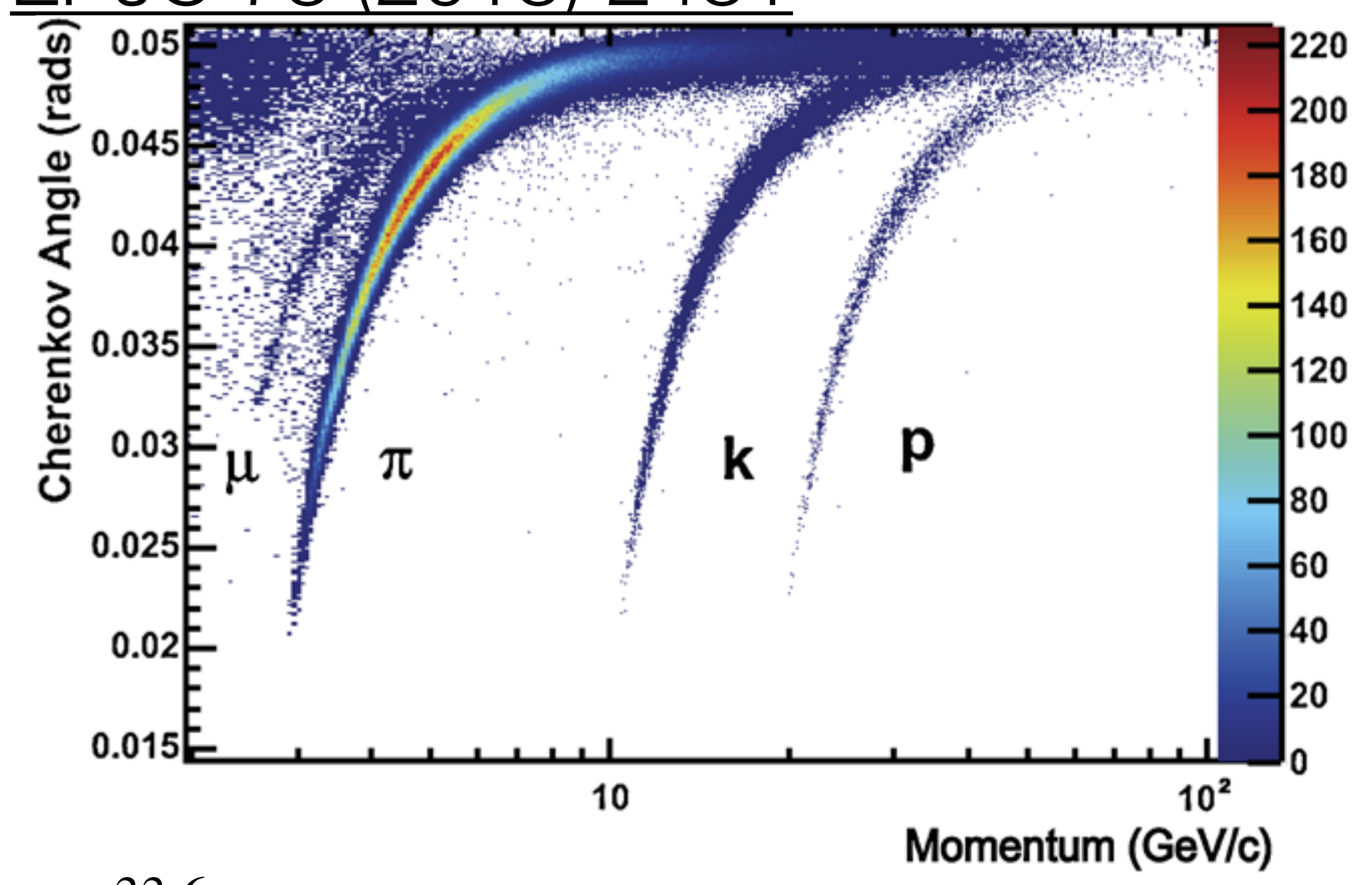
LHCB-TDR-023



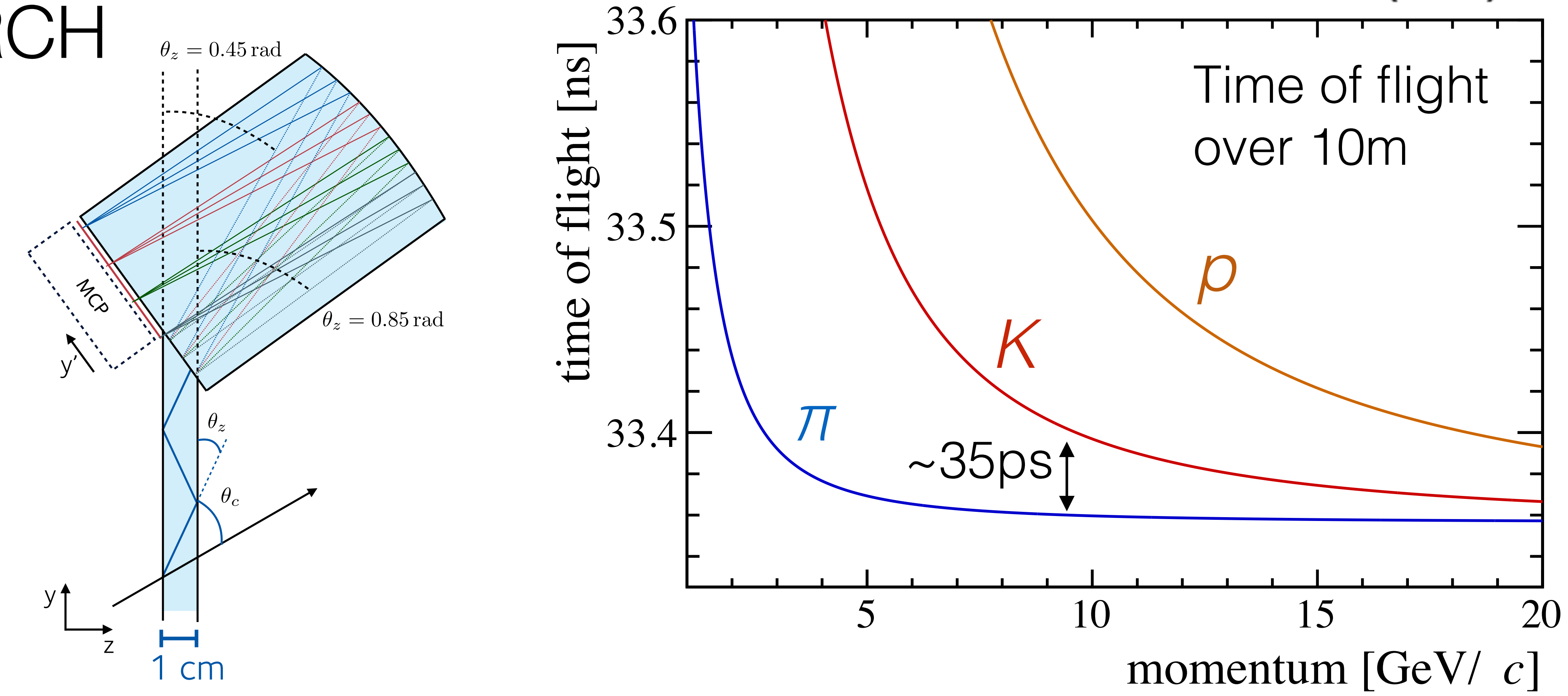
RICH 1



EPJC 73 (2013) 2431



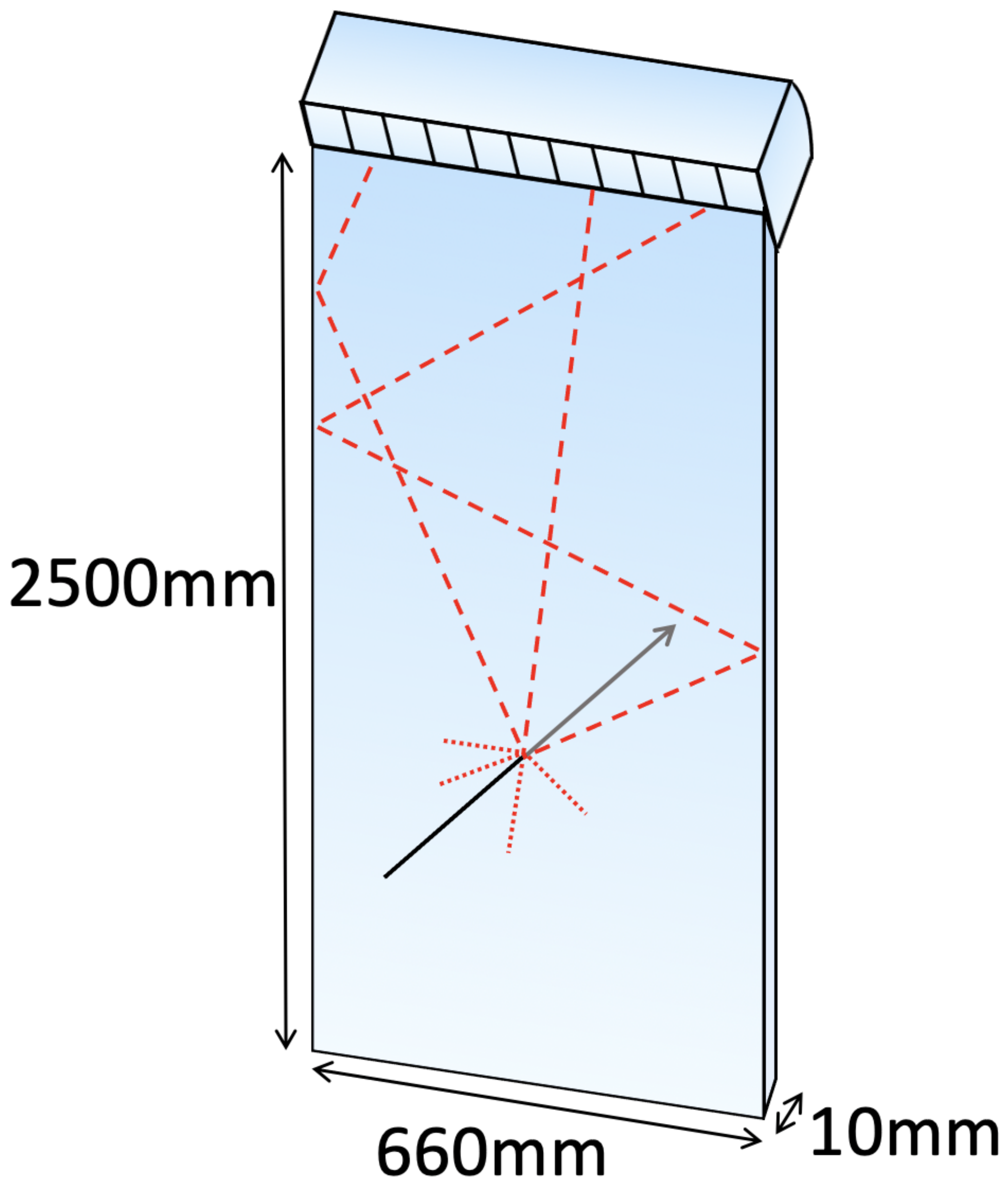
TORCH

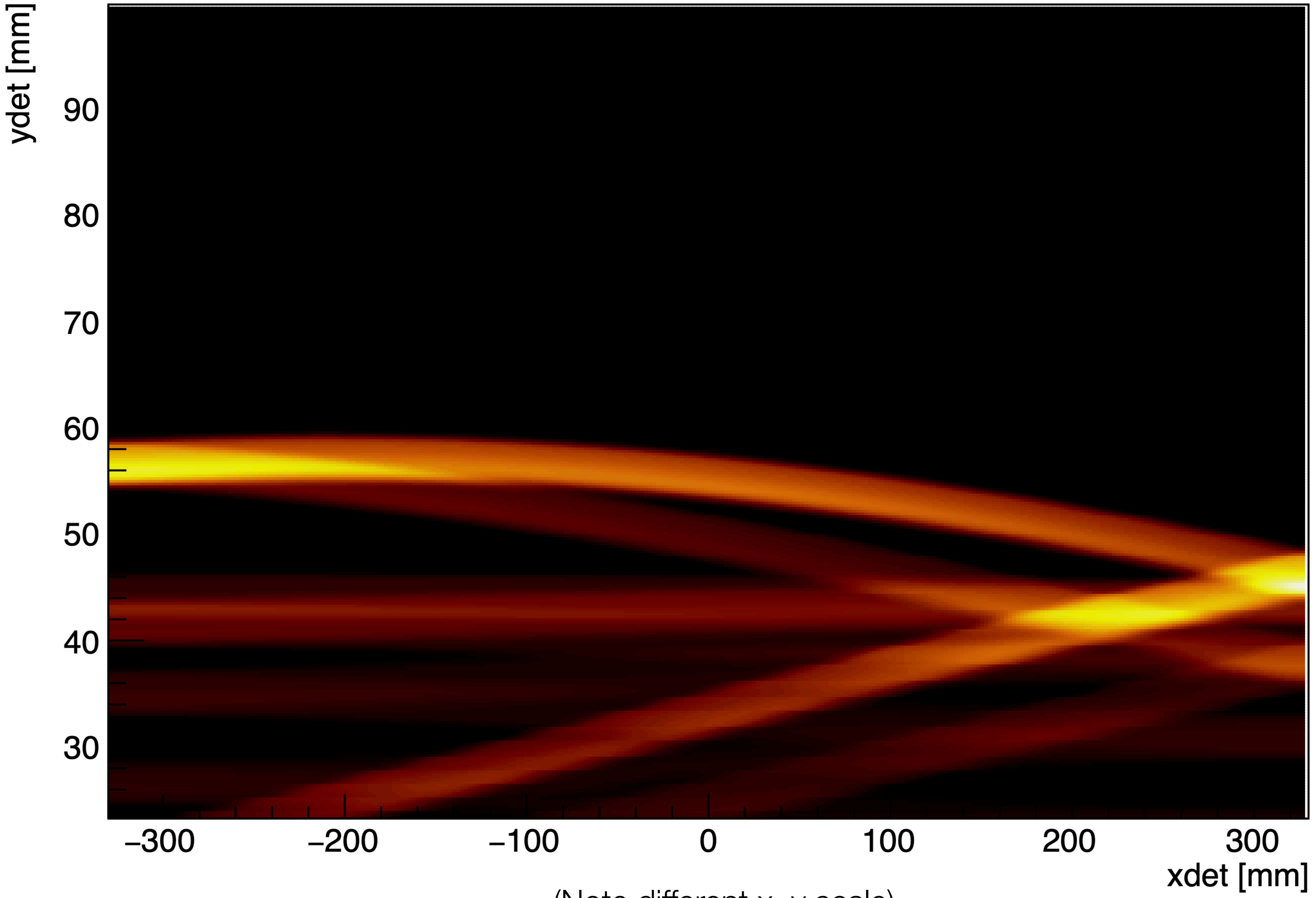


15ps time resolution needed to achieve K-π separation up to 10GeV and K-p separation up to 20 GeV.
Achieved through 70ps per photon, with ~30 photons per track.

TORCH brings positive Kaon ID below 10GeV, positive proton ID below 20GeV

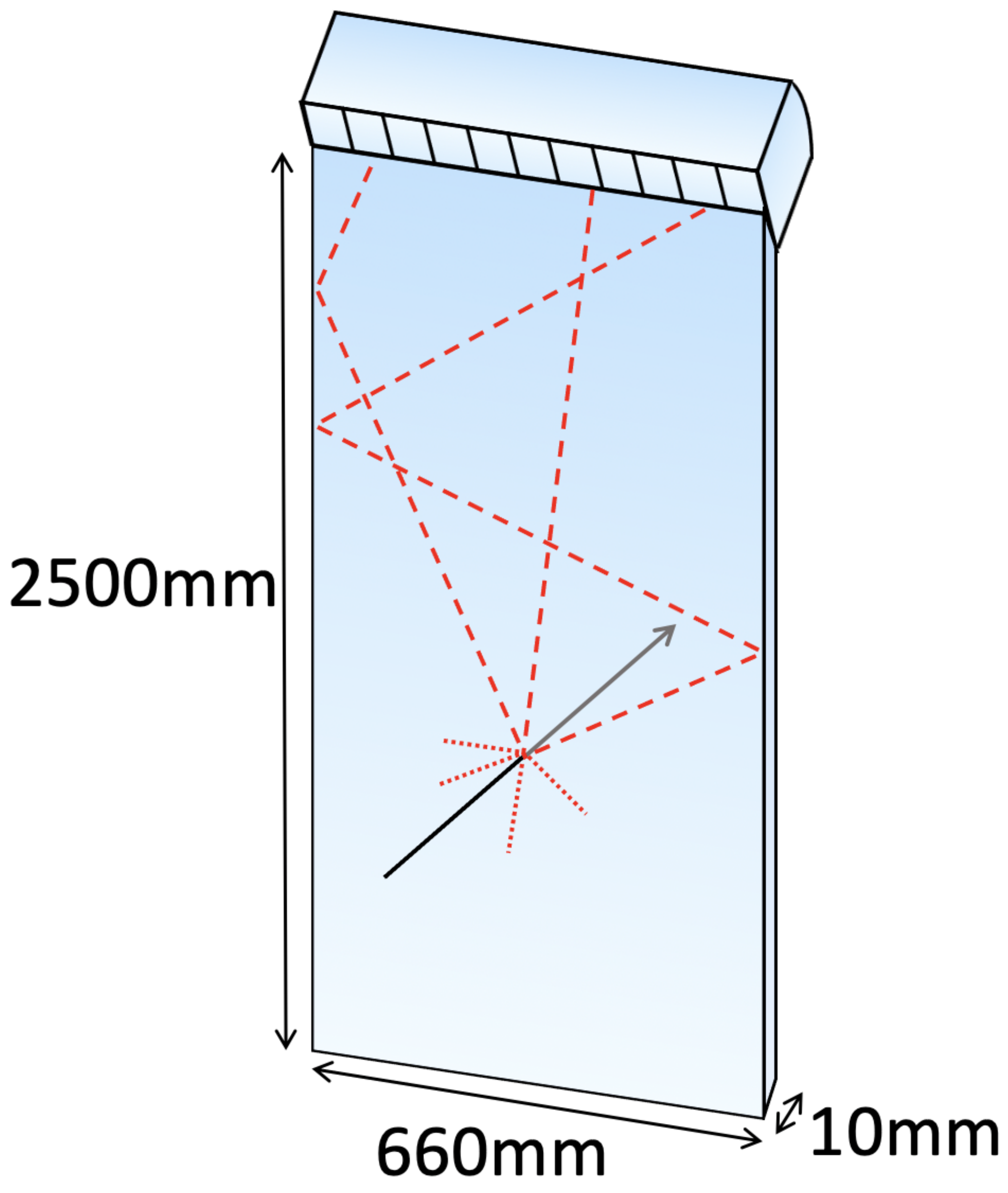
The image on the detector plane from a single track (w/o pixelisation)

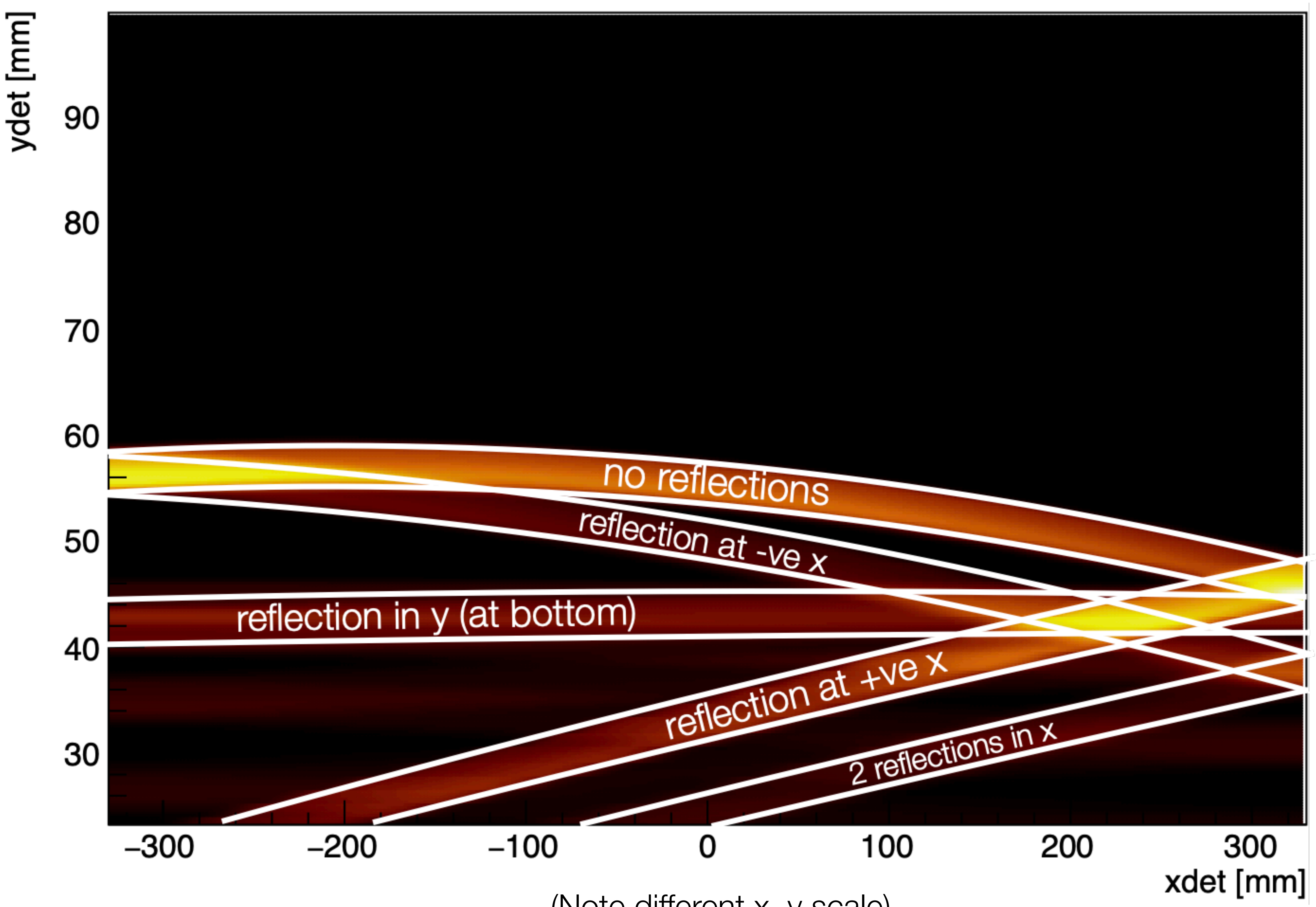




(Note different x, y scale)

The image on the detector plane from a single track (w/o pixelisation)





(Note different x, y scale)

Including the time component

The 2-D image might look busy, but full PDF is in 3 dimensions, where it is actually rather sparse.

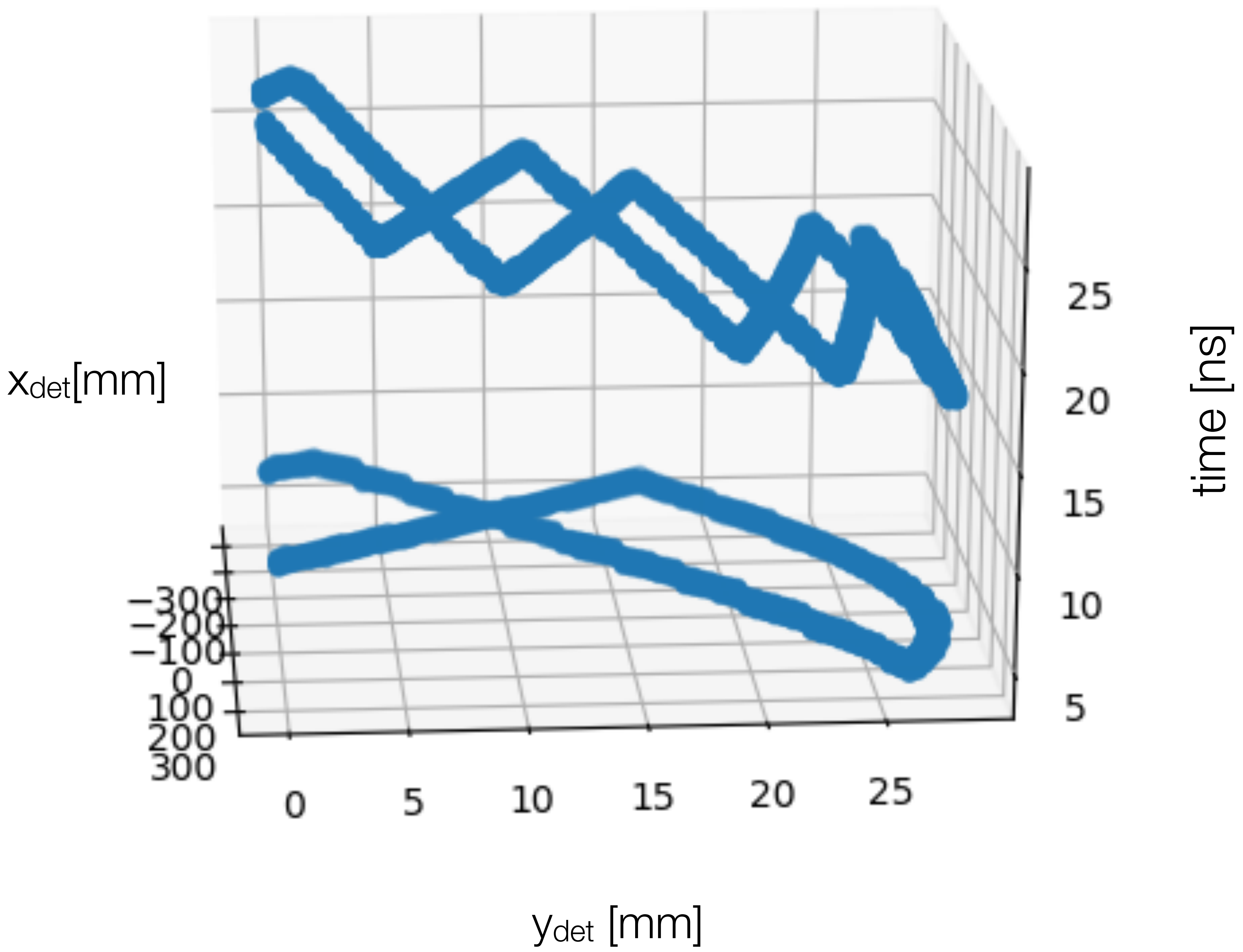
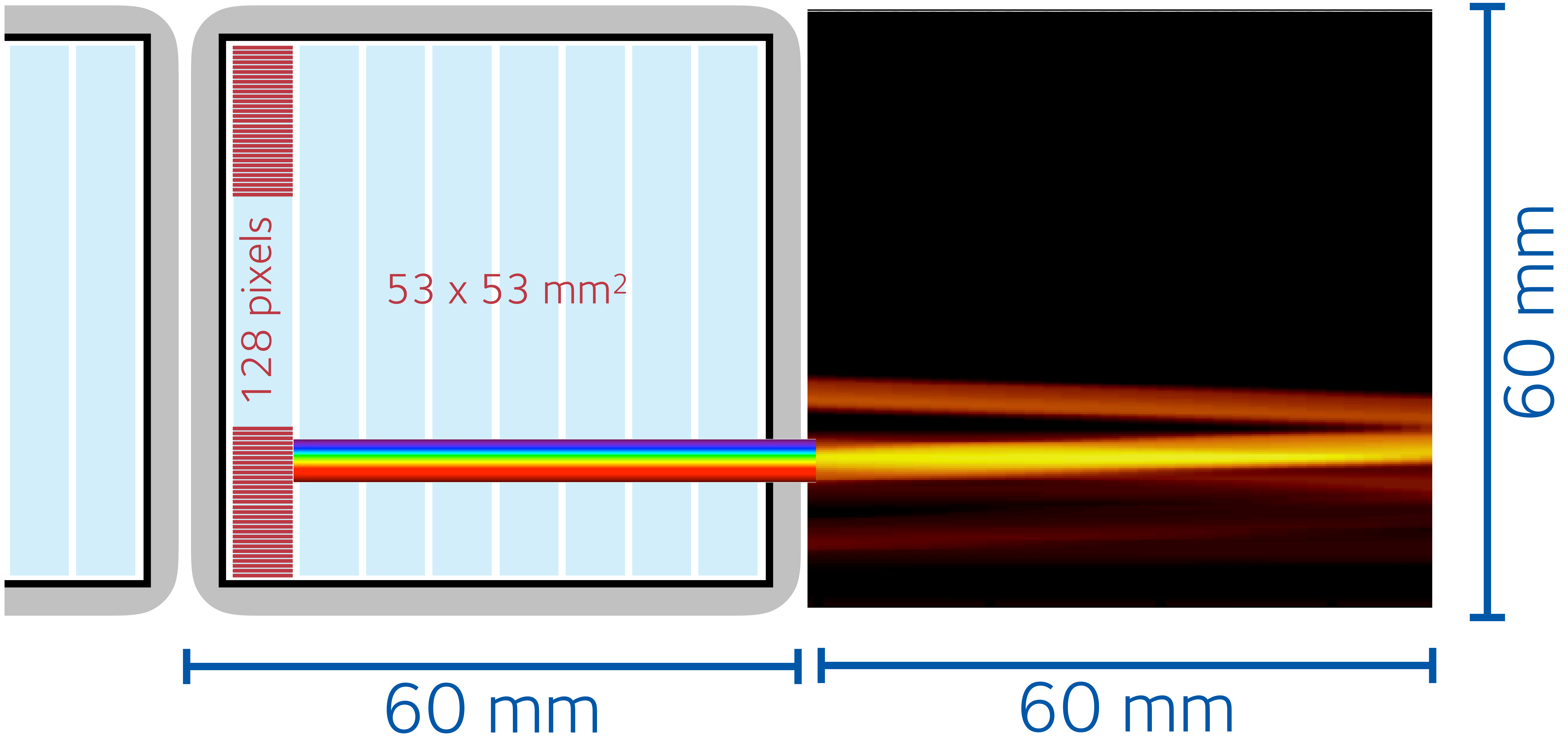


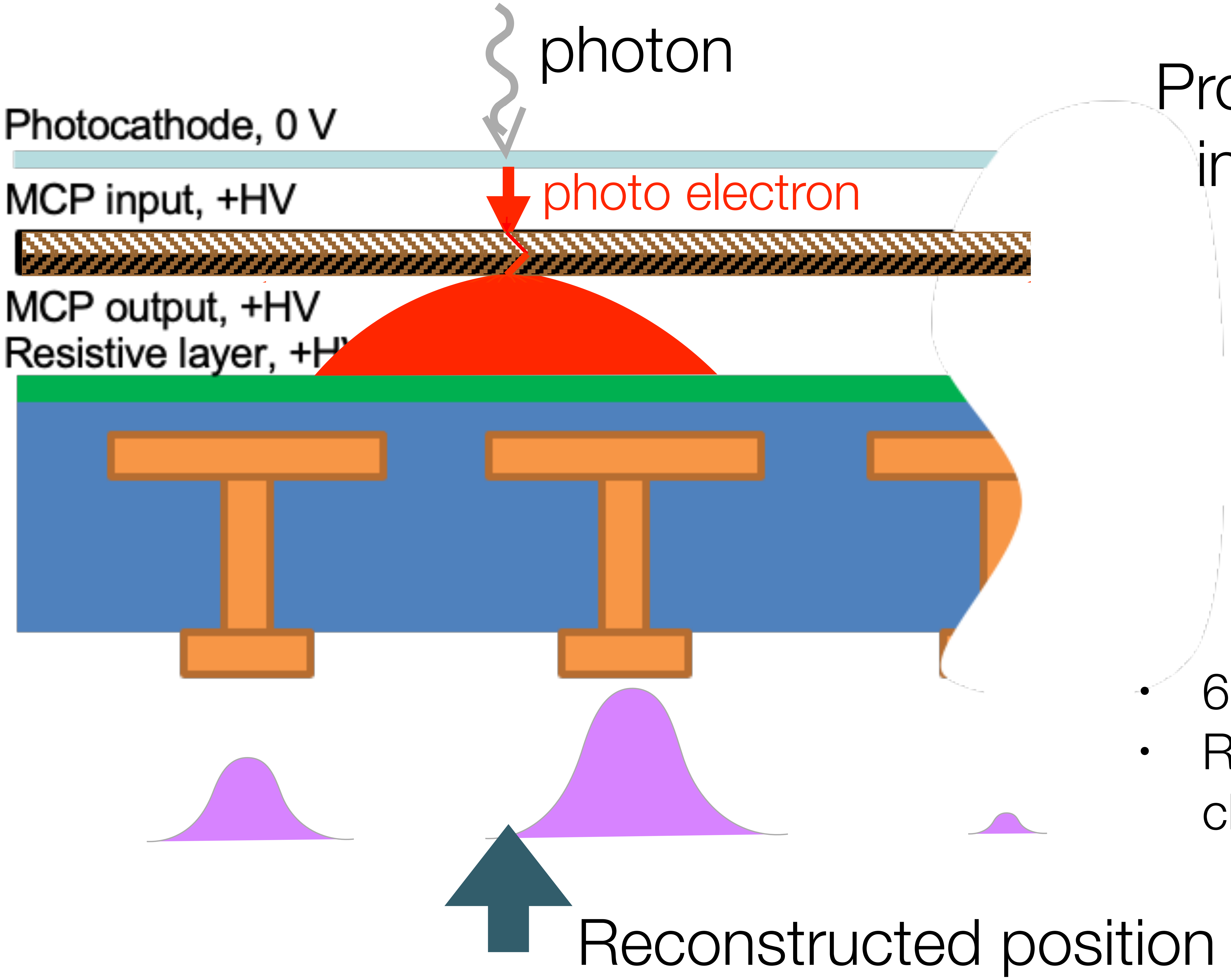
Photo detector geometry

128x8 effective* pixel layout driven by need to resolve wavelength components

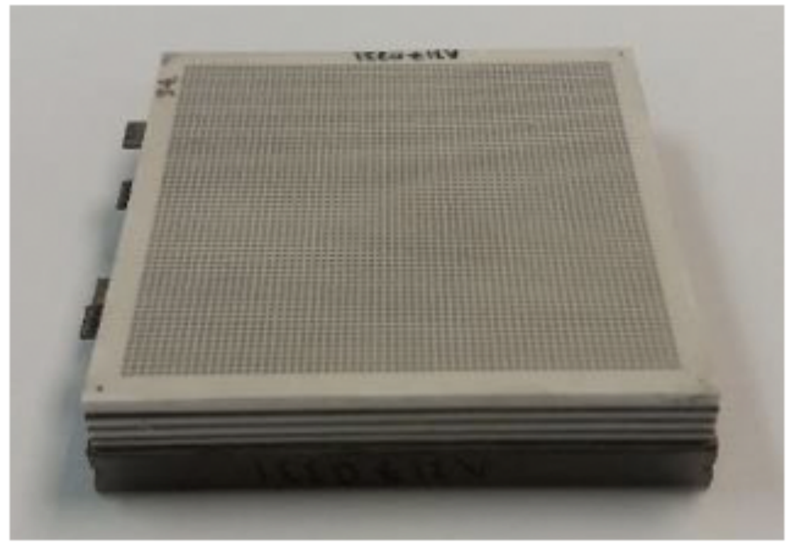


*) achieved with 64x8 physical readout pads, interpolated using charge sharing

The MCP-PMT



Prototype developed by our industrial partner, Photek

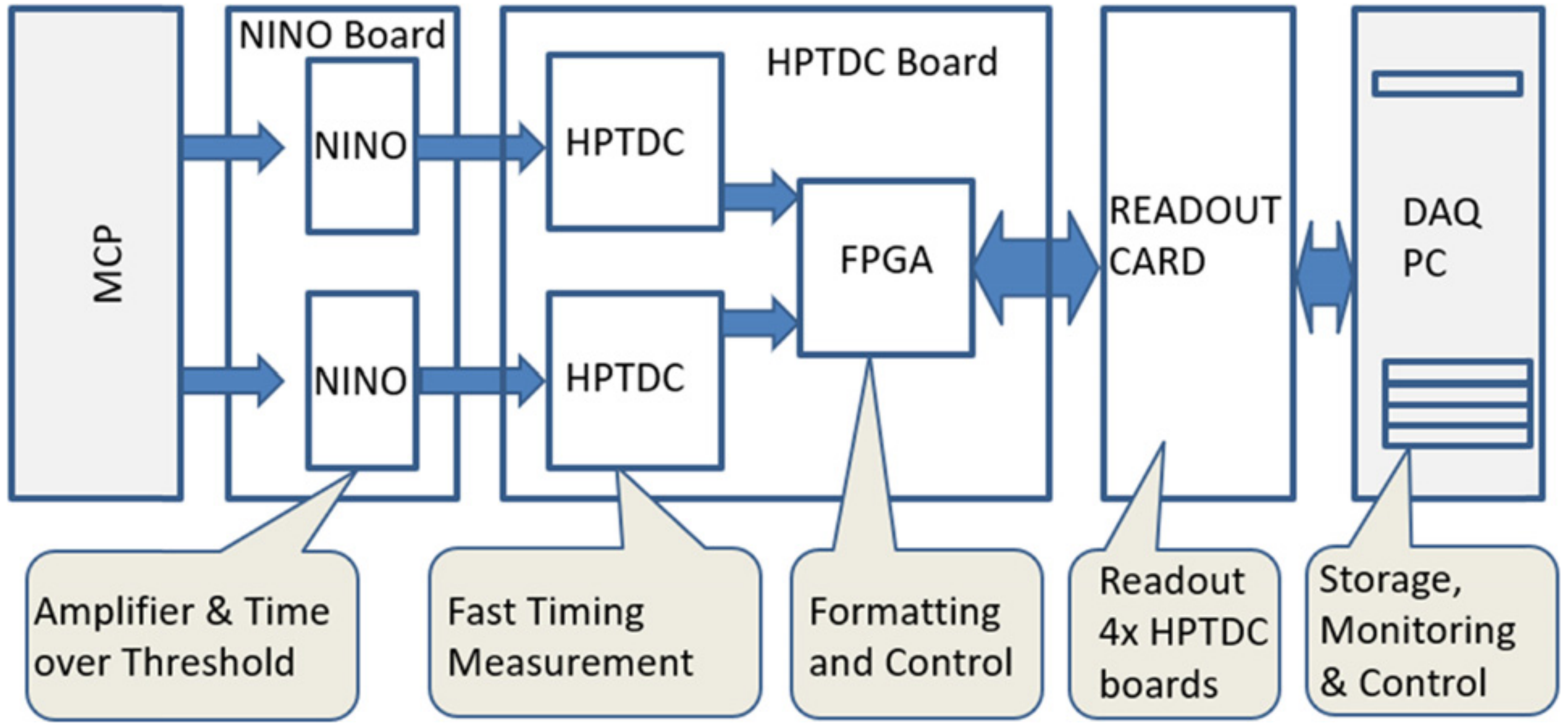


- 64 x 8 readout pads
- Required 128x8 resolution achieved through charge sharing.

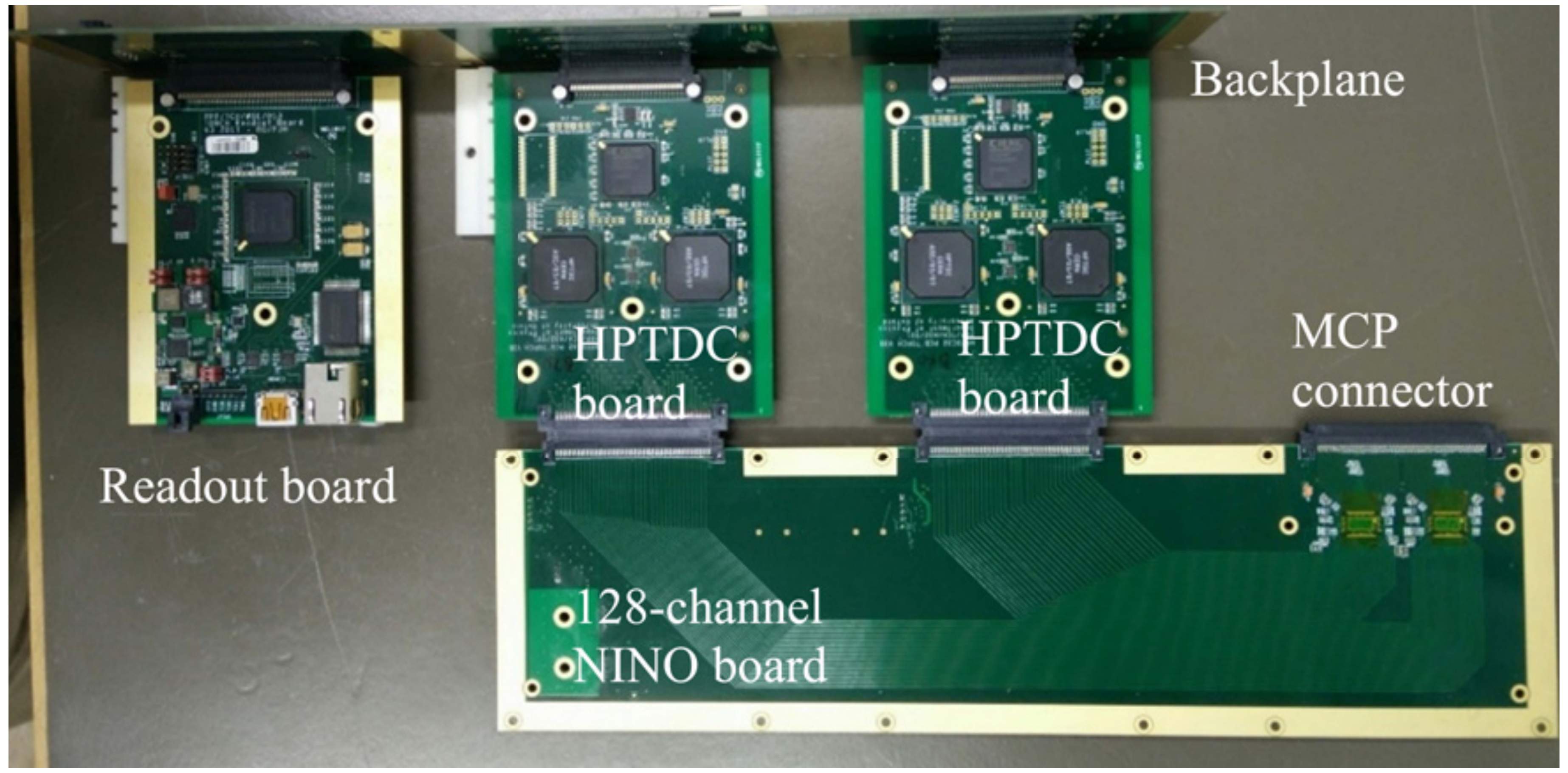
JINST 10 (2015) 05, C05003

Readout electronics

JINST 10 (2015) 02, C02028
JINST 17 (2022) 05, C05015



Current: Custom design inspired by ALICE TOF, based on NINO (NIM A533:183-187(2004)), and HPTDC (IEEE58:202(2011)).

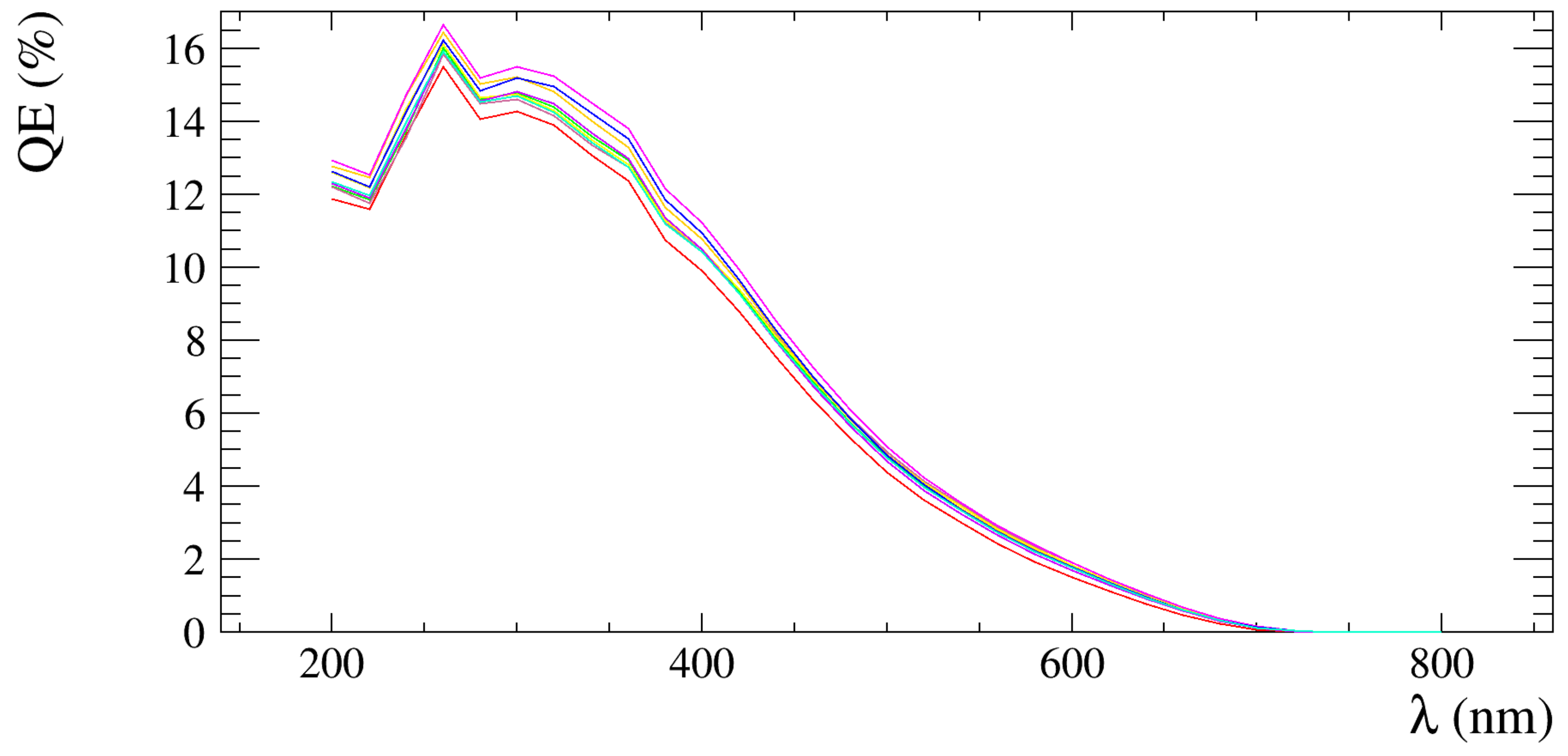


Ongoing: calibration of readout electronics

Future: developing new system based on picoTDC

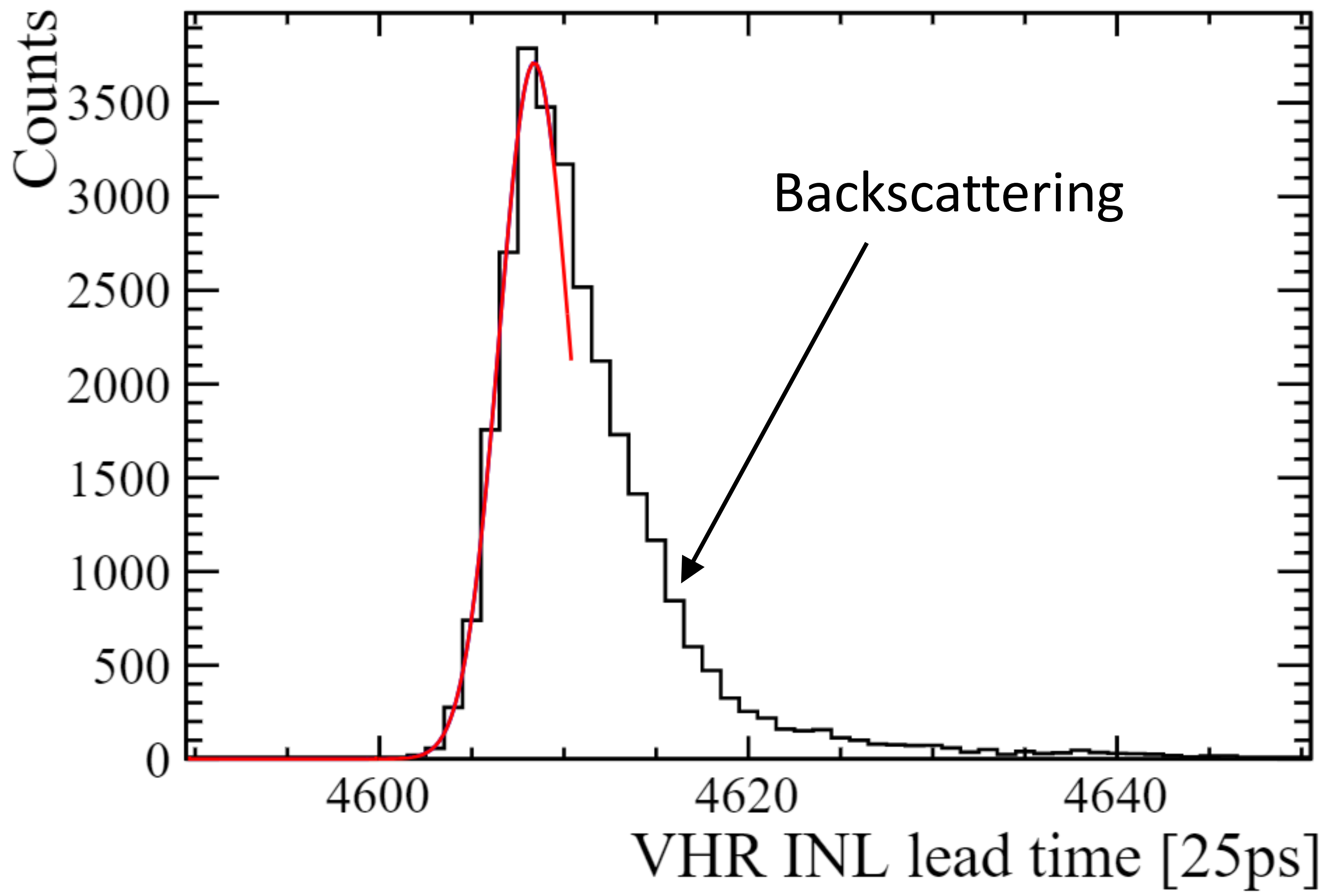
Lab tests of phase III prototype tubes

Quantum Efficiency



Peak QE consistently around15-20% in blue/UV region. Up to 26% has been achieved in earlier prototypes. Expect that performance to be recovered in production tubes.

Time resolution including readout electronics

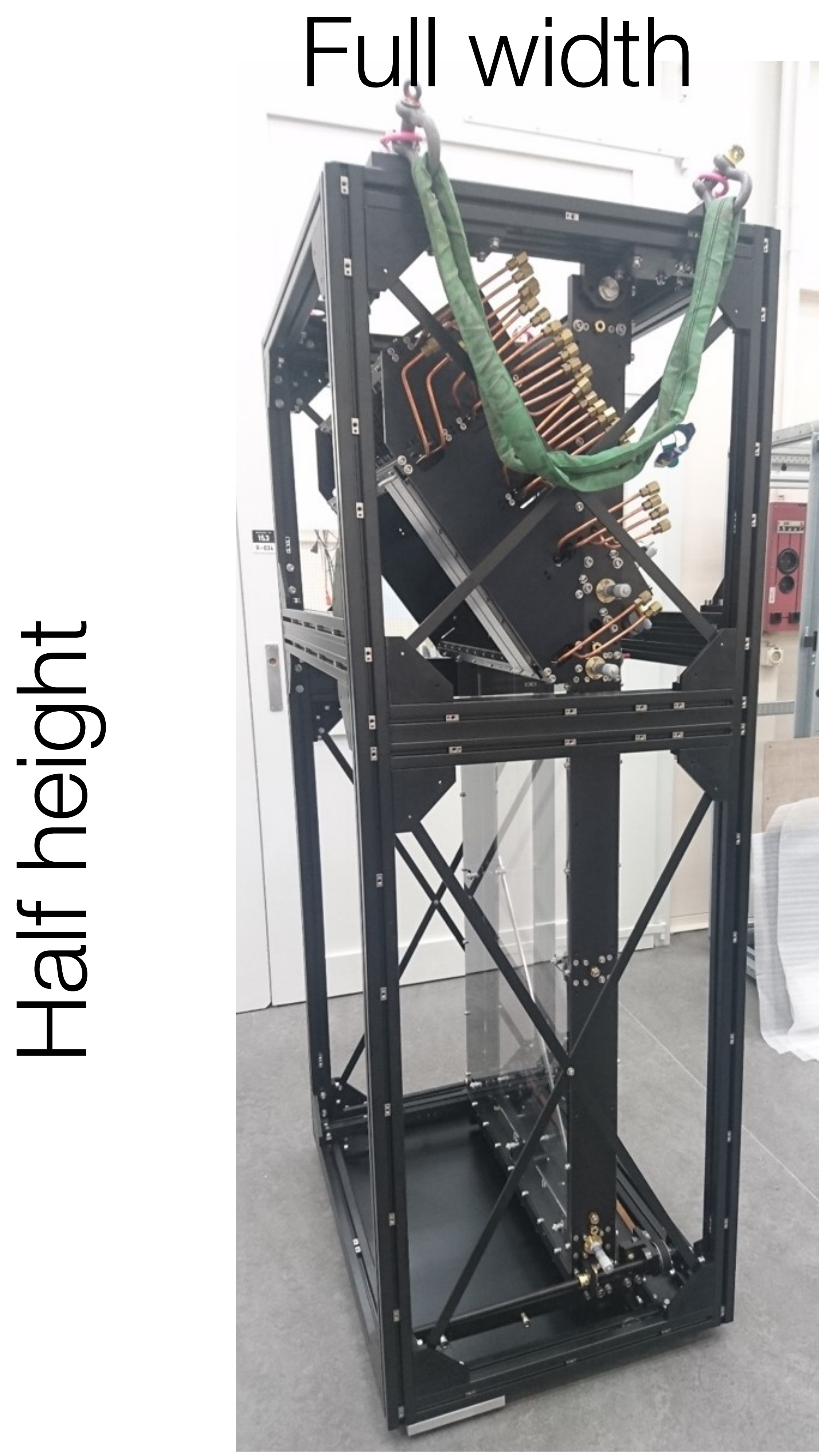


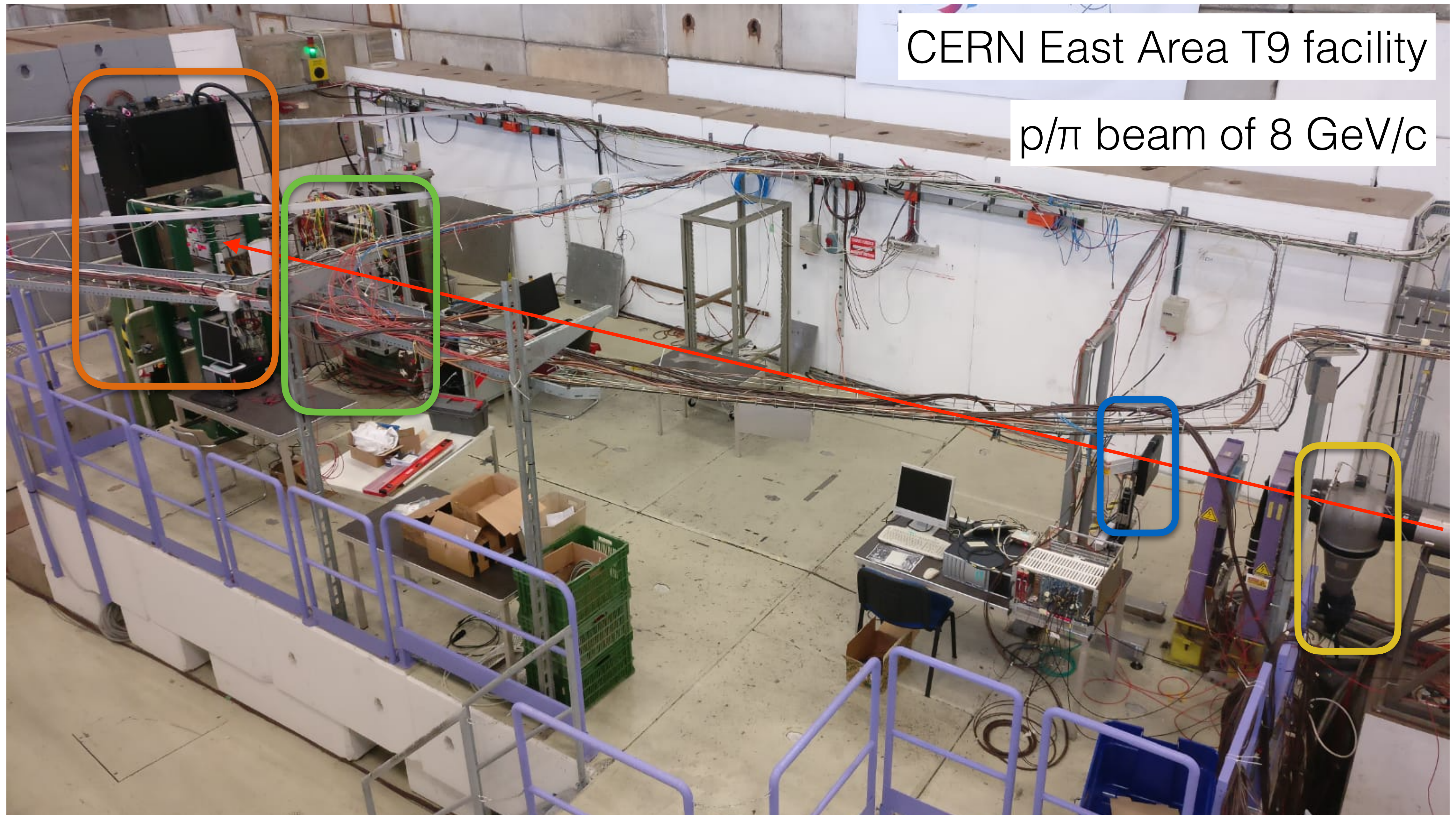
90.0 ± 3 ps (operation of electronics in default mode)
47.5 ± 0.7 ps (operation of HPTDC in special 25ps mode); comparable to expectation of 50 ps

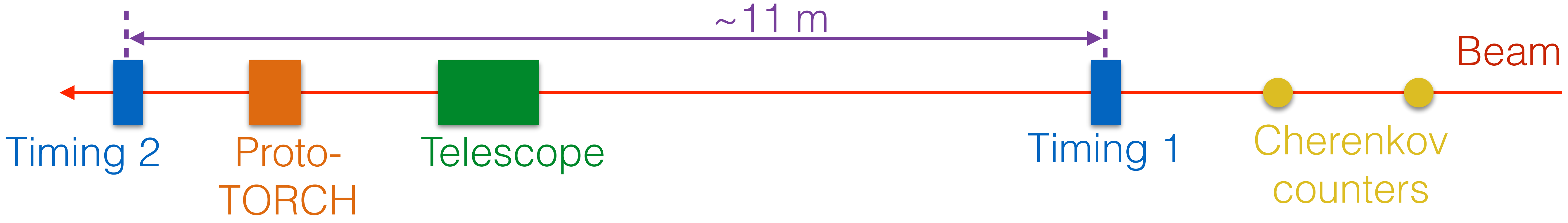
NIM A 1038 (2022) 166950

ProtoTORCH in testbeam

arXiv:2111.04627 (2021)

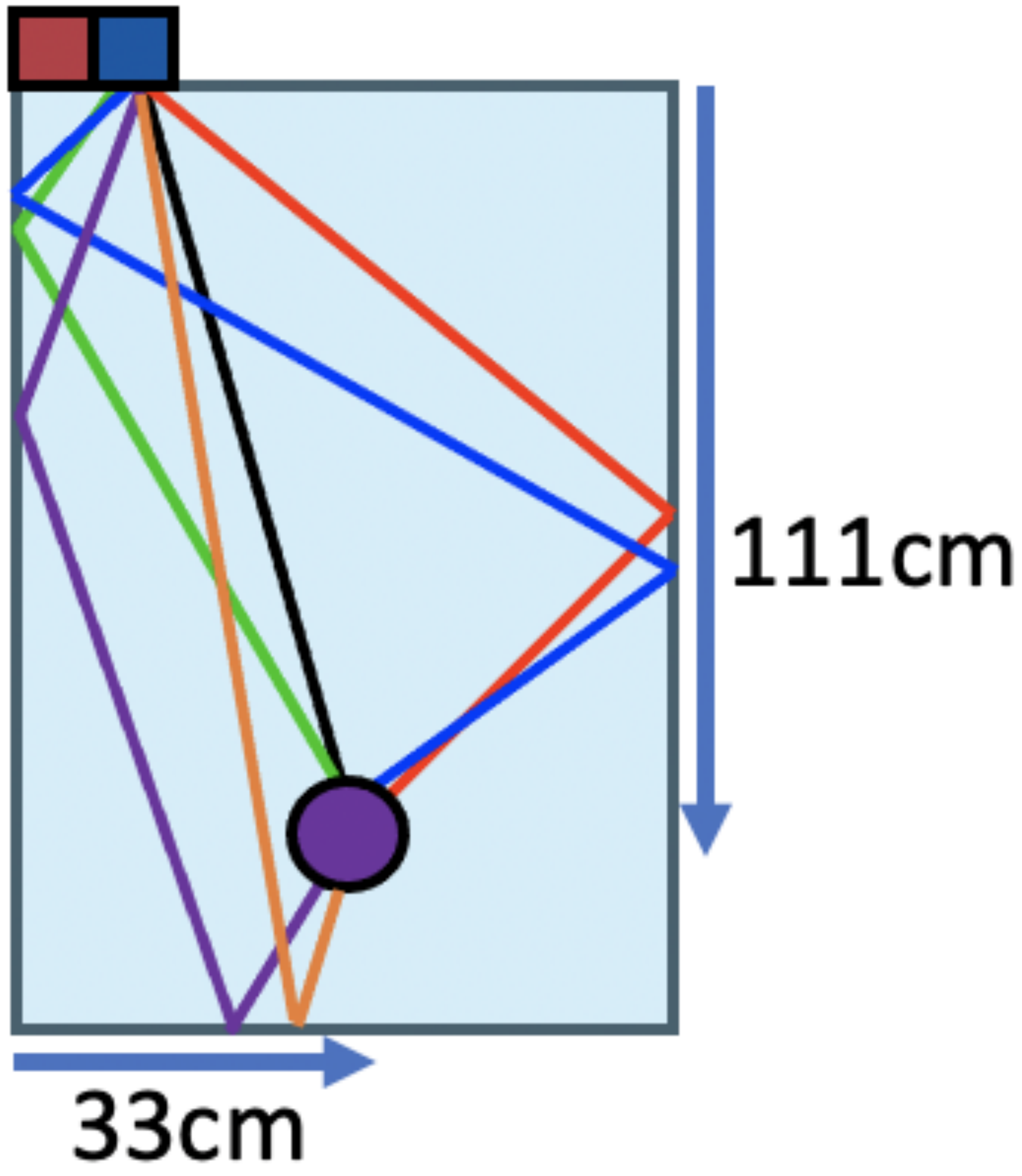


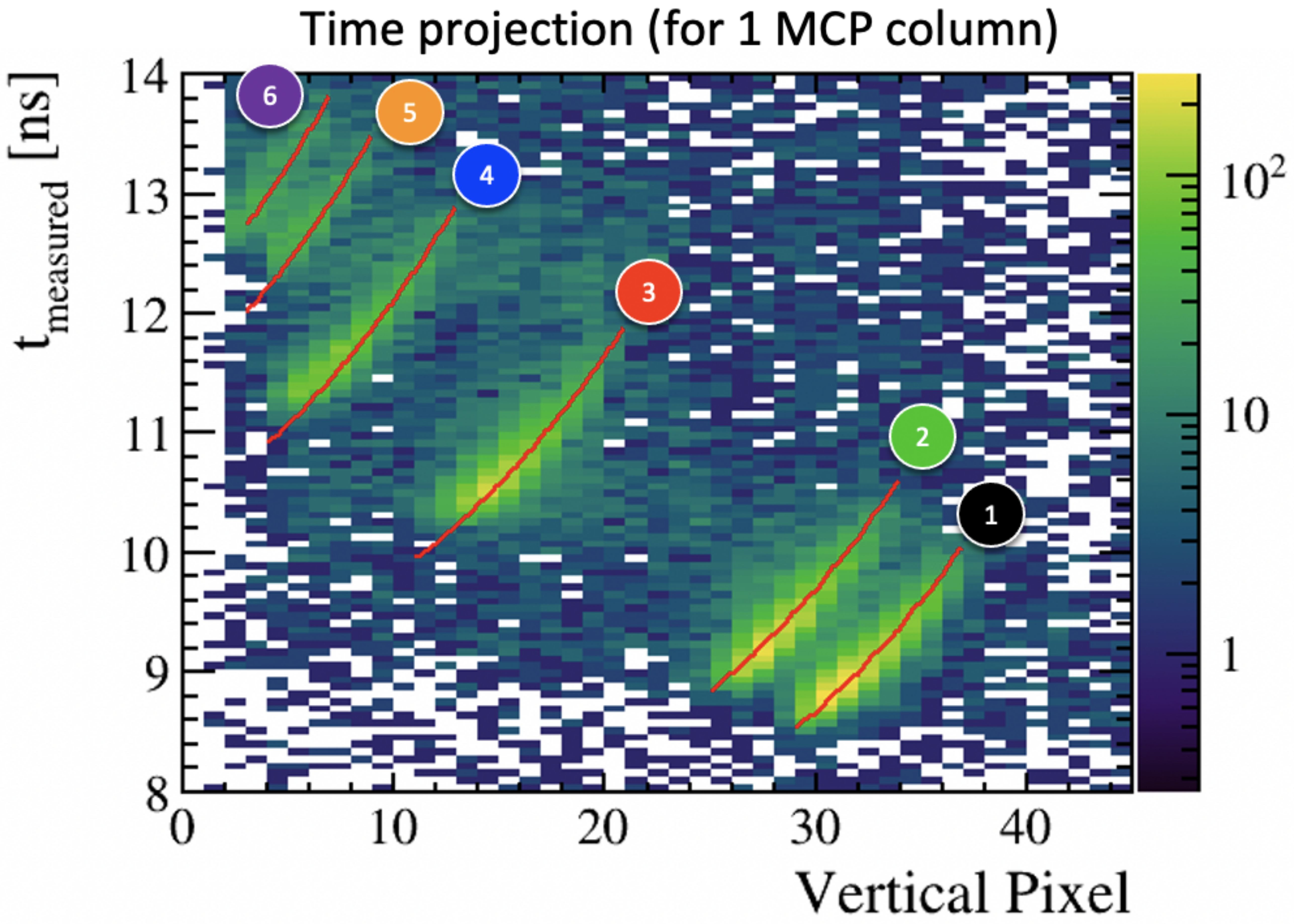




ProtoTORCH testbeam

arXiv:2111.04627 (2021)





ProtoTORCH photon counting in testbeam

arXiv:2111.04627 (2021)

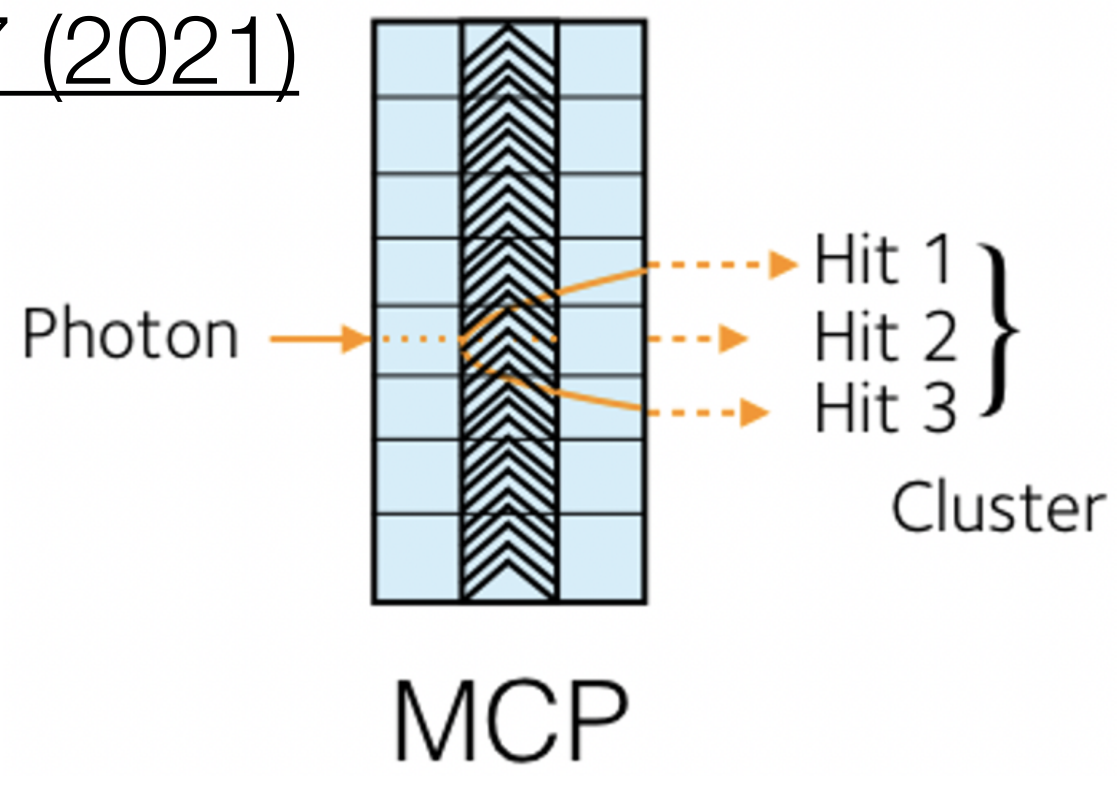
Mean number of photons

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

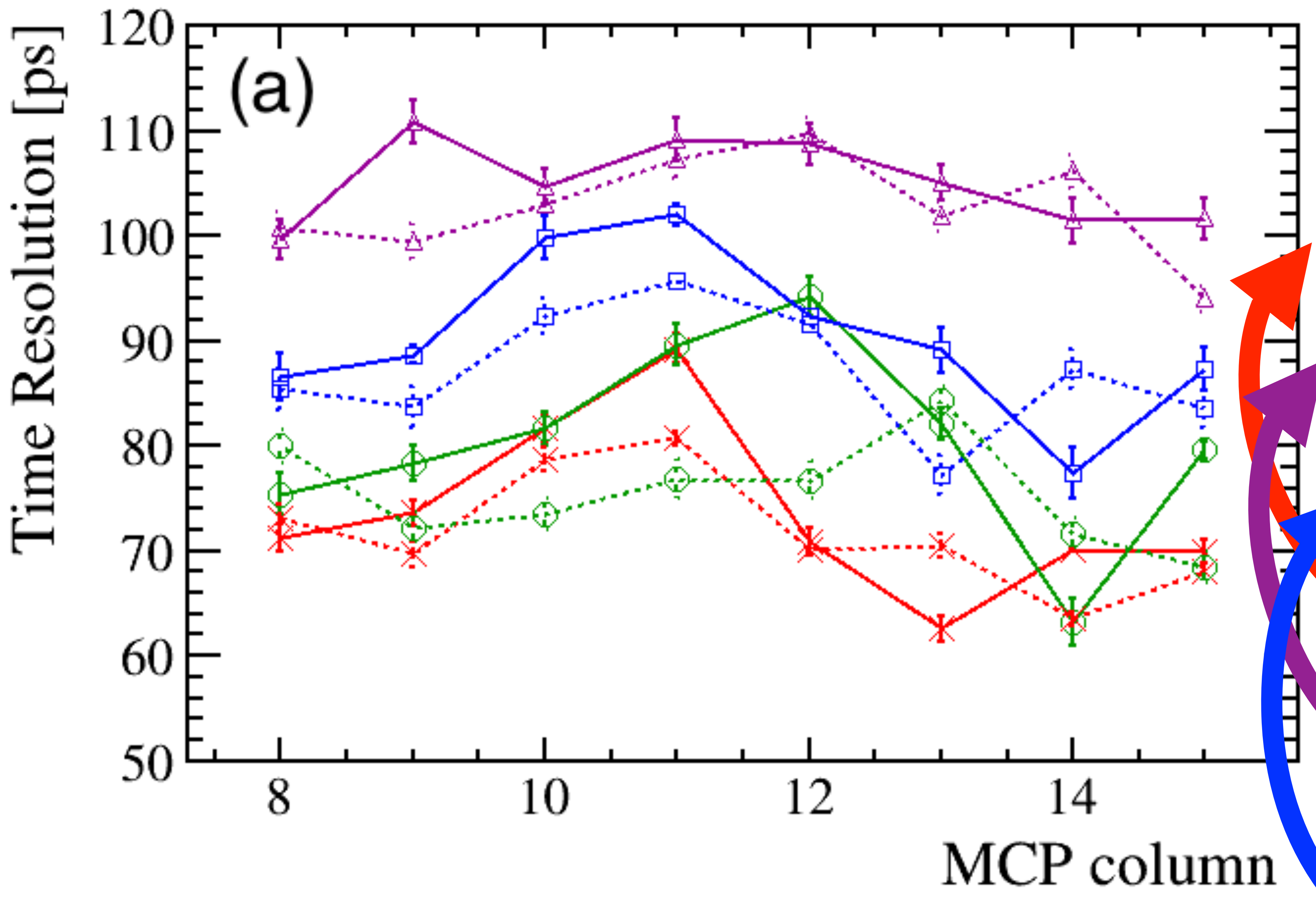
Photon yields well understood.

arXiv:2111.04627 (2021)

Time resolution per photon in testbeam



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



	Measure	Expect
σ_{const}	$= 31.76 \pm 7.6\,\mathrm{ps}$	$\sim 33\mathrm{ps}$
σ_{prop}	$= (7.6 \pm 0.5) \cdot 10^{-3} \cdot t_{\mathrm{p}}$	$\sim 4 \cdot 10^{-3} \cdot t_{\mathrm{p}}$
σ_{RO}	$= \frac{95 \pm 6}{\sqrt{N_{\mathrm{hits/cluster}}}}$	$\sim \frac{60}{\sqrt{N_{\mathrm{hits/cluster}}}}$

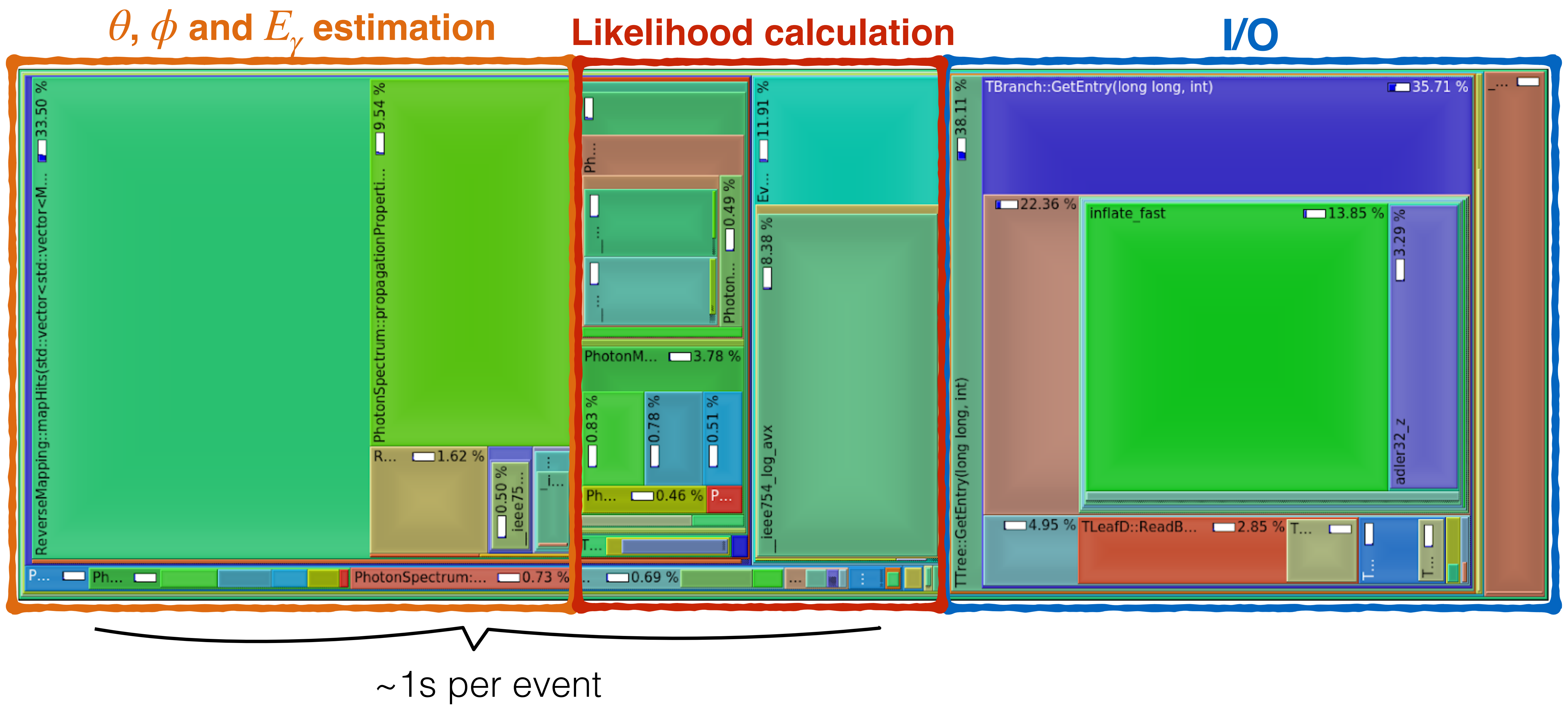
Great!

Under investigation. Alignment?

Expect improvement with calibration (ongoing right now, with newly commissioned system)

Design goal of 70ps/photon is within reach.

Event Reconstruction

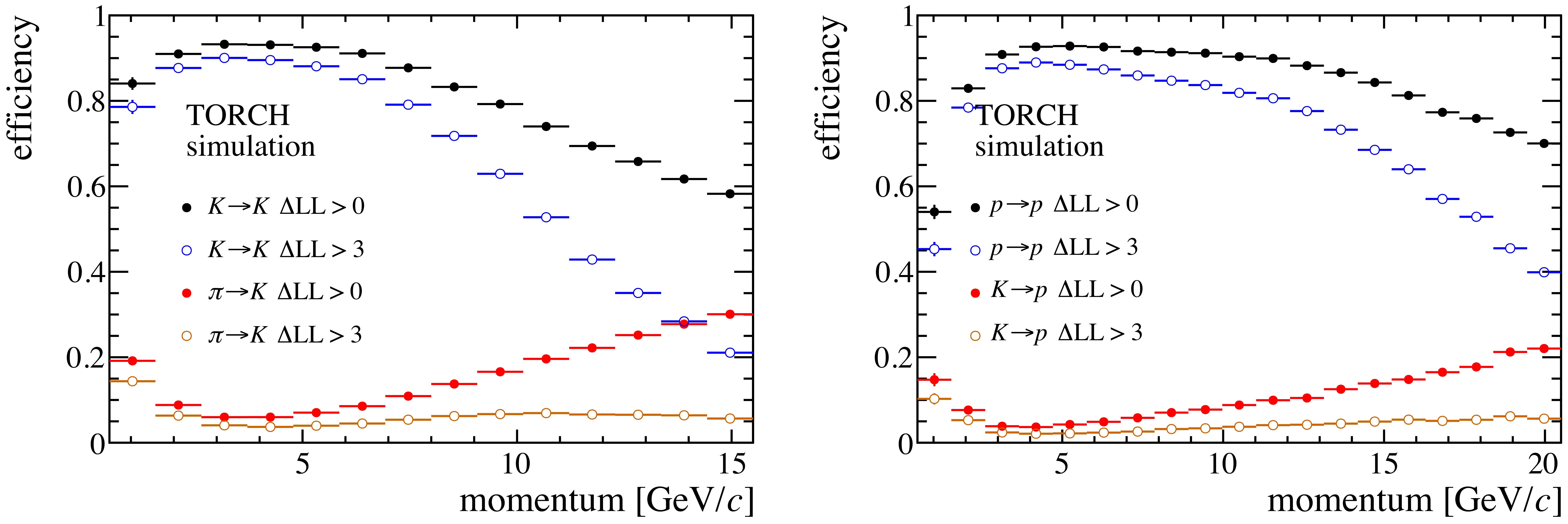


New analytic reconstruction is O(100) time faster than the previous one… but we need even better performance for LHCb UG II conditions.

The algorithm offers a lot of un-explored room for parallelisation. Investigating porting it to GPUs, and novel hardware architectures such as Graphcore's IPUs.

LHCb-PUB-2022-007, LHCb-PUB-2022-004.

Simulated TORCH performance for LHCb Upgrade II



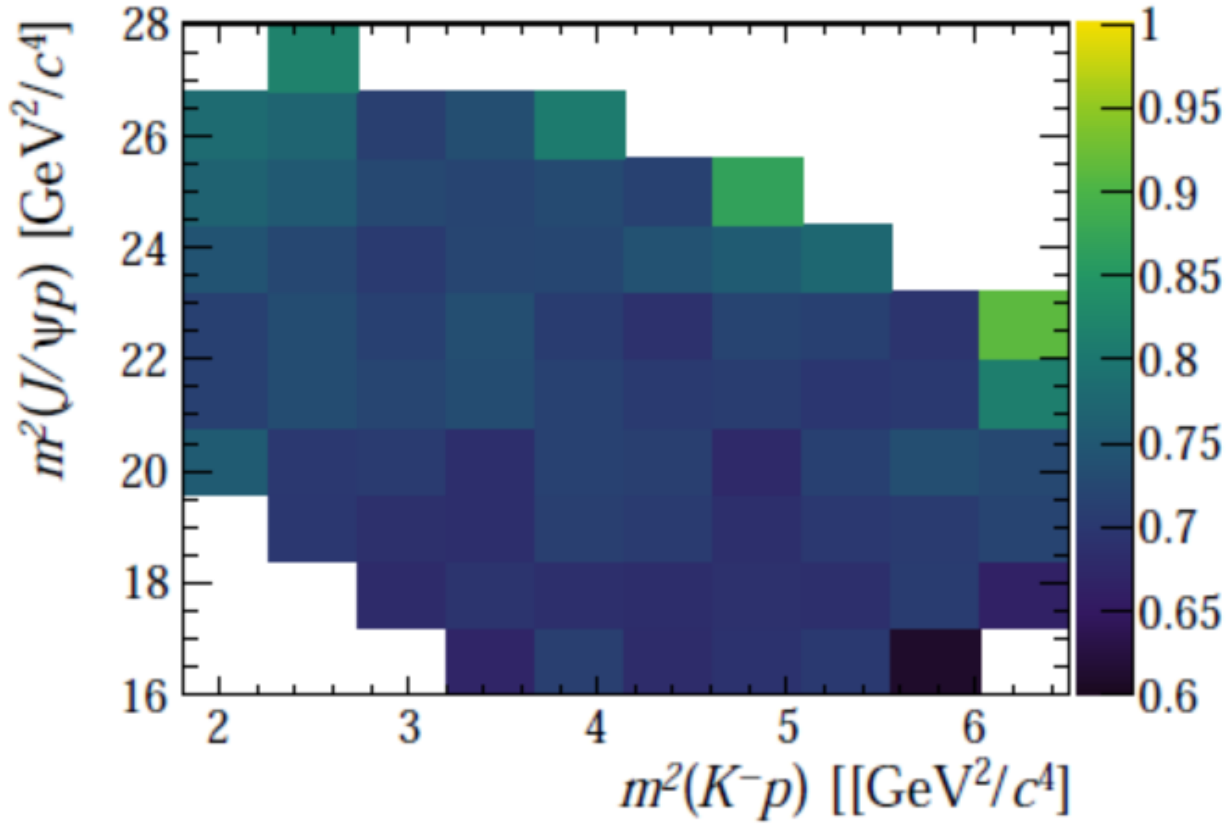
LHCb-PUB-2022-006, LHCb-PUB-2022-007

What physics does it buy us?

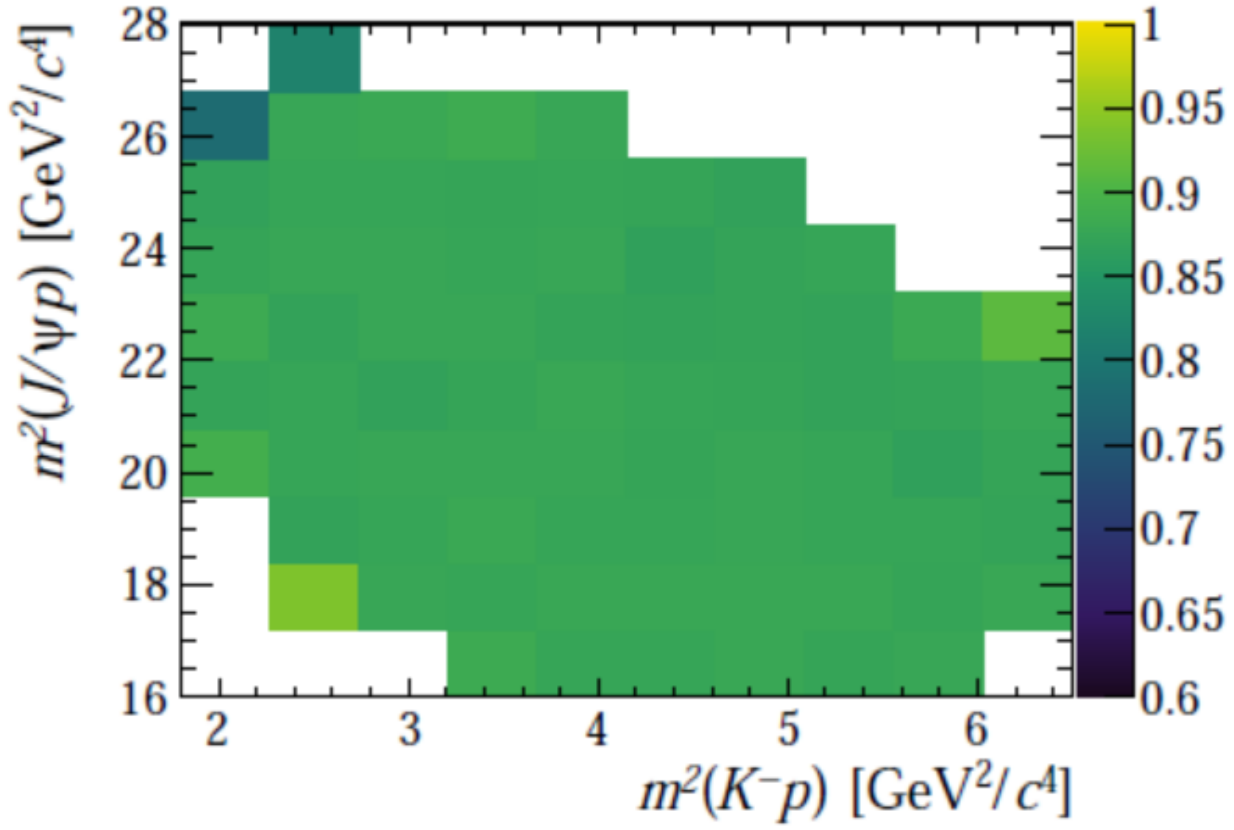
LHCB-TDR-023

Efficiency across Dalitz plot for $\Lambda_b \to J/\psi K p$ (simulation)

Without TORCH



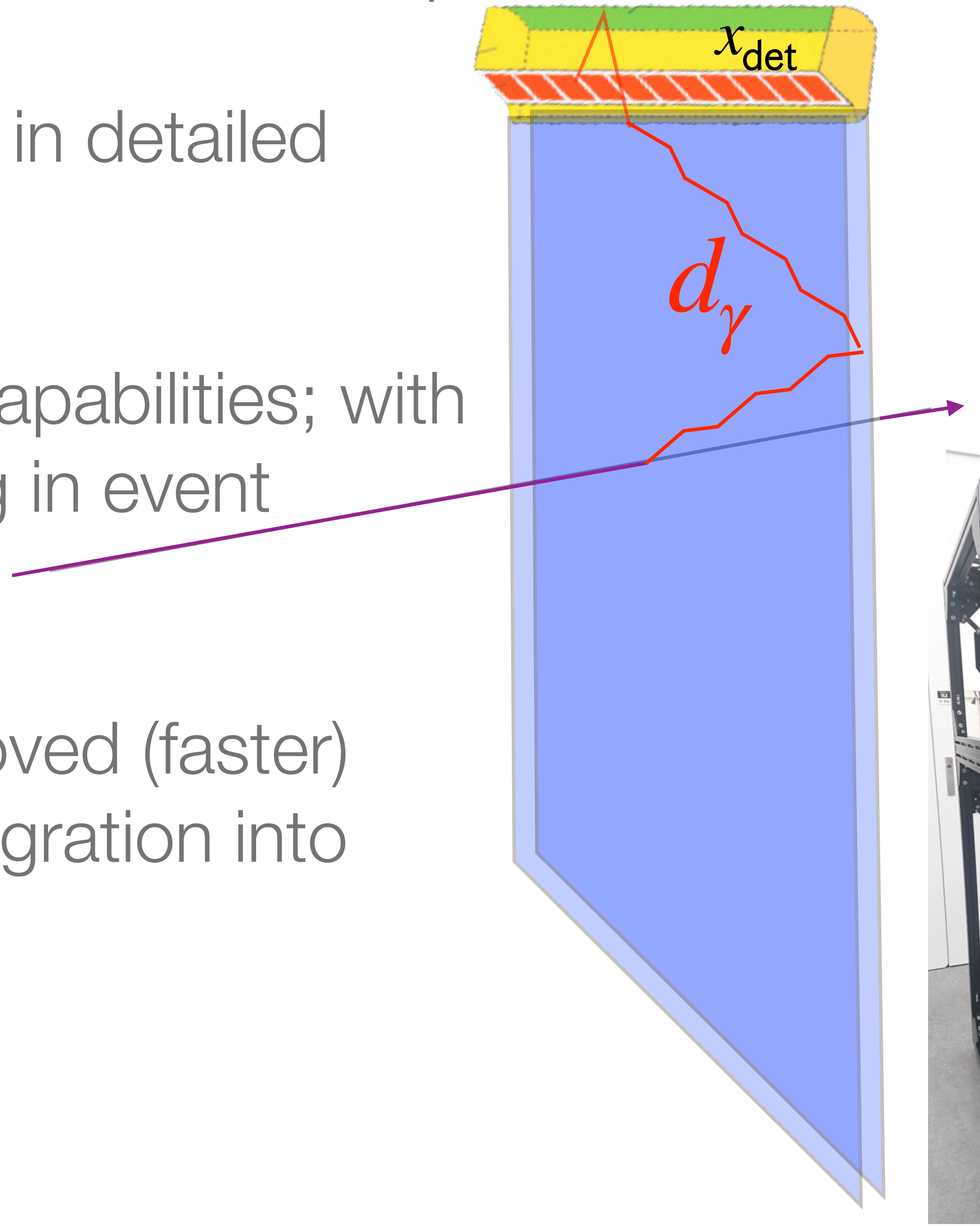
With TORCH



- Amplitude analyses of multi body decays like $\Lambda_b \to J/\psi K p$, and $B^0 \to DDK\pi \to 3K3\pi$ critical, and tend to yield low-momentum particles, where TORCH shines its light.
- Baryons are exciting: CPV in baryons? Exotics hadrons (e.g. pentaquarks), and many more. TORCH critical to identifying the protons that result.
- TORCH substantially improves flavour tagging with soft kaons - especially important for B_S.
- More ideas: Deuteron, search for heavy charge particles (like R-hadrons), …
- But it's not only PID: TORCH timing could help "disentangle" the very busy events in LHCb upgrade II.

Conclusions

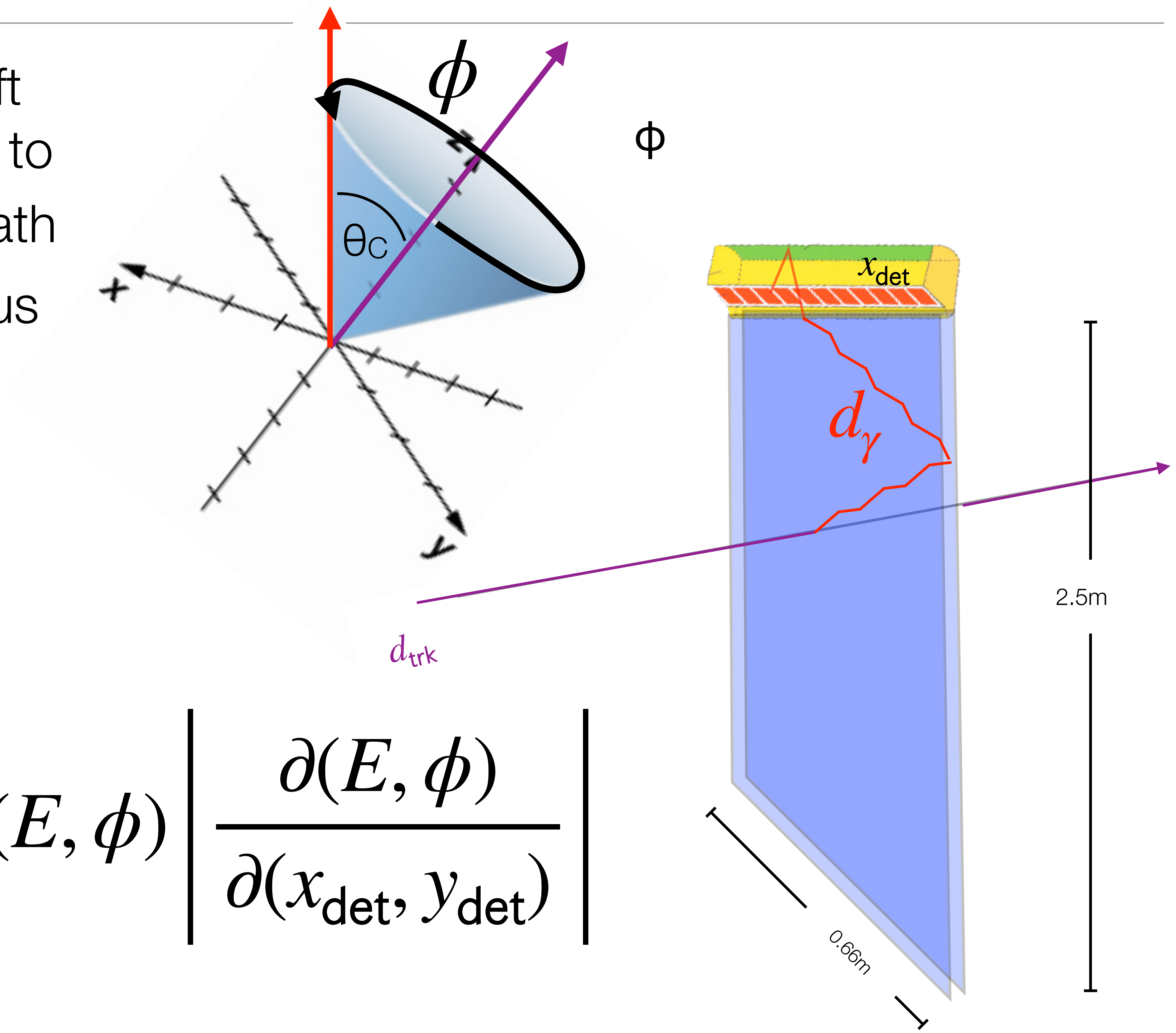
- TORCH is a new, large area time of flight detector with a resolution of ~15ps.
- Concept proven in testbeam and laboratory; impact studied in detailed simulation.
- In LHCb upgrade II, TORCH will extend LHCb's particle ID capabilities; with potentially additional benefits from TORCH's precision timing in event reconstruction.
- Future R&D programme: pico-TDC-based electronics, improved (faster) pattern recognition, mechanical and other aspects of its integration into LHCb UG II.
- Already this autumn: first fully instrumented prototype.



Backup slides

Event Reconstruction

For every track and reflection hypothesis (left, right, left and right, etc), a hit on the detector plane corresponds to one photon path from which we know θ_C, ϕ and the path length. From θ_C we get the wavelength/energy and thus the velocity of the photon.



$$P(E,\phi) \propto \varepsilon(E,\phi)\,\frac{\alpha}{2\pi\hbar c}\,\sin^2\theta_C$$

$$P(x_{det}, y_{det}, t_{det}) = \frac{1}{\sqrt{2\pi\sigma_t}} e^{-\frac{(t_{det} - t(\beta,E,\phi))^2}{2\sigma_t^2}} P(E,\phi) \left| \frac{\partial(E,\phi)}{\partial(x_{det}, y_{det})} \right|$$

LHCb-PUB-2022-004

What physics does it buy us

… mention the below other things such as importance of baryon programme in general, and maybe the deuteron idea

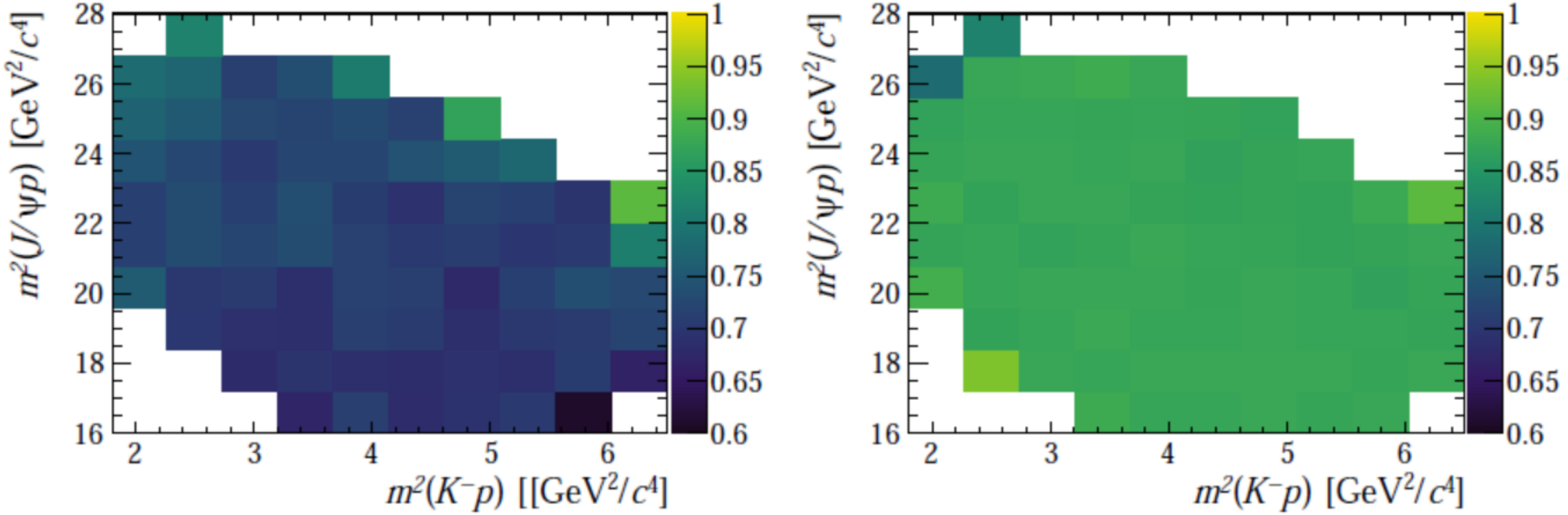
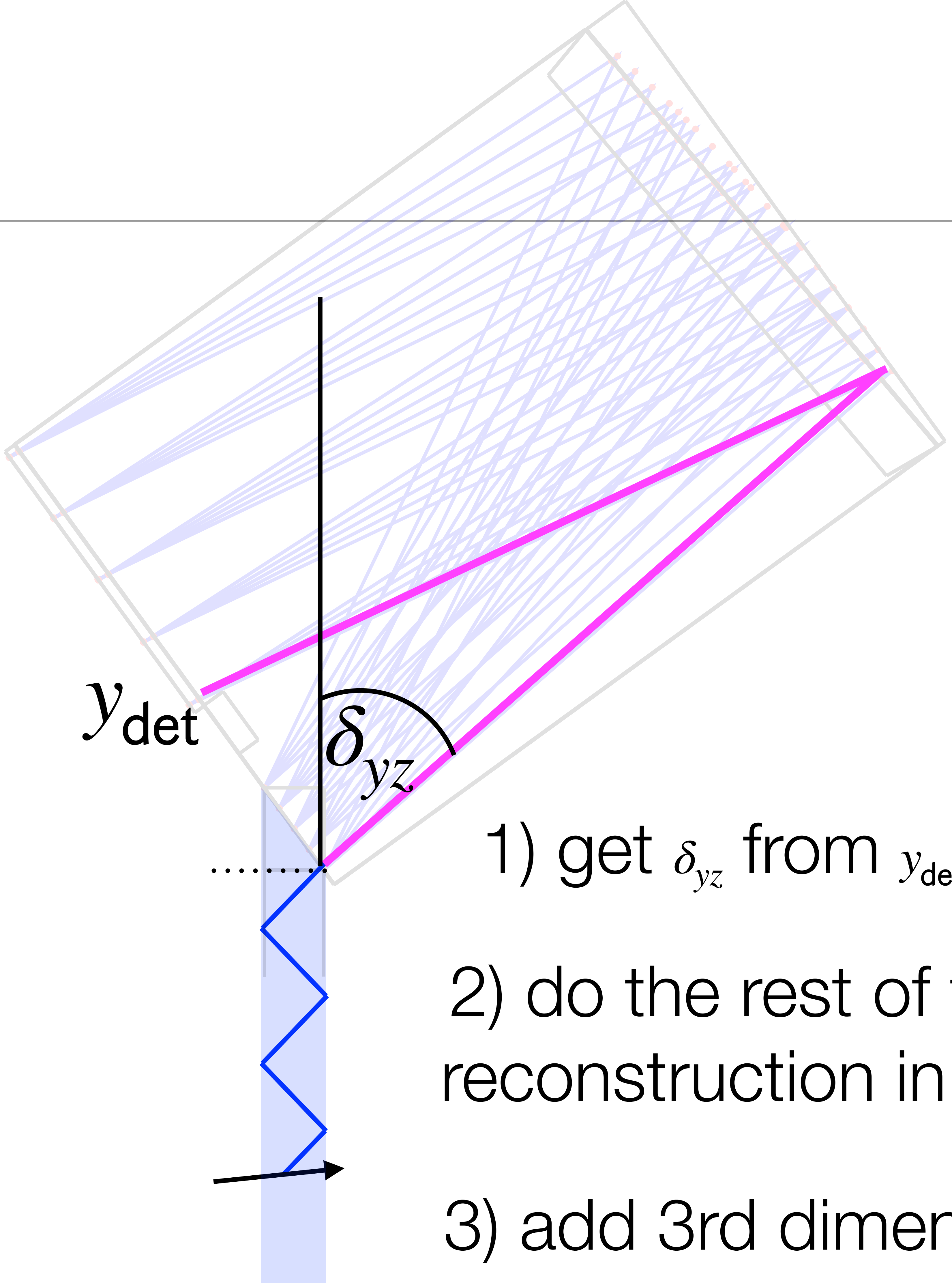


Figure 4.10: The Dalitz plot distribution of $\Lambda_b^0 \to J\psi p K^-$ decays selected with the nominal LHCb PID requirements (left) and with the additional PID provided by TORCH (right).

Reconstruction and simulation notes (in preparation)

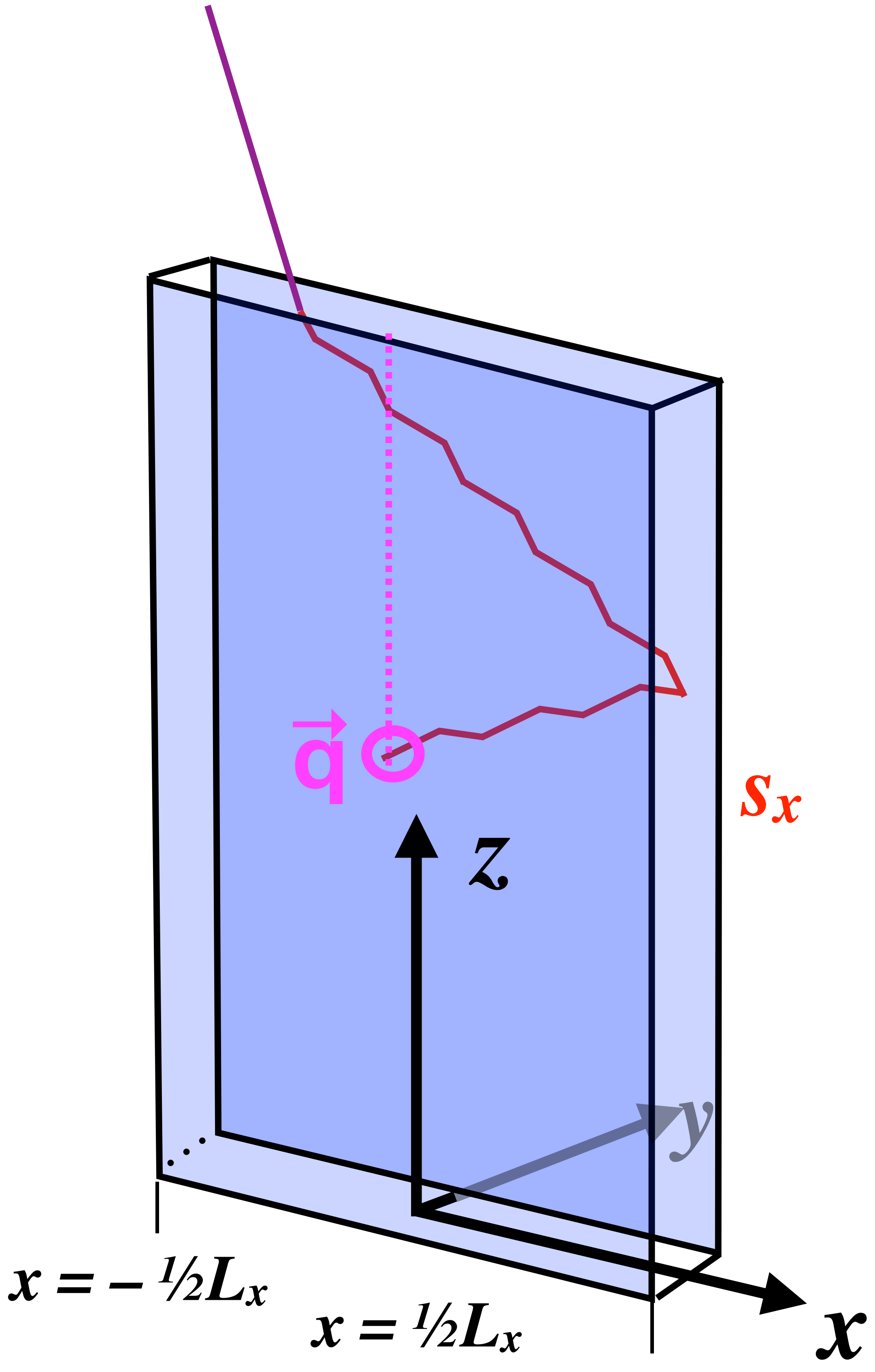
- TORCH simulation, LHCb-PUB-2022-005
- TORCH particle identification performance, LHCb-PUB-2022-006,
- TORCH reconstruction and particle identification algorithm, LHCb-PUB-2022-007.
- TORCH reconstruction, LHCb-PUB-2022-004.

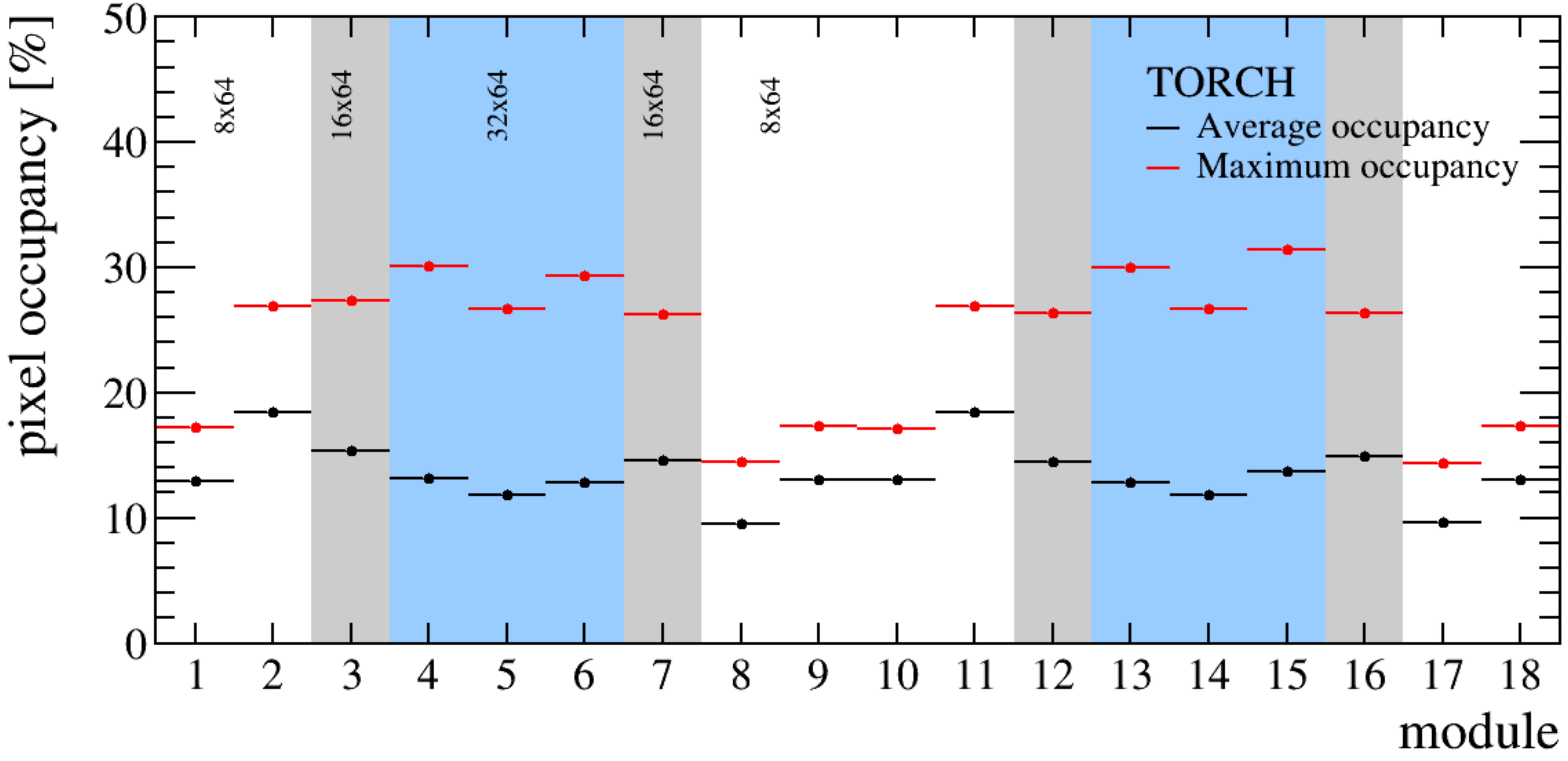


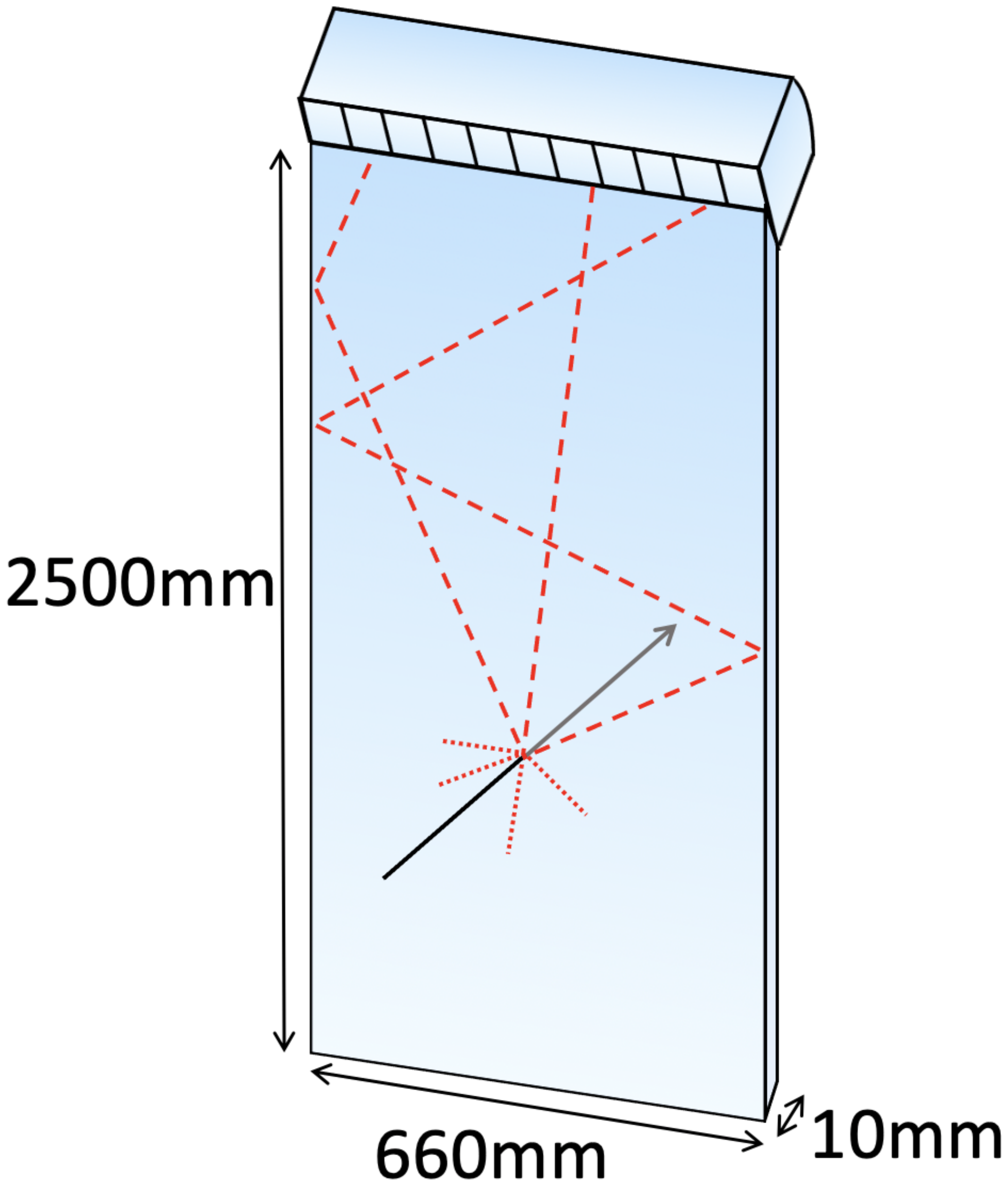
1) get δ_{yz} from y_{det}

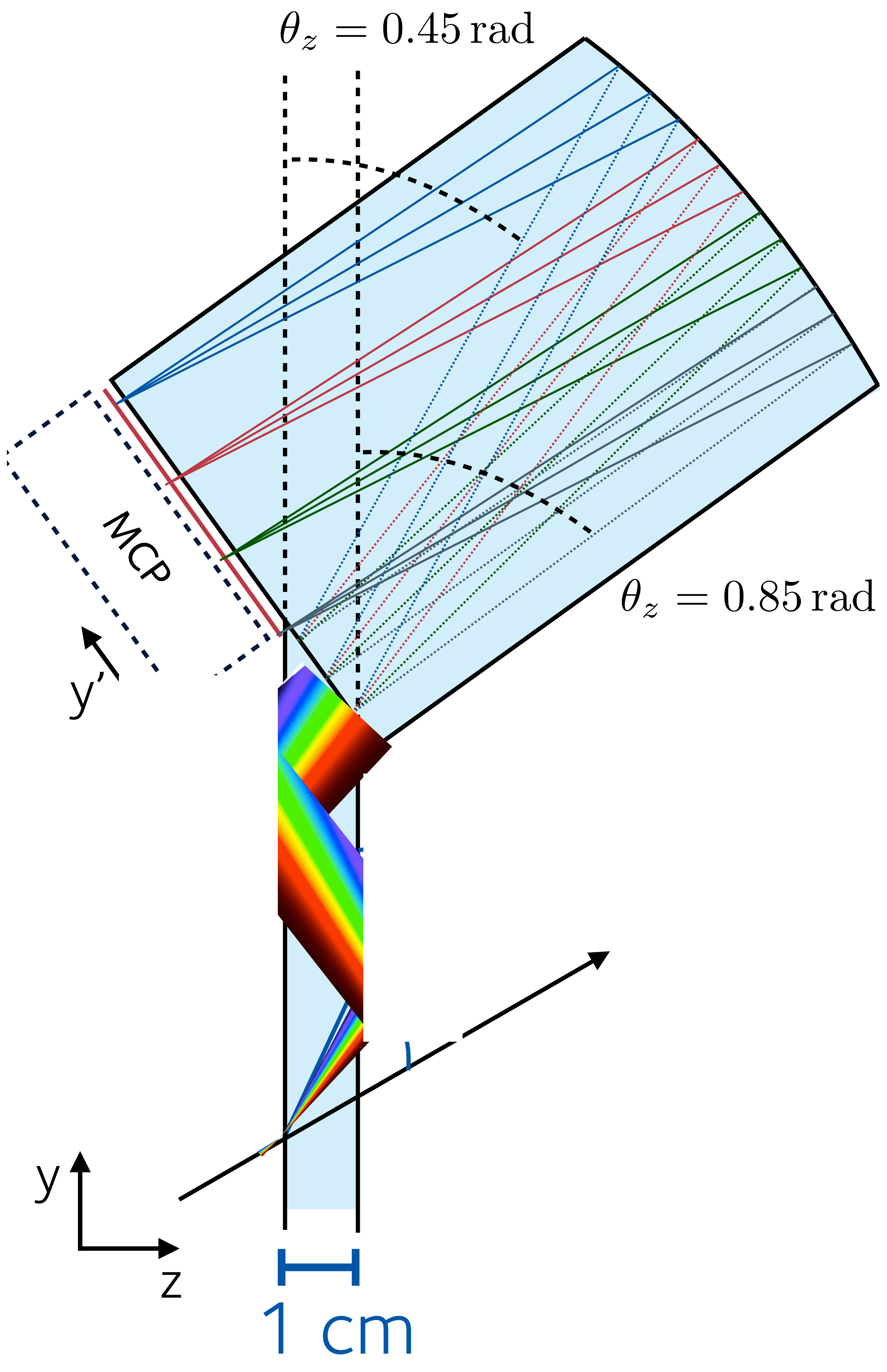
2) do the rest of the reconstruction in 2D

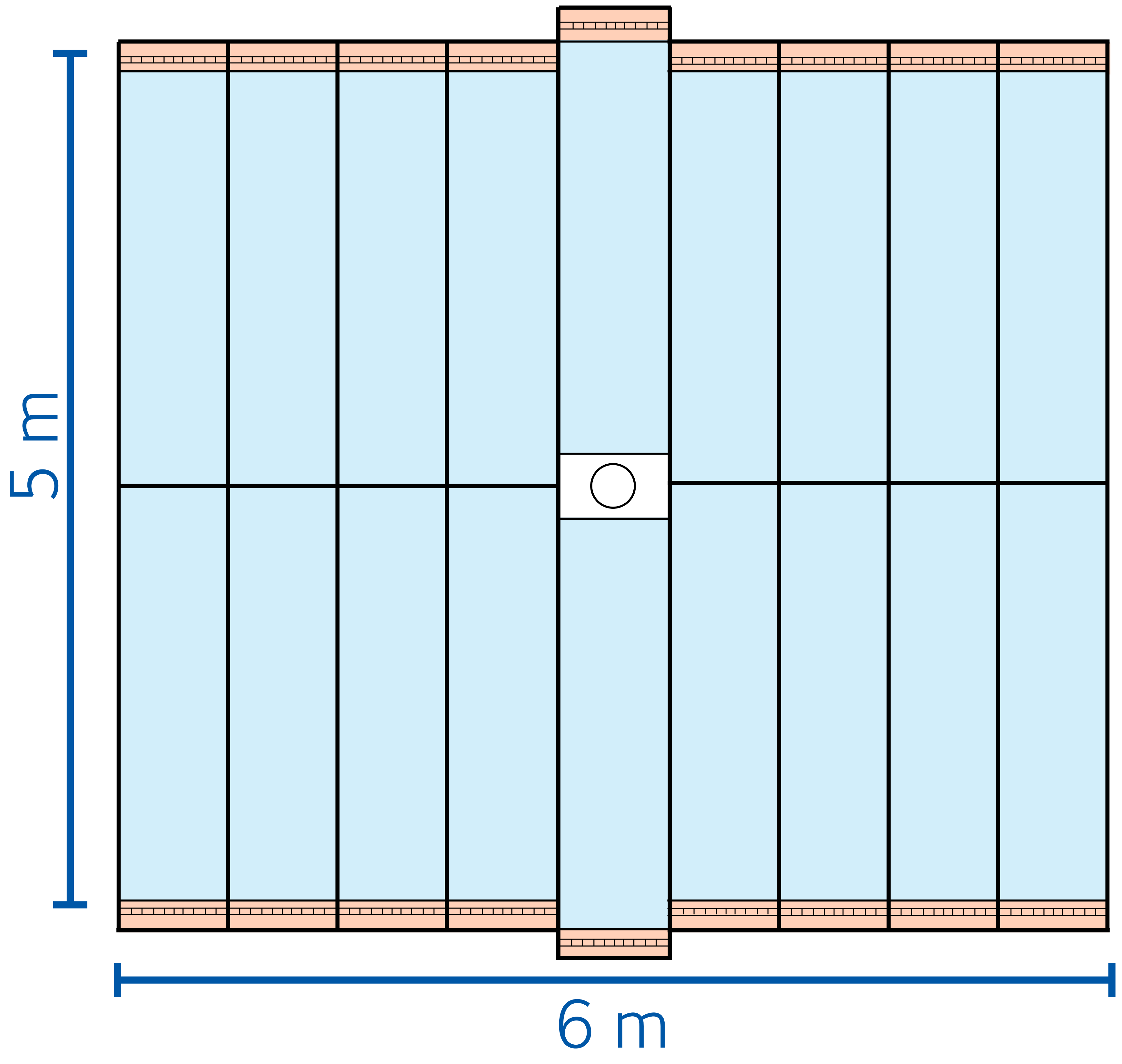
3) add 3rd dimension




pixel occupancy [%]
module
8x64
16x64
32x64
16x64
8x64
TORCH
Average occupancy
Maximum occupancy


2500mm
660mm
10mm

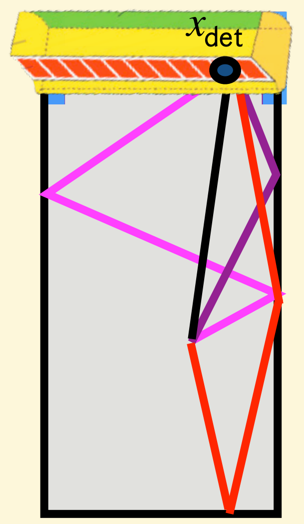

$\theta_z = 0.45\,\mathrm{rad}$
MCP
$\theta_z = 0.85\,\mathrm{rad}$
y'
y
z
1 cm


5 m
6 m

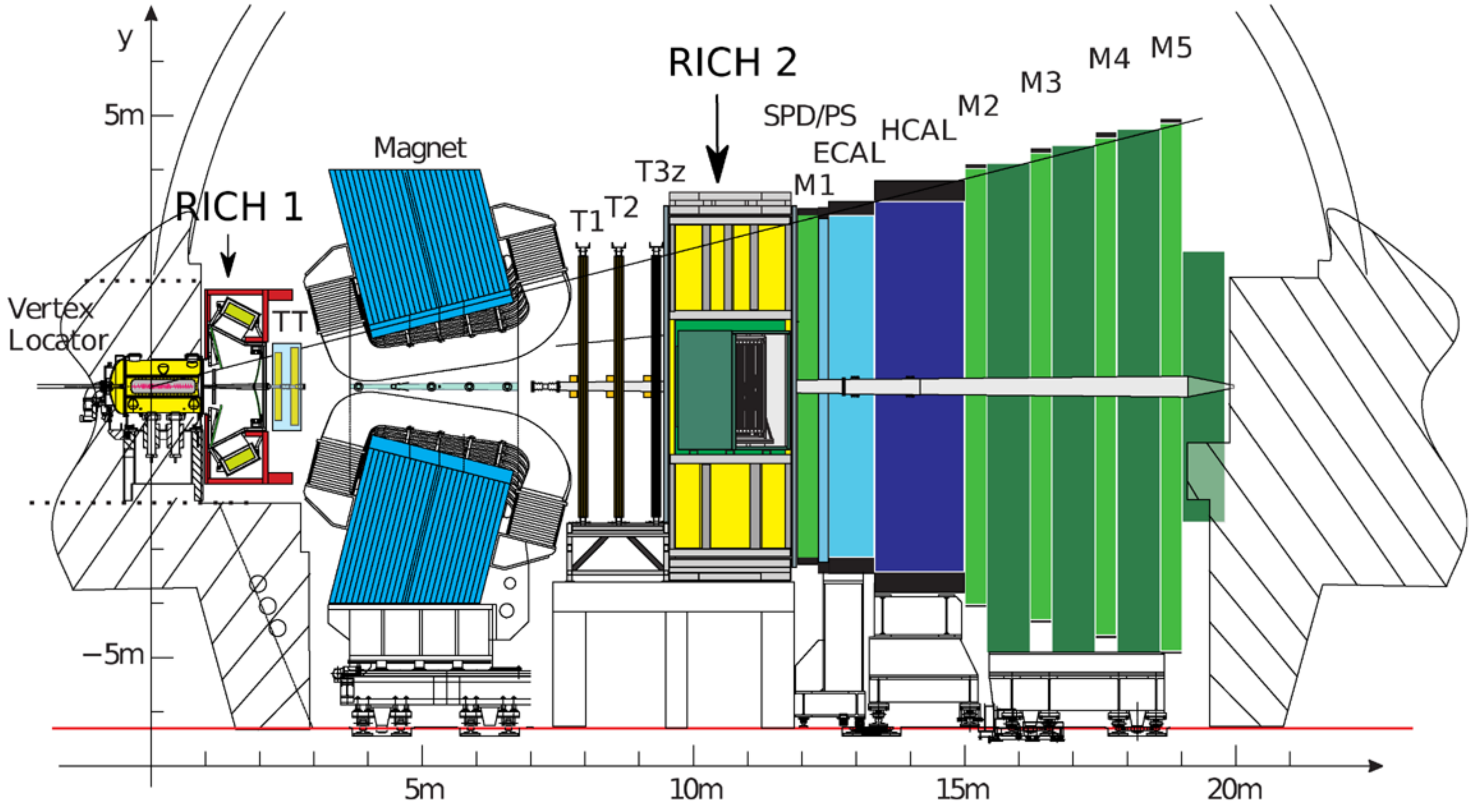
Reconstruction & fit

reconstruction (1× per event)

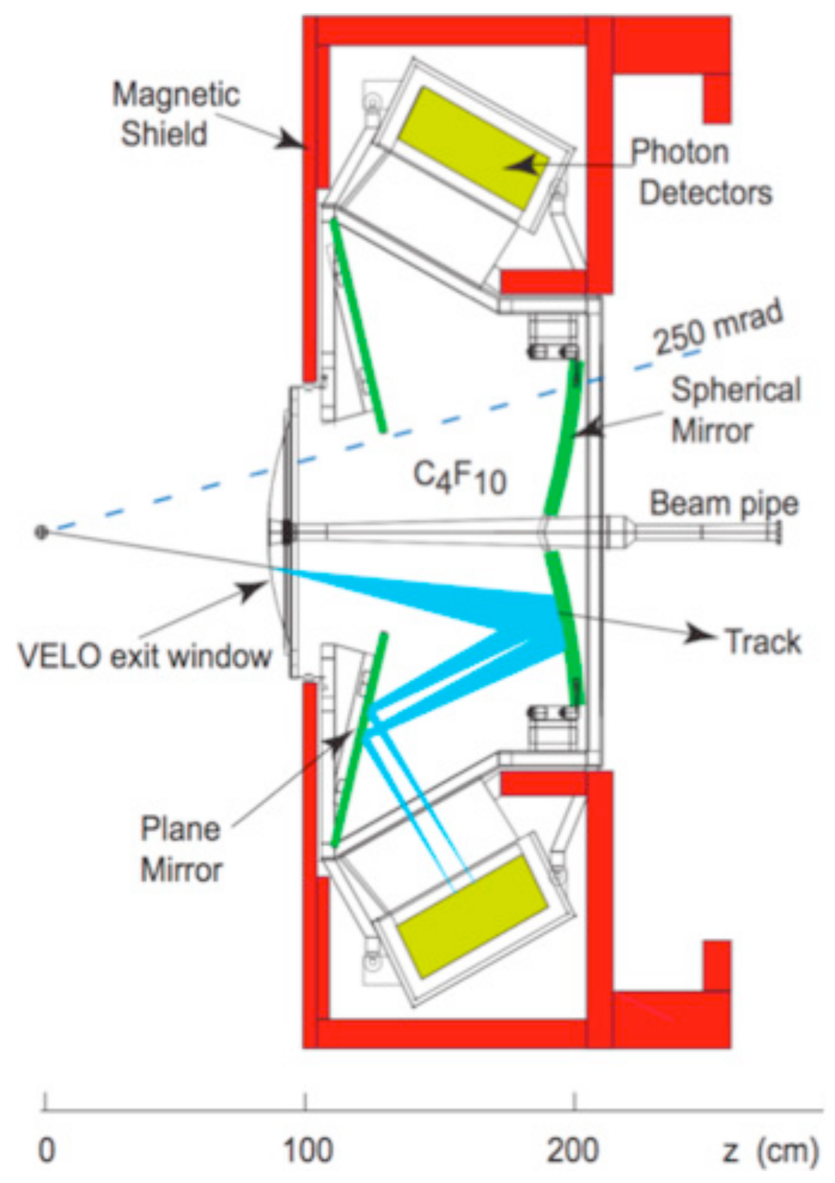
fit

What		How often
focusing block		1 per photon
full photon trace		1 per photon × track × reflection-hypothesis (~25 refl hypos for each photon-track combo)
PDF numerator	$\varepsilon(E, \phi, \beta_{\text{trk}})\sin^2\theta$	1 per photon × track × particle hypothesis
PDF integration	$\iint \varepsilon(E, \phi, \beta_{\text{trk}})\sin^2\theta \, dE \, d\phi$	1 per track per particle hypothesis

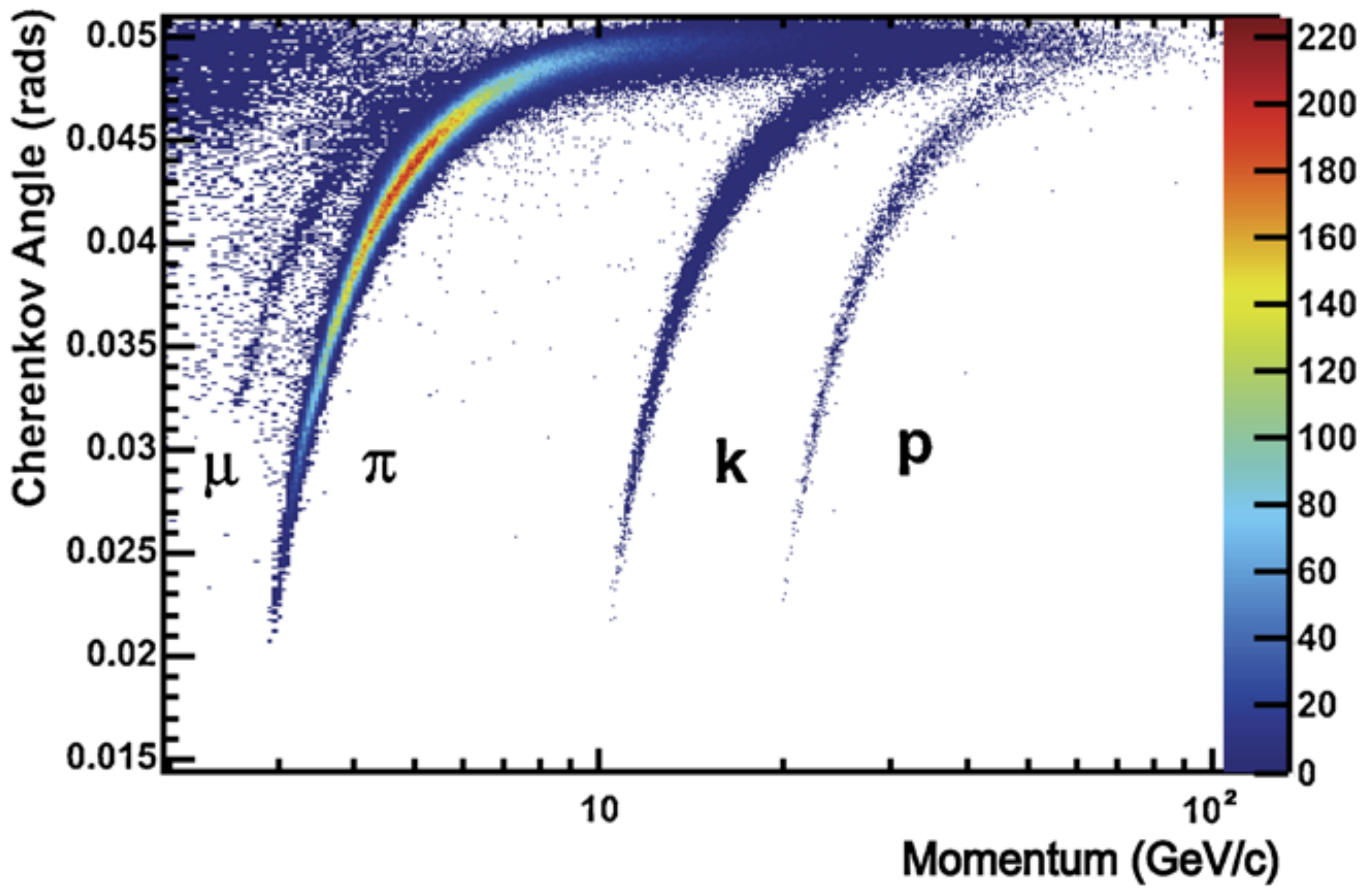
LHCb RICH particle ID

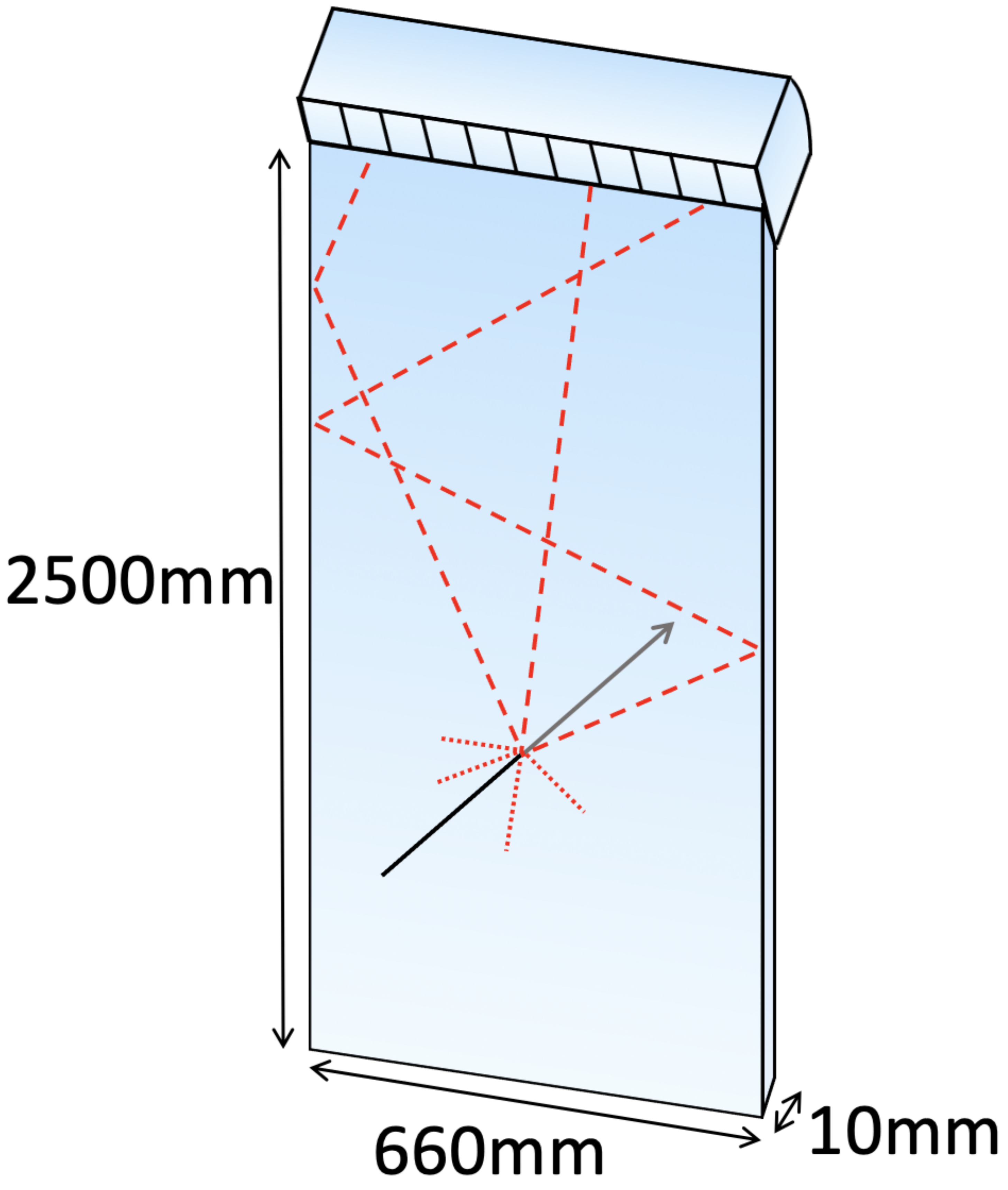


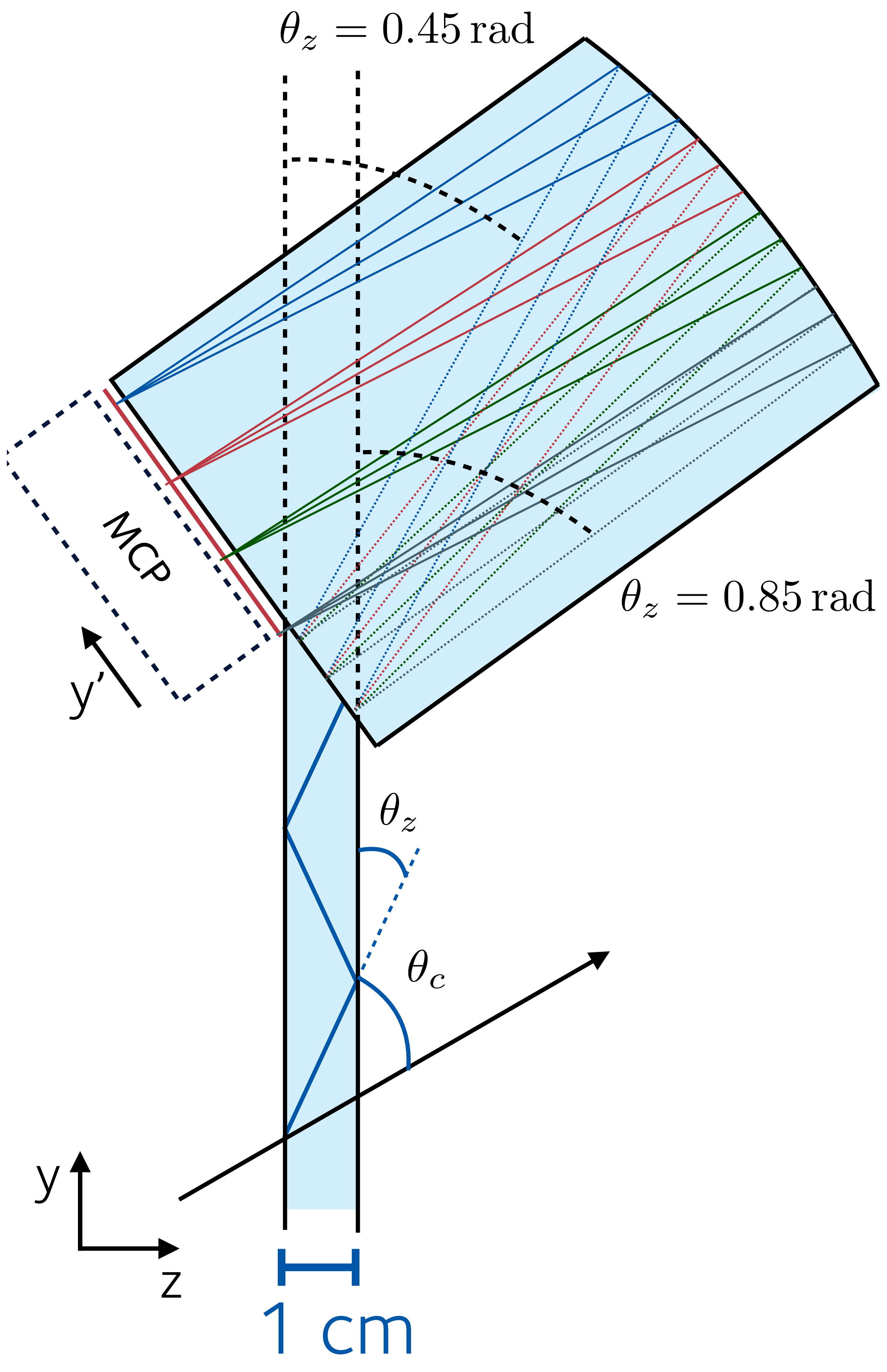
RICH I

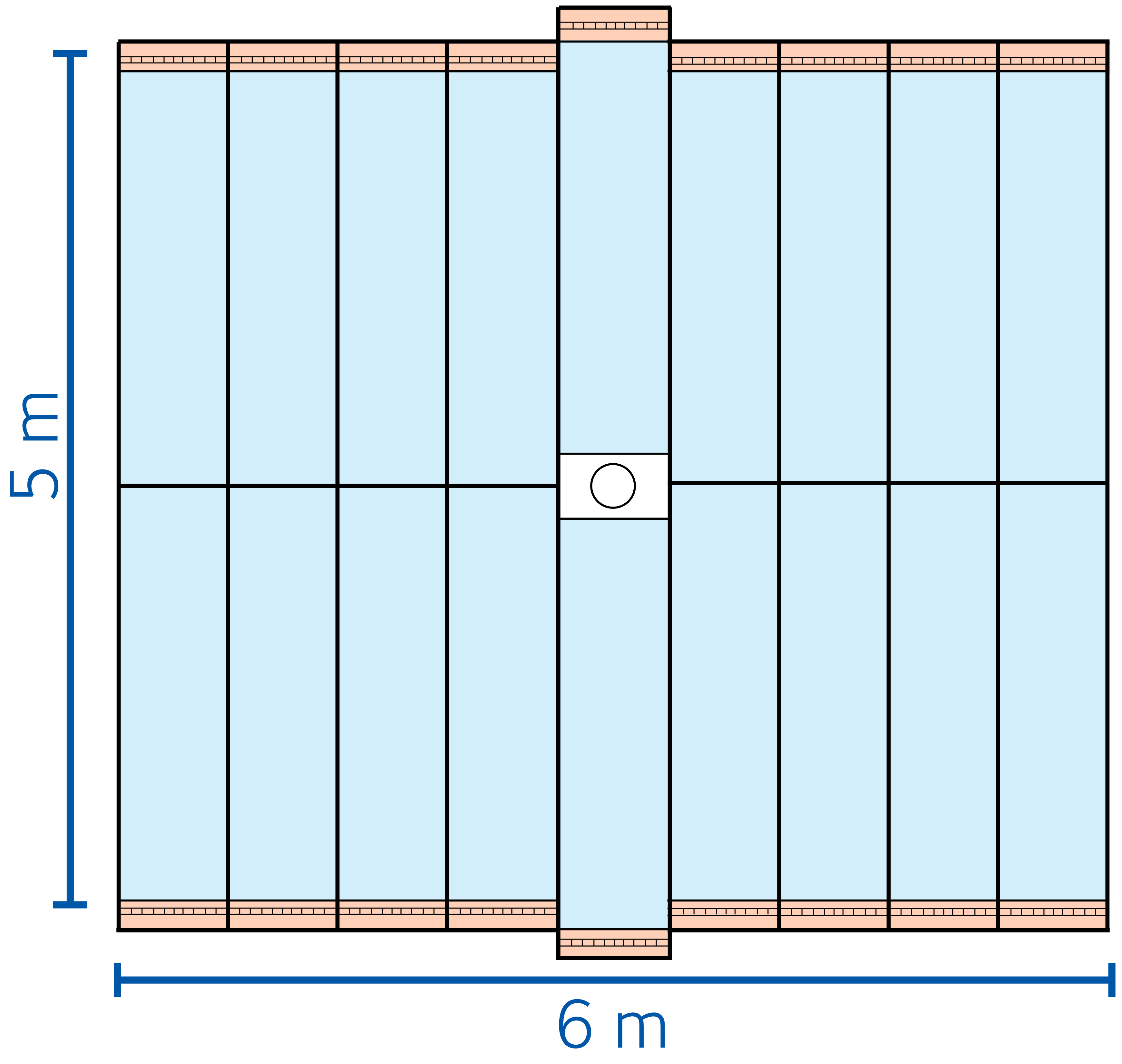


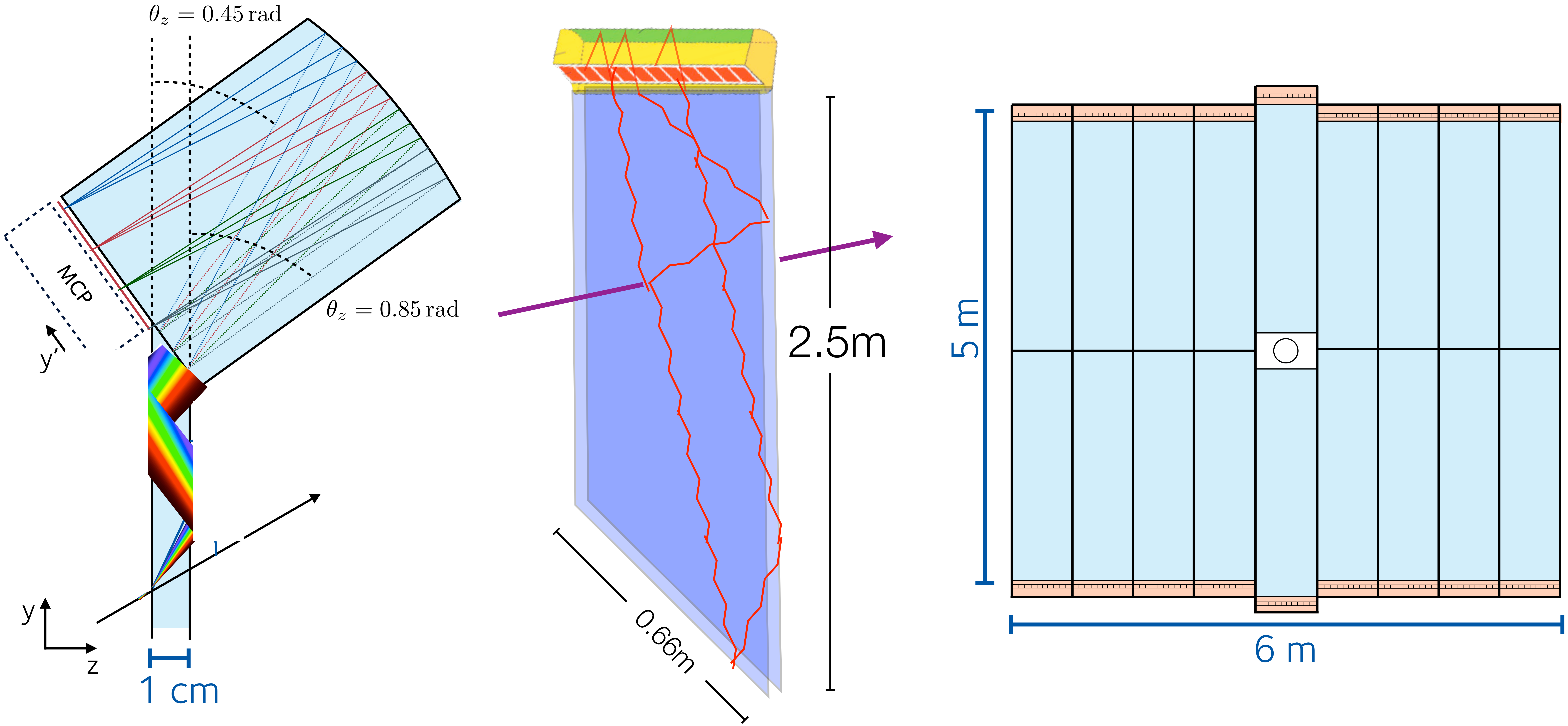
EPJC 73 (2013) 2431



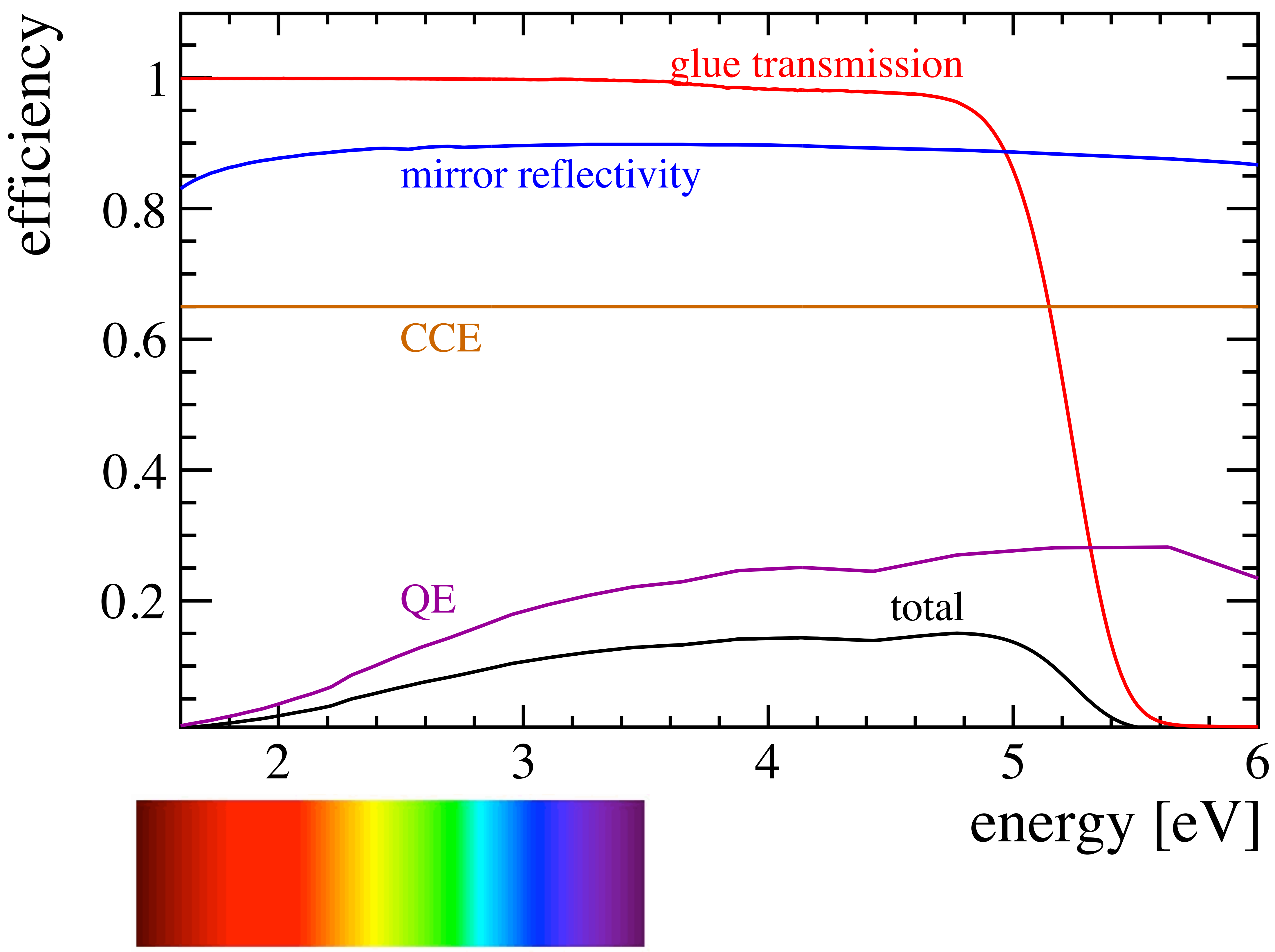

2500mm
660mm
10mm


$\theta_z = 0.45\,\mathrm{rad}$
$\theta_z = 0.85\,\mathrm{rad}$
MCP
y'
θ_z
θ_c
y
z
1 cm


5 m
6 m



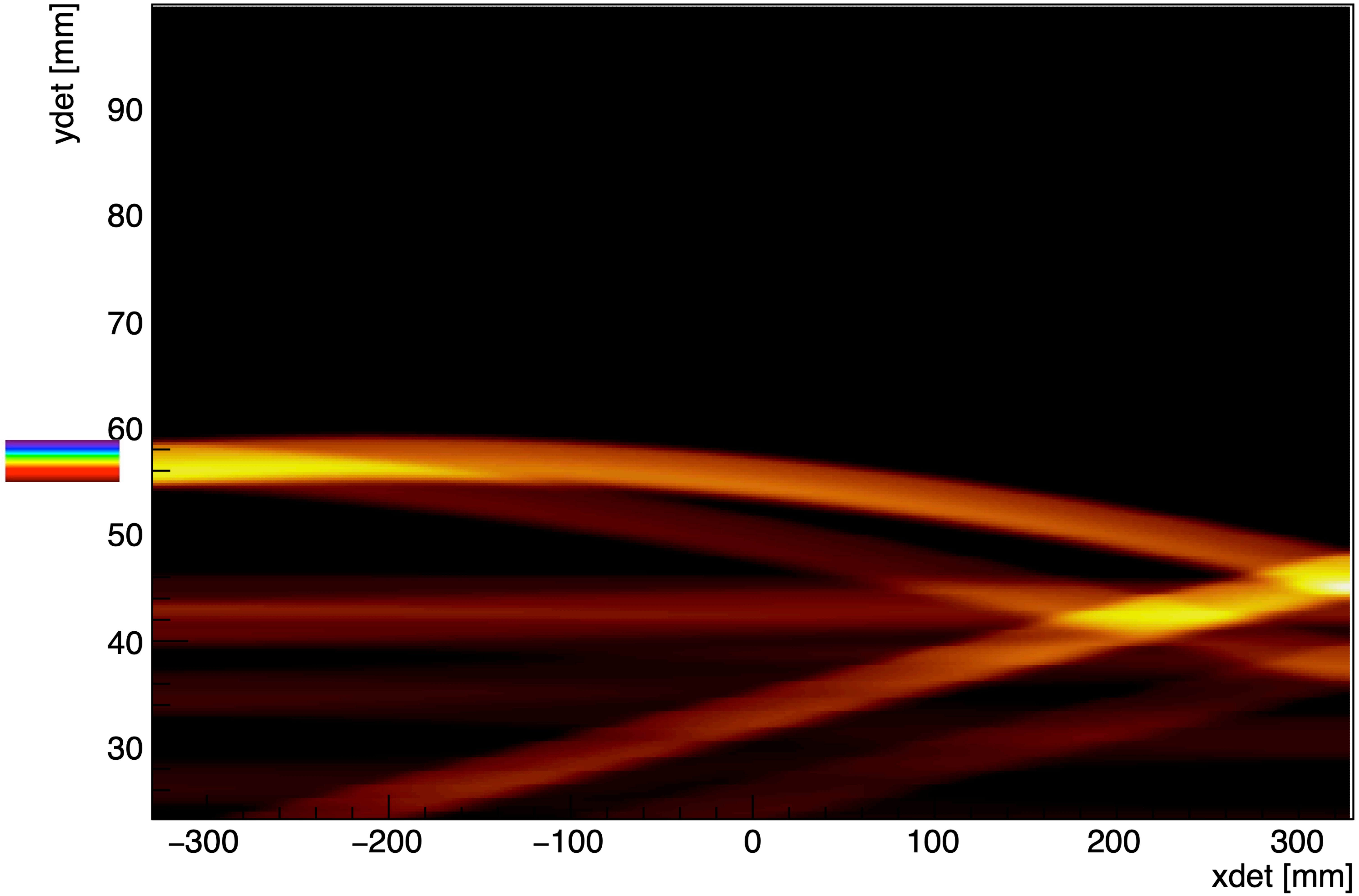
$\theta_z = 0.45\,\mathrm{rad}$
$\theta_z = 0.85\,\mathrm{rad}$
MCP
y'
y
z
1 cm
0.66m
2.5m
5 m
6 m

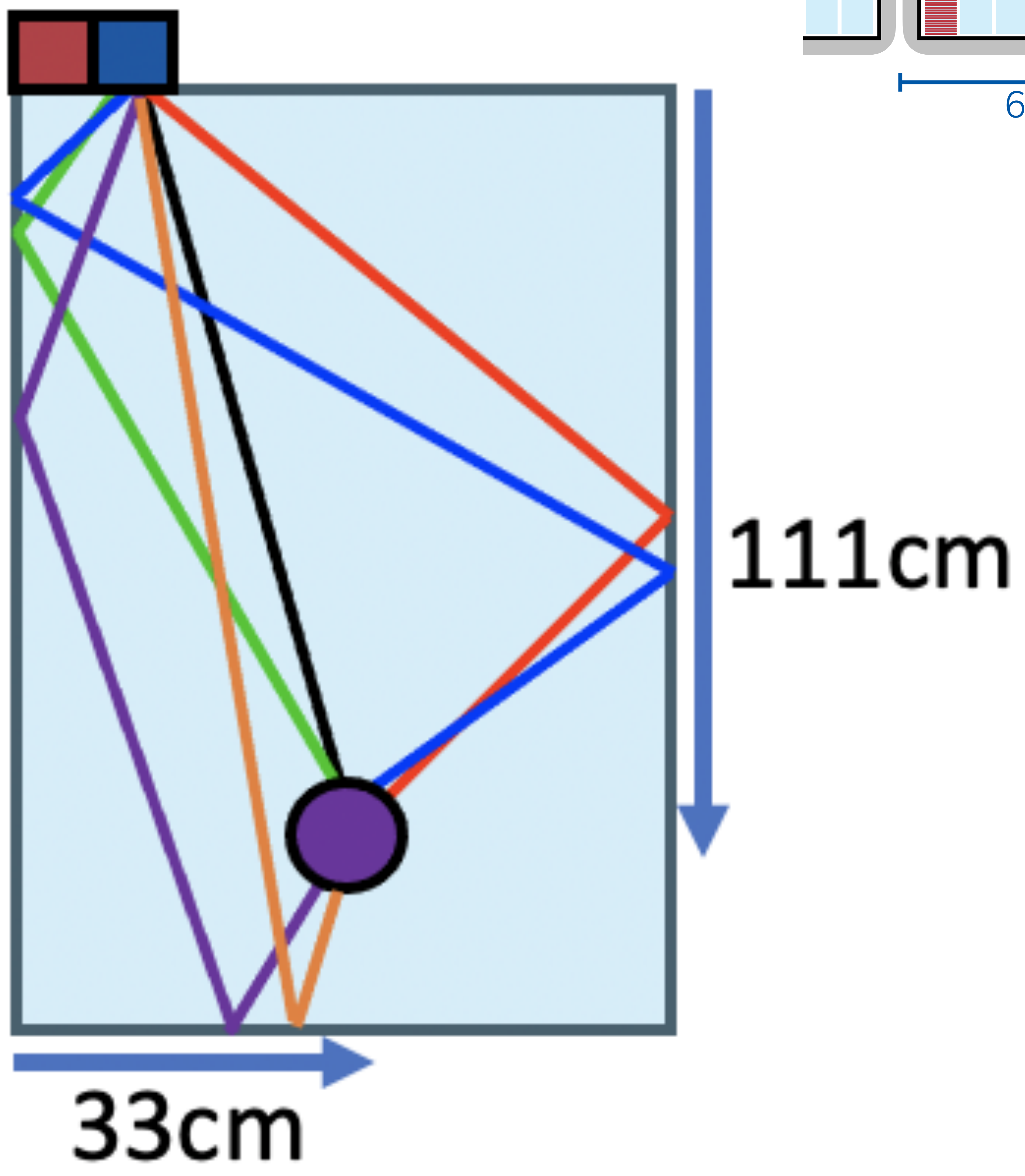

efficiency
1
0.8
0.6
0.4
0.2
2
3
4
5
6
energy [eV]
glue transmission
mirror reflectivity
CCE
QE
total

The image on the detector plane (w/o pixelisation)

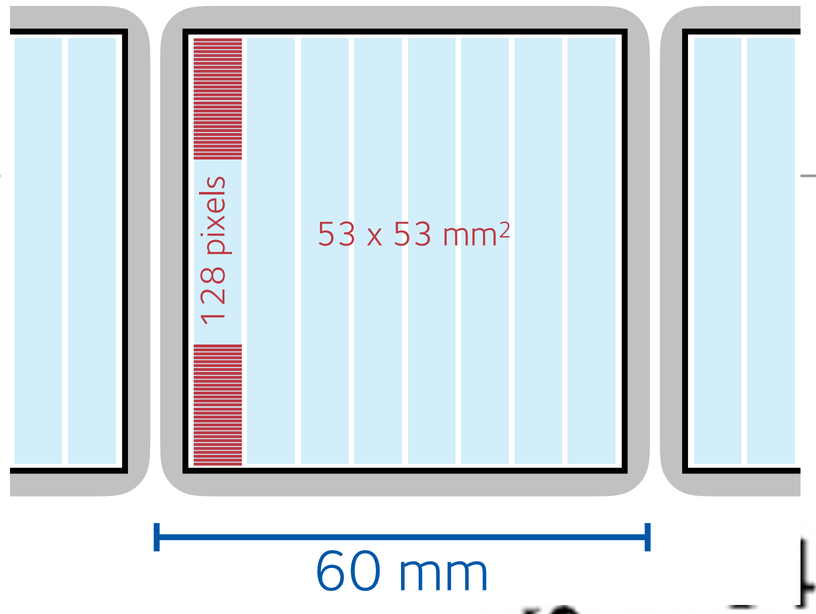
This image represents an analytic PDF (not an MC simulation) that describes the probability to obtain a hit on a point x_{det}, y_{det} on the detector plane at time t_{det} (time dimension not shown, here), for a given particle type hypothesis.

LHCb-PUB-2022-004

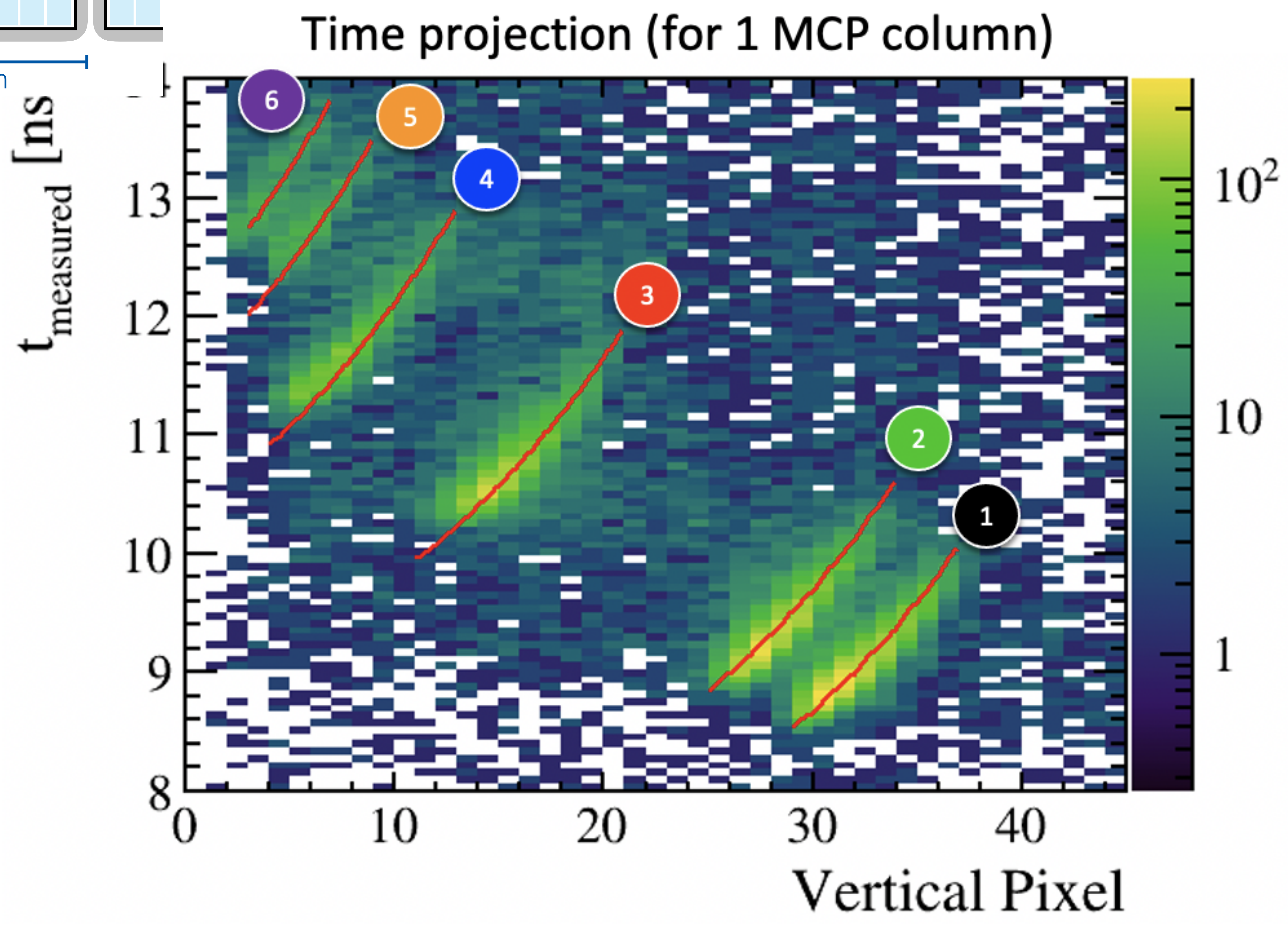




111cm
33cm



128 pixels
53 x 53 mm²
60 mm

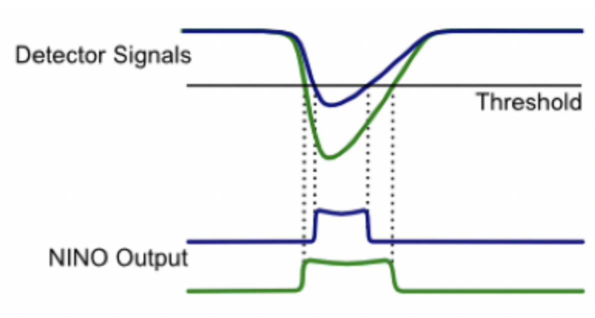


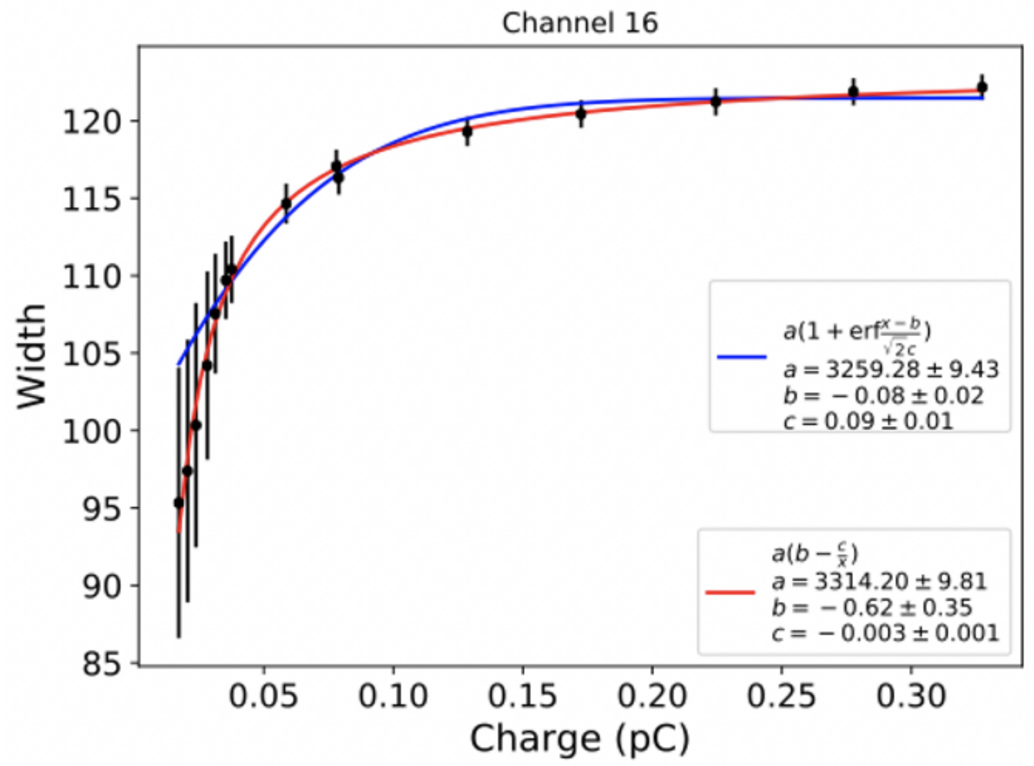
Time projection (for 1 MCP column)
t_measured [ns]
Vertical Pixel
6
5
4
3
2
1

Something like this on on readout?

TORCH readout electronics

- Custom readout electronics developed, based on the ALICE TOF system: NINO + HPTDC [F. Anghinolfi et al., Nucl.Instrum.Meth.A533:183-187(2004), M. Despeisse et al., IEEE58:202(2011)]
- NINO-32 provides time-over-threshold information which is used to correct time walk & charge to width measurement. Non-linearities of HPTDC time digitization (100 ps bins) are also corrected
- 128 channel NINO board developed [R. Gao et al., JINST 10 C02028 (2015)]
- The calibrations are challenging and work is still ongoing to optimize them





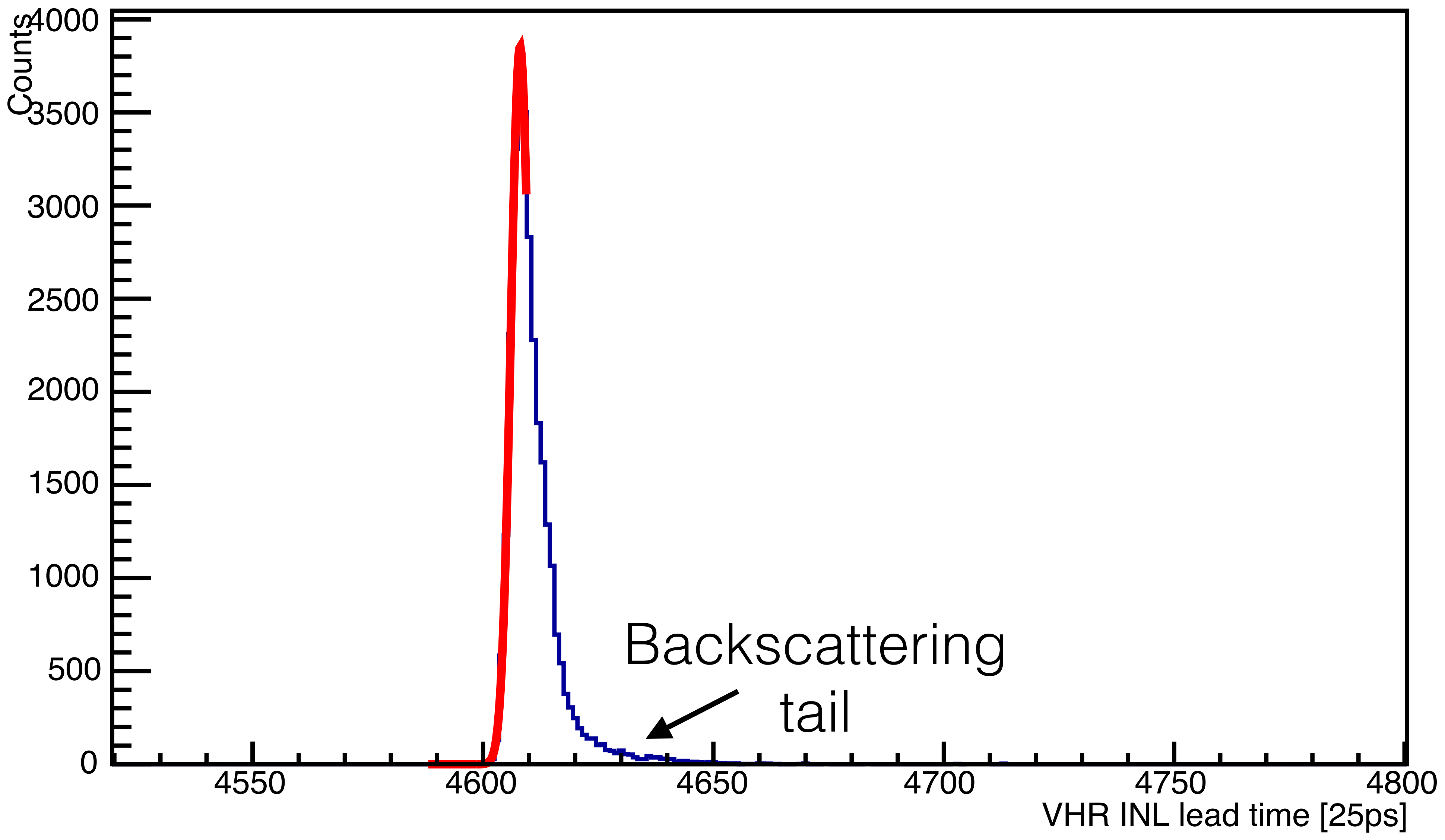
Lab tests

Illuminate MCP-PMT with fast pulsed laser

Full readout electronics connected.

Measured resolution: of 49.6 ps

Comparable to expectation of 50 ps

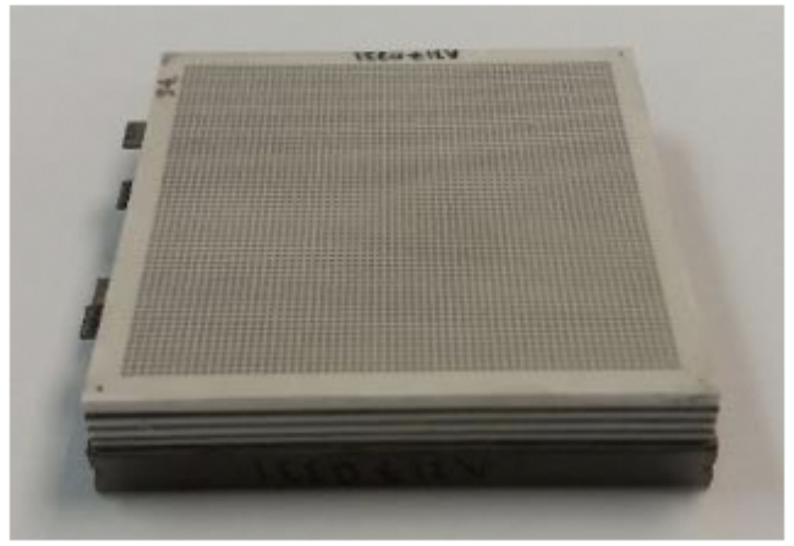


Aiming for 70ps time resolution per photon.

For ~30 detected photons/track, need $\sigma_\gamma \approx 70\text{ps}$ per photon for $\sigma_{total} = 70\text{ps}/\sqrt{30} < 15\text{ps}$

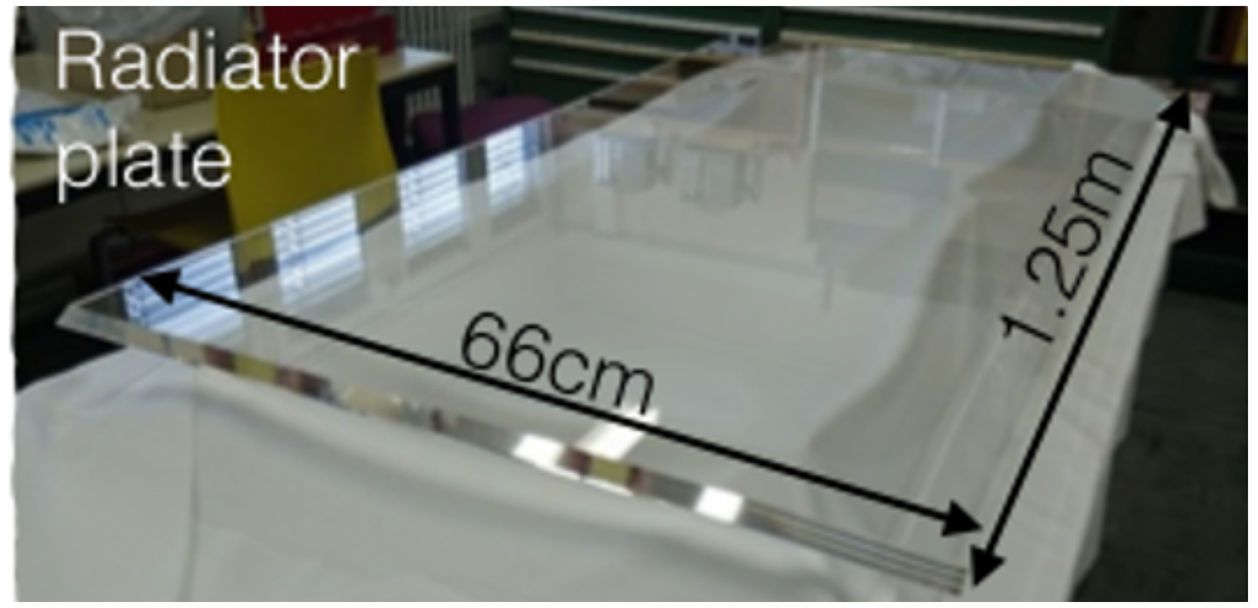
Needs:

Fast photo detectors. Multi-channel plate PMTs



Fast electronics: Custom design (JINST 10 C02028 (2015)) using NINO (NIM A533:183-187(2004)), and HPTDC (IEEE58:202(2011)).

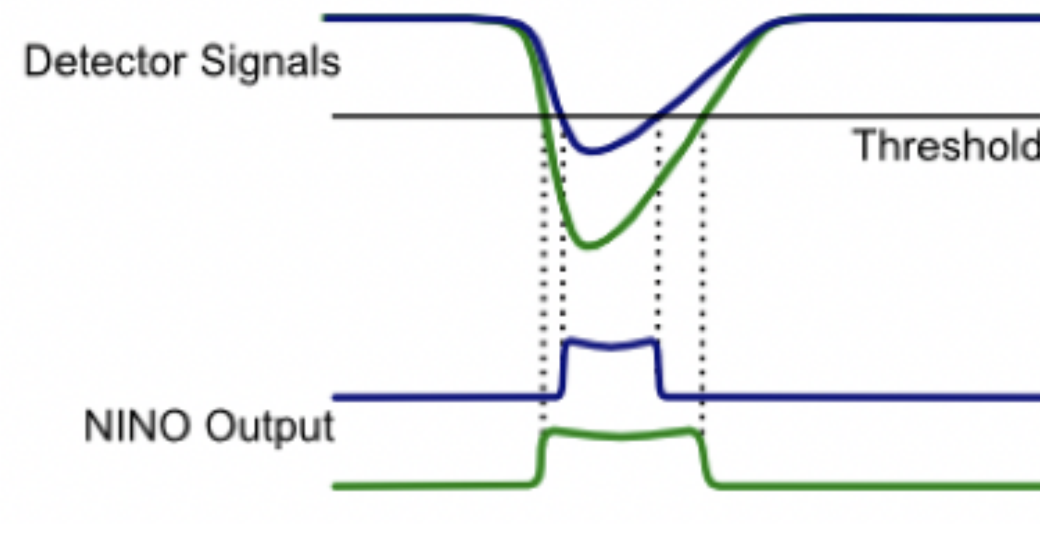
Superb optical components

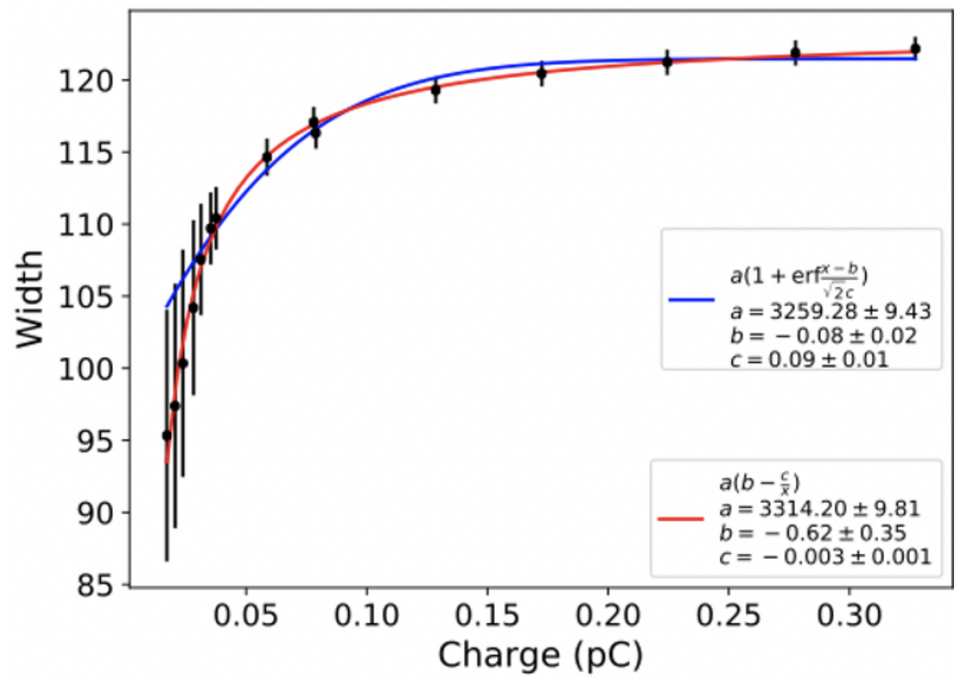


Readout electronics

Current: Custom design (JINST 10 C02028 (2015)) inspired by ALICE TOF, based on NINO (NIM A533:183-187(2004), and HPTDC (IEEE58:202(2011)).

Future: new system based on picoTDC

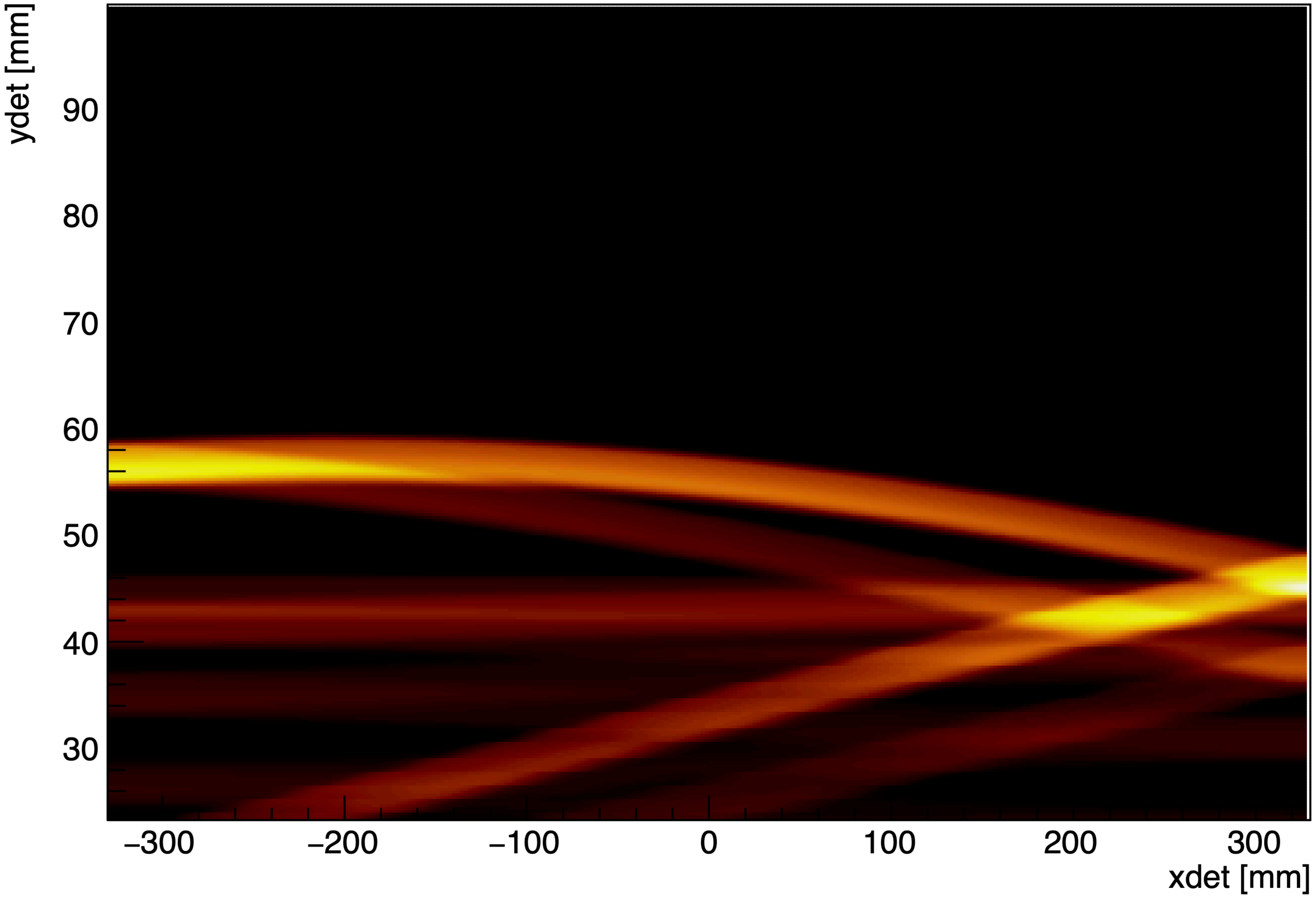




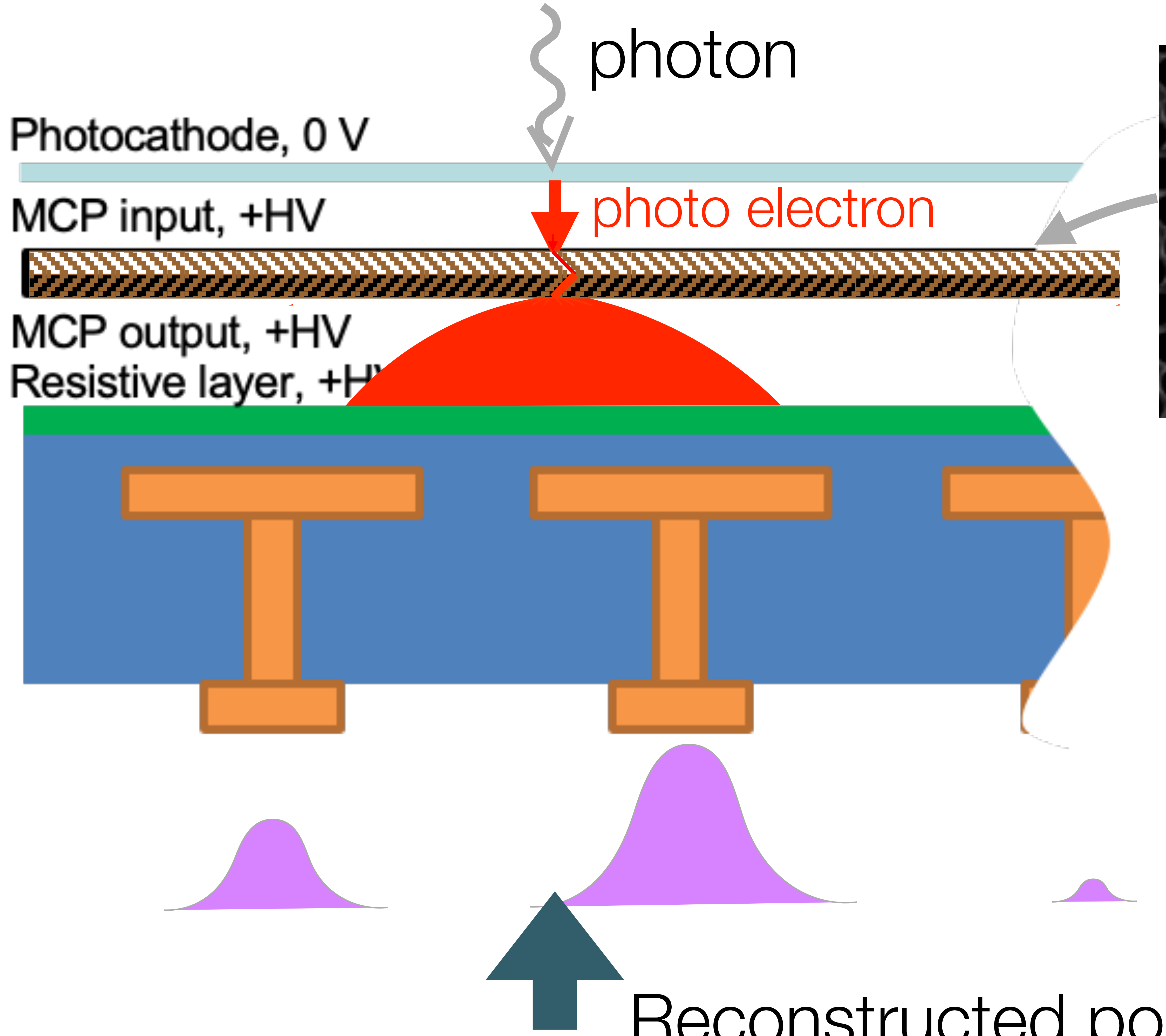
The image on the detector plane from a single track (w/o pixelisation)

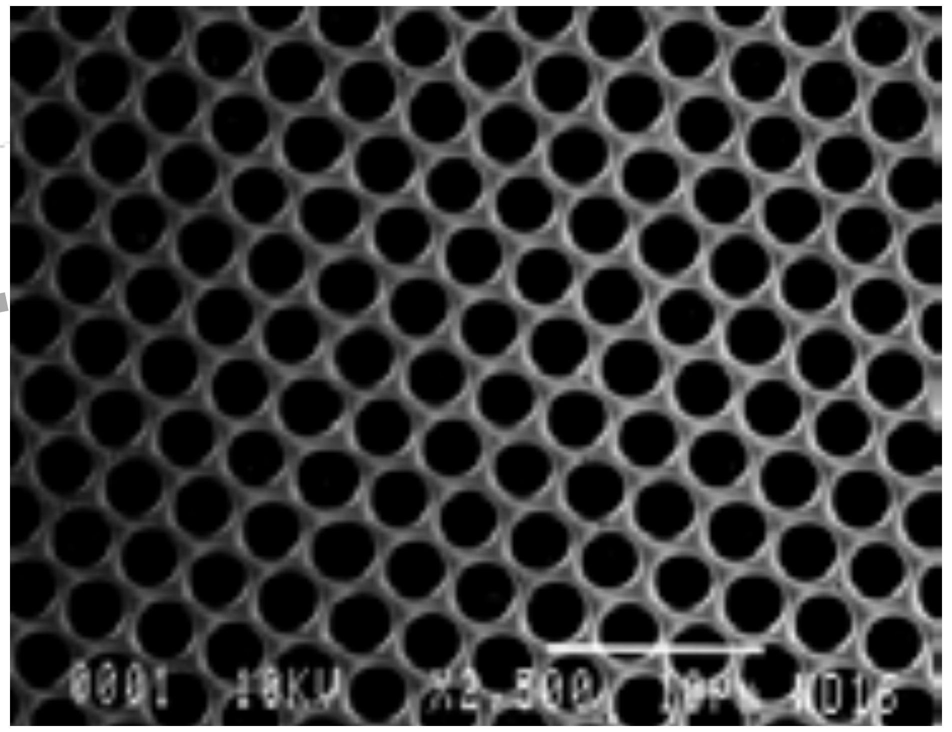
Width of lines because: different wavelengths emitted at different θ_C, travel with different propagation velocity, and different path length. We need to resolve this.

This image represents an analytic PDF (not an MC simulation).
LHCb-PUB-2022-004



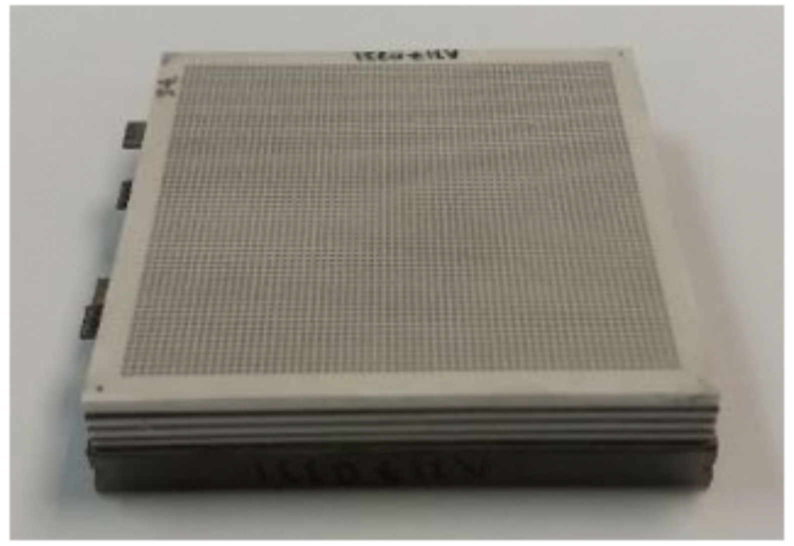
The MCP-PMT





- Dual micro channel plate (MCP) with 10-25 μm pores
- Conformal coating of Al_2O_3 or MgO through Atomic Layer Deposition results extended lifetime of tube ($5\mathrm{C/cm^2}$).

Prototype developed by our industrial partner, Photek



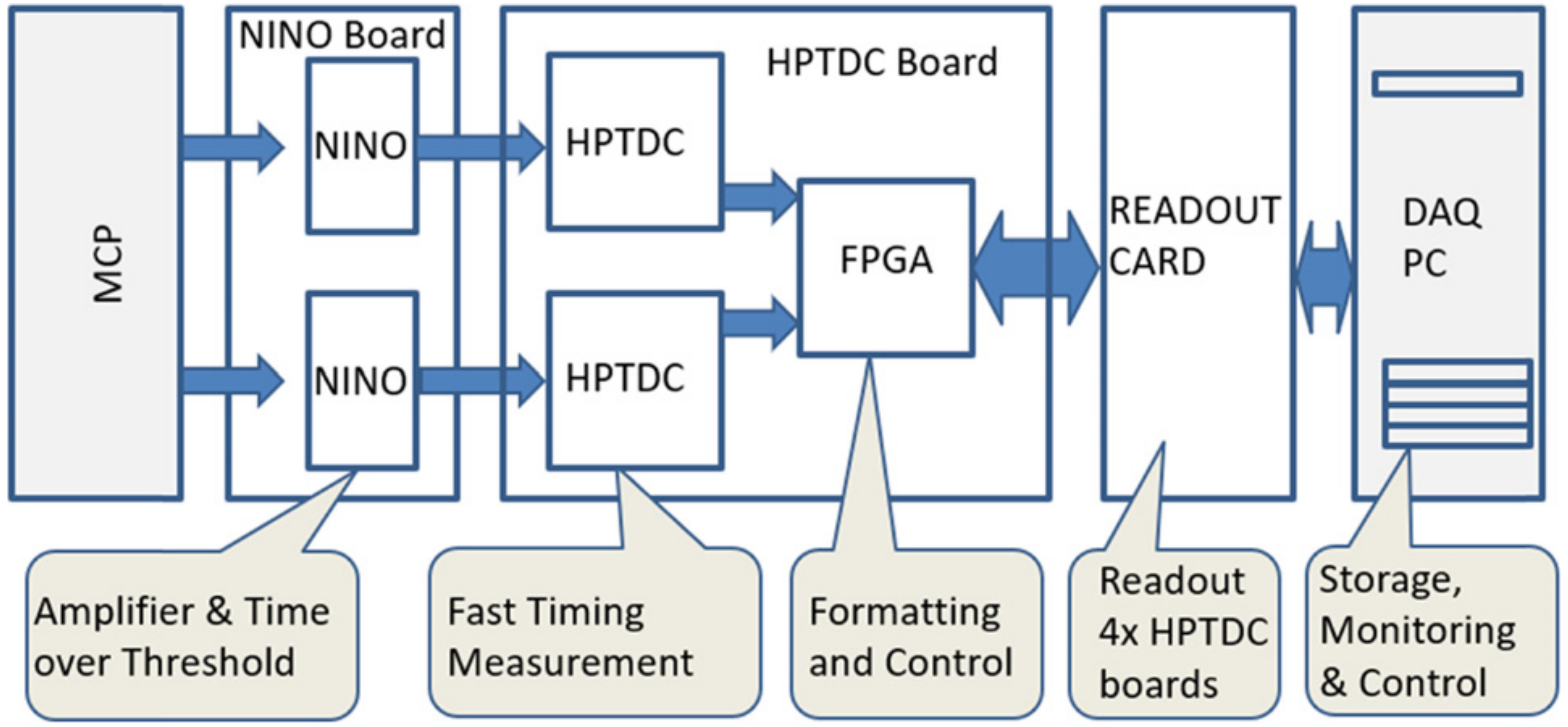
- 64 x 8 readout pads
- Required 128x8 resolution achieved through charge sharing.

JINST 10 (2015) 05, C05003

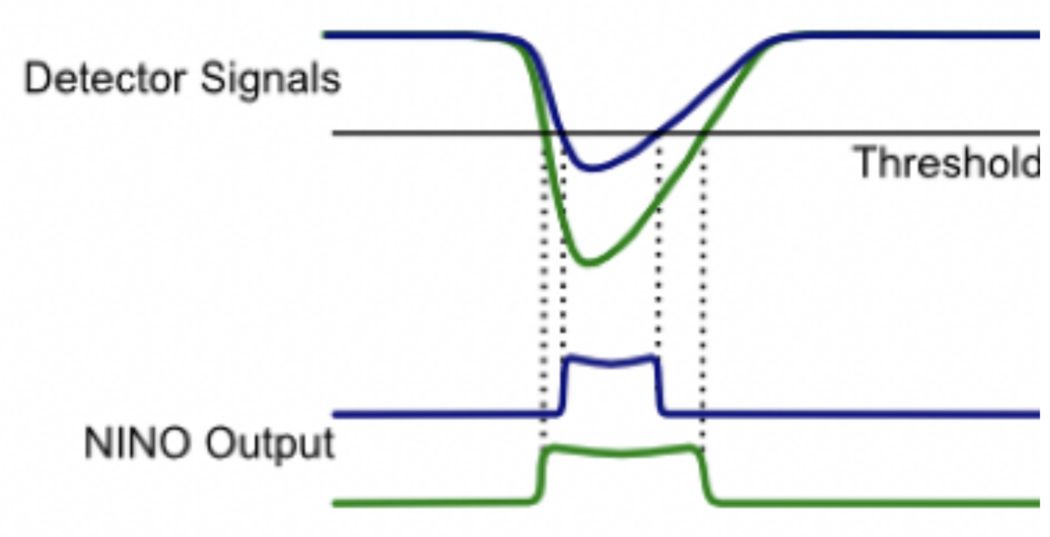
Readout electronics

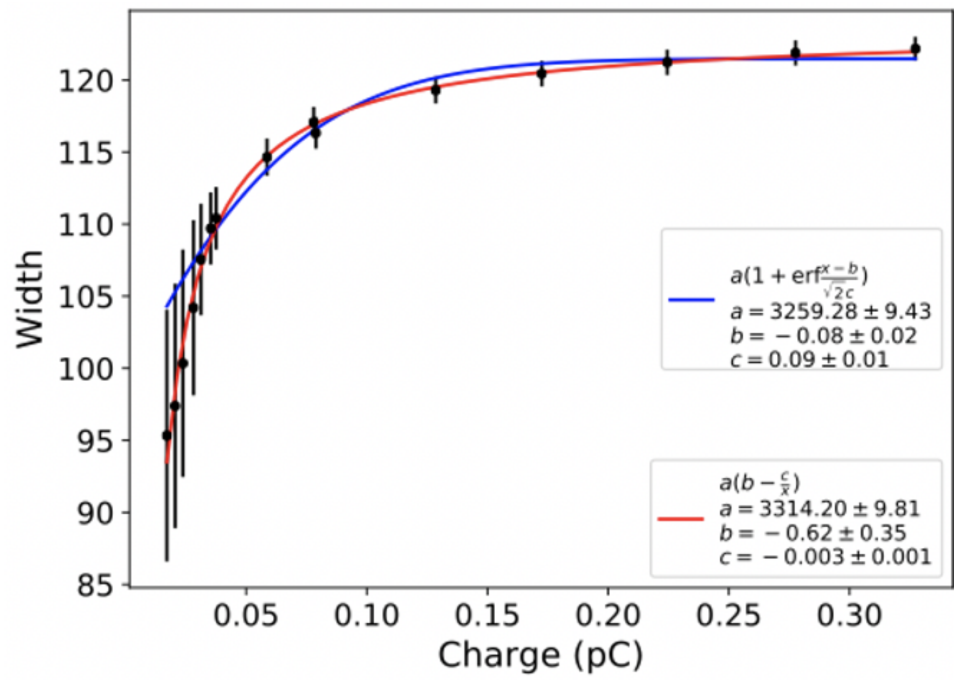
JINST 10 (2015) 02, C02028
JINST 17 (2022) 05, C05015

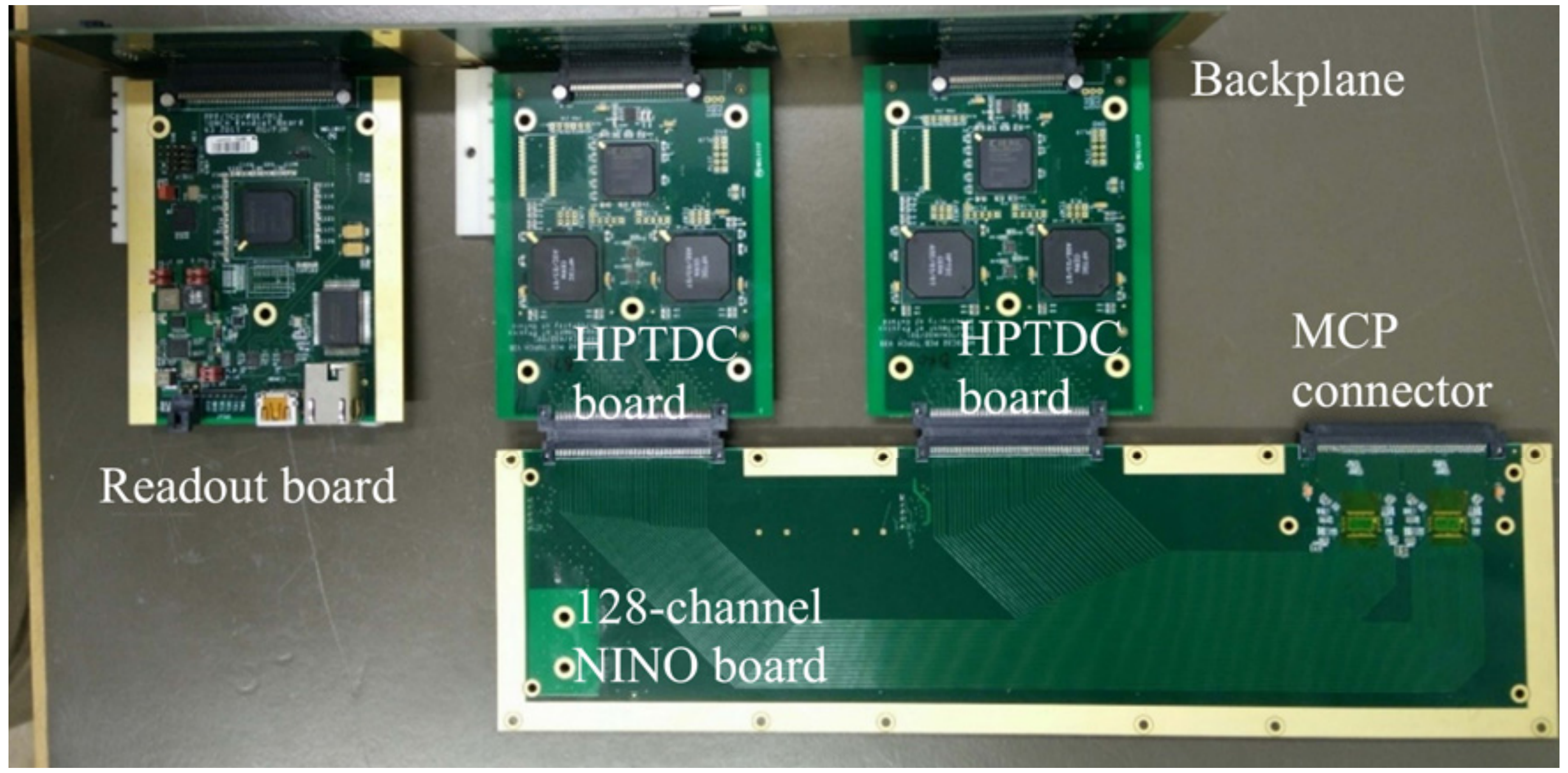
Current: Custom design inspired by ALICE TOF, based on NINO (NIM A533:183-187(2004)), and HPTDC (IEEE58:202(2011)).



Newly commissioned system being used right now to calibrate electronics.

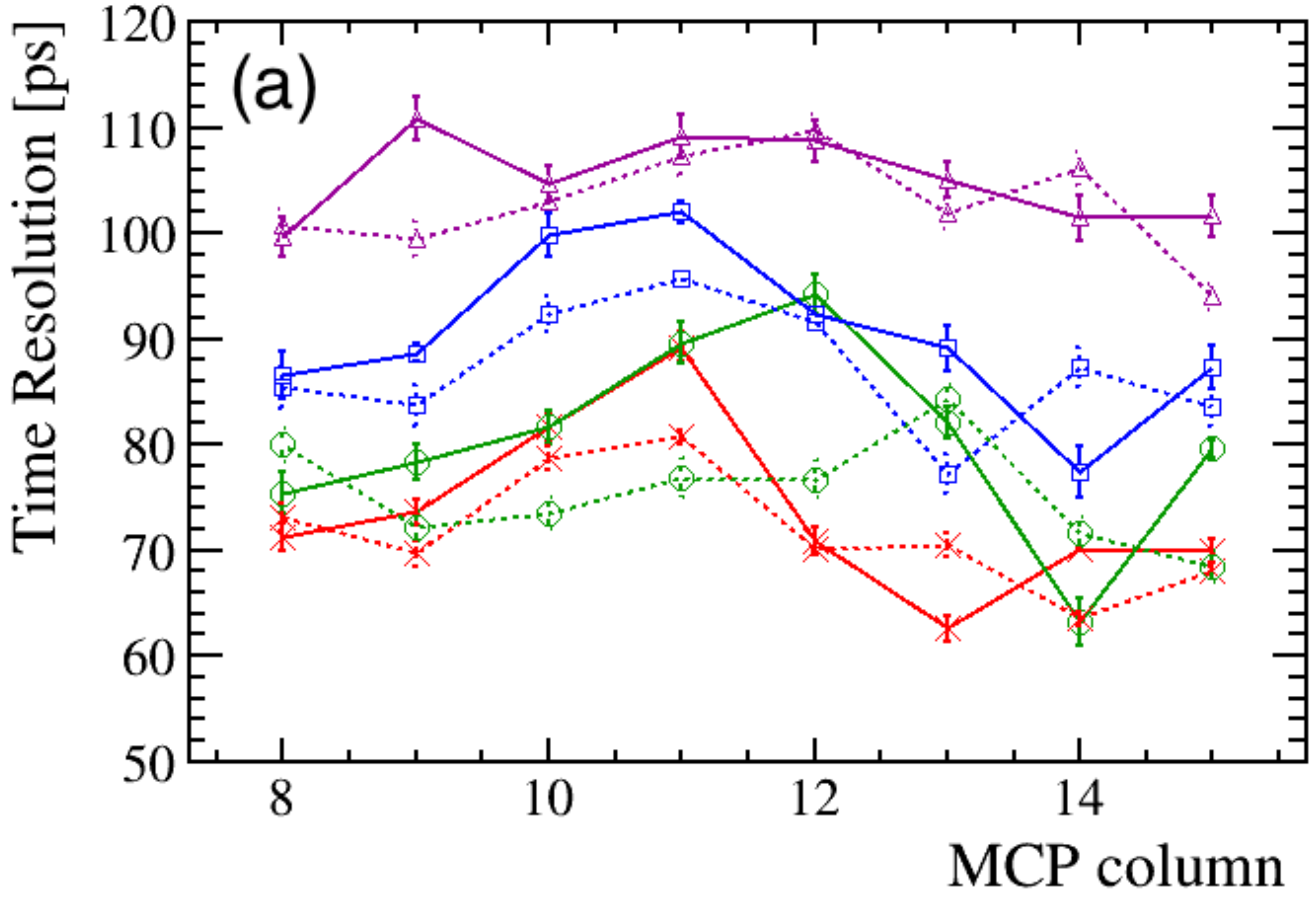






Future: developing new system based on picoTDC

Time resolution per photon in testbeam



Design goal of 70ps/photon is within reach.