PID — time-of-flight detectors

Photon and Particle Identification Detectors
STFC PPTAP meeting

4th of June 2021

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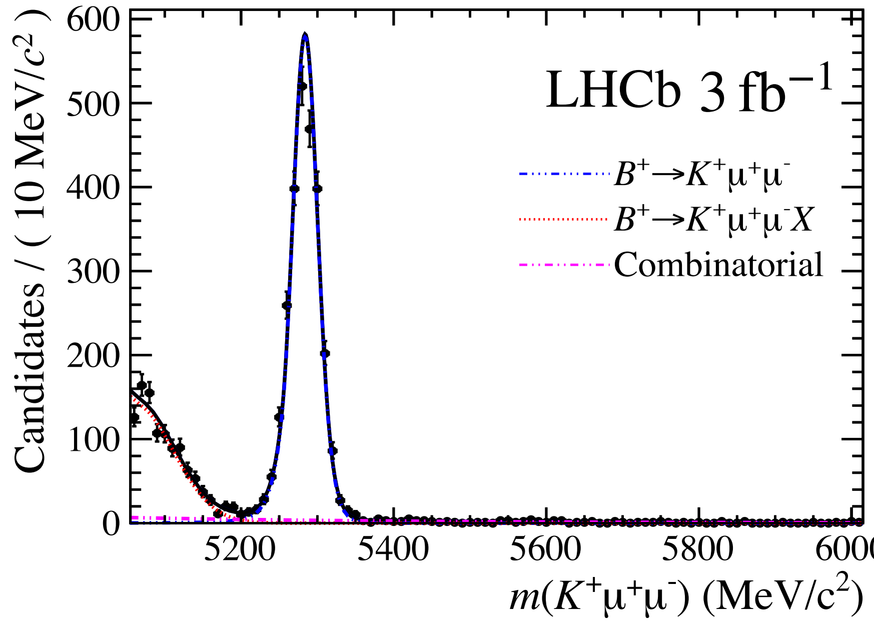
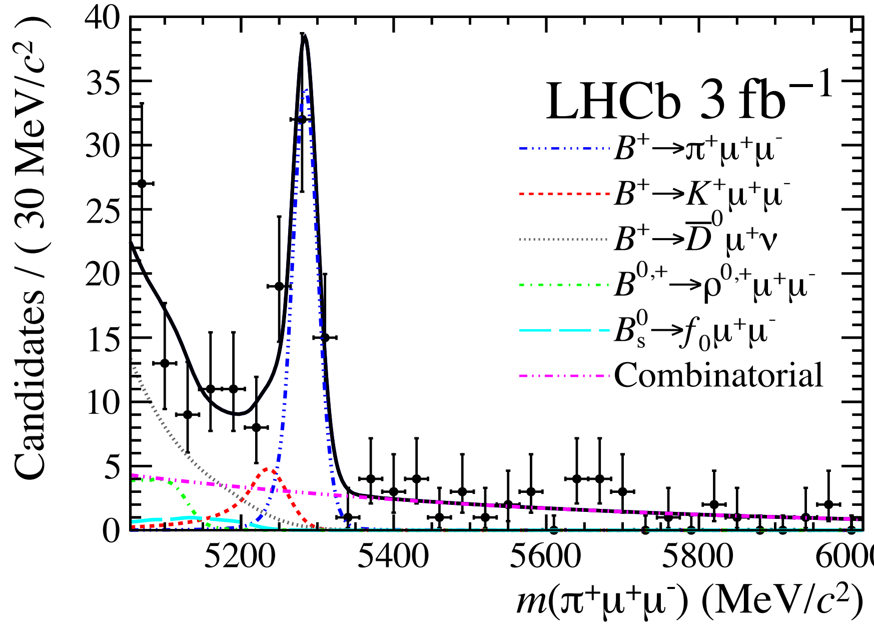
WARWICK
THE UNIVERSITY OF WARWICK

Charged hadron identification

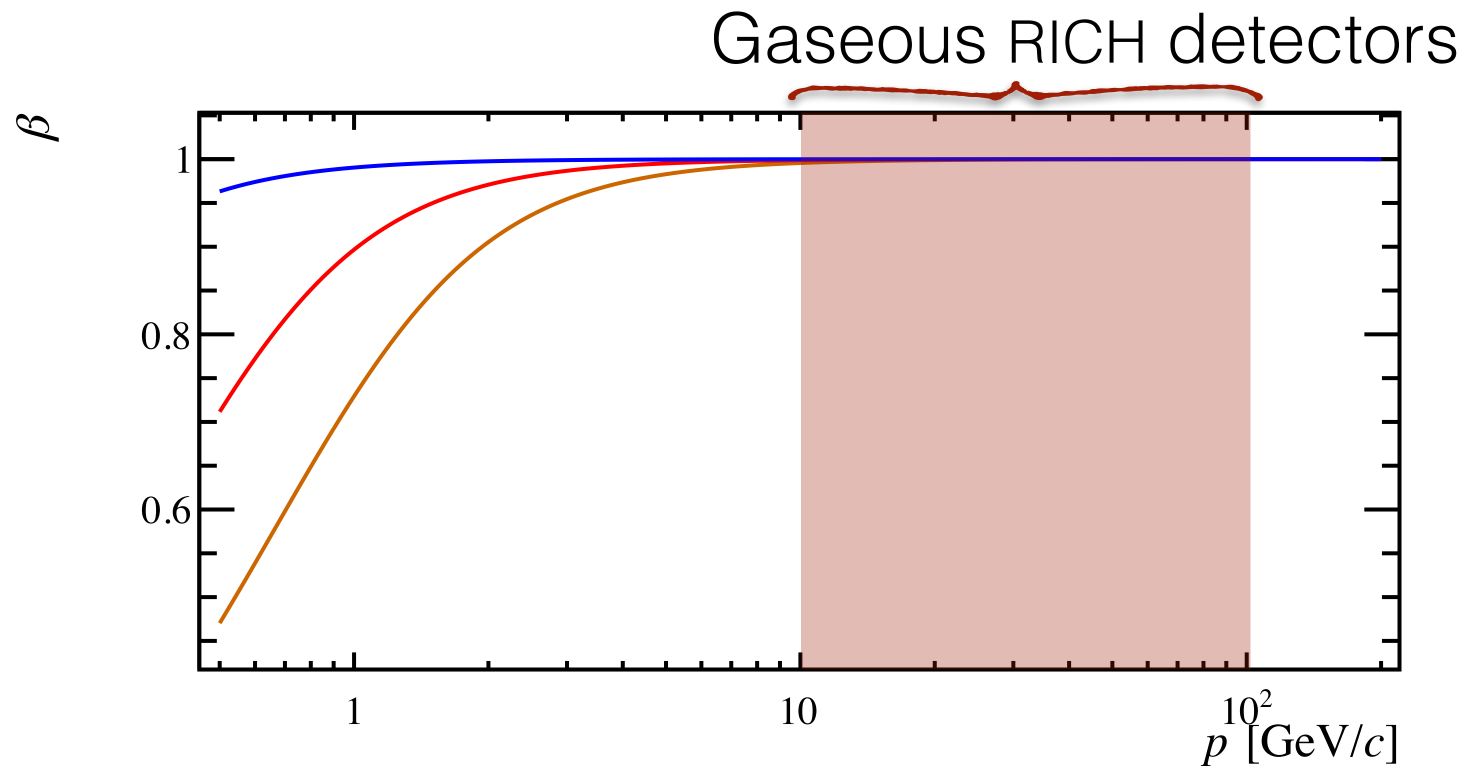
- Charged hadron identification ($\pi/K/p$ separation) is essential for a broad flavour physics programme.
  - Importance of this programme is underlined in the update for the European Strategy for particle physics.
  - Charged hadron ID is a strength of the LHCb and Belle 2 detectors and important ingredient of the proposed phase-II LHCb upgrade.
- Increased focus on flavour with the recent evidence of lepton flavour non-universality in rare B meson decays **[LHCb, LHCb-PAPER-2021-004]**.

[LHCb, JHEP 10 (2015) 034]

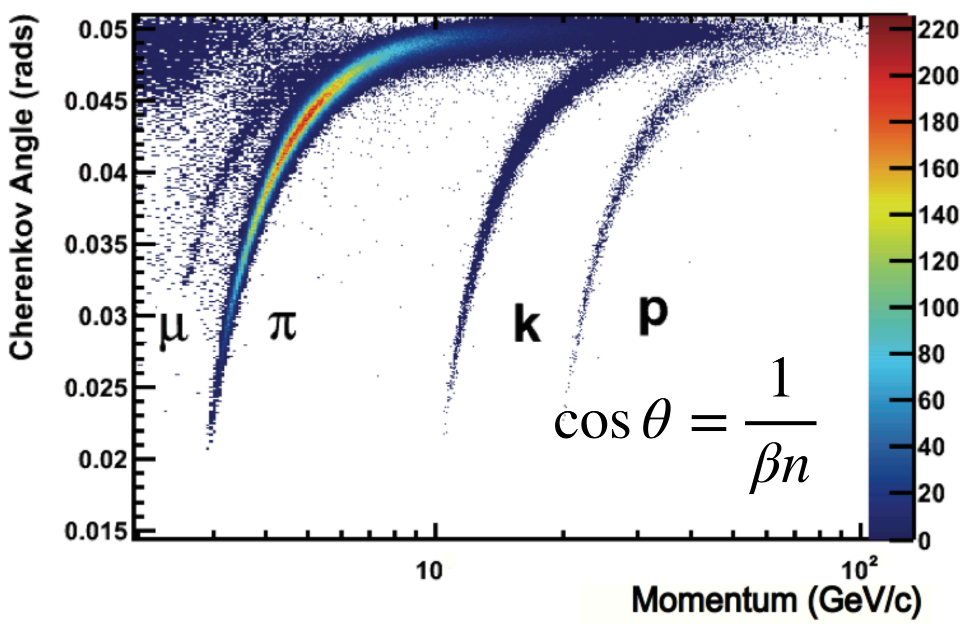




Ring-imaging Cherenkov detectors



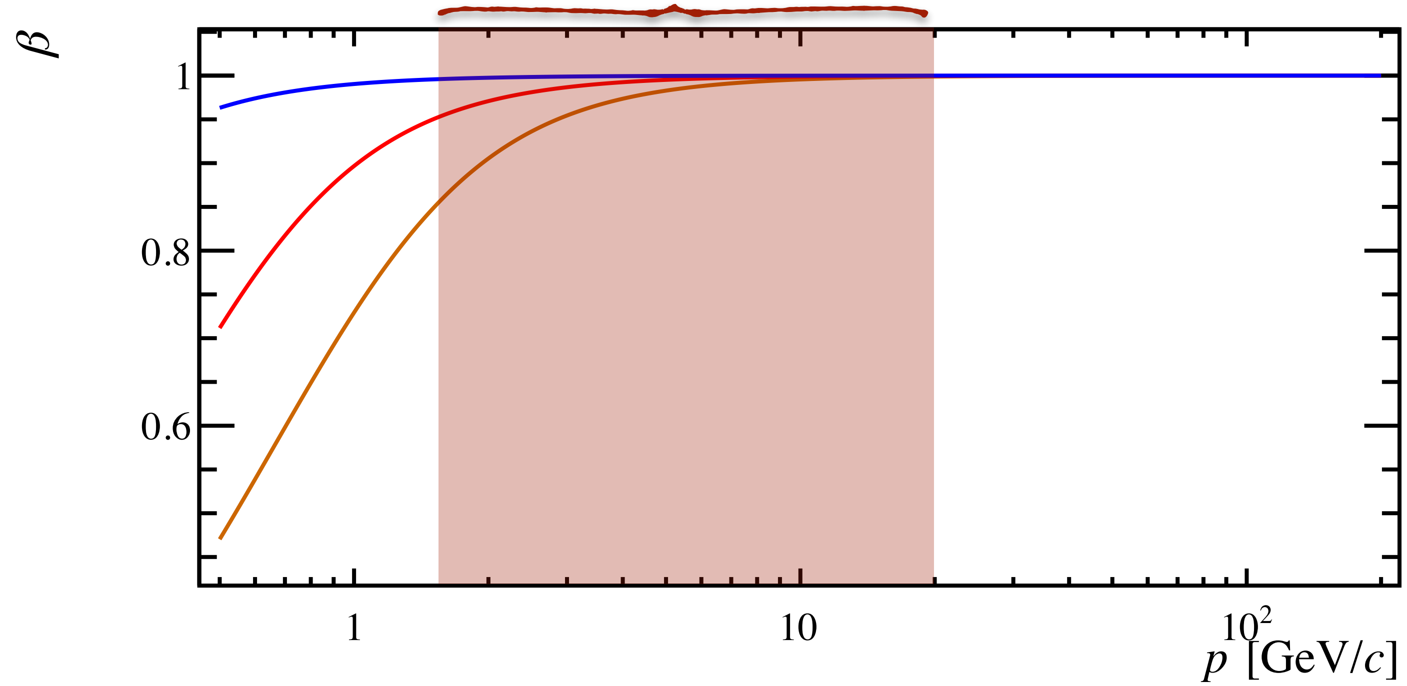
- In $10 < p < 100\,\mathrm{GeV}/c$ can achieve excellent separation using gaseous ring-imaging Cherenkov detectors.
  - Below 10 GeV/c kaons and protons are not above the Cherenkov threshold.
  - Above 100 GeV/c βn saturates.
- See talk by M. McCann.



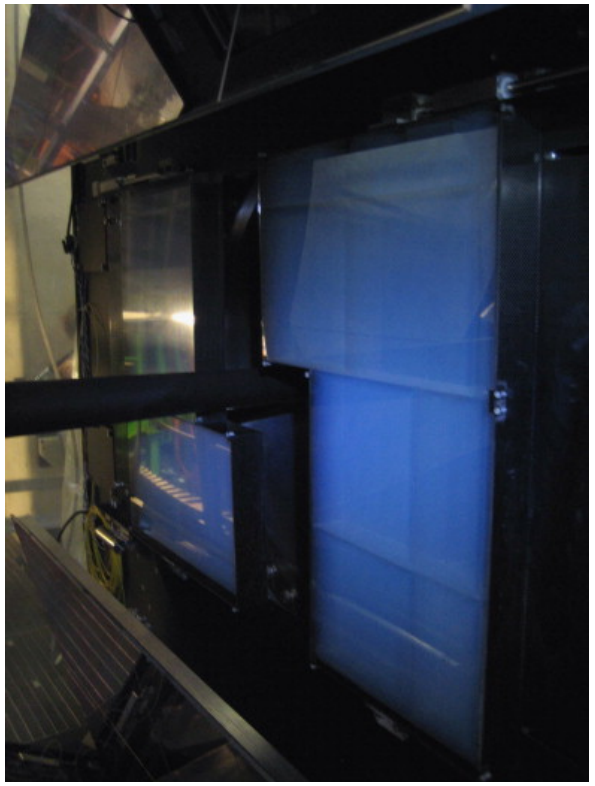
[LHCb, EPJC 73 (2013) 2431]

Ring-imaging Cherenkov detectors

RICH detector with Silica Aerogel



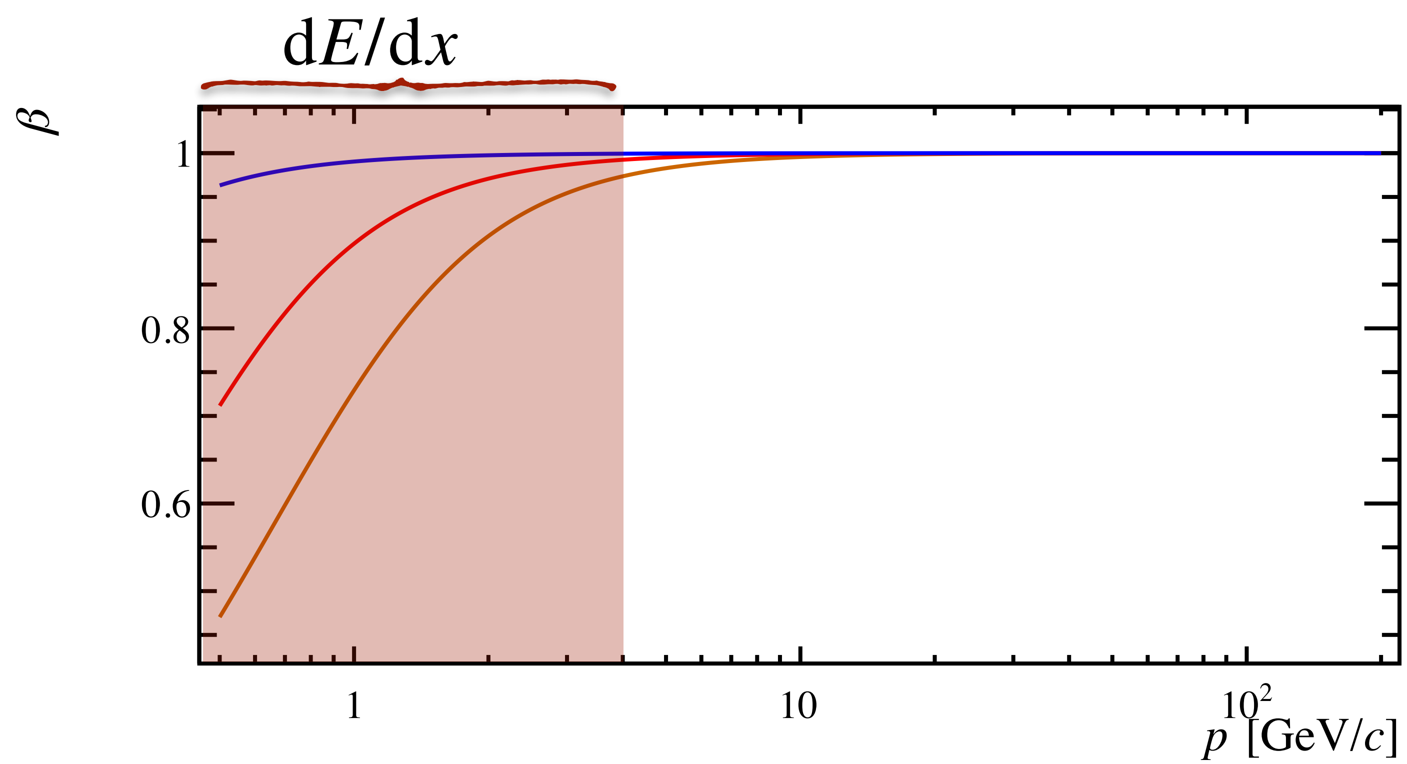
LHCb RICH 1 detector in Run 1

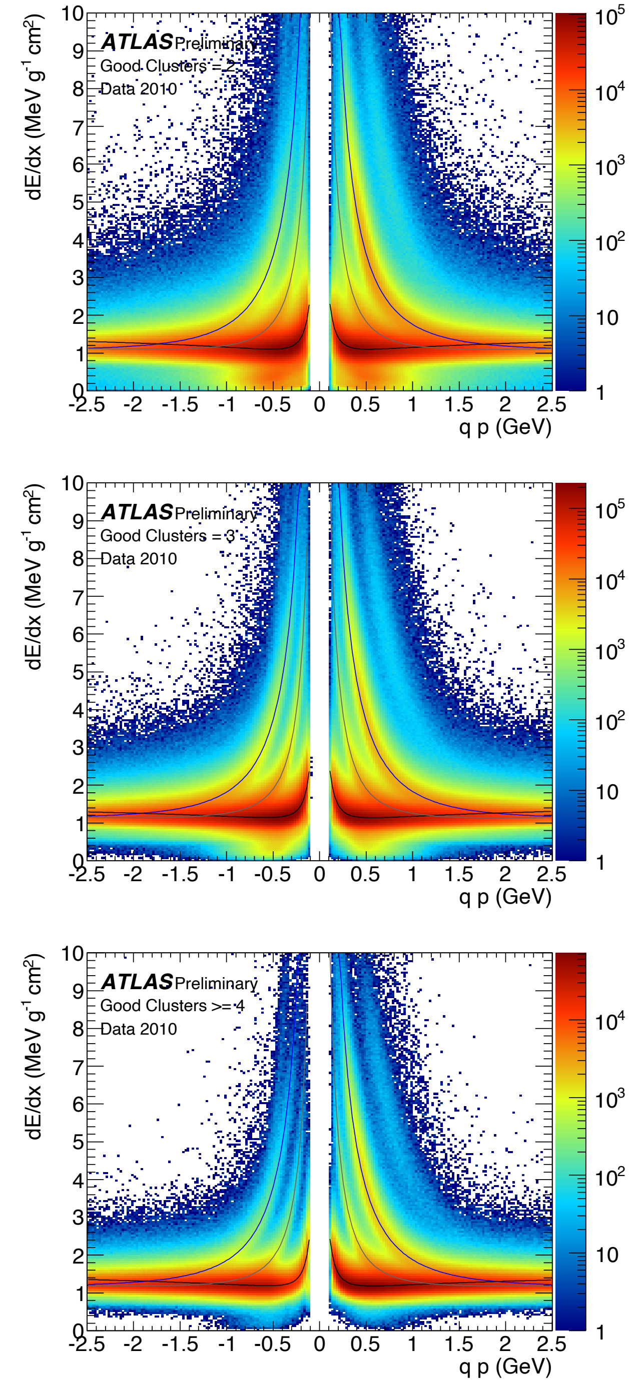


[LHCb, NIM A 639 (2011) 234-237]

- At smaller momentum can use radiators with higher refractive indices, e.g. silica aerogel.
  - Challenge in high-occupancy environments due to large backgrounds and small signal.
- Aim to improve PID in this momentum range using a TOF detector in the phase II LHCb upgrade.

dE/dx





- At low momentum, can exploit dE/dx in tracking detectors to separate pions, kaons and protons.

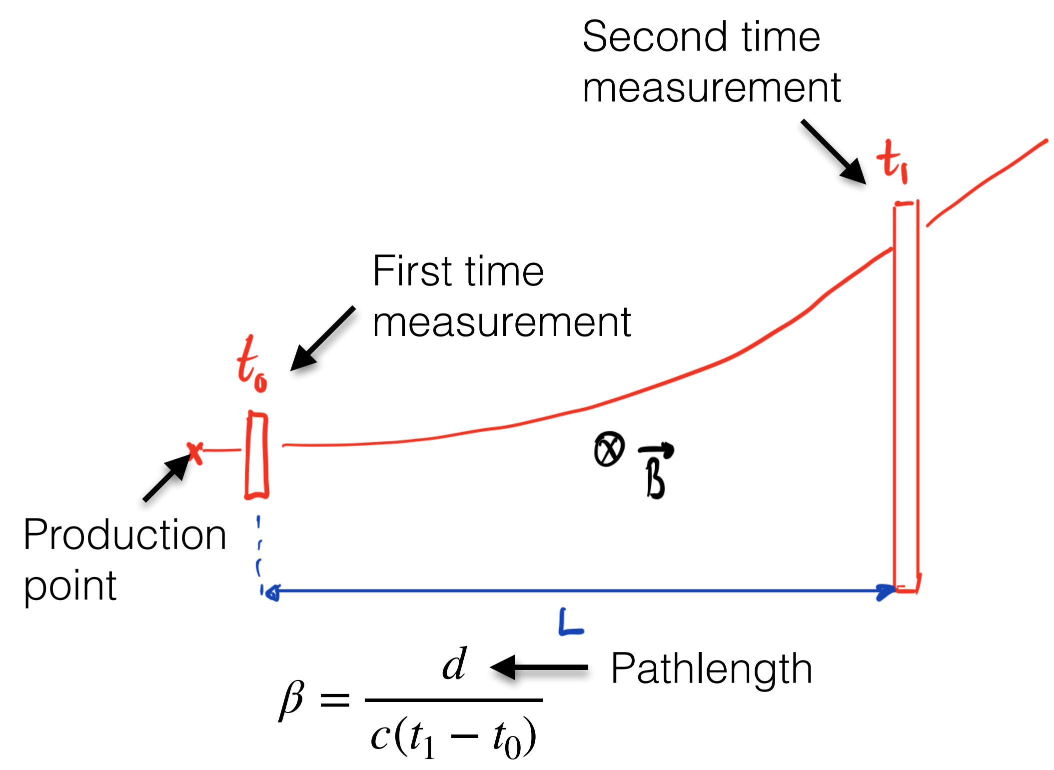
$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 E_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

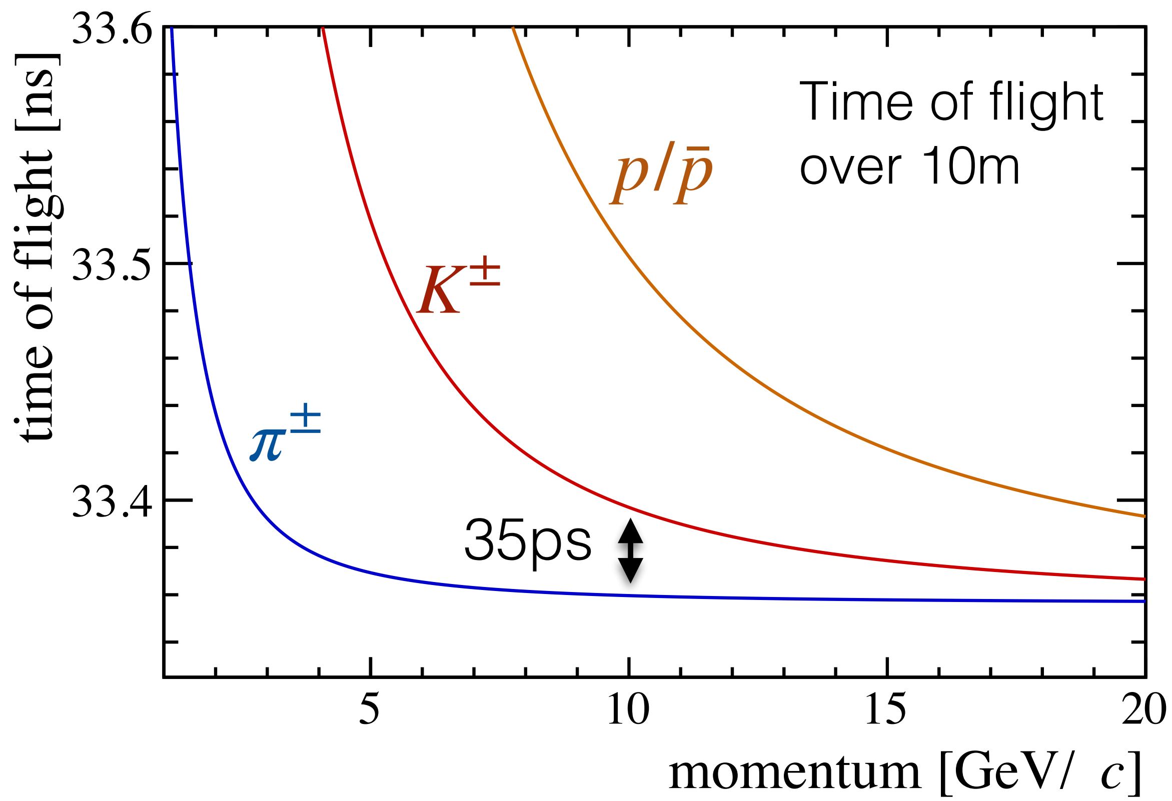
  - e.g. in ATLAS pixel detectors.

[ATLAS-CONF-2011-016]

Time-of-flight

- Measure the arrival time of a charged particle at two planes to determine $\beta = v/c$.
- Combine with a momentum estimate from tracking detectors to determine the mass.
- At higher energies β saturates, need excellent time precision (~15ps per track over a flight distance of 10m at 10 GeV/c).





Fast timing

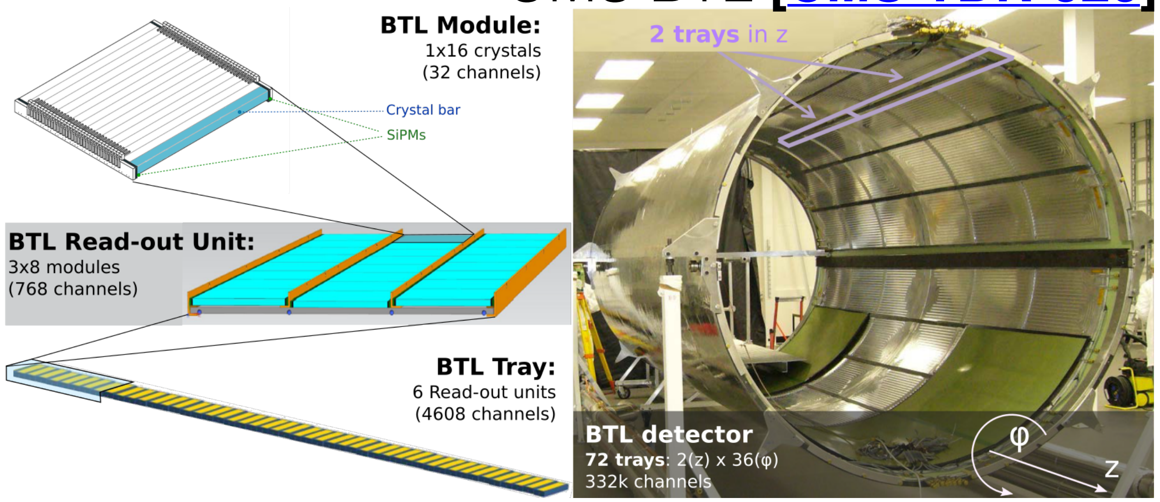
- Fast timing will be a feature of many of the detectors at the HL-LHC (driven by pile-up suppression)
    - Challenge to associate particles with the correct *pp* collision.

e.g.

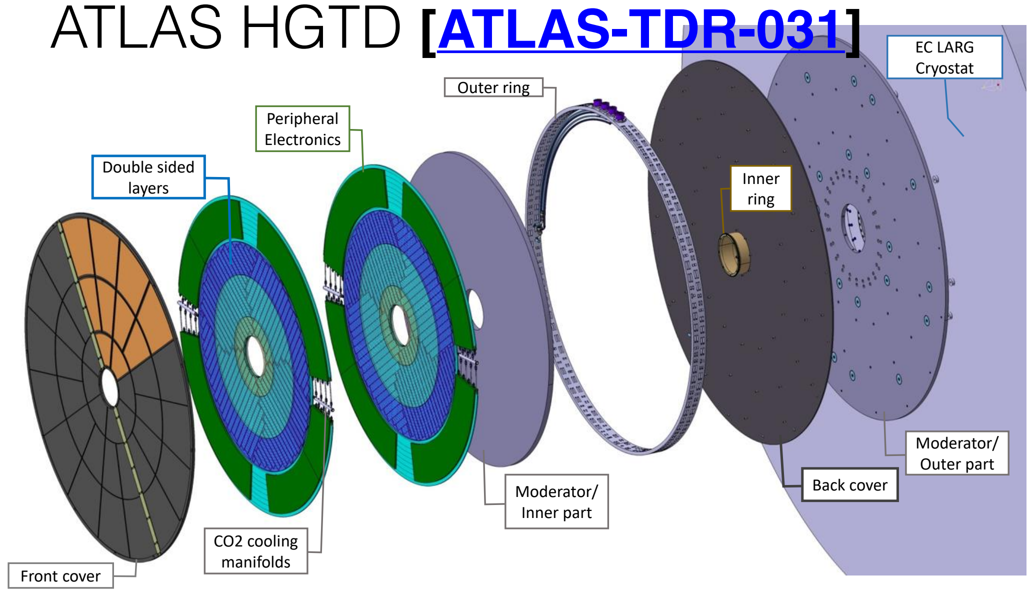
- ATLAS HGTD, CMS ETL, LHCb timing VELO using fast-timing in silicon.
- CMS BTL using fast scintillators (LYSO) and SiPMs.

- Typically target 30-50ps per MIP.

CMS BTL [CMS-TDR-020]



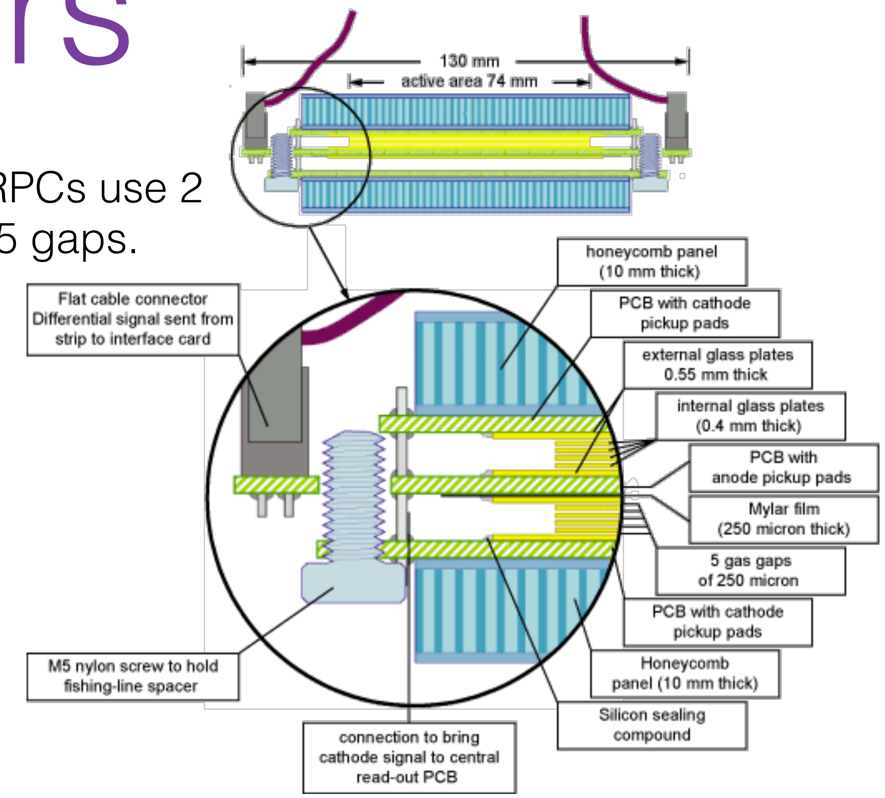
ATLAS HGTD [ATLAS-TDR-031]



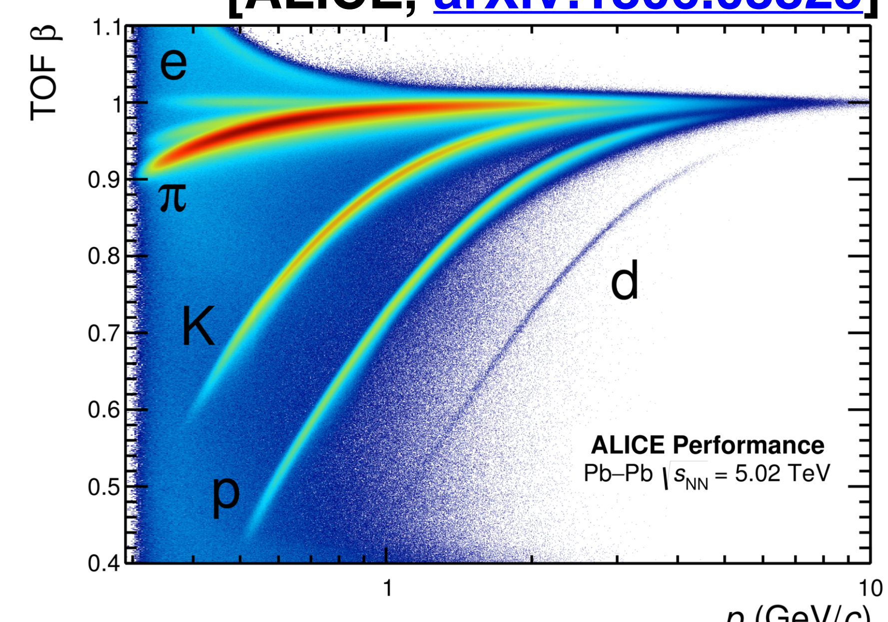
Gaseous timing detectors

- Multi-gap RPCs are a well established technology for fast-timing, e.g. used in ALICE TOF system.
    - ALICE achieved a time resolution of 56ps achieved in LHC Run 2 **[ALICE, arXiv:1806.03825]**.
    - Faster timing possible by increasing the number of gaps.
- MRPCs are also used widely in other existing and proposed TOF systems (e.g. the SHiP proposal).
- RD51 PICOSEC collaboration has developed micromegas with time resolutions of 24ps per MIP **[F. Brunbauer, INSTR-2020]**.

ALICE MRPCs use 2 stacks of 5 gaps.



[ALICE, arXiv:1806.03825]

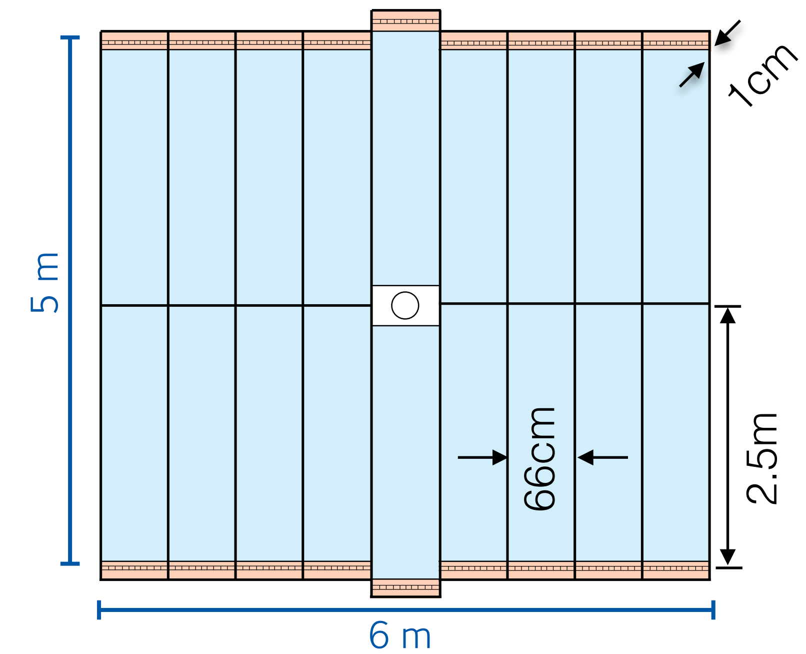


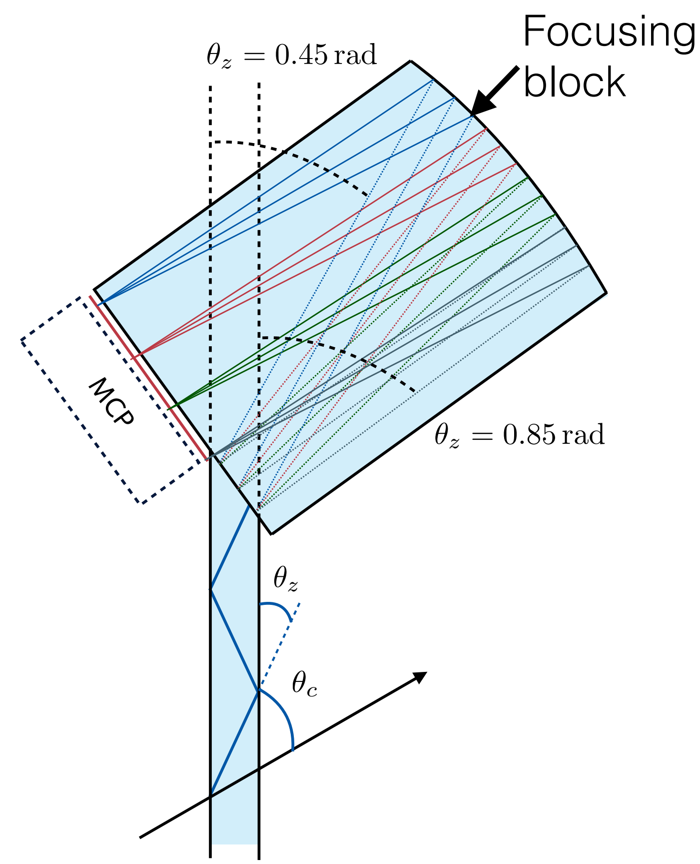
ALI-PERF-106336

ALICE TOF system is located 3.7m from the beam axis.

TORCH concept

- Large area time-of-flight detector designed to cover $2 < p < 10\,\mathrm{GeV}/c$ **[NIM A 639 (1) (2011) 173]**
  - UK-CERN R&D effort.
  - Aiming for installation as part of LHCb's phase II upgrade programme **[CERN-LHCC-2017-003]**
- Exploit prompt production of Cherenkov light in an array of quartz bars to determine time-of-flight.
  - Require a time resolution of 70 ps per photon to reach 15 ps per track.
- Transport photons to detector plane using total-internal-reflection from the quartz air boundary.
- Cylindrical focusing block focuses the image in the 2D (in the y-z plane).
  - Used to correct for chromatic dispersion.





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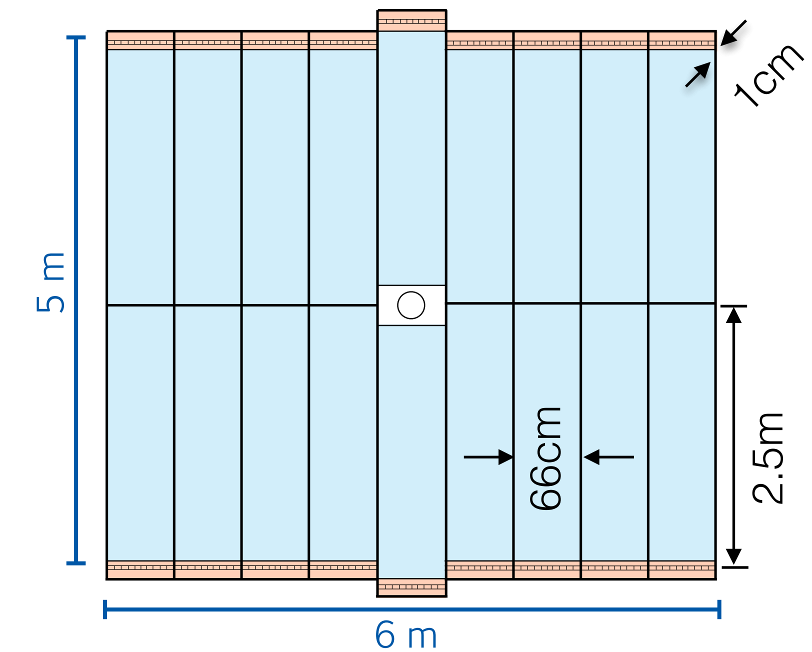
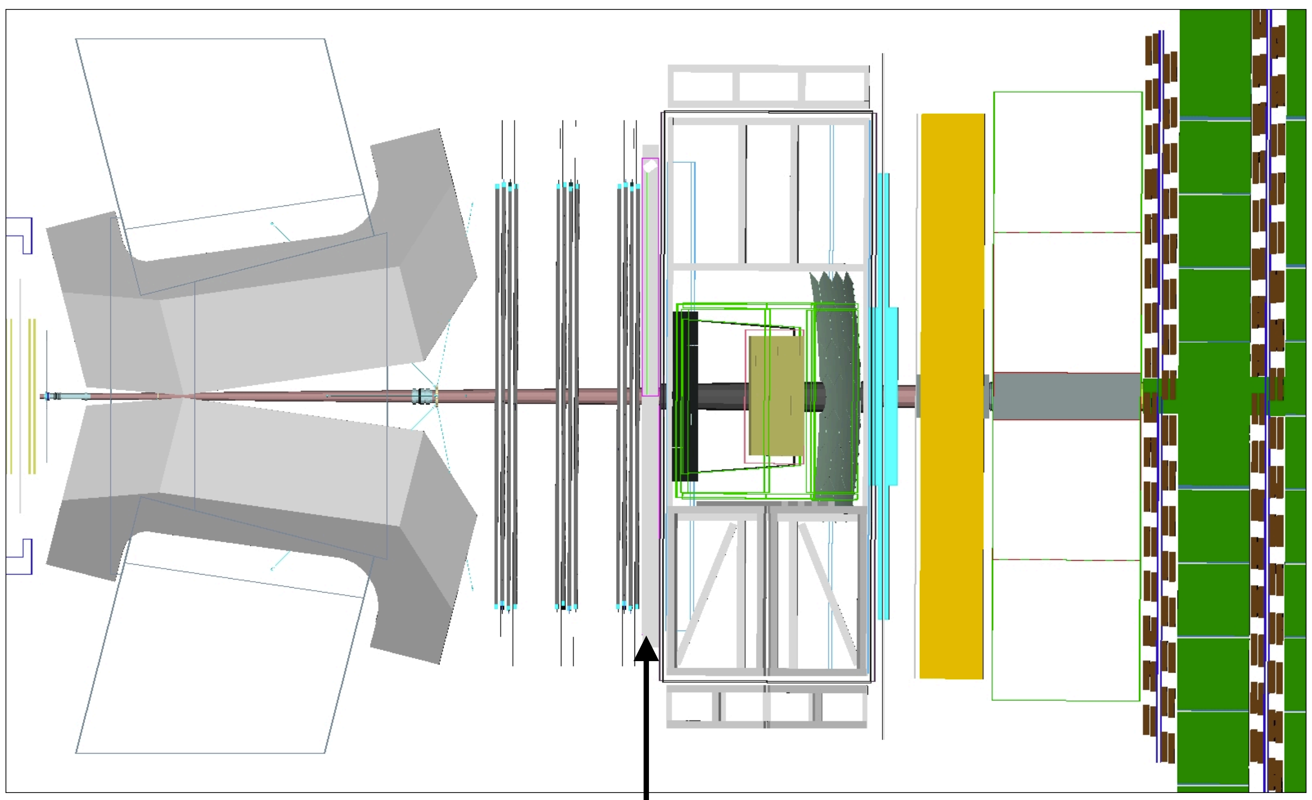


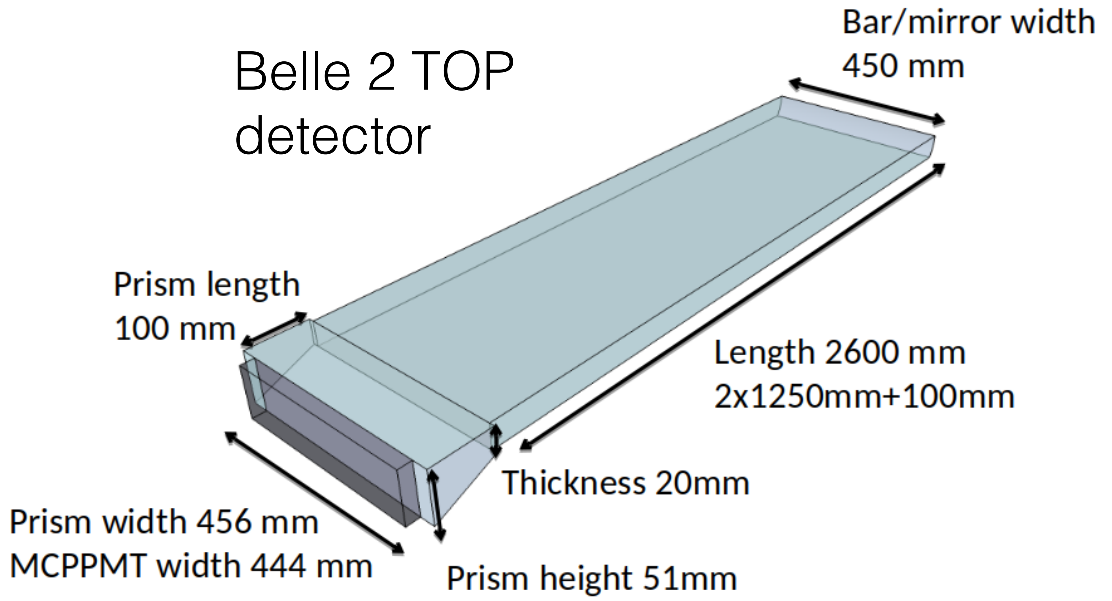


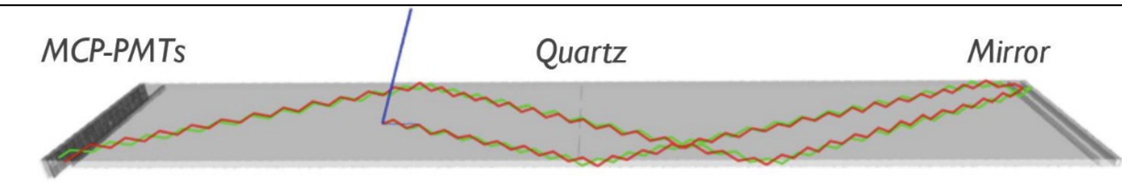
Positioned between downstream tracking system and RICH 2 (9.5m from *pp* interaction region).

- Start time provided by fast timing VELO detector (or by combining information from multiple tracks in TORCH).
  - 200 ps spread in *pp* collisions times.

DIRC evolution

- TORCH design is conceptually similar to a DIRC detector.
- Belle 2 employs a time-of-propagation DIRC counter for PID.
  - Signal-propagation time differs between π and K due to different paths in detector.
- Belle 2 obtains high-precision timing using Hamamatsu MCP-PMT detectors (~50ps per photon).





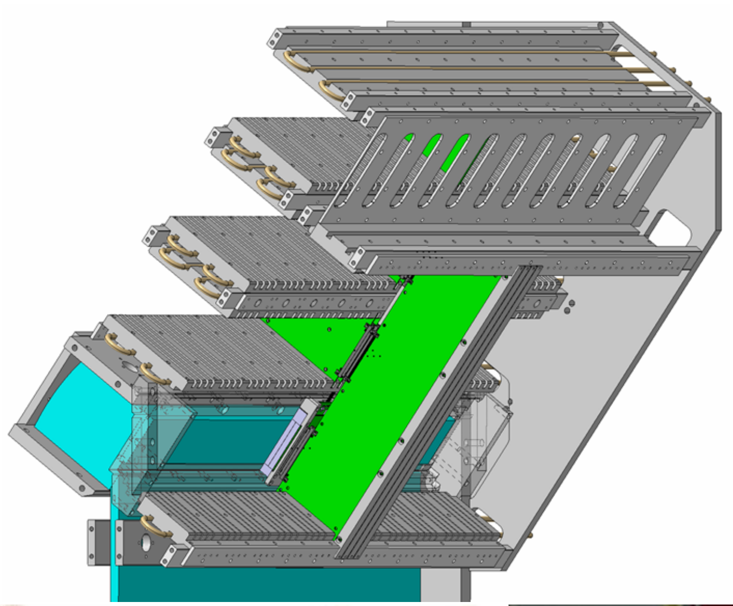
Example of Cherenkov-photon paths for 2 GeV/c $\pi^{\pm}$ and $K^{\pm}$.

[NIM A 952 2020,162208]

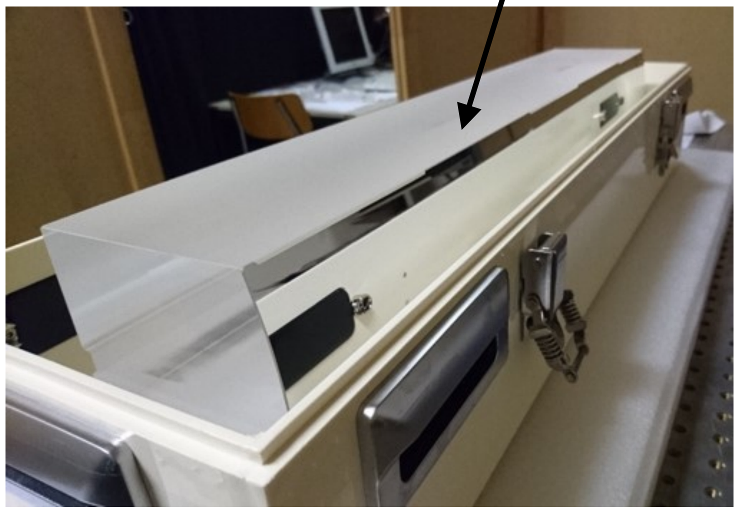
- Key innovation of TORCH is the measurement of the Cherenkov angle to correct for Chromatic dispersion.

TORCH half-scale demonstrator

- TORCH concept has been demonstrated using a half-scale prototype detector in a beam test at the CERN PS.
- Detector instrumented with two 512 channel MCP-PMTs.
- Quartz required to have high clarity and polishing to sub-nm surface roughness.

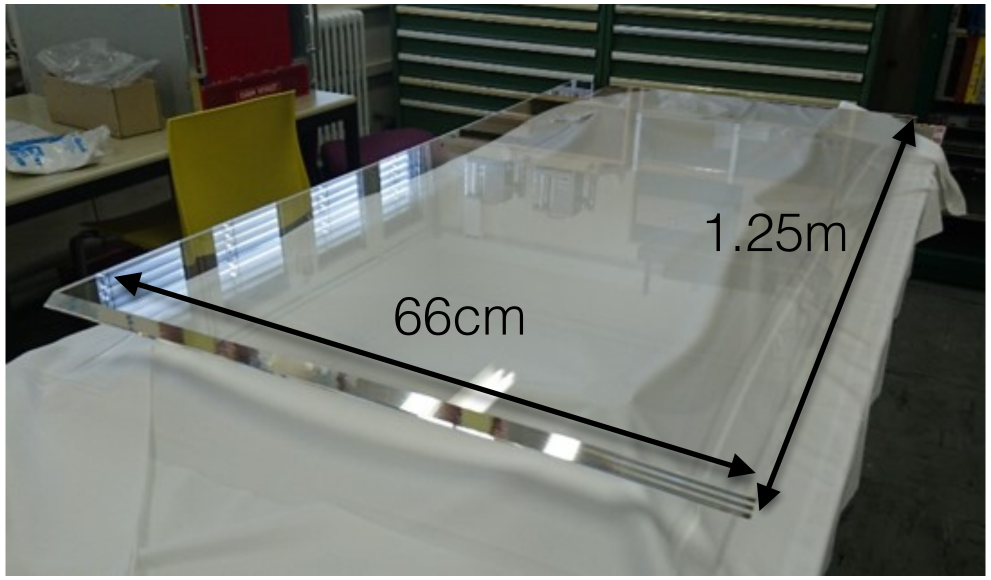


Focusing block



Assembly with holding mechanics

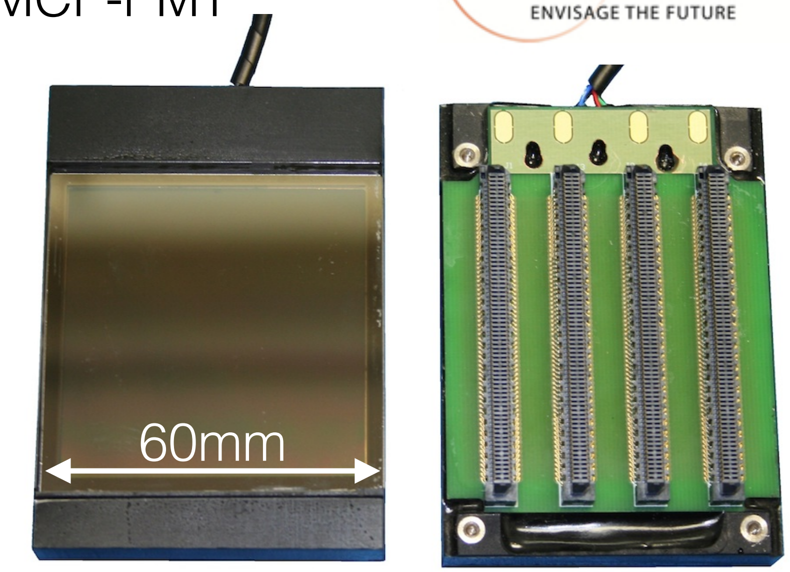
(light weight system will be needed for needed for the LHCb upgrade)

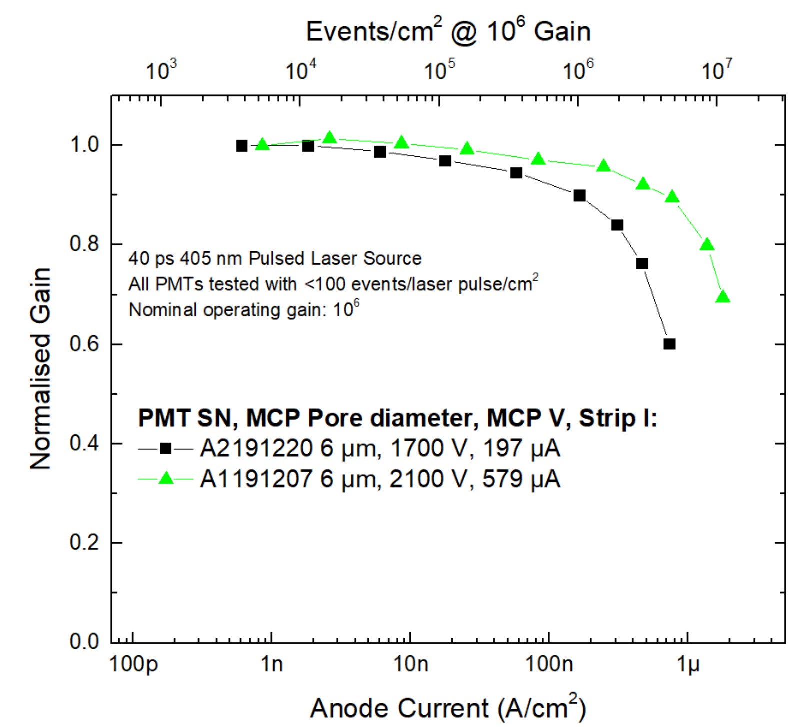


Fast timing photon detectors

- Need fast photon detectors with picosecond timing and fine granularity (obvious candidates are SiPMs and MCP-PMTs).
  - R&D programme with Photek to produce MCP-PMTs for the TORCH with 8-by-64 pixels and long-lifetimes ($>5\,\mathrm{C\,cm^{-2}}$) **[JINST 10 (2015) C05003]**.
- Challenge for LHCb upgrade/future kaon experiments is the development of detectors with long-lifetimes, high-rate capabilities and high-radiation tolerance.
  - R&D needed to improve the rate capabilities of existing devices to ~10MHz/cm^2.
  - Strong synergies between LHCb RICH, TORCH and NA62.
- See talk by S. Gambetta for more details.

Phase-III MCP-PMT

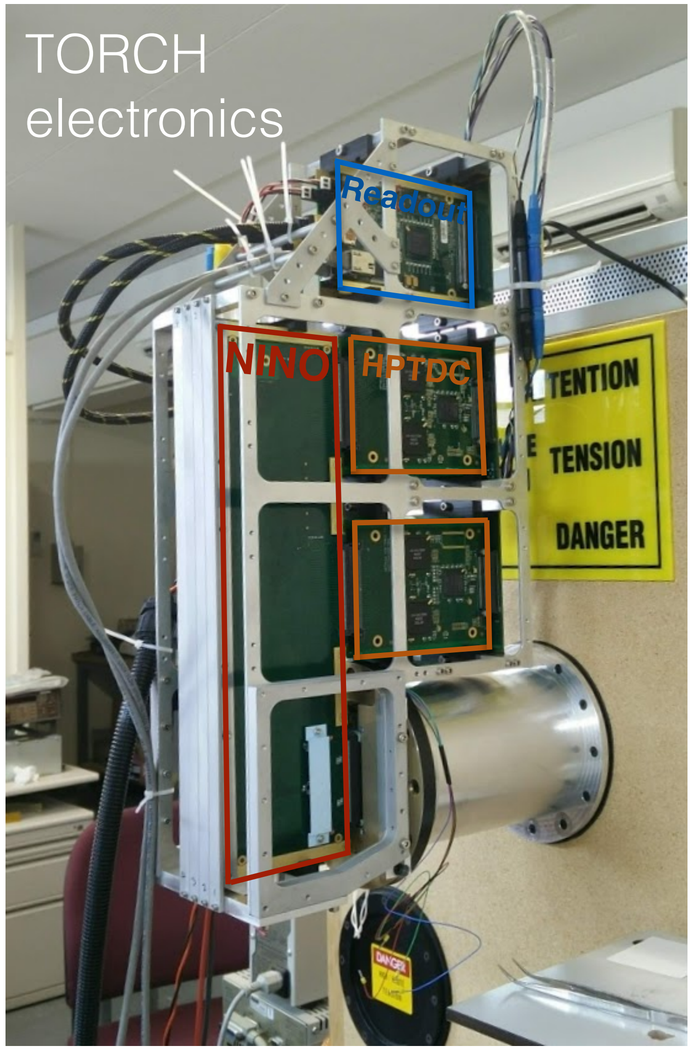


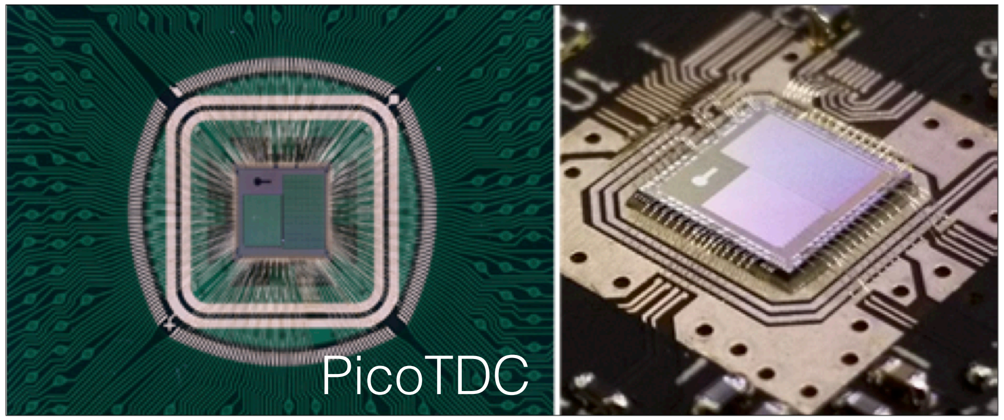


[J. Milnes, IEEE NSS/MIC 2020]

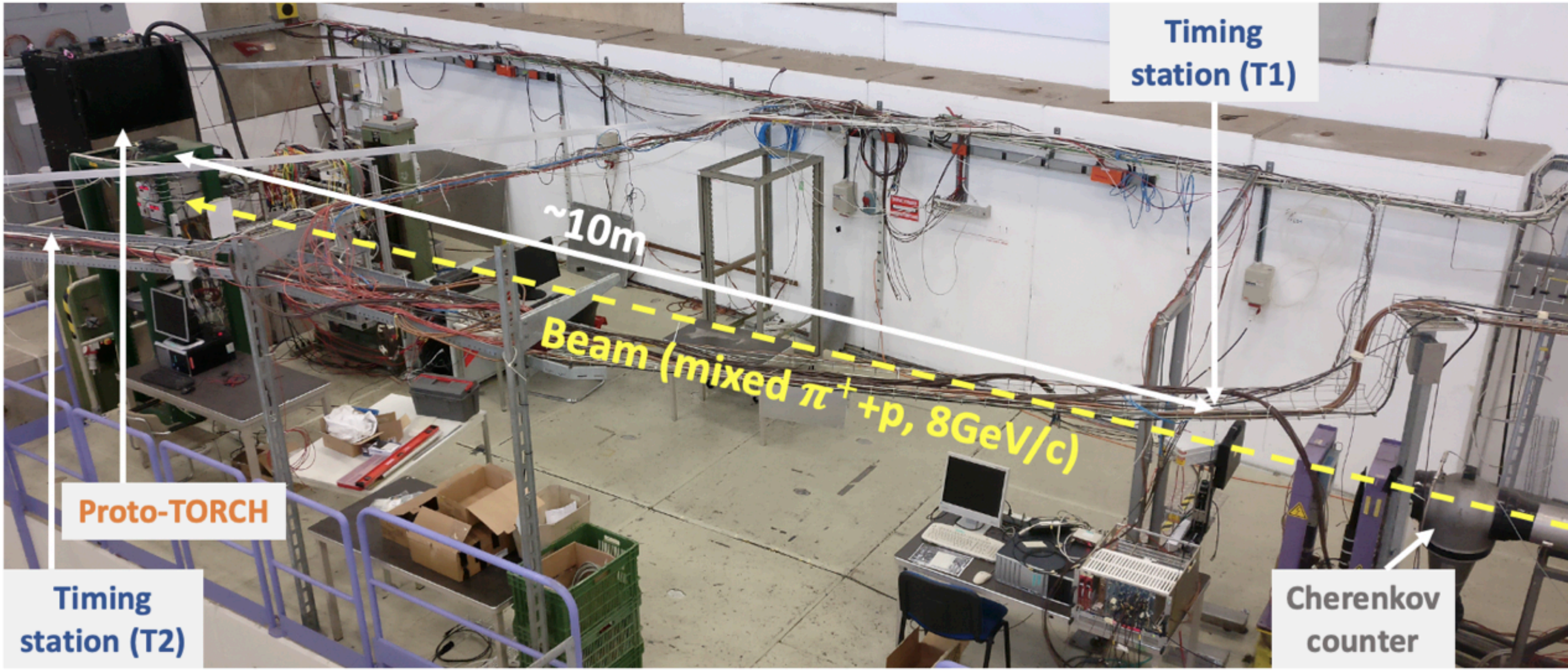
Readout electronics

- TORCH prototype readout is based on the NINO & HPTDC chipsets developed for ALICE TOF (designed for MRPC signals)
  [R. Gao et. al., JINST 11 (2016) 04 C04012].
  - HPTDC operated with 32 channels and 100 ps time bins.
- Successors are the FastIC & PicoTDC
  [R. Ballabriga, J. Christiansen et al. Users meeting].
  - FastIC offers better linearity for signals from SiPM, PMTs, MCP-PMTs.
  - PicoTDC has 64 channels with 12 or 3ps binning.
- Need careful calibration/synchronisation to maintain intrinsic time-resolution (time-walk, integral non-linearities).
- Common development possible for LHCb TORCH and RICH applications.

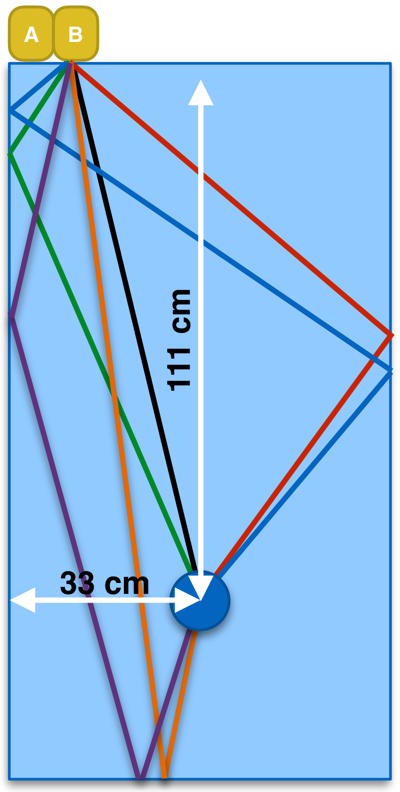




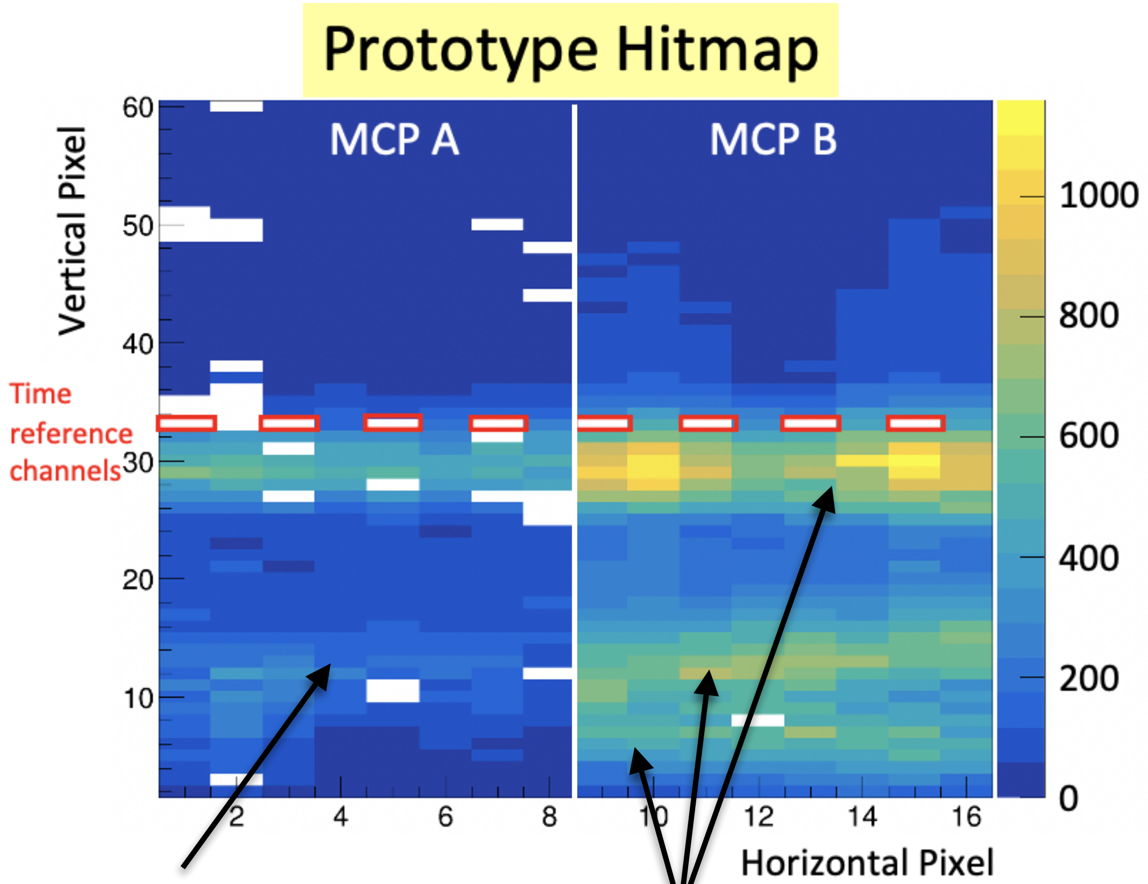
TORCH beam test at CERN PS



TORCH image reconstruction



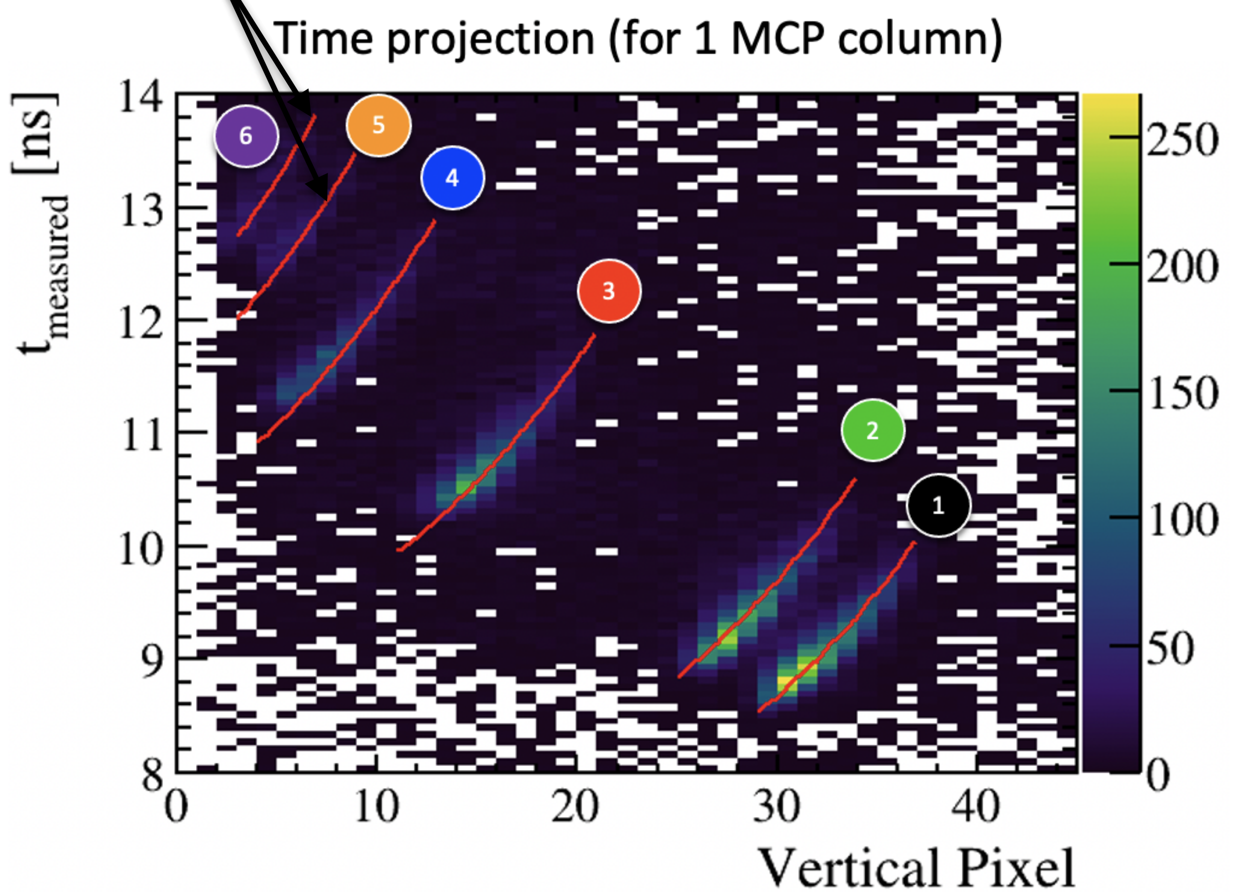
- Image reconstructed in 3D (space and time).



MCP A has a smaller QE

Ring image, folded by reflections from the sides/bottom of the radiator.

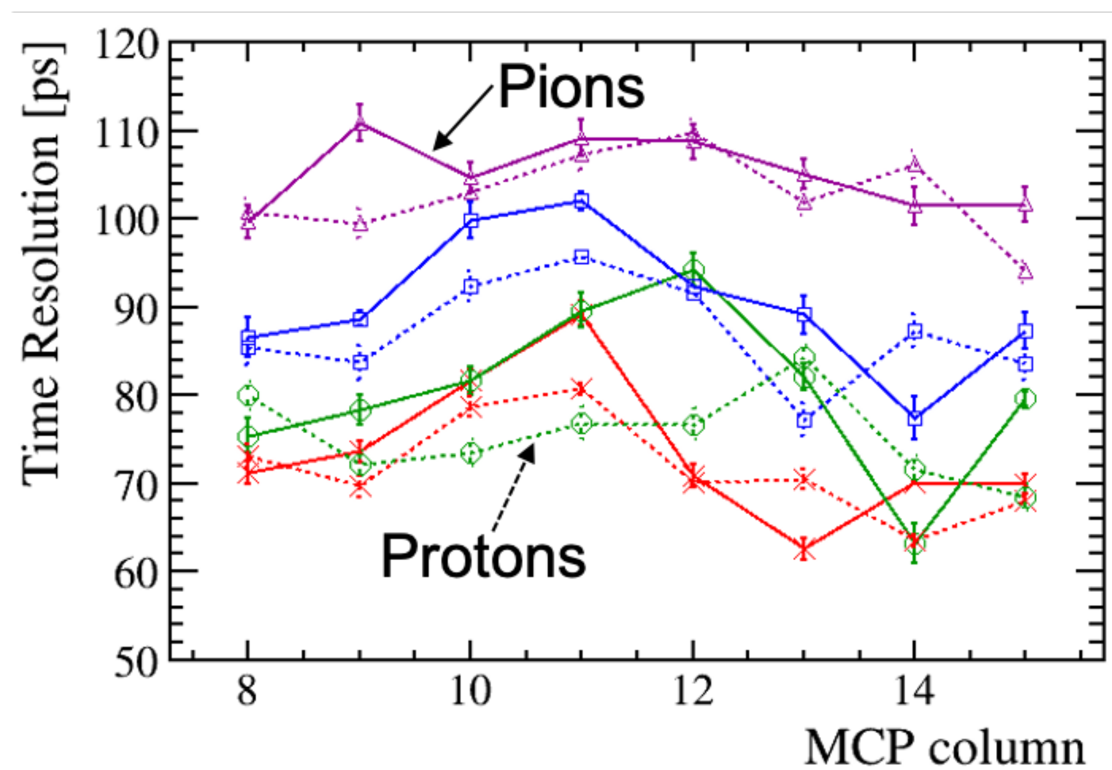
Expected image from GEANT4 simulation

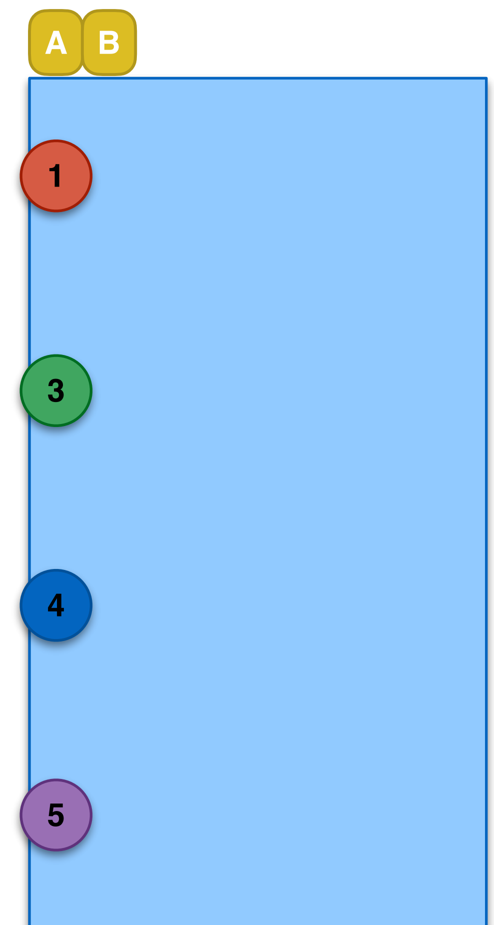


For more details see [J. Smallwood, TIPP]

TORCH single photon resolution

- Compare expected and true arrival time of photons.
    - Correct for the resolution on the time reference and the resolution due to the beam spread (angular divergence).
- Time resolution is close to the design goal of 70ps per photon.
- Expect a linear dependence of the resolution with the distance to the MCP-PMTs due to chromatic dispersion.

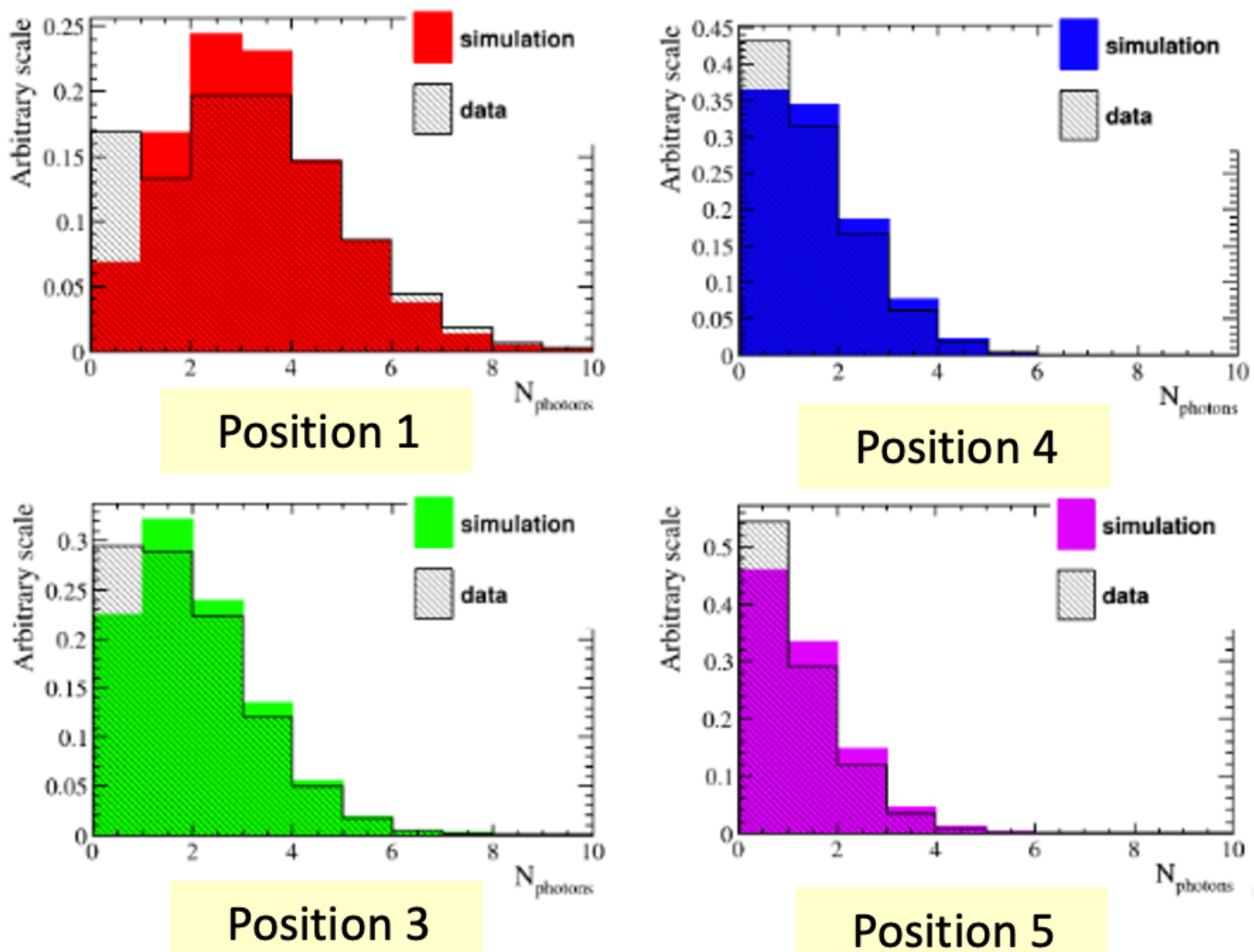




For more details see [J. Smallwood, TIPP]

TORCH photon yield

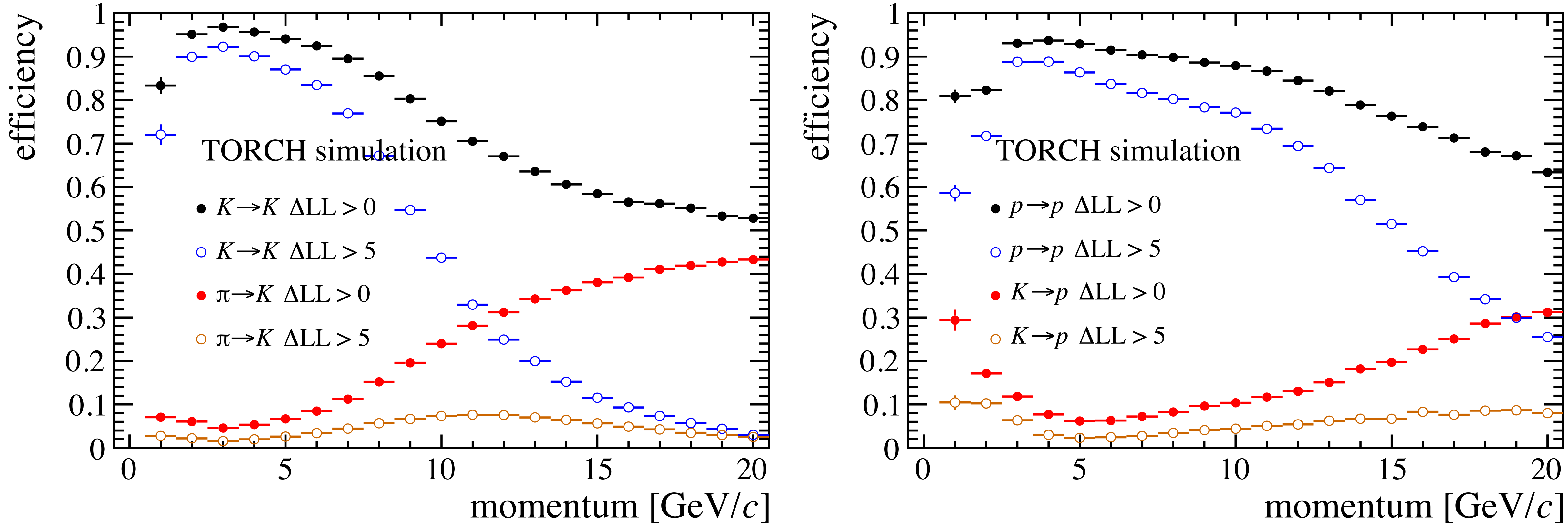
- Determine the photon yield by cluster counting.
- Good agreement found between the data and simulation.



For more details see
[J. Smallwood, TIPP]

Simulated TORCH performance

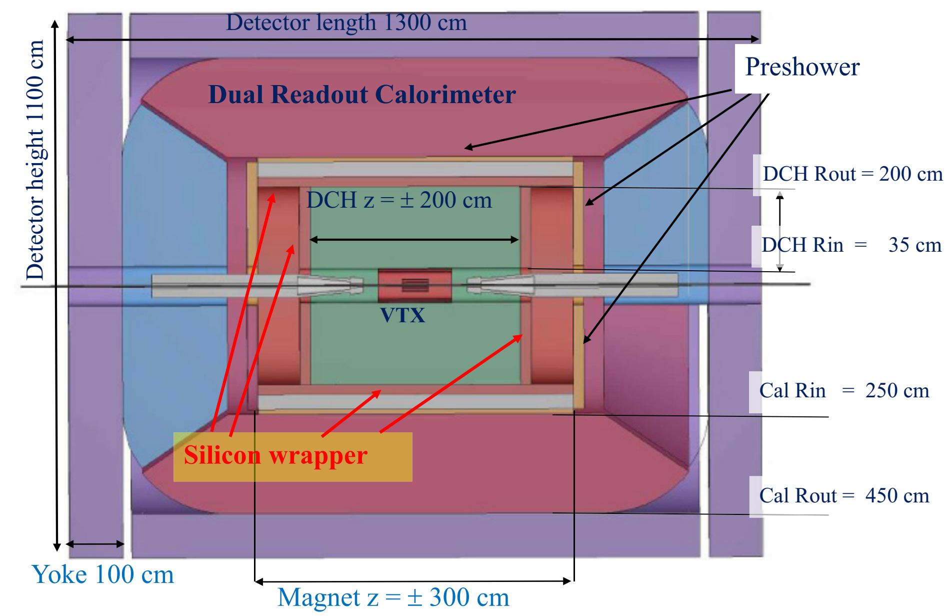
- Simulate TORCH performance in LHCb at instantaneous luminosity of 1.4×10^{34} $cm^{-2}s^{-1}$.

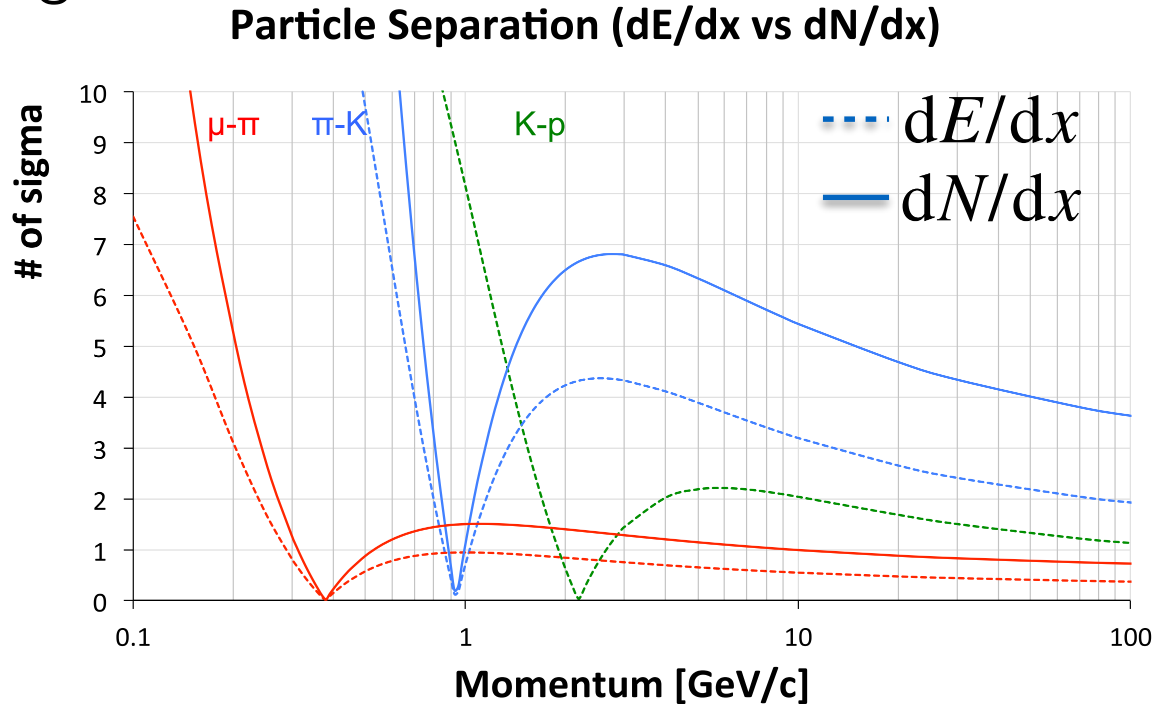


- Good π-K and p-K separation for $2 < p < 10\,\mathrm{GeV}/c$.
  - R&D ongoing to improve detector performance.

Future e^+e^- colliders — FCC-ee

- Detector concepts for future e^+e^-colliders do not currently feature dedicated PID systems.
- Can obtain good particle identification capabilities across part of the momentum range through $\mathrm{d}E/\mathrm{d}x$ (or cluster counting, $\mathrm{d}N/\mathrm{d}x$).
  - IDEA detector concept for the FCC-ee features a high precision drift-chamber.
  - Poor PID performance in the $\mathrm{d}E/\mathrm{d}x$ cross-over region around 1-2 GeV/c.

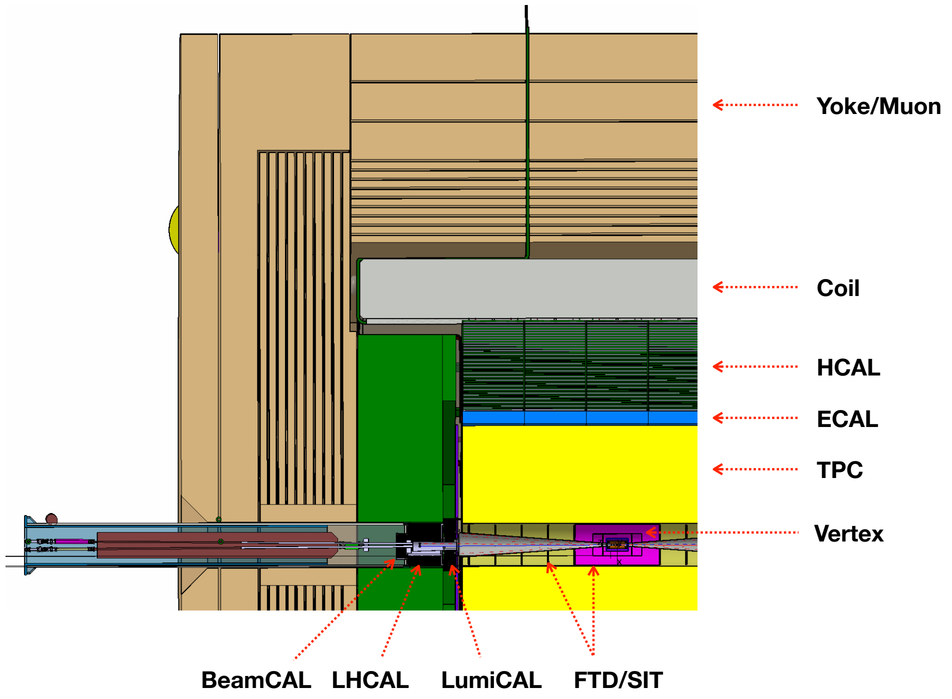


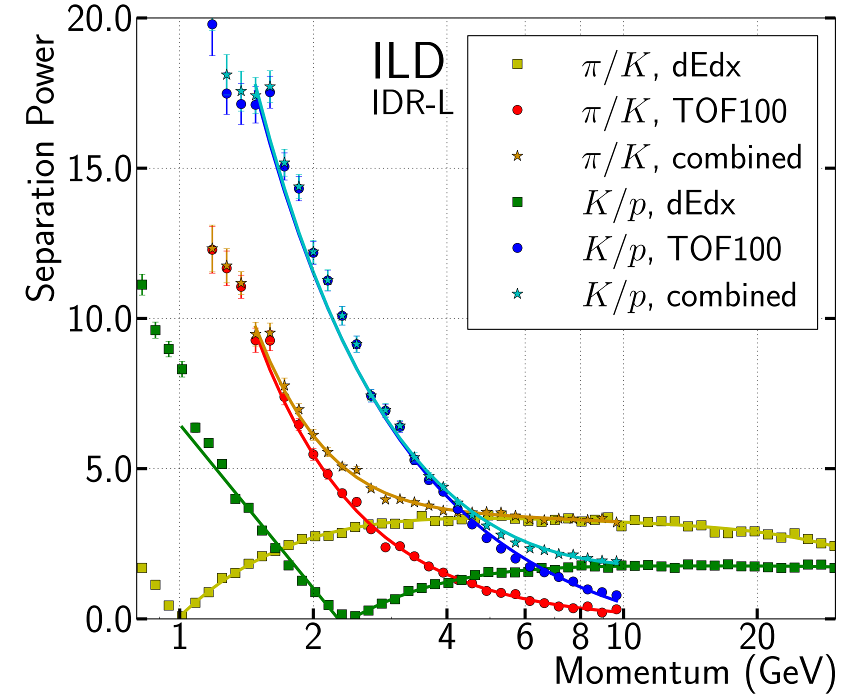


[FCC-ee CDR EPJC 228 261–623 (2019)]

Future e^+e^- colliders — ILC

- Detector concepts for future e^+e^-colliders do not currently feature dedicated PID systems.
- Can obtain good particle identification capabilities across part of the momentum range through $\mathrm{d}E/\mathrm{d}x$ (or cluster counting, $\mathrm{d}N/\mathrm{d}x$).
    - ILD detector design uses $\mathrm{d}E/\mathrm{d}x$ from TPC.
    - Can improve PID performance using time-of-flight information at low momentum, e.g. using timing from calorimeter in ILD design.



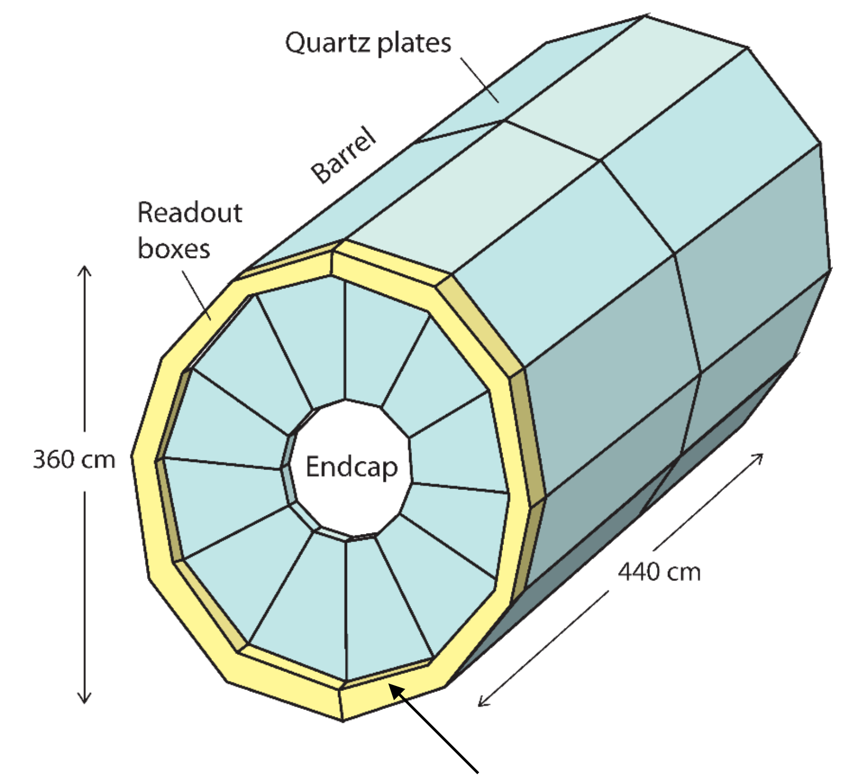


[ILD interim design report]

Cherenkov based TOF at FCC-ee

- A Cherenkov based time-of-flight detector (e.g. the TORCH) could improve the PID in the GeV/c momentum range at a future e^+e^- collider.
- Thin-detector volume placed between the tracking detectors and ECAL (at ~1.8m).
  - 1cm of quartz introduces 8% X_0 (plus light weight support structure).
- Barrel geometry (with endcap modules) to cover the full acceptance.
- Detector measures TOF and TOP.
  - Smaller TOF than LHCb TORCH proposal puts stricter requirements on timing (and granularity).

24 TORCH-like modules with 50m² area



Focusing block sits in this region

Summary

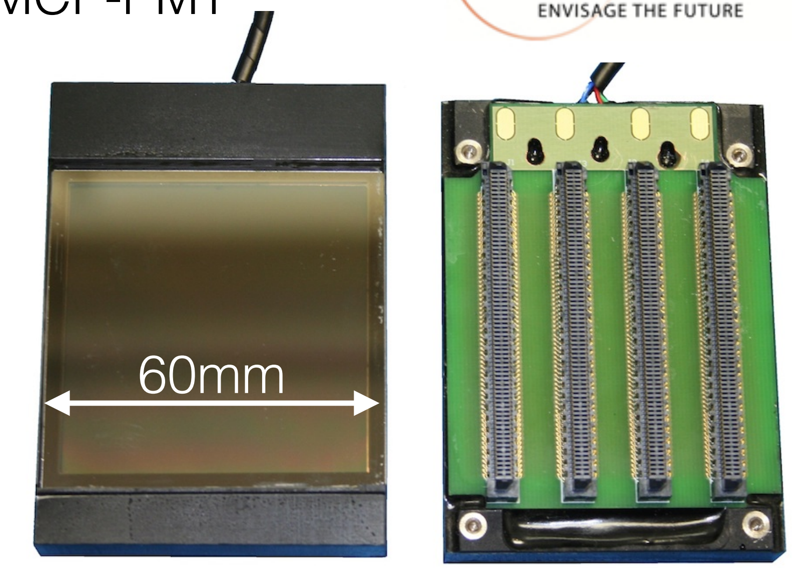
- Charged hadron ID is essential for a broad flavour physics programme.
- Time-of-flight detectors can provide PID coverage up-to 10GeV/c in LHCb and future e^+e^- colliders.
    - Requires 10ps per-MIP time resolution. Achieved in TORCH by combining timing information from ~30 Cherenkov photons.
- Time-of-flight detectors are also useful for background rejection in fixed-target/beam dump experiments at the CERN SPS (future kaon experiments, TauFV, …).
- Photon detector development for TORCH has synergy with the LHCb RICH and NA62 KTAG (driven by fast-timing and rate capabilities).
- Long term goal should be to reach picosecond timing (similar to TOF-PET goals).

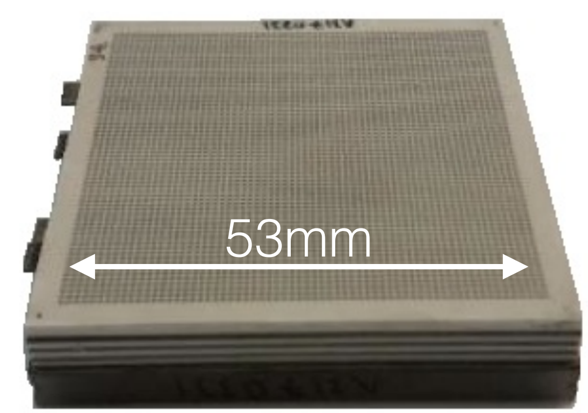
TORCH MCP-PMTs

- Three phase R&D programme to develop MCP-PMTs for TORCH.
- Phase-III tube is a square tube with a 53-by-53 mm active area.
- ALD coated photocathode to improve lifetime.
- AC-coupled anode so that the quartz window can be grounded.
- Readout connectors are mounted on a PCB and are connected by ACF (anisotropic conductive film).
- Granularity of 64-by-64 pixels per tube, ganged to 8-by-64 pixels for TORCH.
  - Provides a 1 mrad angular precision.

Phase-III
MCP-PMT

PHOTEK
ENVISAGE THE FUTURE





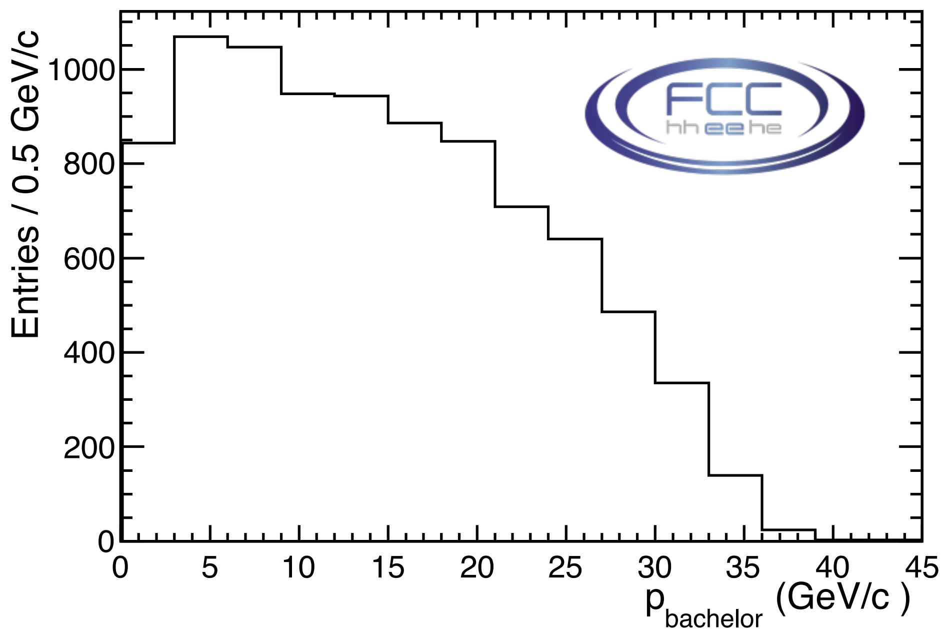
Bare tube

Opportunities at an e^+e^- collider

- Opportunity to produce large samples of heavy flavour at an e^+e^- collider running at the Z pole.

Particle specie at FCC-ee	B^0	B^+	B_s^0	Λ_b	B_c^+
Yield ($\times 10^9$) [for 5.10^{12} Z]	310	310	75	65	$1.5^\dagger$

- Exploit a hermetic detector and known collision energy to reconstruct semileptonic decays and decays with τ final-states.
  - e.g. study $B^0 \to K^{*0}\tau^+\tau^-$



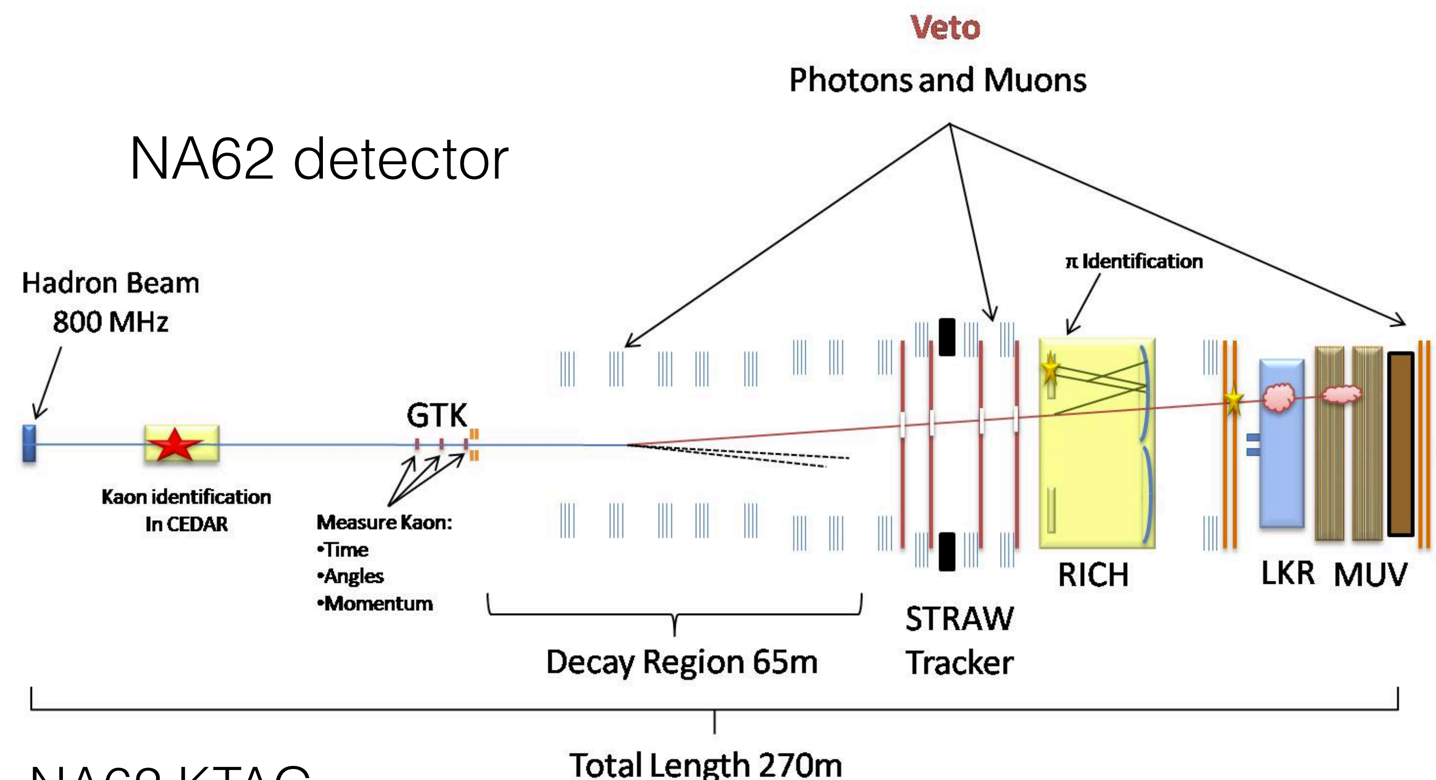
K momentum from $B_s \to D_s K$ decays at the Z

[S. Monteil, FCC-ee workshop 2019]

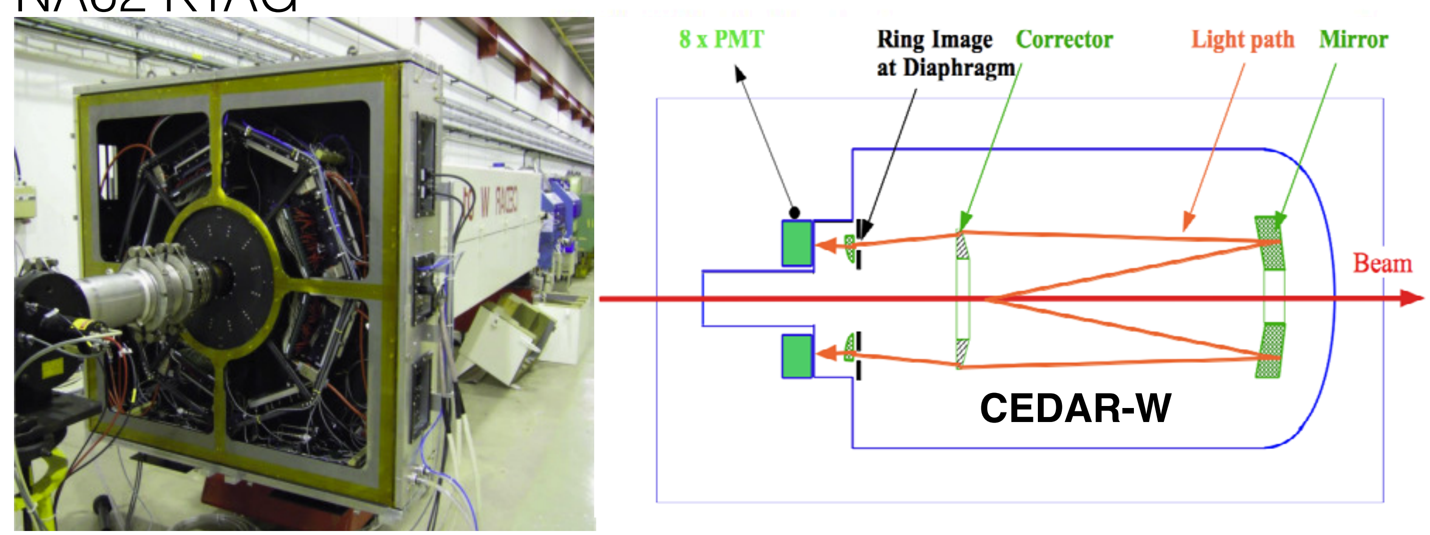
Kaon tagging at NA62

- Charged hadron identification is also crucial for current and future kaon facilities.
  - Only 6% of particles in the NA62 beam are kaons.
- Requires fast photon detectors that are capable of withstanding high rates.
  - KTAG upgrade of NA62 has photon rates of 8MHz/cm^2 and requires 20ps timing.

NA62 detector



NA62 KTAG

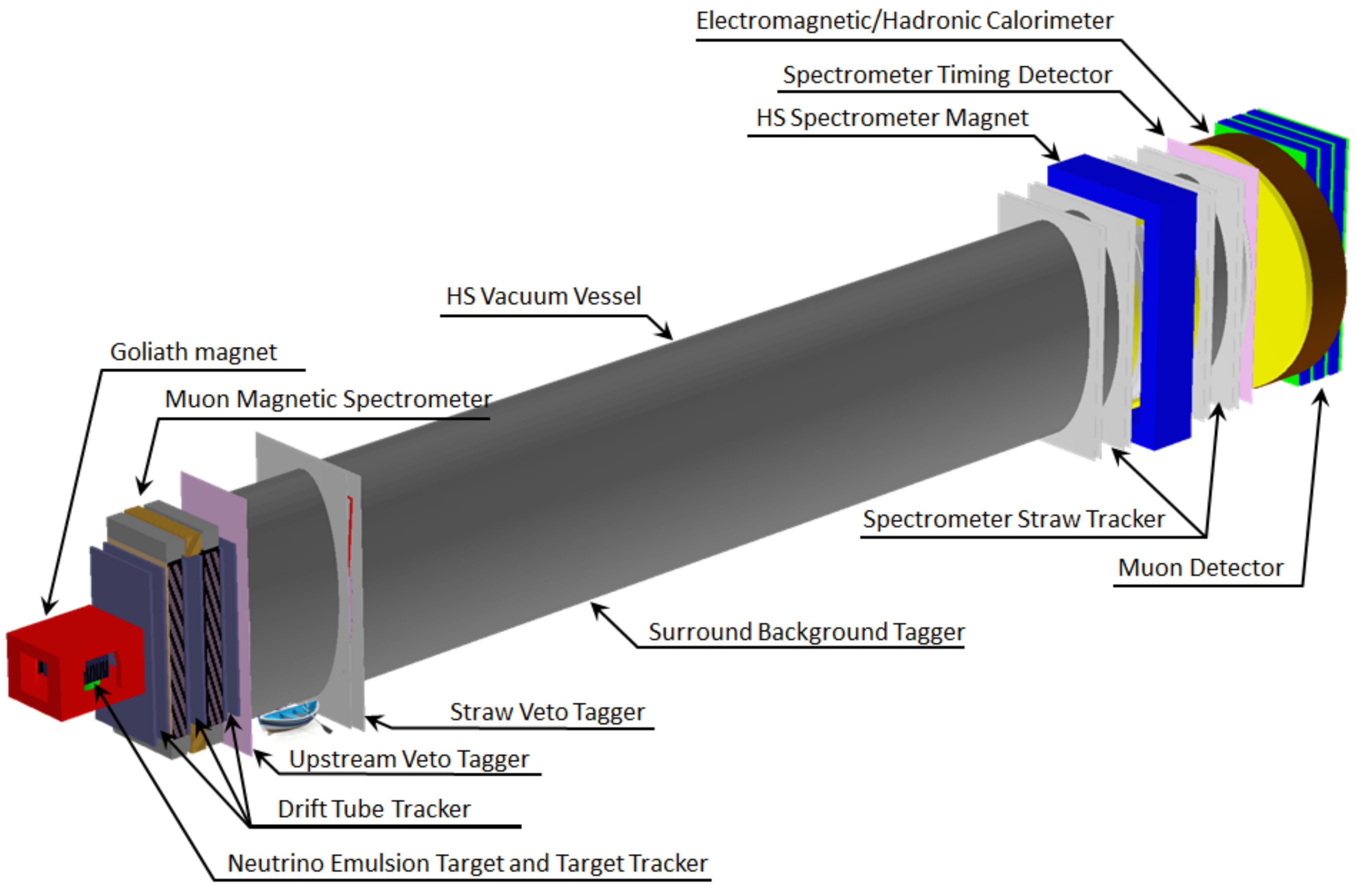


Cherenkov differential counter with a achromatic ring focus design

NA62 KTAG, [NIM A (2015) 86]

SHiP spectrometer timing detector

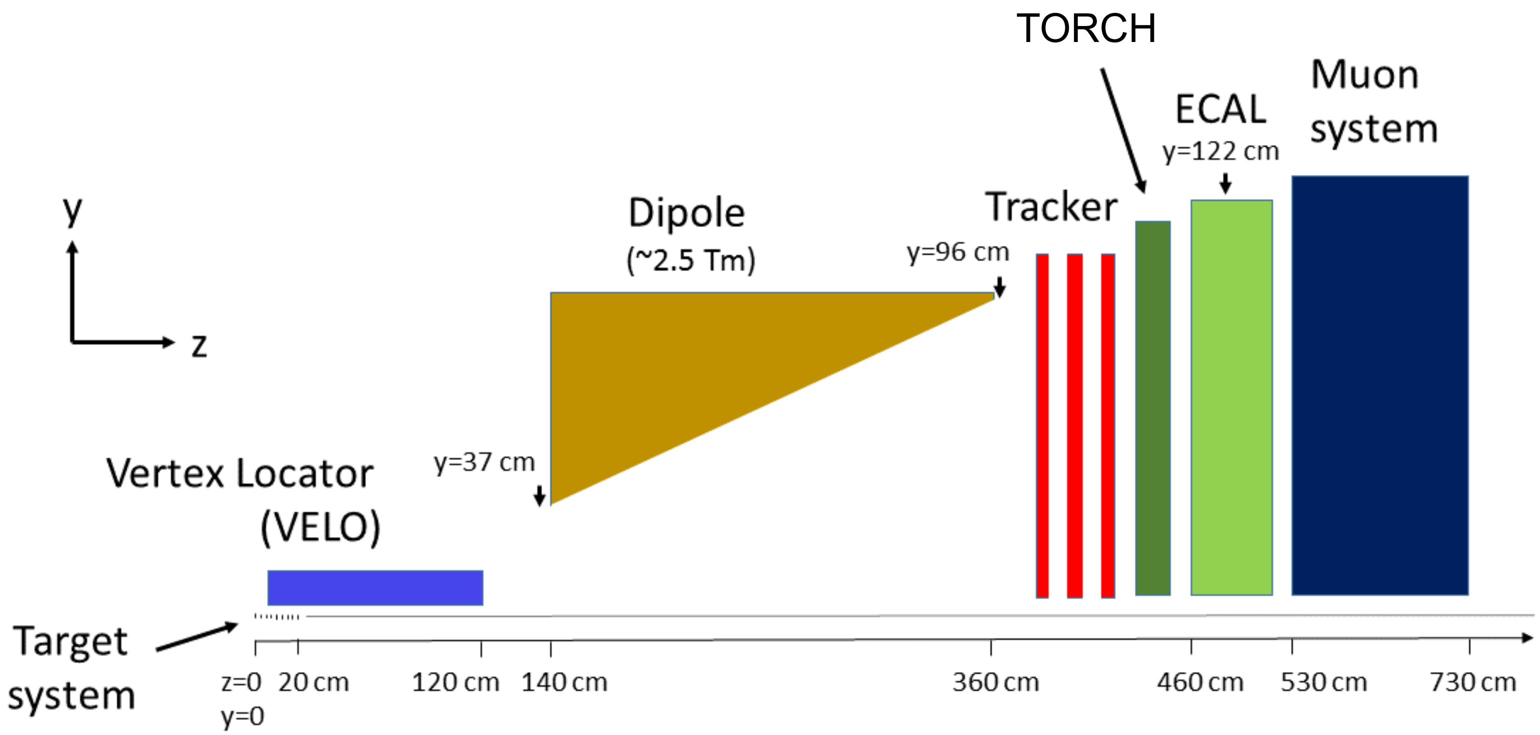
- Reduce backgrounds from random combinations of muons using fast timing.
    - Targeting resolutions <100ps.
- Two technologies considered:
    - MRPC detectors.
    - Fast scintillators (inspired by the NA61/SHINE detector).



[CERN-SPSC-2015-016]

Cherenkov based TOF at TauFV

- Cherenkov based TOF also discussed in the context of the proposed TauFV experiment, a fixed target τ factory at the CERN beam dump facility.



[G. Wilkinson, Physics Beyond Colliders]