LHCb as a 4D precision detector in Upgrade II

Floris Keizer on behalf of the LHCb Collaboration

Wednesday 7 July 2021

OFFSHELL 2021

THE VIRTUAL HEP CONFERENCE

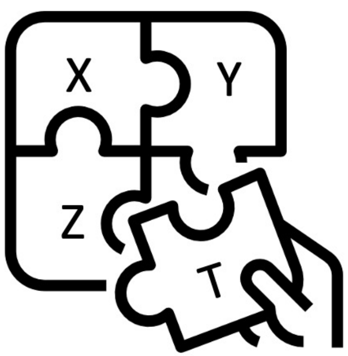
RUN 4 HL LHC

Introduction & timeline

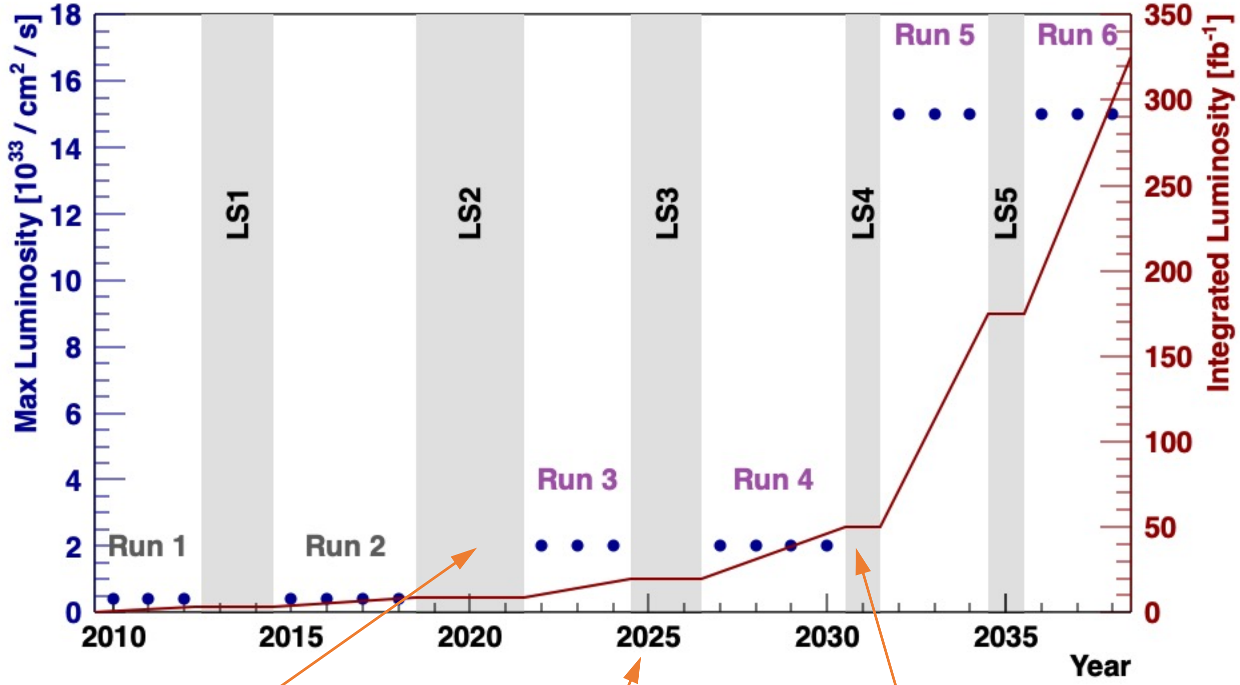
The LHCb experiment will run at **increasingly high luminosity** to acquire more statistics and make optimal use of the HL-LHC. Especially during Run 5&6.

2022 will be an exciting year when the LHCb Upgrade I (Run 3) detector is started up. This presentation will outline the various **challenges, trends and plans** on how this detector will evolve during **Upgrade II**.

A particularly interesting novel feature of the detector will be picosecond time resolution: **LHCb as a 4D experiment**.



2018 physics case



Upgrade I employs a full software trigger and is currently being installed.

Upgrade II will involve a major detector redesign to prepare for the large increase in luminosity.

LS3 enhancements ("Upgrade Ib") are foreseen to improve performance in Run 4 and prepare for Upgrade II. Relatively long period to consolidate the detector.

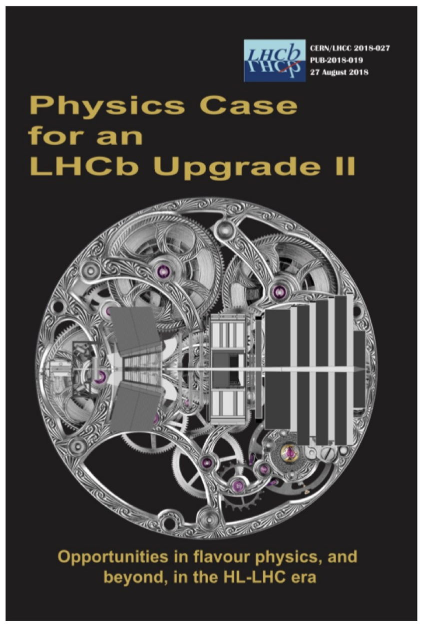
Physics performance prospectives

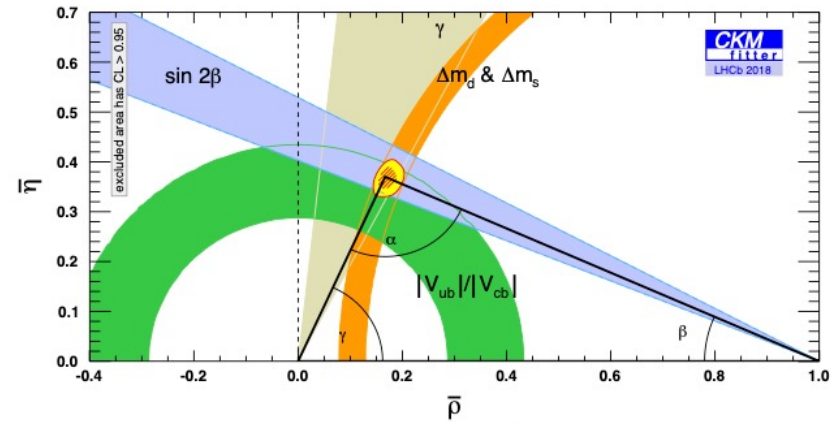
“The LHCb Upgrade II will fully exploit the flavour-physics opportunities of the HL-LHC, and study additional physics topics that take advantage of the forward acceptance of the LHCb spectrometer.”

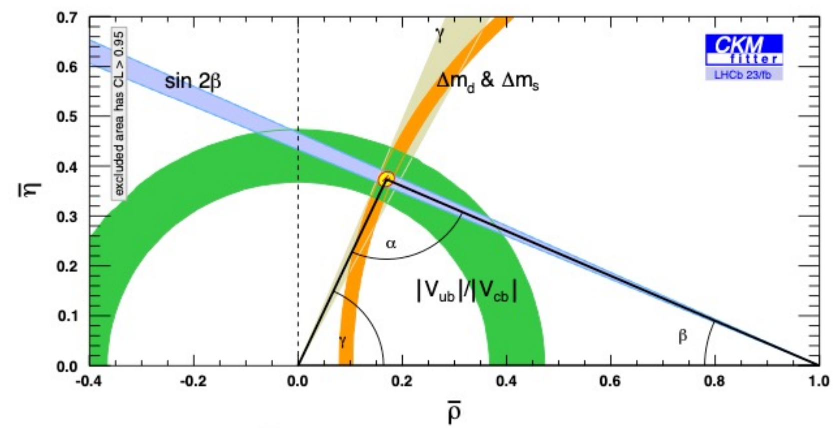
- The **sensitivity is generally limited by statistics**, rather than systematics or theory uncertainties.
- Motivates to take high-luminosity data in LHCb.

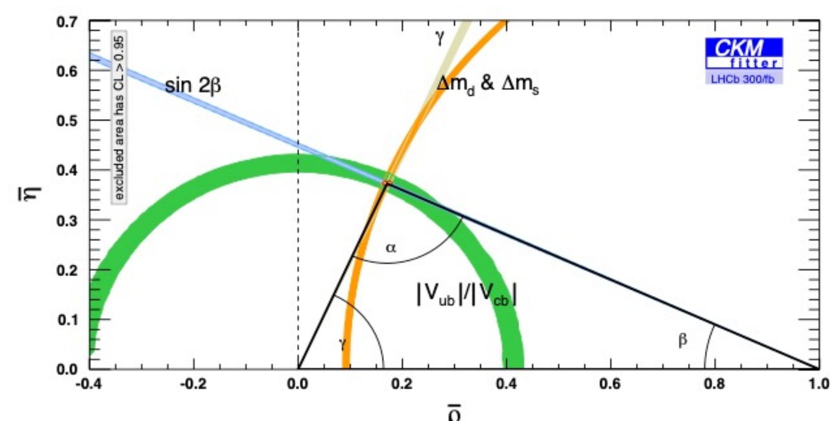
[2017 expression of interest]

[2018 physics case]









The luminosity challenge

Factor 7.5 increase in particle multiplicity and rate.

- 42 expected interactions per crossing.
- 2000 charged particles within the LHCb acceptance.

Good for statistics, challenging for the detector.

Overall aim is to retain (and improve) the physics performance of Run 3 in this much harsher environment.

A) Need **more precise** detectors to help the event reconstruction to cope with the 'packed' events.

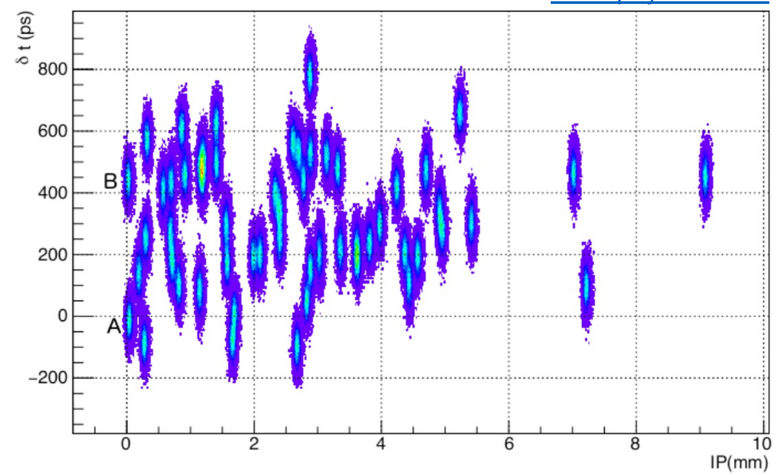
- Improved granularity.
- Fast timing information.

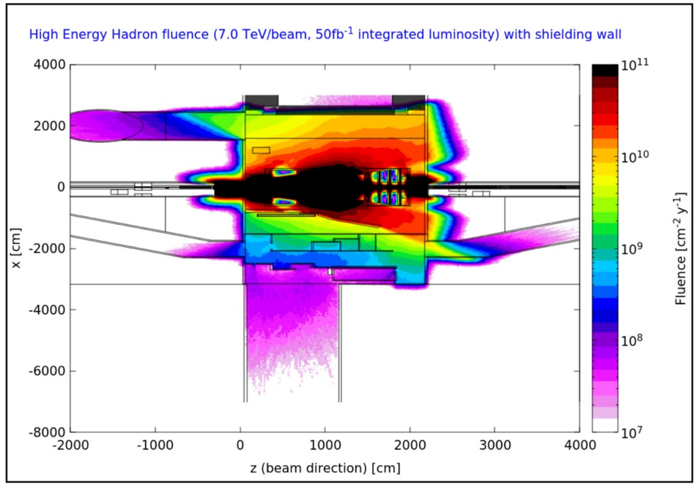
B) Need **more robust** detectors to withstand the increased radiation levels.

- Integrated Circuits in < 65 nm silicon technologies.
- Stringent power and cooling requirements.

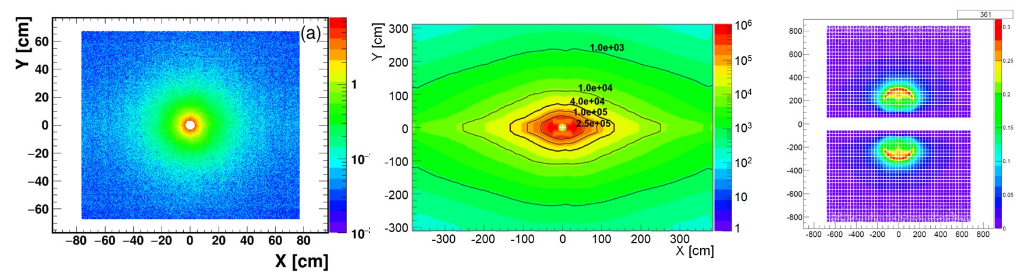
C) Strong **non-uniform track or photon occupancies** in most sub-detectors requires modular approach with various resolutions.

2018 physics case





EDMS 2424228

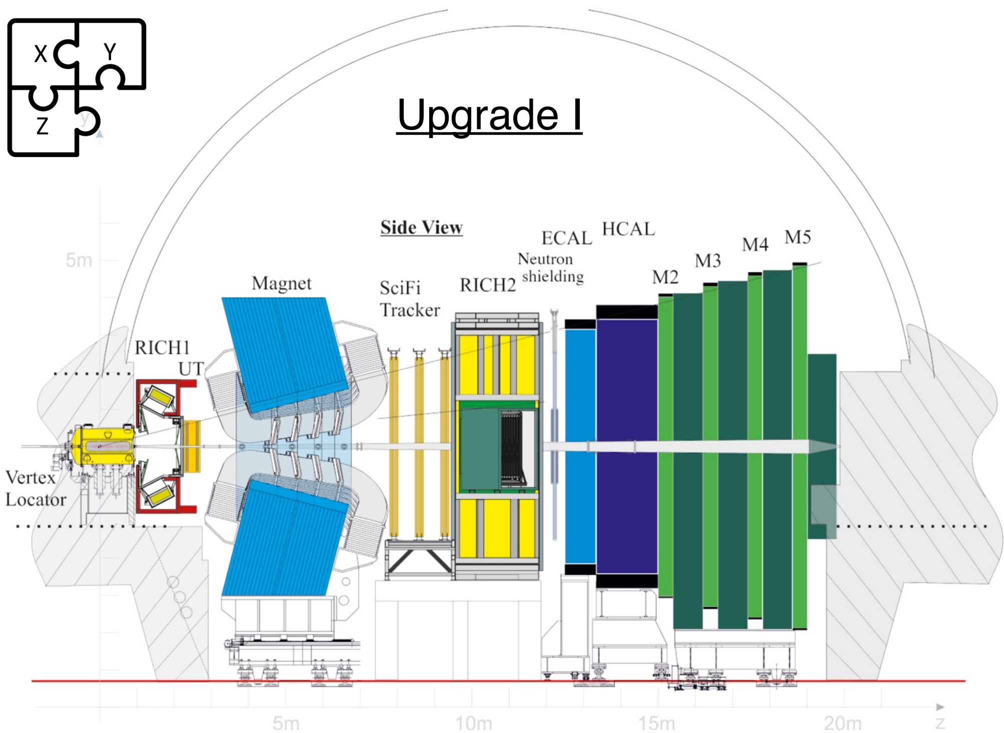


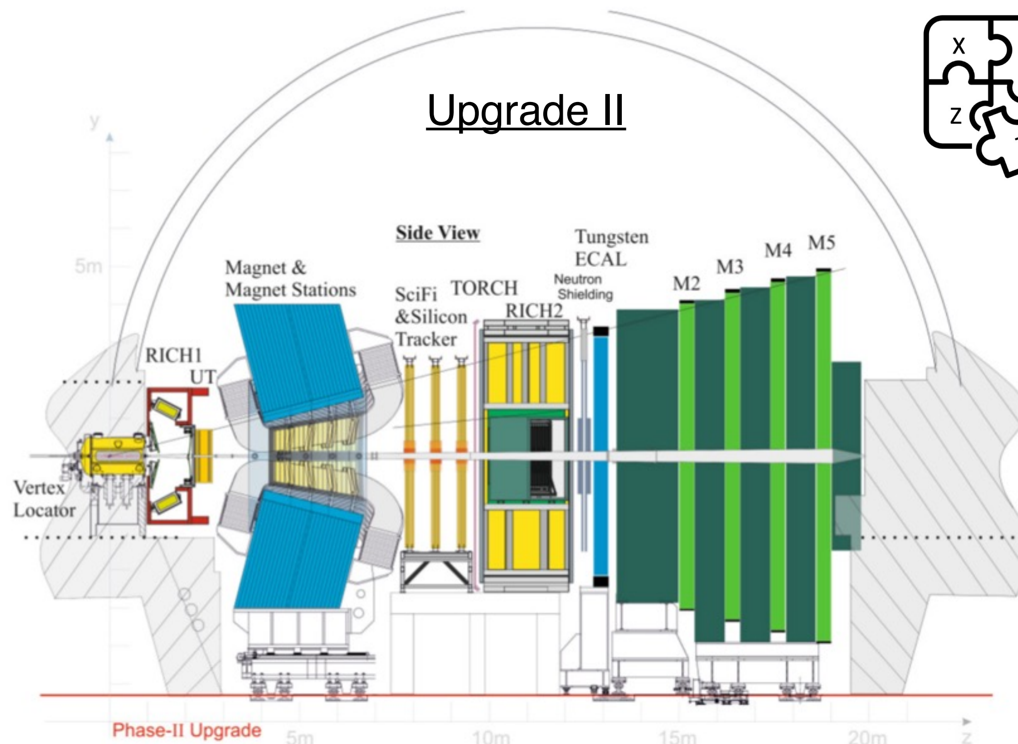
Global changes to the detector

Overall layout of the forward spectrometer remains similar (it works well!), except:

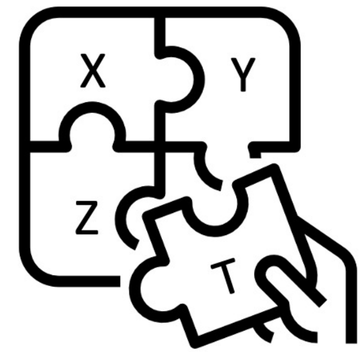
- ➢ HCAL (mostly contributed to hardware trigger, obsolete from Run 3) gets replaced by iron shield.
- ➢ Addition of TORCH detector in front of RICH 2.
- ➢ Addition of tracking stations in the LHCb magnet.

However, each sub-detector will make **huge (technological) advances**.
A wealth of R&D is ongoing and planned to prepare for LS3 and LS4.





Novel feature of the LHCb detector: fast timing

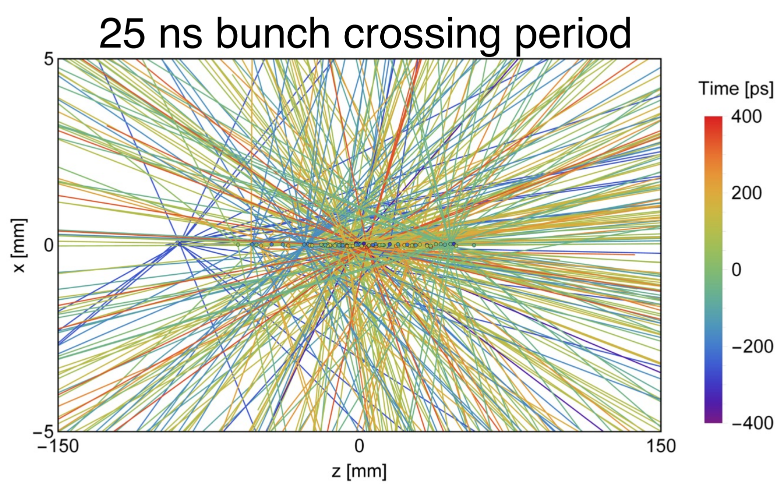


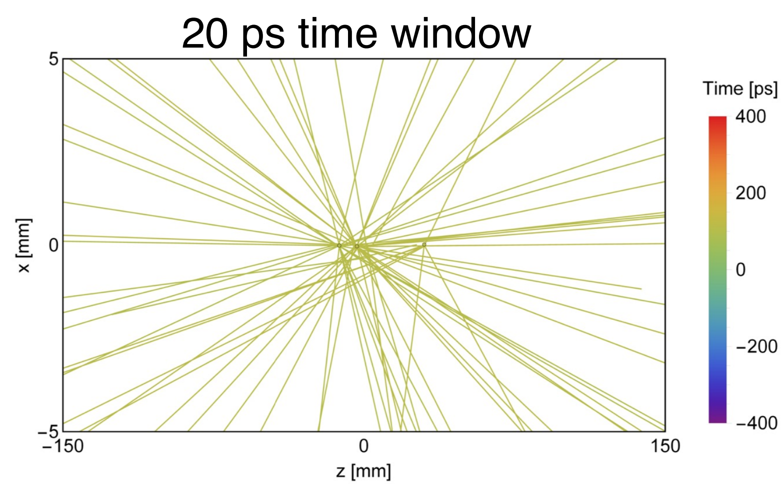
A new dimension will be added to the LHCb experiment.

Timing information with a **few tens of ps resolution** per particle will allow charged tracks and photons to be associated to the correct interaction vertex.

VELO, RICH, ECAL and TORCH will be fast timing detectors.

- Adds a new dimension to the **information exchange** between sub-detectors.
- Could all contribute to the same estimate of the **track time as it passes the detector**.
- Opens up **new avenues for data suppression** in front-end hardware and in software trigger.
- Sets challenging R&D requirements particularly for sensor technologies and front-end ASICs.



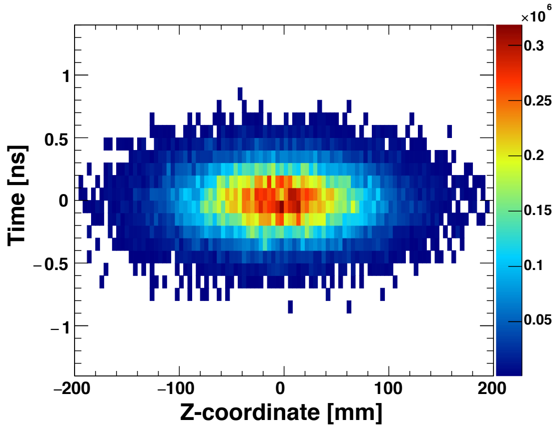


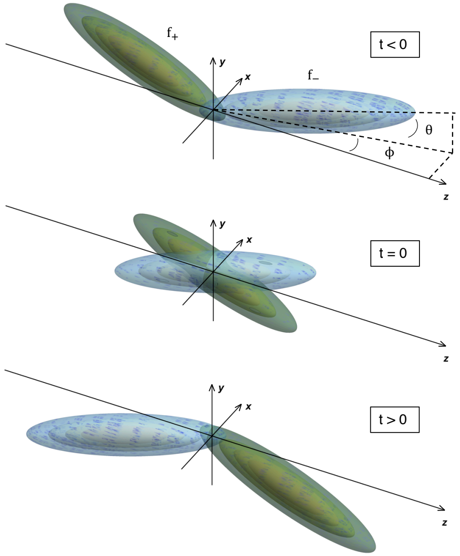
Picosecond timing to reduce combinatorial background

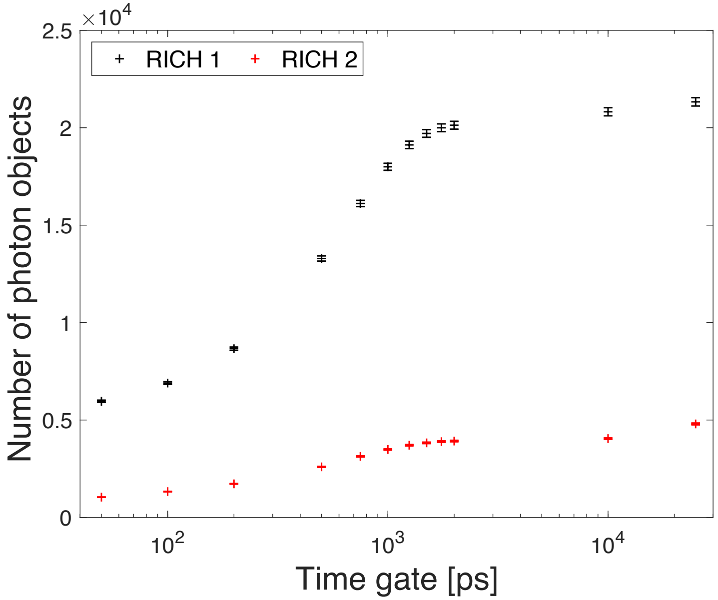
The interactions within an LHC bunch crossing span a time of about 1 to 2 ns.

- To capture all primary vertices (PVs), the **LHCb 'shutter time'** must be of this order.
- A sub-nanosecond resolution is required to differentiate individual PVs.

Doi:10.17863/CAM.45822







Main benefit of fast timing is to suppress significantly the **combinatorial background of tracks from multiple vertices**.

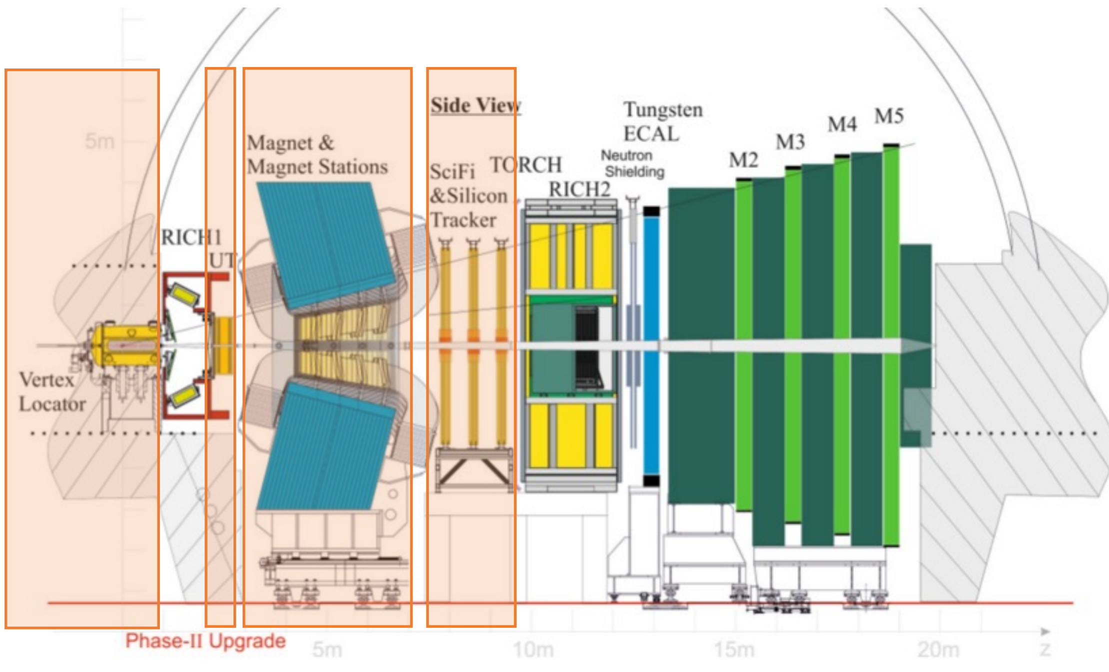
- Shown in this example from the RICH sub-detector: isolating a **time gate / 'slice'** has the greatest effect on the combinatorial background in the region between 1 ns and 100 ps.
- Sets the target for better than 100 ps time resolution for the sensors and readout electronics.

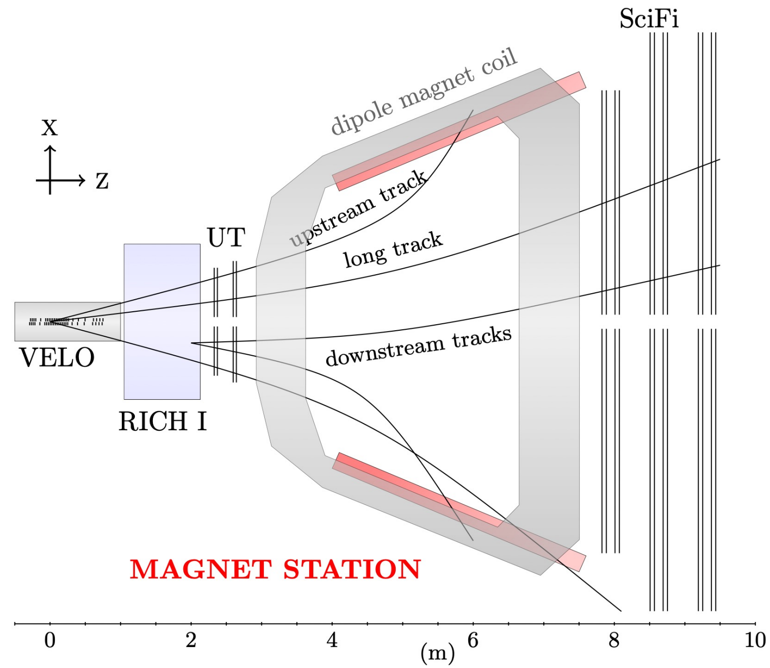
LHCb Tracking system

Vertex Locator (VELO), Upstream Tracker (UT), Magnet Stations (new addition “to close the gap”) and the Mighty Tracker (combined SciFi + inner silicon modules).

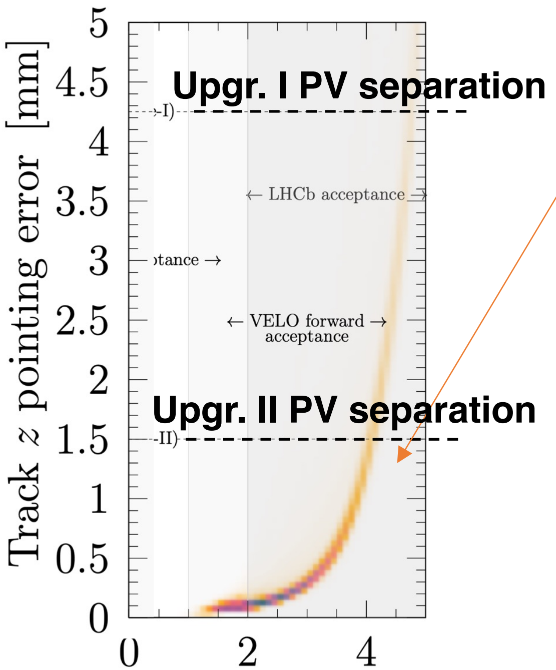
- ➢ Higher occupancies necessitate increased detector granularity.
- ➢ Rate of incorrect matching of upstream and downstream track segments needs to be minimised.
- ➢ Forms the basis to change from **strip to pixel technology and add fast timing**.

Obtained track and momentum resolutions also play an important role for the particle ID performance.





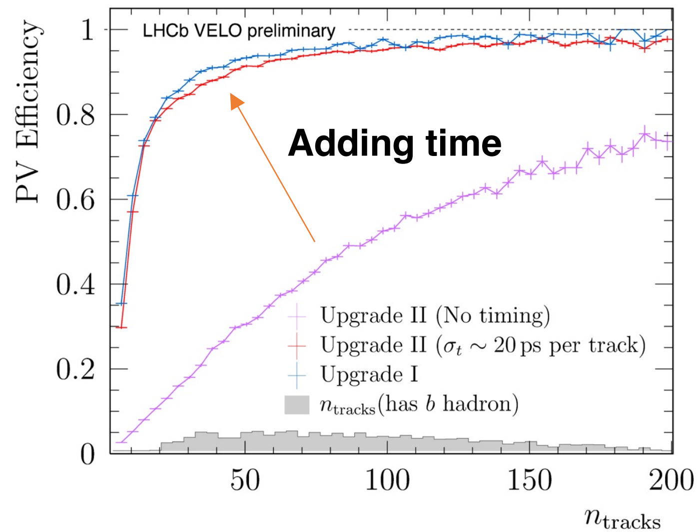
Vertex Locator (VELO)



ICHEP2020

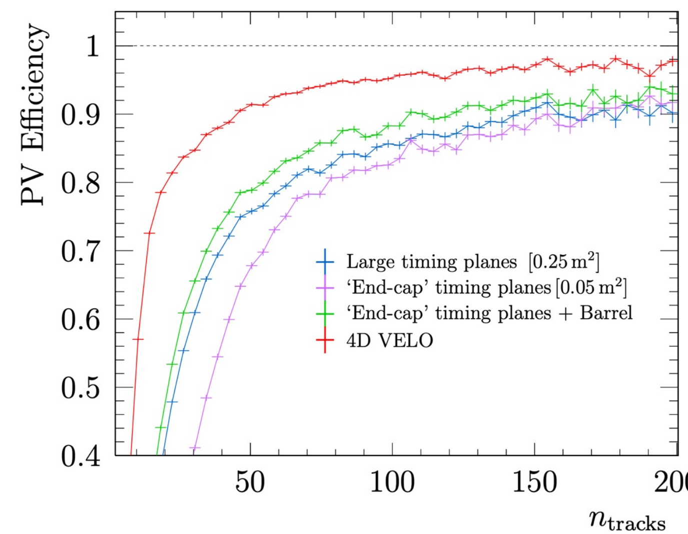
During Run5, the **high pile-up** requires an improved VELO tracking error.

- ➢ Especially in the forward direction where the z-pointing error is worse.

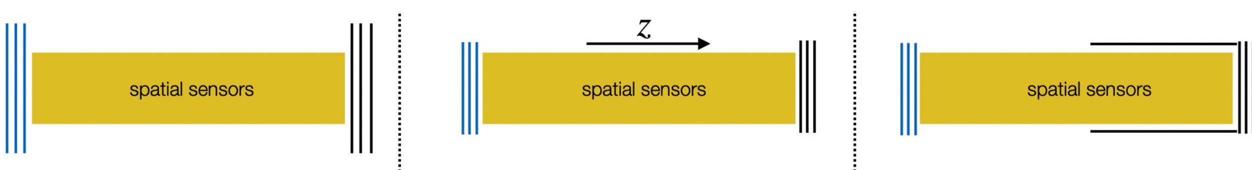


Improvements in spatial resolution alone are not sufficient: require a **track time resolution of ~ 20 ps** resulting in a hit time resolution of ~ 50 ps for the 4D pixels.

- ➢ Almost recover Run 3 performance.



Simulation studies of different track timing methods demonstrate that **4D "hit times" tracking** performs better than dedicated timing planes.



VELO technology requirements

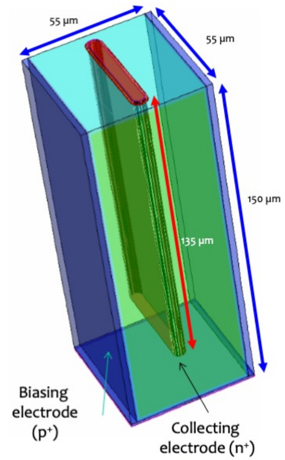
Project page

3D silicon sensors are a promising technology, especially the use of **trenches** instead of pillars as developed by the TIMESPOT project.

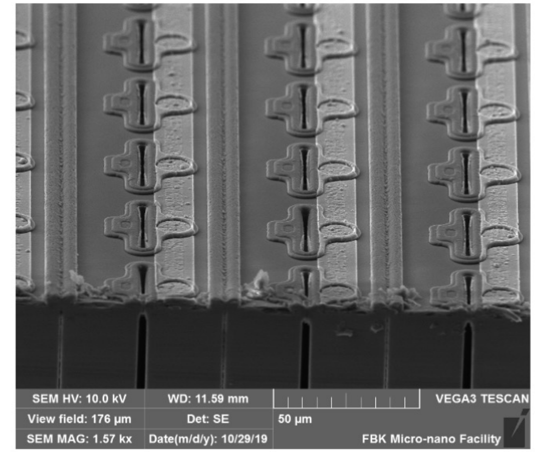
- Fast carrier collection in uniform electric field.

Alternatives are planar silicon sensors or LGADs.

- LGADs have a larger dead region between the pixels.



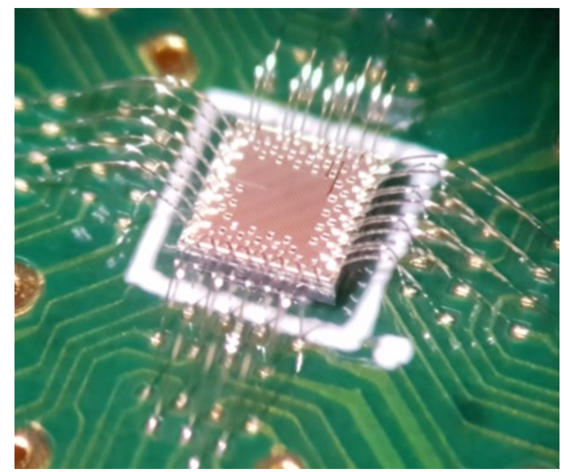
A



B

Readout ASIC: need time resolution of ~ 30 ps at low power.

- (On-chip or back-end) corrections for time-walk and non-uniformities.
- **Exploring 28 nm CMOS technology** node for radiation hardness (> 25 MGy for U2) and faster on-chip data rates.
- High data throughput (~ 100 Gbps per ASIC).
- Closest example is **Timepix4 chip** in a 65 nm technology, with 55 µm pixels, a TDC bin size of 195 ps (56 ps RMS) and a readout bandwidth of 23 Gbps/cm^2.

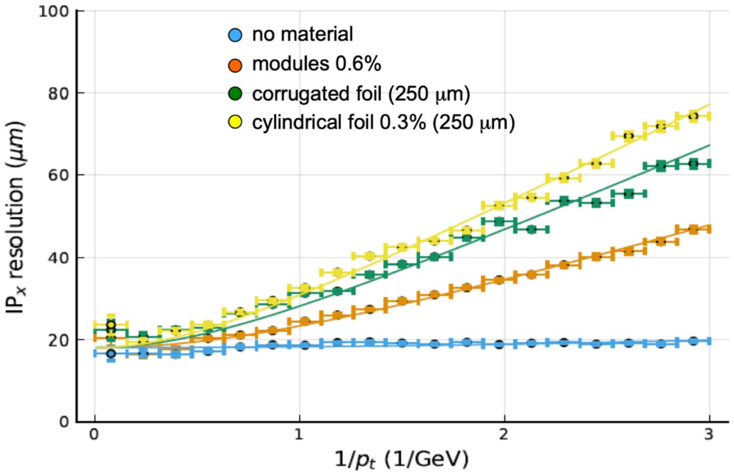


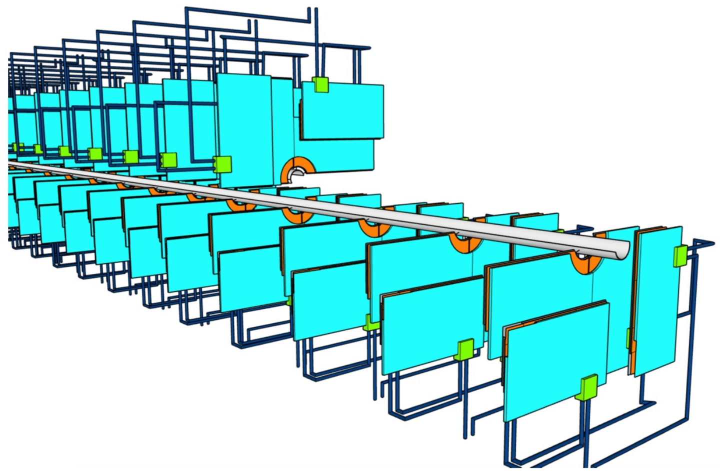
VELO – RF foil

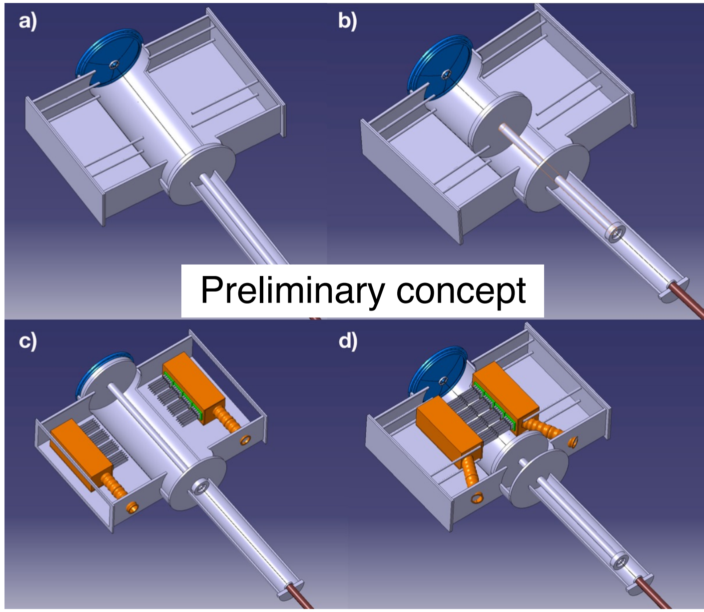
The VELO is positioned closest to the interaction point.

- **High fluence up to 10^{17} n_{eq}/cm^2** at the end of detector lifetime.
- May be practical to pull modules slightly outwards (fluence has a steep gradient radially), but this also requires (a) smaller pixels and (b) less material for the same IP resolution (dominated by RF foil).
- R&D ongoing to see if **RF foil can be replaced by wires / strips** to carry the beam mirror currents.
- Increases outgassing constraints and would require vacuum tank redesign.

doi:10.7566/JPSCP.34.010014





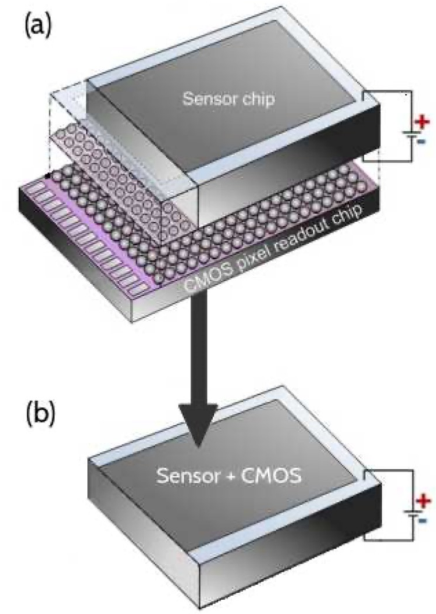


MAPS sensors technology (UT and Mighty tracker)

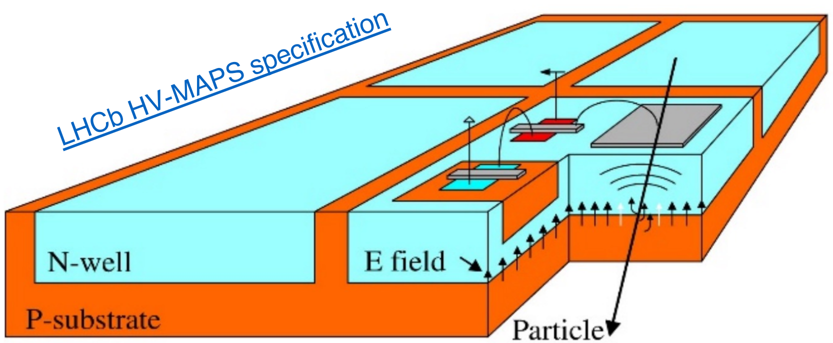
Monolithic Active Pixel Sensors integrate **front-end electronics and sensitive detector volume** in one silicon substrate: improved complexity and handling.

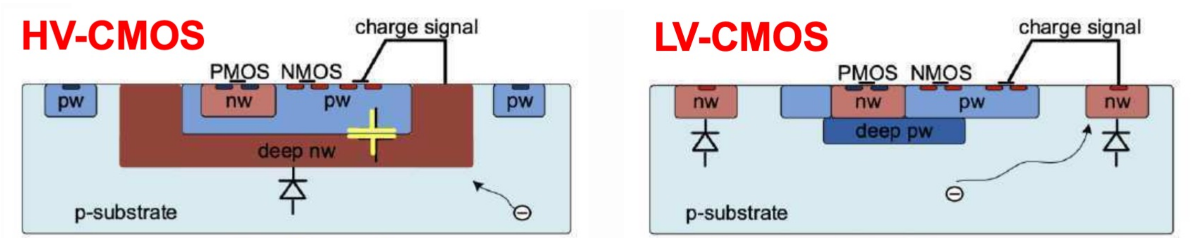
- 180 nm HV-CMOS process results in a good intrinsic **radiation hardness**. HV-MAPS $\geq 10^{15}$ n_{eq} / cm^{2}.
- **Small pixel** sizes give better resolution and lower parasitic capacitance.
- **Low material budget** reduces multiple scattering.
- LV-MAPS have small collection electrode, lower noise, power consumption and cross-talk, but also longer charge collection time.
- ATLASPix3 HV-MAPS: ~ 5 ns time resolution at 160 mW/cm^{2} power consumption and 50 µm × 150 µm pixel size.

Preferred technology for UT and MT detectors.



Thinner MAPS sensor





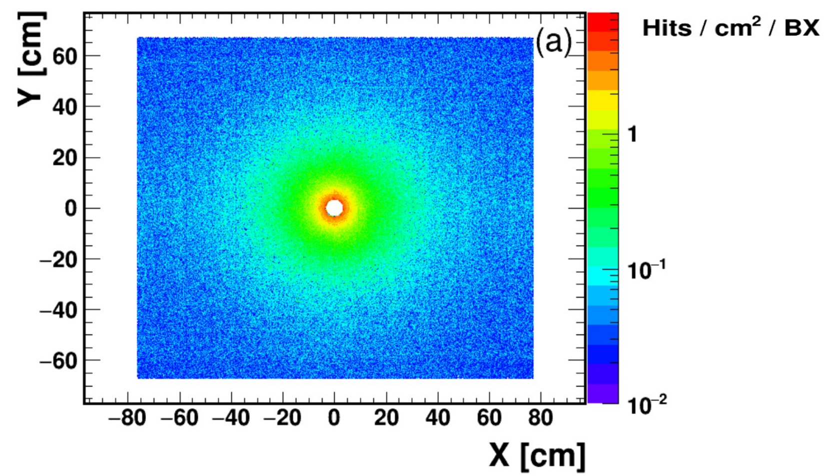
Large collection electrode

Small collection electrode

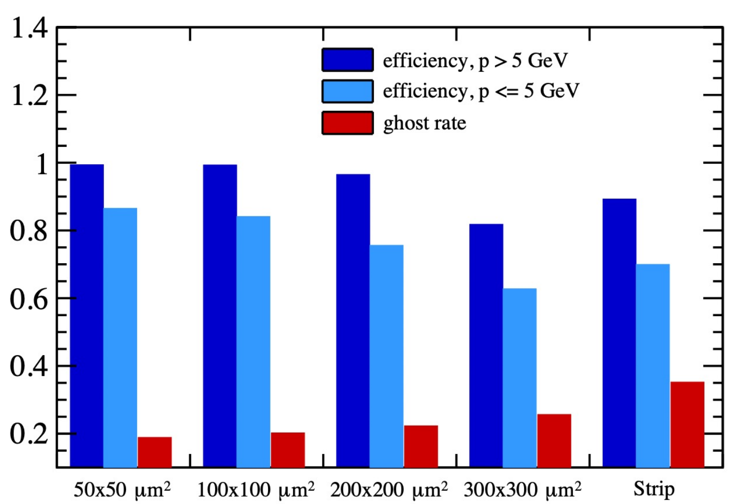
Upstream Tracker (UT)

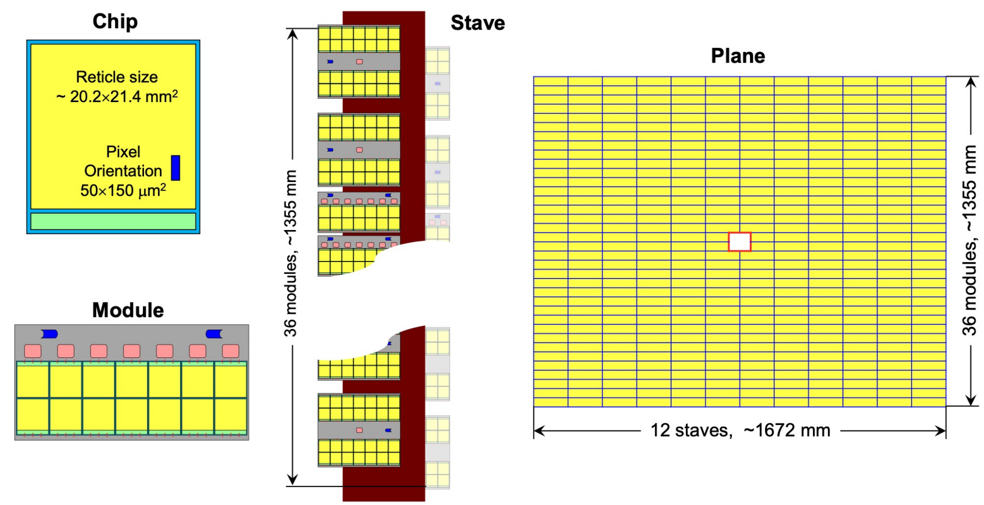
The fluence of about 3×10^{15} n_{eq}/cm^2 and a 240 Mrad TID dictate a radiation-hard, highly segmented technology.

- ➢ Highest values reach several hits / cm^2 / BX.



Novel MAPS **pixel detector** is proposed for the UT to add precision information in the y-projection (where the trajectory is straight). Standalone reconstruction studies for efficiency and ghost rate for various pixel sizes show that the Run 3 performance (strip design) can be achieved.



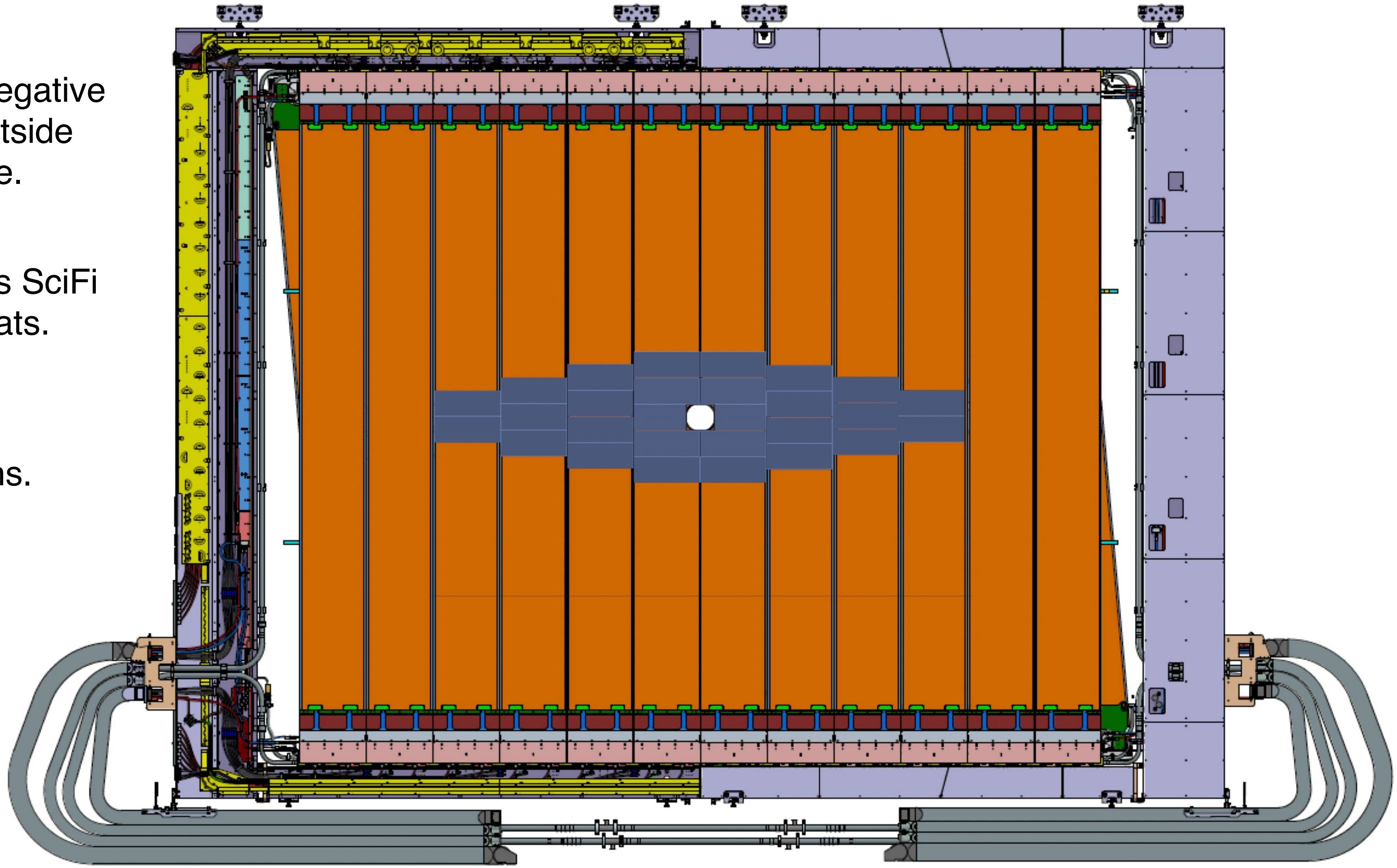


Mighty Tracker

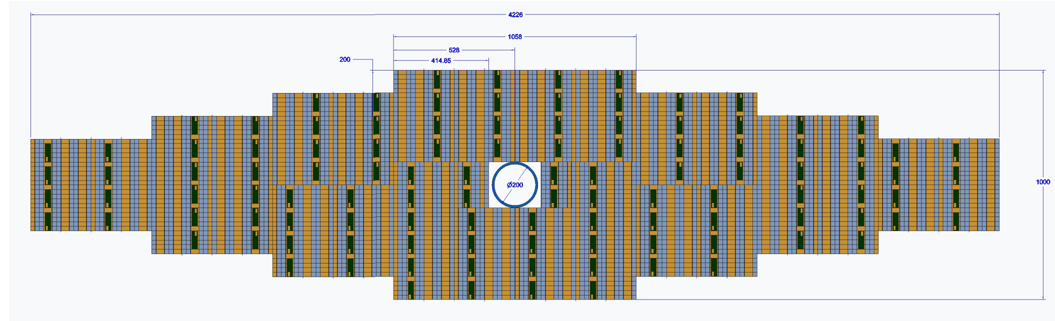
SiPMs operated at negative temperatures and outside the LHCb acceptance.

Outer region contains SciFi (Scintillation fibre) mats.

Silicon inner and middle tracker regions.

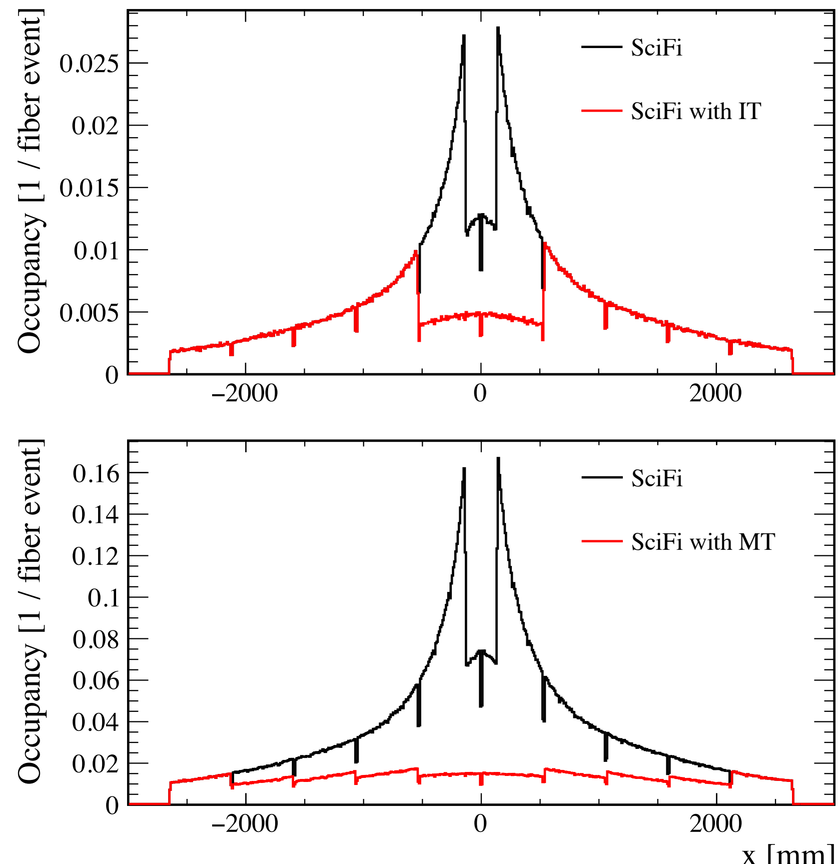


Mighty Tracker

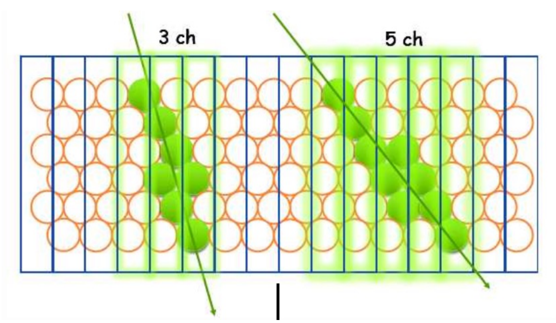


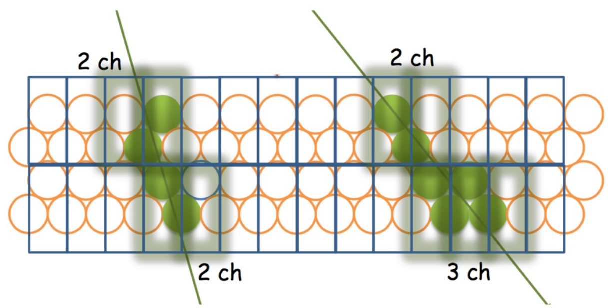
Occupancy and radiation damage is a key challenge for Run 5.

- 6 × 10^{14} n_{eq} cm^{-2} in the inner region.
- Degrades the performance to about 50% tracking efficiency and nearly 100% ghost rate.
- R&D for new **nano-organic luminescence** (NOL) materials. Attenuation length is wavelength dependent and is smaller for green- than for blue-emitting fibres. Promising results obtained (1.3 ns decay time).
- Possibly **reduce the number of fibre layers** per mat.
- **CMOS-pixel modules** at the centre ('middle' MT and 'inner' IT) of the plane.
  Baseline pixel size of 50 µm × 150 µm.



FCC Workshop

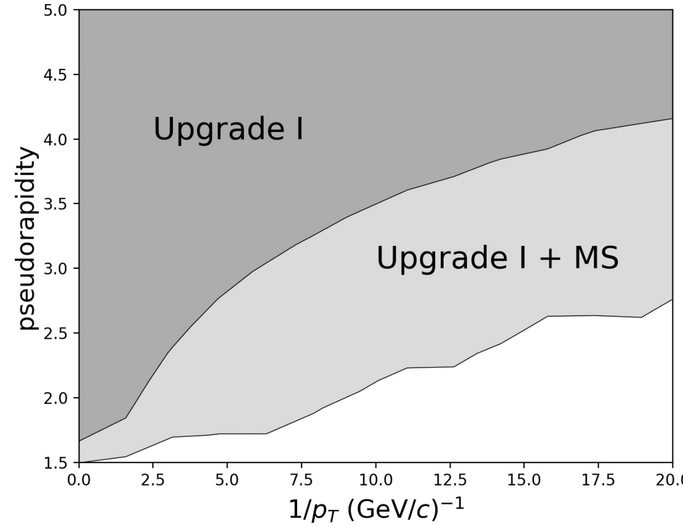


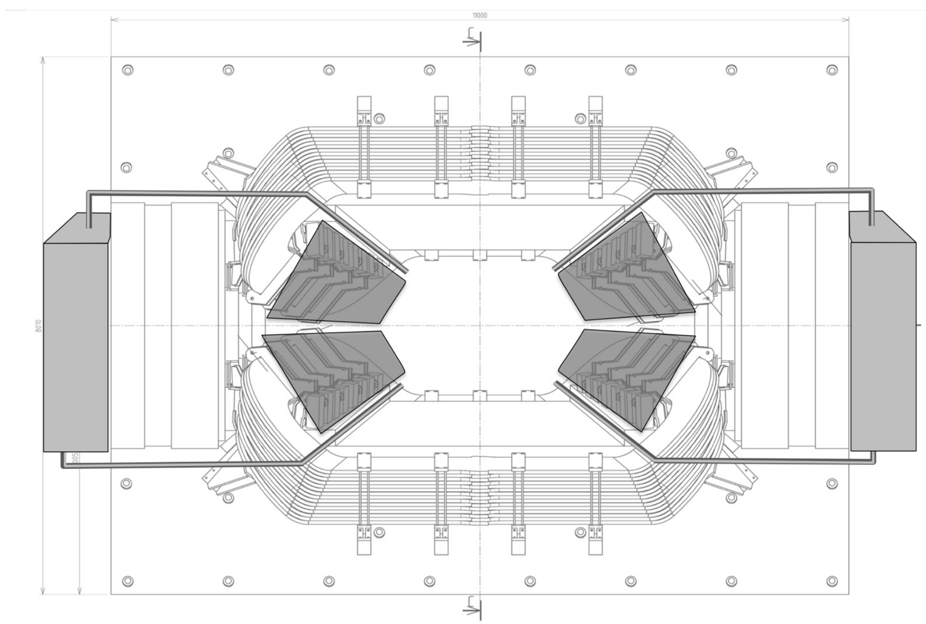


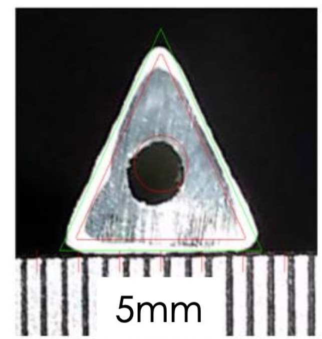
Magnet stations

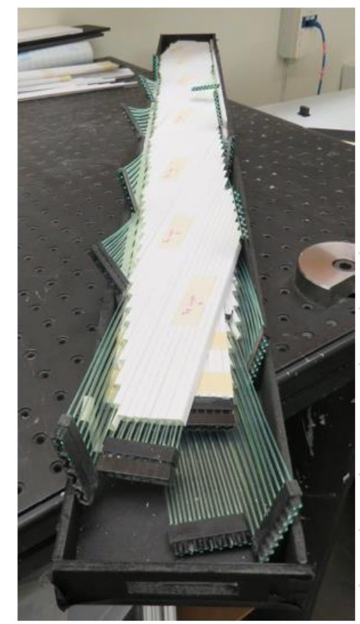
Magnet chambers can **extend the kinematic reach** of the tracking system from LS3 onwards.

- 5 mm side **triangular scintillator bars** with embedded wavelength-shifting fibres readout by SiPMs.
- **SiPM boxes** kept outside acceptance in low radiation environment (water cooling only).
- Readout based on SciFi PACIFIC boards.
- For Upgrade II, new custom ASIC foreseen including TDC information to reject slow particles spiralling inside the magnet.

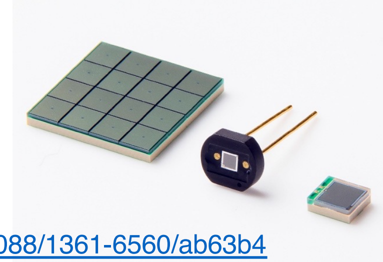








SiPM technology (SciFi and RICH)



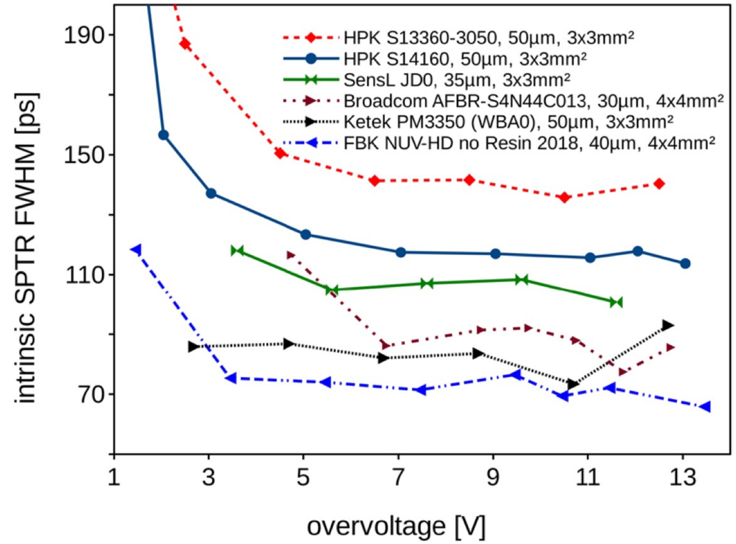
Highly attractive technology for Upgrade II.

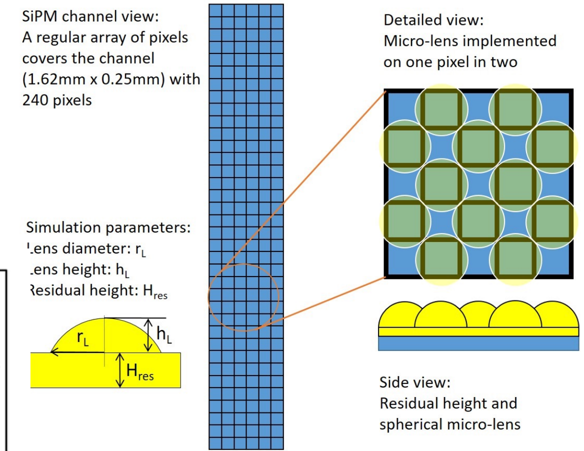
- ➢ Good single photon time resolution.
- ➢ High photon detection efficient in the green wavelength region + photon counting capability due to SPAD structure.
- ➢ Low operating voltage.
- ➢ Not affected by magnetic field.

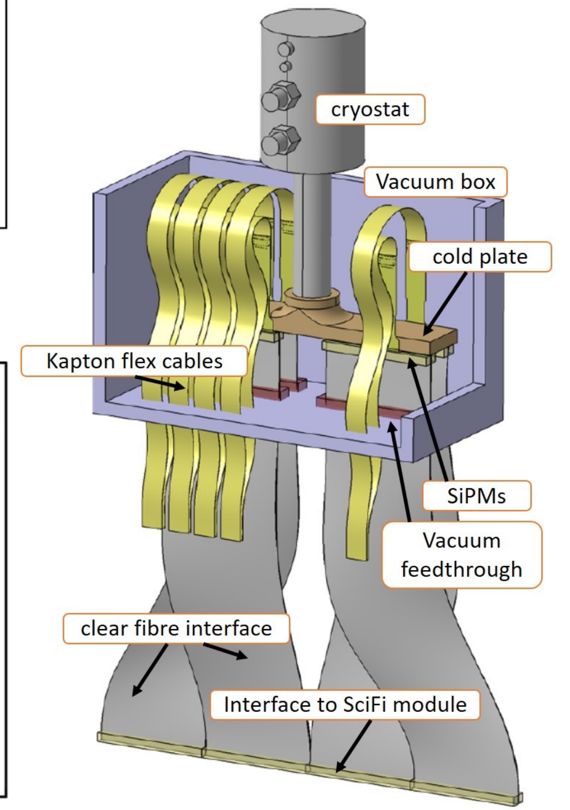
However, high DCR after irradiation.

- ➢ Requires cooling, neutron shielding, annealing during detector down-time.
- ➢ Micro-lensing reduces the silicon area and improves DCR, capacitance and time resolution.

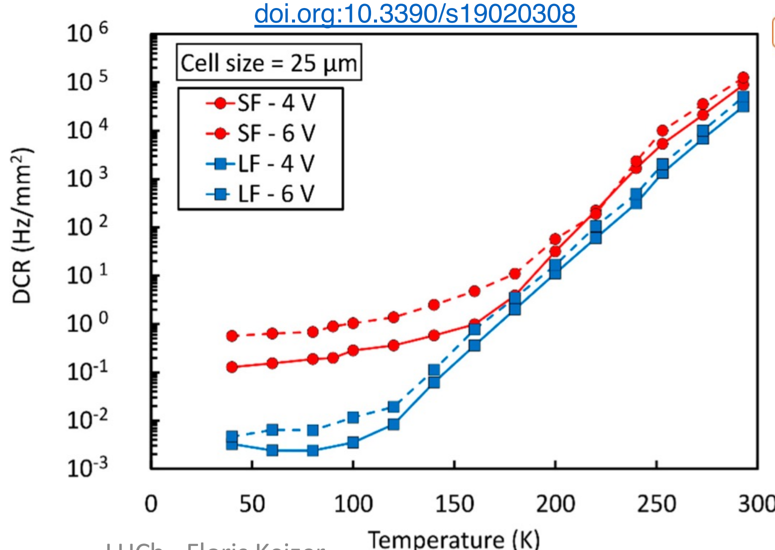
doi:10.1088/1361-6560/ab63b4

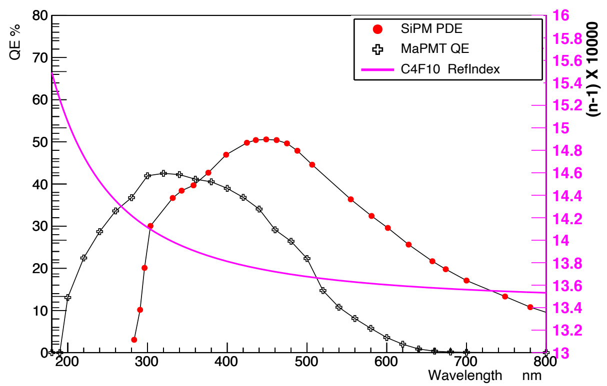






doi.org:10.3390/s19020308





Particle identification system

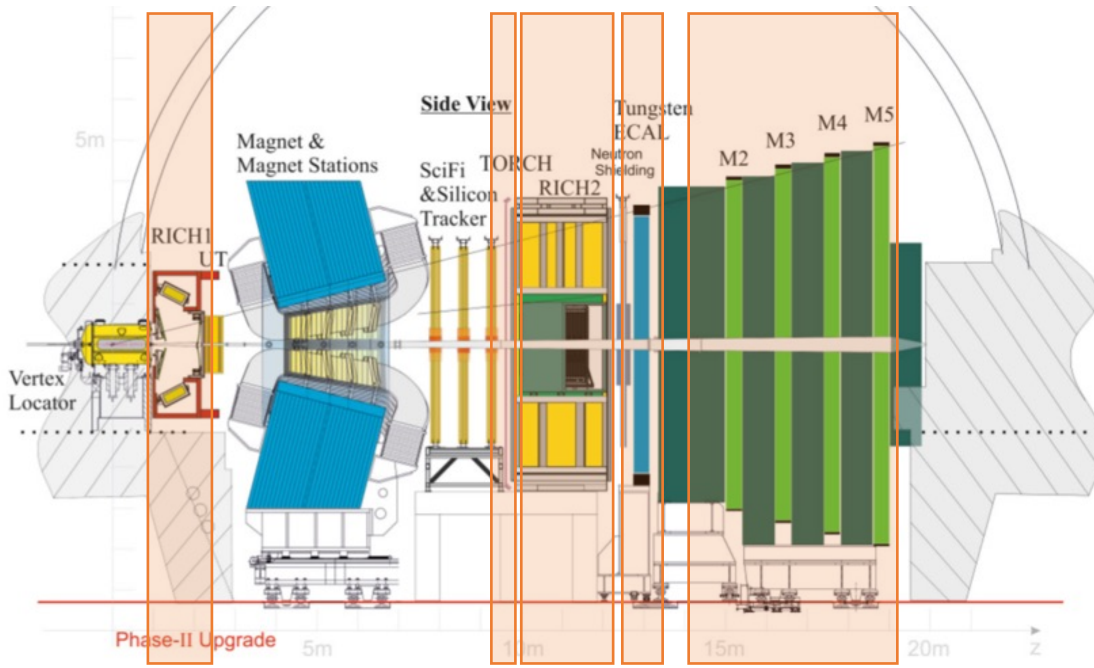
Ring-Imaging Cherenkov detectors (**RICHs**) perform charged hadron ID from 3 GeV/c (veto mode) to 65 GeV/c using C4F20 in RICH 1 and 15-100 GeV/c using CF4 in RICH 2.

The brand-new **TORCH** (Time of internally reflected Cherenkov light) will cover the lower momentum range from 2-10 GeV/c by combining the time-of-flight and time-of-propagation techniques.

The electromagnetic calorimeter (**ECAL**) performs photon, electron and π^0 identification and is separated from the **muon** detectors by a 1.7 m-thick iron shield.

There is a **strong interplay between the tracking and particle ID systems**, as the tracking resolution should match the particle ID resolutions, notably in the photon-ring searches of the RICH detectors.

The use of SiPMs could allow magnetic shielding around RICH 1 to be removed.

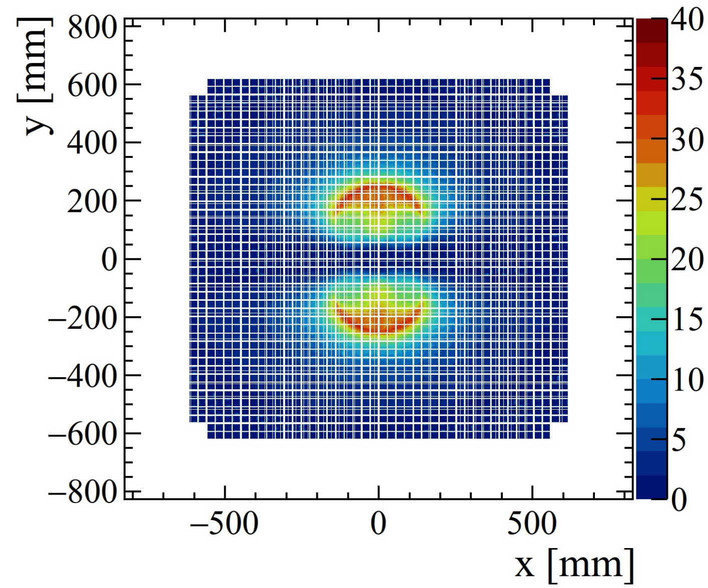


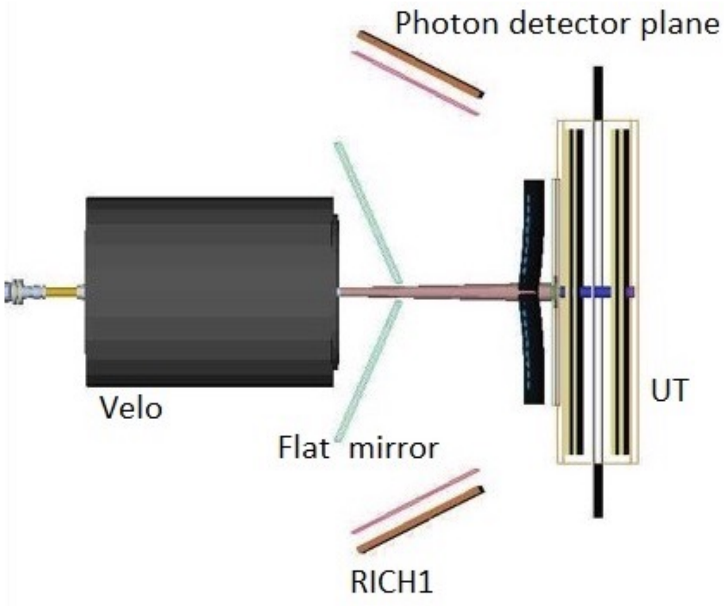
Ring-Imaging Cherenkov (RICH)

RICH1 peak occupancy	MaPMT	SiPM and geometry update
Run 3	35 %	3.9 %
Upgrade II	> 100 %	18 %

A range of modifications foreseen to reduce the photon occupancy and improve the Cherenkov angle resolution.

- Improved **granularity** to 1.0 x 1.0 mm^2 pixels avoids the peak photon occupancy from exceeding 100 %.
- SiPM with **enhanced sensitivity in the green** wavelengths reduces the chromatic error.
  Additional studies ongoing on MCP-based detectors and next generation MaPMTs.
- **Redesign of the optics** with lightweight flat mirrors placed inside the LHCb acceptance reduces emission point error.



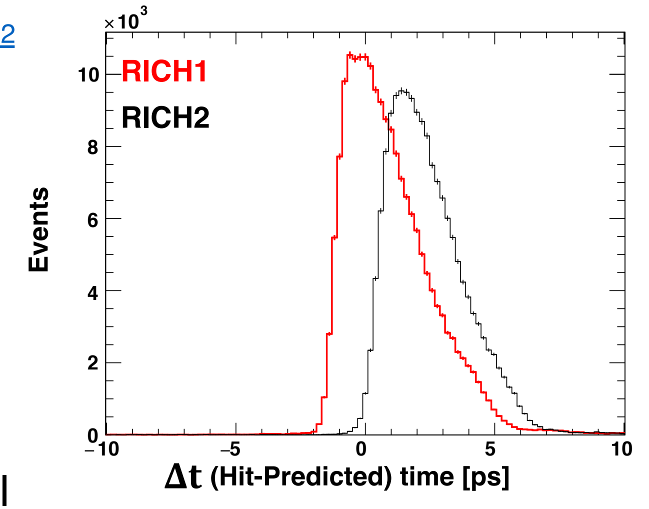


Configuration		Overall mrad	Chromatic mrad	Emission pt. mrad	Pixel mrad	Yield
RICH1	MaPMT	0.80	0.52	0.36	0.50	63
	SiPM	0.40	0.11	0.36	0.15	47
	SiPM & geometry	0.22	0.11	0.12	0.15	34

doi:10.1016/j.nima.2018.12.025

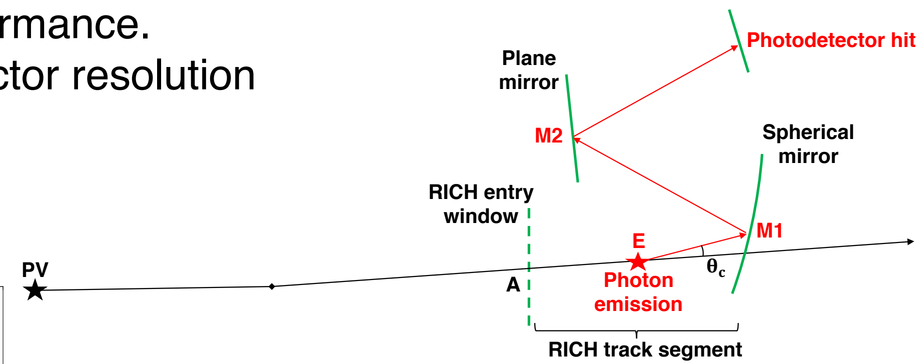
Doi:10.17863/CAM.45822

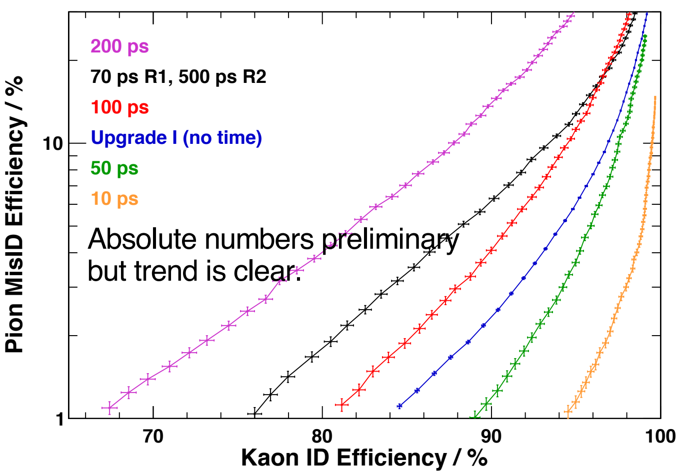
Fast timing in the RICH detectors

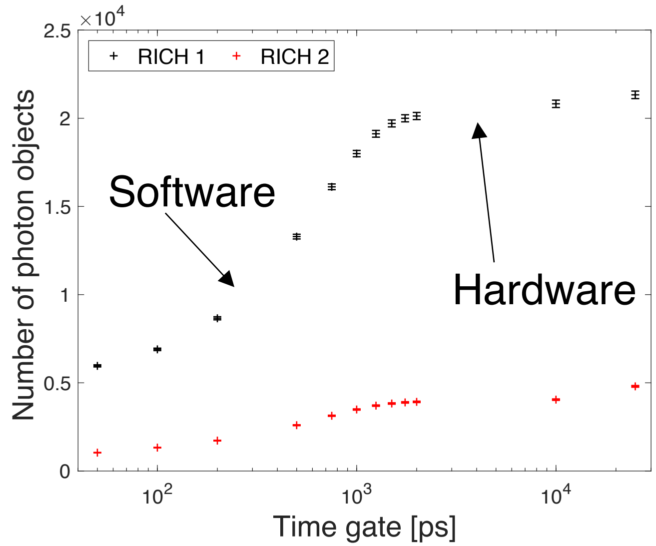


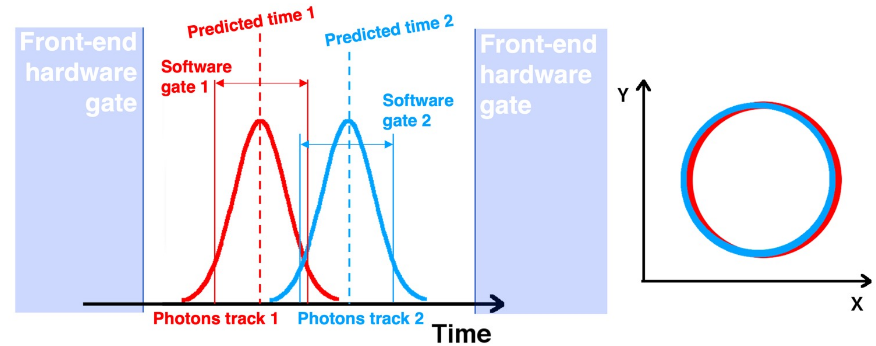
Owing to the prompt Cherenkov radiation and focusing mirror geometry, all photons from a given track arrive at approximately the same time at the photon detector plane.

- Using **reconstructed parameters** in the RICH algorithms and the PV t-zero, can predict the detector hit times to within 10 ps.
- **Time gate around the predicted time** significantly reduces combinatorial background and helps to recover the Run 3 particle ID performance.
- **Faster detectors are better**, as in practice the photon detector resolution will dominate the width of the time gate.
  Aiming for a resolution better than 100 ps.



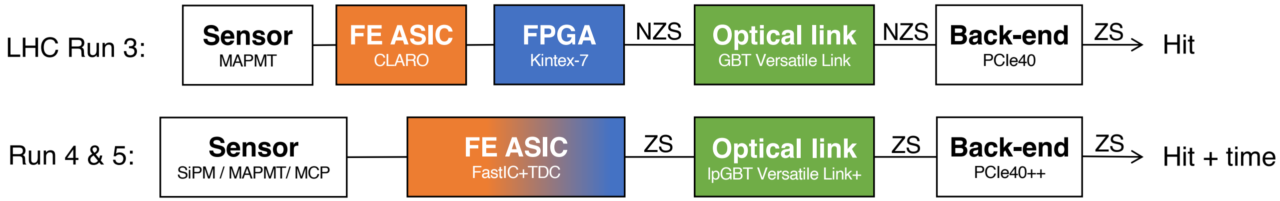


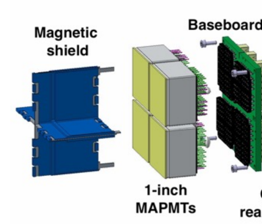


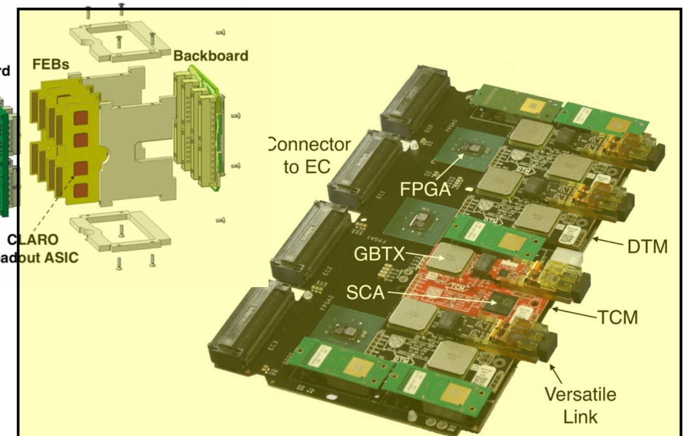


RICH digital readout enhancements for fast timing

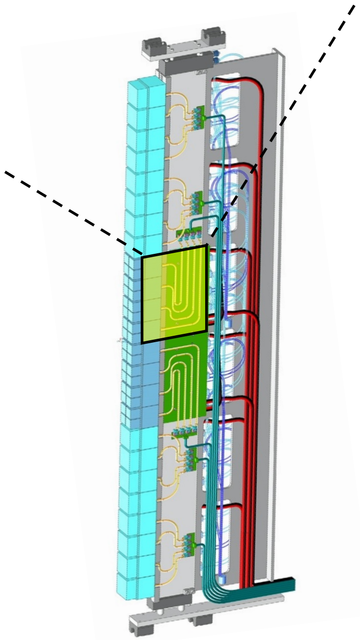
[RICH timing techniques (CDS2770576)](#)







Run 3 readout electronics



During LS3, propose to replace the FE ASIC and FPGA by a single ASIC with **integrated TDC** and direct connectivity to optical links.

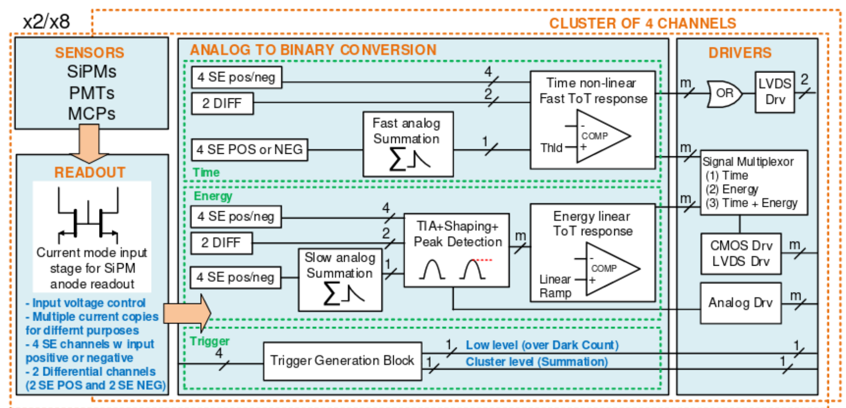
- During Run 4, can **estimate the PV times using the RICH** by measuring the photon times on the Cherenkov ring.

FastIC ASIC development by CERN EP-ESE and ICCUB.

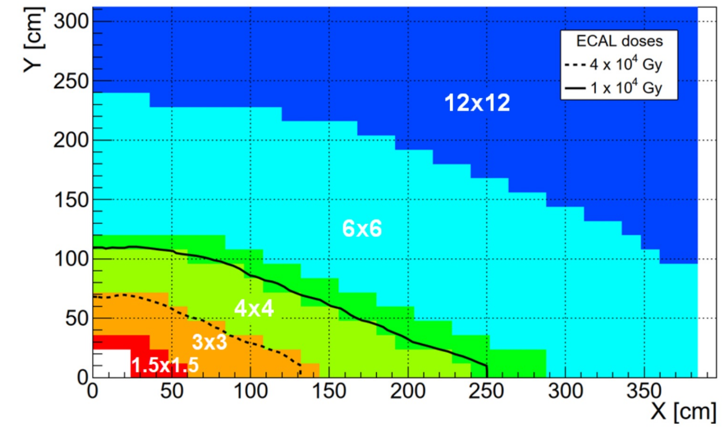
- RICH specifications are input for a custom **FastIC+TDC** adaptation.
- Constant Fraction Discrimination and ns time gate to optimise bandwidth.
- Additional FastIC+TDCPix development for 2D pixel detector readout tightly integrated with SiPM.

25 ps FE ASIC for MAPMT, SiPM or MCP-based detectors.

- 65 nm CMOS.
- 8 channel prototype, 16/32 channel planned.
- > 50 MHz channel with non-inear ToT.
- 1.2 V power with 6 mW/ch.
- Single-ended signalling possible.
- Dynamic range 5 uA to 20 mA.



Electromagnetic calorimeter (ECAL)



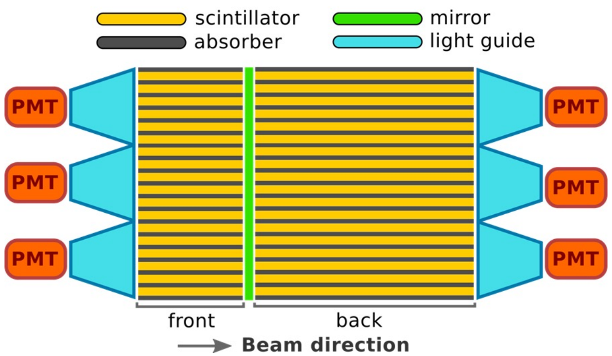
Radiation hardness of the modules is essential.

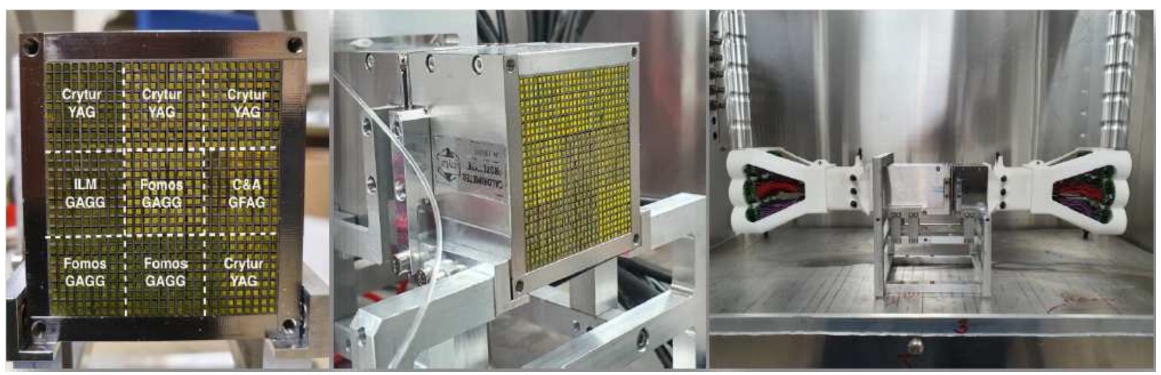
- Expected dose in Upgrade II up to 1 MGy. Current modules have a 40 kGy operational limit, requires inner region to be replaced in LS3.
- Radiation tolerance can be met by crystal fibres, leading to a **'Spaghetti' Calorimeter (SpaCal)** in the central region, whilst keeping Shashlik modules in the outer region.

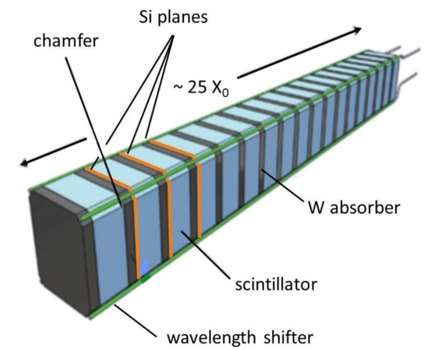
Peak luminosity of Upgrade II will lead to overlapping showers.

- **Finer cell sizes** and **decrease of Molière radius** required in the inner region.

Test beam campaign ongoing with SpaCal module in image.
Additional R&D for Si-W sampling calorimeter (operated with cooling).





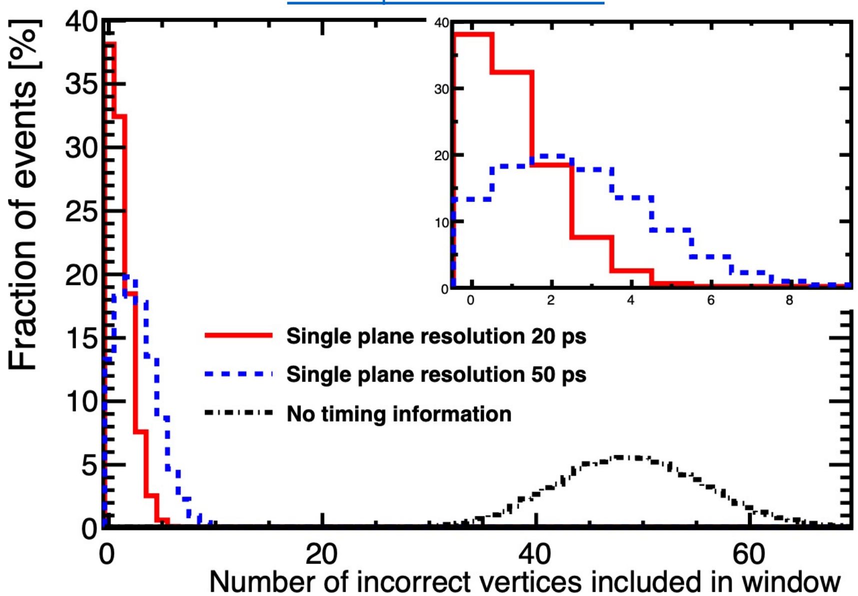


ECAL timing & MCP/LAPPD technology

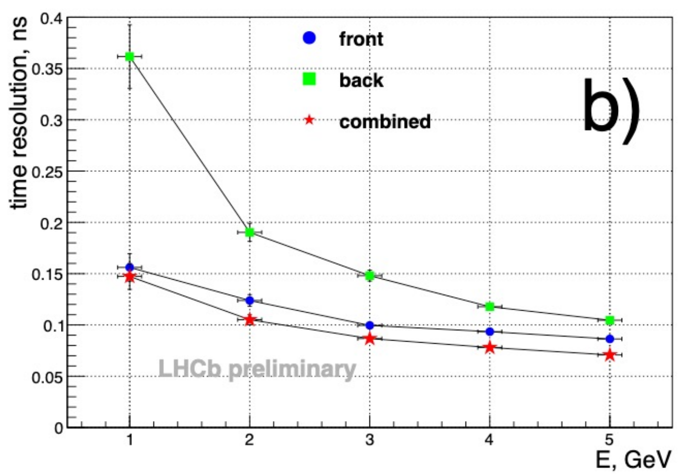
Run 5 luminosity leads to an unacceptably large **combinatorial background**.

- **Fast timing information** will be essential to associate the candidates to individual pp interactions.
- Idea is to **split the SpaCal modules longitudinally** in two sections at around the shower maximum, and read both the front and back sections to improve clustering, reconstruction and particle ID. This improves the intrinsic SpaCal time resolution.
- A **dedicated timing layer** can be inserted in between using MCP-based LAPPD technology (large area picosecond photon detector) or a three-layer silicon detector. R&D campaign foreseen targeting a single plane resolution of 50 ps or better.

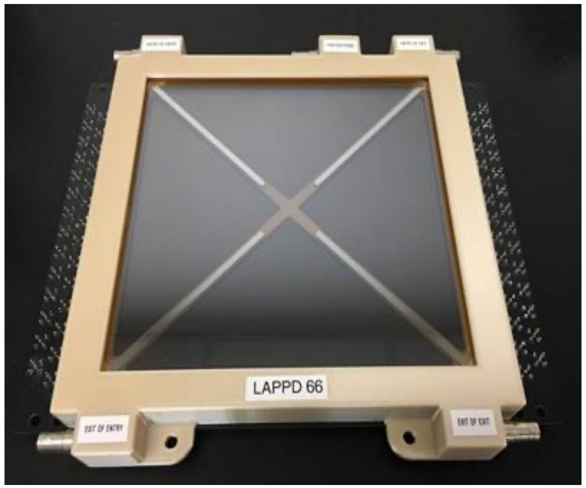
2017 expression of interest



doi:10.1088/1748-0221/15/09/C09046



Incom LAPPD details

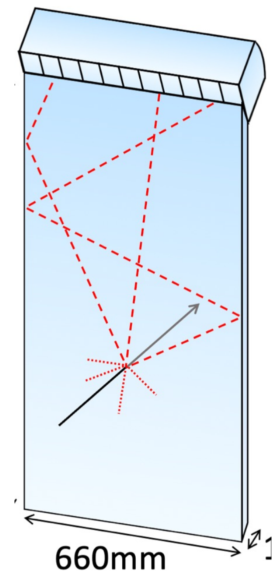


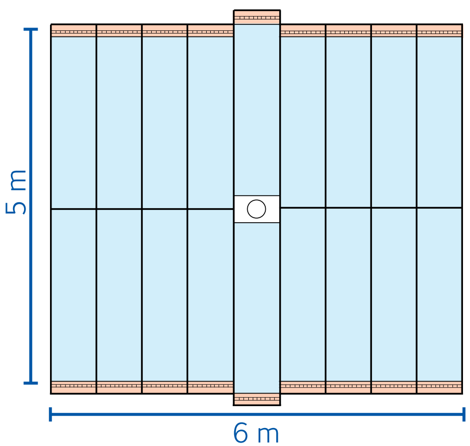
TORCH (Time of internally reflected Cherenkov light)

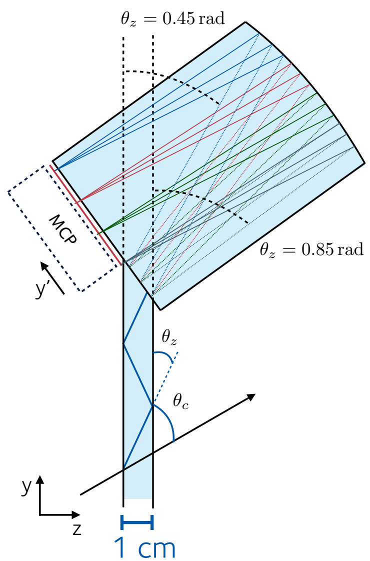
Novel detector combines time-of-flight and detection of internally reflected Cherenkov light techniques.

- ~ 10 m from the collision point,
  Δt ~ 35 ps for 10 GeV/c kaons and pions.
- Results in single photon requirement of about 70 ps.

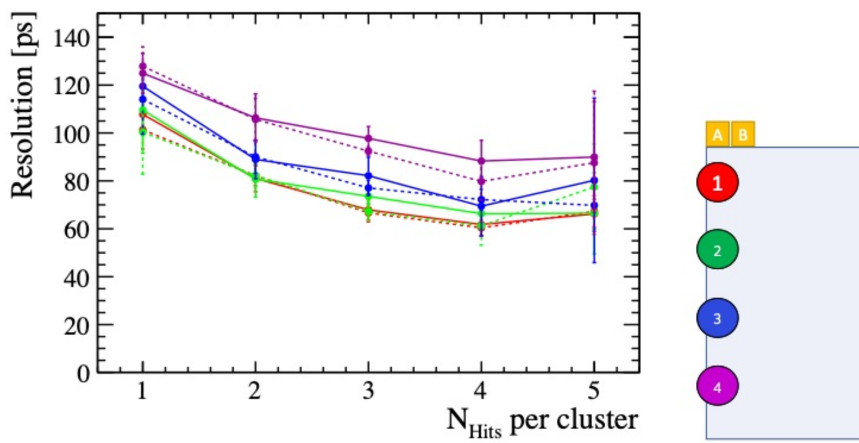
TORCH prototype half-sized module constructed, and beam tests performed. Measured results approach desired time resolution and improve with the number of detected photons.







doi:10.22323/1.364.0140

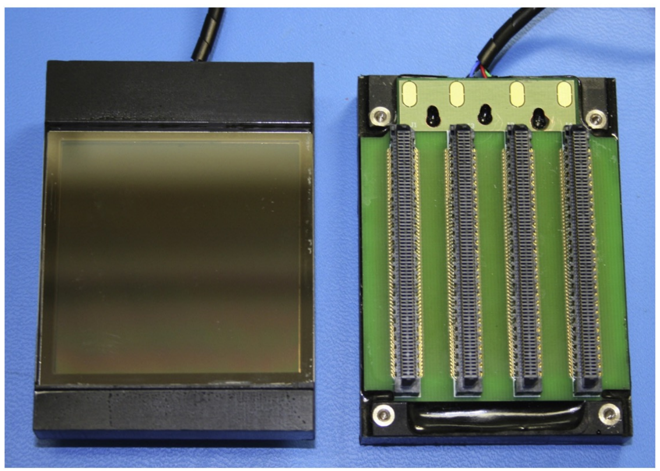


TORCH and MCP-PMT technology

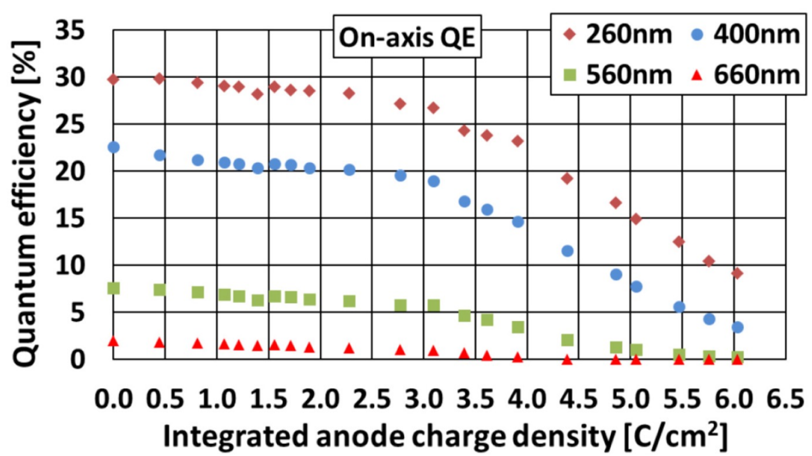
The micro-channel plate (MCP) PMT **tailored to the TORCH application** has been developed.

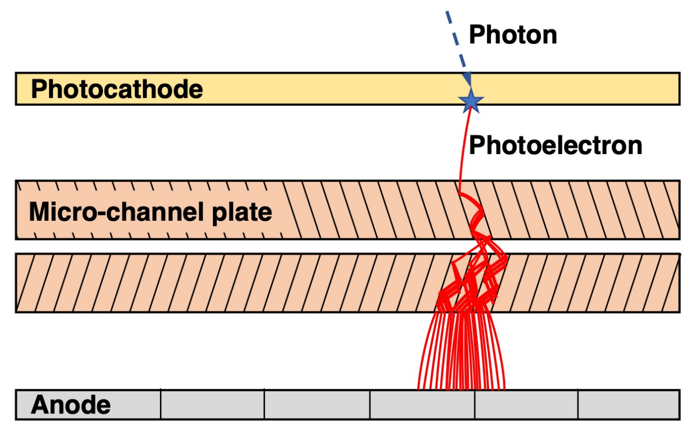
- **Exceptional time resolution** of typically 30 ps combined with a low dark-count rate.
- A drawback of the MCP-family is the restricted lifetime, despite significant improvements using atomic-layer deposition (ALD) coating. MCPs were demonstrated to survive > 5 C/cm^2.
- TORCH MCP-PMT has 64 x 64 pixel achieving 8 x 128 effective pixels through charge sharing, but Upgrade II will require a finer granularity in the central modules.

Synergy with other sub-detectors such as the ECAL timing plane (LAPPD) and the RICH detector (fast photon sensors and FastIC+TDC readout ASIC).



doi:10.1016/j.nima.2018.12.007





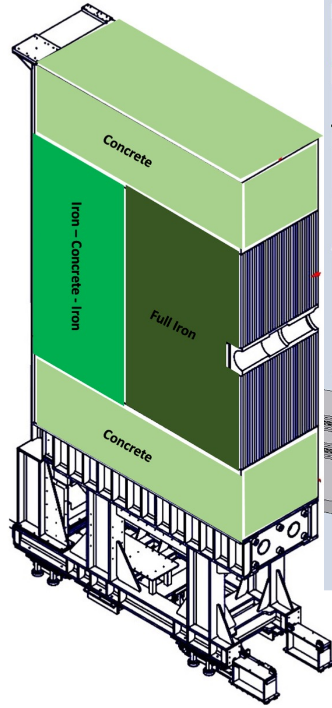
Muon detector

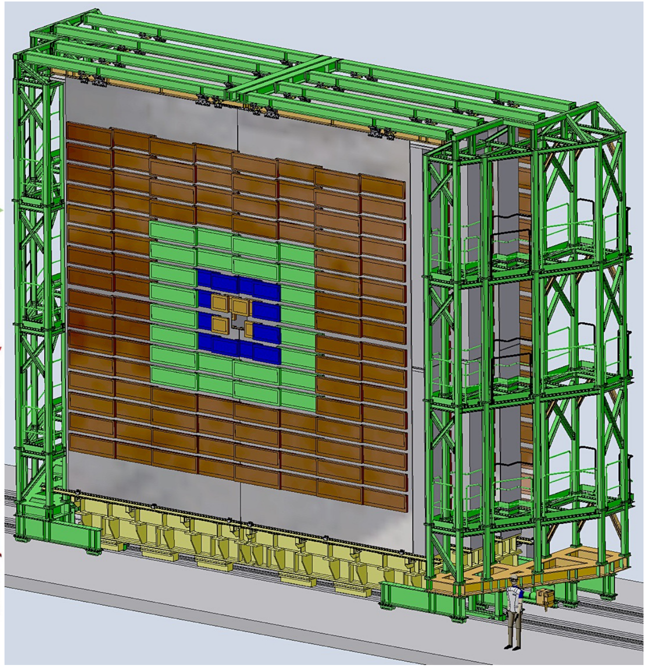
Similar to other detectors, the inner region is exposed to challenging increase in occupancy.

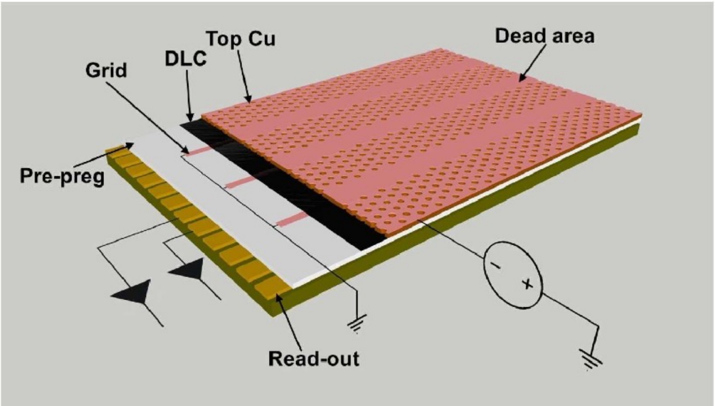
- Mitigate by introducing **'structured' shield** in front.
- **μ–RWELL** technology (GEM principle) is a promising next-gen MPGD for **detection rates of several MHz/cm²** and has been tested during beam tests. ~ 95 % efficiency in 25 ns window.

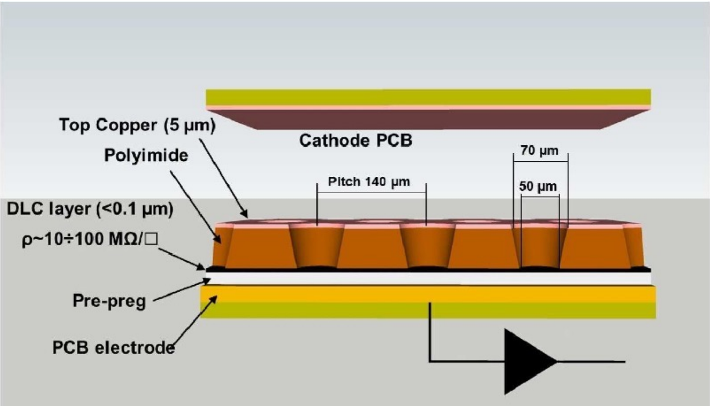
For the lower rate outer region, extensive ageing campaign to confirm the possibility to use **MWPCs** up to the end of the experiment lifetime.

- R&D for alternatives include RPCs (~ 10 kHz/cm²) or scintillating pads with WLS fibres and SiPMs.

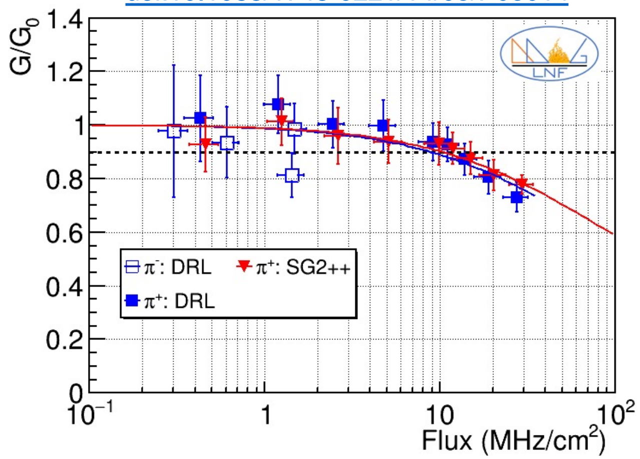








doi:10.1088/1748-0221/14/05/P05014



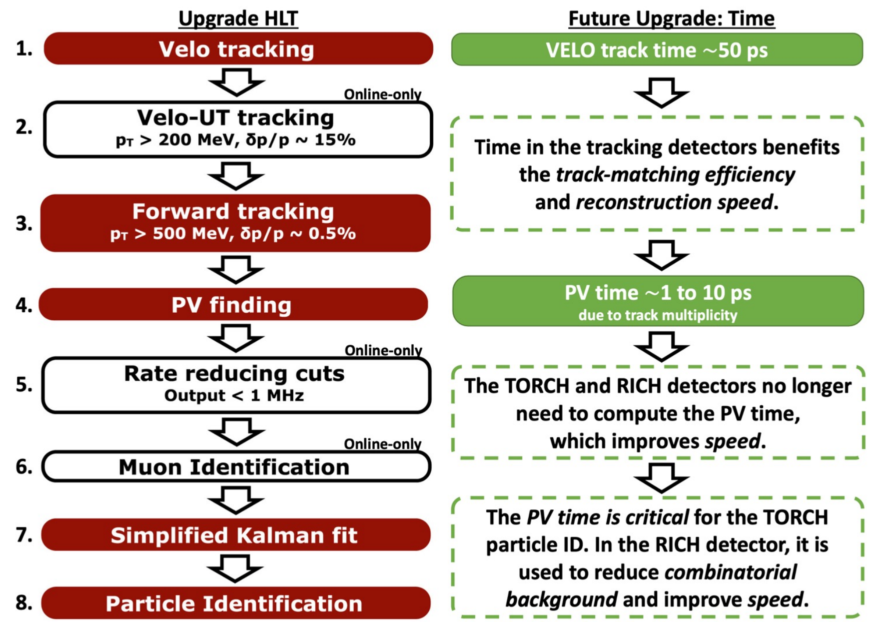
DAQ and online processing

The software trigger is a novel and core part of the LHCb Upgrade I, and will have to cope with the increase in data rates and detector complexity in the HL-LHC.

- ➢ Addition of fast timing information helps for **pile-up suppression**: hits not associated with a pp interaction of interest are immediately discarded.
- ➢ Processing sequence will need to be re-optimised to combine multiple sources of fast-timing information.

High-Level Trigger (HLT) comprises:

- ➢ HLT1: reconstruction to identify inclusive beauty- and charm signatures as well as high-pT muons **on GPUs**.
- ➢ HLT2: full (HLT2) reconstruction of “offline quality” on CPUs (in Run 3).



Range of R&D options including:

- ➢ FE higher speed links suitable for the high radiation environment.
- ➢ **FE: local processing** e.g. clustering, track-stub creation (RETINA) and a readout + tracking FPGA board.
- ➢ Disk buffer: the use of solid-state technology.
- ➢ Online: co-processors, such as FPGAs or IPUs, to complement the present CPUs and GPUs.

Conclusion

The HL-LHC Run 5 allows LHCb to acquire more statistics and make optimal use of the HL-LHC.

The high luminosity leads to a challenging increase in track and photon multiplicity in the detector.

In order to mitigate this effect, LHCb will transform into a 4D (x,y,z,t) detector and take the approach of:

- Improving the granularity and time resolution of the sensors.
- Transitioning to robust, integrated, low-power technologies.
- Introducing better modularity to address the non-uniform occupancies.

A wealth of R&D is ongoing for detector designs and next-generation technologies.

The picosecond time information will add a new dimension to the experiment,
with high synergy between the sub-detectors to improve resolutions and to share technologies.