Future timing detectors in LHCb and Beyond

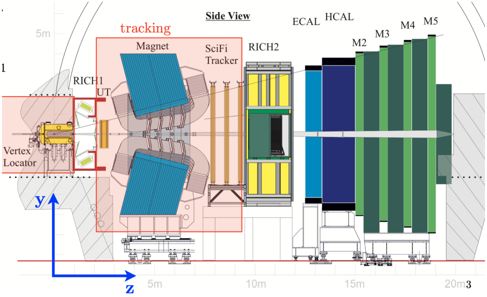
Matteo Bartolini* (University of Cambridge)

*__On behalf of the LHCb Collaboration__

LHCP 2023

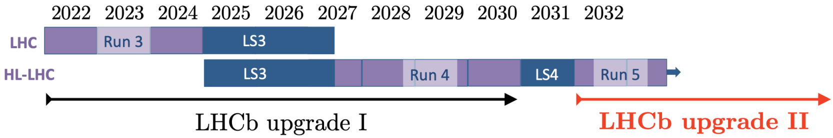
Belgrade, 22-26 May 2023

The LHCb detector (Run3)

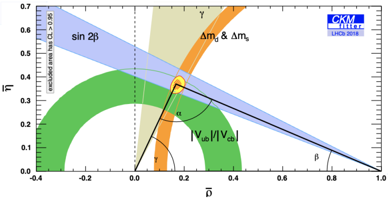


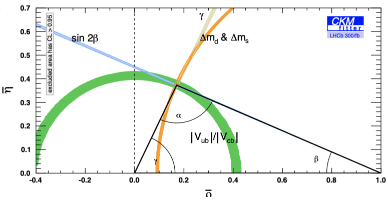
- Single arm forward spectrometer $2 < \eta < 5$
  - excellent vertex resolution
  - tracking stations before and after 4Tm dipole magnet
  - particle identification with two ring-imaging Cherenkov detectors, calorimeters and muon detectors
- Full software trigger at 40 MHz → GPU-based HLT1 & CPU-based HLT2
- $\mathcal{L} = 2 \times 10^{33} cm^{-2} s^{-1}$
- We aim to collect up to 50 fb^{-1} by the end of Run4

The Upgrade II physics program ‣ LHCB-TDR-023



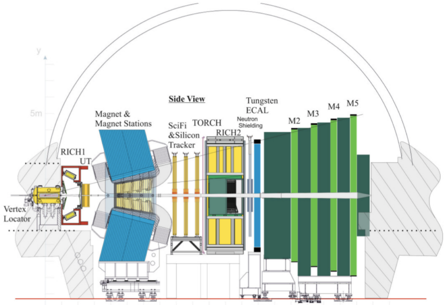
- Accumulate data to a minimum of 300 fb^{-1}, sensitivity generally limited to statistics
- Ambitious physics program with many observables to be measured with a precision unattainable at competing experiments
- Operate at $\mathcal{L}=2\times10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$





The Upgrade II detector

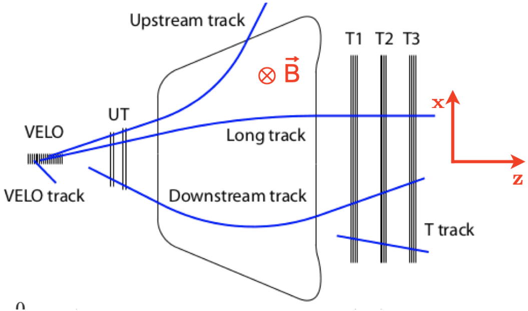
- Factor 7.5 increase in particle multiplicity and rate wrt to Upgrade I
    - 42 expected interactions per crossing.

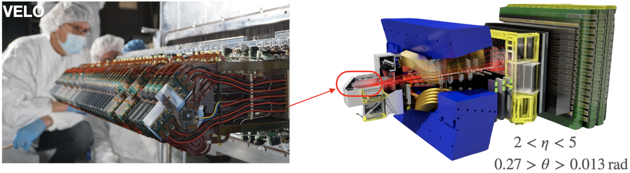


- The current arrangement of subsystems will be maintained, but
    - The inner part of the SciFi will be made of silicon (Mighty tracker)
    - Installation of a new time of flight detector (TORCH)
    - No more hadron calorimeter.
    - **Addition of timing information** to cope with increased detector occupancy

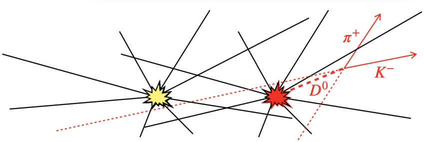
Tracking in LHCb

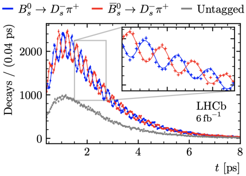
- Trajectories reconstructed by matching track stubs up and down-stream of magnet
- VELO, UT (1 station) and SciFI (3 stations)
- Momentum resolution dominated by multiple scattering
- Tracking efficiency and ghosts rate depend on detector occupancy





- Designed to work at $\mu = 5.5$ for the Upgrade I
- 40 M of pixels:
  - 200 μm thickness, 55 μm pitch
- Reconstructs tracks and PVs in real time
- Association of heavy flavour decays to correct primary vertex crucial for the physics program (ex B_s^0–$\bar{B}_s^0$ oscillation)

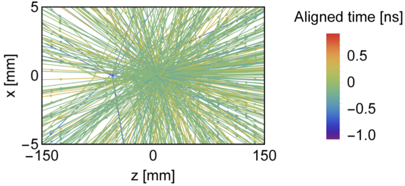


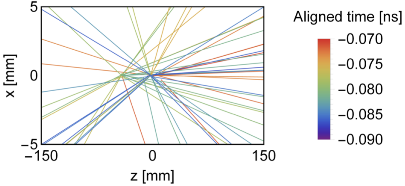


arXiv:2104.04421

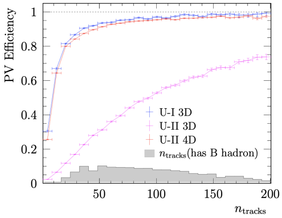
4D tracking with the Upgrade II VELO ▸ LHCB-TDR-023

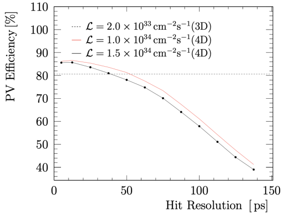
- The precision and the efficiency of the Upgrade I detector must be maintained at $\mu = 42$
- Fluence expected to reach 6×10^{35} 1 MeV n_{eq}/cm^2 at 5.1 mm inner radius
- Addition of timing to reduce pile-up $\rightarrow$ single hit time resolution of 50 ps required

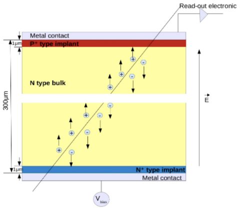


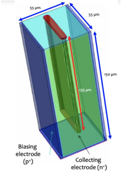


- The addition of timing allows to recover the Upgrade I performances

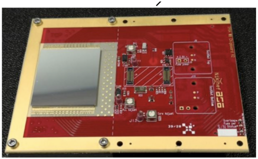




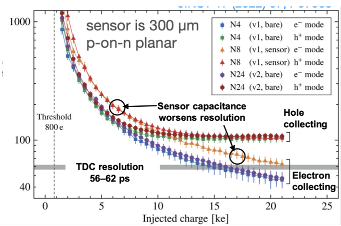




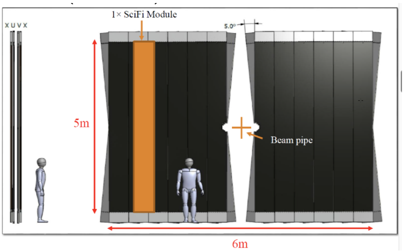
- Rad-hard technologies up to 10^{16} 1MeV n_{eq}/cm^2:
  - Planar sensors
    JINST 16 07, P07035
  - 3D sensors
    Nucl.Instrum.Meth.A 981 164491
  - LGAD sensors
    J.Phys.Conf.Ser 2374, 012175
  - SiEM sensors
    Nucl.Instrum.Meth.A 1041, 167325

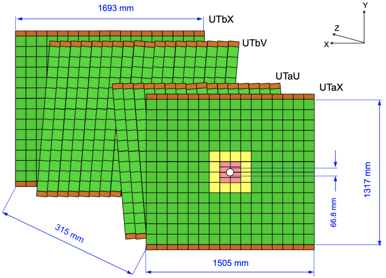


- TimePix4 ASIC JINST 17 C01044
  - 65 nm technology
  - 58 ps TDC binning
- Test beam with TimePix4 + planar sensors with pixel pitch of 55 × 55 μm JINST 17 07, P07006



The Upgrade I SciFi and UT ▸ LHCB-TDR-015



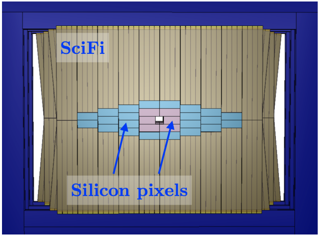


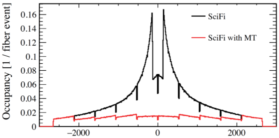
- 3 stations of 4 detection planes
- each plane made of 6 layers of 2.5m fiber arrays
- readout by multichannel SiPMs
- Spacial resolution $< 100\mu$m

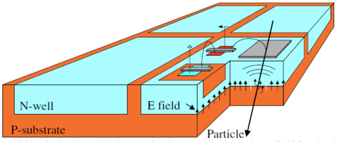
- 4 detection planes
- two planes with vertical strips, two rotated by $\pm 5^o$
- Silicon strips with $\sim$200 μm pitch and 100 mm length

Mighty tracker for the Upgrade II phase ▸ LHCB-TDR-023

- Significant fibre radiation damage in inner region
- SciFi must be replaced near beam pipe to maintain the same (or better) tracking performance
- UT strip sensors not suitable for Upgrade II, need to change to pixels
- High-Voltage Monolithic Active Pixel Sensors (HV-MAPS) technology for SciFi and UT



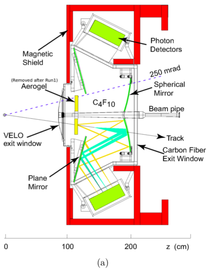




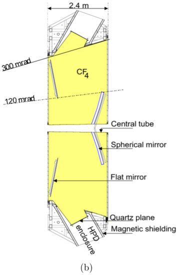
- Integrated readout electronics and sensor in a CMOS process
  ▸ IEEE J.Solid State Circuits 56 8, 2488-2502
- Requirements:
  - Pixel size: 100×300 μm^2
  - Time resolution: 3 ns
  - Sensor thickness: 150 μm

The Upgrade I RICH ▸ LHCB-TDR-014

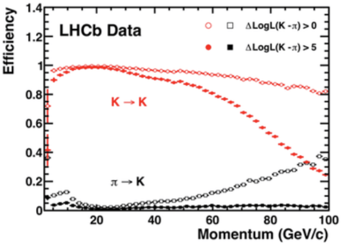
- Physics programme at LHCb relies on good PID
- The 2 RICHes provide the PID of charged hadrons in final state: π, K e p



(a)



(b)

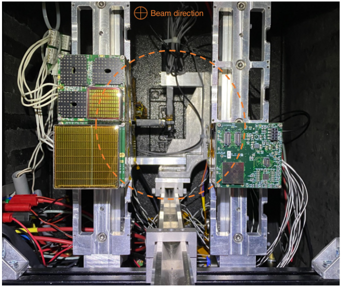


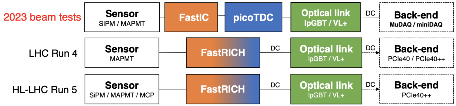
- 2 detector provide PID in the momentum range 10-100 GeV/c
- MaPMTs as photodetector with pixel size of 3×3 mm^2

- the RICH requires tracking information for the reconstruction
- To maintain current performances the occupancy in the photo-detector plane must be below 30%

The Upgrade II RICH ▸ LHCB-TDR-023

- Need to add timing information to the Cherenkov photons



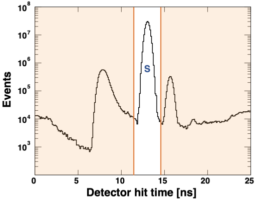


- Need photodetectors with smaller pixel size $\sim 1\text{mm}^2$
- Need time resolution better than 100 ps
- R&D ongoing with SiPMs/MaPMTs/LAPPD ▸ Incom LAPPD ▸ FBK SiPM

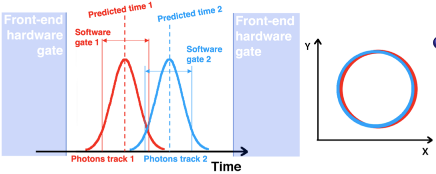
- Sensor coupled directly to an ASIC(FastIC+picoTDC) without the use of FPGA ▸ FastIC Collabaoration
- Data are sent to PCIe40++ back-end via optical links

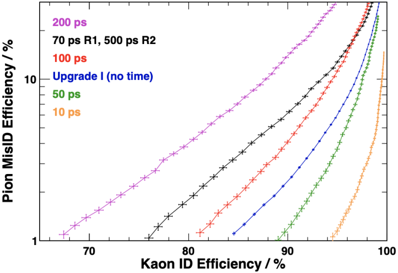
Timing information in the RICH

Doi:10.17863/CAM.45822



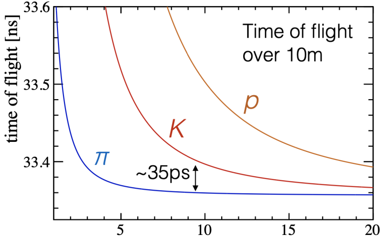
- Time distribution of photon hits within 25 ns shows clear Cherenkov peak signal
- Apply nanosecond front-end hardware time gate of $\sim$ 4ns
  - Assign timestamp to each detected photon

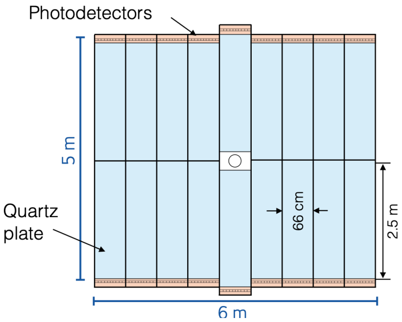




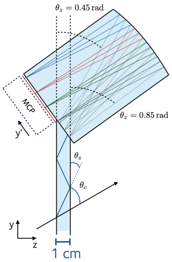
- Current PID performance will be maintained if $\sigma_t < 100$ ps
- **Assumes precise knowledge of PV time for reconstruction$\rightarrow$ Info provided by the VELO**

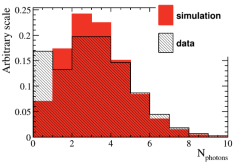
- Physics programme at LHCb relies on good PID
- At low momentum (< 10 GeV/c) both kaons and protons are below the RICH threshold
- Add large area detector before RICH2 to measure TOF (~ 10 m from interaction point)

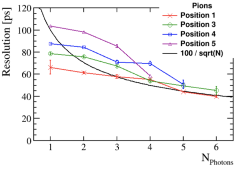




TORCH principle



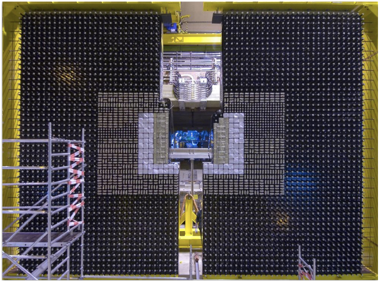


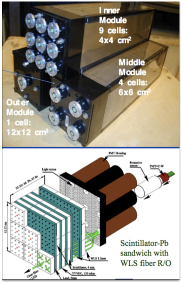


- Exploits Cherenkov light in quartz bar
- Need 15 ps/track → 70 ps single photon time resolution
- Requires knowledge of PV time for the reconstruction→ provided by the VELO

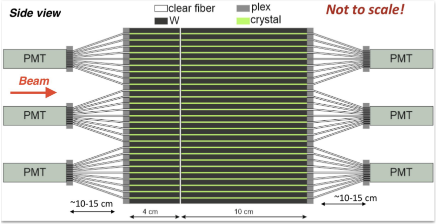
- MCP-PMT designed by Photek UK used as photodetector ▸ JINST 10 C05003
- Sensor is coupled to NINO and HPTDC chips developed by ALICE for TOF
- Investigate the use of FastIC and PicoTDC like the RICH
- Test beams show σ_t is approaching 70 ps/photon ▸ arXiv:2111.04627

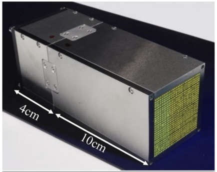
The Upgrade I ECAL ▸ LHCB-TDR-014



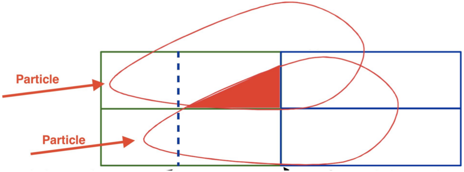


- ECAL is crucial for wide range of flavour-physics goals
  - Provides precise measurement for $e^{\pm}$, γ and PID
- Must be able to sustain radiation dose up 6×10^{15} for 1MeV n_{eq}/cm^2 during Upgrade II
- WLS in the current shashlik are not rad-hard
- Need to introduce fast timing resolution (few tens of ps) for pile up mitigation



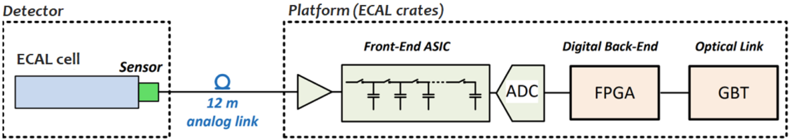


- Rad hard crystal fibers scintillate and transport light
  - coupled to optical fibers to create a cell size of 1.5 $\times$ 1.5 cm^2 readout by PMTs/SiPMs
- YAG and GAGG crystals studied ▸ Nucl. Instrum. Meth. A 1000 (2021), 165231
- Asymmetrical separation to enhance shower seperation

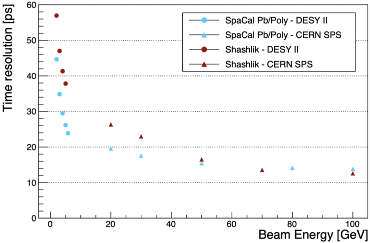


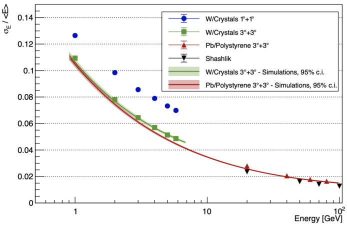
ECAL readout

- waveform sampling at several giga-samples per second
- The digital time and energy measurements will be processed by FPGAs



- First test beam results reveal impressive timing capabilities and the required energy resolution ▸ Nucl. Instrum. Meth. A 999 (2021), 165169





Conclusions

- The upgrade II will allow LHCb to acquire an unprecedented amount of statistics
- The high luminosity condition 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 detector:
  - 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.
- Lots of R&Ds are ongoing for detector designs and next-generation technologies.
- The picosecond time information will add a new dimension to the experiment and increase synergy between the sub-detectors to improve resolutions and to share technologies.