MAPS-based Upstream Tracker for LHCb Upgrade II

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Introduction

LHCb detector (Fig. 1) is dedicated to the flavour physics studies, serving as a forward general-purpose detector:

- Forward **single-arm spectrometer** with a unique coverage in pseudo-rapidity (2 < η < 5)
- Observing 40% of the **heavy quark** production cross-section in 4% of the solid angle
- Precision measurements in the **beauty and charm** sectors
- Also study of QCD, EW, heavy ion collisions, etc.

Upstream Tracker (UT) is located upstream of the LHCb bending magnet.

LHCb operates at $\mathcal{L}_{\max} = 2\times10^{33}\ cm^{-2}s^{-1}$ since 2022 with an upgraded detector. It will take data at $1.5\times10^{34}\ cm^{-2}s^{-1}$ during Runs 5 & 6, about ×7.5 times higher than Runs 3 & 4 (Fig. 2). The current UT cannot cope with the **data rate** and the **high occupancy** (up to ~ 10%).

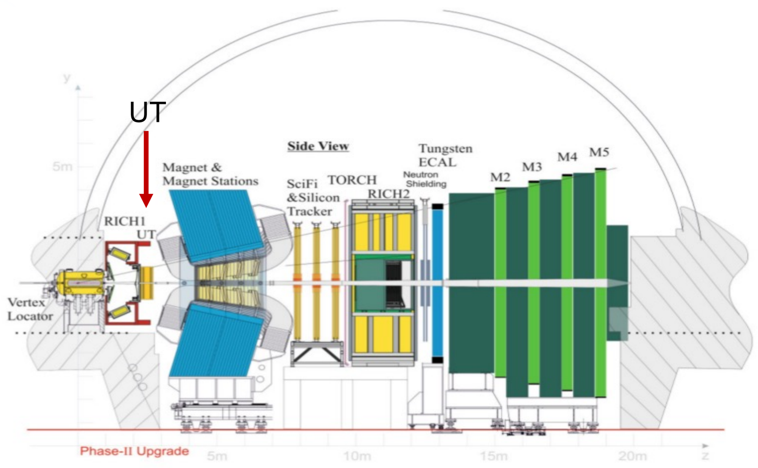


Fig. 1: LHCb Detector at Upgrade II

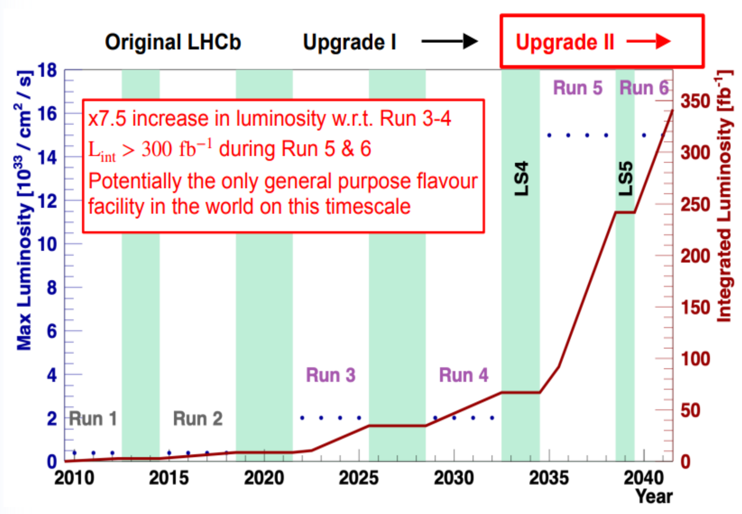


Fig. 2: Upgrade II timeline

The upgrade II UT (U2UT) detector will use **CMOS Monolithic Active Pixel Sensors (MAPS) technology**. We present the proposed design, performance studies, and R&D plan.

Luminosity Simulation

Performance studies are based on simulation samples generated in Upgrade II conditions using the available Run 3 UT material & design in Geant4 and Run 5 luminosity.

The two relevant occupancy related quantities for the future UT design are the **mean and maximum hit density per bunch crossing**, respectively.

Figure 3 shows the average hit densities per bunch crossings in p-p and Pb-Pb collisions.

- In p-p running conditions, the average density is **5.9 hits/cm²/BX** in colliding bunch crossings, or 4.0 hits/cm²/BX in all bunch crossings, while it is **2.9 hits/cm²/BX** for colliding Pb-Pb bunch crossings

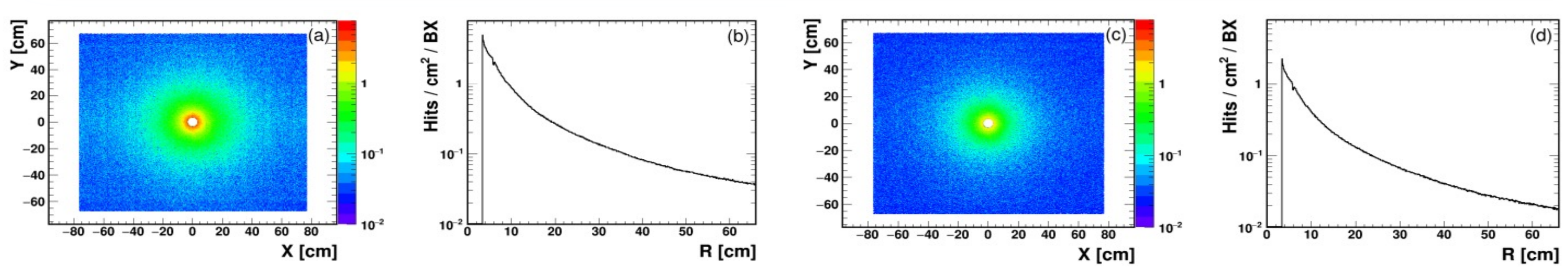


Fig. 3: The mean UT hit density per BX at the first plane per beam-beam colliding bunch in (a and b) the p-p programme, and (c and d) the Pb-Pb programme

Detector Design and Layout

A potential detector layout is illustrated in Fig.4. A plane consists of 12 staves, which in turn, is composed of multi-MAPS modules per stave.

- **Fourteen chips in a 7 × 2 array** are interconnected to a flex circuit to form a module.
- The common HL-LHC radiation tolerant ASIC for data, timing, trigger and control, known as the lpGBT, will be utilized for data acquisition.
- **A total of 36 modules** are mounted alternately on both sides of a supporting bare stave, **in total 12 staves per plane**.

A four-plane detector based on HVCMOS is proposed. Layout using other MAPS technology like LVCMOS is similar.

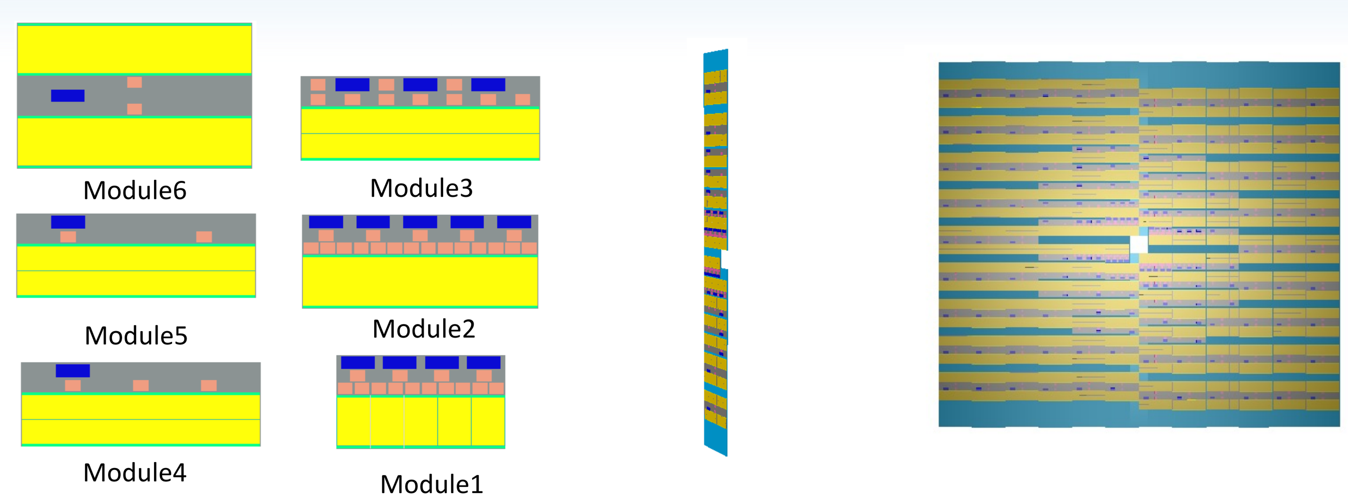


Fig. 4: Geometry construction using DD4hep

CMOS Sensor Options

The ongoing R&D studies indicate that monolithic active pixel sensors can be considered as very strong candidates for UT.

To achieve substantial depletion in the sensing volume and improve the speed and radiation tolerance of the detector, DMAPS implementations follow two different approaches, namely large fill-factor or high-voltage (**HVCMOS**) and low fill-factor or low-voltage (**LVCMOS**) with small electrode.

More details in Zhiyu's poster "Test of CMOS chip using 55nm process".

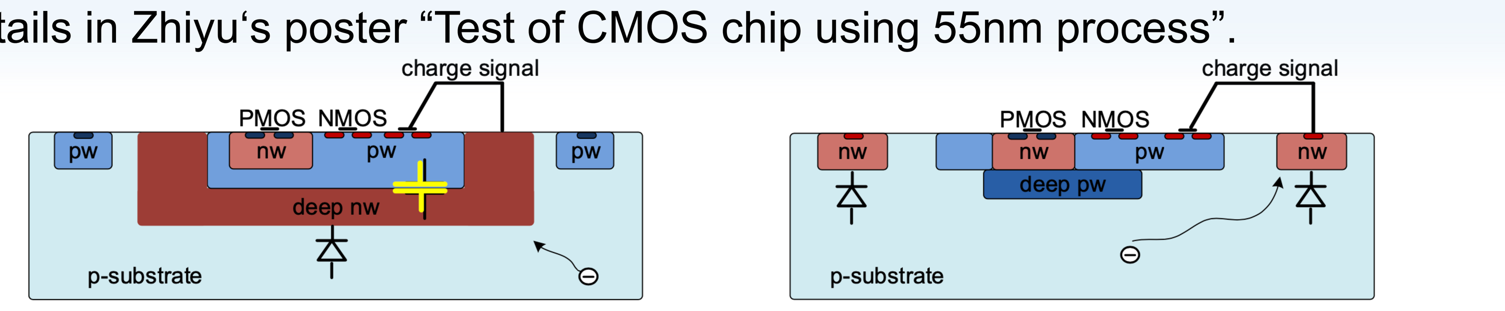


Fig. 5: The schematic of HV-CMOS (left) and LV-CMOS (right)

Software Development

Detector description has been developed both in DetDesc and DD4hep framework. "Fake digitization" study was based on MCTruth level. The **material budget** scan was performed in two frameworks with consistent results.

Figure 6 shows the radiation length of the first layer of U2UT plane in x/y and η/φ view. The last plot shows the projection map on the η axis.

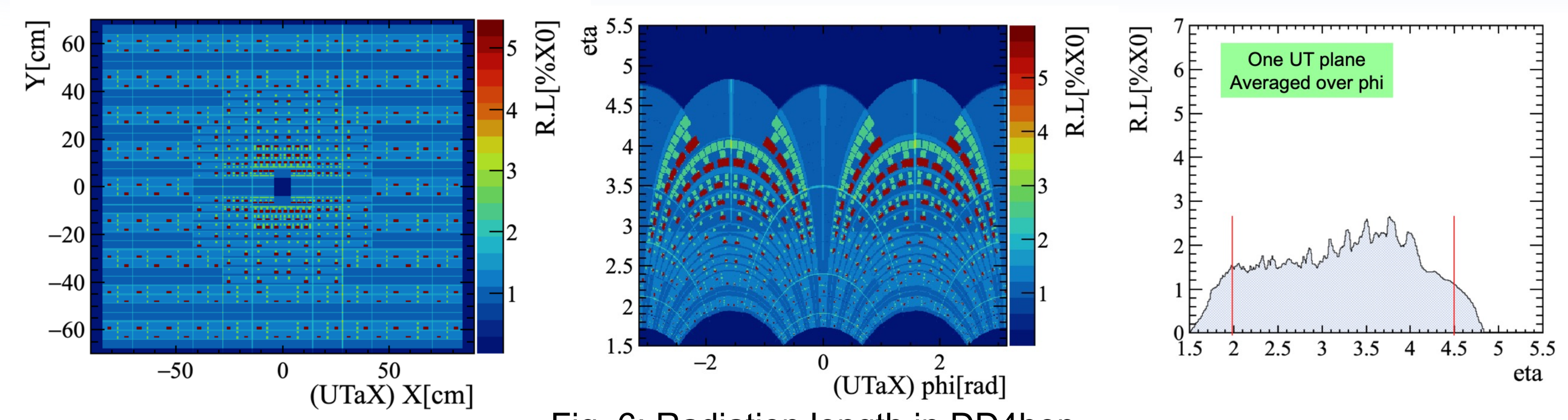


Fig. 6: Radiation length in DD4hep

Full Simulation Framework

The LHCb simulation framework consists of several software packages and tools that work together to simulate the entire data flow process, from the initial generation of events to the final reconstruction and analysis of the simulated data.

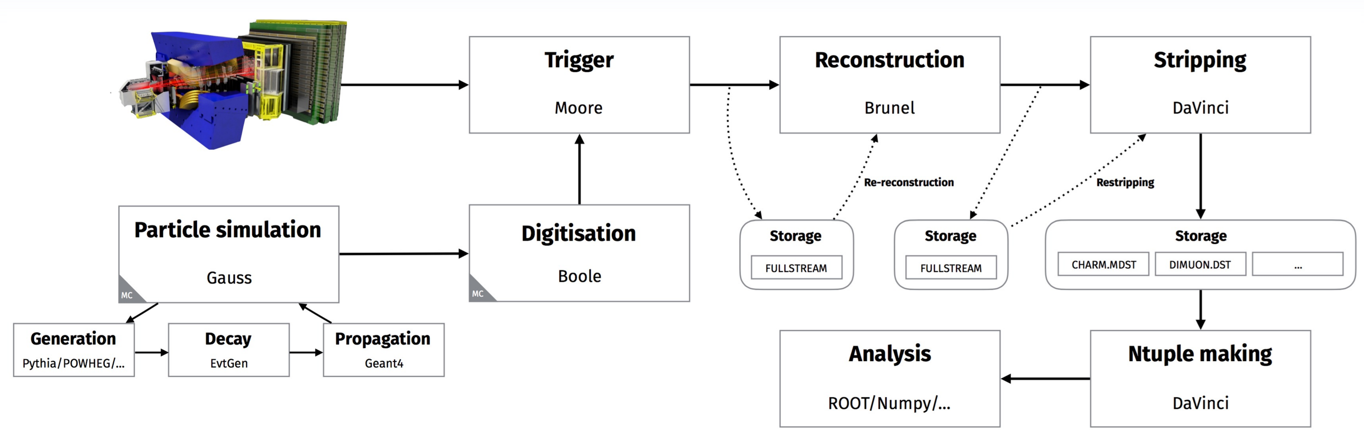


Fig. 7: The LHCb data flow and the associated applications

Related studies are accomplished at Boole level:

- **The hottest pixel occupancy**(0.256%) was estimated based on 1.2K miniBias MC events, consistent with estimation in FTDR.
- **Particle response efficiency** was treated as a function of particle momentum per layer compared with the current UT, both with efficiencies around 95%.

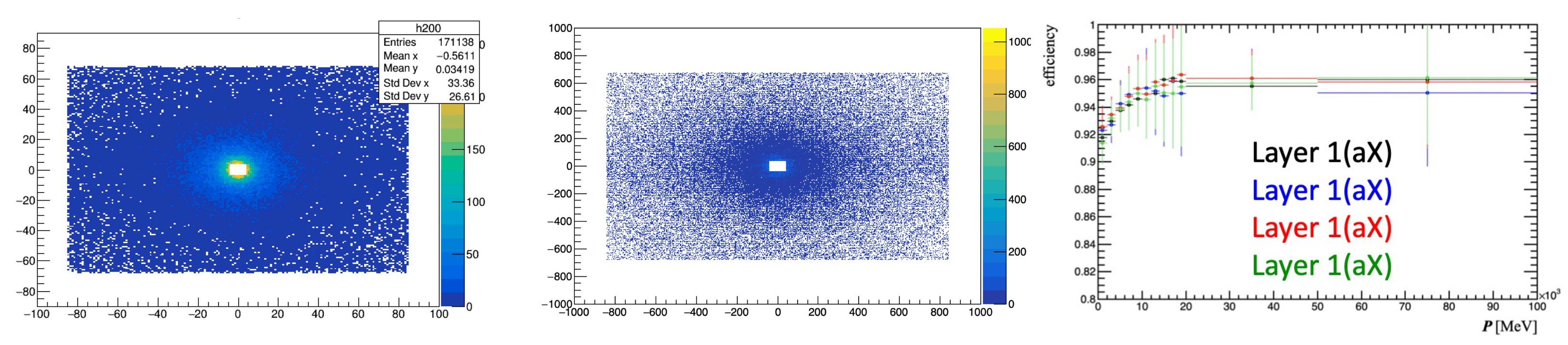


Fig. 8: 100 MCHits distribution in Gauss of first layer(left) and corresponding 100 MCDeposits in Boole(middle); particle response efficiency(right)

Comparison of UTDigits and MCHits:

- By decoding from MCDeposits to UTDigit, we get the **ChannelID** and **ADC value**. Decoded hits are consistent with MC inputs.
- Position of each ChannelID of trajectory is obtained.
- The decoded UTDigits are used for subsequent **track reconstruction**.

The track reconstruction framework added in Moore is ongoing.

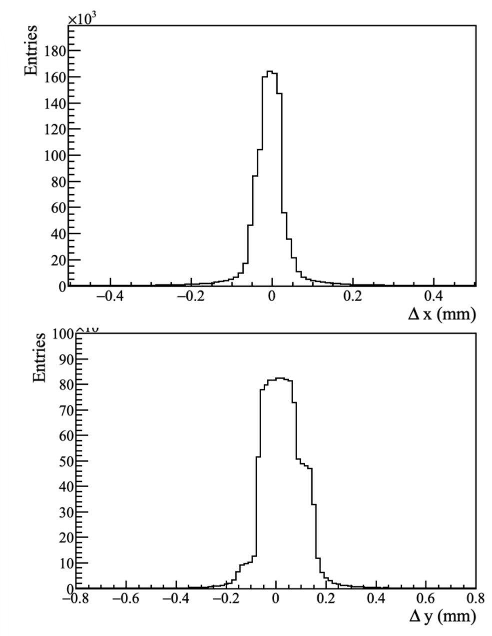


Fig. 9: Difference of UTDigits and MCHits in x(Up) and y direction(Down)

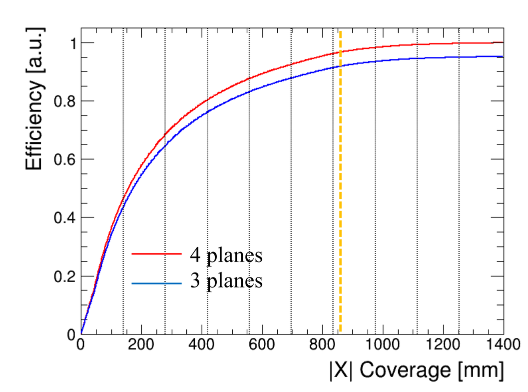
Track Efficiency

In order to study alternative scenarios aiming to **enhance the detector performance** for U2UT, the performance of 3- or 4-layer detectors were evaluated. We found that the performance is significantly compromised with **3-plane solution**.

Tracking efficiency of pions was studied for U2UT coverage optimisation using $\overline{B}^0 \to D^{*+}\pi^-, D^{*+} \to D^0\pi^+, D^0 \to K_S\pi^+\pi^-, K_S \to \pi^+\pi^-$ process, as shown in Fig.10. The impact on the reconstruction efficiency was assessed by increasing the horizontal coverage. And more decays will be studied afterwards.

$$\overline{B}^0 \to D^{*+}\pi^-,\ D^{*+} \to D^0\pi^+, D^0 \to K_S\pi^+\pi^-, K_S \to \pi^+\pi^-$$

(a) (b) (c) (d)



Single Track With 3 UT Hits, $\lvert x\rvert$ < 836.2 mm				
Requirement	(a)	(b)	(c)	(d)
Total 4 planes	0.962	0.971	0.962	0.960
Total 3 planes	0.913	0.925	0.913	0.914

Fig. 10: Efficiency vs X Coverage and Number of Planes

Reference and links:

[1] *"Framework TDR for the LHCb Upgrade II Opportunities in flavour physics, and beyond, in the HL-LHC era", CERN, Geneva, LHCb Collaboration, CERN (Meyrin)*

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The 2023 International Workshop on the High Energy Circular Electron Positron Collider
October 23-27, 2023, Nanjing