PROCEEDINGS OF SCIENCE

The LHCb SciFi Tracker

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The LHCb Experiment completed its first major upgrade and is running for LHC Run 3 and beyond, improving on many world-best physics measurements. Some of the LHCb sub-detectors and the experiment read-out system have been re-designed, raising the experiment's luminosity data acquisition limits and - consequently - expanding its statistical accumulation rates. To cope with upgrade requirements, a new tracker based on scintillating fibers (SciFi) was designed and implemented, replacing the previous Outer and Inner trackers. SciFi sub-detector delivers improved spatial resolution tracking information to LHCb for its new trigger-less era, with a readout capable of reading ~524k channels at 40MHz full rate. Automated calibration routines for SciFi detector devices, based on dedicated software tools and operational procedures, were validated during SciFi commissioning and have been applied to further improve the detector performance since the beginning of Run 3. The oral presentation at ICHEP2024 briefly described the SciFi Tracker, demonstrated the experience gained on SciFi operations during data taking, and presented early results showing the detector performance after commissioning.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

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PoS(ICHEP2024)901

1. Introduction

The LHCb Experiment is optimized to investigate *CP* violation and indications of physics phenomena beyond the Standard Model by measuring decays of particles containing beauty (b) and charm (c) quarks. The topology of these events requires outstanding vertex and tracking capabilities.

LHCb collected a total integrated luminosity of ~9 fb^{-1} at instantaneous luminosity of ~4 $\times$ 10^{-32} cm^{-2} s^{-1} during LHC Runs 1 and 2. From 2018 to 2022 the first upgrade [1] took place, enabling LHCb to run at 5$\times$ the previous luminosity, significantly expanding its physics reach. Integrated luminosity of ~50 fb^{-1} is expected until 2033[1], before the next upgrade [2].

2. The LHCb SciFi Tracker

Figure 1 shows the new LHCb Scintillating Fiber Tracker (SciFi) for Runs 3 and 4. Covering an area of 340 m^2, a novel technology with ~10′000 km of 250 μm diameter scintillating fiber is used to achieve spatial resolution $\leq 80\,\mu m$ and hit efficiency $\geq$ 99%. Its higher granularity and trigger-less read-out can handle higher luminosity and deliver information to feed the new online event filter. This design boosts LHCb selection efficiency for numerous physics event types.

SciFi is composed of 4096 128-ch Silicon Photomultipliers (SiPM) arrays cooled to -40 °C and placed at the fiber ends. A sensitive digitizer [3] was required due to the low photo-electron statistics. High channel density ($4mm^{-1}$) demanded careful Front-End Electronics (FEE) design [4], and sheer data volume required the implementation of a zero-suppression algorithm in the FEE.

A detailed description of the SciFi Tracker is given in Refs. [1], [5], and [6]. For the sake of conciseness, this conference manuscript will not repeat such a detailed description.

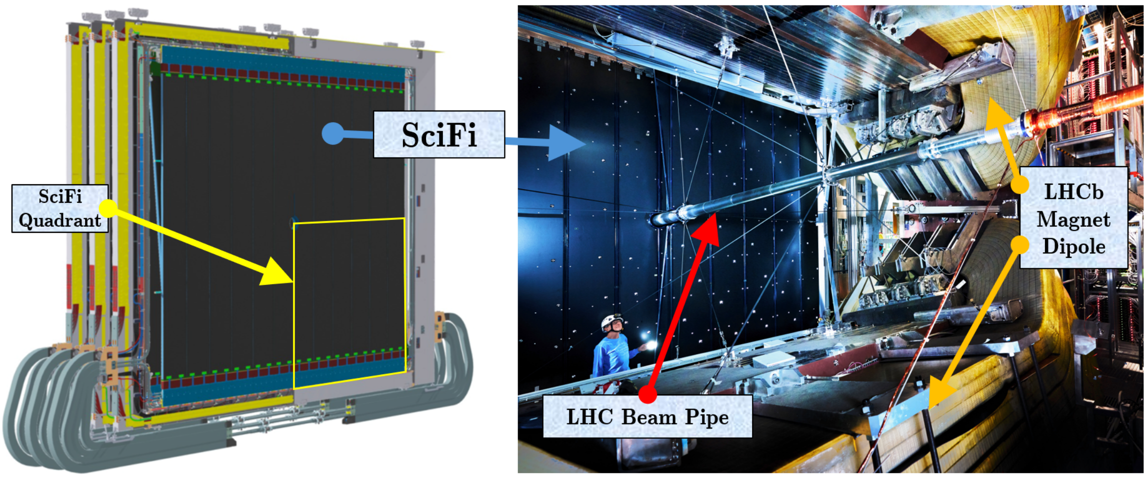

Figure 1: CAD-generated 3D representation of the SciFi Tracker (left) associated with a photo of the installed detector at LHCb experimental area (right). The photo was taken from the upstream side of the LHCb Magnet Dipole and shows the SciFi detector fully closed around the LHC Beam Pipe. The Interaction Point (IP-8) is towards the right side of the photo. A yellow box highlights a portion of the detector named as "quadrant".

[1] Already considering the revised LHC schedule [7], published in Oct-2024

3. Results on detector performance with Run 3 data

In April 2022 the last Read-Out module was assembled in the SciFi detector. This milestone represented the completion of its installation in the LHCb experimental area and, since then, calibration procedures extensively described in Ref. [6] have been used multiple times to further improve the detector's performance.

Six plots have been chosen to illustrate the SciFi Tracker's current performance and are presented in this Section. All plots were obtained with acquired data from experimental *pp* collisions over the LHC Fill number 9877 (8-Jul-2024, 16:40 to 9-Jul-2024, 07:33 - Geneva Time).

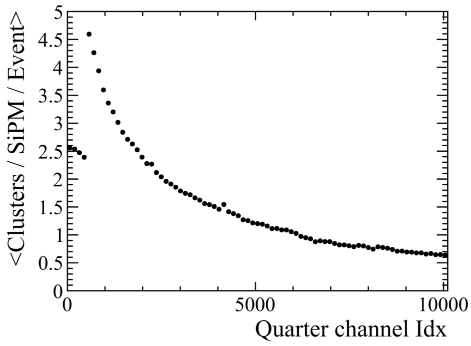

Figure 2: Average number of clusters per SiPM per event in one quadrant of the SciFi Tracker for LHC Fill 9877. Reproduced from [8] CC BY 4.0.

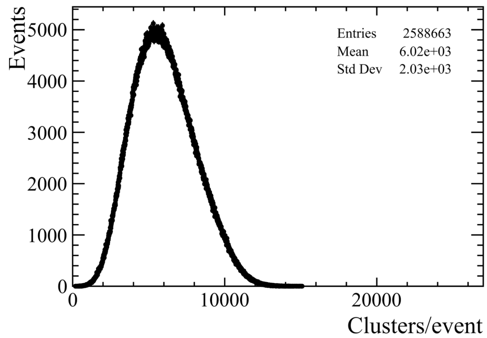

Figure 3: Number of clusters seen in all layers of the SciFi Tracker, over LHC Fill 9877. Reproduced from [8] CC BY 4.0.

Figure 2 presents the number of clusters as a function of the channel number for a selected quadrant (see Fig. 1 for quadrant definition). The distribution is compatible with simulated events, apart from a few noisy channels. The smooth Gaussian-like distribution at Figure 3 shows no sign of saturation and is an indicator of the excellent performance of the detector's overall data chain.

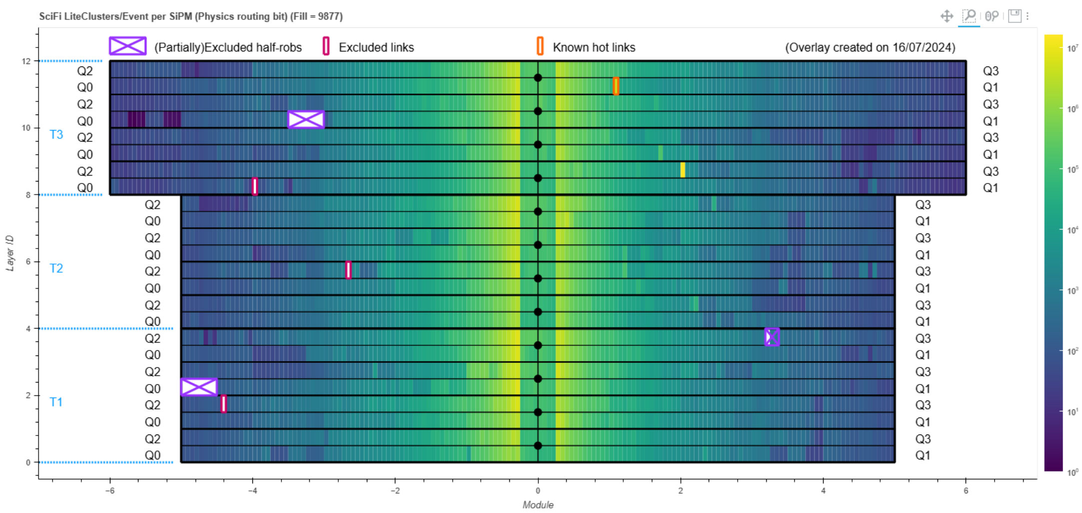

Figure 4: Cluster occupancy for the entire SciFi detector in LHC Fill 9877. The color bar represents the number of clusters accumulated by each 128-channel SiPM array. Reproduced from [8] CC BY 4.0.

Figure 4 presents the cluster occupancy for each one of the 4096 data links[2]. Each tracking station is marked as T1, T2, and T3 along the Y-axis. Each station has four layers, shown as Layer ID on the Y-axis. Each layer comprises its upper (Q2 and Q3) and lower (Q0 and Q1) quadrants, one for each detector side. The color of each bin represents the number of clusters of the corresponding link. Excluded half-robs (Read-Out Module elements), excluded links, and known hot links[3] are flagged with specific boxes overlaying the plot. Those nonconformities are due to hardware failures and require a major intervention to be solved, scheduled for the next end-of-year technical stop (2024-2025 winter). It is also relevant to note the High Occupancy region around the Beam Pipe and the gap over the Beam Pipe hole, both expected due to LHCb's geometry. Some other discontinuities are due to ongoing threshold calibration.

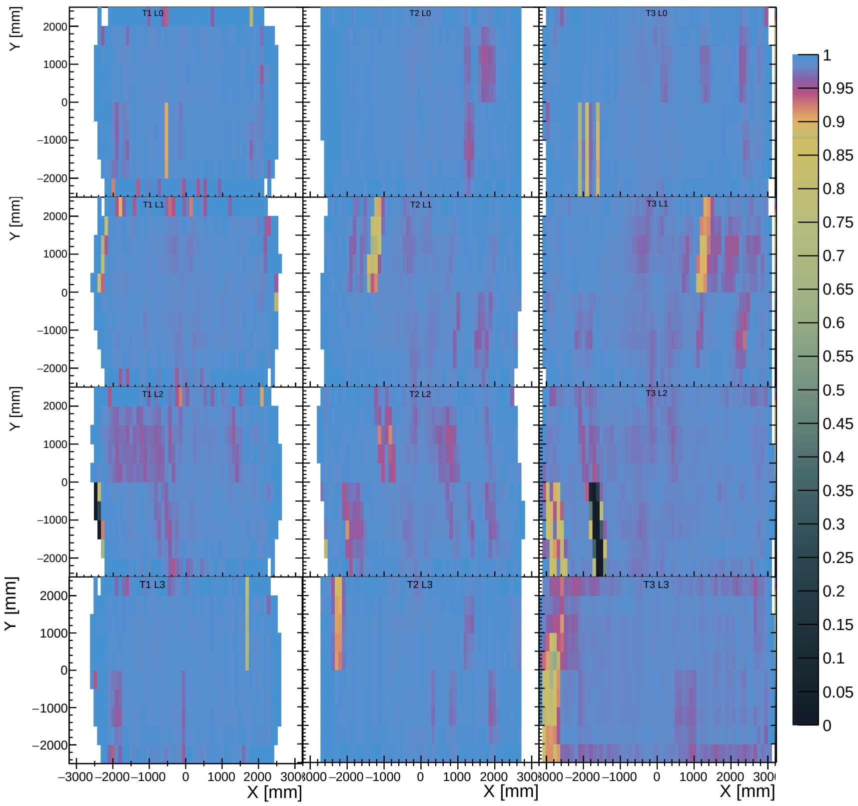

Figure 5: The hit efficiency in X and Y coordinates over the 12 layers of the SciFi Tracker for LHC Fill 9877. The dark regions are due to excluded data links. Some regions with a reduced hit efficiency require further threshold calibration. Reproduced from [8] CC BY 4.0.

The previous figures 2 to 4 shows the detector performance in terms of occupancy, observed as clusters counting. Figure 5 introduces the concept of Hit Efficiency[4] by presenting an overview of SciFi Layer Hit Detection Efficiency for all 12 layers. Each layer is presented in a sub-plot.

[2]Each SciFi data link transmits clusters from a 128-channel SiPM array at 4.8 Gbps.

[3]Hot Links are defided as data links with non-expected high occupancy due to technical issues.

[4]Hit Efficiency is determined by excluding the studied layer from the track reconstruction algorithm and looking for matched SciFi hits at this layer.

Each column at Figure 5 represents one tracking station, and rows represent different layers. Each sub-plot is scaled in geometrical units (millimeters) along X and Y axis, following the standard coordinate system of the LHCb Experiment. Each bin represents one data link. Its color is scaled from 0 to 1 (0 to 100%) and represents the Hit Detection Efficiency for the given detector area.

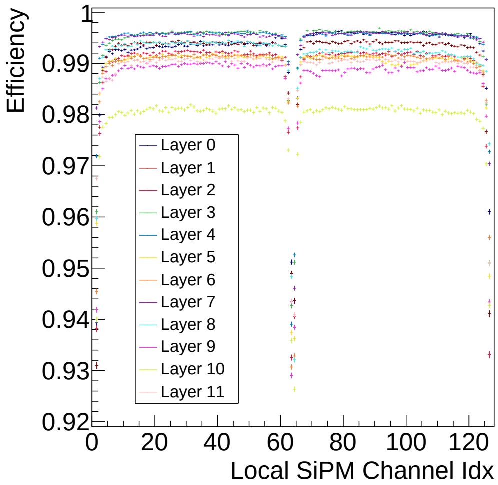

Figure 6: The average hit efficiency across an SiPM in each layer of the SciFi Tracker for LHC Fill 9877. Reproduced from [8] CC BY 4.0.

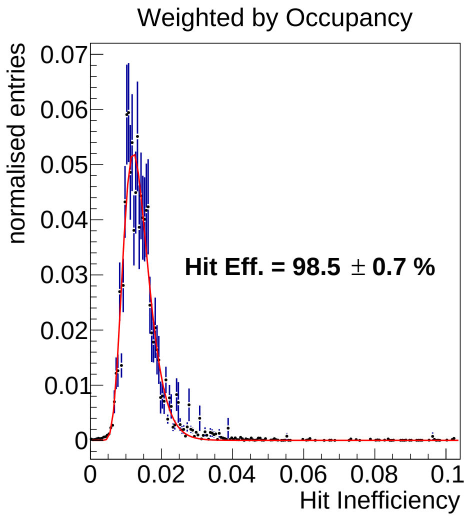

Figure 7: Single hit inefficiency for long tracks for all layers weighted by the occupancy, for LHC Fill 9877. Reproduced from [8] CC BY 4.0.

Figure 6 presents the SciFi average hit detection efficiency for each SciFi layer. The reduced efficiency in the edges is due to the gaps between detector elements (Fiber Mats), and the drop in the center is due to a small gap between the two SiPM 64-channel dies that are glued together to compose a 128-channel array, both gaps are expected by design. Layer 10 efficiency is unusually low due to some SiPMs excluded from data taking, as seen in Fig. 4. Other regions have slightly reduced efficiency due to a few percent of channels requiring further threshold calibration.

Figure 7 summarizes in a single number the overall hit efficiency of the SciFi Tracker by fitting its distribution over all the data links among the twelve detector layers, weighing the hit inefficiency of multiple detector regions by the corresponding occupancy of each region.

4. Conclusions

The LHCb SciFi Tracker is the largest system of its kind ever built, covering a sensitive area of 340 m^2 with ~520k analog Read-Out channels. The detector was fully integrated into LHCb systems in 2022 (see Figure 8) and, since then, has operated continuously, delivering meaningful data for the LHCb Experiment. Before reaching this point, a long way of R&D, manufacturing, assembly, and installation involved multiple high-skilled scientists over the past decade.

The commissioning and calibration of this detector proved to be a huge enterprise, demanding the development of multiple dedicated software and methodologies, as described in Reference [6].

Implementing those calibration methodologies led to a detector operating well within the required performance, capable to deliver improved tracking reconstruction information to LHCb.

Some well-understood degraded regions are due to fixable hardware failures already scheduled for repair. The hit efficiency is > 99% (design specification) in most of the SciFi area. Additional improvements are expected as the hardware failures are addressed to be fixed over the next end-of-year technical stop (2024-2025 winter) and final calibration activities are well underway.

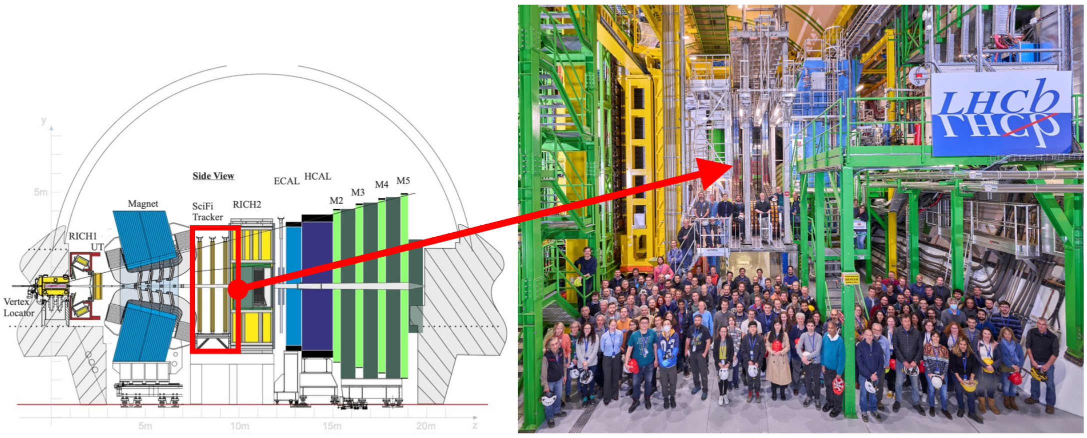

Figure 8: CAD-generated representation of the upgraded LHCb Experiment (left) associated with a photo of the installed upgraded detector at the LHCb experimental area (right). The photo (Reproduced from [9] CC BY 4.0) was taken on 30 March 2022, a few days before cavern closure for LHC Run 3.

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[7] CERN, Online: Updated schedule for CERN's accelerators Accessed: 07-Oct-2024

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