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Background measurements and simulation for CODEX-b

CERN summer student report

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Abstract

CODEX-b is a newly proposed detector [1] to be housed inside the existing LHCb cavern that will search for weakly interacting long-lived particles, predicted in many extensions of the Standard Model. A critical component in the physics reach studies is good understanding of the expected background rates inside the cavern. As a CERN summer student during June-August, 2018, I participated in a campaign to measure the background rate in the UX85A cavern during Run 2 *pp* collision data-taking. The measurements were performed at various positions and different configurations on the D3 platform in UXA just behind the existing concrete shield wall. The campaign was very successful with over 50,000 recorded triggers. In addition, I also developed a simulation framework for CODEX-b and the measurement setup, using a `ROOT` based Detector Description package called `DD4Hep`, that will be used by the LHC experiments in the Upgrade era. Preliminary results not officially approved by the LHCb collaboration, are presented here.

List of changes between versions

- version 1
  - Start version.
- version 1.01
  - Add figures in each section and rewrite.
- version 1.02
  - Add contents at each section.
- version 1.03
  - Write summary and change the size of pictures.
- version 1.04
  - First draft for the report.
- version 1.05
  - Remove empty paper.
  - Change the author list and mention that this is a summer student report.
  - Remove bold, fix colloquial, change word.
  - Modify the first sentence in meamesurment (Reference should be fixed).
  - Mention at the Figure 5, this is not approved officially.
  - Fix caption at the Table 1.
  - Add more explanation at the last part of simulation chapter.
  - Divide to subfigure (Need to fix).
  - Enlarge the last figure at the simulation chapter.
  - Add acknowledgements.
  - Add abstract
- version 1.06
  - Modifications to figures etc. by BD.
- version 1.07
  - Fix the sentences in section 2.1.
  - Add DD4hep reference at the first sentence in section 3.1 (Reference should be updated at the last page).
- version 1.08
  - Add content of other detector proposals at introduction section.
  - Put references of other detector papers in "main.bib" but complie is not working.

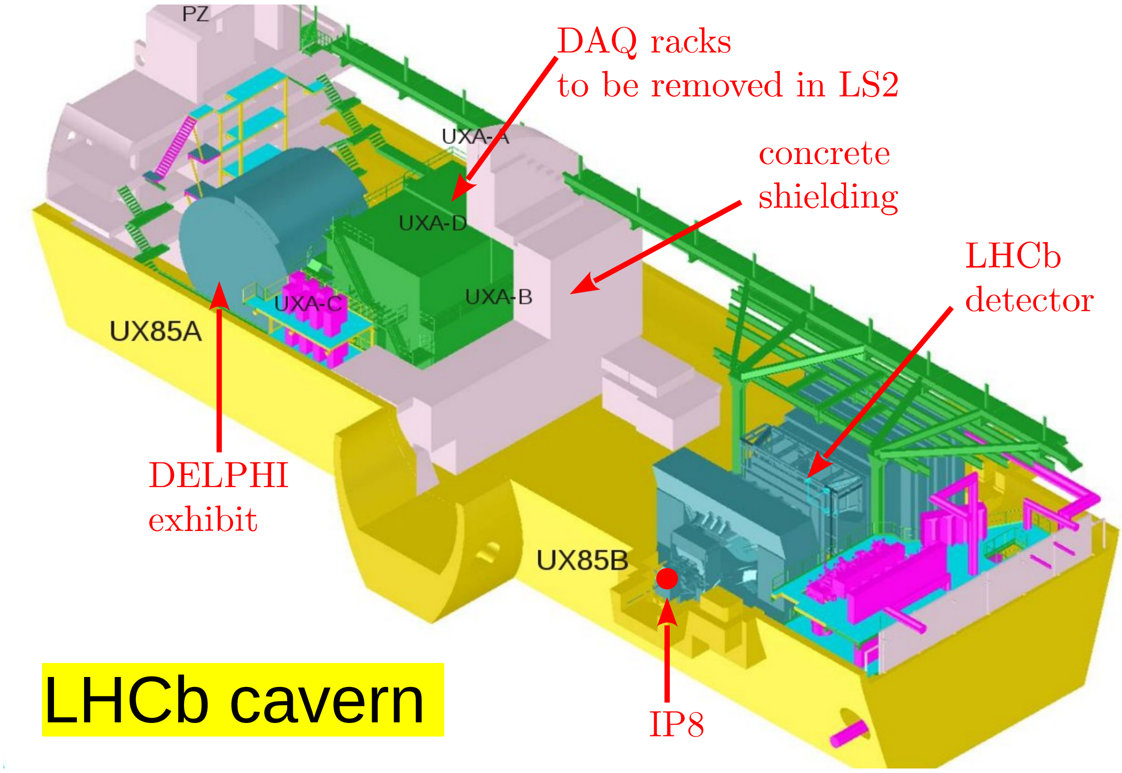
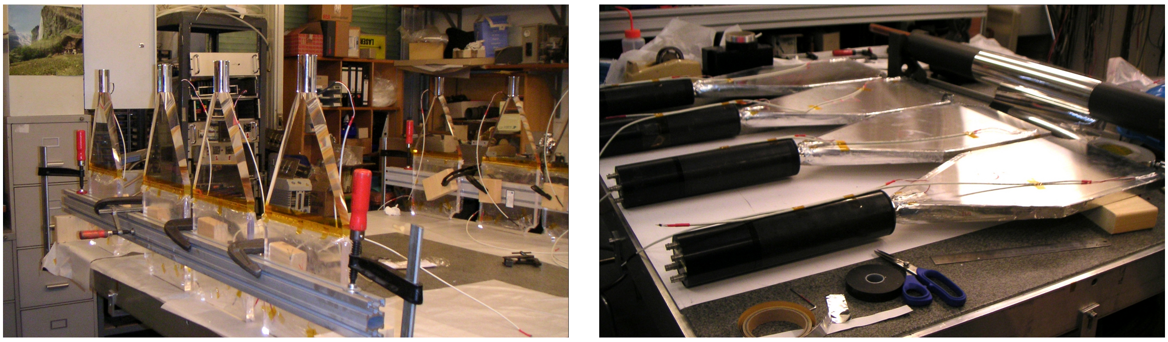


Figure 1: A schematic plot of the LHCb cavern.

1 Introduction and motivation

The discovery of the Higgs particle at the LHC in 2012 filled in the last missing piece of the Standard Model (SM). Apart from a few so-called "anomalies" (see Ref. [2] for recent review talk), mostly in the flavor sector, the SM has been a spectacular successly theoretical framework that can account for all observed phenomena. Yet, we know that it is also an incomplete theory that can not account for gravity, dark matter, observed matter-antimatter asymmetry in the universe, among other problems. New Physics (NP) searches at the LHC experiments have mostly focused on production of new particles that decay close to the collision point, and can be detected within the detector volume. However, an important NP portal is one that is very weakly coupled sector with the SM and therefore includes particles with long lifetimes. In fact, long lifetimes are very generic in any theory with multiple mass scales, broken symmetries, or restricted phase-space [3]. The SM itself contains templates for low mass, long-lived particles (LLP) such as electron, neutrino, proton and neutron. Current searches for exotic LLP's at ATLAS and CMS suffer from high p_{T} trigger requirements (high masses) and large QCD backgounds, while LHCb is limited by the legth of the VeLo detector to search for displaced vertices.

Inkeeping with these general observations, there has been a strong thrust recently to ensure that the High-Luminosity LHC does not miss NP signals from the LLP sector. Several new experiments, MATHUSLA [4], FASER [5], MilliQan [6] and SHiP [7], have been proposed within the CERN complex. There are either aligned with ATLAS/CMS or a new beam-dump facility, such as for SHiP.



(a) (b)

Figure 2: HeRSCheL scintillators: (a) scintillator and light-guide assembly, (b) wrapped scintillators coupled to the PMT in the casing with additional electronics.

1.1 Compact Detector for Exotics at LHCb

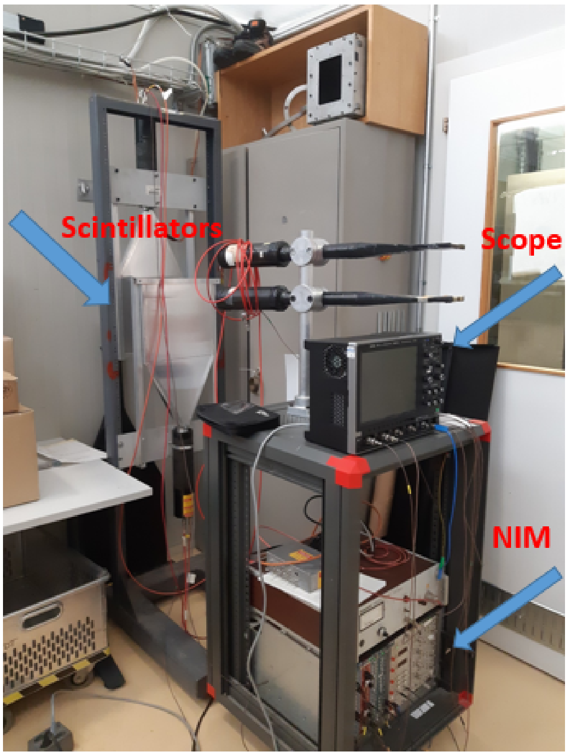
The Compact Detector for Exotics at LHCb (CODEX-b) [1] is a proposed inexpensive setup, to be housed inside the existing LHCb cavern shown schematically in Fig. 1. During the upcoming Long Shutdown 2, the DAQ racks will be moved to the surface allowing for a shielded (behind the existing concrete wall), underground $10 \times 10 \times 10$ m^3 empty space. The nominal proposal is to instrument this volume with tracking layers. If the current DELPHI exhibit is removed, the size can be expanded to $20 \times 10 \times 10$ m^3. The CODEX-b volume will sit approximately 25 m from the collision point at Point 8.

2 The background measurement campaign

2.1 Scintillator, PMT and the test bench

The measurement setup re-uses scintillators, light-guides and photomultiplier tubes (PMT) taken from the HeRSCheL detector [8] in LHCb. The plastic scintillating material is EJ-200 ($300 \times 300 \times 20$ mm^3) and light-guides providing the coupling to the PMT is made of Plexiglass. The scintillator and light-guide are wrapped in light-protecting aluminium foil. Each light guide is coupled to a Hamamatsu R1828-01 PMT chosen due to its high anode current upper limit, wide range of gain variation, fast time response to fit in 25 ns, large entry window for enhanced light yield and good single electron separation. Figure 2 shows the scintillator-PMT assembly [8].

Figure 3 shows the test bench assembly in the lab. It includes a vertical iron mechanical stand holding the wrapped scintillator pair and the NIM crate power supply providing -1.5kV HV, with an additional -350V bias voltage. The horizontal distance between the two scintillators is 2 cm. The DAQ system utilized an oscillosscope (LeCroy WaveRunner) with extended functions (autosave waveforms, coincidence logic, etc). Before transporting the setup to Point 8, it was tested with a cosmic stand also shown in Fig. 3.



(a)

(b)

Figure 3: Test-bench assembly in the VeloPix lab showing the (a) HeRSCheL scintillators, the DAQ system comprising a NIM crate and oscilloscope. The cosmic stand used for initial tests is also shown, (b) close-up look at the mechanical stand.

2.2 Trigger

We use a simple 2-fold coincidence between the two scintillators, with a discrimination threshold set as 30 mV on the oscilloscope. The time-window for the coincidence is 5 ns. The scope automatically saves two waveforms from each scintillator, as shown in Fig. 4, along with the timestamp, for every mip)minimum ionising particle) hit event (not to be confused with collision events). This timestamp is important to correlate with the beam status during data-taking.

2.3 Measurement positions and configurations on the D3 platform

The background measurements were taken in the LHCb cavern on D3 platform level, just behind the concrete shield wall, on the access side. The equipment was set up at 3 positions on the passarelle between DAQ racks and the concrete shield wall, one position between the DELPHI exhibit and DAQ racks. For orientation, the scintillator stand was mostly parallel to the beam line but was also rotated 45° and perpendicular to the beam line. Figure 5 shows the positions and configurations for the measurements, and Fig. 6 shows pictures of the equipment at these positions on the D3 platform.

Figure 4: Trigger setup using coincidence occurence of signals from the two scintillator PMT's within 5 ns.

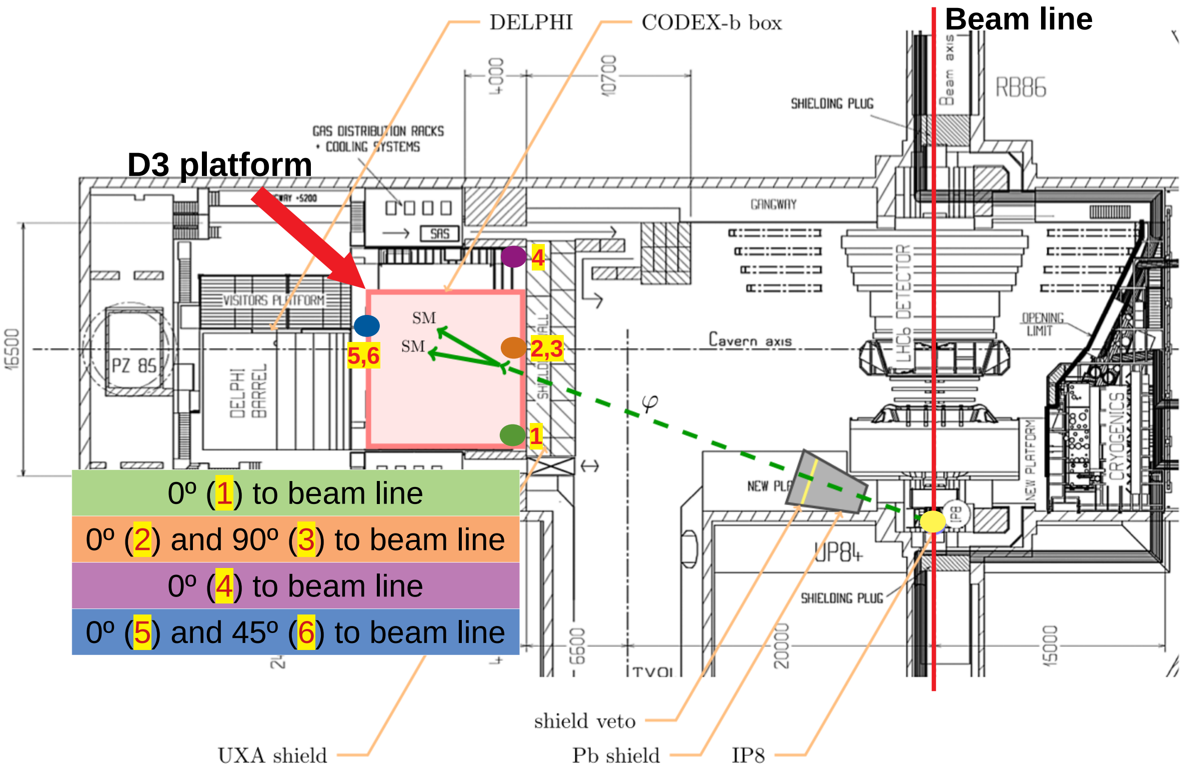
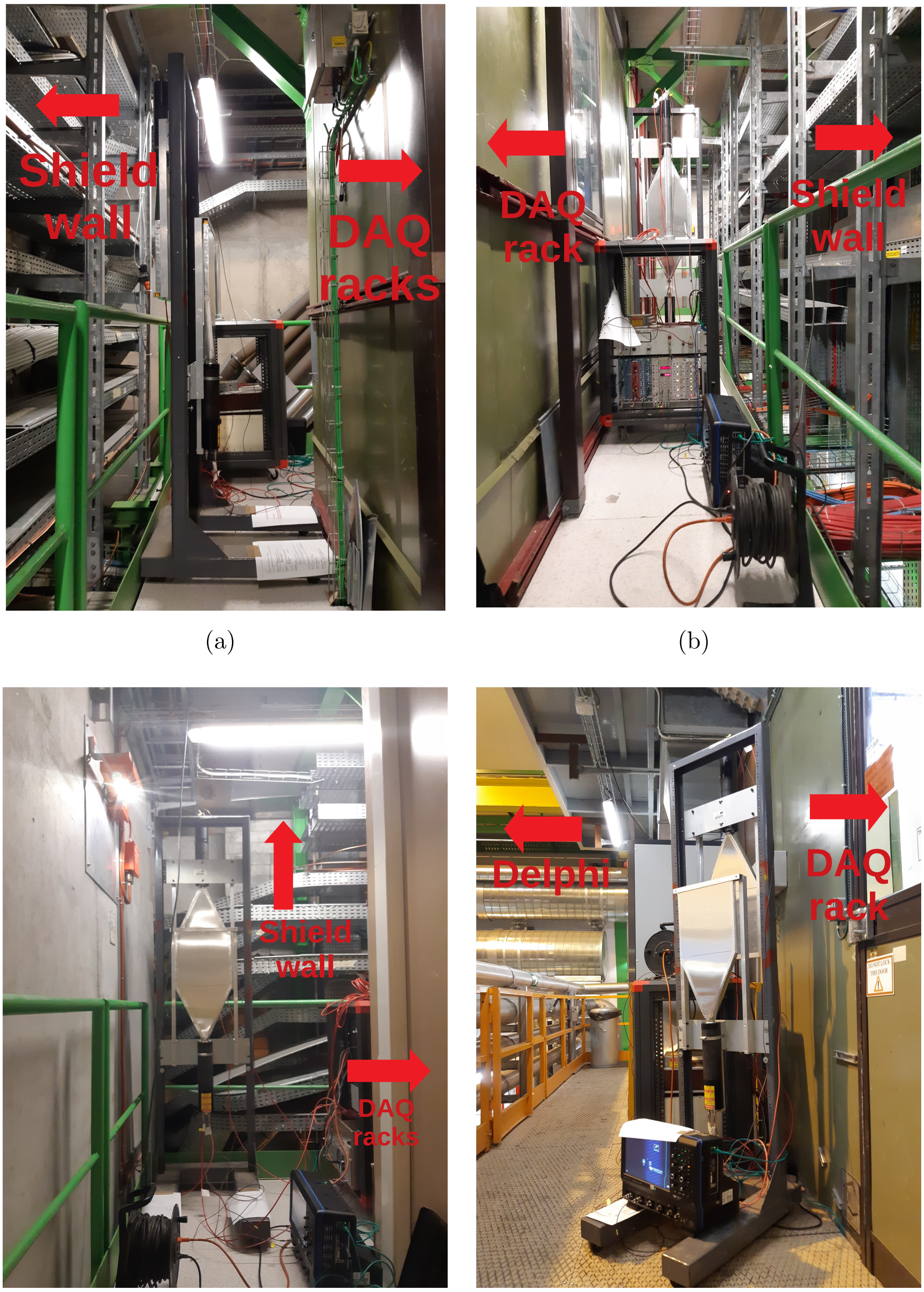


Figure 5: The four measurement positions on the D3 level inside the LHCb cavern. The configurations are labelled from P1-P6.



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

Figure 6: Photos of the equipment setup at various positions on the D3 platform: (a) P1, (b) P3, (c) P4, and (d) P6.

2.4 Results

The measurement campaign spanned over 17 days between 25th July and 10th August, 2018. There were 52,036 recorded triggers during the run.The LHCb instantaneous luminosity rate was stable during the measurement. There was no beam till July 30th because of

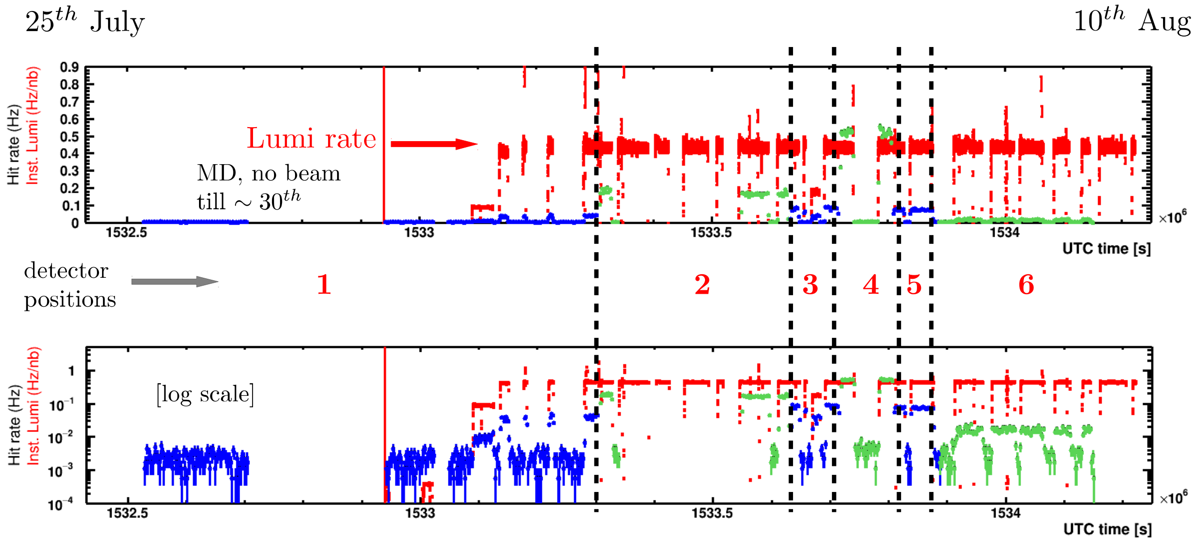


Figure 7: The Hit rate plots during the run based on 6 positions/configurations linear and log scale. Red dots mean the lumi rate of LHCb, blue and green dots mean hit rates. The results are not officially approved by the LHCb collaboration.

Position	Description	Hit rate [mHz]
P1	shield, right corner, $\parallel$ to beam	1.99 ± 0.07
P2	shield, center, $\parallel$ to beam	2.76 ± 0.03
P3	shield, center, $\perp$ to beam	2.26 ± 0.03
P4	shield, left corner, $\parallel$ to beam	3.11 ± 0.03
P5	shield + D3 racks, center, $\parallel$ to beam	1.95 ± 0.03
P6	shield + D3 racks, center, 45° to beam	2.22 ± 0.02

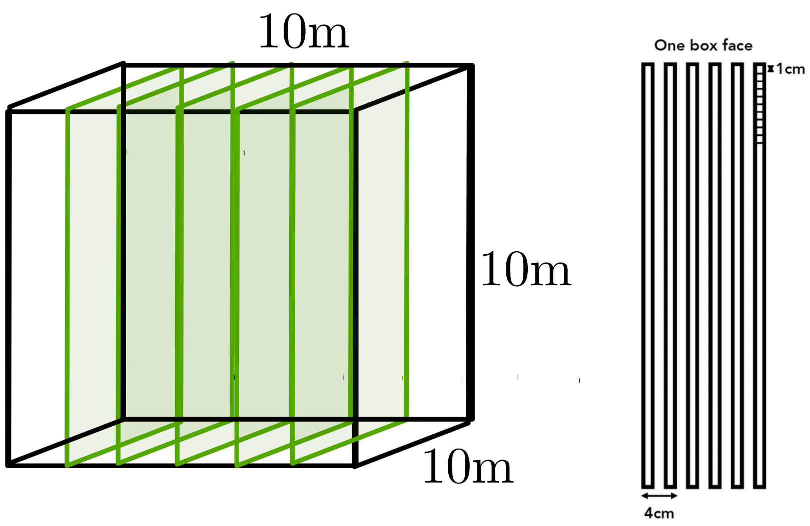
Table 1: Background hit rates based on each configuration when the beam is off.

machine development and an inadvertent power loss happened during this initial phase. Figure 7 show the main results from the measurement campaign. The red dots correspond to the instantaneous luminosity measured by LHCb in Hz/nb. The green and blue dots show the hit rate in Hz, alternating between the 6 different configurations/positions, for better visibility. The plots are shown in both normal and logarithmic scales.

Table 1 lists the hit rate from ambient background in between fills or during MD, without beam. The average hit rate at each position and configuration is 2 mHz. THis indicates that the ambient background can be considered negligible for this measurement. Table 2 lists the hit rate during stable beam. The rate is non-negligible, even for a small area of 300×300 mm^2. The rate increases from P1$\rightarrow$P2$\rightarrow$P4, which, from Fig. 5 indicates that the downstream region sees more activity. This dependence on the η has to be corroborated with the simulation. Further, comparing the rate at P2 with P5, behind the DAQ racks, the racks are seen to add shield material. Finally, comparing the rate at P5 and P6, for the angular scan, the flux depends on the orientation with respect to the beam direction, as expected.

Position	Description	Hit rate [mHz]
P1	shield, right corner, $\parallel$ to beam	38.99 ± 0.99
P2	shield, center, $\parallel$ to beam	167.10 ± 1.43
P3	shield, center, $\perp$ to beam	82.81 ± 1.55
P4	shield, left corner, $\parallel$ to beam	517.45 ± 3.52
P5	shield + D3 racks, center, $\parallel$ to beam	73.58 ± 1.18
P6	shield + D3 racks, center, 45° to beam	15.71 ± 0.33

Table 2: Average hit rates measured during stable beam, at various configurations.



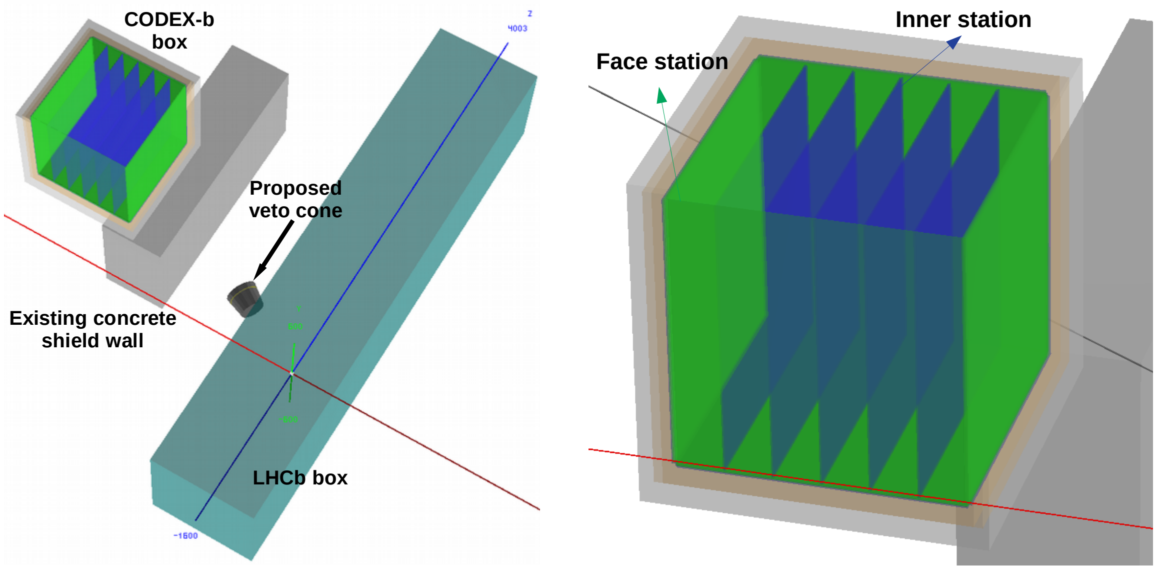
(a) (b)

Figure 8: CODEX-b nominal geometry: (a) box showing the $5\times$ inner stations and (b) the 6 layers for the face stations.

3 Simulation

3.1 Detector Description for High Energy Physics

As the second part of my project, I developed the simulation framework for both the CODEX-b tracking layers as well as the two-scintillator configuration required for the measurements. We used the Detector Description for High Energy Physics (`DD4hep`) [9] toolkit for this, in conjunction with `Gauss`, the standard LHCb simulation package. `DD4hep` uses the `ROOT` `TGeometry` class for loading the detector geometry in memory and is being developed for high-luminosity LHC. Further, the project is a software framework to provide overall detector description for experiments. It offers consistent description through a single source of detector information for simulation, reconstruction, conditions (alignment), *et al.*, and will be adopted by LHCb for the Upgrade. During my internship, I built the geometry of CODEX-b constructing hierachy system, from scratch. I included the concrete shield wall to block particles generated at the interaction point (IP) from particle gun or minimum bias simulation and also checked for the energy deposits and



(a) (b)

Figure 9: CODEX-b simulation geometry in `DD4hep`: (a) overall, (b) close-up view.

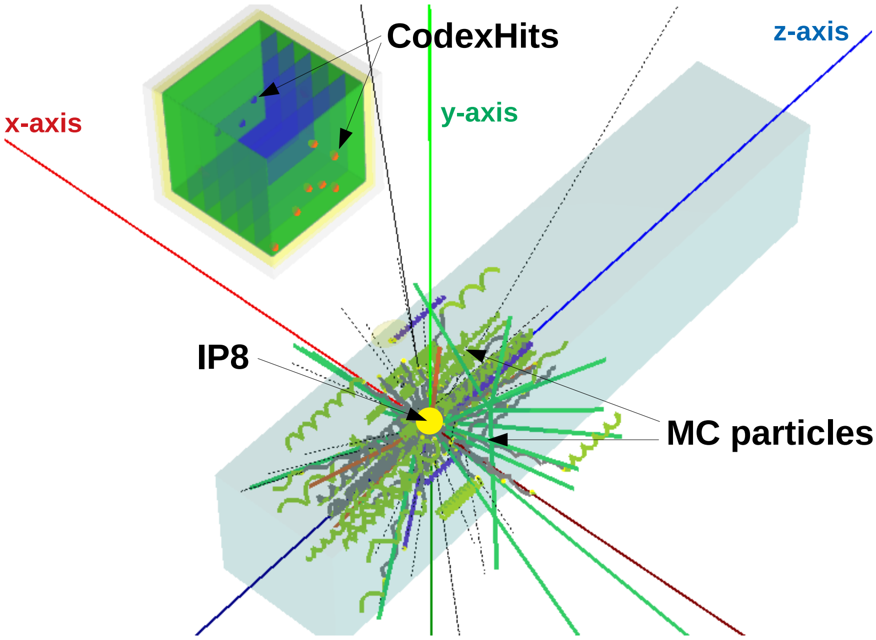
positions of CODEX-b hits, simulated used `DDG4`, the in-built `GEANT` package for `DD4hep`.

3.2 Geometry construction

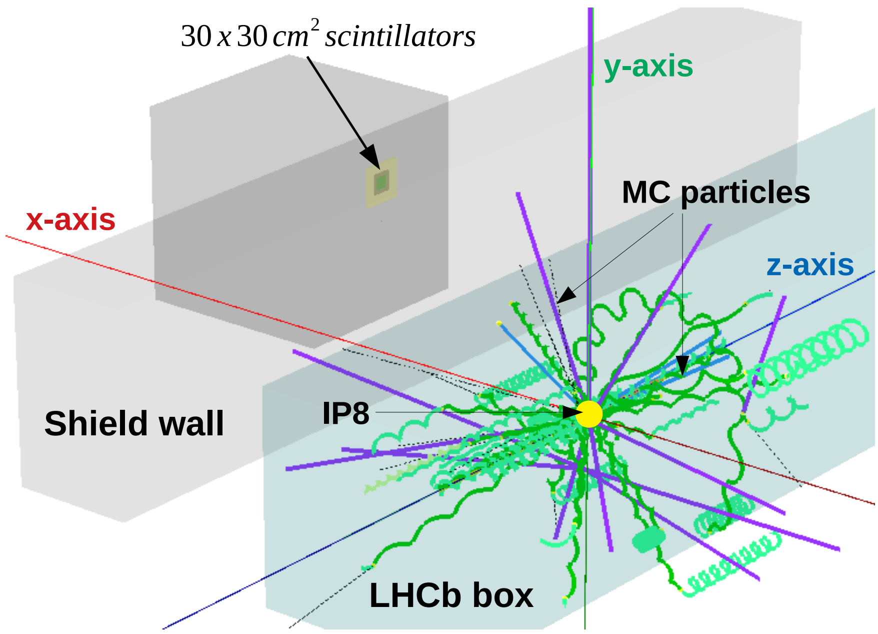
The first geometry I constructed was CODEX-b, consisting of two parts, face stations and inner stations. In the nominal version in the proposal [1], there is a face station on each face of the Codex-b box volume, and each face station has 6 layers of resistive plate chambers (RPC) at 4 cm intervals with 1 cm granularity, as shown in Fig. 8b. The size of each layer is $10 \times 10\ m^2$ and the thickness is 2 cm. Further, the geometry also included 5 inner stations, as shown in Fig. 8a, each containing a triplet of RPC layers. For simplicity, we replaced the RPC's by Silicon tracker layers, and noted the timestamps of the hits in the simulation, since RPC's also provide timing information. We also created a concrete shield wall with 3.2 m thickness, placed just in front of CODEX-b box. In addition, there is a proposed veto cone [1] with two lead absorber and one active silicon layer sandwitched in between. Figure 9 shows the geometry construction in `DD4hep`. The second geometry comprise two scintillator plates which is the same as our measurement configurations. The plastic material composition in `GEANT` was adopted from HeRSCheL.

3.3 Simulation status

As mentioned above, we designed two different detector geometries based on the proposal paper (Codex-b) and the measurement configuration (HeRSCheL scintillators). Both were tested with μ particle gun generated at 1 TeV, and minimum bias events generated in `Gauss` and loaded in `DDG4` using `HepMC` files. No hits were recorded in the CODEX-b volume when tested with $32,000$ minbias events with the concrete wall included. Therefore, we decided to remove the shield wall to make sanity checks. Figure 10a shows hits from minimum bias events with the concrete wall removed. Figure 10b shows the two-scintillator



(a)



(b)

Figure 10: Validation of the `DD4hep` based simulation with minimum bias events: (a) CODEX-b box with the shield wall removed, and (b) two-plate scintillators for measurement campaign.

configuration. Again, no hits were recorded at this point, due to the small acceptance, low statistics samples and presence of the contrete wall. However, the geomery setup is validated with these checks.

4 Summary

In summary, I participated in a very successful measurement campaign and we obtained the data we needed. We measured hit rates of charged mip's based on 2-fold coincidence trigger using elements from the HeRSCheL detector and scope. We also managed to take data efficiently by remote connection to the scope. The average hit rate under the stable beam condition is much higher than the average hit rates of pure ambient background. Based on this result, we can ignore pure background. The background rate just behind the concrete shield wall around 0.5 Hz over 900 cm^2 size scintillators. Also the hit rates have η dependence when moving further downstream, from the impact point. The D3 racks behave like a shield from the P5 and P6 results but it is difficult to simulate due to the complicated material.

For the simulation, I used `DD4hep` to design CODEX-b and backgrond measurement geometries and built a hierachy system to implement a bundle of 6 silicon layers (these layers are planed to change to RPC layers) and a triplet bundle, per station. I note here that this CODEX-b geometry is not final, but will be further developed, using the current setup. Each layer is simulated as a Silicon tracker that records the hit position of particles; its size is 10×10 m^2 with 2 cm thickness. Using a similar hierachy system, the geometry for the background measurement campaign geometry been built. The size of scintillator plate is 30×30 cm^2 and 2 cm thickness. The material of scintillator is the same as the Herschel detector. The proposed veto cone and concrete shield wall were also generated using `DD4hep`.

All geometries were tested with μ particle gun with and without concrete shield wall. WE found hits on the layers without shield wall and checked the hit positions and deposited energies. We also tested with minimum bias events generated from `Gauss` and found hits on the layers without the concrete wall. When the shield wall as reinstated, there was no hits on the layers, indicating that simulation works as expected.

The future plan is to develop more efficient MOnte Carlo generation in `Gauss` with optimized generator cuts and large enough statitics, to validate the measurement data.

Acknowledgements

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