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MEASUREMENT OF THE TRANSVERSAL MUON RATE AT THE PROPOSED CODEX-B EXPERIMENT WITH THE TIMEPIX3 RADIATION MONITOR

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Abstract

Using a Timepix3 Radiation Monitor, we measured the muon rate at the proposed CODEX-b experiment location within the Large Hadron Collider during luminosity production at the LHCb collision point. Filters were applied to the data to differentiate the background radiation from the muon signal by analyzing the particle track morphology—specifically cluster type, length, and angle within the detector. The resulting filtered muon rate was determined to be $(4.27 \pm 0.60) \cdot 10^{-3}$ counts/cm^2/nb^{-1}. These results were further compared to simulations performed with the FLUKA Monte Carlo code, revealing a good agreement within a factor of 2.

INTRODUCTION

Data-driven decision-making based on real collision data from accelerators as is the Large Hadron Collider (LHC) [1], is paramount to assess the feasibility of proposals for future experiments. For this purpose, a test campaign was performed to measure the background particle flux in the foreseen location of the CODEX-b experiment [2–4], which is envisioned as a Standard Model (SM) background-free detector searching for Long Lived Particles (LLPs). Located at IP8 of the LHC, the CODEX-b experiment is planned to be hosted in the D1 shielded area, which is separated from the LHCb [5] experimental cavern by an existing 3.2 m thick concrete wall. Our measurements have been performed during October and November of 2022, the first year of Run 3 (2022-2026) operation with proton-proton (pp) collisions.

The particle (mostly muons) flux during luminosity production at the LHCb Interaction Point (IP8) was measured with the recently developed Timepix3 Radiation Monitor [6], within the Radiation to Electronics (R2E) [7, 8] activity at CERN. It measured an increased count rate during luminosity production, owing to its ability to detect Minimum Ionising Particles (MIPs) on a particle-by-particle basis with virtually 100% detection efficiency [9]. The measured signal, both as a flux rate and as energy deposition, was compared with dedicated simulations [10] performed with the FLUKA Monte Carlo code [11–13]. A previous campaign for muon measurements [14] was done with repurposed scintillators, light-guides and photomultiplier tubes, revealing a systematic disagreement (under-measurement) with simulations, which is not the case for this study. In parallel, a BatMon unit [15] has been deployed for almost 82 days, measuring no signal above its threshold, indicating that the proposed area is safe from a point of view of radiation effects on electronics [16].

Prior to these measurements, a full FLUKA geometry has been implemented, as described in detail in Ref. [10]. The radiation shower is dominated by inelastic proton–proton collisions at IP8. The simulation predictions have been benchmarked with the Beam Loss Monitor (BLM) system [17] in the tunnel and with the RadMon system [18] in the shielded alcoves, similar to other interaction regions [19, 20]. Although not directly benchmarked in the D1 area, the FLUKA model represents the best available tool to predict the collision-driven muon flux in the location of the CODEX-b experiment.

In the D1 cavern, where the Timepix3 Radiation Monitor was installed, only muons and possibly neutrons are assumed to arrive, as the other particles would stop within the concrete shieldings. To understand the muon flux that arrives at the detectors, there are several features of the LHCb cavern that are critical, covered in Ref. [3, 14], which indicate that the infrastructure of the LHCb cavern generally stops muons with momentum below $p_{thres} \approx 1500$ MeV/c. The slowed-down muon momenta at the detector position peaks around a momentum of $p \approx 200$ MeV/c [14], which are close to the MIP regime with roughly constant stopping power $dE/dx|_{Si} \approx 4.15$ MeV/cm in Silicon. Considering the track length inside the sensitive volume, the energy deposition of muons coming from IP8 in the Timepix3 sensor is expected to be approximately:

$$E_{dep} = \int_0^L \frac{dE}{dx} dx \approx L \cdot \left.\frac{dE}{dx}\right|_{p=200\,\mathrm{MeV}} = 107\,\mathrm{keV}. \quad (1)$$

TIMEPIX3 RADIATION MONITOR DATA

The detector has been oriented with an incidence (polar) angle of $\theta = 15°$ wrt. the normal from the IP (i.e. wrt. the incoming muons). This choice has been made because a particle that arrives at an angle of $\Theta^{max}_{monopixel}$=12° or larger must interact with at least two pixels of the detector, thereby allowing to filter the signal by the number of pixels in the particle track, while minimally compromising on the acceptance angle with a $1/\cos\theta$ factor.

The reconstructed cluster event rate during collisions increases with the instantaneous luminosity, however the Signal-to-Noise Ratio (SNR) is less than 2, due to the small active area of the detector ($A_{tpx} = 2.12\,\mathrm{cm}^2$). As such, the natural background will have to be taken into account during the analysis. It consists of averaging the total counts N_{bkg} over the background time period, revealing an average background count rate of:

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$$R_{bkg}^{LHCb} = \frac{N_{bkg}}{\tau_{bkg}} = (7.54 \pm 0.26) \text{ pixel hits/60 s}, \quad (2)$$

where the total acquisition time of about 104.01 hours has been divided into background (no pp collisions) for τ_{bkg} = 58.66 hours, and signal time periods, during pp collisions (luminosity production) summing up to τ_{signal} = 43.45 hours. This background is assumed to come primarily from cosmic rays, with a lower count rate compared to the surface (where the same detector measured about $R_{bkg}^{surface} \approx 20$ pixel hits/60 seconds), since the LHC is about 100 m underground. Moreover, natural decay chains could also play a role underground (e.g. Radon). Finally, there is no background assumed to come from beam-induced activation of materials or other equipment at the installed location.

To extract the signal from the total Timepix3 particle counts and to correlate it with the total luminosity delivered, the background count rate from Eq. 2 multiplied by the duration of luminosity production is subtracted for each time period, thus obtaining only the signal induced by proton-proton collisions at IP8, as:

$$N_{signal} = N_{total} - R_{bkg} \cdot \tau_{signal}. \quad (3)$$

A good linear correlation ($R^2 = 0.97$) is obtained between the Timepix3 reconstructed count rate and the total luminosity, at (38 ± 1) counts/pb^{-1}.

SIGNAL AND BACKGROUND SELECTION

The signal discrimination from background is done using the directionality of the incoming muons, by analysing their tracks inside the detector pixel array, forming multi-pixel clusters. The x (y) axis of the detector was placed parallel (perpendicular) to the normal from the IP, in order to discriminate the muons coming from the collision point and those that constitute the background. In the following discussion, the clusters are treated separately according to the number of pixels N in the cluster. At first, the difference between the signal and background time periods is tackled, by looking at the raw (non-normalized) counts measured by the Timepix3 Radiation Monitor along the horizontal direction (parallel to the normal from the IP, on the line of sight, corresponding to the signal).

Clusters of just one pixel cannot be attributed to any direction. However, from the detector geometry wrt. the interaction point, if a muon originates from a collision it should have an angle of at least $\Theta_{incidence} = 15°$ as mentioned above, implying that its track inside the Timepix3 sensor is strictly greater than 1 pixel. This is confirmed by the 1-pixel cluster rate and energy distribution, where no difference can be observed between the signal and the background data sets. Cluster tracks that cannot be assigned to any direction (e.g. circular blobs) are discarded from the analysis.

For clusters with $N = 2$ and more pixels, a directionality can be assigned. For the purpose of this analysis, the

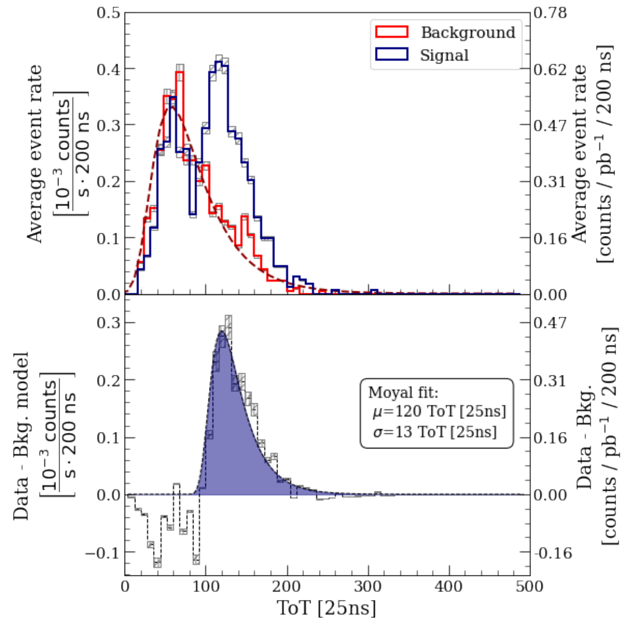

Figure 1: (**Top panel**) Time-over-Threshold (ToT) distribution of the 2-pixel clusters aligned along the x-direction, for signal and background data sets. The background is fitted using a Moyal distribution and subtracted from the signal. (**Bottom panel**) Signal after the background subtraction, fitted using a Moyal distribution, revealing a clear peak at the expected signal location and along the expected direction.

directionality is restricted to either horizontal (corresponding to the signal) or vertical. The background data set does not reveal any difference between the two aforementioned directions, confirming the angular isotropy of the cosmic background radiation arriving at the detector location. Differently, the signal data sets (during pp collisions) reveal a cluster rate excess in the horizontal-direction, as expected from the detector orientation. The background is fitted using a Moyal [21] distribution and then subtracted from the signal histogram. Then, the signal thus obtained is fitted as well using a Moyal distribution revealing a peak at the expected energy, as shown in Fig. 1. This procedure is applied for all clusters from $N = 2$ up to 5 pixels. The summed results reveal an excess count rate that is fitted with a Moyal distribution, revealing a peak at an energy deposition of 118±16 keV, matching the expected signal from Eq. 1. Subsequently, the total average event rate, with its energy distribution shown in Fig. 2, is:

$$\Phi_0 = (5.64 \pm 0.34) \cdot 10^{-3} \quad \frac{\text{counts}}{\text{s}}, \quad (4)$$

where the error is the statistical one evaluated at $\Delta_{stat} = 6\%$ from the Poisson counting process of the events.

In order to compare to previous measurements [14] and FLUKA simulations [10], the total measured count rate of Fig. 2 has to be renormalized for three factors: (i) the Timepix3 detector area of A_{tpx} = 2.12 cm^2, (ii) the acceptance angle via cos ($\theta = 15.17°$) factor, (iii) the average

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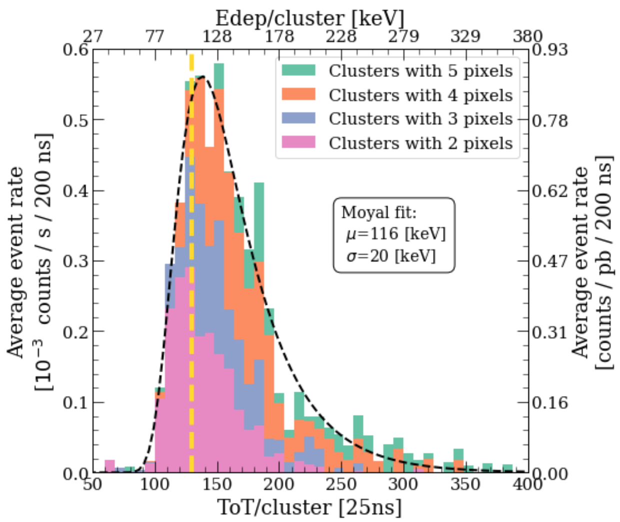

Figure 2: The full reconstructed signal using 2- to 5-pixel clusters, fitted with a Moyal distribution (black dashed curve), revealing a peak at the expected energy deposition value of 107 keV (yellow dashed vertical line).

instantaneous luminosity of $\mathcal{L}^{meas}_{inst,LHCb} = 2.32\ \text{pb}^{-1}/\text{h} = 0.645\ \text{nb}^{-1}/\text{s}$ during the Timepix3 campaign, compared to the nominal $\mathcal{L}^{nominal}_{inst} = 0.45\ \text{nb}^{-1}/\text{s}$ used for both the previous measurements [14] and the simulations [10]. Thus, the calibrated Timepix3 Radiation Monitor measured a muon flux of:

$$\begin{aligned}\Phi^{exp,calib}_{tpx3} &= \Phi_0 \cdot \frac{1}{A_{tpx}} \cdot \frac{1}{\cos\theta} \cdot \frac{\mathcal{L}^{nominal}_{inst}}{\mathcal{L}^{meas}_{inst}} \\ &= (1.94 \pm 0.28) \cdot 10^{-3} \frac{\text{counts}}{\text{cm}^2\ \text{s}} \\ &= (4.27 \pm 0.60) \cdot 10^{-3} \frac{\text{counts}}{\text{cm}^2\ \text{nb}^{-1}},\end{aligned} \tag{5}$$

where the value given also per unit luminosity $\mathcal{L}$ (pb^{-1}) is also given. In addition to $\Delta_{stat} = 6\%$, the error also contains a luminosity measurement uncertainty assumed at $\Delta\mathcal{L} = 2\%$ [1] and an angular error of $\Delta\theta = 1°$.

Figure 3 shows the hit rate from the simulation across a vertical plane parallel to the beam line, normalized to the Run 2 (2015-2018) LHCb luminosity production and per unit area. Geometrically, from the installation location, the Timepix3 Radiation Monitor result corresponds to a data point at $z = 700$ cm, agreeing with the FLUKA simulations of LHCb reported in Ref. [10] at:

$$\Phi^{sim,FLUKA}_{tpx3} = (3.80 \pm 0.76) \cdot 10^{-3} \frac{\text{counts}}{(\text{cm}^2\ \text{s})}, \tag{6}$$

where we considered a systematic simulation uncertainty of $\sigma^{syst}_{sim} = 20\%$ (benchmark studies usually have an agreement of a few tens percent [10, 19, 20]). Finally, the ratio of FLUKA to measured Timepix3 data reveals itself at:

$$R_\Phi = \Phi^{sim,FLUKA}_{tpx3} / \Phi^{exp,calib}_{tpx3} = 1.96 \pm 48\%. \tag{7}$$

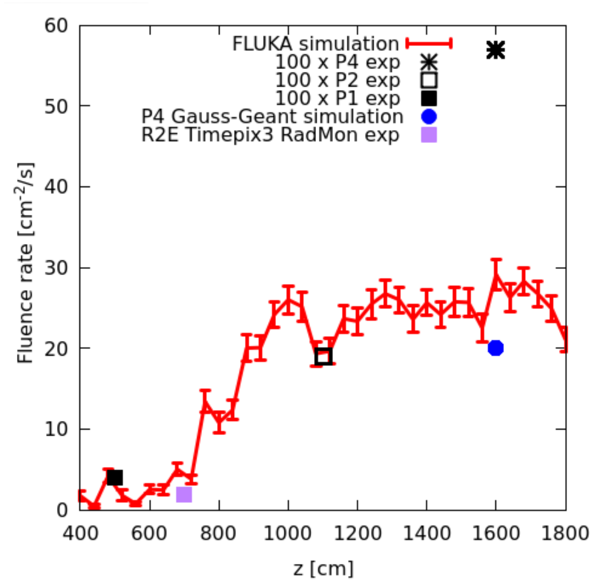

Figure 3: Comparison of muon fluence from FLUKA simulations and measurements. This study adds the Timepix3 measurement (purple square), compared to the previous measured results using scintillating fibers reported in Ref. [10] (here, scaled up by a factor of 100). The assumed luminosity rate production was the nominal (levelled) $0.45\ \text{nb}^{-1}/\text{s}$.

The agreement within a factor of 2 confirms that the collision-induced muon background in the D1 cavern is well understood and within expected levels.

SUMMARY AND PROSPECTS

In summary, a successful background measurement campaign was held to measure the muon flux rate in the proposed CODEX-b location, during LHCb pp luminosity production. The lower energy threshold of the Timepix3 Radiation Monitor allowed to measure a slight increase in the instantaneous count rate during luminosity production, with a SNR of about 2. The expected muons originating from the proton-proton pp collision point are only aligned along one direction, allowing to geometrically discriminate the signal from the background; hence, the analysis then looks at clusters with 2 up to 5 pixels. Finally, the total count results are compared to dedicated FLUKA simulations reported in Ref. [10]. The Timepix3 measured count rate was found to be $(4.27 \pm 0.60) \cdot 10^{-3}$ counts/($\text{cm}^2\ \text{nb}^{-1}$), matching the normalized simulated predictions with a ratio of simulated to measured data of $R_\Phi = 1.96 \pm 48\%$.

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REFERENCES

[1] O. S. Brüning *et al.*, *LHC Design Report, Vol. I: The LHC Main Ring*, CERN Yellow Report, 2004. doi:10.5170/CERN-2004-003-V-1

[2] V. V. Gligorov *et al.*, "Searching for long-lived particles: A compact detector for exotics at LHCb", *Phys. Rev. D*, vol. 97, no. 1, p. 015 023, 2018. doi:10.1103/PhysRevD.97.015023

[3] G. Aielli *et al.*, "Expression of Interest for the CODEX-b Detector", *Eur. Phys. J. C*, vol. 80, no. 12, p. 1177, 2020. doi:10.1140/epjc/s10052-020-08711-3

[4] G. Aielli *et al.*, "The Road Ahead for CODEX-b", *arXiv*, 2022. doi:10.48550/arXiv.2203.07316

[5] LHCb Collaboration, "The LHCb Detector at the CERN Large Hadron Collider", *JINST*, vol. 3, p. S08005, 2008. doi:10.1088/1748-0221/3/08/S08005

[6] D. Prelipcean *et al.*, "Towards a Timepix3 Radiation Monitor for the Accelerator Mixed Radiation Field: Characterisation with Protons and Alphas from 0.6 MeV to 5.6 MeV", *Appl. Sci.*, vol. 14, no. 2, 2024. doi:10.3390/app14020624

[7] *Radiation to Electronics (R2E) at CERN*, https://r2e.web.cern.ch/.

[8] R. García Alía *et al.*, "LHC and HL-LHC: Present and future radiation environment in the high-luminosity collision points and RHA implications", *IEEE Trans. Nucl. Sci.*, vol. 65, pp. 448–456. 2018. doi:10.1109/TNS.2017.2776107

[9] K. Akiba *et al.*, "LHCb VELO Timepix3 telescope", *J. Instrum.*, vol. 14, no. 05, p. P05026, 2019. doi:10.1088/1748-0221/14/05/P05026

[10] A. Ciccotelli *et al.*, "Energy deposition studies for the Upgrade II of LHCb at the CERN Large Hadron Collider", *Phys. Rev. Accel. Beams*, vol. 27, no. 6, p. 061 003, 2024. doi:10.1103/PhysRevAccelBeams.27.061003

[11] *FLUKA website*, https://fluka.cern.

[12] FLUKA CERN Collaboration, "Overview of the FLUKA code", *Ann. Nucl. Energy*, vol. 82, pp. 10–18, 2015. doi:10.1016/j.anucene.2014.11.007

[13] FLUKA CERN Collaboration, "New Capabilities of the FLUKA Multi-Purpose Code", *Front. Phys.*, vol. 9, 2022. doi:10.3389/fphy.2021.788253

[14] B. Dey *et al.*, "Background studies for the CODEX-b experiment: measurements and simulation", *arXiv*, 2019. doi:10.48550/ARXIV.1912.03846

[15] S. Danzeca, A. J. Cass, A. Masi, R. Sierra, and A. Zimmaro, "Wireless IoT in Particle Accelerators: A Proof of Concept with the IoT Radiation Monitor at CERN", in *Proc. IPAC'22*, Bangkok, Thailand, pp. 772–775, 2022. doi:10.18429/JACoW-IPAC2022-TUOXGD2

[16] A. Zimmaro and S. Danzeca, *Report on the Radiation on Electronics measurements in UX85 - LHCB*, EDMS document 2811940.

[17] E. B. Holzer *et al.*, "Beam Loss Monitoring System for the LHC", *IEEE Nucl. Sci. Symp.*, vol. 2, pp. 1052–1056, 2005. doi:10.1109/NSSMIC.2005.1596433

[18] G. Spiezia *et al.*, "The LHC radiation monitoring system - RadMon", *Proceedings of Science*, no. 143, pp. 1–12, 2011. https://pdfs.semanticscholar.org/78a0/5e489d7ad51deed31b6e178a29d476d33349.pdf

[19] D. Prelipcean, *Comparison between measured radiation levels and FLUKA simulations at CHARM and in the LHC tunnel of P1-5 within the R2E project in Run 2*. 2021. https://cds.cern.ch/record/2777059

[20] A. Lechner *et al.*, "Validation of energy deposition simulations for proton and heavy ion losses in the CERN Large Hadron Collider", *Phys. Rev. Accel. Beams*, vol. 22, no. 7, 2019. doi:10.1103/PhysRevAccelBeams.22.071003

[21] C. Walck, *Handbook on Statistical Distributions for Experimentalists; International Report SUF-PFY/96-01*. University of Stockholm, 2007.