

Trigger Studies for LHCb Upgrade 2

CERN Summer Student Programme
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1 Introduction

The High Luminosity era at the LHC is expected to begin after the third Long Shutdown in 2027. Major upgrades to the LHC are proposed to be accompanied by detector upgrades, including a proposed second upgrade to the LHCb detector for Run 5. These changes will result in ~ 7.5 more collisions per event than expected in Run 3, thus producing more b- and c-hadrons. This increase in potentially interesting decays leads to more events being selected by the trigger system, causing data storage problems. Additionally, the problem of selecting events with simple signatures at high efficiencies becomes harder, further complicating the full reconstruction of events. Therefore, significant updates to the trigger system will be required to account for the effects of higher luminosities.

2 Run 3 trigger system

The goal of the LHCb trigger system is to drastically reduce the number of stored background events to reach a high efficiency for events later used for analysis. The current trigger system for Run 3 is entirely software based, the hardware trigger being used in Run 1 and Run 2 only. The trigger itself is divided into two “high level” triggers, HLT 1 and HLT 2. Events are passed to HLT 1 at a rate of 30 MHz, or 5 TB/s. HLT 1 reconstructs particle trajectories for particles which are charged, pass through the entire detector and fulfill the requirement $p_T > 500$ MeV. Additionally, events passing through HLT 1 have to contain either one track or two tracks originating from the same vertex, which show a significant displacement from the primary vertex, also called the impact parameter. At this stage of the trigger systems, no particle-identification algorithms can be applied due to time constraints. The HLT 1 strategy results in an event rate reduction to 1 MHz.

The remaining output is buffered, allowing for full event reconstructions to be executed by HLT 2. This includes track reconstructions of charged particles, as well as the reconstruction of neutral particles and particle identification. Requirements for b-hadrons are vertices with two, three, or four tracks and significant p_T and impact parameter values, as well as a fitting decay topology.

The resulting data of 10 GB/s is then sent to storage [2].

3 Datasets and particle properties

In the high luminosity era, LHCb is expected to operate at a maximum luminosity of $1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Up to 42 interactions per bunch crossing (or event) will lead to multiple heavy-flavour hadrons being detected per event [1]. The first level of a fully software-based trigger is expected to reduce the input rate of 30 MHz to 5 MHz [1].

The Monte Carlo simulations made with PYTHIA used to study the effects of higher luminosity on the trigger system simulated pp-collisions only, the detector resolution was

not taken into consideration.

In this study, the detector resolution is not taken into consideration. The VELO acceptance is simplified by requiring particles to be in the pseudorapidity range of $2 < \eta < 5$. The Mighty Tracker acceptance is simplified by extrapolating the particles tracks through the B-field and checking that the particle passes through the active area of the detector. No detector interaction is simulated.

4 Quark production

Using the simulated data, a closer look at the expected b-, c-, and s-quark production is possible. The fraction of events containing at least one respective quark in the LHCb acceptance can be found in Table 1.

b quarks	c quarks	s quarks
$(15.69 \pm 0.36)\%$	$(89.05 \pm 0.31)\%$	100%

Table 1: Fractions of events containing at least one b-, c- or s-quark.

The expected numbers of b- and c- quarks per event are shown in Figures 1a and 1b.

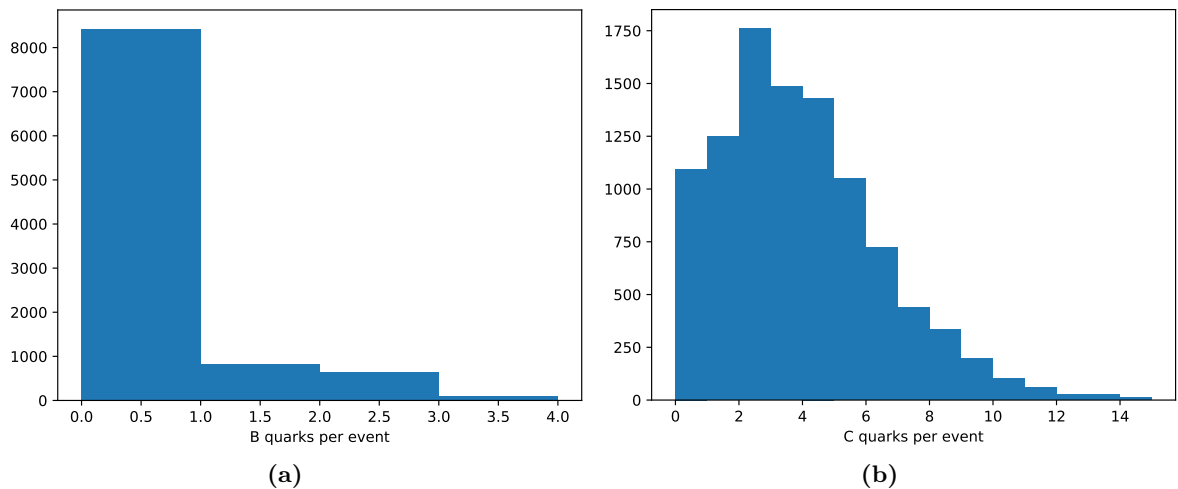


Figure 1: Distributions of expected b and c quarks per event.

5 Primary Vertices

The number of primary vertices per event is expected to be 56.97 ± 7.56 , as shown in Figure 2a. The distribution of tracks per primary vertex is visible in Figure 2b.

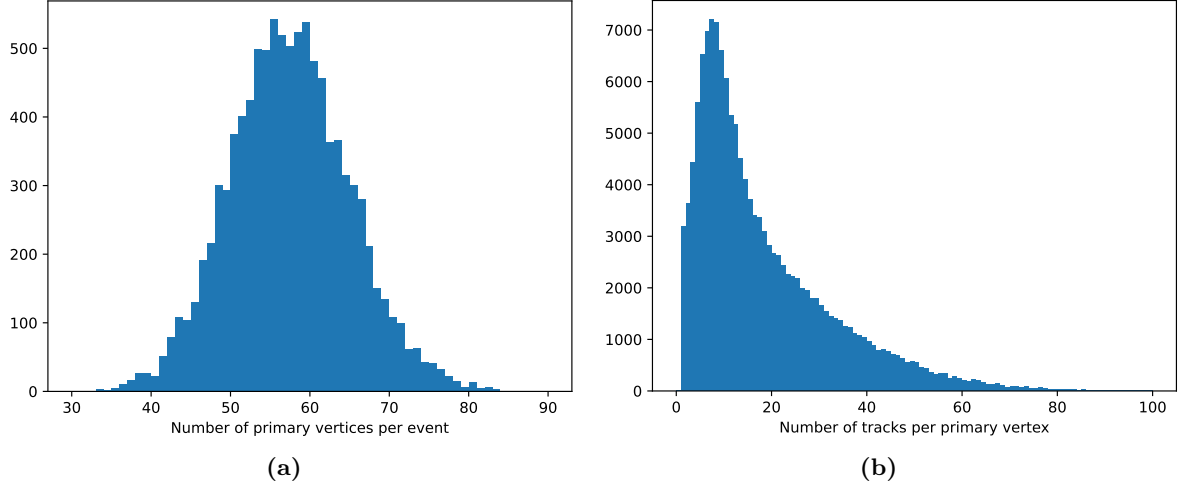


Figure 2: Distributions of primary vertices per event (*left*) and tracks per primary vertex (*right*).

6 Efficiencies

For each decay product, charge, momentum, pseudorapidity and calculated impact parameter are saved for further analysis.

The dataset is used to determine the expected numbers of b- and c-hadrons per event as well as detector efficiencies, which are described in Table 2.

B- and c-hadrons in 4π describe the total number of expected candidates per event, while the number of expected hadrons in the forward direction is given by those in a pseudorapidity range of $2 < \eta < 5$. The efficiency of candidates having at least two associated tracks in the VELO acceptance is given by $\epsilon(\text{VELO})$. $\epsilon(\text{LHCb} \cap \text{VELO})$ describes the efficiency of all decay products of a candidate being in the LHCb acceptance.

Category	In 4π	In $2 < \eta < 5$	$\epsilon(\text{VELO})$	$\epsilon(\text{LHCb})$
b-hadrons	1.010 ± 0.010	0.243 ± 0.005	$(26.5 \pm 0.4)\%$	$(11.1 \pm 0.3)\%$
c-hadrons	13.959 ± 0.037	3.466 ± 0.019	$(20.7 \pm 0.1)\%$	$(15.0 \pm 0.1)\%$

Table 2: Total number of candidates and efficiencies.

Accordingly, there are expected to be 0.112 ± 0.014 reconstructible b-hadrons and 2.090 ± 0.140 c-hadrons per event.

The results in Table 3 showcase the same requirements applied to low luminosity data.

Category	In 4π	In $2 < \eta < 5$	$\epsilon(\text{VELO})$	$\epsilon(\text{LHCb})$
b-hadrons	0.136 ± 0.005	0.035 ± 0.003	$(28.3 \pm 1.7)\%$	$(11.3 \pm 1.2)\%$
c-hadrons	1.853 ± 0.019	0.465 ± 0.010	$(20.8 \pm 0.2)\%$	$(15.0 \pm 0.4)\%$

Table 3: Cross check with low luminosity data.

7 Cuts

To reduce the number of events selected by the trigger, certain requirements have to be applied. These cuts should reduce the incoming event rate from 30 MHz to 5 MHz [1], while achieving a high efficiency for b- and c-hadrons.

The efficiencies and output rates for different numbers of analysed tracks presented in Table 4 result from the requirements of individual impact parameters of at least 0.3 mm and respective p_T .

	One track	Two tracks	Three tracks
	$p_T > 2 \text{ GeV}$	$p_T > 1.52 \text{ GeV}$	$p_T > 1.12 \text{ GeV}$
b efficiency	$(25.51 \pm 1.87)\%$	$(22.00 \pm 1.78)\%$	$(22.92 \pm 1.81)\%$
c efficiency	$(18.66 \pm 0.38)\%$	$(18.95 \pm 0.38)\%$	$(23.89 \pm 0.42)\%$
$\epsilon(p_T)$	$(16.46 \pm 0.53)\%$	$(16.78 \pm 0.42)\%$	$(14.97 \pm 1.53)\%$
Output rate	$(4.94 \pm 0.16) \text{ MHz}$	$(5.04 \pm 0.13) \text{ MHz}$	$(26.39 \pm 0.14) \text{ MHz}$

Table 4: Fraction of selected events, b (c) efficiency and output rates for an input rate of 30 MHz.

The same cuts applied to lower luminosity as seen in Table 5, as will be reached during Run 3, showcases the difference in b and c efficiencies achieved by the trigger set up.

	One track	Two tracks	Three tracks
	$p_T > 2 \text{ GeV}$	$p_T > 1.52 \text{ GeV}$	$p_T > 1.12 \text{ GeV}$
b efficiency	$(8.54 \pm 0.22)\%$	$(1.83 \pm 1.05)\%$	$(1.83 \pm 1.05)\%$
c efficiency	$(2.66 \pm 0.30)\%$	$(0.79 \pm 0.16)\%$	$(0.58 \pm 0.14)\%$
$\epsilon(p_T)$	$(1.48 \pm 0.12)\%$	$(0.47 \pm 0.07)\%$	$(0.22 \pm 0.05)\%$
Output rate	$(0.440 \pm 0.036) \text{ MHz}$	$(0.14 \pm 0.02) \text{ MHz}$	$(0.07 \pm 0.02) \text{ MHz}$

Table 5: Run 3 luminosity: Fraction of selected events, b (c) efficiency and output rates for an input rate of 30 MHz.

Another trigger method which can be applied is based on tracks stemming from the same

vertices. An event is selected if there are two (three) tracks from the same vertex with a combined $p_T > 2$ G/eV, while each track is required to have a minimum p_T of 0.8 G/eV and an impact parameter of at least 0.3 mm. Additionally, two tracks combined should be associated with a momentum larger than 5 G/eV. The resulting efficiencies and event rates are shown in Table 6.

	Two tracks	Three tracks
b efficiency	$(30.31 \pm 1.98) \%$	$(22.18 \pm 1.79) \%$
c efficiency	$(18.87 \pm 0.38) \%$	$(13.66 \pm 0.24) \%$
$\epsilon(\text{IP}, p_T, p)$	$(15.86 \pm 0.52) \%$	$(11.44 \pm 0.45) \%$
Output rate	$(4.76 \pm 0.11) \text{ MHz}$	$(3.42 \pm 0.14) \text{ MHz}$

Table 6: Fraction of selected events, b and c efficiencies and output rates for an input rate of 30 MHz.

The difference to Run 3 luminosity simulations can be seen in Table 7.

	Two tracks	Three tracks
b efficiency	$(8.54 \pm 2.18) \%$	$(1.83 \pm 1.05) \%$
c efficiency	$(2.56 \pm 0.29) \%$	$(0.24 \pm 0.09) \%$
$\epsilon(\text{IP}, p_T, p)$	$(1.31 \pm 0.11) \%$	$(0.03 \pm 0.01) \%$
Output rate	$(0.39 \pm 0.30) \text{ MHz}$	$(0.009 \pm 0.003) \text{ MHz}$

Table 7: Low lumi: Fraction of selected events, b and c efficiencies and output rates for an input rate of 30 MHz.

As shown in Table 6, the efficiency of c hadrons is only slightly higher than the fraction of selected events. This is an indication that a better understanding needs to be gained of what is triggered on, that is if the involved b- or c- hadrons cause an event to be selected by the simplified trigger.

8 Outlook and Summary

During Run 5 of the LHC, the upgraded LHCb detector is expected to measure many charm and beauty hadrons. As shown in this study, it will be challenging to trigger at a high efficiency while maintaining low rates.

Due to the idealised nature of this study, including the perfect resolution of impact parameters and only the physics background being taken into consideration, the calculated trigger rates are likely imprecise. To study the trigger rates more precisely, the analysis should be repeated using a full detector simulation.

References

- [1] Roel Aaij et al. “Physics case for an LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era”. In: (Aug. 2018). arXiv: 1808.08865 [hep-ex].
- [2] “RTA and DPA dataflow diagrams for Run 1, Run 2, and the upgraded LHCb detector ”. In: (Sept. 2020). URL: <https://cds.cern.ch/record/2730181>.