Preparation of Lepton Universality tests with LHCb Run 3 data

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Abstract: The Standard Model of particle physics predicts lepton universality. In 2021, LHCb Collaboration presented evidence for the violation of lepton universality in beauty quark decays, but more precision is needed to proof it with higher significance. After upgrading the accelerator and the detector, the new LHCb Run 3 data coming in 2022 will enable further analysis of such decays. In this work, the efficiency of the new detector has been studied for decay modes $B^{\pm} \to J/\Psi(\to e^{+}e^{-})K^{\pm}$, $B^{\pm} \to J/\Psi(\to \mu^{+}\mu^{-})K^{\pm}$, $B^{\pm} \to \Psi(2S)(\to e^{+}e^{-})K^{\pm}$, $B^{\pm} \to \Psi(2S)(\to \mu^{+}\mu^{-})K^{\pm}$. Also the expected number of detected events per luminosity unit has been computed for these four decay modes, and compared with its value before the upgrade.

I. INTRODUCTION

The Standard Model (SM) of particle physics provides our best description of fundamental particles and their interactions. Nevertheless, it does not explain some important topics such as dark matter or dark energy. Finding small inaccuracies in the predictions of the SM would open the door for new physics that might help to better understand these yet unexplained topics. This is one of the goals of the Large Hadron Collider (LHC) in the European Organization for Nuclear Research (Conseil européen pour la recherche nucléaire - CERN).

One prediction of SM is that the different leptons (electron e^{-}, muon μ^{-} and tau τ^{-}) have the same fundamental interaction strengths. This is known as lepton universality (LU), and it has been studied in the LHCb, one of the four main particle detectors in LHC. In 2021, the LHCb collaboration presented evidence for the violation of LU in beauty-quark decays with a significance of 3.1 standard deviations [1]. It was achieved using the LHCb Run 2 data, and although it is an unprecedented result it is not yet considered a proof of violation of LU. More precision is needed in order to achieve a significance of 5 standard deviations.

After upgrading the detector [2], this year the LHCb aims to start collecting data again in the so-called LHCb Run 3. The upgrade will allow for further study on LU.

This work focuses on studying the new efficiencies of the detector after the upgrade. The main goal is to compute the expected number of events -the yield- that LHCb will be detecting in comparison to what it was detecting before the upgrade. More specifically, decays of a charged beauty hadron, $B^{\pm}$, into a charged kaon, $K^{\pm}$, and two charged leptons, $l^{+}l^{-}$, are studied, comparing the decays into electrons, $B^{\pm} \to K^{\pm}e^{+}e^{-}$, and into muons, $B^{\pm} \to K^{\pm}\mu^{+}\mu^{-}$.

This article starts with a brief description of LHCb and its LU tests, in section II. Section III specifies how the efficiency of the detector is studied. Finally, the obtained efficiencies and yields are presented in section IV.

II. LHCb

LHCb is one of the four particle detectors of the LHC in CERN, Geneva. The detector allows to study $b\bar{b}$ quark pairs formed in the pp collisions, and also b- and $\bar{b}$-hadrons formed thereafter. It is a cone-shaped single-arm spectrometer [3], as shown in Figure 1. This conic shape of the detector around the beam is used because, at such high energies, both the b- and $\bar{b}$-hadrons are predominantly produced in the forward and backward directions.

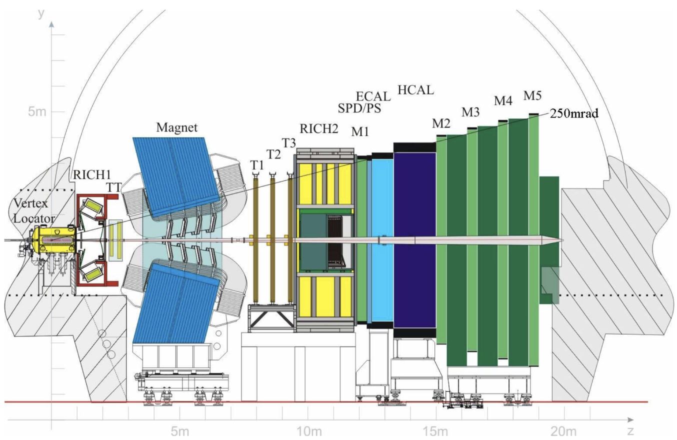

FIG. 1: Lateral view of the LHCb detector before the upgrade. Image from [3].

LHCb has been upgraded to increase its efficiency and detect more decays [2]. This increase is mainly thanks to the new triggering system. Before the upgrade, there was a hardware trigger and a software trigger. The elimination of the hardware trigger and the implementation of all the trigger in software allows to perform more sophisticated selections, which helps detect more events.

LHCb collects a vast amount of data that cannot be stored right away. The storage of the data in the upgraded LHCb is triggered by a software called High Level Trigger (HLT). It is responsible for filtering an input rate of up to 40 million collisions per second down to an output rate of around 100 kHz, which corresponds to an output storage rate of 10 GB/s [4, 5].

Moreover, computing limitations affect the selection process itself: even though HLT has access to all data of each collision, it aims to reject the uninteresting events by using only part of the full event data. To do so, HLT is subdivided in two stages: HLT1 and HLT2 [Figure 2]. HLT1 performs a fast track reconstruction and makes a decision based on one- and two-track objects. The purpose of HLT1 is to reduce the rate to a sufficiently low level to allow for full pattern recognition. This is done in HLT2, which performs a high-fidelity reconstruction and makes a decision based on the full detector read-out information.

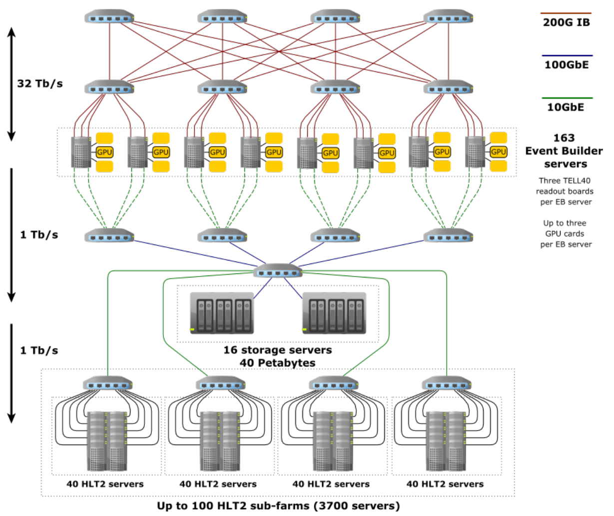

FIG. 2: Scheme of the HLT trigger. Image from [5]

The first trigger stage (HLT1) is implemented in GPUs, using its great parallelization capacity. This stage reduces the overall data rate by a factor 15-30 [5]. The second trigger stage (HLT2) is implemented on a farm of around 3700 CPU servers. Since the HLT is fully implemented in software, it is very flexible and it is subject to developments and adjustments.

A. LHCb LU tests

In the LHCb experiments, several decays are studied to perform LU tests. The decays that have given the most accurate measurements are those of a charged beauty hadron, $B^{\pm}$, into a charged kaon, $K^{\pm}$, and two charged leptons, $l^{+}l^{-}$ [1, 6]. We write this decay as $B^{\pm} \to K^{\pm}l^{+}l^{-}$, which is illustrated in Figure 3.

The goal of LU tests is to check if there are the same number of decays for electrons than for muons. The proportion of decays that fall into a specific group of particles is called the branching fraction $\mathcal{B}$. To check LU, we have to compute the ratio R_K (Equation 1) between the branching fraction of electrons $\mathcal{B}(B^{+} \to K^{+}e^{+}e^{-})$ and the branching fraction of muons $\mathcal{B}(B^{+} \to K^{+}\mu^{+}\mu^{-})$ and

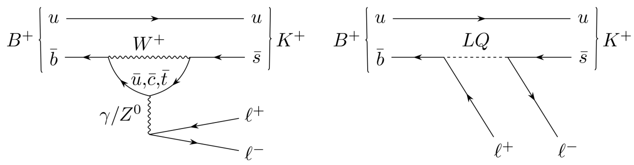

FIG. 3: Diagram of the decay $B^{+} \to K^{+}l^{+}l^{-}$: a B^{+} meson, consisting of b and u quarks, decays into a K^{+}, containing s and u quarks, and two charged leptons, $l^{+}l^{-}$. (Left) The decay according to SM, involving electroweak bosons γ, W^{+} and Z^{0}. (Right) Possible new model for the decay with a hypothetical leptoquark (LQ) which, unlike the electroweak bosons, could have different interaction strengths with the different types of leptons [1].

see whether it is equal to one or not.

$$R_K = \frac{\mathcal{B}(B^{\pm} \to K^{\pm}\mu^{+}\mu^{-})}{\mathcal{B}(B^{\pm} \to K^{\pm}e^{+}e^{-})} \tag{1}$$

The notation $B^{\pm} \to K^{\pm}l^{+}l^{-}$ is used to denote *non-resonant* decays whereas the notation $B^{\pm} \to J/\psi(\to l^{+}l^{-})K^{\pm}$ and $B^{\pm} \to \psi(2S)(\to l^{+}l^{-})K^{\pm}$ is used to denote *resonant* decays trough channels J/ψ and $\psi(2S)$ respectively.

To avoid systematic uncertainties, the branching fractions of $B \to Kl^{+}l^{-}$ decays are measured relative to those of $B \to J/\psi K$. Then the R_K ratio is determined via the following double ratio (Equation 2).

$$R_K = \frac{\mathcal{B}(B^{+} \to K^{+}\mu^{+}\mu^{-})}{\mathcal{B}(B^{+} \to J/\psi(\to \mu^{+}\mu^{-})K^{+})} \bigg/ \frac{\mathcal{B}(B^{+} \to K^{+}e^{+}e^{-})}{\mathcal{B}(B^{+} \to J/\psi(\to e^{+}e^{-})K^{+})} \tag{2}$$

This procedure is legitimate because the branching fractions of the channel $J/\psi \to l^{+}l^{-}$ are known to respect lepton universality within 0.4% [7, 8]. The branching fractions of $\psi(2S) \to l^{+}l^{-}$ also respect lepton universality but with a higher uncertainty, of about 10% [7].

The fact that channels J/ψ and $\psi(2S)$ do respect LU is used check that the efficiencies of the detector are correct, since their ratios $r_{J/\psi}$ and $r_{\psi(2S)}$ must be one (Equations 3, 4).

$$r_{J/\psi} = \frac{\mathcal{B}(B^{+} \to J/\psi(\to \mu^{+}\mu^{-})K^{+})}{\mathcal{B}(B^{+} \to J/\psi(\to e^{+}e^{-})K^{+})} \tag{3}$$

$$r_{\psi(2S)} = \frac{\mathcal{B}(B^{+} \to \psi(2S)(\to \mu^{+}\mu^{-})K^{+})}{\mathcal{B}(B^{+} \to \psi(2S)(\to e^{+}e^{-})K^{+})} \tag{4}$$

The first thing to be done when the Run 3 data is available is to compute again these ratios of branching fractions $r_{J/\psi}$ and $r_{\psi(2S)}$ to check that the efficiencies of the detector are correct.

III. METHODS

We want to study the efficiency of the LHCb detector for beauty quark decays on channels J/ψ and $\psi(2S)$. In other words, we need to check the proportion of events that the HLT will recognize as such decays. In order to test HLT, Monte Carlo simulations are needed and the software Moore is used [5], which is the LHCb HLT application.

More specifically, we used the HltEfficiencyChecker of MooreAnalysis, which runs Moore and writes the trigger decisions to output files arranged in a ROOT ntuple. Finally, the software Root [9] is used to read and manipulate these ouptut files.

When running the application, the number of events arriving to the detector was set to 10000 in order to have a sufficient statistical sample to compute the efficiency with a low uncertainty but without compromising the computation time. Increasing this number of events could be done in future studies but would have a low impact in the uncertainty of the results since the other uncertainties are higher.

In order for HLT to know what events to trigger, specific trigger lines have to be specified. A trigger line is a physical condition for the triggering of the events. At the end, we need to study the events that passed at least one of the trigger lines of each HLT level. In order to compute the logical OR of all the trigger lines, a brief .C program has been written that reads the TTrees using ROOT::RDataFrame Class Reference and computes how many events passed at least one of the specified lines in each case, to obtain the efficiency.

IV. RESULTS

Using the tools detailed in the previous section, the expected number of detected decays, or yield, is computed for each decay mode. This is done in 3 steps: first, the total number of events before the detector; second, how many of them arrive to the detector; and finally, how many of them are selected by the trigger. This third term is the efficiency of the detector and is essentially what has changed with LHCb upgrade, since this efficiency strongly depends on the triggering system of the detector.

The number of events is dependant on how many collisions have taken place along the period of time of the experiments: the integrated luminosity. For the LHCb Run 2, the total integrated luminosity was $L = 9\text{fb}^{-1}$ and for LHCb Run 3 the expected total integrated luminosity is 14fb^{-1}. Since achieving such luminosity will likely take several years, it is interesting to compute the number of events for a low luminosity such as $L = 100\ \text{pb}^{-1}$, in order to see the expected yield of the detector in a few months. This is known as $100\ \text{pb}^{-1}$ challenge.

A. Expected number of events before the detector

The expected number of events, or yield, for a given channel is the product of three terms (Equation 5): the number of collision events, the probability for a B^+ meson to be created in a collision (together with anything else, denoted by X), and the probability for B^+ to decay through the specific channel Y into two leptons l^+l^- [10].

$$\begin{aligned} &N_{expected}(\text{channel } Y) = \\ &= L \cdot \sigma(pp \to B^+X) \cdot \mathcal{B}(\text{channel } Y) = \\ &= L \cdot \sigma(pp \to B^+X) \cdot \mathcal{B}(B^+ \to YK^+)\mathcal{B}(Y \to l^+l^-) \end{aligned} \tag{5}$$

where we pick the integrated luminosity to be $L = 100\ \text{pb}^{-1}$ and where $\sigma(pp \to B^+X) = \sigma(pp \to B^{\pm}X, \sqrt{s} = 13\ \text{TeV}) = (86.6 \pm 9.3)\ \mu\text{b}$ is the cross section for the events we are interested in, which we take from [11]. The branching fractions are taken from the Particle Data Group (PDG) [7].

If we do this computation for the channel J/ψ we get:

$$\begin{aligned} &N_{expected}\big(J/\psi\ (\to e^+e^-)\big) = \\ &= N_{expected}\big(J/\psi\ (\to \mu^+\mu^-)\big) = \\ &= (530 \pm 70) \cdot 10^3 \end{aligned} \tag{6}$$

And for the channel $\psi(2S)$ we get:

$$\begin{aligned} &N_{expected}\big(\psi(2S)\ (\to e^+e^-)\big) = (43 \pm 7) \cdot 10^3 \simeq \\ &\simeq N_{expected}\big(\psi(2S)\ (\to \mu^+\mu^-)\big) = (43 \pm 9) \cdot 10^3 \end{aligned} \tag{7}$$

where the uncertainties are propagated from each element in Equation 5 and are dominated by the uncertainty in the cross section σ.

Note that we get the same results for electrons and for muons here. This is because, as said before, the decays $J/\psi \to l^+l^-$ and $\psi(2S) \to l^+l^-$ do respect LU, so $\mathcal{B}(J/\psi \to e^+e^-) = \mathcal{B}(J/\psi \to \mu^+\mu^-)$ and $\mathcal{B}(\psi(2S) \to e^+e^-) = \mathcal{B}(\psi(2S) \to \mu^+\mu^-)$.

B. Acceptance efficiencies

Since the detector does not cover all the solid angle around the collisions but only a relatively small conic region, not all the particles that are generated in the collisions get to the detector. The proportion of events that get to the detector is the acceptance efficiency. The acceptance efficiencies for the different decay modes are very similar, as seen in Table I.

Decay mode	Acceptance efficiency
$J/\psi\ (\to e^+e^-)$	0.1731
$J/\psi\ (\to \mu^+\mu^-)$	0.1735
$\psi(2S)\ (\to e^+e^-)$	0.1760
$\psi(2S)\ (\to \mu^+\mu^-)$	0.1756

TABLE I: Acceptance efficiencies.

These acceptance efficiencies were obtained from the MC samples.

C. Detector efficiencies

Since the detector is not perfect, once the particles get to the detector not all of them are identified. We are interested in the proportion of events that the LHCb detects and triggers to storage: the efficiency of the detector. As said in section II, this efficiency strongly depends on what trigger lines are being run, apart from the decay mode. We computed the efficiencies for the two trigger levels separately, and also for both of them one after another. This last efficiency for both levels accounts for the events that first passed HLT1 and afterwards also passed HLT2. The obtained efficiencies are shown in Table II.

	Trigger level	Efficiency
$J/\psi\ (\to e^+e^-)$	1	0.48
	2	0.23
	both	0.19
$J/\psi\ (\to \mu^+\mu^-)$	1	0.61
	2	0.56
	both	0.43
$\psi(2S)\ (\to e^+e^-)$	1	0.48
	2	0.25
	both	0.21
$\psi(2S)\ (\to \mu^+\mu^-)$	1	0.60
	2	0.46
	both	0.37

TABLE II: Efficiencies of the different HLT levels for each channel

The relative uncertainty of these efficiencies is less than 1%. This could be improved by increasing computation time, but it was not necessary for the purposes of this work, since other uncertainties dominate when the yield of the detector is computed later on.

We have seen that there is a lot of overlap between the triggered events of different trigger lines. This is, different trigger lines end up selecting essentially the same events. In fact, there are some lines that could trigger the interesting events almost by themselves, because they already select most of the events. In HLT1, we observed that the line "Hlt1TwoTrackMVADecision" contributes the most to the selection, both for muons and for electrons. In HLT2, the line "Hlt2RD_BuToKpJpsi_JpsiToEE_LineDecision" is the most important line for electrons and for muons the line "Hlt2BandQ_DiMuonJPsiHighPT_LineDecision" selects almost all the triggered events.

We can see that the efficiencies are higher for muons than for electrons. This is because muons go through most parts of the detector without interacting with it, so they get to the end of the detector where they are detected and hardly ever misidentified. Nevertheless, electrons interact more with the detector and other particles, and slow down due to bremsstrahlung radiation, so they are more difficult to identify.

The application Moore Analysis also gives plots of the efficiencies as a function of different variables. For example, the HLT1 efficiencies as a function of the transverse moment p_T of the electron for the channel $J/\psi\ (\to e^+e^-)$ and as a function of the transverse moment p_T of the muon for channel $J/\psi\ (\to \mu^+\mu^-)$ are in Images 4 and 5. The efficiency of any line is the weighted average with

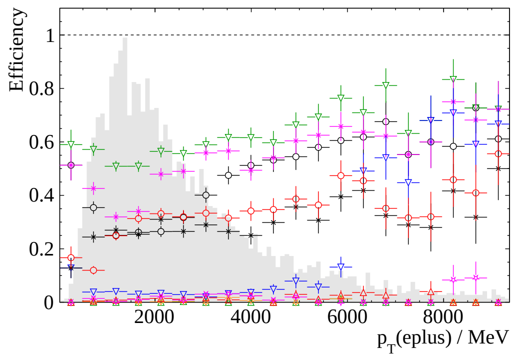

FIG. 4: HLT1 efficiencies for channel $J/\psi\ (\to e^+e^-)$ as a function of the transverse moment p_T of e^+. Each colored shape represents a different trigger line. In gray, the theoretical normalized distribution.

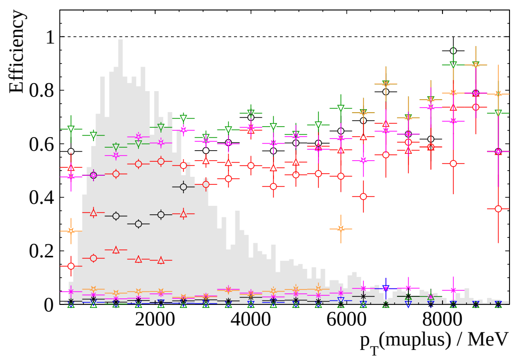

FIG. 5: HLT1 efficiencies for channel $J/\psi\ (\to \mu^+\mu^-)$ as a function of the transverse moment p_T of μ^+. Each colored shape represents a different trigger line. In gray, the theoretical normalized distribution.

the normalized distribution, which is seen in gray in the plots. The total HLT1 efficiency is not represented in these plots, since the selected events by different trigger lines overlap with one another.

Comparing both plots, we see that the general behaviour is qualitatively similar for both electrons and muons, but with higher efficiencies for muons.

D. Expected number of events after the detector

If we take the expected number of events of Equations 6 and 7, take into account the acceptance efficiencies of Table I, and also the HLT efficiencies of Table II, we obtain the expected total number of events that have been detected and stored: the yield. The results are collected in Table III.

	Expected yield for $L = 100\ pb^{-1}$	Expected yield for $L = 1\ fb^{-1}$
$J/\psi\ (\rightarrow e^+e^-)$	$17\,000 \pm 2\,000$	$170\,000 \pm 20\,000$
$J/\psi\ (\rightarrow \mu^+\mu^-)$	$39\,000 \pm 5\,000$	$390\,000 \pm 50\,000$
$\psi(2S)\ (\rightarrow e^+e^-)$	$1\,600 \pm 300$	$16\,000 \pm 3\,000$
$\psi(2S)\ (\rightarrow \mu^+\mu^-)$	$2\,800 \pm 600$	$28\,000 \pm 6\,000$

TABLE III: Expected number of events and for each channel

The yield is higher for muons than for electrons due to the difference in the efficiencies of the detector, as commented before. We also see that the yield is higher for channel J/ψ than for $\psi(2S)$. This is because there are more trigger lines that search for J/ψ events than for $\psi(2S)$. There is no physical reason why there should be less efficiency for $\psi(2S)$, so the missing $\psi(2S)$ trigger lines could be introduced to HLT in order to increase efficiency to similar levels of J/ψ.

The previous yields with Run 2 [1] are in Table IV. The uncertainty of these yields is statistical. It is the square root of the number of events because it is a Poisson process.

	Yield for $L = 9\ fb^{-1}$	Yield for $L = 1\ fb^{-1}$
$J/\psi\ (\rightarrow e^+e^-)$	$743\,300 \pm 900$	$82\,600 \pm 300$
$J/\psi\ (\rightarrow \mu^+\mu^-)$	$2\,288\,500 \pm 1500$	$254\,300 \pm 500$

TABLE IV: Yield of LHCb in previous LU tests [1].

Comparing the results, we see that the LHCb upgrade allows for a remarkably higher number of detected decays per luminosity unit.

V. CONCLUSIONS

After the upgrade of LHCb with the new HLT, the yield of the detector has increased by a factor of 2 for the decay mode $B^\pm \rightarrow J/\psi\ (\rightarrow e^+e^-)K^\pm$ and by a factor of 1.5 for the decay mode $B^\pm \rightarrow J/\psi\ (\rightarrow \mu^+\mu^-)K^\pm$. This improvement is much more relevant for electrons than for muons, since electrons had a lower yield. This new yields will directly translate into an improvement in LU measurements.

If we look at the decay modes of channel $\psi(2S)$, $B^\pm \rightarrow \psi(2S)\ (\rightarrow e^+e^-)K^\pm$ and $B^\pm \rightarrow \psi(2S)\ (\rightarrow \mu^+\mu^-)K^\pm$, the yield is one order of magnitude smaller than for channel J/ψ. Nevertheless, it could be improved by adding trigger lines focused on the selection of these events, in order to achieve a yield of the same order.

In conclusion, this increase in the yield of the detector, together with the other improvements in LHC and LHCb, will provide the same resolution than before for LU tests with barely half the time, or alternatively, will significantly increase the resolution of the results of the LU tests that will take place within Run 3.

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