EFFICIENT TRIGGERING WITH THE LHCb DETECTOR FOR PRECISE CP MEASUREMENTS*

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The LHCb experiment is designed to study CP violation in B-decays at the LHC machine at a luminosity of $2 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ and a rate of 40 MHz. It is crucial to efficiently select those pp-interactions containing the B-meson decays of interest. The expected physics reach of the LHCb experiment has recently been re-evaluated, after changes in the detector geometry and using full detector simulation and reconstruction. Both the trigger strategy and performance, as well as the new results on the expected physics reach will be presented for a few specific channels.

1. Introduction

The LHCb experiment is designed to study CP violation and rare decays in the B-system in pp-collisions at the LHC machine with a center-of-mass energy of $\sqrt{s} = 14 \text{ TeV}$. With a $b\bar{b}$ cross section of 0.5 mb and a nominal luminosity of $2 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, a total amount of 10^{12} $b\bar{b}$ -pairs will be produced per year. This will allow precise measurements of the angles β , γ and χ of the well known unitarity triangles, see Fig. 1. The large production of B^0 and B_s^0 -mesons leads to a significant discovery potential for physics beyond the standard model¹. New particles in loop diagrams might introduce new CP violating phases of the couplings, or alter the branching ratios of rare decays by changing the strength of the couplings.

The LHCb detector is a single arm spectrometer covering the range $1.9 < \eta < 4.9$ and has recently been redesigned (Sec. 2) in order to increase the trigger efficiency (Sec. 3) and to optimize the physics performance of the experiment (Sec. 4).

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2. The re-optimized LHCb detector

The LHCb apparatus² consists of a vertex locator (VELO), a tracking system with a dipole magnet, two Ring Imaging Cherenkov counters (RICH), electromagnetic and hadronic calorimeters, and a muon system. The VELO is made of 21 stations, consisting of two silicon disks each. The full silicon Trigger Tracker (TT) consists of four planes, split into two pairs that are 30 cm apart, and is placed in front of the magnet, inside the magnetic fringe field, see Fig. 1. The tracking system is made of three tracking stations (of four planes each) behind the magnet with silicon sensors in the inner region and straw tubes in the outer region. This setup ensures a high track finding efficiency of 95% and an excellent proper time resolution of 40 fs.

Figure 1. (a) The re-optimized LHCb detector. (b-c) Two unitarity triangles.

3. Trigger

The trigger has the challenging task to efficiently select interesting B-decays, given the low branching ratios, the high interaction rate, the low b-cross section compared to the total cross section and the high-multiplicity environment. The reduction of the interaction rate of 40 MHz to the rate of a few hundred Hz with which the events will be written to storage, is achieved in a three-level system³.

3.1. Level-0

The first trigger level (L0) uses the high mass of the B-mesons, resulting in decay products with large transverse momentum (p_T). High- p_T photons,

electrons, hadrons and muons are reconstructed in the electromagnetic, hadronic calorimeter and the muon system, respectively. The pileup system, consisting of two VELO disks upstream the interaction region, identifies multiple interactions and is used to suppress events with multiple vertices or with large hit multiplicity. Hence more low-multiplicity events are retained, while keeping the same accept rate, and therefore both the average event size and computing time are reduced, with even a slight increased selection efficiency. The pileup information, together with the highest- p_T photon, electron and hadron, and the two highest- p_T muons, are passed to the L0 decision unit, which forms the final decision. The fully synchronous L0-trigger, with a fixed latency of 4 μ s, is implemented in custom boards and reduces the rate to 1 MHz. Efficiencies of approximately 90%, 70% and 50% are achieved for events with muons, hadrons and photons respectively, as is shown in Table 1.

3.2. Level-1

The second trigger level (L1) reduces the rate further to 40 kHz, using information from the VELO and the TT station. The algorithm will be implemented on a commodity processors farm, that will be shared with the High Level Trigger (HLT) and the offline reconstruction. The available time at L1 is on average ~ 1 ms^a, with a maximum latency of 52.4 ms given by the L1 buffer size. Large impact parameter tracks are reconstructed and matched to clusters in the TT station. The fringe field between the VELO

Table 1. The estimated trigger performance is listed for a few selected channels, together with the branching ratio of the B-decay.

Channel	L0 eff.	L1 eff.	BR(10^{-6})
$B^0 \rightarrow J/\psi(\mu^+\mu^-)K_S$	$89.3 \pm 0.5\%$	$67.7 \pm 0.9\%$	19.8 ± 1.3
$B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi$	$89.7 \pm 0.1\%$	$71.4 \pm 0.2\%$	31 ± 11
$B_s^0 \rightarrow D_s^\pm K^\mp$	$47.2 \pm 0.3\%$	$62.6 \pm 0.4\%$	10 ± 4
$B^0 \rightarrow \pi^+\pi^-$	$53.6 \pm 0.4\%$	$62.7 \pm 0.5\%$	4.8 ± 0.5
$B_s^0 \rightarrow K^+K^-$	$51.8 \pm 0.3\%$	$60.0 \pm 0.4\%$	18.5 ± 1.2
$B^0 \rightarrow \bar{D}^0 K^{*0}$	$53.0 \pm 1.4\%$	$66.7 \pm 1.8\%$	1.2 ± 0.3
$B_s^0 \rightarrow D_s^- \pi^+$	$49.4 \pm 0.6\%$	$63.0 \pm 0.9\%$	120 ± 30
$B^0 \rightarrow K^{*0} \gamma$	$72.9 \pm 1.0\%$	$51.9 \pm 1.4\%$	29 ± 3

^aThis corresponds to a size of the L1 farm of about 1000 CPUs.

and the TT is sufficient to obtain momentum information with a precision of $\sim 30\%$. In addition, the tracks are matched to muon candidates from L0, enhancing the performance for channels containing muons. Using two high impact parameter tracks with the highest p_T , efficiencies between 50% and 70% are achieved, see Table 1.

3.3. High Level Trigger

The full detector information is available at the High Level Trigger (HLT). The tracking stations (T1-T3) provide more precise momentum information, with which the L1 decision can be confirmed within 4 ms, reducing the rate by a factor 2, while retaining signal efficiencies above 95%. The remaining time (~ 14 ms) is used to select the individual channels with an output rate of ~ 10 Hz per channel.

4. Physics Reach

The current e^+e^- B-factories have measured CP violation in the B-system with very high accuracy⁴, $\sin 2\beta = 0.731 \pm 0.055$, and in excellent agreement with the indirect measurements of $|V_{ub}|/|V_{cb}|$ and Δm_d from semi-leptonic B^0 -decays and B^0 - $\bar{B}^0$ oscillations¹, $\sin 2\beta = 0.695 \pm 0.055$. After one year of nominal operation of LHC the data sample collected by LHCb will be sufficient to determine β with a similar accuracy as is foreseen by the B-factories. The Standard Model analysis predicts a value of the CKM angle γ of $64.5^\circ \pm 7^\circ$. The direct measurement of γ is one of the main purposes of LHCb². The high $b\bar{b}$ cross section and luminosity will provide an unprece-

Table 2. The expected statistical precision for various CP parameters is listed, as measured with a few specific decay channels. The expected annual event yields are given for the indicated decays and their charge conjugates, together with the estimated B/S , or 90% CL upper limits.

Quantity	Channel	Yield	B/S	Precision
$\sin 2\beta$	$B^0 \rightarrow J/\psi(\mu^+\mu^-)K_S$	216k	0.8	0.022
χ	$B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi$	100k	< 0.3	0.058
$\gamma - 2\chi$	$B_s^0 \rightarrow D_s^\pm K^\mp$	5.4k	< 1.0	$14 - 15^\circ$
γ	$B_{d(s)}^0 \rightarrow \pi^+\pi^-(K^+K^-)$	26k(37k)	$< 0.7(0.31)$	$4 - 6^\circ$
γ	$B^0 \rightarrow \bar{D}^0 K^{*0}$	3.4k	< 0.5	$7 - 8^\circ$
Δm_s	$B_s^0 \rightarrow D_s^- \pi^+$	80k	0.32	0.06%
rare decay	$B^0 \rightarrow K^{*0}\gamma$	35k	< 0.7	

dedented large sample of B_s^0 -mesons, with which this can be achieved. In Table 2 three decay channels are listed that will enable the extraction of γ .

- The decay $B_s^0 \rightarrow D_s^\pm K^\mp$ measures the angle $\gamma - 2\chi$, where the B_s^0 -mixing phase χ arises from the B_s^0 - $\bar{B}_s^0$ mixing and is obtained from the $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi$ analysis. The angle γ comes from the phase of $|V_{ub}|$ in the tree level decay. Both the B_s^0 and the $\bar{B}_s^0$ meson can decay into $D_s^+ K^-$ and $D_s^- K^+$, causing large interference effects and good sensitivity to γ .
- A comparison of the decays $B^0 \rightarrow \pi^+\pi^-$ and $B_s^0 \rightarrow K^+K^-$ will provide a second theoretically clean measurement of γ . The method relies only on the assumption of SU(3) symmetry, reducing largely the uncertainties from penguin contributions. New particles participating in the loop might result in a different value of γ , compared to the $B_s^0 \rightarrow D_s^\pm K^\mp$ -result, hence indicating new physics.
- The decay $B^0 \rightarrow \bar{D}^0 K^{*0}$ is ‘self-tagging’ by the flavour of K^{*0} and therefore no time dependent measurements are required, resulting in small statistical uncertainty. Both γ and the strong phase difference Δ can be obtained by measuring the three time-integrated decays (to D^0 , $\bar{D}^0$ and the CP eigenstate D_{CP}^0), and their charge conjugates.

In addition, basic parameters like the mass difference Δm_s and lifetime difference $\Delta\Gamma_s$ of the two B_s^0 -mass eigenstates will be determined with high precision. Finally, any new particles present in the loop diagrams could significantly enhance the branching ratios of channels with very low branching ratios in the Standard Model, such as $B^0 \rightarrow K^{*0}\gamma$, or with the experimentally very clean decays containing muons, $B^0 \rightarrow \mu^+\mu^-K^{*0}$, $B_s^0 \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$, with estimated Standard Model branching ratios of $8 \cdot 10^{-7}$, $4 \cdot 10^{-9}$ and 10^{-10} , respectively.

References

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