The Compact Muon Solenoid Experiment

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Feasibility study of $B_s \rightarrow \phi\phi \rightarrow 4K$ with L1 Tracks at the CMS Phase-II Detector

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Abstract

$B_s \rightarrow \phi\phi \rightarrow 4$ Kaons is an important physics process to study during the LHC Phase-II which is expected to start in 2024. In this process, the CP violating weak phase arises due to the CP violation of the $B_s - \bar{B}_s$ mixing and the gluonic penguin decay of $b \rightarrow s\bar{s}s$. The penguin decay of the b-quark makes it a rare process also. The CMS experiment is planning to include tracker information at Level-1 Trigger to keep event rate manageable in the high luminosity regime of the LHC PhaseII. The aim of the present study is to understand whether CMS will be able to trigger on the $B_s \rightarrow \phi\phi \rightarrow 4$ Kaons events and be competitive with LHCb during LHC PhaseII. We shall discuss about signal efficiency and event rate both at the trigger as well as physics analysis levels and also look at several ways of optimization of efficiency and event rate.

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Study of $B_s^0 \rightarrow \phi\phi \rightarrow 4 \text{ Kaons}$ with the CMS Phase II Detector

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Abstract. $B_s^0 \rightarrow \phi\phi \rightarrow 4 \text{ Kaons}$ is an important physics process to study in the High Luminosity LHC (HL-LHC), also known as LHC Phase II, which is expected to start in 2024-25. The process involves a CP violating weak phase which arises due to CP violation in $B_s^0 - \bar{B}_s^0$ mixing and through the rare gluonic penguin decay, $b \rightarrow s\bar{s}s$. The CMS experiment will install a new tracking system for the LHC Phase II and include tracker information at Level-1 (L1) trigger which is crucial to keep the event rate manageable without sacrificing any physics potential. The aim of the present study is to understand whether the CMS detector will be able to trigger on the fully hadronic $B_s^0 \rightarrow \phi\phi \rightarrow 4 \text{ Kaons}$ events and complement the LHCb experiment. We shall discuss about signal efficiency and event rate both at the trigger as well as physics analysis levels and also look at several ways of optimization of the working point.

1 Introduction

In the Standard Model (SM) of particle physics, CP violation is described by a single phase in the CKM quark mixing matrix [1, 2]. The interference between $B_s^0 - \bar{B}_s^0$ oscillation and decay amplitude leads to an asymmetry in the decay time and amplitude distributions for B_s^0 and $\bar{B}_s^0$ mesons. This asymmetry can be related to CP violating phases ϕ_s , whose values depend on the decay amplitude and therefore can differ in decay processes.

The SM provides precise predictions for ϕ_s in various decay channels. Any significant deviation of a measurement from the SM prediction would indicate physics beyond the SM (BSM). Heavy flavor physics could see BSM effects that are beyond the direct reach of the LHC. This sensitivity to scales significantly above the direct LHC reach is a major motivation to pursue heavy flavor physics at the LHC and elsewhere.

The decay $B_s^0 \rightarrow \phi\phi$ (with $\phi \rightarrow K^+K^-$) proceeds predominantly via a $b \rightarrow s\bar{s}s$ penguin amplitude (cf. Fig. 1). The first evidence for this decay was obtained by the CDF experiment [3] at the Tevatron. Both CDF and LHCb [4–7] searched for CP violation through decay time and angular distributions. The LHCb experiment has measured the branching fraction $\mathcal{B}(B_s^0 \rightarrow \phi\phi) = (1.84 \pm 0.05_{\text{stat}} \pm 0.07_{\text{syst}} \pm 0.11 \pm 0.12_{\text{norm}}) \times 10^{-5}$ [8]. To date, the most precise

determination of the phase $\phi_s = -0.17 \pm 0.15_{\text{stat}} \pm 0.03_{\text{syst}}$ was performed by the LHCb experiment [7], based on a signal yield of approximately 4000 B_s^0 candidates, with a tagging power of $\varepsilon \mathcal{D}^2 \approx 3\%$. In the SM, ϕ_s in the decay $B_s^0 \rightarrow \phi\phi$ is expected to be very small: QCD factorization calculations provide an upper limit of $\phi_s < 0.02$ [9–11].

Fig. 1. Feynman diagram of the dominant process contributing to the decay $B_s^0 \rightarrow \phi\phi$.

The present analysis is a study of the CMS sensitivity for the overall decay mode $B_s^0 \rightarrow \phi\phi \rightarrow 4$ Kaons during the LHC Phase II [15]. Due to high luminosity CMS Level1 trigger rate will be unmanageable with the calorimeter and muon chamber information only. To reduce the event rate while retaining full physics potential, it will be crucial to include tracker information in Level1. The goal of the analysis is to investigate how well the decay $B_s^0 \rightarrow \phi\phi$ can be triggered with the L1 track trigger, whether the trigger rate is manageable, and what overall signal event yield can be achieved. This is the first purely hadronic B decay investigated in the CMS experiment.

2 Phase II Tracker

The LHC accelerator will be upgraded to provide peak instantaneous luminosity of $\sim 5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ during 2024-2025, which will allow individual experiments to collect integrated luminosity of the order of 300 fb^{-1} annually. This so-called HL-LHC upgrade will greatly increase the physics potential of the LHC, in particular for rare SM and BSM physics. The present tracking system of CMS will be replaced with new detectors to cope with the HL-LHC condition where 140-200 collisions per bunch crossing (also known as pileup) will take place. The new tracking system will feature increased radiation hardness, higher granularity, compatibility with higher data rates, a longer trigger latency, and increased acceptance in the forward direction to take advantage of the physics potential of HL-LHC [12]. The outer part of the tracking system will be equipped with pT modules capable of identifying high p_T tracks ($> 2 \text{ GeV}$) which will enable CMS to use tracking information at the Level1 trigger system at 40 MHz and significantly improve the performance of the L1 trigger decision to cope with the huge interaction rate.

3 Dataset

The signal events are generated with Pythia6 [14] and EvtGen at $\sqrt{s} = 14$ TeV with Kaons having $p_T > 1.95$ GeV. At the analysis level the Kaons are further required to have $p_T > 2$ GeV. On each signal event 140 pileup events are superimposed. MinimumBias events with $\langle \text{PU} \rangle = 70, 140, 200$ composition are used to study event rate.

4 Analysis Strategy

ϕ candidates in an event are first reconstructed from all pairs of oppositely charged Kaon tracks coming from the same vertex. In the second pass, B_s^0 candidates are formed from a pair of reconstructed ϕ candidates compatible with the same vertex. The lowest- p_T Kaon p_T lies very close to the threshold of the Level1 tracking which is the major cause for the loss of signal efficiency. Signal efficiency is studied both at the L1 and offline. The offline study involving tracks reconstructed with much higher precision is performed to check if one should expect any further significant reduction in efficiency after L1. Event rate is studied only at L1. Offline background can be reduced further using higher precision at analysis level, due to better treatment of pileup reduction and availability of secondary vertex tagging tools.

5 Baseline Selections

Three different baselines for event selection, namely loose, medium and tight have been used to find the optimum working point acceptable by CMS at L1. The selection conditions corresponding to the three baselines are shown in Table 1.

Table 1. Baseline event selection conditions. The variables d_z represent the distance between a pair of tracks or trajectories of a pair of reconstructed particles along the beam axis (z) while d_{xy} represents that in the plane perpendicular to the beam axis (xy).

Working point	loose	medium	tight
Tracks	$p_T \geq 2 \text{ GeV}$		
Track pair	$d_{xy} \leq 1 \text{ cm}, d_z \leq 1 \text{ cm}$		$d_{xy} \leq 0.5 \text{ cm}, d_z \leq 0.3 \text{ cm}$
ϕ -pair	$d_{xy} \leq 1 \text{ cm}, d_z \leq 1 \text{ cm}$		$d_{xy} \leq 0.5 \text{ cm}, d_z \leq 1 \text{ cm}$
ϕ -pair	$0.2 \leq \Delta R(\phi_1, \phi_2) \leq 1, \Delta R(K^+, K^-) \leq 0.12$		
ϕ mass	$0.99 \leq M_{K^+K^-} \leq 1.04 \text{ GeV}$		$1.0 \leq M_{K^+K^-} \leq 1.03 \text{ GeV}$
B_s^0 mass	$5.27 \leq M_{\phi\phi} \leq 5.49 \text{ GeV}$		$5.29 \leq M_{\phi\phi} \leq 5.48 \text{ GeV}$

Figure 2 shows the reconstructed B_s^0 mass with the loose baseline selection. More than one B_s^0 candidates within the selected mass window can contribute to the same event.

Fig. 2. Invariant mass distribution of all the ϕ -pairs with $|d_z|$ (ϕ -pair) < 1 cm, d_{xy} (ϕ -pair) < 1 cm, $0.2 < \Delta R(\phi\text{-pair}) < 1$, $\Delta R(K^+, K^-) < 0.12$ [15]. Plots are normalized to unit area. The blue and red lines correspond to the offline and L1 signals respectively, while the green filled area represents the L1 background.

6 Results

Table 2 summarizes the efficiency and rate for all the selection baselines. We have also studied the rate for three different pileup scenarios $\langle PU \rangle = 70, 140, 200$ shown in the same table.

Table 2. Efficiency and rate for loose, medium and tight baselines respectively. Pileup dependence of event rate is presented for $\langle PU \rangle = 70, 140$ and 200. Uncertainty is statistical only.

Baseline	Efficiency (%)		Rate (kHz)		
	L1	Offline	$\langle PU \rangle = 70$	$\langle PU \rangle = 140$	$\langle PU \rangle = 200$
Loose	41.6 ± 1.2	64.6 ± 1.4	6.3 ± 1.5	27.9 ± 1.7	61.8 ± 5.2
Medium	36.6 ± 1.1	57.7 ± 1.3	2.5 ± 0.9	13.3 ± 1.2	29.6 ± 3.6
Tight	31.1 ± 1.0	57.6 ± 1.3	1.4 ± 0.7	5.1 ± 0.7	12.2 ± 2.3

All the results presented in Table 2 have been presented in Fig 3.

7 Summary and Plan

$B_s^0 \rightarrow \phi\phi \rightarrow 4$ Kaons is an important benchmark channel to study the capabilities of the CMS detector in low- p_T fully-hadronic final states. Signal efficiency and L1 trigger rate have been found for several selection baselines. It has also been found that the offline efficiency for the events triggered at L1 is high. Possible areas of improvement include displaced vertex tagging for low p_T tracks and mitigation of pileup effects at L1. The analysis is limited by the absence

Fig. 3. Efficiency and rate for different baseline selection and for different pileup scenarios [15]. Uncertainty is statistical only.

of an equivalent analysis with Run-1 or Run-2 data, which has not been pursued because there is no possibility to trigger on hadronic B decays. This makes extrapolation to the upgrade scenarios difficult.

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