The Compact Muon Solenoid Experiment

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Prospects of CMS in B physics in Phase 2

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Abstract

The Standard Model of Particle Physics precisely predicts the cross-sections for the processes $B_s \rightarrow \mu\mu$ and $B_d \rightarrow \mu\mu$ which are suppressed in the SM. Beyond SM (BSM) contribution can enhance the decay rates. Precise measurement of branching fractions and of the $B_s \rightarrow \mu\mu$ decay effective lifetime is of prime concern for experiments like CMS in the quest for new physics. The SM also precisely predicts the CP violating phase ϕ_s in the $B_s \rightarrow \phi\phi \rightarrow 4$ Kaons decay, a significant deviation from the SM prediction would provide a clear signature for BSM. During the High Luminosity (HL) period of the LHC, also known as LHC Phase-2, which will start from 2026, CMS will try to look for these processes. The $B_{d/s} \rightarrow \mu\mu$ is an extremely rare FCNC process with a fully leptonic final state whereas $B_s \rightarrow \phi\phi \rightarrow 4$ Kaons too is a rare process with a fully hadronic final state. The inclusion of the tracking information in the Level1 Trigger during Phase-2 will help a general purpose detector like CMS to look for such fully hadronic final states for the first time. In this talk, we shall discuss about the CMS Phase-2 Tracker, Level1 tracking and present results obtained from Phase-2 simulation for $B_{d/s} \rightarrow \mu\mu$ and $B_s \rightarrow \phi\phi \rightarrow 4$ Kaons.

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Prospects of CMS in B Physics in Phase 2

Rajarshi Bhattacharya, on behalf of the CMS Collaboration

Abstract The Standard Model of Particle Physics precisely predicts the cross-sections for the extremely rare Flavour Changing Neutral Current (FCNC) processes $B_{d/s} \rightarrow \mu\mu$. Although, the processes are suppressed in the SM, beyond Standard Model (BSM) contributions can significantly enhance the decay rates. Therefore, a precise measurement of branching fractions and the $B_s \rightarrow \mu\mu$ lifetime is of prime concern for experiments like CMS in the quest for new physics. The SM also precisely predicts the CP violating phase ϕ_s in the $B_s \rightarrow \phi\phi \rightarrow 4$ Kaons decay process. Any significant deviation from the SM prediction for this rare FCNC process would provide a clear signature for BSM. During the High Luminosity (HL) period of the LHC, also known as LHC Phase-2, CMS will continue to look for $B_{d/s} \rightarrow \mu\mu$ and will also study $B_s \rightarrow \phi\phi \rightarrow 4$ Kaons, which will be possible for the first time in CMS due to inclusion of the tracking information in the Level1 trigger. In this article, we shall discuss the CMS Phase-2 Tracker, Level 1 Tracking and present results obtained from Phase-2 simulations for $B_{d/s} \rightarrow \mu\mu$ and $B_s \rightarrow \phi\phi \rightarrow 4$ Kaons.

1 High Luminosity LHC

The LHC will undergo a major luminosity upgrade during the third Long Shutdown (LS3) period resulting in a ten-fold increase in instantaneous luminosity ($5-7 \times 10^{-34} \text{ fb}^{-1} \text{ s}^{-1}$) compared to the current value [1]. Over a ten year period beginning in 2026, the LHC is expected to deliver a total integrated luminosity of $\geq 3 \text{ ab}^{-1}$ at $\sqrt{s} = 14 \text{ TeV}$ to CMS [2]. This increase is equivalent to ten times the data collected during LHC Runs 1-3 [1].

During the HL-LHC period, the increase in luminosity, will cause the number of interactions per bunch crossing (known as pileup or PU) to increase and the average pileup or $\langle \text{PU} \rangle$ is foreseen to have a value between 140 and 200 which is 5 times the current value ($\approx 40-50$). Without an detector upgrade the increased pileup will severely the impact B physics during Phase-2.

To retain the full physics potential during HL-LHC, the CMS detector will undergo a major upgrade, known as Phase-2 upgrade [3]. The present tracking detec-

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tor will be replaced with a new improved detector. Tracking information will also be made available at Level1 (L1) trigger for the first time in CMS [4], which plays crucial role in the physics results we are going to discuss.

2 CMS Phase-2 Tracker and L1 Tracking

The layout of the CMS Phase-2 tracker [4] is shown in figure 1(a). The Phase-2 tracker will be extended from $|\eta| \approx 2.4$ to $|\eta| \approx 4$. The tracker will consist of 4 pixel layers as the innermost barrel layers and 12 endcap discs on each side of the barrel region. Surrounding the pixel layers, the outer tracker will have 6 barrel layers and 5 endcap discs on either sides. The unit of the outer tracker is known as “ p_T modules”, where each module will consist of two closely placed silicon sensors which are separated by very small distance (between 1 - 4 mm). A p_T module can correlate hits in its two layers to create a “Stub”. By construction a p_T module can accept “Stubs” with $p_T \geq 2$ GeV. L1 tracks are formed by connecting stubs in different layers. The new tracker will feature less material, better radiation hardness and improved p_T and vertex resolution.

Fig. 1 (a) The CMS Phase-2 Tracker layout [4]. (b) Concept of the “ p_T module” [4].

3 $B_{d/s} \rightarrow \mu\mu$

$B_{d/s} \rightarrow \mu\mu$ is a FCNC process which proceeds through Electro-Weak Penguin or box diagrams and hence is suppressed in the Standard Model. It is further suppressed due to helicity suppression. The SM predicts the branching ratios for these two processes to be [5]

- $Br(B_s \rightarrow \mu\mu) \approx (3.57 \pm 0.16) \times 10^{-9}$
- $Br(B_d \rightarrow \mu\mu) \approx (1.02 \pm 0.06) \times 10^{-10}$

Several extensions of the SM, such as supersymmetric models [6, 7, 8] and models with a non-standard Higgs sector [9], SUSY may enhance or suppress the branching fractions. Any deviation of the measured branching fractions from the SM values would imply presence of new physics. Therefore, precise measurement of the two branching fractions are an important goal of various experiments in search for new physics. So far the measured values of the branching fractions by various experiments have large uncertainty and are in agreement with the Standard Model prediction.

The expected improvements in the mass measurement of B_d and B_s from the CMS Phase-2 upgrade is discussed in this section. B candidates are formed from two oppositely charge muon candidates having $p_T > 4$ GeV if $|\eta| < 1.4$ or $p_T > 2$ GeV if $|\eta| > 1.4$. A simple Gaussian fit is performed on the di-muon invariant mass to find the peak position and resolution of the distribution. In figure 2(a) an overlay of the mass distributions for B_s and B_d in Phase-2 is shown, where the pseudorapidity of the most forward muon candidate is restricted to $|\eta_f| < 1.4$. Improvement in the mass resolution, due to improvement in the p_T resolution of the tracks for Phase-2 leads to better separation of the B_d and B_s mass peaks compared to current CMS data. In figure 2(b), the B_s mass resolution as a function of $|\eta_f|$ has been plot-

Fig. 2 (a) Overlay of the mass distributions for B_s (blue dashed area) and B_d (red dashed area) in Phase-2 for pseudorapidity of the most forward muon candidate $|\eta_f| < 1.4$ [4]. The distribution for $B_s \rightarrow \mu\mu$ is normalized to unit area, whereas the distribution for $B_d \rightarrow \mu\mu$ is normalized to SM predicted value. (b) B_s mass resolution with respect to pseudorapidity of the most forward muon candidate $|\eta_f|$ [4]. The blue circles are for Run-2 (current LHC running) and red squares are for Phase-2.

ted both for Run 2 (current LHC running) and Phase-2. The mass resolution has a

$\approx 40\%$ gain for $|\eta_f| < 1$ in Phase-2 compared to Run-2.

The mass peak separation with respect to $|\eta_f|$ is shown in figure 3(a). For Phase-2, 25% improvement in mass peak separation can be achieved in the region $|\eta_f| < 1.4$, which reduces the overlap between B_s and B_d signals and also helps to reject some rare semi-leptonic decays.

The leakage variable, defined as the ratio of number of B_d events over the number of B_s events in the B_d invariant mass range, is a measure of overlap between the B_s and B_d events and is plotted with respect to $|\eta_f|$ for both Run-2 and Phase-2 in figure 3(b). From the plot, it can be seen that Phase-2 performs better in the region $|\eta_f| < 0.8$. High leakage in the high $|\eta_f|$ region does not allow a clear separation between the $B_d \rightarrow \mu\mu$ and $B_s \rightarrow \mu\mu$ events.

Fig. 3 (a) Mass peak separation between the B_s and B_d mass distribution with respect to pseudorapidity of the most forward muon candidate $|\eta_f|$ [4]. The blue circles represent the mass peak separation for Run-2 (current LHC running) where the red squares represent same for Phase-2. (b) Leakage of the B_s events in the B_d invariant mass region with respect to $|\eta_f|$ [4]. The blue circles represent Run-2 (current LHC running) where the red squares represent Phase-2.

At the end of Phase-2 running, we expect to observe $B_d \rightarrow \mu\mu$ events with 5.6 - 8.0 σ confidence level and we expect to measure the branching fractions of $B_d \rightarrow \mu\mu$ and $B_s \rightarrow \mu\mu$ and their ratios more precisely [10].

4 $B_s \rightarrow \phi\phi \rightarrow 4$ Kaons

$B_s \rightarrow \phi\phi \rightarrow 4$ Kaons is a FCNC process which is forbidden at tree level and proceeds through $b \rightarrow s\bar{s}s$ penguin loop. This process may provide a new insight to the CP violating phase in the B_s system and may receive contributions from heavy particles

which are beyond direct reach of the LHC.

This is also a rare process with a fully hadronic final state. The PDG value of the branching fraction $Br(B_s \rightarrow \phi\phi)$ is $\approx (1.84 \pm 0.18) \times 10^{-5}$ [11]. Triggering on such low p_T , fully hadronic final states is impossible in CMS without tracking at L1. The final state kaons have very low p_T , close to the threshold of the L1 tracking. So, it is usually difficult to reconstruct all the tracks corresponding to the 4 final state kaons and this is the main source of inefficiency in this analysis. This analysis tries to estimate CMS sensitivity about triggering the $B_s \rightarrow \phi\phi \rightarrow 4$ Kaons events with L1 tracking.

First, ϕ candidates are reconstructed from two oppositely charged tracks coming from the same primary vertex, with the kaon mass assigned to each track. Then the B_s candidates are reconstructed from pairs of ϕ candidates in an event coming from the same primary vertex. Events having at least one B_s candidate, compatible with the true B_s mass, are selected.

To study signal efficiency, $B_s \rightarrow \phi\phi \rightarrow 4$ Kaon events were generated and simulated through the Phase-2 CMS detector with an average pileup of 140 or 200. An offline study is performed to check whether there is any further loss of efficiency at offline level. To study the event rate at L1 trigger, Minimum bias events with $\langle PU \rangle = 70, 140$ and 200 are used.

Three different selection baselines have been studied to optimize the signal efficiency and event rate. For the extreme Pileup scenario, $\langle PU \rangle = 200$, a signal efficiency of 30% can be achieved at a rate ~ 15 kHz at L1. Figure 4(a) shows the invariant mass distribution of B_s candidates while figure 4(b) shows the rate and efficiencies for three Pileup scenarios.

5 Conclusion

With a total 3 ab^{-1} data of Phase-2, CMS expects significant improvement in the mass resolution for $B_{d/s} \rightarrow \mu\mu$ which in turn implies better separation of $B_s \rightarrow \mu\mu$ and $B_d \rightarrow \mu\mu$ mass peaks. We expect to observe $B_d \rightarrow \mu\mu$ events with 5σ and more precise measurement of $Br(B_{d/s} \rightarrow \mu\mu)$ and their ratio. Measurement in the very forward region will be difficult due to high leakage between B_s and B_d events in this region.

Study of the $B_s \rightarrow \phi\phi \rightarrow 4$ Kaons with L1 tracking showcases the power of L1 tracking in CMS. The signal is still distinctly visible even in the extreme pileup scenario, i.e., $\langle PU \rangle = 200$. Further work continues to optimize the signal event rate and efficiency.

Fig. 4 (a) Invariant mass of ϕ pair candidates [4]. The solid red line represents L1 signal, whereas the blue dashed line represents the offline signal. The green filled area represents L1 background. All the plots are normalized to unit area. (b) Efficiency and rate for different baseline selections and different Pileup scenarios [12]. Uncertainties are statistical only.

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