

## B-Physics at CMS with LHC Run-II and Beyond

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The LHC is entering into operation with an increased centre-of-mass energy of 13 TeV, and within the next 3 years of operations (Run-II) the foreseen integrated luminosity delivered to CMS will be about  $100 \text{ fb}^{-1}$ . The B hadron production cross section is expected to nearly double at this energy, thus potentially increasing by almost one order of magnitude the collected statistics relative to the previous operation period. This will enable CMS to perform enhanced measurements in the B-physics sector. A further increase in integrated luminosity is expected to occur in two more steps after the second LHC long shutdown (LS) in 2018 and the third LS in 2021, thus enabling to significantly improve the precision of several B-physics measurements, including  $B_s(B_d) \rightarrow \mu^+\mu^-$ , and search for rarer decays. This proceeding reports on the prospects for B-physics measurements with high statistics data at CMS.

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## 1. Introduction

Right before summer 2015, LHC started its new operation period with centre-of-mass energy of 13 TeV. This is a new era of the physics searches at the energy frontier. The discovery potential of new heavy particles has been improved dramatically, but such gain on the physics sensitivities also applies to the field of B-physics. The B hadron production cross section is expected to nearly doubled at this energy, combined with the foreseeable integrated luminosity delivered by the collider, the high statistics of the B hadron samples collected by the CMS detector will have a strong impact to the measurements in the B-physics sector.

It is a unique test bench for flavour physics predictions. Some B-physics measurements which require huge statistics, such as the CP-phase in the  $B_s \rightarrow J/\psi\phi$  decays, the forward-backward asymmetries for  $B \rightarrow K^*\mu^+\mu^-$ , will be improved dramatically. In particular, the large data sample will allow us to probe some ultra-rare processes at a sensitivity which has never been reached before. It includes the decay of  $B_{s,d} \rightarrow \mu^+\mu^-$  and the lepton-flavor violating decays such as  $B \rightarrow \mu\tau$  and  $\tau \rightarrow \mu\mu\mu$ . In this proceeding the measurement of  $B_{s,d} \rightarrow \mu^+\mu^-$  decays is introduced as a benchmark analysis. The results included in this document are obtained from Ref. [1].

The LHC is expecting to operate under the condition of 25 ns bunch spacing up to 2023 with an instantaneous luminosities up to  $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ . The expected integrated luminosity is  $300 \text{ fb}^{-1}$ . After this operation period there will be an upgrade of the LHC accelerator, which will allow to level the instantaneous luminosity at  $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ , with a potential peak value of  $2 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ . Such a much higher instantaneous luminosity at the high-luminosity upgrade of Large Hadron Collider (HL-LHC) will lead to an average of 140 proton-proton interactions per crossing. The upgrade is foreseen to be deployed in 2024, and will require improvements on the detectors, as well as backend electronics in order to operate under the new conditions. The HL-LHC machine is expected to deliver around  $250 \text{ fb}^{-1}$  integrated luminosity per year, and up to  $3000 \text{ fb}^{-1}$  of data after 10 years of operation.

The CMS experiment is designing an upgrade of the detector (denoted as the Phase-II upgrade). The new design is based on top of the already scheduled Phase-I CMS upgrade, which is expected to be deployed in 2019. Many of the sub-detectors will either be completely replaced or significantly enhanced. The upgrade requirement is to overcome the challenging environment at HL-LHC. The detector requires the capability of operating at a very high pile-up of 140 interactions, and has to survive up to year 2035. A similar performance as the current detector as in Run-I should be preserved. The lowest possible trigger and analysis thresholds should be kept as well. There are two upgrades which are essential for B-physics analysis: the new tracker system and the enhanced L1 (hardware) trigger. The new CMS Phase-II tracker features four pixel barrel layers and five disks on the endcaps. The material budget in the central region has been reduced by a factor of two. Combining with a smaller silicon sensors pitch, the momentum resolution will be improved, and help to separate the  $B_d \rightarrow \mu\mu$  from  $B_s \rightarrow \mu\mu$  signals. The L1 trigger system will adopt the new hardware track-trigger and will help to maintain low thresholds at HL-LHC luminosities. Extended trigger capabilities for the muon system will improve the coverage in the forward direction. A more detailed description of the CMS upgrade can be found in Ref. [2].

## 2. Reference Analysis

The study presented in this document was based on the CMS analysis published in Ref. [3]. Several updates on background decay model and physics parameters presented in the CMS and LHCb combination [4] are incorporated. The target  $B_{s,d} \rightarrow \mu^+ \mu^-$  decays only proceed through flavour-changing neutral current (FCNC) processes and are highly suppressed in Standard Model (SM). The predicted branching fractions [1] are  $(3.65 \pm 0.23) \times 10^{-9}$  and  $(1.06 \pm 0.09) \times 10^{-10}$  for  $B_s \rightarrow \mu^+ \mu^-$  and  $B_d \rightarrow \mu^+ \mu^-$  decays, respectively. However, these decays are an excellent place to look for the physics beyond the SM, given the new heavy particles may enter the loop diagrams and then enlarge the decay rates by a couple orders of magnitude. Theoretical calculations for these channels are particularly robust and any deviations from the predicted branching fractions are the smoking gun signal of new physics.

The CMS analysis of these decay channels has the following features incorporated. The events were triggered with dimuon events at L1, and at the high-level software trigger (HLT) mass and displaced vertex requirements were introduced. The muon identification was carried out with a multi-variant analysis (a boosted decision tree, BDT) based tool, which combining several important information from the detectors. The normalization was determined from the reference channel,  $B^+ \rightarrow J/\psi K^+$ . The  $B \rightarrow \mu^+ \mu^-$  candidates were also classified with BDT, which includes the kinematical information, vertexing quality, and the information about the nearby activities of the candidates. The BDTs were trained for different detector regions and for different data taking conditions. The branching fractions of  $B_s \rightarrow \mu^+ \mu^-$  and  $B_d \rightarrow \mu^+ \mu^-$  decays were obtained from a unbinned maximum likelihood fit to the invariant mass distributions of dimuons simultaneously to the events in BDT categories.

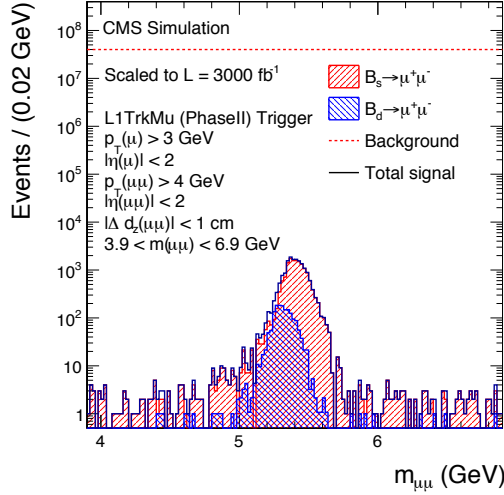
## 3. Extrapolation for Run-II and Beyond

Pseudo experiments are used to estimate the expected CMS performance in two different scenarios. The ‘‘Phase-1 scenario’’ is corresponding to the expected performance of the CMS experiment, including the data up to LHC Run-II and Run-III, and to an integrated luminosity of  $300 \text{ fb}^{-1}$  at 14 TeV. The ‘‘Phase-2 upgrade scenario’’ is defined for the CMS performance after the full Phase-2 upgrades and to a total luminosity of  $3000 \text{ fb}^{-1}$  at 14 TeV. In order to provide a valid estimation, the standard GEANT4-based simulated samples were used to estimate the performance of the trigger, detector resolutions, and the effects of pile-up at the phase-2 running condition. The core performance for muons, including the reconstruction efficiency and the power of muon identification are assumed to be at the same level as the previous Run-I analysis. All of the estimations were based on the branching fractions predictions based on the SM.

### 3.1 Inputs for the Pseudo Experiments

The low- $p_T$  dimuon L1 trigger algorithm is studied with full simulation based on the Phase-2 scenario. The capabilities of trigger with the upgraded CMS tracker has been exploited. Based on the estimation with simulated samples, the resolution for  $B \rightarrow \mu^+ \mu^-$  invariant mass at the L1 trigger is estimated to be around 70 MeV. The rate of the L1 trigger, which is totally driven by the background processes, is estimated from the minimum-bias simulated sample. The obtained

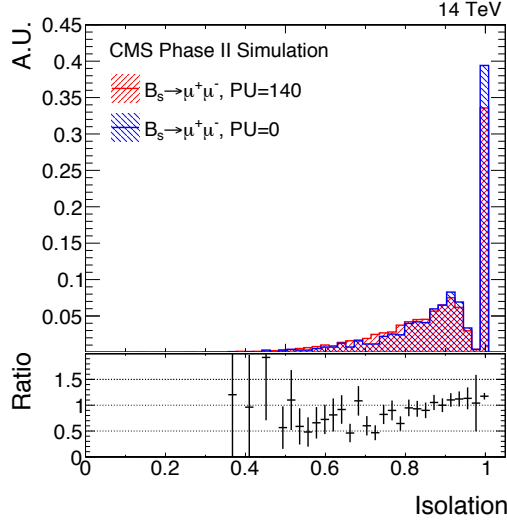
rate is up to a few hundred Hz, which is corresponding to a small fraction of the total available bandwidth of the L1 triggers (around 1 MHz). Based on such an estimation, a low- $p_T$  track-trigger-based algorithm with a performance very similar to the trigger condition in Run-I is expected to be entirely feasible for the Phase-2 scenario. Figure 1 shows the simulated dimuon invariant mass at the L1 trigger. The shaded histograms show the simulated  $B \rightarrow \mu^+\mu^-$  events, while the dashed line indicate the expected background level, which determines the rate of trigger.



**Figure 1:** The simulated dimuon invariant mass at the L1 trigger level. The shaded histograms are the simulated  $B_s \rightarrow \mu^+\mu^-$  and  $B_d \rightarrow \mu^+\mu^-$  events, while the dashed line indicate the expected background level.

Given the trigger at Phase-2 is totally within the capability, the performance at off-line reconstruction is more relevant for this study. The offline dimuon invariant mass resolution is estimated from  $B \rightarrow \mu\mu$  simulated samples. In these samples the detector simulations of the Phase-I and Phase-II scenarios were implemented. The simulated samples are also used to study the effects of high pile-up running condition. Figure 2 shows the isolation variable used in the  $B \rightarrow \mu\mu$  analysis with a comparison of zero and 140 pile-up environments. At the condition of high pile-up it is unavoidable to produce some visible difference in the isolation variable, especially for the last bin at the right edge. This observed difference, together with other possible effects, are included in the sensitivity estimations. The following parameters are considered in the generation of pseudo experiments. The offline dimuon invariant mass resolutions are set to 42 MeV and 28 MeV for the Phase-1 and Phase-2 scenarios, respectively. The trigger and the performance of muon identification are assume to be the same as the Run-I analysis. At the Phase-1 scenario, the effect of PU should be similar to Run-I, while a reduction on the efficiency (30% on the signal, 35% on the background) is expected for Phase-2 scenario. The uncertainty on the  $B^+$  normalization channel is estimated to be 5% for Phase-1, and 3% for Phase-2. Some minimal improvement is also assumed for the uncertainties on the peaking background (which was originated from  $B \rightarrow K\pi$ ,  $KK$ , and  $\pi\pi$  decays mostly) and on the semileptonic B decays. The uncertainties for these two background sources are set to 20% and 25%, respectively, for the Phase-1 scenario, while the reduced uncertainties 10% and 20%, are assumed for the Phase-2 condition. Another key input, the understanding

of hadronization fraction ratio,  $f_s/f_u$ , is assumed to be the same at a 5% level though out the whole running period, although it is likely to be improved in the near future.

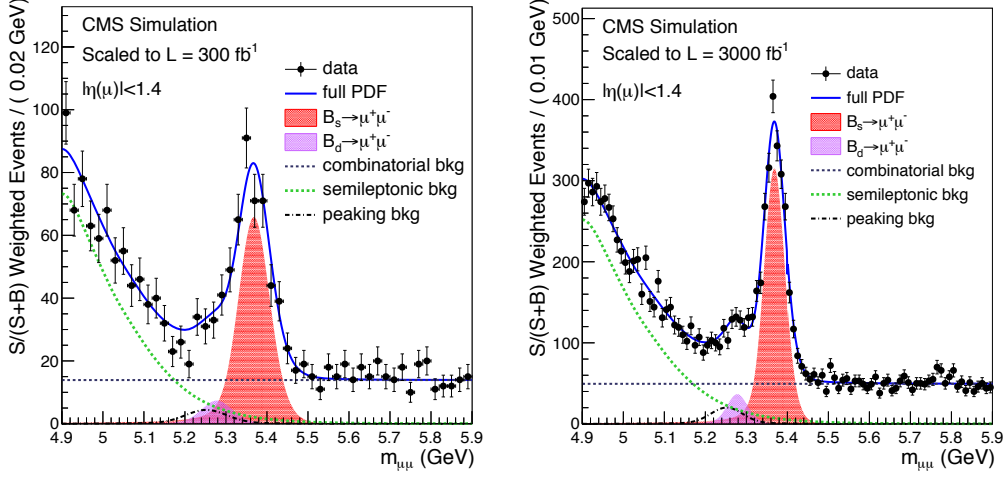


**Figure 2:** A comparison of the isolation variable in the condition of zero pile-up events, and with the high pile-up (in average 140 interactions) environment.

#### 4. Results and Summary

Based on the models used in the previous summer publication, together with the performance numbers described above, many pseudo experiments have been generated and the expected sensitivities are determined by the maximum likelihood fits to the pseudo experiments data. In order to keep the robustness of the estimation, instead of the default fitting construction in the summer 2013 paper which was implemented for 12 BDT categories, the fits in this sensitivity estimation are carried out with a simplified method with only four BDT categories and with a tighter threshold on the output BDT values. This alternative fitting method was treated as a cross check in the former analysis. The expected dimuon invariant mass distributions for the Phase-1 and Phase-2 scenarios are shown in Fig. 3. The data points are obtained from the pseudo experiments. A comparison between the mass distributions for these two scenarios shows a dramatic improvement of the mass resolution of the newly designed Phase-2 tracker. The estimated performance numbers are summarized in Tab 1. According to the estimation, even if the  $B_d \rightarrow \mu^+ \mu^-$  branching fraction is as low as the SM prediction, it can be measured eventually with the high statistics data from the HL-LHC.

In summary, the large data from LHC run-II and future operations will provide an excellent probe for the flavor physics. As a benchmark study, we estimate the CMS potential to trigger and reconstruct the  $B_s \rightarrow \mu^+ \mu^-$  and  $B_d \rightarrow \mu^+ \mu^-$  processes at future LHC and HL-LHC runs. With the upgraded CMS detector, it will be possible to trigger and reconstruct the signal events even with the high pile-up running conditions at HL-LHC. The upcoming large data set will leads to high precision measurements and provide stringent tests of the SM.



**Figure 3:** The dimuon invariant mass distributions from the pseudo experiments for the Phase-1 scenario (left) and the Phase-2 scenario (right). The cross points are showing the pseudo data generated by the random number generators with the expected resolution and detector performance. The shaded distributions show the contributions for  $B_s \rightarrow \mu^+ \mu^-$  and  $B_d \rightarrow \mu^+ \mu^-$ .

**Table 1:** The expected uncertainties on the  $B_s \rightarrow \mu^+ \mu^-$  branching fraction ( $\delta\mathcal{B}(B_s)$ ) and on the  $B_d \rightarrow \mu^+ \mu^-$  branching fraction ( $\delta\mathcal{B}(B_d)$ ), the significance of  $B_d \rightarrow \mu^+ \mu^-$  decays ( $\Sigma(B_d)$ ), and the uncertainties on the ratio of  $B_d$  and  $B_s$  branching fractions ( $\delta[\mathcal{B}(B_d)/\mathcal{B}(B_s)]$ ) at the given integrated luminosity ( $\mathcal{L}$ ). The Phase-1 and the Phase-2 scenarios are assumed in the estimations. The ranges in  $\Sigma(B_d)$  indicates the resulting  $\Sigma(B_d)$  distributions from the pseudo experiments.

$\mathcal{L}$ [ $\text{fb}^{-1}$ ]	$\delta\mathcal{B}(B_s)$	$\delta\mathcal{B}(B_d)$	$\Sigma(B_d)$	$\delta[\mathcal{B}(B_d)/\mathcal{B}(B_s)]$
100	14%	63%	0.6–2.5 $\sigma$	66%
300	12%	41%	1.5–3.5 $\sigma$	43%
300 (barrel only)	13%	48%	1.2–3.3 $\sigma$	50%
3000 (barrel only)	11%	18%	5.6–8.0 $\sigma$	21%

**References**

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 [2] S. Chatrchyan *et al.* [CMS Collaboration], CERN-LHCC-2015-010. LHCC-P-008 (2015).  
 [3] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. Lett. **111** (2013) 101804 [arXiv:1307.5025 [hep-ex]].  
 [4] V. Khachatryan *et al.* [CMS and LHCb Collaborations], Nature **522** (2015) 68 [arXiv:1411.4413 [hep-ex]].