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Search for $B_s \to \mu\mu\gamma$ at Large Hadron Collider

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Abstract. The branching ratio for $B_s \to \ell^+\ell^-\gamma$ mode is of the same order as $B_s \to \ell^+\ell^-$, since there is no helicity suppression in the 3-body decay mode. New Physics beyond Standard Model may affect these rates favourably for experimental observation at LHC and simultaneous measurements of the modes $B_s \to \mu^+\mu^-$ and $B_s \to \mu^+\mu^-\gamma$ at LHC experiment will indicate the basic nature of the interaction at play. A simulation study has been performed to evaluate the potential of CMS detector to observe the more difficult mode of $B_s \to \mu^+\mu^-\gamma$. An upper limit of 2.08×10^{-7} on the branching ratio is expected to be achieved corresponding to an integrated luminosity of 10 fb^{-1}.

Keywords. B_s mesons; CMS detector; Large Hadron Collider.

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1. Introduction

The decay $b \to s(d)\ell^+\ell^-$ is a flavour-changing-neutral-current (FCNC) process, where the flavour of the original quark is changed but not the electric charge. There are other FCNC processes like $b \to s\gamma$ and B^0–$\bar{B}^0$ mixing, and similar situations in K- and D-meson systems, whose studies have led to important discoveries in the decades of 1960s and 1970s. $K_L \to \mu^+\mu^-$ decay was supposed to be of same order as $K^+ \to \mu^+\nu_\mu$ but it was not observed. This riddle was explained subsequently by GIM (Glashow–Illiapoulous–Maiani) mechanism, which predicted no tree-level FCNC, for quarks belonging to weak isospin doublets. This idea was further strengthened by the observation of $b \to c\ell\nu$ and $b \to u\ell\nu$ and simultaneous negative search for $b \to s\ell^+\ell^-$ and $b \to d\ell^+\ell^-$.

The study of FCNC also leads to the knowledge of potential existence and the nature of new, high mass particle(s), which may not be produced at the laboratory directly. Much before actual discovery, from the oscillations in B-meson system the existence of top-quark was evident. The $b \to s\ell^+\ell^-$ transition is possible in Standard Model (SM) via box and penguin diagrams as represented in figure 1. The purely leptonic decays are helicity suppressed and require an

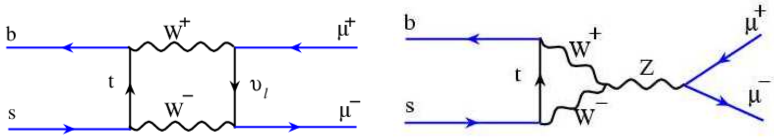

Figure 1. Standard Model box diagram and penguin diagram for $B_s \to \mu^+\mu^-$ transition. The photon will be radiated from any of the fermion legs.

internal quark annihilation within the B-meson which provides a further reduction factor of $(f_B/m_B)^2 \sim 2 \times 10^{-3}$ where f_B, m_B are the decay constant and mass of the B-meson. Hence the corresponding branching ratios are very small and is proportional to the mass squared of the lepton. The rate of $B_s \to \mu^+\mu^-$ mode is also proportional to $|V_{ts}|^2$ whereas $B_d \to \mu^+\mu^-$ mode is further suppressed by the factor $|V_{td}/V_{ts}|^2$ [1]. The other possibility, where γ or Z couple to the top-quark in the loop rather than in the W-boson, is not shown. In scenarios beyond SM, these diagrams will have additional contributions from the corresponding new particles resulting in enhancement of branching ratio.

At LHC, due to large production rate of B-mesons, many rare decay modes will be studied in detail for the first time to look for indirect hints of New Physics (NP) beyond SM [2]. NP often leave its signatures via quantum corrections manifesting in tiny deviations from standard expectations and hence measurement of the rare branching ratios are always interesting. Only high luminosity machines provide the opportunities to search for rare decays and has the capability to probe physics of much higher energy scale.

At present, the theoretical value for the branching ratio $\mathcal{B}(B_s \to \mu^+\mu^-)$ is $(3.86 \pm 0.15) \times 10^{-9}$ and $\mathcal{B}(B_s \to e^+e^-) \sim 7 \times 10^{-14}$. Current experimental upper limit on $\mathcal{B}(B_s \to \mu^+\mu^-)$ and $\mathcal{B}(B_d \to \mu^+\mu^-)$, at 95% confidence level, from CDF experiment at Tevatron are $<1 \times 10^{-7}$ and $<3 \times 10^{-8}$, respectively [3].

Now if there is an additional photon in the final state, there is no more helicity suppression in the 3-body decay mode. In fact in SM, the decay rate is comparable to that without the photon. In SM, the rate of radiative decay for muon channel is slightly lower than that of electron channel due to the phase space effect. The SM prediction for $\mathcal{B}(B_s \to \mu^+\mu^-\gamma)$ is 5×10^{-9} [4].

Theoretically, NP can be invoked in a model-independent way through effective Lagrangian method. Thus, a set of generic parameters can be defined which describe in the most general way the allowed forms of $B \to \ell^+\ell^-$ decays. This approach has the virtue of imposing relations among the many otherwise arbitrary parameters, and allowing an *a priori* estimate of the relative importance of different contributions. Different processes, which can be related to each other in SM are: (1) Semi-leptonic decay of $B \to (K, K^*)\ \ell^+\ell^-$, where the measured branching ratio is $\mathcal{O}(10^{-7})$, (ii) leptonic decay of $B_s \to \ell^+\ell^-$ and (iii) leptonic-radiative decay of $B_s \to \ell^+\ell^-\gamma$. Thus, any violation of the relations dictated from SM will indicate NP beyond SM.

New physics effects, depending on their nature, can enhance either one of these rates. If the nature of the new physics interaction is of scalar/pseudoscalar type, the rate of $B_s \to \ell^+\ell^-$ mode can be very high [5]. On the other hand, the tensor coupling can lead to a branching ratio for $\mathcal{B}(B_s \to \mu^+\mu^-\gamma) \geq 10^{-8}$, an order of magnitude higher than SM prediction [6]. Due to experimental constraints on decays of type $B \to (K, K^*)\ell^+\ell^-$, new physics, in the form of vector/axial-vector couplings cannot provide a large branching ratio for either $B_s \to \mu^+\mu^-$ or $B_s \to \mu^+\mu^-\gamma$ decay channels [7]. Hence it is extremely important that both the decays, $B_s \to \mu^+\mu^-$ and $B_s \to \mu^+\mu^-\gamma$ are measured simultaneously in the same experimental condition with accuracy.

At LHC, the b-quark production rate is very large, about 500 μb at 14 TeV, and the probability of a b-quark to hadronize to a B_s meson is about 10%, the mass of the B_s meson being 5.369 GeV/c^2. Thus, with data corresponding to an integrated luminosity of 10 fb^{-1}, one expects to be able to search for rare decays of B_s meson with branching ratios lower than $\mathcal{O}(10^{-6})$, even with general purpose detectors, like, compact muon solenoid (CMS). Although the dedicated experiment for b-physics, LHC-b, will perform much better (and faster) in most cases, it is still worthwhile to study the same modes in a complementary experiment as in the case here.

Since CMS detector is capable of detecting $B_s \to \mu^+\mu^-$ mode, it is interesting to study the observability of the decay $B_s \to \mu^+\mu^-\gamma$. The dimuon mass resolution is estimated to be about 36 MeV for the B_s resonance. However, unlike the 2-body decay of $B_s \to \mu^+\mu^-$, the 3-body decay results in softer spectrum for the final-state particles which is a deterrant. Hence, the QCD background in the 3-body final-state of $B_s \to \mu^+\mu^-\gamma$ pose a worse situation and in this note we address to tackle it. A simulation study has been performed to estimate the potential of the experiment to observe the channel in low luminosity running condition where pile-up effects in the detector are not severe. We consider the situation of data collected corresponding to an integrated luminosity of 10 fb^{-1} at the centre-of-mass energy of 14 TeV.

2. Compact muon solenoid (CMS) detector

The present analysis has been performed using CMS detector configuration at the LHC, one of the two general purpose experiments, the other being ATLAS. A characteristic feature of the CMS detector is its large superconducting solenoid delivering an axial magnetic field of about 4 Tesla. The detector has components like tracker, electromagnetic calorimeters (ECAL) and hadronic calorimeters (HCAL) and muon chambers positioned radially outwards from the beam–beam collision point [8].

The tracker is designed for high resolution momentum measurement of charged particles and vertex reconstruction in the pseudorapidity range of $|\eta| < 2.4$. The ECAL is designed for detection and energy measurement of electromagnetic particles up to $|\eta| < 3$. The HCAL is meant for detection and energy measurement of hadronic particles and extends up to $|\eta| < 5$ providing the hermiticity of the detector, specially for missing energy measurements. The outermost subdetector is the muon chamber system to identify and measure muons accurately within the fiducial region $|\eta| < 2.4$.

3. Signal and background simulation

The signal of $B_s \to \mu^+\mu^-\gamma$ process as well as the primary background events arise due to QCD interaction via gluon fusion, flavour excitation and gluon splitting modes involving quarks and gluons in the initial state. These generic minimum bias processes are produced using PYTHIA 6.4 Monte Carlo event-generator package [9] with the structure functions determined according to CTEQ5L parametrization. The total cross-section at the centre-of-mass energy of 14 TeV is about 55 mb which will surely be measured in the actual experiment more accurately. Though event generation and in particular the simulation of the detector effect is very time-consuming, it is essential to start with a huge statistics to have a good estimate of background rejection capabilities.

For optimum use of the computer resources, some criteria have been applied based on kinematic properties of the daughter particles during the generation of events. The requirements for each event are: two muons with minimum transverse momentum $P_{\mathrm{T}} \geq 2.5$ GeV/c and $|\eta| < 2.5$, and at least one photon with $P_{\mathrm{T}} \geq 2$ GeV/c and $|\eta| < 2.7$. In addition, importantly for the signal, the event is required to contain a B_s meson which decays to two muons and a photon only. About 70 K such signal events were studied after emulating the detector effects. This corresponds to a very high integrated luminosity, of 1900 fb^{-1}, but starting with a large number of events, the reduction of successive selections still leave a number which is statistically stable. On the other hand, the background events have large rate for passing the above conditions and hence it is impossible to generate and simulate them with full statistics at a reasonable time. We used a statistics of 1.7 $\times 10^{10}$ events for background studies and the final calculation takes into account both the numbers via appropriate scaling factors.

4. Selection of events

At LHC the rate of proton–proton interaction being very high ($\sim 10^9$ Hz at 14 TeV), on-line event-trigger conditions have to be applied to reject most of the low-energy collision or unwanted events. The experiments will still record events, most of which had to be discarded later, at a rate limited by archiving technology at present. We have applied trigger-like conditions in our analysis as foreseen to be implemented during the actual experiment. The recorded events are again reconstructed with better accuracy and calibration and the physics analysis is done later, offline, as explained below.

- At least two muons of opposite signs in the event with $P_{\mathrm{T}} \geq 4$ GeV/c and $|\eta| \leq 2.4$, should satisfy the value of dimuon invariant mass ($M_{\mu\mu}$) in the range 1 to 6 GeV/c^2. This is actually the condition applied at trigger level of the experiment.
- The invariant mass distribution for the dimuon pair is displayed after the trigger selection in figure 2, which shows that a large fraction of recorded events is due to the decay of the resonance $J/\psi \to \mu\mu$. Further, lack of any sharp feature in the signal distribution is evident which makes the background

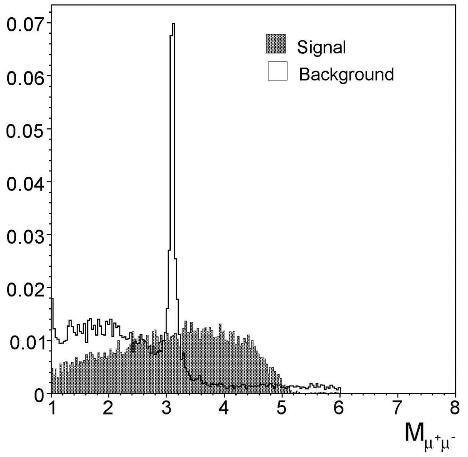

Figure 2. Invariant mass of the dimuon pair, after the event passes through high level trigger, for signal and background distribution. The histograms are normalized to unity.

rejection difficult. A mass veto criterion has been applied to exclude events which have dimuon invariant mass in the range 2.95 GeV/c^2 $\leq M_{\mu\mu} \leq$ 3.25 GeV/c^2. The distribution from signal events, with very large scale factor, shows a broad bump over the mass range limited by the B_s mass on the higher side.

- For signal events, both the muons and the photon have transverse momenta probability distributions increasing at the lower side and continuously falling on the higher side. At LHC, the B_s mesons are likely to be produced with reasonable boost and due to the limited detector acceptance, events can be selected only when the final-state particles of interest are reconstructed in the central region of the detector. Thus events are required to have two leading muons and the leading photon each with transverse momenta $P_{\mathrm{T}} \geq 6$ GeV/c. Since the CMS experiment is designed mainly for high-transverse momentum physics, the above condition also ensures that the objects are reconstructed and identified with reasonable efficiency.
- For further analysis, we consider the invariant mass of the 3-body system, two muons and a photon, expected from the B_s meson decay and we restrict ourselves to events which statisfy $M_{\mu\mu\gamma} \leq 10$ GeV/c^2 taking into account possible degradation in measurements due to detector resolution. We term the total selection efficiency up to this stage as ϵ_{A}.
- In the signal event we do not expect too many additional particles around the B_s decay products and hence we require the muons and the photon to be isolated. The sum of the transverse momenta of all the tracks (excluding muon tracks) in the η–ϕ space annular region (0.5, 1.5) of dimuon direction is calculated and required to be less than 1 GeV/c. The photon of interest does not contribute in the sum since it cannot produce a track in the detector. The corresponding efficiency is referred to as ϵ_{B}.

Table 1. The relative efficiency of sequential selection for reconstructed signal and QCD background events.

	Signal $B_s \to \mu\mu\gamma$		QCD Background	
Selection criteria	No. of events	Efficiency	No. of events	Efficiency
Total no. of events analysed	68786		111276	
Trigger	10594	0.15	9355	0.08
J/ψ mass veto	9644	0.91	7001	0.74
$P_{\rm T}^{\mu} \geq 6$ GeV/c	5205	0.54	2032	0.29
$P_{\rm T}^{\gamma} \geq 6$ GeV/c	1896	0.37	350	0.17
$M_{\mu\mu\gamma} \leq 10$ GeV/c^2	931	0.5	82	0.23
Basic selection		0.014		7.3×10^{-4}

- Since the B_s meson has a finite life-time, $\mathcal{O}$(ps), it traverses a finite and measurable distance within the detector before decaying. Thus we require that the muons and photon should all originate from a common vertex which is displaced from the nominal collision vertex. The flight length of the B_s candidate provides a good handle against the combinatorial background. The variable regarding the flight length in the transverse plane is scaled by the error of measurement and is defined as the significance, l_{xy}/σ_{xy}. The hits observed in the vertex detector elements due to passages of muons are fitted to tracks originating from the displaced dimuon vertex and the corresponding χ^2 value provides the quantitative measure of fit quality. We demand that two-dimensional decay length significance l_{xy}/σ_{xy} to be greater than two and for the secondary vertex fit χ^2 should be less than six. The efficiency of selection based on this vertex criteria is referred to as $\epsilon_{\rm C}$.
- Since the muons and the photon share a common mother which is boosted at production, we do not expect the daughter particles to be too far from each other. The distance between the dimuon and the photon direction is calculated again in η–ϕ space, $\Delta R_{\mu\mu\gamma}$, and is required to be less than 0.5. The corresponding efficiency for this selection is referred to as $\epsilon_{\rm D}$.

The relative efficiencies of each criterion for signal and background event selection are provided in tables 1 and 2. It is to be noted that the individual efficiencies for selections based on dimuon isolation, displaced vertex and the distance between the photon and the dimuon system are independent of each other. These selections can be applied sequentially and the grand total efficiency can be considered as the product of all the individual efficiencies.

5. Results

The total efficiency of selecting reconstructed signal events is given by

$$\epsilon_{\rm sig} = \epsilon_{\rm A} \cdot \epsilon_{\rm B} \cdot \epsilon_{\rm C} \cdot \epsilon_{\rm D} \cdot \epsilon_{\rm E} = 9.8 \times 10^{-4},$$

Table 2. Efficiencies of independent selections for reconstructed signal and QCD background events.

	Signal $B_s \to \mu\mu\gamma$		QCD Background	
Selection criteria	No. of events	Efficiency	No. of events	Efficiency
Dimuon isolation	364	0.40	10	0.12
Displaced dimuon vertex	811	0.89	48	0.58
$\Delta R_{\mu\mu\gamma} \leq 0.5$	242	0.26	15	0.18

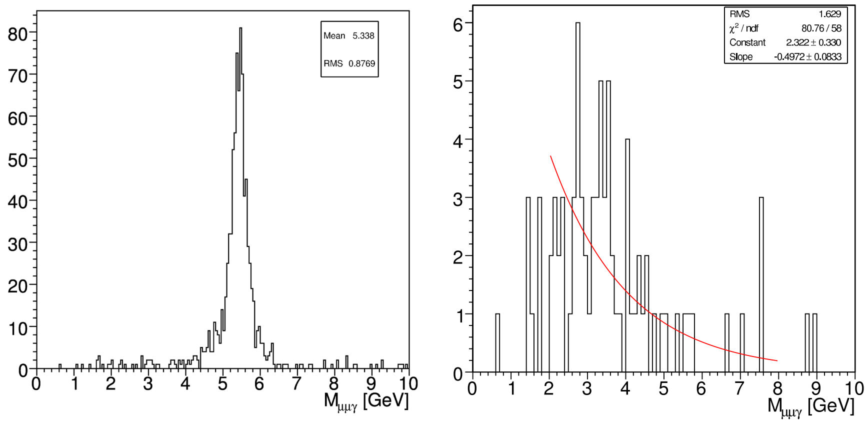

Figure 3. Invariant mass distribution of μ, μ and γ systems in final selected sample for signal and background events. Plots are for arbitrary statistics. Due to low statistics background spectrum is fitted with exponential curve (see text for details).

where ϵ_{E} is the ratio of signal events for the mass window 5–6 GeV/c^2 to the full mass range and is estimated to be 0.75. Thus the total number of signal events surviving after all the cuts, in the above mass range for the luminosity 10 fb^{-1} is even less than 1.

After applying all the basic selections up to the condition $M_{\mu\mu\gamma} \leq 10$ GeV/c^2, the background sample is left with limited statistics which needs to be multiplied by a very large scale factor to obtain the actual number of background events expected for 10 fb^{-1}. Hence we proceed to find the possibility of discriminating the signal against background using statistical method. In figure 3 the invariant mass of the two muons and the photon system from the final selected sample is displayed for arbitrary statistics in each case. Since the QCD spectrum is a falling one, we can estimate the background rate with an exponential curve defined as $f(x) = \exp(y_0 - y_1 \times x)$ where y_0 and y_1 are constants. After fitting we obtain the parameters of exponential function as: $y_0 = 2.322 \pm 0.312$ and $y_1 = 0.4972 \pm 0.087$.

The number of background events expected in the signal mass-window of 5–6 GeV/c^2 for luminosity 10 fb^{-1}, is determined by scaling from the total number of events expected in the range of 2–8 GeV/c^2 after all the selections with efficiencies as given in tables 1 and 2. This number is estimated to be 1977 ± 44.

From the above numbers it is evident that the QCD background is too severe and it overwhelms the signal completely. However in such a situation one can obtain a 90% confidence level (CL) upper limit (UL) on the branching ratio assuming that the signal and background are both distributed (independently as well as jointly) according to Poisson statistics. The final number of background events which survived all the above cuts is estimated from the total rate and the efficiencies for an integrated luminosity of 10 fb^{-1}. The upper limit on the number of signal events can be obtained taking into account the total number of B_s events produced within CMS detector fiducial region and the signal selection efficiency after all the cuts for the mass window of 5–6 GeV/c^2. The total number of events containing a B_s meson corresponding to an integrated luminosity of 10 fb^{-1} is 10^{12}, assuming the production cross-section $b\bar{b}$ at LHC proton–proton collision at 14 TeV to be 500 μb and taking into account the probability of a b or $\bar{b}$ quark to hadronize into a B_s meson to be 10%. The efficiency of a B_s meson to have all the three daughter particles, the two muons and the photon, to be well within the geometric acceptance of CMS detector and to be subsequently reconstructed and identified well, is obtained from generator-level information and is found to be 0.4. Thus the upper limit on the branching fraction is

$$\mathcal{B}(B_s \to \mu^+\mu^-\gamma) \leq 2.08 \times 10^{-7}.$$

This number can be compared with the much better sensitivity of CMS experiment for the 2-body decay mode of $B_s \to \mu^+\mu^-$ with an achievable upper limit of 1.4×10^{-8} at 90% CL. This performance is anticipated since the dimuons from $B_s \to \mu^+\mu^-$ channel form a sharp peak around the B_s mass, and hence signal selection is relatively easier. For the radiative mode, the dimuon mass spectrum is broad and hence the finally selected sample with reasonable efficiency for the signal has very large background. However, as LHC experiments will take data for a long time, with more accumulated statistics at higher integrated luminosity, better analysis techniques can be applied to tackle the background and a significant signal-to-background ratio can be achieved. Such a study is beyond the scope of the present work.

6. Summary

Using simulated events in CMS detector, a simple cut-based analysis study has been performed to estimate the sensitivity of the experiment for observing the rare decay mode $B_s \to \mu\mu\gamma$ with an integrated luminosity of 10 fb^{-1} at 14 TeV energy of LHC. The QCD background is estimated to be too large and the selected signal statistics is found to be too small to observe the final state. However, an upper limit on the branching ratio can be achieved, as $\mathcal{B}(B_s \to \mu^+\mu^-\gamma) \leq 2.08 \times 10^{-7}$.

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