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$B_s \to \mu^+\mu^-$ at the LHC

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Due to its sensitivity to New Physics contributions, the branching ratio of the very rare decay $B_s \to \mu^+\mu^-$ is one of the most interesting measurements that can be performed at the LHC. The current limit from the CDF experiment is still one order of magnitude above the Standard Model prediction. In this article, the analysis strategy for this channel in the LHC experiments is presented, as well as the potential of the LHC experiments in such studies. The first 10 months of LHC running can be enough to overtake the current CDF upper limit, or even the expected limit at the end of Tevatron's Run II. With five years of data taking at nominal luminosity, values smaller than the Standard Model prediction can be observed.

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1. Introduction and motivation

Precision observables at low energy allow access to information at higher energy scales, constraining possible New Physics (NP) scenarios. The branching ratio $BR(B_s \to \mu^+\mu^-)$ has been identified as a very interesting potential constraint on the parameter space of NP models [1]. The Standard Model (SM) prediction is $BR(B_s \to \mu^+\mu^-) = (3.35 \pm 0.32)\times10^{-9}$ [2] while the current upper limit given by Tevatron is $BR(B_s \to \mu^+\mu^-) < 36\times10^{-9}$ @ 90% CL [3]. Hence, NP can still contribute to increase the BR value up to one order of magnitude with respect to the SM expectation. For example, in the Minimal Supersymmetric Standard Model this BR can be as large as the current experimental upper limit, but can also be smaller than the SM prediction, having strong dependence on $\tan\beta$ [4].

This article explains how the measurement of $BR(B_s \to \mu^+\mu^-)$ is planned to be performed in ATLAS [5], CMS [6] and LHCb [7]. The identification of signal events and separation from background is explained in Section 2. In Section 3, simulation of signal and background is used to extract the potential of CMS and LHCb in the measurement/exclusion of $BR(B_s \to \mu^+\mu^-)$. Finally, Section 4 explains the use of control channels to minimize the dependence on Monte Carlo (MC) simulations.

2. Signal identification and yields

Three detectors installed at the LHC [8] accelerator have a b-physics program and will search for the rare decay $B_s \to \mu^+\mu^-$. ATLAS [9] and CMS [10] have a geometry covering the pseudorapidity (η) region $|\eta| < 2.5$. They are general purpose experiments in which b-physics relies on high transverse momentum (p_t) muon triggers, and are planning to run with an instantaneous luminosity up to 2×10^{33} cm^{-2}s^{-1} for the first three nominal years. LHCb [11] is a forward spectrometer covering $1.9 < \eta < 4.9$ and is planning to take data with an instantaneous luminosity of $\sim2\times10^{32}$ cm^{-2}s^{-1}. Its b-physics dedicated trigger [12] allows access to lower p_t regions as well as to select purely hadronic modes. This capability of triggering at low p_t increases the effective cross section for b-physics analyses by approximately a factor 2.3 with respect to ATLAS and CMS.

In order to separate the small signal from the large amount of background, several signatures can be used. These include the flight distance of the B meson, the quality of the secondary vertex, the consistency of B flight direction with momentum direction, the isolation (i.e., no other tracks around the decay vertex or making an alternative vertex with the signal muons) or the invariant mass of the $\mu^+\mu^-$ pair. A selection of distributions is shown in Figure 1. The invariant mass is probably the most important; for combinatorial background (which is the dominant component) the sensitivity scales with the inverse square root of the invariant mass resolution. The corresponding resolutions are 90 MeV/c^2 in ATLAS, 53 MeV/c^2 in CMS and 22 MeV/c^2 in LHCb.

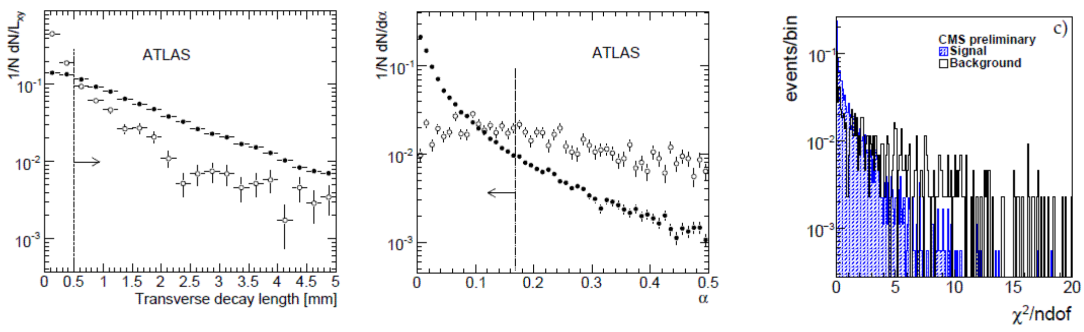

Figure 1: Distribution of a selection of discriminating variables. Left: Distance, in the transverse plane to the beam, from the interaction point to the decay vertex at ATLAS. Open circles correspond to background and filled circles to signal. Centre: α is the angle of the momentum vector of the B meson with respect to the flight direction (which should be 0 for perfectly reconstructed signal candidates) at ATLAS. Open circles correspond to background and filled circles to signal. Right: χ^2/ndof of the fitted decay vertex at CMS. The filled histogram is signal and the open histogram is background.

After trigger and selection cuts, the ATLAS experiment expects 5.6 signal events (for $BR(B_s \to \mu^+\mu^-) = 3.35\times10^{-9}$) and 14^{+13}_{-10} background events with 10 fb^{-1}. The CMS expectations for 1 fb^{-1} are 2.36 signal events (assuming $BR\ (B_s \to \mu^+\mu^-) = 3.9\times10^{-9}$[13] as the SM expectation) and 6.5 ± 2.4 background events.

After initial selection cuts, LHCb uses a likelihood analysis[7], by classifying the selected events in bins of a 3D parameter space. The axes of the space are the $\mu^+\mu^-$ invariant mass, a PID likelihood combining information from the different subdetectors, and a geometry-likelihood (GL) combining several geometrical signatures of the decay. Finally, the bins are combined using a Modified Frequentist Approach (MFA) [14]. The bins with geometry-likelihood larger than 0.5 (see Figure 2) constitute the 'sensitive region' as almost all the LHCb sensitivity is accumulated there. About 11 signal events (for $BR(B_s \to \mu^+\mu^-) = 3.35\times10^{-9}$) and 86^{+68}_{-41} background events per fb^{-1} are expected in this sensitive region. Out of them, 3.8 signal and 11 background events fall in the most sensitive bin (GL > 0.65 and $\mu^+\mu^-$ invariant mass in the window 5353.4 - 5384.1 MeV/c^2).

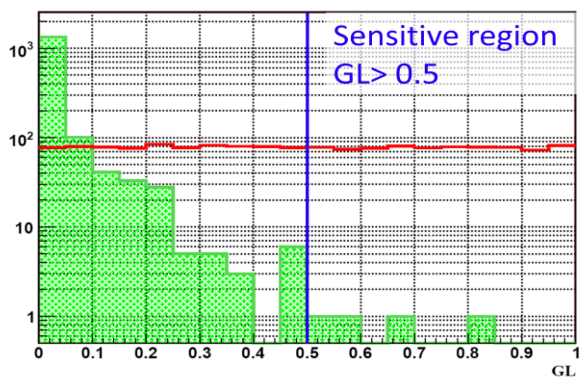

Figure 2: Distribution of LHCb's geometry-likelihood. Open histogram is signal; filled histogram is $b\bar{b} \to \mu^+\mu^- X$ background. The two histograms are normalized to the same area, corresponding to ~5pb^{-1} for the background.

3. LHC sensitivity

From the expected signal and background events as a function of integrated luminosity, the sensitivity of each experiment can be evaluated. This section shows new sensitivity for CMS and LHCb computed using MFA and neglecting systematic errors. Figure 3 shows the value for the BR excluded at 90% CL in the case of absence of signal. The plot on the left shows the sensitivity as a function of integrated luminosity, where we see that 2 fb^{-1} are sufficient for LHCb to exclude values down to the SM prediction. However, ATLAS and CMS can run at higher instantaneous luminosities and therefore accumulate more data for the same period of time. The plot on the right shows the sensitivity as a function of nominal time, assuming 10(2) fb^{-1} per nominal year at CMS (LHCb). The capability of CMS to run at higher instantaneous luminosities allows CMS to match the LHCb sensitivity for the same period of time, and to exclude any enhancement of $BR(B_s \to \mu^+\mu^-)$ with respect to the SM prediction with the first nominal year of data taking.

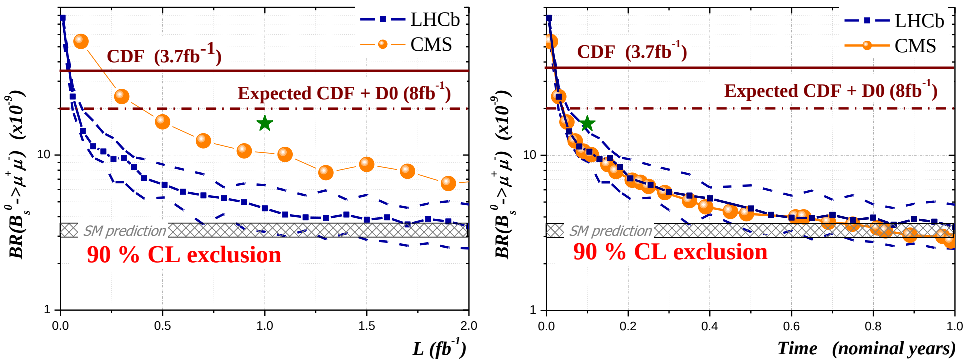

Figure 3: 90% CL exclusion sensitivity for $B_s \to \mu^+\mu^-$ at the LHC. Left: The excluded BR as a function of integrated luminosity. Right: as a function of nominal time. The orange circles correspond to CMS expectation, and the blue squares to LHCb. The dashed lines show the uncertainty on LHCb sensitivity due to the limited statistics in the current simulation of the background, and correspond to 90% CL interval of the background estimation in the sensitive region. The star corresponds to the expected exclusion from CMS for 1 fb^{-1} including systematic errors: $BR(B_s \to \mu^+\mu^-) < 1.6\times10^{-8}$ at 90% CL[6]. The horizontal full line shows the current upper limit from CDF, the dot-dashed line shows the expected limit at the end of Tevatron's Run-II, assuming 8fb^{-1} for each experiment. The hatched horizontal bar shows the SM prediction.

In the presence of signal, the amount of data needed for a 3σ evidence[1] of a given BR is plotted in Figure 4. For a given integrated luminosity LHCb provides the best result (left) but as a function of nominal time the CMS sensitivity is comparable within uncertainties (right). Approximately one or two nominal years will be enough for either of the two experiments to obtain evidence of the decay for a BR larger or equal to the SM prediction.

[1] Corresponding to a CL = 0.9973 for only-background hypothesis.

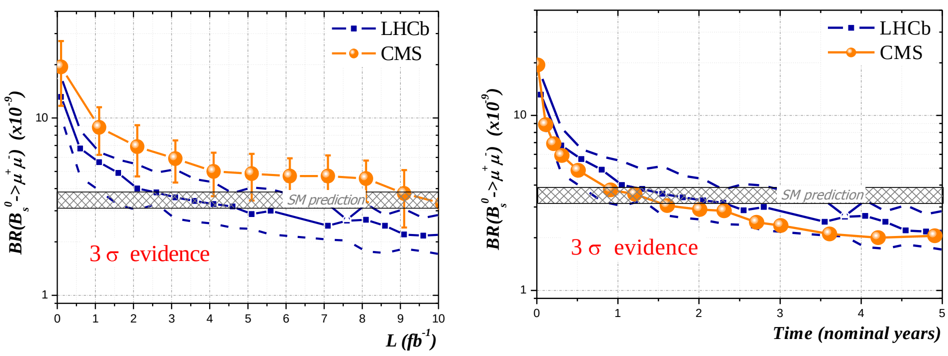

Figure 4: Three sigma evidence sensitivity for CMS and LHCb. Left: as a function of integrated luminosity; right: as a function of nominal time. See Figure 3 caption for definition of the lines.

Sensitivity at LHC startup

It is interesting to study the sensitivity which can be reached with the first data, taking into account that the LHC will not be running at nominal performance from the beginning. The accelerator will provide collisions at 7 TeV (instead of the nominal 14 TeV) and will increase the energy when possible. The instantaneous luminosity will also be below the nominal value. At the time of writing, the current schedule is to deliver 300 pb^{-1} per experiment in the first 10 months of operation.

Figure 5 shows, for the first 300 pb^{-1}, the BR excluded at 90% CL in the absence of signal in the LHCb data sample. The $b\bar{b}$ cross section is assumed to be 225 μb (i.e., 45 % of the nominal), corresponding to the ratio between the values at 7 TeV and 14 TeV in Pythia 6.4 [15]. The first 10 months of data taking will be enough to allow LHCb to improve upon any exclusion limit from the Tevatron, if no signal is present.

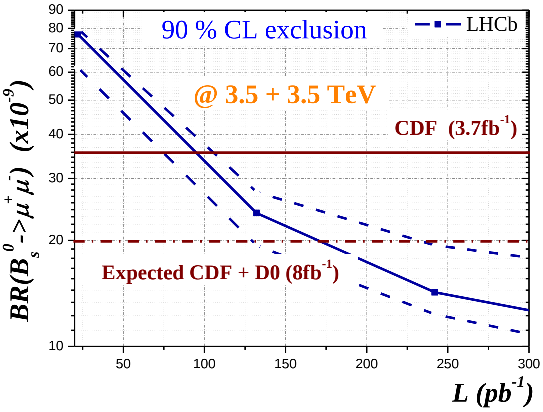

Figure 5: 90% CL exclusion sensitivity for initial LHC conditions.

4. Normalization and calibration

In order to convert the number of signal events into a BR without relying on the knowledge of the $b\bar{b}$ cross section and integrated luminosity, a control channel with a known BR is needed. Then BR($B_s \to \mu^+\mu^-$) can be extracted from:

$$BR = BR_n \frac{\varepsilon}{\varepsilon_n} \cdot \frac{P(b \to B_n)}{P(b \to B_s)} \cdot \frac{N}{N_n}.$$

The quantities with subscript n refer to the normalization control channel. N is the number of $B_s \to \mu^+\mu^-$ events, ε is the product of the corresponding efficiencies (acceptance, reconstruction, selection and trigger) and $P(b \to B)$ is the probability of the b quark to hadronize into the given meson. As there is no accurate measurement of any BR for the B_s, normalization to B^+ (or B_d) decays is preferred. However, this introduces a systematic error of 13% from the uncertainty in the ratio $P(b \to B^+)/P(b \to B_s)$ [16].

The normalization channel chosen in the three experiments is the decay $B^+ \to J/\psi\,(\mu\mu)K^+$ because of its high event yield and the similarity with signal in PID and trigger due to the J/ψ muons. The disadvantage for this decay comes from the presence of an extra track (the kaon) in the final state, but this can be addressed by studying other ratios of control channels where the BR's are also known, such as $B_d \to J/\psi\,(\mu\mu)K^*(K\pi)$ / $B^+ \to J/\psi\,(\mu\mu)K^+$, where the difference between these two last channels is again an extra track in the final state. Those ratios can also be used for properly tuning the MC to reproduce tracking and acceptance efficiencies.

The LHCb analysis will also normalize to $B \to h^+h'^-$ (h,h' being kaons or pions), where the most suitable is $B_d \to K\pi$. The $B \to h^+h'^-$ decays have the advantage of having similar kinematics to $B_s \to \mu^+\mu^-$, but very different trigger and PID properties. These disadvantages can be solved by looking at those events triggered independently of the signal (TIS), where other particles in the event caused the trigger, and thus trigger bias can be minimized. Calibration muons (for example those from $J/\psi \to \mu^+\mu^-$) can be used to emulate online and offline muon identification as a function of track momentum and angle in order to determine the desired $B_s \to \mu^+\mu^-$ trigger and PID efficiencies. In addition, $B \to h^+h'^-$ will be used at LHCb for calibration of signal likelihood distributions, as the signal fraction in each bin of the 3D parameter space needs to be known. The amount of background inside the signal region (or in each bin of the 3D parameter space in the case of LHCb) will be derived from invariant mass sidebands. Hence, these strategies will allow a minimization of simulation dependence and to keep systematic errors under control.

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