OBSERVATION OF $B_s^0 \to \mu^+\mu^-$ AT CMS AND LHCb AND FUTURE PLANS AT LHCb*

Hannah Evans

University of Cambridge, Cavendish Laboratory
J.J. Thomson Avenue, Cambridge, CB3 0HE, UK

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The branching fractions of the decays $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$ are highly suppressed in the Standard Model but can be modified by contributions from new physics models. The combined result from the CMS and LHCb Run 1 data for the $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$ branching fractions is presented here. The measured results are $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$ at 6.2σ statistical significance and $\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$ at 3.0σ statistical significance, both results are consistent with Standard Model predictions. A brief discussion of the future prospects for the study of $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$ at the LHCb is also included.

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1. Introduction

In the Standard Model (SM), the weak decays $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$ are highly suppressed, leading to very small branching fraction predictions. However, theories which go beyond the SM can greatly enhance their predictions. Measuring these decays provides constraints on new physics models and allows insights into how the SM can be extended. At the Large Hadron Collider (LHC), the CMS and LHCb experiments have put together their data sets for the study of these decays. These proceedings present the combined analysis of the data taken during Run 1 of the LHC by the CMS and LHCb collaborations and provide a brief discussion of future prospects at the LHCb. Full details of the combined analysis can be found in paper [1].

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2. Theoretical motivation

The $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$ decays occur by flavour changing neutral currents, highly suppressed transitions in which quark flavour changes but not quark charge. These decays are further suppressed by CKM contributions and helicity constraints.

The SM effective branching fraction for $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$ decays can be expressed in terms of Wilson coefficients

$$\mathcal{B}\left(B_q^0 \to \mu^+\mu^-\right) \propto \left|V_{tq}V_{tq}^*\right|^2 \left(|\mathcal{C}_{\mathrm{S}}|^2 + \left| \mathcal{C}_{\mathrm{P}}{}^2 + \frac{m_\mu}{M_{B_q^0}}(\mathcal{C}_{10}) \right|^2 \right) . \qquad (1)$$

The dominant contribution in the SM Hamiltonian comes from $\mathcal{C}_{10}$ which contains the contributions from Z^0 penguins and W-box diagrams resulting from axial and vector couplings. Scalar and pseudo-scalar contributions, $\mathcal{C}_{\mathrm{S}}$ and $\mathcal{C}_{\mathrm{P}}$, corresponding to Higgs-penguins, which are not helicity suppressed, are negligible in the SM and can be ignored. However, these contributions can be substantially increased by new physics processes altering the effective branching fraction.

Therefore, measuring the $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$ branching fractions is an indirect search for new physics and could either reveal new physics, if the measurement is incompatible with the SM, or provide constraints for new physics models.

The predictions for the SM branching fractions [2–5], including the latest top quark measurement, are: $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$.

In addition to the branching fractions, the ratio of the two branching fractions is also an interesting observable. The ratio gives a measure of the difference in the flavour structure of the two modes and provides a powerful discriminator for the flavour structure in new physics models [6]. The ratio is precisely predicted by the SM [3, 7–9] to be $\mathcal{R} = \frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \mu^+\mu^-)} = 0.0295^{+0.0028}_{-0.0025}$.

3. The CMS and LHCb experiments

CMS and LHCb are two experiments at the Large Hadron Collider, which produce complementary data sets for studying $B_{(s)}^0 \to \mu^+\mu^-$ decays. The CMS is a 4π detector designed to search for new physics particles in the mass range from 100 GeV/c^2 to a few TeV/c^2. Many heavy new physics particles could decay into b-hadrons, therefore, good sensitivity to b-hadron decays is a key part of the CMS design. The LHCb experiment is a single

arm forward spectrometer covering the range of $2 < \eta < 5$ of in pseudo-rapidity, it was designed specifically to study CP violation and to make precise measurements of b-hadron decays. Although the experiments were designed with different physics aims, they are both sensitive to b-hadron decay, furthermore, the two detectors cover different angular regions making their data sets complementary to each other.

During the Run 1 data taking period at the LHC in 2011 and 2012, the total integrated luminosity collected by CMS was 25 fb^{-1} and 3 fb^{-1} was collected by LHCb. Although CMS has a larger data set, the detector is less efficient than LHCb at reconstructing low mass particles characteristic of the B meson decays, therefore, the sensitivity of both experiments to $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$ decays is comparable.

4. The combination

The CMS and LHCb collaborations published independent results of the $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$ branching fractions on the Run 1 data [10, 11], data sets have been put together and the branching fractions measured on the combined data sets. The analysis of combined data is presented here and follows closely the methods used to obtain the independent results. The data sets are selected separately and the information is combined using a log-likelihood fit which accounts for the correlations in the data.

4.1. Analysis strategy

The analysis strategy is very similar for CMS and LHCb, firstly a soft preselection is applied and a multivariate classifier, in both cases a Boosted Decision Tree (BDT) is used to separate signal candidates from background events composed of random combinations of muons. To combine the two measurements, the data sets are split into categories: the CMS splits the data by year of data taking and the part of the detector in which the muons were detected, subsequently splitting each of the obtained categories in 3 bins of BDT output; the LHCb splits their data set into 8 categories based only on the output of the BDT. A simultaneous fit for the branching fractions is performed on the invariant mass distributions of each category, taking into account correlations between the data sets. In order to extract the branching fractions, the $B^+ \to J/\psi K^+$ decay is used to normalise the observed number of B^0 and B_s^0 events to the total number of B_s^0 and B^0 mesons produced. The $B^+ \to J/\psi K^+$ decay is used because it has a precisely measured branching fraction [7] and a large signal. Figure 1 shows the fit on the invariant mass distribution in the six best categories. Included into the

invariant mass fit are models for the background contributions from various semi-leptonic decays and mis-identified peaking backgrounds, as well as the combinatorial background.

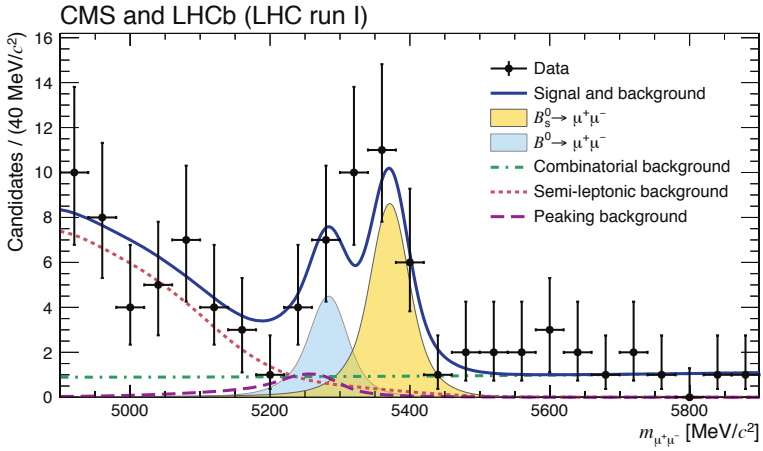

Fig. 1. Dimuon mass distribution for the six best categories, where categories are ranked by $S/(S+B)$ with S the number of signal events and B the number of background events under the B_s^0 peak in the category, assuming SM branching fractions. There are three categories from CMS and three from LHCb.

4.2. The results

The results from the combined analysis of CMS and LHCb Run 1 data sets are $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$ and $\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$, where the errors include both systematic and statistical uncertainties. The statistical significance of the results from Wilks theorem is 6.2σ for $B_s^0 \to \mu^+\mu^-$ and 3.2σ for $B^0 \to \mu^+\mu^-$. The significance for the B^0 result was checked using the Feldman–Cousins procedure which does not rely on the assumptions used in Wilks' theorem, and the resulting significance is 3.0σ. A further fit to the ratio of each branching fraction with its SM prediction was performed to compute the signal strength, the B_s^0 branching fraction is compatible with the SM prediction within 1.2σ and the B^0 is compatible within 2.2σ. Finally, a fit was performed for the ratio of branching fractions, obtaining $\mathcal{R} = 0.14^{+0.06}_{-0.08}$ which is compatible with the SM prediction within 2.3σ. The results presented here give the first observation of $B_s^0 \to \mu^+\mu^-$ and the first evidence for the $B^0 \to \mu^+\mu^-$ decay.

5. Future prospects at LHCb

The $B^0_{(s)} \to \mu^+\mu^-$ branching fraction results from Run 1 have a precision of 25% for the B^0_s mode and 38% for the B^0 mode which leaves room for contributions from new physics models. These decays are, therefore, still interesting for Run 2 where the B^0_s and B^0 production rates will approximately double. Further into the future, after Run 2 in the second long shut down of the LHC, LHCb will undergo an upgrade to increase the precision achievable by the experiment. This increase in achievable precision, as well as the increased statistics available as more data is taken, will not only enable more precise branching fraction measurements but also new observables will become accessible, specifically the $B^0_s \to \mu^+\mu^-$ effective lifetime [12].

In the SM, light and heavy B^0_s mass eigenstates do not follow the same $B^0_s \to \mu^+\mu^-$ dynamics. It is only the heavy mass eigenstate that can decay into two muons, leading to an interesting observable: the asymmetry rate.

Figure 2 illustrates how new physics models can change the $B^0_s \to \mu^+\mu^-$ asymmetry rate and branching fraction, and move them away from their SM predictions, contributions from new physics models can affect the branching fraction and asymmetry rate in orthogonal ways. The asymmetry rate is proportional to the $B^0_s \to \mu^+\mu^-$ effective lifetime which can be measured using the same untagged events to measure the branching fraction. After the LHCb upgrade and during the high luminosity LHC era, LHCb could achieve an uncertainty of 5% on the effective lifetime with 46 fb^{-1}.

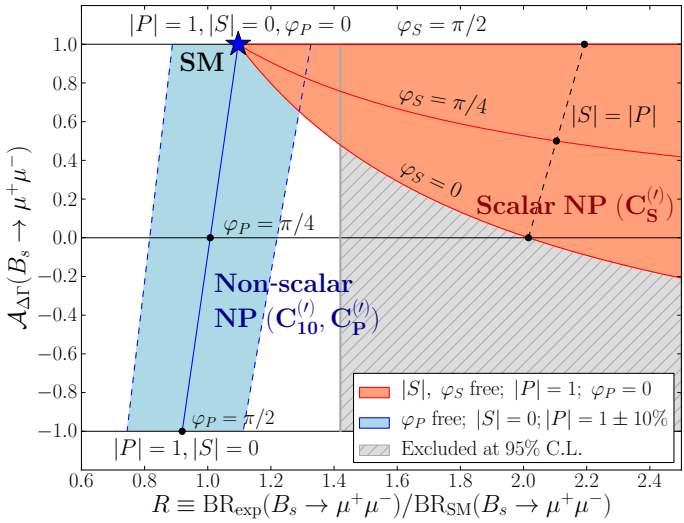

Fig. 2. Plot of allowed regions of new physics scenarios in the $B^0_s \to \mu^+\mu^-$ decay in the plane $\mathcal{R}$ and the asymmetry parameter $A_{\Delta\Gamma}$[12].

6. Summary

The combined analysis of the CMS and LHCb Run 1 data sets provides the first observation of the $B_s^0 \to \mu^+\mu^-$ decay and the first evidence for the $B^0 \to \mu^+\mu^-$ decay. The data collected during the future running of the LHC will enable greater precision to be achieved for the branching fraction measurements and with greater experimental precision new interesting observables such as the $B_s^0 \to \mu^+\mu^-$ effective lifetime will become accessible.

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