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$\mathrm{B} \to \mu^+\mu^-$ rare decays at CMS

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We report on the results obtained from the search for leptonic decays $\mathrm{B_s^0} \to \mu^+\mu^-$ and $\mathrm{B^0} \to \mu^+\mu^-$ in pp collisions at $\sqrt{s} = 7$ TeV and 8 TeV, collected at CMS during 2011 and 2012 data-taking, for a total of 25 fb^{-1} of integrated luminosity. We measured the branching fraction $\mathscr{B}(\mathrm{B_s^0} \to \mu^+\mu^-)$=$(3.0^{+1.0}_{-0.9}) \times 10^{-9}$ and we observed an excess of $\mathrm{B_s^0} \to \mu^+\mu^-$ events with a significance of 4.3 standard deviations. We measured the upper limit for the branching fraction of the $\mathrm{B^0} \to \mu^+\mu^-$, $\mathscr{B}(\mathrm{B^0} \to \mu^+\mu^-)$<1.1 $\times 10^{-9}$, at 95% confidence level. We also report on the combined analysis of LHCb and CMS results and present the first observation of the $\mathrm{B_s^0} \to \mu^+\mu^-$ decay. The branching fractions of this decay as well as of the $\mathrm{B^0} \to \mu^+\mu^-$ decay are presented.

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1. Introduction

Hints of new physics can be pursued with indirect approaches, such as searching for deviations in the physics measurements with respect to the expectations calculated or extrapolated in the framework of the Standard Model (SM), which can allow us to get hints of new particles that cannot be directly produced. For example, particles predicted by beyond the SM models can significantly enhance or reduce the branching fraction of particle decays. Searches for new physics particles usually use clean and rare decays to increase the sensitivity of the measurement. Examples of such decays are the B^0 and the B^0_s decaying into a pair of leptons. Both meson decays are highly suppressed in the SM because they involve flavour-changing neutral current (FNCN) transitions. Those are forbidden at tree level and can only occur through high-order processes corresponding to box and penguin topologies. Moreover, these processes are helicity suppressed and require an internal quark annihilation.

Previous measurements of the B^0 and B^0_s into dileptons were performed in electron collider experiments. More recently these measurements were done at the Tevatron and at the LHC using proton collisions, searching for the dimuon decays. The branching fraction for $\mathscr{B}(\mathrm{B}^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$ and $\mathscr{B}(\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$ are predicted in SM using QCD calculations [1]. The small uncertainty of the predictions allows us to potentially discover deviations from the SM expectations. At the LHC the CMS, LHCb, and ATLAS [2] experiments demonstrated the possibility to do these searches. LHCb had a slightly better performance with respect to the other experiments, but the higher proton collision luminosity and the renovated tracker sub-detectors of ATLAS and CMS during the last years could result in a comparable performance.

By measuring the lifetime of the B^0_s meson along with the $\mu^+\mu^-$ invariant mass, the collaborations can also search for hints of new physics highlighting possible deviations from the expected B^0_s effective lifetime[3], which is an additional handle for the search for NP.

The results obtained from the search for leptonic decays $\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-$ and $\mathrm{B}^0 \to \mu^+\mu^-$ in pp collisions at $\sqrt{s} = 7$ TeV and 8 TeV is reported. The data were collected at CMS during 2011 and 2012 data-taking, for a total of 25 fb^{-1} integrated luminosity. The combined LHCb and CMS analysis, which led to the first observation of the $\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-$ decay and to an improved $\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-$ and $\mathrm{B}^0 \to \mu^+\mu^-$ branching ratio estimation, is also reported.

It was possible to achieve these results thanks to the excellent muon detection of the CMS [6] and LHCb [7] detectors. All the information about the detectors and their performance is reported in the corresponding references.

2. Methodology

The signal is reconstructed searching for two isolated muons with a common vertex and an invariant mass around the B mass. The sample of B meson candidates is selected during the data-taking with hardware triggers (L1 triggers) that require two generic muons, and with software triggers (HLT triggers) that require a pair of oppositely charged muons with an invariant mass within [4.8 - 6.0] GeV, with a vertex probability greater than 0.5% and a transverse momentum p_T greater then [3.0 - 4.0] GeV depending on the data-taking period.

The background events can be divided into three categories: the combinatorial background, estimated from sidebands, is composed of two separated $b \to c\mu\bar{\nu}$ decays or a single $b \to c\mu\bar{\nu}$ decay combined with a misidentified hadron; the peaking background, composed of B mesons decaying into a pair of hadrons (e.g. $\mathrm{B^0_s} \to \mathrm{K^+K^-}$); and the rare semileptonic decays, such as $\mathrm{B^0} \to \pi^-\mu^+\nu$. The peaking and rare semileptonic decays are studied using Monte Carlo simulations.

To improve the muon identification purity and to reduce the hadronic misidentification of the muons a dedicated multivariate discriminator [8] was trained on Monte Carlo simulations, which achieved a 50% reduction of hadron-to-muon misidentification probability with respect to the standard selections of CMS, keeping the muon efficiency high (90%). The B meson candidates were selected using Boost Decision Trees (BDTs) [8] trained for different detector regions and for the different data-taking periods, using Monte Carlo simulations for the signal and the data from the sidebands for the background. There are numerous variables that are inputs to the BDT, and their number depends on the different BDT. The most powerful selecting variables are based on the vertex properties, such as the impact parameter and its significance between the B meson and the primary vertex, and isolation variables, such as muon and B meson isolation.

The branching fractions are determined with respect to the normalization channel $\mathrm{B^+} \to \mathrm{J}/\psi\mathrm{K^+}$ using this formula:

$$\mathscr{B}(\mathrm{B^0_s} \to \mu^+\mu^-) = \frac{n^{obs}_{\mathrm{B^0_s}}}{\varepsilon \mathscr{L} \sigma(pp \to \mathrm{B^0_s})} = \frac{n^{obs}_{\mathrm{B^0_s}}}{n^{obs}_{\mathrm{B^+}}} \frac{A_{\mathrm{B^+}}}{A_{\mathrm{B^0_s}}} \frac{\varepsilon_{\mathrm{B^+}}}{\varepsilon_{\mathrm{B^0_s}}} \frac{f_u}{f_s} \mathscr{B}(\mathrm{B^+} \to \mathrm{J}/\psi\mathrm{K^+}), \tag{2.1}$$

for the $\mathrm{B^0_s} \to \mu^+\mu^-$ channel. For the $\mathrm{B^0} \to \mu^+\mu^-$ channel the same formula is used, changing the $\mathrm{B^0_s}$ notation with the $\mathrm{B^0}$ notation. The n^{obs} is the number of observed B mesons and it is obtained fitting the data sample with an unbinned maximum likelihood; A represents the detector acceptance measured using Monte Carlo simulations; ε is the reconstruction and selection efficiency; and f_u/f_s is the hadron fragmentation ratio obtained from LHCb measurements [9].

3. Results

The outputs of the BDTs are used in two different approaches: in the first approach, called 1D-BDT method, a threshold is applied to the outputs of the BDTs to select the candidates to optimize the significance of the signal; in the second approach, called "categorized BDT", the BDT outputs are divided in 2 bins for 2011 data and in 4 bins for 2012 data.

The 1D-BDT method is used to determine the upper limit of the branching fraction of the $\mathrm{B^0} \to \mu^+\mu^-$ decay channel, while the categorized BDT method is used to extract the branching fraction of the $\mathrm{B^0_s} \to \mu^+\mu^-$ decay channel.

The selected events by the 1D-BDT and the events in the bins of the categorized BDTs are fit with an unbinned maximum likelihood (UML) fit. The probability density function used in the UML fit are: a Crystal Ball function for the $\mathrm{B^0_s}$ and $\mathrm{B^0}$ signal; a Crystal Ball plus a Gaussian function for the peaking background with the yields constrained to the expectation normalized to the $\mathrm{B^\pm}$ yield; a first-degree polynomial for the combinatorial background with the yield free to float; a Gaussian kernel method modeling the rare semileptonic background determined using the Monte Carlo simulations with the yield constrained to the simulation predictions.

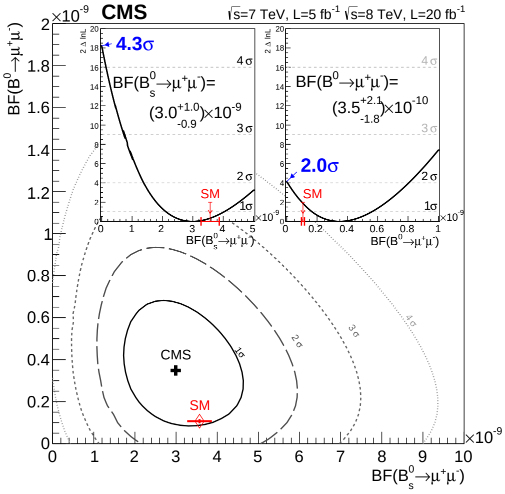

Figure 1: Two-dimensional likelihood scan for the branching fraction of $\mathrm{B}^0 \to \mu^+\mu^-$ versus the branching fraction of $\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-$ [10]. Black cross is the best CMS estimation and red cross is SM prediction.

The systematics uncertainties are constrained in the UML fit using Gaussian constraints. The main sources of systematic uncertainties are the following: the hadron-to-muon misidentification; the branching fraction uncertainty in the background probability density function estimation; the hadronization fraction ratio f_s/f_u uncertainty.

Fitting the binned events from the categorized BDT, the following branching fractions are obtained: $\mathscr{B}(\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$ with a B^0_s peak significance of 4.3σ (4.8σ expected); and $\mathscr{B}(\mathrm{B}^0 \to \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10}$ with a B^0 peak significance of 2.0σ [10]. The likelihood scan of the fit is shown in fig. 1.

Since the B^0 excess is not significant, instead of the value of the branching fraction, an upper limit is set using the CL_s method and fitting the events selected with the 1D-BDT method. From the fit, $\mathscr{B}(\mathrm{B}^0 \to \mu^+\mu^-) < 1.1 \times 10^{-9}$ is measured at the 95% confidence level.

4. CMS-LHCb combined results

The CMS and LHCb samples obtained during the 2011 and 2012 data-taking are merged to improve the sensitivity on the $\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-$ and $\mathrm{B}^0 \to \mu^+\mu^-$ decay channel branching fractions [11]. The analysis method is the same as the one explained in the previous sections for the categorized BDT approach for both experiments' data. The CMS analysis was modified in a few details to improve the semileptonic background estimation and take into account B^0_s lifetime biases.

A total of 20 BDT-catetorized bins are fitted to extract the number of B^0_s and B^0 candidates. The measured branching fractions are the following: $\mathscr{B}(\mathrm{B}^0_\mathrm{s} \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$ with a B^0_s peak significance of 6.2σ (7.4σ expected); and $\mathscr{B}(\mathrm{B}^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$ with a B^0 peak significance of 3.2σ (0.8σ expected). The likelihood scan of the fit is shown in fig. 2.

5. Conclusions

The CMS and combined CMS-LHCb searches for rate B^0_s and B^0 dimuon decays has been

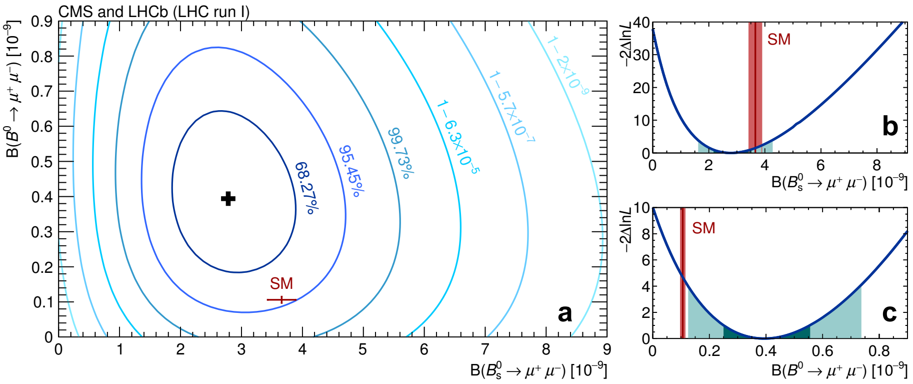

Figure 2: Two-dimensional likelihood scan for the branching fraction of $B^0 \to \mu^+\mu^-$ versus the branching fraction of $B_s^0 \to \mu^+\mu^-$ [11]. Black cross is the best CMS-LHCb estimation and red cross is SM prediction.

presented. The CMS collaboration measured the branching fraction of the $B_s^0 \to \mu^+\mu^-$ decay $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$ with a significance of 4.3σ, while for the $B^0 \to \mu^+\mu^-$ decay an upper limit is set $\mathscr{B}(B^0 \to \mu^+\mu^-) < 1.1 \times 10^{-9}$ at the 95% confidence level. The measured values are in agreement with the SM predictions.

The CMS-LHCb combined analysis significantly improved the measurement of the branching fractions:

$$\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$
$$\mathscr{B}(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}.$$

The $B_s^0 \to \mu^+\mu^-$ excess is measured with a significance of 6.2σ leading to the first observation of the B_s^0 meson decaying into a dimuon pair. The $B^0 \to \mu^+\mu^-$ decay has not been yet observed, thus new searches with additional statistics need to be done. CMS is currently analyzing data collected during the 2016 and 2017 data-taking. At the end of the Run2 data-taking period of LHC the CMS collaboration expects to measure about 430 B_s^0 events from the $B_s^0 \to \mu^+\mu^-$ decay and about 50 B^0 events from the $B^0 \to \mu^+\mu^-$ channel, assuming a final integrated luminosity of 300 fb^{-1} [12].

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