PROCEEDINGS OF SCIENCE

Rare B meson decays at LHC

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Rare decays of B mesons are fundamental tools to probe physics beyond the Standard Model. The LHC experiments are studying these decays thanks to the unprecedented available statistics. We review in this contribution the latest searches for $B^0_{d,s} \to \mu^+\mu^-$ decays at the ATLAS, CMS and LHCb experiments and the search for $B^0_{d,s} \to \mu^+\mu^-\mu^+\mu^-$ decays at LHCb. We discuss the perspectives for some rare B decays in the future of the three experiments and give a summary of the discussion of these topics at this conference.

VI Italian workshop on p-p physics at the LHC,
8-10 May 2013
Acquario di Genova, Ponte Spinola, Area Porto Antico, Genova, Italy

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PoS(LHCPP2013)033

1. Introduction

Rare decays of heavy flavours are a fundamental place to look for physics beyond the Standard Model (SM) for various reasons. Dealing with tiny effects New Physics can be of the same order of the SM; the SM predictions are very precise leading to unambiguous interpretation of the results; higher energy scales are accessible, through virtual loops, than the ones that can be probed with direct production; finally, probing the flavour structure gives clear signatures of the type of new physics to expect.

In this contribution we describe the present status of searches for rare B mesons decays at the LHC by the ATLAS, CMS and LHCb collaborations.

2. Searches for $B^0_{d,s} \to \mu^+\mu^-$ decays

The $B^0_{d,s} \to \mu^+\mu^-$ decays are among the cleanest decays, both experimentally and theoretically, for the searches of new physics. Being flavour changing neutral currents within the Standard Model they are allowed only at loop level and suppressed by the GIM mechanism; furthermore they carry an additional suppression due to helicity reasons. Therefore within the SM they are very rare and the most precise theoretical predictions of the branching fractions are [8, 7]:

$$\begin{aligned}\mathscr{B}^{t=0}(B^0_s \to \mu^+\mu^-) &= (3.25 \pm 0.17) \times 10^{-9} \\ \mathscr{B}^{t=0}(B^0 \to \mu^+\mu^-) &= (1.07 \pm 0.10) \times 10^{-10} \quad .\end{aligned}$$

The superscript $t = 0$ means CP-averaged branching fractions at time zero in opposition to the usually experimentally measured time integrated branching fractions. This distinction is important since, as firstly noted in Ref. [6], owing to the finite lifetime difference between the B^0_s and the $\bar{B}^0_s$, the integrated branching fraction is different and in particular [9]:

$$\mathscr{B}^{\langle t\rangle}(B^0_s \to \mu^+\mu^-) = \left(\frac{1+\mathscr{A}_{\Delta\Gamma} y_s}{1-y_s^2}\right) \mathscr{B}^{t=0}(B^0_s \to \mu^+\mu^-) \overset{SM}{=} (3.56 \pm 0.18) \times 10^{-9}$$

where the last equality includes the last measurement of y_s [10] but also the Standard Model value for $\mathscr{A}_{\Delta\Gamma}$ [9] and is therefore valid only for SM: we take the occasion to note here that because of this correction the comparison between time integrated and $t = 0$ branching fraction is model dependent and requires to take into account the CP structure of the model under investigation.

Various New Physics models can add contributions to these decays making them standard candles for the flavour sector of new theories: we refer the interested reader to a contribution at this same conference for the discussion of the theoretical aspects [20].

3. Recent results on $B^0_{d,s} \to \mu^+\mu^-$ decays at LHC

In the following we present the results of the three LHC experiments on the search for $B^0_{d,s} \to \mu^+\mu^-$ decays. The basic analyses are similar: they start with a soft selection to get rid of most of the background, selecting well identified di-muons separated from primary vertices; after that a strong selection based on simple cuts or on multivariate operators is performed in order to classify signal and background events. The final search is performed as a counting experiment in the signal invariant mass region for the ATLAS and CMS experiment while as a two-dimensional search in the invariant mass and in the full operator range for LHCb.

The signal yield is converted into a branching fraction normalising to the $B^+ \to J/\psi K^+$ decay (and in addition also to the $B^0 \to K^-\pi^+$ for LHCb) as follows:

$$\mathscr{B}(B^0_q \to \mu^+\mu^-) = \frac{\varepsilon_{\rm nc}}{\varepsilon_{\rm sig}} \cdot \frac{f_{\rm nc}}{f_q} \cdot \frac{N_{B^0_q \to \mu^+\mu^-}}{N_{\rm nc}} \cdot \mathscr{B}_{nc} = \alpha_q \cdot N_{B^0_q \to \mu^+\mu^-} \tag{3.1}$$

where the subscript *nc* refers to the normalisation channel, $q = d, s$ and α_q is referred to as single event sensitivity. Apart from the branching fraction of the normalisation channel $\mathscr{B}_{nc}$, the formula requires the ratio of efficiencies ($\varepsilon_{\rm nc}/\varepsilon_{\rm sig}$) and the ratio of the yields. The ratio of hadronisation fractions (f_{nc}/f_s) is taken from the LHCb measurement [11]. No additional systematics is added to take into account the possible kinematic variation of this factor in ATLAS and CMS, but the latter collaboration cross-checked this value with the ratio of $B^0_s \to J/\psi\phi$ to $B^+ \to J/\psi K^+$ events.

In the following we will present the latest results for the three experiments and the combination of ATLAS and CMS results with the previous LHCb measurement. We refer the reader to the respective articles for a full account of the analyses [1, 2, 3, 4, 14].

3.1 ATLAS

The ATLAS $B^0_s \to \mu^+\mu^-$ search, based on the first 2.4 fb^{-1} of 2011 data [1] is performed in three bins of $|\eta|_{max}$, the maximum pseudorapidity ($|\eta|$) value of the two (signal) decay muons (Barrel, Transition and Endcap).

The signal extraction is optimized using half of the background sample in the sidebands while the other half is used to estimate the combinatorial background in the signal region from the sidebands. This avoids an optimization bias on the upper limit, while reduces the size of the data sample available for the background determination from the sidebands by a factor of two. The analysis follows a multivariate approach based on 14 independent variables.

With the analysed data, no excess of events over the background expectation is found, giving an upper limit of $\mathscr{B}(B^0_s \to \mu^+\mu^-) < 22 \times 10^{-9}$ at 95% C.L. obtained with the CL$_{\rm s}$ method [19]. The corresponding CL$_{\rm s}$ plot is shown in Figure 1.

3.2 CMS

The CMS collaboration has performed a search of $B^0_{d,s} \to \mu^+\mu^-$ decays in 5fb^{-1} of integrated luminosity collected in 2011 at $\sqrt{s} = 7$ TeV [2]. Since the background level and the invariant mass resolution depend significantly on the pseudorapidity of the B^0_s candidate, in the CMS analysis the events are separated into two exclusive categories: the Barrel category contains the candidates where both muons have $|\eta| < 1.4$ while the Endcap category contains the rest.

Data are collected with a trigger requesting two opposite-charge muons with asymmetric p_T cuts ($p_T > 4$ and 3.5 GeV), and with an invariant mass close to the one of the B^0_s candidate ([4.8, 6.0] GeV). A very loose cut on the distance of the closest approach of the muon pair is applied to reduce the bandwidth due to the pile-up.

The analysis selection has been optimized with a random grid search trained with MC simulation signal events and data sidebands. The most separating selection variables were the significance

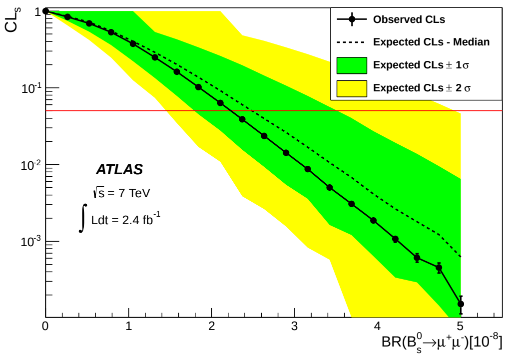

Figure 1: Expected (dashed) and observed (connected dots) $\mathrm{CL_s}$ as a function of the $\mathscr{B}(B_s^0 \to \mu^+\mu^-)$ as obtained in the ATLAS analysis [1].

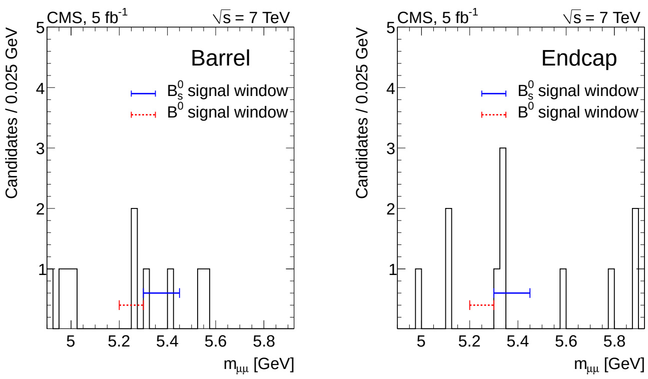

Figure 2: Invariant mass distributions in the CMS search for $B^0_{d,s} \to \mu^+\mu^-$ events in (left) the Barrel region and (right) the Endcap one [2].

of the decay length, the pointing angle and the isolation. All the analysis selection cuts have been checked to be pile-up independent.

The expected number of combinatorial background events in the search window is extracted from the invariant mass sidebands. The contribution of the misidentified peaking or semileptonic backgrounds is extracted from the normalization channel.

The number of observed events is consistent with the expectation from background plus SM signal predictions (Figure 2).

The resulting upper limits on the branching fractions are $\mathscr{B}(B_s^0 \to \mu^+\mu^-) < 7.7 \cdot 10^9$ and $\mathscr{B}(B^0 \to \mu^+\mu^-) < 1.8 \cdot 10^9$ at 95% C.L..

3.3 LHC combination

The analyses from ATLAS [1] and CMS [2] were combined with the first two LHCb [3, 4] analyses in the first combination from the three LHC experiments [5]. The results are shown in Figure 3 as a function of the assumed $\mathscr{B}(B_s^0 \to \mu^+\mu^-)$. The expected and measured limits are reported in the first row of Table 1. This observed distribution of events, when compared with the expected background distribution, results in $1-\mathrm{CL_b}$ (or p-value) of 5%, and in $1-\mathrm{CL_{s+b}}$ of 84% when compared with the expected background plus SM signal distribution, indicating a slight excess of events with respect to the background predictions compatible with a SM signal at 1 σ.

The expected and observed $\mathrm{CL_s}$ value derived from CMS and the two LHCb analyses are shown in Figure 3 (right) as a function of the assumed $\mathscr{B}(B^0\to\mu^+\mu^-)$. The expected and measured limits are reported in the second row of Table 1.

Table 1: Expected and observed upper limit on $\mathscr{B}(B_q^0\to\mu^+\mu^-)$, obtained from the combination of ATLAS, CMS, and the two LHCb analyses for $B_s^0\to\mu^+\mu^-$ and from CMS and the two LHCb analyses for $B^0\to\mu^+\mu^-$.

	Background only		SM signal + background		Observed	
C.L.	90%	95%	90%	95%	90%	95%
$\mathscr{B}(B_s^0\to\mu^+\mu^-)$ (10^{-9})	1.9	2.3	5.4	6.1	3.7	4.2
$\mathscr{B}(B^0\to\mu^+\mu^-)$ (10^{-10})	5.9	7.3			6.7	8.1

The combined upper limits on $\mathscr{B}(B_s^0\to\mu^+\mu^-)$ and $\mathscr{B}(B^0\to\mu^+\mu^-)$ improve on the limits obtained by the individual experiments by about 15% for the background plus SM signal expected limits and by 32% for the background only ones.

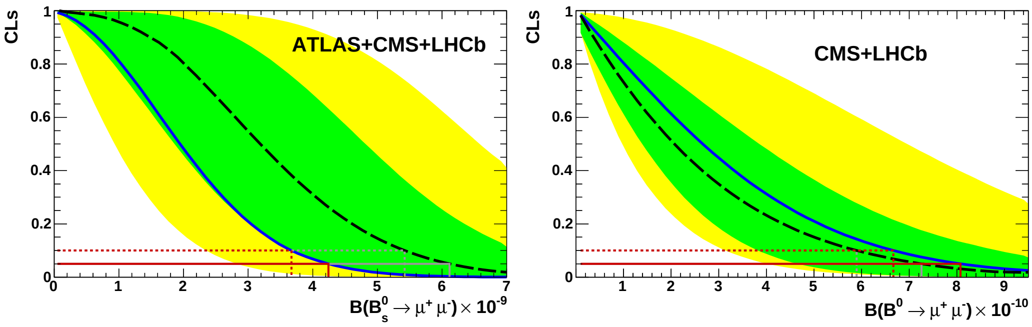

Figure 3: $\mathrm{CL_s}$ as a function of the assumed branching fraction for (left) $B_s^0\to\mu^+\mu^-$ and (right) $B^0\to\mu^+\mu^-$. The long dashed black curves are the medians of the expected $\mathrm{CL_s}$ distributions in case of background only observation. The green (yellow) areas cover, for each branching fraction, 34% (48%) of the expected $\mathrm{CL_s}$ distribution on each side of its median, corresponding to $\pm1(2)\sigma$ intervals. The solid blue curves are the observed $\mathrm{CL_s}$. The upper limits at 90 % (95 %) C.L. are indicated by the dotted (solid) horizontal lines in red (dark grey) for the observation and in argy for the expectation [5].

3.4 LHCb

The LHCb Collaboration has updated its search of $B_{d,s}^0\to\mu^+\mu^-$ decays in November 2012 including $1\mathrm{fb}^{-1}$ of integrated luminosity collected in 2012 at $\sqrt{s}=8$ TeV in addition to the $\sim 1\mathrm{fb}^{-1}$ of 2011 [14].

The core of the analysis stayed the same and the final search was performed in 6 bins of invariant mass and 8 and 7 bins of the multivariate BDT operator for the 2011 and 2012 samples respectively, in a simultaneous way sharing the branching fractions of the searched signals.

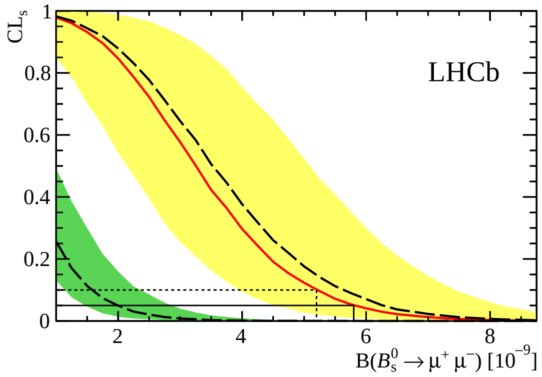

Figure 4: $\mathrm{CL_s}$ versus (left) $\mathscr{B}(B^0_s \to \mu^+\mu^-)$ and (right) $\mathscr{B}(B^0 \to \mu^+\mu^-)$ as obtained in the LHCb analysis [14]. Dashed lines are expected distributions in case of no signal observation (surrounded by 1σ green bands) or in case of background plus SM signal observation (surrounded by 1σ yellow bands). Continuous red line represents the observed distribution.

The $\mathrm{CL_s}$ distribution as a function of the $\mathscr{B}(B^0_s \to \mu^+\mu^-)$ is shown in Figure 4(left). As it can be seen the observed line is inconsistent with the expectations for the case of background only; the p-value of this excess was estimated as $1-\mathrm{CL_b} = 5\cdot 10^{-4}$ corresponding to a significance of 3.5σ representing therefore the first evidence of this decay.

The analogous distribution of the B^0_d channel is reported in Figure 4(right) where only a non significant excess in instead present. The upper limit on the signal branching fraction obtained at 95% CL is:

$$\mathscr{B}(B^0 \to \mu^+\mu^-) < 9.4\times 10^{-10} \quad .$$

Having an evidence in the $B^0_s \to \mu^+\mu^-$ channel the LHCb collaboration has also performed a simultaneous unbinned fit to the invariant mass distributions in the different BDT bins in order to estimate the branching fraction, reporting a result of:

$$\mathscr{B}(B^0_s \to \mu^+\mu^-) = (3.2^{+1.4}_{-1.2}(\mathrm{stat})^{+0.5}_{-0.3}(\mathrm{syst}))\times 10^{-9} \tag{3.2}$$

well compatible with the Standard Model predictions.

4. Search for $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ and other rare B meson decays at LHCb

The core physics program of the LHCb experiment includes a broad range of analyses of rare B meson decays: study of the $B^0 \to K^*\mu^+\mu^-$ decay, which is discussed in a separate contribution in this proceedings [21]; study of the radiative B meson decays (e.g. $B^0_s \to \phi\gamma$ and $B^0 \to K^*\gamma$ [12]) which are not discussed in this paper as of major interest of LHCb only, and various searches for Lepton or Baryon number violating decays [15, 13].

Here we will only discuss the recent search for $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ decays [16] performed by the LHCb collaboration. This decay is possible in the Standard Model mediated by the $B^0_s \to J/\psi\phi$ decay where both resonances decay into two muons, corresponding to a total branching fraction of $(2.3\pm 0.9)\cdot 10^{-8}$. The non-resonant component is instead a flavour changing neutral current, the principal contribution of which comes from the $B^0_s \to \mu^+\mu^-\gamma(\to \mu^+\mu^-)$ decay and has an expected

Standard Model branching fraction lower than 10^{-10} [17]. In New Physics models however this could be mediated by new scalar and pseudoscalar particles which could enhance its branching fraction of various orders of magnitude [18].

A search for B decays with four muons in the final state has been performed at LHCb exploiting 1fb^{-1} of integrated luminosity collected in 2011 at $\sqrt{s} = 7$ TeV. The search is based on four good quality muon tracks forming a secondary vertex, with $\chi^2/\mathrm{ndof} < 30$, displaced from the primary one. Tight muon identification criteria are applied and the di-muon invariant mass regions corresponding to the resonances are excluded from the search and used as control channel. The dominant background is the combinatorial one, while the largest peaking background, due to $B^0 \to \psi(2S)K^*$ decays, has a negligible expected yield of 0.44 events.

The signal event yield was converted into a branching fraction normalising to the $B^0 \to J/\psi(\to \mu^+\mu^-)K^{*0}(\to K^+\pi^-)$ decay with S-wave excluded. This was selected with the very same selection of the signal channel with the exception of the particle identification.

No events in excess of the expected background levels were observed and upper limits on the branching fractions were put using the CLs method at 90% (95%) CL:

$$\begin{aligned}\mathscr{B}(B_s^0 \to \mu^+\mu^-\mu^+\mu^-) &< 1.2(1.6)\times 10^{-8}\\ \mathscr{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) &< 5.3(6.6)\times 10^{-9}\end{aligned} \quad ,$$

using a phase space model for the signal decay. Since the efficiency did not vary significantly using a model with a scalar and a pseudoscalar mediating particle similar upper limits were put also in this case.

5. Discussion

Despite large enhancements on the branching fractions have now been excluded, the search for $B^0_{d,s} \to \mu^+\mu^-$ decays is just at the beginning. After a first evidence from the LHCb experiment for the $B_s^0 \to \mu^+\mu^-$ decay a confirmation with more statistics and independently from the other experiments is awaited. The three experiments are expected to update their searches in the near future exploiting the full statistics of 2011 and 2012 runs (corresponding to about 25fb^{-1} for ATLAS, CMS and 3.1 fb^{-1} for LHCb). Given the current analysis performances an event yield of about 10 $B_s^0 \to \mu^+\mu^-$ SM events is expected for both ATLAS and CMS in the final search window while about 10 events per fb^{-1} are foreseen in LHCb in the full BDT range.

Furthermore all the three experiments are implementing improvements in their respective analyses: an invariant mass fit is being developed instead of the counting experiment search by ATLAS and CMS, and better multivariate operators are under study by the three collaborations. Therefore performances should be better than an extrapolation with luminosity of the previous results. Furthermore ATLAS and CMS are performing measurements of the hadronisation fractions ratio (f_s/f_u) needed in the normalisation, in order not to have to use the LHCb measurement which has shown how this parameter is dependent on the B meson kinematics [11].

The $B^0 \to \mu^+\mu^-$ decay, at the SM level, should be still out of reach of the experiments, but tight limits will be put on its branching fraction. Alternatively, with a significant signal on the B_s^0 channel, a limit on the ratio of branching fractions ($R = \mathscr{B}(B^0 \to \mu^+\mu^-)/\mathscr{B}(B_s^0 \to \mu^+\mu^-)$)

can be assessed: this is the most precise observable in these channels for testing the Minimal Flavour Violation hypothesis and from the experimental point of view cancels the need for an external normalisation, diminishing the uncertainties. This observable will certainly be the next step in precision measurements of these decays for the three experiments. In view of the LHC Run II, and especially of the upgrade, other observables could be also considered [9]: while the CP violation, due to the need of flavour tagging could be still out of reach, the effective lifetime should be measurable with enough $B^0_s \to \mu^+\mu^-$ events. On this long term extrapolation, while LHCb is expected to keep the overall efficiency roughly constant ATLAS and CMS will have to cope with unprecedented luminosity conditions and are studying improvements on their dedicated triggers: ATLAS is studying an invariant mass cut to be applied at a Level 1 topological trigger while CMS is foreseeing the possibility of moving some of the offline analysis cuts directly at the L1 and/or HLT level.

5.1 Other rare B decays

While various analysis of other rare B decays will be continued or started at LHCb in the future, not all of them can be backed by the other two experiments. In particular searches not involving at least one muon in the final state are almost impossible at ATLAS and CMS due to the harsh environment with which the trigger at so low masses would have to cope. Therefore apart from the already mentioned decays only the previously described $B^0_s \to \mu^+\mu^-\mu^+\mu^-$ decay could be added.

Acknowledgements

The authors would like to thank the organisers for the invitation to present this topic and for providing such a nice environment for the discussion.

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