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Search for the rare decay $B_s^0 \to \mu^+\mu^-$ at the LHC with the CMS and LHCb experiments

The CMS and LHCb collaborations[1]

Abstract

A combination of the results of the search for the decay $B_s^0 \to \mu^+\mu^-$ is performed using about 0.34 fb^{-1} and 1.14 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV, collected by the LHCb and CMS experiments, respectively, at the Large Hadron Collider at CERN. The observed candidates in both experiments are consistent with the expectation from the sum of backgrounds and Standard Model signal. The combination results in an upper limit on the branching ratio, $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.08 \times 10^{-8}$ at 95% confidence level.

[1]Conference report prepared for the EPS-HEP conference, Grenoble, 21–27 July 2011; contact authors Frederic.Teubert@cern.ch, cms-pag-conveners-bphysics@cern.ch.

1 Introduction

Within the Standard Model (SM) the exclusive dimuon decay of the B_s^0 meson is rare, as it occurs only via loop diagrams and is helicity suppressed. The predicted branching ratio is [1]:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM} \quad = \quad (3.2 \pm 0.2) \times 10^{-9} \ .$$

New Physics models, especially those with an extended Higgs sector, can significantly enhance the branching ratio.

The most restrictive limits on the search for $B_s^0 \to \mu^+\mu^-$ have so far been achieved at the Tevatron [2, 3] and at the LHCb experiment [4], due to the large $b\bar{b}$ cross-section at hadron colliders. The CDF collaboration recently released a new result [5] based on 7 fb^{-1} of integrated luminosity, where they observe an excess of events over the background-only hypothesis (p-value[2] of 0.27%), and determine $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (1.8^{+1.1}_{-0.9}) \times 10^{-8}$. CDF also provides an upper limit of $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 4.0 \times 10^{-8}$ at 95% CL, which is the most restrictive limit prior to the LHCb and CMS measurements that are combined in this note.

The CMS collaboration has analyzed a total of 1.14 fb^{-1} of pp collisions at $\sqrt{s} =$ 7 TeV collected in 2011, up to early July. The observed number of candidates [6] is consistent with the sum of background and SM signal, correspoding to an upper limit of $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.9 \times 10^{-8}$ at 95% CL.

The LHCb collaboration has analyzed a total of 0.037 fb^{-1} and 0.30 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV, collected in 2010 and 2011, respectively. The results obtained with the 2010 data sample are published [4] and provide an upper limit of $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ $< 5.6 \times 10^{-8}$ at 95% CL. The new preliminary results obtained with the 2011 data sample [7] show a slight excess over the background-only hypothesis (p-value of 14%), which is consistent with the presence of a SM signal, and provide an upper limit of $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.6 \times 10^{-8}$ at 95% CL. The combination of the 2010 and 2011 data samples results in an upper limit of $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.5 \times 10^{-8}$ at 95% CL.

In this note, the LHCb and CMS results on the search for the $B_s^0 \to \mu^+\mu^-$ decay are combined. Although both collaborations also have interesting results on the search for the $B^0 \to \mu^+\mu^-$ decay [4, 7, 6], the combination of those results requires further work to properly take into account the correlations in the analyses. In the case of the B_s^0 decay the combination is relatively straightforward, as the background is completely dominated by combinatorial background, and other sources of background such as the peaking background from $B \to hh'$ decays (with the hadrons misidentified as muons) are small.

[2]The calculation of p-values is discussed in Sect. 3.

2 Input to the combination

Since the background level depends significantly on the pseudorapidity of the B_s^0 candidate, the CMS analysis [6] separates the events into two categories: the Barrel contains the candidates where both muons have $|\eta| < 1.4$ and the Endcap contains those where at least one muon has $1.4 < |\eta| < 2.4$. The expected number of signal events (assuming the SM branching ratio) is evaluated using a normalization factor computed from the observed number of $B^+ \to J/\psi K^+$ candidates. To compute the normalization factor, CMS uses the value of the ratio of fragmentation functions as quoted in Ref. [8], $f_s/f_d = 0.282 \pm 0.037$. In the combination procedure the more precise value recently measured by LHCb [9], $f_s/f_d = 0.267 \pm 0.021$, has been used to compute the expected number of signal events, as quoted in Table 1. We assume this value is also valid in the CMS acceptance, and do not assign any additional systematic uncertainty. The expected number of combinatorial background events in the search window quoted in the table is extracted from a fit to the invariant mass sidebands. The contribution of the misidentified peaking background from $B^0_{(d,s)} \to h^+h^{'-}$ in the B_s^0 search window is very small, as can be seen in Table 1. The only relevant correlation between uncertainties is due to the uncertainty on f_s/f_d, which is taken to be 100% correlated between the number of expected signal events in the Barrel and Endcap measurements. Other sources of correlation, such as the uncertainty on $\mathcal{B}(B^+ \to J/\psi K^+)$, can be neglected at the current level of precision.

The LHCb analysis [7] is very similar to the one previously published [4]. The analysis is performed in four bins of the multivariate discriminant variable, and six bins of the invariant mass. For each of these 24 bins in the two-dimensional plane, the expected number of signal events quoted in Table 2 is computed using a combination of three normalization factors obtained from the numbers of $B^+ \to J/\psi K^+$, $B_s^0 \to J/\psi\phi$ and $B^0 \to K^+\pi^-$ candidates. The probability of a signal event to fall in each bin is obtained from the data sample itself using $B^0_{(d,s)} \to h^+h^{'-}$ decays to evaluate the multivariate discriminant variable probability and dimuon resonances to measure the dimuon invariant mass resolution. The expected number of combinatorial background events quoted in Table 2 is extracted from a fit to the invariant mass sidebands. As in the CMS analysis, the contribution of the misidentified peaking background in the B_s^0 search window is very small. The only relevant correlation with the CMS analysis is again the uncertainty on f_s/f_d, which is taken to be 100% correlated between the number of expected signal events in all the LHCb bins and with the two CMS bins.

As mentioned before, LHCb also includes the 2010 results in the final combination, hence Table 3 extracted from Ref. [4], corrected by the latest value of f_s/f_d used here, is also an input to the combination.

Table 1: Expected background events (excluding misidentification), expected background events from misidentification, expected signal events assuming the SM branching ratio prediction, and observed events in the $B_s^0 \to \mu^+\mu^-$ search window, from the CMS analysis of the 2011 data. Uncertainties include systematic effects.

Invariant Mass (MeV/c^2)		Barrel region	Endcap region
5300 – 5450	Exp. bkg.	0.60 ± 0.35	0.80 ± 0.40
	Exp. misid.	0.07 ± 0.02	0.04 ± 0.01
	Exp. signal	0.76 ± 0.11	0.34 ± 0.06
	Observed	2	1

Table 2: Expected background events (excluding misidentification), expected background events from misidentification, expected signal events assuming the SM branching ratio prediction, and observed events in the $B_s^0 \to \mu^+\mu^-$ search window, from the LHCb analysis of the 2011 data.

			Multivariate discriminant			
			$0. - 0.25$	$0.25 - 0.5$	$0.5 - 0.75$	$0.75 - 1.$
Invariant Mass (MeV/c^2)	$5298 - 5318$	Exp. bkg.	514^{+12}_{-11}	$4.32^{+0.39}_{-0.39}$	$0.504^{+0.158}_{-0.095}$	$0.118^{+0.078}_{-0.039}$
		Exp. misid.	$0.052^{+0.056}_{-0.039}$	$0.052^{+0.055}_{-0.039}$	$0.050^{+0.056}_{-0.039}$	$0.052^{+0.057}_{-0.040}$
		Exp. sig	$0.058^{+0.016}_{-0.014}$	$0.0280^{+0.0096}_{-0.0075}$	$0.0306^{+0.0074}_{-0.0057}$	$0.0332^{+0.0079}_{-0.0061}$
		Obs.	486	5	1	0
	$5318 - 5338$	Exp. bkg.	506^{+12}_{-11}	$4.25^{+0.38}_{-0.38}$	$0.502^{+0.157}_{-0.094}$	$0.115^{+0.076}_{-0.038}$
		Exp. misid.	$0.029^{+0.027}_{-0.017}$	$0.028^{+0.028}_{-0.017}$	$0.028^{+0.027}_{-0.016}$	$0.028^{+0.027}_{-0.016}$
		Exp. sig.	$0.199^{+0.046}_{-0.044}$	$0.097^{+0.030}_{-0.024}$	$0.106^{+0.021}_{-0.016}$	$0.114^{+0.023}_{-0.018}$
		Obs.	483	3	0	1
	$5338 - 5358$	Exp. bkg.	499^{+11}_{-11}	$4.19^{+0.38}_{-0.38}$	$0.499^{+0.156}_{-0.094}$	$0.112^{+0.074}_{-0.037}$
		Exp. misid.	$0.0192^{+0.0229}_{-0.0081}$	$0.0190^{+0.0220}_{-0.0082}$	$0.0199^{+0.0226}_{-0.0080}$	$0.0186^{+0.0212}_{-0.0083}$
		Exp. sig.	$0.371^{+0.084}_{-0.081}$	$0.181^{+0.056}_{-0.044}$	$0.197^{+0.039}_{-0.029}$	$0.214^{+0.043}_{-0.032}$
		Obs.	511	6	1	1
	$5358 - 5378$	Exp. bkg.	491^{+11}_{-11}	$4.13^{+0.37}_{-0.37}$	$0.496^{+0.155}_{-0.093}$	$0.109^{+0.072}_{-0.036}$
		Exp. misid.	$0.0139^{+0.0184}_{-0.0044}$	$0.0139^{+0.0189}_{-0.0048}$	$0.0138^{+0.0196}_{-0.0045}$	$0.0149^{+0.0198}_{-0.0042}$
		Exp. sig.	$0.371^{+0.085}_{-0.080}$	$0.181^{+0.056}_{-0.045}$	$0.197^{+0.039}_{-0.029}$	$0.214^{+0.043}_{-0.032}$
		Obs.	472	3	0	0
	$5378 - 5398$	Exp. bkg.	483^{+11}_{-10}	$4.07^{+0.37}_{-0.37}$	$0.494^{+0.154}_{-0.093}$	$0.106^{+0.070}_{-0.035}$
		Exp. misid.	$0.0105^{+0.0160}_{-0.0027}$	$0.0116^{+0.0164}_{-0.0025}$	$0.0110^{+0.0165}_{-0.0026}$	$0.0110^{+0.0163}_{-0.0028}$
		Exp. sig.	$0.199^{+0.047}_{-0.044}$	$0.097^{+0.030}_{-0.024}$	$0.106^{+0.021}_{-0.016}$	$0.114^{+0.023}_{-0.017}$
		Obs.	484	4	1	0
	$5398 - 5418$	Exp. bkg.	476^{+11}_{-10}	$4.01^{+0.36}_{-0.36}$	$0.491^{+0.154}_{-0.092}$	$0.103^{+0.069}_{-0.034}$
		Exp. misid.	$0.0085^{+0.0123}_{-0.0022}$	$0.0084^{+0.0122}_{-0.0020}$	$0.0082^{+0.0128}_{-0.0020}$	$0.0087^{+0.0123}_{-0.0023}$
		Exp. sig.	$0.057^{+0.017}_{-0.014}$	$0.0276^{+0.0095}_{-0.0074}$	$0.0302^{+0.0077}_{-0.0058}$	$0.0327^{+0.0083}_{-0.0064}$
		Obs.	436	5	0	0

Table 3: Expected background events, expected signal events assuming the SM branching ratio prediction, and observed events in the $B_s^0 \to \mu^+\mu^-$ search window, from the LHCb analysis of the 2010 data.

			Multivariate discriminant			
			0. – 0.25	0.25 – 0.5	0.5 – 0.75	0.75 – 1.
Invariant Mass (MeV/c^2)	5303 – 5323	Exp. bkg.	$56.9^{+1.1}_{-1.1}$	$1.31^{+0.19}_{-0.17}$	$0.282^{+0.076}_{-0.065}$	$0.016^{+0.021}_{-0.010}$
		Exp. sig	$0.0076^{+0.0034}_{-0.0030}$	$0.0050^{+0.0027}_{-0.0020}$	$0.0037^{+0.0015}_{-0.0011}$	$0.0047^{+0.0015}_{-0.0010}$
		Obs.	39	2	1	0
	5323 – 5343	Exp. bkg.	$56.1^{+1.1}_{-1.1}$	$1.28^{+0.18}_{-0.17}$	$0.269^{+0.072}_{-0.062}$	$0.0151^{+0.00195}_{-0.0094}$
		Exp. sig.	$0.0220^{+0.0084}_{-0.0081}$	$0.0146^{+0.0067}_{-0.0054}$	$0.0107^{+0.0036}_{-0.0027}$	$0.0138^{+0.0035}_{-0.0025}$
		Obs.	55	2	0	0
	5343 – 5363	Exp. bkg.	$55.3^{+1.1}_{-1.1}$	$1.24^{+0.17}_{-0.16}$	$0.257^{+0.069}_{-0.059}$	$0.0139^{+0.0179}_{-0.0086}$
		Exp. sig.	$0.038^{+0.015}_{-0.015}$	$0.025^{+0.012}_{-0.010}$	$0.0183^{+0.063}_{-0.047}$	$0.0235^{+0.0060}_{-0.0044}$
		Obs.	73	0	0	0
	5363 – 5383	Exp. bkg.	$54.4^{+1.1}_{-1.1}$	$1.21^{+0.17}_{-0.16}$	$0.246^{+0.066}_{-0.057}$	$0.0128^{+0.0165}_{-0.0080}$
		Exp. sig.	$0.038^{+0.015}_{-0.015}$	$0.025^{+0.012}_{-0.010}$	$0.0183^{+0.0063}_{-0.0047}$	$0.0235^{+0.0060}_{-0.0044}$
		Obs.	60	0	0	0
	5383 – 5403	Exp. bkg.	$53.6^{+1.1}_{-1.0}$	$1.18^{+0.17}_{-0.15}$	$0.235^{+0.063}_{-0.054}$	$0.0118^{+0.0152}_{-0.0073}$
		Exp. sig.	$0.0220^{+0.0084}_{-0.0081}$	$0.0146^{+0.0067}_{-0.0054}$	$0.0107^{+0.0036}_{-0.0027}$	$0.0138^{+0.0035}_{-0.0025}$
		Obs.	53	2	0	0
	5403 – 5423	Exp. bkg.	$52.8^{+1.0}_{-1.0}$	$1.14^{+0.16}_{-0.15}$	$0.224^{+0.060}_{-0.052}$	$0.0108^{+0.0140}_{-0.0068}$
		Exp. sig.	$0.0076^{+0.0031}_{-0.0027}$	$0.0050^{+0.0025}_{-0.0019}$	$0.0037^{+0.0013}_{-0.0010}$	$0.0047^{+0.0013}_{-0.0010}$
		Obs.	55	1	0	0

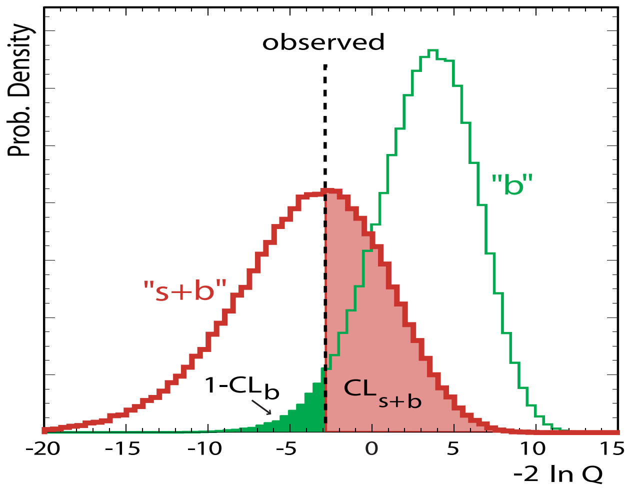

Figure 1: Illustration of the distribution of the classifier $-2\ln Q$ for the background-only hypothesis (green histogram) and signal-plus-background hypothesis (red histogram, thick line). The vertical dashed line shows an example of the observed value. The quantity $\mathrm{CL_{s+b}}$ is the integral of the red histogram from the observed value upwards and the quantity $1-\mathrm{CL_b}$ is the integral of the green histogram from the observed value downwards.

3 Combination procedure

The observed data configuration in the 48 LHCb bins (2010 and 2011 data) and 2 CMS bins is subjected to a likelihood ratio test of two hypotheses. In the background scenario it is assumed that the data receive contributions from the background processes only, while in the signal-plus-background scenario the contributions from a given value of $\mathcal{B}(B^0_s \to \mu^+\mu^-)$ are assumed in addition. The expressions for the corresponding likelihoods $\mathcal{L}_\mathrm{b}$ and $\mathcal{L}_\mathrm{s+b}$ can be found for instance in Ref. [10].

In a search experiment, the likelihood ratio

$$Q = \mathcal{L}_\mathrm{s+b}/\mathcal{L}_\mathrm{b}$$

makes efficient use of the information contained in the event configuration. For convenience, the logarithmic form $-2\ln Q$ is used as the test statistic since this quantity is approximately equal to the difference in χ^2 when the data configuration is compared to the background-only and signal-plus-background hypotheses.

The expected distributions of the test statistic $-2\ln Q$ using different branching ratio hypotheses are probability density functions for the background and the signal-plus-background hypotheses and include both the effects of random statistical variations in the numbers of events and the systematic uncertainties affecting the expected rates. Systematic uncertainties are incorporated by randomly varying the signal and background estimates in each bin. For a given source of uncertainty, correlations are addressed by applying these random variations simultaneously to all those bins where the uncertainty is relevant. For each $\mathcal{B}$ hypothesis in the range $(0.1-20)\times10^{-9}$, 10k background and

10k signal-plus-background pseudo-experiments are generated, and the results compared with the observed likelihood ratio in data.

In Fig. 1 examples of $-2\ln Q$ distributions are shown for the background hypothesis and for the signal-plus-background hypothesis. The quantity $\mathrm{CL_{s+b}}$ is the integral of the "s+b" hypothesis distribution from the observed value upwards, hence represents the probability that another experiment would give a lower likelihood than the observed one, under the hypothesis of signal-plus-background. $\mathrm{CL_{s+b}}$ is a measure of the incompatibility with the "s+b" hypothesis. The quantity $\mathrm{CL_b}$ is the integral of the "b" hypothesis distribution from the observed value upwards, hence the quantity $1-\mathrm{CL_b}$ (also referred to as the p-value) represents the probability that another experiment would give a lower likelihood than the observed one, under the hypothesis of background only. $1-\mathrm{CL_b}$ is a measure of the compatibility with the background hypothesis. The modified frequentist approach used in this note uses the ratio $\mathrm{CL_s} = \mathrm{CL_{s+b}}/\mathrm{CL_b}$ to calculate the exclusion limit, which is more conservative than using $\mathrm{CL_{s+b}}$, as it is less affected by background fluctuations.

4 Results and conclusions

The observed distribution of events from LHCb and CMS, when compared with the expected background distribution, results in $1-\mathrm{CL_b}$ (or p-value) of 8%. When a signal is included at the level expected in the Standard Model the p-value increases to 57%, indicating that the observed candidates are consistent with the sum of backgrounds and the Standard Model expectation.

The value of $\mathrm{CL_s}$, as computed from the distribution of events observed by LHCb and CMS, is shown in Fig. 2 as a function of the assumed branching ratio. The observed value of $\mathrm{CL_s}$ results in the limits:

$$
\begin{aligned}
\mathcal{B}(B_s^0 \to \mu^+\mu^-) &< 1.08 \times 10^{-8} \text{ at } 95\,\% \text{ CL},\\
\mathcal{B}(B_s^0 \to \mu^+\mu^-) &< 0.90 \times 10^{-8} \text{ at } 90\,\% \text{ CL},
\end{aligned}
$$

which clearly improve on the limits obtained by the individual experiments, and represent the best existing limits on this decay. An enhancement of the branching ratio by more than 3.4 times the Standard Model prediction is excluded at 95% CL. There still remains, however, room for a contribution from physics beyond the Standard Model.

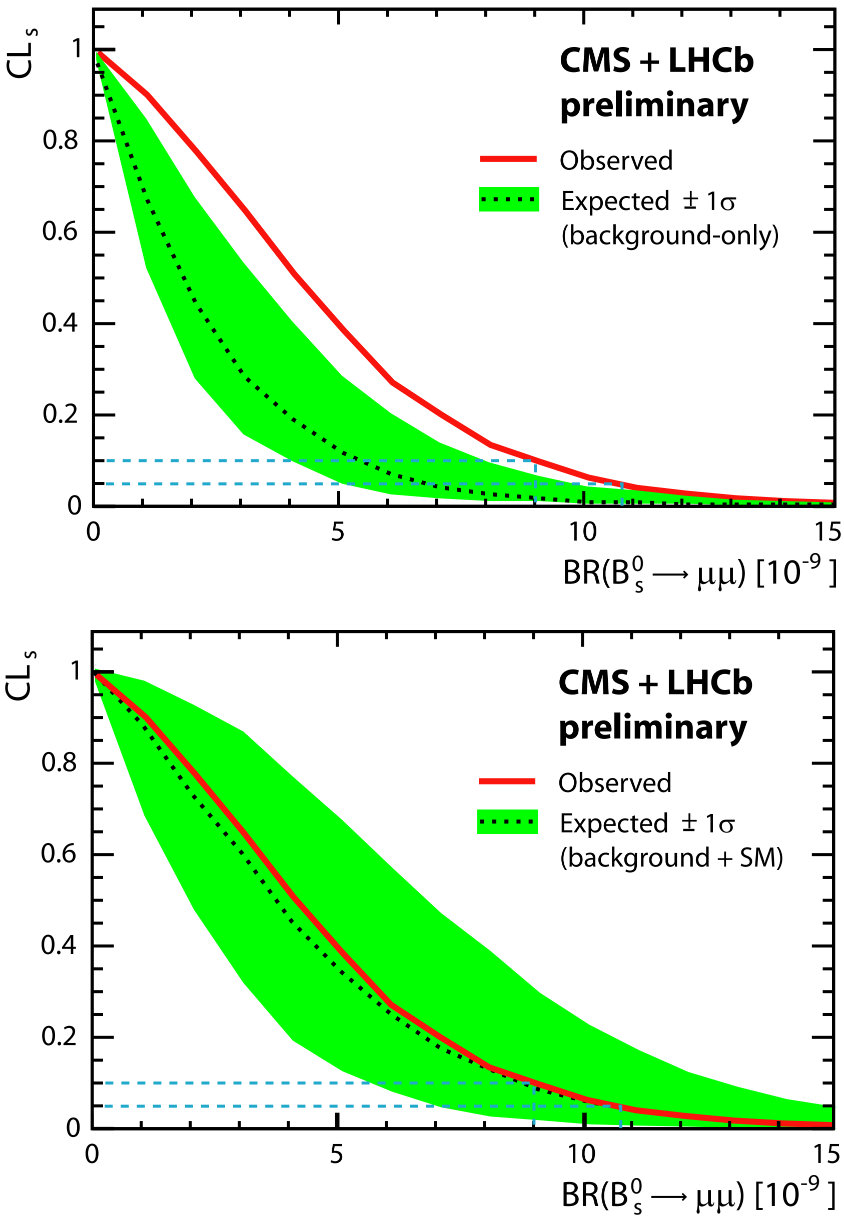

Figure 2: The observed (solid curve) and expected (dotted curve) CLs values, for background-only (top) and background plus the Standard Model signal (bottom), as a function of $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$. The green shaded area contains the $\pm 1\sigma$ interval of possible results compatible with the expected value; the 90% and 95% CL observed limits are illustrated by the dashed lines.

References

[1] C. Bobeth *et al.*,"Analysis of neutral Higgs-boson contributions to the decays $B^0_s \to l^+l^-$ and $B^0 \to Kl^+l^-$", Phys. Rev. D **64** (2001) 074014;
G. Buchalla and A.J. Buras, "The rare decays $K \to \pi\nu\bar{\nu}$, $B \to X\nu\bar{\nu}$ and $B \to l^+l^-$ – an update", Nucl. Phys. B **548** (1999) 309;
A.J. Buras, "Minimal flavour violation and beyond: Towards a flavour code for short distance dynamics", arXiv:1012.1447;
E. Gamiz *et al*, "Neutral B meson mixing in unquenched lattice QCD", Phys. Rev. D **80** (2009) 014503;
A.J. Buras, "Relations between $\Delta M_{s,d}$ and $B_{s,d} \to \mu^+\mu^-$ in models with Minimal Flavour Violation", Phys. Lett. B **566** (2003) 115.

[2] V. Abazov *et al.* [D0 collaboration], "Search for the rare decay $B^0_s \to \mu^+\mu^-$", Phys. Lett. B **693** (2010) 539.

[3] T. Aaltonen *et al.* [CDF collaboration], "Search for $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays with $2\,\mathrm{fb}^{-1}$ of $p\bar{p}$ Collisions", Phys. Rev. Lett. **100** (2008) 101802.

[4] R. Aaij *et al.* [LHCb collaboration], "Search for the rare decays $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$", Phys. Lett. B **699** (2011) 330.

[5] T. Aaltonen *et al.* [CDF collaboration], "Search for $B^0_s \to \mu^+\mu^-$ and $B^0_d \to \mu^+\mu^-$ Decays with CDF II", arXiv:1107.2304v1 [hep-ex] (2011).

[6] The CMS collaboration, "Search for $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays in pp collisions at $\sqrt{s} = 7$ TeV", CERN-PH-EP-2011-120, submitted to Phys. Rev. Lett.

[7] The LHCb collaboration, "Search for the rare decays $B^0_{(s)} \to \mu^+\mu^-$ with 300 pb^{-1} at LHCb", LHCb-CONF-2011-037, 27 July 2011.

[8] K. Nakamura *et al.* [Particle Data Group], "Review of particle physics", J. Phys. G **37** (2010) 075021.

[9] The LHCb collaboration, "Average f_s/f_d b-hadron production fraction for 7 TeV pp collisions", LHCb-CONF-2011-034, 26 July 2011.

[10] A.L. Read, "Presentation of search results: the $\mathrm{CL_s}$ technique", J. Phys. G **28** (2002) 2693;
T. Junk, "Confidence level computation for combining searches with small statistics", Nucl. Instrum. Meth. A **434** (1999) 435.