PROCEEDINGS OF SCIENCE

Very rare decays at LHCb

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Very rare decays are processes that are highly suppressed in the Standard Model, however theories that go beyond the Standard Model can often predict significant enhancements to their branching fractions making the study of very rare decays interesting as indirect searches for new physics. The results from searches for very rare decays at the LHCb experiment and combined analysis of CMS and LHCb Run 1 data for $B^0_{(s)} \to \mu^+\mu^-$ are reviewed.

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1. Introduction

Very rare decays are processes that are highly suppressed in the Standard Model (SM), however the branching fractions of these decays can be significantly affected by new physics models. These proceedings present the observation of $B^0_s \to \mu^+\mu^-$ and evidence for $B^0 \to \mu^+\mu^-$ from the combined analysis of the CMS and LHCb Run 1 data sets [1], the search for lepton flavour violating decays $B^0_{(s)} \to e^+\mu^-$ [3] and $\tau^- \to \mu^-\mu^+\mu^-$ [2] at LHCb and the search for $B^0 \to \mu^+\mu^-\mu^+\mu^-$ [4] at LHCb.

2. Observation of $B^0_s \to \mu^+\mu^-$ and Evidence for $B^0 \to \mu^+\mu^-$

In the SM the decays $B^0_{(s)} \to \mu^+\mu^-$ occur via flavour changing neutral currents and are highly suppressed by helicity and CKM constraints. The very small branching fractions can be enhanced in theories beyond the SM (BSM) by the presence of scalar and pseudoscalar particles contributing to the process, an example of this process is shown in Fig. 1 alongside the SM process. The SM provides precise predictions for the branching fractions of $B^0_{(s)} \to \mu^+\mu^-$ making the study of these decays interesting as indirect searches for new physics. As well as the individual branching fractions being interesting, the ratio of the branching fractions for each mode is also another interesting observable, as it has a more precise SM prediction that the individual fractions and is a probe of the flavour structure of the SM and BSM theories.

The Run 1 data sets of the CMS and LHCb collaborations have similar sensitivities to the $B^0_{(s)} \to \mu^+\mu^-$ decays and an analysis of the combined data sets has been performed [1]. The branching fractions were measured to be

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

These results have significances above the null hypothesis of 6.2 σ and 3.0 σ, respectively. They are compatible with the SM predictions within 1.2σ for the B^0_s and 2.2σ for the B^0. The ratio of the two decay modes was found to be $\mathscr{R} = 0.14^{+0.06}_{-0.08}$ which is compatible with the SM prediction within 2.3σ.

Although the results narrow the allowed phase space available to new physics models, the measured central value for the $B^0 \to \mu^+\mu^-$ branching ratio is approximately 4 times larger than

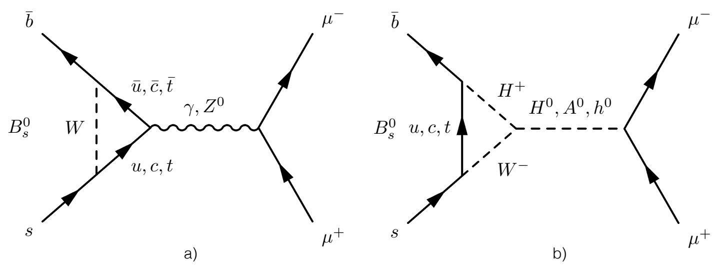

Figure 1: Feynman diagrams for $B^0_s \to \mu^+\mu^-$ a) shows a SM flavour changing neutral current and b) new physics particles entering into the loop.

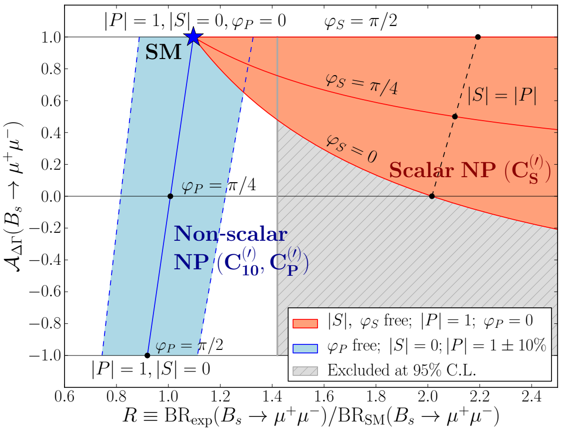

Figure 2: Plot of the allowed regions of new physics scenarios in the $B_s^0 \to \mu^+\mu^-$ decay in the plane $\mathscr{R} = \mathscr{B}(B^0 \to \mu^+\mu^-)/\mathscr{B}(B_s^0 \to \mu^+\mu^-)$ and the asymmetry parameter $A_{\Delta\Gamma}$ [5].

predicted and the measured uncertainties allow for new physics the same size as the observed anomaly in the so-called P_5' observable seen in $B^0 \to K^*\mu^+\mu^-$ decays [6, 7]. Therefore the study of $B_{(s)}^0 \to \mu^+\mu^-$ is still very much of interest in Run 2. Furthermore with higher statistics available in Run 2 and beyond new observables become accessible, specifically the $B_s^0 \to \mu^+\mu^-$ effective lifetime. The effective lifetime of the B_s^0 is sensitive to the asymmetry rate $\mathscr{A}_{\Delta\Gamma}$ which offers an independent probe of new physics complementary to the branching fraction measurements, as illustrated in Fig. 2 [5]. In the high luminosity era of the LHC and after the LHCb upgrade, LHCb could achieve an uncertainty of 5% on the effective lifetime, with around 50 fb^{-1} of data.

3. Lepton Flavour Violating Decays

Lepton flavour violating (LFV) decays are allowed in the SM within the context of massive neutrinos with branching fractions of $<10^{-40}$, well beyond the current experimental sensitivity. BSM theories can greatly enhance the branching fractions of LFV decays meaning that an observation would be an unambiguous sign of new physics. The anomalies observed in electroweak penguin decays [8] make the search for LFV decays very interesting.

3.1 The Search for $B_{(s)}^0 \to e^+\mu^-$

The decays $B_{(s)}^0 \to e^+\mu^-$ are predicted in the SM with branching fractions of the order of 10^{-54} but these branching fractions can be enhanced in various BSM theories including supersymmetric models [9], heavy singlet Dirac neutrinos [10] and the Pati-Salam model [11]. The Pati-Salam model allows $B_{(s)}^0 \to e^+\mu^-$ to occur via the exchange of a spin 1 gauge boson called a lepto-quark, Fig. 3. This lepto-quark would carry both colour and lepton quantum numbers. The $B_{(s)}^0 \to e^+\mu^-$ decays can be mediated by lepto-quarks that are not always from the same generation therefore the search for $B_{(s)}^0 \to e^+\mu^-$ is complementary to the lepto-quark searches preformed at ATLAS [12, 13, 14] and CMS [15, 16, 17] for 1$^{\text{st}}$, 2$^{\text{nd}}$ and 3$^{\text{rd}}$ generation lepto-quarks.

A search for $B_s^0 \to e^+\mu^-$ and $B^0 \to e^+\mu^-$ was performed on 1.0 fb^{-1} of data collected by LHCb at 7 TeV in 2011 [3]. The results are consistent with the background expectations, the

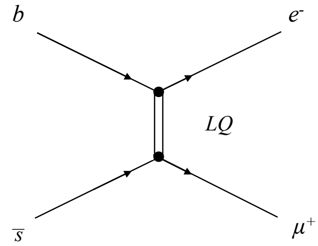

Figure 3: Feynman diagrams for $B_s^0 \to e^+\mu^-$ occurring the exchange of a lepto-quark in the Pati-Salam model [11].

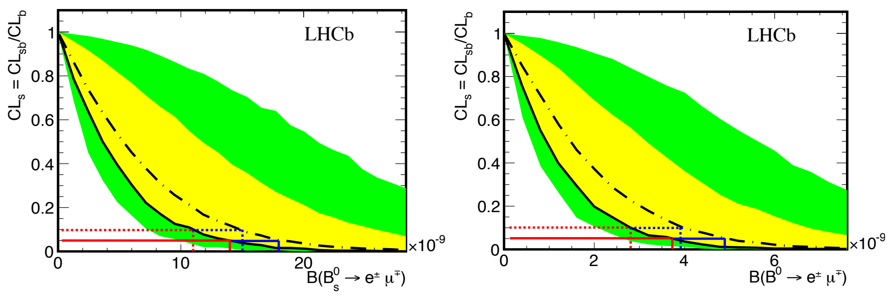

Figure 4: The distribution of CL$_s$ values for assumed branching fractions $B_s^0 \to e^+\mu^-$ on the left and $B^0 \to e^+\mu^-$ on the right. The dashed line shows the expected limit assuming only background events and the solid line shows the observed limit. The 90%(95%) limits are shown by the dotted (solid) lines in red for the observation and blue for the exception [3].

expected and observed CL$_s$ values are shown in Fig. 4 and upper limits were set on the branching fractions at

$$\mathscr{B}(B_s^0 \to e^+\mu^-) < 1.1(1.4) \times 10^{-8} \text{ at the } 90\%(95\%) \text{ C.L.}$$

$$\mathscr{B}(B^0 \to e^+\mu^-) < 2.8(3.7) \times 10^{-9} \text{ at the } 90\%(95\%) \text{ C.L.}$$

In the Pati-Salam model limits on the branching fractions can be translated into limits on lepto-quark masses [18] . Using this framework the branching fraction limits provide the following lepto-quark mass constraints when the lepto-quarks couple to different generations of quarks and leptons.

$$M_{LQ}(B_s^0 \to e^+\mu^-) > 107(101)\text{TeV/c}^2 \text{ at the } 90\%(95\%) \text{ C.L.}$$

$$M_{LQ}(B^0 \to e^+\mu^-) > 135(125)\text{TeV/c}^2 \text{ at the } 90\%(95\%) \text{ C.L.}$$

The limits for $B^0_{(s)} \to e^+\mu^-$ are the most stringent limits yet set and the lepto-quark mass limits are a factor 2 higher than previous bounds.

3.2 The Search for $\tau^- \to \mu^-\mu^+\mu^-$

The decay $\tau^- \to \mu^-\mu^+\mu^-$ is allowed in the SM in the context of massive neutrinos, Fig. 5a, with a branching fraction $< 10^{-40}$ [19, 20]. New physics particles can enter into loops, Fig. 5b,

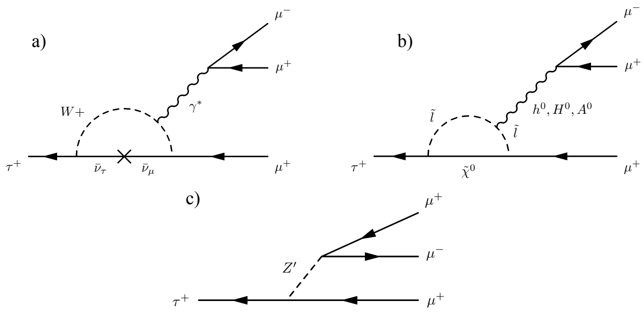

Figure 5: Feynman diagrams for $\tau^- \to \mu^-\mu^+\mu^-$ a) shows the SM process b) new physics particles entering into the loop and c) new physics particles allowing the decay to occur at the tree level.

increasing decay rates or can allow the decay to occur at tree level, Fig. 5c. These new physics models can increase the $\tau^- \to \mu^-\mu^+\mu^-$ branching fraction up to $10^{-9} - 10^{-7}$ placing this decay within the current experimental sensitivity [21]. A search for $\tau^- \to \mu^-\mu^+\mu^-$ was performed on 3fb^{-1} of data collected in 2011 and 2012 at 7 and 8 TeV by LHCb [2]. The observed number of events were consistent with the background expectations. The expected and observed CL$_s$ values are shown in Fig. 6 and an upper limit was placed on the branching fraction assuming that the muons are distributed depending on the available 3-body decay phase space at

$$\mathscr{B}(\tau^- \to \mu^-\mu^+\mu^-) < 4.6(5.6) \times 10^{-8} \text{ at the } 90\%(95\%) \text{ C.L.}$$

However the kinematic properties of the muons can depend on what process caused the lepton violation, an effective field theory approach can be used to provide a model independent analysis [22] and gives a range for the limit $\mathscr{B}(\tau^- \to \mu^-\mu^+\mu^-) < 4.1 - 6.8 \times 10^{-8}$ at the 90% C.L. Although the limit is not competitive with the results from the *B* factories, when combined with the *B* factory results the LHCb limits help to improve the world average. Run 2 of the LHC and the future LHCb upgrade will allow higher sensitivity to be reached which will benefit the search for $\tau^- \to \mu^-\mu^+\mu^-$.

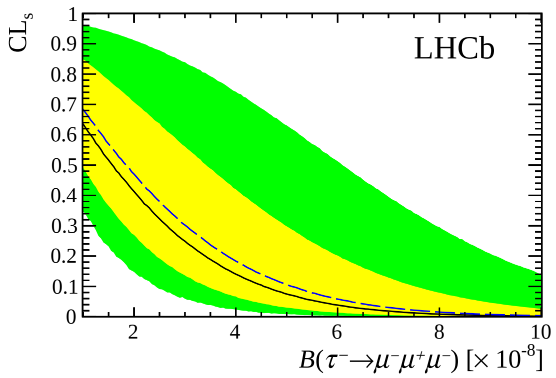

Figure 6: Distribution of CL$_s$ values for assumed branching fraction $\tau^- \to \mu^-\mu^+\mu^-$. The dashed line shows the expected limit assuming only background events and the solid line shows the observed limit. The green and yellow bands represent the 68% and 95% confidence level of the expected limits [2].

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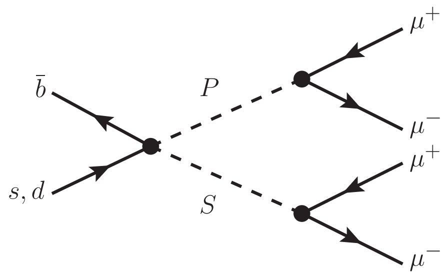

Figure 7: Feynman diagram for $B_s^0 \to \mu^+\mu^-\mu^+\mu^-$ occurring via the scalar, S, and pseudoscalar, P, particles in the minimal supersymmetric model [23].

4. The Search for $B_s^0 \to \mu^+\mu^-\mu^+\mu^-$

In the SM $B_s^0 \to \mu^+\mu^-\mu^+\mu^-$ is a highly suppressed decay but its branching fraction can be enhanced significantly by BSM theories [23, 24]. In the minimal supersymmetric model (MSSM) $B_s^0 \to \mu^+\mu^-\mu^+\mu^-$ can occur via scalar and pseudoscalar particles which in turn decay into muons, $B_s^0 \to S(\mu^+\mu^-)P(\mu^+\mu^-)$, as shown in Fig. 7 [23]. This type of process is particularly interesting because the HyperCP collaboration found evidence for $\Sigma^+ \to p\mu^+\mu^-$ consistent with the decay occurring via $\Sigma^+ \to pP(\mu^+\mu^-)$, with the pseudoscalar particle of mass 214.3 ± 0.5 MeV/c^2 [25].

A search for $B_s^0 \to \mu^+\mu^-\mu^+\mu^-$ was performed on 1.0 fb^{-1} of data collected at LHCb in 2011 at 7 TeV [4]. The search was sensitive to the supersymmetric decay $B_s^0 \to SP$ when the S and P particles are not significantly displaced for the B_s^0 decay vertex and the P has a mass similar to that of observed by the HyperCP collaboration. The observed events were consistent with the background expectations and upper limits were placed on the branching fraction assuming that the muons are distributed according to the available phase space

$$\mathscr{B}(B_s^0 \to \mu^+\mu^-\mu^+\mu^-) < 1.6(1.2) \times 10^{-8} \text{ at the } 90\%(95\%) \text{ C.L.}$$

$$\mathscr{B}(B_s^0 \to \mu^+\mu^-\mu^+\mu^-) < 6.6(5.3) \times 10^{-9} \text{ at the } 90\%(95\%) \text{ C.L.}$$

Upper limits were also set on the MSSM branching fraction $\mathscr{B}(B_s^0 \to SP)$ assuming a mass of 214.3 MeV/c^2 for the P and 2.5 GeV for the S at

$$\mathscr{B}(B_s^0 \to SP) < 1.6(1.2) \times 10^{-8} \text{ at the } 90\%(95\%) \text{ C.L.}$$

$$\mathscr{B}(B_s^0 \to SP) < 6.6(5.1) \times 10^{-9} \text{ at the } 90\%(95\%) \text{ C.L.}$$

This search produced the first constraints on the both the branching fractions $B_s^0 \to \mu^+\mu^-\mu^+\mu^-$ and $B_s^0 \to SP$.

5. Summary

These proceedings present an overview of results and searches for very rare decay at the LHCb experiment. The study of very rare decays is challenging due to the limited statistics available, however Run 2 of the LHC will significantly improve the reach of searches at LHCb for these decays. The current Run 1 results still leave plenty of room for new physics contributions to be found in very rare decays.

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