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Very rare decays at LHCb

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Rare decays are indirect probes of physics beyond the Standard Model. In this contribution the latest searches for New Physics in rare decays at LHCb are reported based on data collected in 2011 and 2012 at the LHC.

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1. Introduction

No signs of physics beyond the Standard Model (SM) have been found yet in direct searches therefore pushing the most probable scales of new effects higher in energy and smaller in cross-sections. Rare decays, especially of heavy flavours, are therefore a fundamental place to look for physics beyond the SM for various reasons. Considering effects which are tiny in the SM opens the possibility that New Physics (NP) effects contribute at the same level and, if the SM predictions are very precise, this leads to unambiguous interpretation of the results. The study of processes occurring via virtual loops probes energy scales higher than those that can be accessed for direct production. Finally, probing the flavour structure gives clear signatures of the type of NP to expect.

In this contribution we describe the latest searches for NP in rare decays with the LHCb experiment. The LHCb detector is appositely designed to collect the forward $b\bar{b}$ pairs production in high energy pp collisions. It is built as a forward single arm spectrometer and equipped as a standard multi-purpose detector with a tracking system with excellent momentum, and therefore mass, resolution, RICH detectors and muon stations for particle identification and electromagnetic and hadronic calorimeters. A fully detailed description is available elsewhere [1].

2. Search for lepton and baryon number violation in τ decays

Baryon number (B), lepton number (L) and lepton flavour (LF) are strictly conserved in the SM. The only notable exception are neutrino oscillations, and they would mediate LF violation in the charged lepton sector at the level of 10^{-40} in branching fractions. Many NP theories predict instead large violations to the conservation of these numbers, though most of them maintain the conservation of $|B-L|$. Any sign of these violations would mean physics beyond the SM, and searches are therefore important to constrain NP parameters.

A search for lepton flavour violation and for lepton and baryon number violation has been done at LHCb searching for $\tau^- \to \bar{p}\mu^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$ and $\tau^- \to \mu^-\mu^+\mu^-$ decays [2]. The inclusive production of τ leptons in LHCb is relatively large with a cross-section of 80 μb mainly from c- and b-hadron decays. This search was performed on a sample of 1fb^{-1} integrated luminosity collected in 2011 at $\sqrt{s} = 7$ TeV.

The three signal channels and the normalisation $D_s^- \to \phi(\to \mu^+\mu^-)\pi^-$ decay are reconstructed and selected with common criteria. Three tracks, well identified as muons, protons or pions, depending on the channel, are required to have transverse momentum $p_{\mathrm{T}} > 300$ MeV/c and not to come from the primary interaction (impact parameter $\chi^2 > 9$). The tracks have to make a common good quality vertex ($\chi^2 < 15$) displaced from the primary one ($c\tau > 100$ μm). The invariant mass of the three tracks have to be close to the τ^+ (D_s^-) mass. For the signal channels, opposite sign dimuons with mass around the ϕ are discarded, and an additional cut on $m_{\mu\mu} > 450$ MeV/c^2 is applied to the $\tau^- \to \mu^-\mu^+\mu^-$ to discard the background from $D_s^- \to \eta(\mu^+\mu^-\gamma)\mu^-\bar{\nu}_\mu$ decays; for same sign dimuons the latter cut is at 250 MeV/c^2.

The final classification of signal and background events is achieved, for the $\tau^- \to \mu^-\mu^+\mu^-$ decay, by means of three likelihoods: one to include all the topological information to distinguish three body from multi-body decays and to reject events with tracks from different vertices, one to summarise all the particle identification properties (PID), and the invariant mass likelihood. For

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$\tau \to p\mu\mu$ decays (both same and opposite sign muons) the PID likelihood is replaced by simple cuts. The invariant mass shape of signal events is taken from Monte Carlo simulations corrected for data-MC difference seen in the control channel $D_s^- \to \phi(\to \mu^+\mu^-)\pi^-$.

The signal yields are converted into a branching fraction as follows:

$$\mathscr{B}(\tau^- \to \mu^-\mu^+\mu^-) = \mathscr{B}(D_s^- \to \phi(\to \mu^+\mu^-)\pi^-) \times \frac{f_\tau^{D_s}}{\mathscr{B}(D_s^- \to \tau^-\bar{\nu}_\tau)} \times \frac{\varepsilon_{cal}}{\varepsilon_{sig}} \times \frac{N_{sig}}{N_{cal}}$$

where $f_\tau^{D_s}$ is the fraction of τ decays that originate from D_s^- decays calculated using the $b\bar{b}$ and $c\bar{c}$ cross-sections measured by LHCb [3, 4].

The expected remaining background for the three signal channels is due mainly to random combinations of correctly identified tracks. Therefore the final estimate of expected background events was obtained from fits to the invariant mass sidebands (shown in Figure 1). No excess of events over the expected background levels was observed in the signal regions and upper limits on the branching fractions were put with the $\mathrm{CL_s}$ method at the 90% (95%) C.L.:

$$\begin{aligned}\mathscr{B}(\tau^- \to \mu^-\mu^+\mu^-) &< 8.0(9.8) \times 10^{-8}\\ \mathscr{B}(\tau^- \to \bar{p}\mu^+\mu^-) &< 3.3(4.3) \times 10^{-7}\\ \mathscr{B}(\tau^- \to p\mu^-\mu^-) &< 4.4(5.7) \times 10^{-7}\end{aligned}$$

using phase space models of the signals. This represents the first limit on the $\tau^- \to \mu^-\mu^+\mu^-$ decay at a hadronic collider experiment, compatible with previous results. The limits on the $\tau \to p\mu\mu$ decays are the first direct constraints on these modes.

3. Search for $B^0_{d,s} \to \mu^+\mu^-$ decays at LHCb

The $B^0_{d,s} \to \mu^+\mu^-$ decays have been widely searched for about 40 years now [5]. This long lasting search is due to their importance in the comprehension of the SM and of any possible hint of physics beyond it. The $B^0_{d,s} \to \mu^+\mu^-$ decays are flavour changing neutral currents and are therefore allowed only at loop level within the SM and further suppressed by the GIM mechanism and due to helicity reasons. Therefore within the SM they are very rare and the most precise theoretical predictions of the branching fractions are [6, 7]:

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

Here the superscript $t = 0$ means CP-averaged branching fractions at time zero to distinguish from the experimental definition of branching fraction which is a time integrated measurement. This distinction is important when comparing measurements with predictions [8] since, owing to the finite lifetime difference between the heavy and the light mass eigenstates, the integrated branching fraction is different and in particular [9]:

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

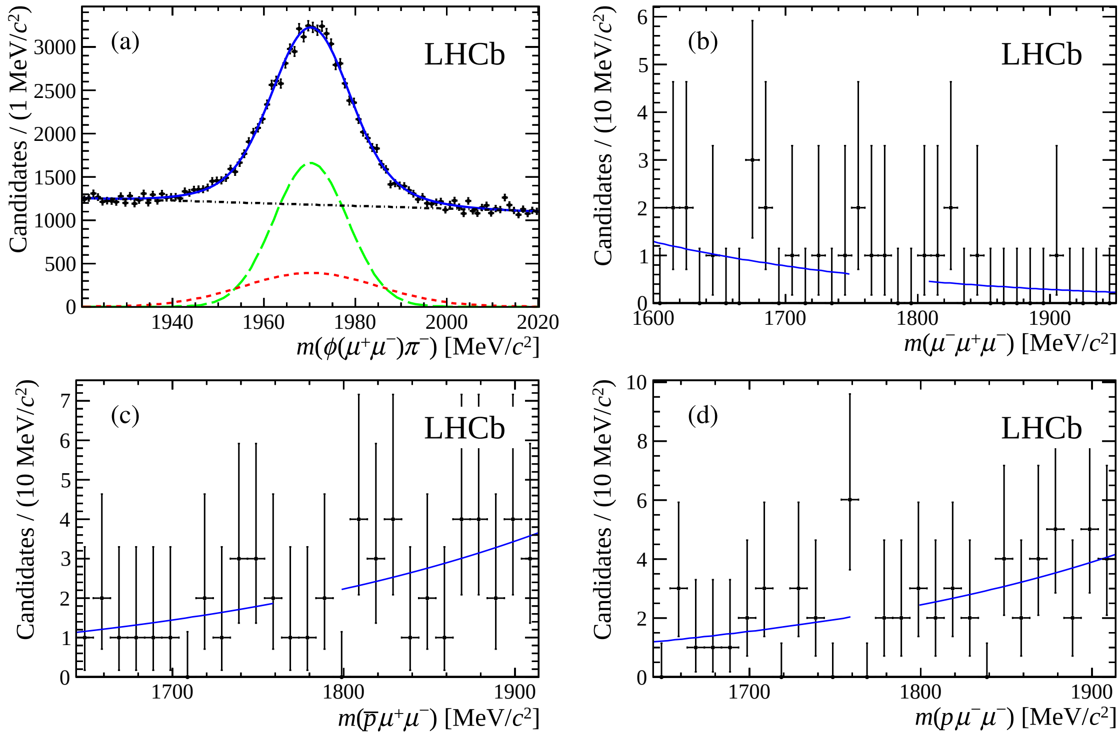

Figure 1: Invariant mass distribution of (a) $D_s^- \to \phi(\to \mu\mu)\pi$ candidates used as normalisation channel; invariant mass distributions of candidates in the search of (b) $\tau^- \to \mu^-\mu^+\mu^-$ (c) $\tau^- \to \bar{p}\mu^+\mu^-$ (d) $\tau^- \to p\mu^-\mu^-$ [2].

the last equality includes the last measurement of y_s [10] but also the SM value for $\mathscr{A}_{\Delta\Gamma}$ [9] and is therefore valid within this theory: 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 NP models can add contributions to these decays increasing or suppressing the branching fractions. A summary of the current status of theory predictions in the SM landscape and in the different NP panoramas can be found in these same proceedings [11].

Here we report on the last update of the search for $B^0_{d,s} \to \mu^+\mu^-$ decays at LHCb [12] which was performed on 1fb^{-1} and 1.1 fb^{-1} collected in 2011 at $\sqrt{s} = 7$ TeV and in 2012 at $\sqrt{s} = 8$ TeV respectively. An additional sample of about 1 fb^{-1} has been collected in 2012 and will be analysed in the near future. The analysis strategy for $B^0_{d,s} \to \mu^+\mu^-$ decays at LHCb is the following: first a loose selection rejects most of the background while having high efficiency on the signal, second a classification is performed in a two dimensional plane of the invariant mass and a multivariate operator. Events are triggered predominantly by dimuon and single muon trigger both at the hardware trigger level and at the first software level, while a selection very close to the offline one is applied at the second level of the software trigger. The offline selection requires pairs of oppositly charged well identified muons, and applies cuts on the quality of their common vertex, on the displacement with respect to the primary one and on $p_{\rm T}$ and IP of the muons. $B^+ \to J/\psi K^+$ and $B^0 \to K^-\pi^+$ decays are selected with a very similar selection and used both as control and normalisation channels.

Three kind of backgrounds have to be considered for this analysis. The combinatorial background, composed of random combinations of real muons, is the largest background and is estimated with fits to the invariant mass sidebands and extrapolated to the signal region. The misidentification background, due to mis-identified $B \to h^+h'^-$ decays (with $h^{(\prime)} = \pi, K, p$) and peaking in the signal invariant mass region, is carefully estimated directly on data with measurements of the misidentification probability. Finally, exclusive B decay channels, composed of decays with at least one real muon (e.g. $B_d \to \pi^-\mu^+\nu$, $B^+ \to \pi^+\mu^+\mu^-$), not being distributed exponentially in mass, have to be considered in the left invariant mass region in order not to overestimate the combinatorial background. All these components have been included in the description of the invariant mass distribution and evaluated in the signal region prior its unblinding.

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

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

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 efficiencies has been determined on Monte Carlo simulations but corrected with data driven methods. For what concerns tracking and particle identification, the efficiency has been measured directly on data. Finally the ratio of hadronisation fractions (f_{nc}/f_s) is taken from the LHCb measurement [13].

A multivariate operator built with a Boosted Decision Trees algorithm (BDT) has been used for the final search. Nine input variables have been used and the operator has been trained using MC simulations of the $B_s^0 \to \mu^+\mu^-$ signal and of the combinatorial background. The final search of signal events has been performed in a grid of 6 invariant mass bins and 7 (8) BDT bins for the 2012 (2011) sample. The PDFs for the two variables have been calibrated on data both for the signal using exclusive $B \to h^+h'^-$ decays and quarkonia decays in two muons, and for the background extrapolating from fits to the invariant mass sidebands in bins of BDT. The final assessment of the compatibility with the background-only and background-plus-signal hypotheses has been obtained with the $\mathrm{CL_s}$ method [14]. The $\mathrm{CL_s}$ value as a function of the $\mathscr{B}(B_s^0 \to \mu^+\mu^-)$ is shown in Figure 2 (left). The observed $\mathrm{CL_s}$ (red continuous line) is not compatible with the background only hypothesis (dashed with green bands) and lies close to the background plus signal one (dashed with yellow bands). 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 results for the $B^0 \to \mu^+\mu^-$ are reported in Figure 2 (right) where only a non significant excess is instead present. The upper limit on the signal branching fraction obtained at 95% CL is: $\mathscr{B}(B^0 \to \mu^+\mu^-) < 9.4\times 10^{-10}$. Given the evidence for the $B_s^0 \to \mu^+\mu^-$ decay a measurement of its branching fraction has been performed by means of a simultaneous unbinned fit to the invariant mass distributions in the different BDT bins. The fit resulted in a measured branching fraction of:

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

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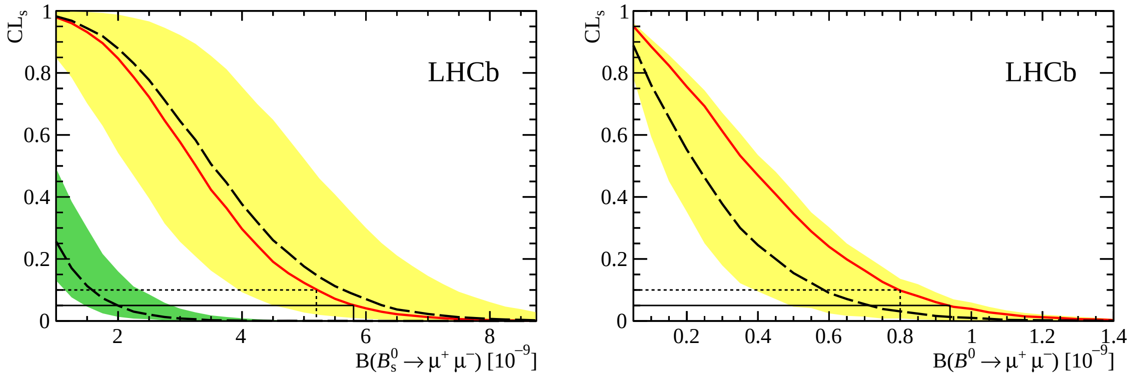

Figure 2: $\mathrm{CL_s}$ versus (left) $\mathscr{B}(B_s^0 \to \mu^+\mu^-)$ and (right) $\mathscr{B}(B^0 \to \mu^+\mu^-)$ as obtained in the LHCb analysis [12]. Dashed lines are expected distributions in case of no signal observation (surrounded by 1σ green bands) or in case of background plus SM signal observation (surrounded by 1σ yellow bands). Continuous red line represents the observed distribution [12].

in perfect agreement with the SM predictions and therefore limiting the parameter space of NP theories.

4. Search for $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$

The $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ decay is allowed in the SM as final state of the $B_s^0 \to J/\psi\phi$ decay when 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 $B_s^0 \to \mu^+\mu^-\gamma(\to \mu^+\mu^-)$ decay and has an expected SM branching fraction lower than 10^{-10} [15]. On the contrary in NP models this could be mediated by new scalar and pseudoscalar particles which could enhance its branching fraction of various orders of magnitude [16].

A search for B decays with four muons in the final state has been performed at LHCb exploiting $1\mathrm{fb}^{-1}$ of integrated luminosity collected in 2011 at $\sqrt{s} = 7$ TeV [17]. 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 channels. The dominant background is due to random combinations, 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 a similar selection to the signal channel one with the exception of the particle identification. The invariant mass distribution of the $B^0 \to J/\psi(\to \mu^+\mu^-)K^{*0}(\to K^+\pi^-)$ candidates is shown in Figure 3 (left) where the clear B_d^0 peak can be seen and a smaller B_s^0 peak is visible on the side.

When considering the signal region no events in excess of the expected background levels were observed, as it can be seen in Figure 3(right). Therefore upper limits on the branching fractions

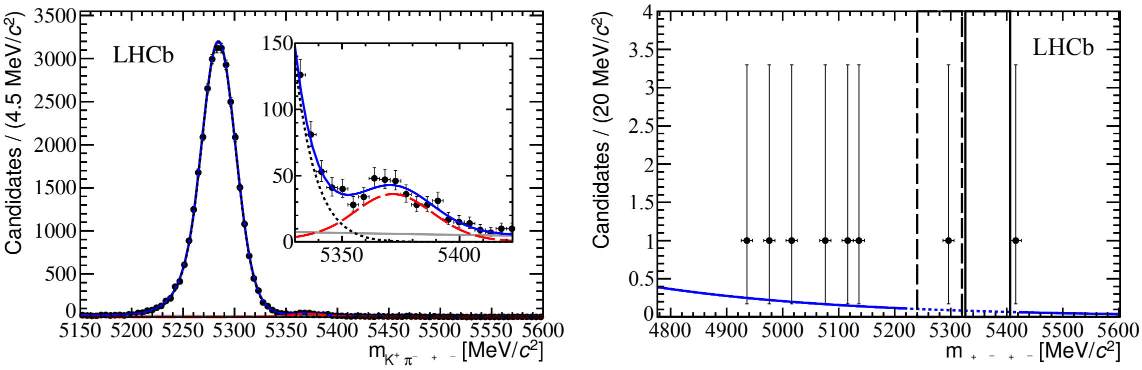

Figure 3: Invariant mass distribution of (left) $B^0 \to J/\psi(\to \mu^+\mu^-)K^{*0}(\to K^+\pi^-)$ candidates used for normalisation and (right) invariant mass distribution of the four muon candidates: the dashed and continuous lines show the borders of the B_d^0 and B_s^0 signal regions respectively [17].

were put using the $\mathrm{CL_s}$ method at 90% (95%) CL:

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

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. Conclusions

Rare decays are fundamental tools for the search and the characterisation of physics beyond the Standard Model. LHCb has searched for New Physics in various rare decay modes without success so far but finding the first evidence for the long awaited $B_s^0 \to \mu^+\mu^-$ decay, whose branching fraction seems to be in perfect agreement with SM predictions.

The search for different final states, like the $B^0 \to \mu^+\mu^-\mu^+\mu^-$ decay, opens further channels for the search of NP. Furthermore LHCb has demonstrated to be able to search also for rare τ and D decays in the harsh hadronic environment, putting constraints on different models of NP.

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