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Rare decays at LHCb

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Abstract

We review recent results from the LHCb experiment on studies of particle decays that are forbidden or rare in the Standard Model. The studies include searches for lepton flavour violating decays of the τ lepton and the B and D mesons, and of B and D meson decays that would be mediated by Majorana neutrinos. Results are also presented for the rare processes $B_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$, $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$, $b \rightarrow s\gamma$ transitions, and $B \rightarrow K^{(*)}\mu^+\mu^-$.

Keywords: Rare decays, Lepton flavor violation, Majorana neutrinos

1. Introduction

Searches for decays that are forbidden by symmetries of the Standard Model (SM) provide the potential for direct observations of new physics (NP), while branching fractions and differential decay distributions for decays which are allowed, but rare in the SM, such as those mediated by loop or box processes, may be particularly sensitive to NP contributions. Measurements of such processes therefore make for powerful tests of the SM. Here we discuss a number of forbidden and rare processes recently studied at the LHCb experiment.

2. The LHCb experiment and data sets

LHCb [1] is a dedicated flavour physics experiment at CERN's Large Hadron Collider, covering the forward rapidity region in proton-proton collisions, between approximately 2.0 and 5.0 units of rapidity, where heavy mesons are preferentially produced. The detector includes a precision vertex detector (VELO [2]) that is capable of achieving a resolution of better than $10\mu\text{m}$ in the horizontal plane, which is the bending plane of the 4 Tm dipole magnet. The entire tracking system provides momentum measurement with precision of about 0.5% over the momentum range 2–100 GeV/c. Two ring-imaging Cherenkov detectors (RICH) [3], together

with an electromagnetic calorimeter, a hadron calorimeter and a muon filter [4], provide charged and neutral particle identification. Typically 95% efficiency is obtained for kaon identification with a background of about 10% from misidentified pions. Muons are identified with up to 98% efficiency with a background of about 1%. The experiment runs with a flexible low- p_T trigger [5], down to transverse momenta of 250 MeV/c.

During the LHC's first run, LHCb collected 1 fb^{-1} of pp collision data at a centre-of-mass energy of 7 TeV in the year 2011, and a further 2 fb^{-1} at 8 TeV in 2012.

3. Searches for forbidden decays

3.1. Lepton flavour and baryon number violation in tau decays

In the SM, lepton flavour and baryon number are conserved by construction, due to so-called accidental symmetries, although neutrino flavour oscillations are now known to exist. Amplitudes for loop-mediated, charged lepton flavour violating decay processes (LFV), such as $\tau^- \rightarrow \mu^-\mu^+\mu^-$, which involves the virtual transition $\nu_\tau \rightarrow \nu_\mu$, are suppressed by factors of $\Delta m_\nu^2/M_W^2$, where Δm_ν^2 is the difference between the squared neutrino masses and M_W is the W -boson mass. As a result branching fractions for such decays would be smaller

than $O(10^{-40})$ [6, 7]. Many models of NP incorporate LFV and predict rates up to the present observational limits, which in the case of tau lepton decays are $O(10^{-8} - 10^{-7})$ [8].

LHCb has made a search for LFV in the decay $\tau^- \rightarrow \mu^- \mu^+ \mu^-$ using the full 3 fb^{-1} data sample [9]. The inclusive cross-section for tau production is $\sigma(pp \rightarrow \tau X) \approx 85 \mu\text{b}$ in the LHCb acceptance, and about 70% of all taus come from the decay of $D_s \rightarrow \tau \nu$. The current best limits on the branching fraction for this process come from the B factory experiments, BaBar and Belle (see [10] for a summary of LFV measurements). Unlike these experiments, LHCb has a high-multiplicity hadronic environment and an absence of tau tagging, and so a fundamentally different approach is required for such searches. The LHCb analysis looks for an isolated vertex that is consistent with being produced by a tau decay to three muons. Two multivariate classifiers are used to help suppress backgrounds. One uses quantities such as the vertex and track fit qualities, the vertex isolation and the direction of the tau candidate momentum, to help select events with the correct topology. The other classifier uses particle identification information for the three muon candidates. A channel in the data with similar properties to the signal, $D_s \rightarrow \phi(1020)\mu^-$ with $\phi(1020) \rightarrow \mu^+\mu^-$, is used to calibrate the responses of the classifiers and to normalise the measured rates of the signal channel, in order to produce limits on the branching fraction. LHCb obtains a limit $\mathcal{B}(\tau^- \rightarrow \mu^- \mu^+ \mu^-) < 4.6 \times 10^{-8}$ at 90% confidence level (CL).

In a similar analysis [11], using 1 fb^{-1} of data, LHCb also searched for the decays $\tau^- \rightarrow \bar{p}\mu^+\mu^-$ and $\tau^- \rightarrow p\mu^-\mu^-$, which would violate baryon number (B) and lepton number (L), as well as lepton flavour, and which would correspond to $|\Delta(B - L)| = 2$ transitions. No previous limits exist for these processes. LHCb obtains $\mathcal{B}(\tau^- \rightarrow \bar{p}\mu^+\mu^-) < 3.3 \times 10^{-7}$ and $\mathcal{B}(\tau^- \rightarrow p\mu^-\mu^-) < 4.4 \times 10^{-7}$, both at 90% CL.

3.2. Searches for Majorana neutrinos

Figure 1 shows a tree-level diagram for the decay $B^- \rightarrow \pi^+\mu^-\mu^-$, involving a massive Majorana neutrino N , which couples to the W^- as an antineutrino and to the W^+ as a neutrino. This process would be enhanced for Majorana neutrino masses between about 250 and 5000 MeV (i.e. $m_\pi + m_\mu$ and $m_B - m_\mu$), when the neutrino could be on-shell. LHCb has used its full 3 fb^{-1} data set in a search for this process, $B^- \rightarrow \pi^+\mu^-\mu^-$, which is sensitive for neutrino lifetimes up to about 1000 ps, with highest efficiency for short lifetimes [12]. By normalising to the control channel $B^- \rightarrow J/\psi K^-$ with

Figure 1: A possible Feynman diagram for the decay $B^- \rightarrow \pi^+\mu^-\mu^-$, mediated by a massive Majorana neutrino. (Figure from [12].)

$J/\psi \rightarrow \mu^+\mu^-$, LHCb obtains limits $\mathcal{B}(B^- \rightarrow \pi^+\mu^-\mu^-) < 0.5 - 4 \times 10^{-9}$ at 95% CL over the neutrino mass range from 250 to 5000 MeV/c^2 for a neutrino lifetime of 1 ps (see figure 2). The limits are higher for longer lifetimes, rising to $< 10^{-7}$ for a lifetime of 1000 ps and mass below $4.5 \text{ GeV}/c^2$. Limits are also placed on possible fourth-generation couplings $|V_{\mu 4}|^2$ as a function of the Majorana neutrino mass, in the context of the model of Ref. [13].

Figure 2: LHCb upper limits on the branching fraction for the decay $B^- \rightarrow \pi^+\mu^-\mu^-$, mediated by a possible Majorana neutrino, as a function of the neutrino mass. In this example, the neutrino is assumed to have a lifetime of 1 ps. (Figure from [12].)

LHCb has also performed searches for massive Majorana neutrinos in decays of charmed mesons, specifically in the processes $D_{(s)}^+ \rightarrow \pi^-\mu^+\mu^+$, for which the Feynman diagram is similar to that shown in figure 1 [14]. Before this work, the world best limits were from the BaBar experiment, $\mathcal{B}(D^+ \rightarrow \pi^-\mu^+\mu^+) < 2 \times 10^{-6}$ and $\mathcal{B}(D_s^+ \rightarrow \pi^-\mu^+\mu^+) < 2 \times 10^{-6}$, both at 90% CL [15]. In the LHCb analysis, multivariate classifiers are used to discriminate signal from background, using particle identification information together with kinematic and geometric variables, trained on Monte Carlo simulations of the signal together with a small sample of data (for the background) that is not used in the final analysis. Peaking backgrounds are seen to arise from

$D_{(s)}^+ \rightarrow \pi^+\pi^+\pi^-$, with a pion misidentified as a muon; these backgrounds are measured with the data sample. The normalisation channel for this analysis is $D_{(s)}^+ \rightarrow \phi(1020)\pi^+$, with $\phi(1020) \rightarrow \mu^+\mu^-$. Fits to the $\pi^-\mu^+\mu^+$ mass spectra are made for bins of the $\pi^-\mu^+$ mass in order to give improved sensitivity to the presence of a Majorana neutrino at a specific mass, decaying into $\pi^-\mu^+$. LHCb obtains limits $\mathcal{B}(D^+ \rightarrow \pi^-\mu^+\mu^+) < 2.2 \times 10^{-8}$ and $\mathcal{B}(D_s^+ \rightarrow \pi^-\mu^+\mu^+) < 1.2 \times 10^{-7}$, which are a factor of about 50 better than the previous best results.

3.3. Lepton flavour violation in B -meson decays

Lepton flavour violating decays of B mesons are allowed in several NP models such as those with heavy singlet Dirac neutrinos [16], R-parity violating and lepton number violating SUSY [17] and models with leptoquarks coupling leptons and quarks of different generations (so-called Pati-Salam leptoquarks) [18]. LHCb has made searches for the two channels $B_{(s)}^0 \rightarrow e^\pm\mu^\mp$ using their 1 fb^{-1} sample of data taken at $\sqrt{s} = 7\text{ TeV}$ [19]. Potential signal is normalised using the channel $B^0 \rightarrow K^+\pi^-$, with $B_{(s)}^0 \rightarrow h^+h'^-$ as a control channel, where h, h' indicate pions or kaons. The principal background in this analysis comes from semileptonic b decays ($b\bar{b} \rightarrow e^\pm\mu^\mp X$) and from particle misidentification. Candidates are classified according to the $e^\pm\mu^\mp$ mass and the output of a boosted decision tree with nine input variables related to the event topology. No signal is observed and limits on the branching fractions are set at $\mathcal{B}(B_s^0 \rightarrow e^\pm\mu^\mp) < 1.1 \times 10^{-8}$ and $\mathcal{B}(B^0 \rightarrow e^\pm\mu^\mp) < 2.8 \times 10^{-9}$, both at 90% CL. These limits are an order of magnitude smaller than the previous world best. The $B^0 \rightarrow e^\pm\mu^\mp$ limit is used to set a limit on the mass scale of leptoquarks in the Pati-Salam model [18], $M_{LQ} > 135\text{ TeV}$ at 90% CL.

4. Rare Standard Model decays

4.1. B^0 and B_s decays to dimuons

Using their 3 fb^{-1} data sample, LHCb has measured the rare decays $B_s \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ [20]. In this analysis the events are classified according to their mass and the output of a boosted decision tree. Selection efficiencies were calibrated and rates were normalised using the channels $B^0 \rightarrow K^+\pi^-$ and $B^+ \rightarrow J/\psi\pi^+$ with $J/\psi \rightarrow \mu^+\mu^-$. Figure 3 shows the $\mu^+\mu^-$ mass spectrum for signal candidates with BDT output larger than 0.7. The solid (blue) curve shows the result of an unbinned maximum likelihood fit in which the signal yields are free parameters, while the long-dashed (red) and medium-dashed (green) lines show the B_s and B^0 contributions (the other curves give various background contributions, as described in Ref. [20], from where the figure is taken).

B^0 contributions (the other curves give various background contributions). A signal is seen at the level of 4σ for the B_s decay, with a measured branching fraction $\mathcal{B}(B_s \rightarrow \mu^+\mu^-) = (2.9_{-1.0}^{+1.1}) \times 10^{-9}$, while a limit is placed for the B^0 decay, $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 7.4 \times 10^{-10}$ at 95% CL. The LHCb measurements have been combined with results from the CMS experiment [21], as reported in [22].

Figure 3: Invariant mass of selected $\mu^+\mu^-$ candidates with BDT output greater than 0.7, for the decays $B_{(s)} \rightarrow \mu^+\mu^-$. The solid (blue) curve shows the result of an unbinned maximum likelihood fit, while the long-dashed (red) and medium-dashed (green) lines show the B_s and B^0 contributions (the other curves give various background contributions, as described in Ref. [20], from where the figure is taken).

4.2. Flavour-changing neutral currents in $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$

Figure 4 shows the lowest order Feynman diagrams for the rare decay $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$. The GIM suppression of the flavour changing neutral current is more effective in charm than in beauty decays. In the SM the branching fraction is expected to be of order 10^{-9} , but this could be enhanced by the presence of NP, which motivates the search by LHCb for this channel [23]. The analysis uses D^0 mesons tagged by the decay $D^{*+} \rightarrow D^0\pi^+$ in 1 fb^{-1} of data, with the decay mode $D^0 \rightarrow \pi^+\pi^-\phi$, $\phi \rightarrow \mu^+\mu^-$ used for normalization. Fits to signal yields are made in four bins of $\mu^+\mu^-$ mass. As expected, signals are seen from $D^0 \rightarrow \pi^+\pi^-\rho^0$ and $\pi^+\pi^-\phi$ with $\rho/\phi \rightarrow \mu^+\mu^-$, but there is no evidence for a signal outside of these resonance regions. By combining the low ($< 525\text{ MeV}$) and high ($> 1100\text{ MeV}$) dimuon mass regions, LHCb obtain $\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-) < 5.5 \times 10^{-7}$ at 90% CL, which is a factor of 50 below the previous world best limit.

Figure 4: Feynman diagrams for the flavor-changing neutral current decay $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$. (Figure from [23].)

4.3. Photon polarization in $b \rightarrow s\gamma$ transitions

In the SM, photons from $b \rightarrow s\gamma$ transitions are predominately left-handed, while NP contributions to loop diagrams may introduce a right-handed component. In the decay $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$, the three-momenta of the two pions may be used to define a plane, and a direction normal to it, in the B rest frame, $\vec{p}_{\text{slow}} \times \vec{p}_{\text{fast}}$, where $p_{\text{slow}} < p_{\text{fast}}$. Then an up-down asymmetry, A_{ud} , may be defined for the photon direction relative to this plane. The value of the asymmetry is proportional to the photon polarization. LHCb has made (independent) measurements of A_{ud} in four bins of the $K\pi\pi$ mass [24], as indicated on figure 5. Over the four bins, up-down asymmetries are seen to be different from zero at the level of 5.2σ , giving the first observation of photon polarization in $b \rightarrow s\gamma$ transitions. As can be seen in figure 5, the structure of the $K\pi\pi$ mass spectrum is rather complex, which prevents for now interpretation of the results in terms of specific values for the average photon polarization in each mass bin.

Figure 5: Mass spectrum of $K\pi\pi$ from $B^+ \rightarrow K^+ \pi^- \pi^+ \gamma$ decays, showing the ranges chosen for the measurements of photon up-down asymmetry, A_{ud} . (Figure from [24].)

4.4. Isospin asymmetries in $B \rightarrow K^{(*)} \mu^+ \mu^-$ decays

The isospin asymmetry in $B \rightarrow K^{(*)} \mu^+ \mu^-$ decays is defined as

$$A_I = \frac{\Gamma(B^0 \rightarrow K^{(*)0} \mu^+ \mu^-) - \Gamma(B^+ \rightarrow K^{(*)+} \mu^+ \mu^-)}{\Gamma(B^0 \rightarrow K^{(*)0} \mu^+ \mu^-) + \Gamma(B^+ \rightarrow K^{(*)+} \mu^+ \mu^-)}$$

In a previous analysis [25] using 1 fb^{-1} of data, LHCb found a 4.4σ discrepancy in A_I from the SM. A new analysis using the full run 1 data set, comprising 3 fb^{-1} , gives a result that is consistent with the SM [26]. The data are analysed in bins of q^2 , the effective mass squared of the dimuon system. While the values of A_I in the q^2 bins are consistent with the SM, differential branching fractions, $d\mathcal{B}/dq^2$, are systematically below light-cone sum rule [27, 28] and lattice QCD [29, 30] predictions, as shown for $B^0 \rightarrow K^0 \mu^+ \mu^-$ in figure 6.

Figure 6: Differential branching fractions for $B^0 \rightarrow K^0 \mu^+ \mu^-$ as a function of q^2 . The bands show predictions of light-cone sum rules and lattice QCD. (Figure from [26].)

4.5. Angular analysis of charged and neutral $B \rightarrow K \mu^+ \mu^-$ decays

The differential decay rates for the rare, penguin-mediated $B^+ \rightarrow K^+ \mu^+ \mu^-$ and $B^0 \rightarrow K^0 \mu^+ \mu^-$ decays can be written in terms of the muon forward-backward asymmetry A_{FB} and the so-called flat parameter F_H , which is related to the contribution of pseudoscalar and tensor amplitudes to the decay rate. The distribution is [31]

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta} = \frac{3}{4} (1 - F_H) (1 - \cos^2\theta) + \frac{1}{2} F_H + A_{FB} \cos\theta,$$

where θ is the angle between the $\mu^- (\mu^+)$ and $K^+ (K^-)$ directions in the $B^+ (B^-)$ decay, measured in the dimuon rest frame. For the $K_s^0 \mu^+ \mu^-$ state, the flavour of the parent B meson is unknown, and the μ^+ direction is always

used to define θ . Figures 7 and 8 show the measurements of these parameters for the decay $B^+ \rightarrow K^+ \mu^+ \mu^-$ obtained in the LHCb analyses of these channels [32] using the full 3 fb^{-1} data set. The values of A_{FB} are consistent with zero, in line with SM predictions [33], and those for F_H also agree with the SM, shown as the curve on figure 8.

Figure 7: Forward-backward asymmetry for the decay $B^+ \rightarrow K^+ \mu^+ \mu^-$ in bins of q^2 , the effective mass squared of the dimuon system. (Figure from [32].)

Figure 8: The parameter F_H for in bins of q^2 , the effective mass squared of the dimuon system. The curve shows an SM prediction. (Figure from [32].)

4.6. Angular observables in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays

The decay angular distribution of the flavour-changing neutral current decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ can be described by three angles: θ_K , the angle between the kaon direction in the K^* rest frame relative to the K^* direction in the B^0 rest frame; θ_l , the angle between the μ^+ direction in the dimuon rest frame relative to the dimuon

direction in the B^0 rest frame; and the azimuthal angle ϕ between the K^* and dimuon decay planes. The distribution is a function of decay amplitudes that depend on Wilson co-efficients, which describe the short distance dynamics, and form factors describing the long-distance phenomena. Several observables can be constructed from the amplitudes, that are relatively free from uncertainties in the form factors, particularly at low values of q^2 [34]. LHCb has measured [35] four such observables, P'_4 , P'_5 , P'_6 and P'_8 in six bins of q^2 (i.e. 24 independent measurements). The results for two of the observables are shown in figure 9, compared with the SM predictions [33]. There is a 3.7σ discrepancy with the SM in the bin $4.3 < q^2 < 8.68 \text{ GeV}^2$; the probability of such a discrepancy or a larger one is 0.5% within 24 independent measurements.

Figure 9: Measured values of observables P'_4 and P'_5 in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ as functions of q^2 , the effective mass squared of the dimuon system. The points show the measurements and the shaded areas give the SM predictions. (Figure from [35].)

5. Conclusions and outlook

With the data from the LHC's first run, the LHCb experiment has improved on previous world best lim-

its on branching fractions for several lepton flavor and lepton number violating channels, and has made a number of studies of rare decay modes of B and D mesons that could be sensitive to new physics. These studies at LHCb form a vital strand in the search for new physics, complementing direct searches for new particles at the LHC and elsewhere. With the forthcoming second run of the LHC, and, on a longer time scale, the LHCb upgrade, we can expect more such measurements to come, providing more precise probes for new physics.

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