cLFV SEARCHES AT LHCb*

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The Large Hadron Collider beauty (LHCb) detector is an experiment designed for the study of heavy-flavour physics. These proceedings describe a set of searches for charged Lepton Flavour Violating (cLFV) decays at the LHCb detector. Analyses are performed with 1 fb^{-1} and 2 fb^{-1} of proton–proton collision data collected at center-of-mass energies of 7 and 8 TeV, respectively.

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1. Introduction

The LHCb detector [1, 2] covers a pseudorapidity region of $2 < \eta < 5$, in which most of the b and c production occurs. This feature, together with excellent tracking and particle identification systems (shown in Fig. 1), makes it an excellent machine to study very rare decays.

The LHCb Collaboration has reported numerous precise measurements aimed at observing indirect signals of new physics (NP). Interesting tensions with respect to SM expectations have been seen in lepton universality tests, where branching fraction ratios involving different leptons are measured. Measurements of these ratios using $B \to K^*\ell\ell$ and $B \to K\ell\ell$ decays [3, 4] lie below their Standard Model (SM) predictions, where the ratios are defined as

$$R_K = \frac{\mathcal{B}\left(B^+ \to K^+\mu^+\mu^-\right)}{\mathcal{B}\left(B^+ \to K^+e^+e^-\right)}\,, \qquad R_{K^{*0}} = \frac{\mathcal{B}\left(B^0 \to K^{*0}\mu^+\mu^-\right)}{\mathcal{B}\left(B^0 \to K^{*0}e^+e^-\right)}\,. \tag{1}$$

Additionally, a study of lepton flavour universality in semileptonic decays with a D^* meson resulted in a ratio that lies above the SM predictions [5],

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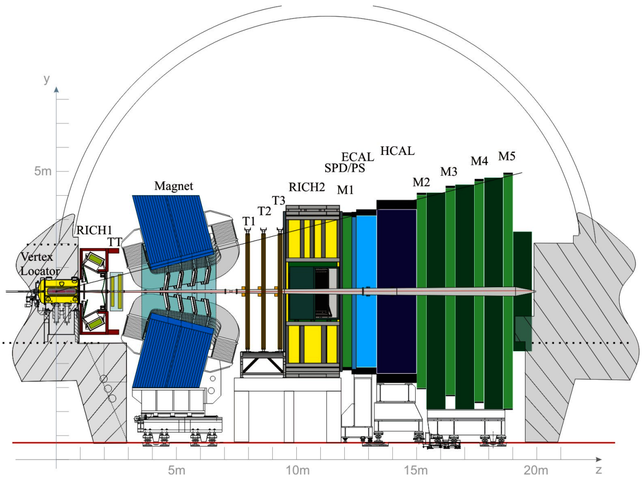

Fig. 1. The LHCb detector [1]. Particle identification detectors: Cherenkov light detectors — RICH1 and RICH2, calorimeters — ECAL, HCAL, SPD/PS, and muon stations — M1–M5. Tracking detectors: Vertex Locator — VELO, Tracker Turicensis — TT, and T stations — T1–T3.

where the ratio is defined as

$$R_{D^*} = \frac{\mathcal{B}\left(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau\right)}{\mathcal{B}\left(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu\right)} . \tag{2}$$

In fact, an existence of the lepton universality violation (LUV) in a lepton flavour conserving decay channel may imply an existence of a charged lepton flavour violation [6]. Any observation of a lepton flavour violating decay would be a clear sign of physics beyond the SM.

2. cLFV searches at LHCb

2.1. The search for $B^0_{(s)} \to e^\mp\mu^\pm$ decays

This analysis searches for the decays $B^0_s \to e^\mp\mu^\pm$ and $B^0 \to e^\mp\mu^\pm$ using 3 fb^{-1} of data collected at center-of-mass energies of 7 and 8 TeV. Two decay channels are used for normalisation: $B^+ \to K^+J/\psi\ (\to \mu^+\mu^-)$ and $B^0 \to K^+\pi^-$. The high purity first normalisation channel is chosen because of its comparable trigger selection and its copious yield, the second one is chosen because of its similar topology. The data sample is split in two categories: candidates with no bremsstrahlung photon recovered and candidates with at least one associated bremsstrahlung photon. The motivation for this split is a possibility that the bremsstrahlung effect affects kinematic distributions of signal candidates. Only candidates within the invariant mass range $m_{e^{\pm}\mu^{\mp}} \in [4900, 5850]$ MeV/c^2 are considered. The separation of the $B^0_{(s)} \rightarrow e^{\mp}\mu^{\pm}$ signal and the combinatorial background is obtained with a Boosted Decision Tree (BDT) classifier, trained on simulated signal events and the same-sign $e^{\pm}\mu^{\pm}$ data sample. Only events with the BDT classifier response greater or equal than 0.25 are selected, and later gathered in bins of BDT response and bremsstrahlung category. Among possible background sources, the most dangerous are decays of the B^0 to two hadrons, and partially reconstructed decays with misidentified particles. Non-negligible background decays ($B^0 \rightarrow \pi^-\mu^+\nu_\mu$ and $\Lambda^0_b \rightarrow p\ell^-\overline{\nu}_\ell$) are included in the fit. The fit is performed in two previously mentioned bremsstrahlung categories, in several BDT bins (see an example for the most signal-like BDT bin in Fig. 2).

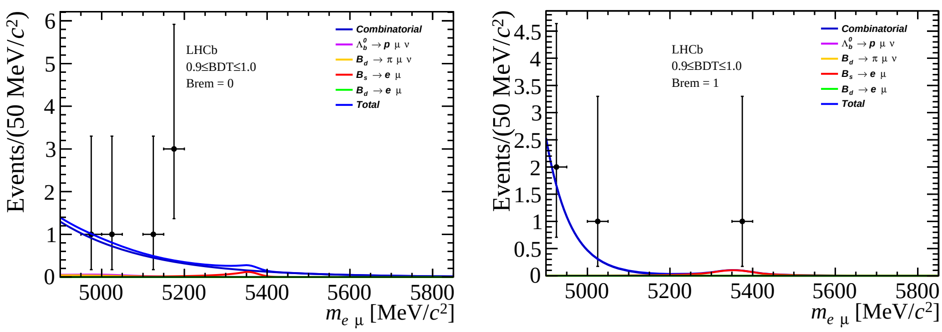

Fig. 2. Fit to the invariant mass of the $e\mu$ system for the bremsstrahlung-0 category (left) and the bremsstrahlung-1 category (right) [7].

No excess of signal events is observed, thus limits on the branching fractions are calculated

$$\mathcal{B}\left(B^0 \rightarrow e^{\pm}\mu^{\mp}\right) < 1.0\ (1.3) \times 10^{-9}\,,$$
$$\mathcal{B}\left(B^0_s \rightarrow e^{\pm}\mu^{\mp}\right) < 5.4\ (6.3) \times 10^{-9}$$

at 90% (95%) C.L.

2.2. The search for $D^0 \rightarrow e^{\mp}\mu^{\pm}$ decays

A search for the lepton flavour violation is performed with $D^{*+} \rightarrow D^0(\rightarrow e^{\pm}\mu^{\mp})\pi^+$ decays. The normalisation channel used is the $D^0 \rightarrow K^{\pm}\pi^{\mp}$. The $e^{\pm}\mu^{\mp}\pi^+$ system invariant mass is restricted to the 1815–1915 MeV/c^2 range. Candidates are required to have two good quality tracks for particles with opposite charges, separated from primary vertex (PV) and pointed to the same PV. Electron momentum is corrected with the recovered bremsstrahlung photon. Among possible background sources are misidentified $D^0 \to K^-\pi^+$, $D^0 \to \pi^- e^+\nu_e$, $D^0 \to \pi^-\mu^+\nu_\mu$, or $D^0 \to \pi^+\pi^-$. The mass of the first background is well below the signal mass region due to the pion–lepton mass difference. Semileptonic decays contributions are included in the combinatorial background fit. The only non-negligible peaking background is the $D^0 \to \pi^+\pi^-$ decay, which is included in the fit. The BDT classifier is trained on a simulated $D^0 \to e^\mp\mu^\pm$ signal sample as a signal proxy and data candidates with an invariant mass within 300 MeV/c^2 around the D^0 mass (excluding the aforementioned $m_{e^\pm\mu^\mp\pi^+}$ region) as a background proxy. Samples are divided into three BDT response categories. An unbinned maximum likelihood fit is performed simultaneously to the $e^\pm\mu^\mp\pi^+$ invariant mass and $m_{e\mu\pi} - m_{e\mu}$ in each bin of BDT response (see Fig. 3). The second one is restricted to the 135–155 MeV/c^2 range. The fit shows no excess. As a result, a limit on the branching fraction is set [8]

$$\mathcal{B}\left(D^0 \to e\mu\right) < 1.3 \times 10^{-8}\,.$$

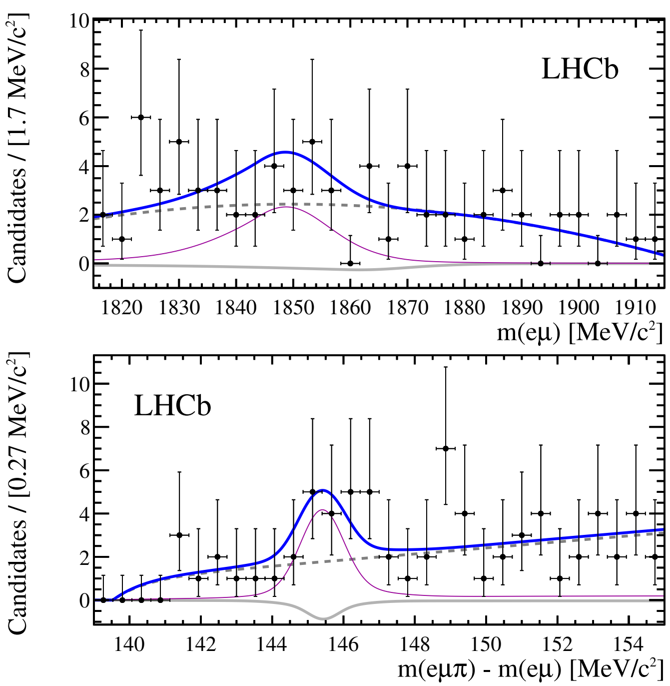

Fig. 3. (Colour on-line) Fits to the $m_{e^\pm\mu^\mp\pi^+}$ and the $m_{e\mu\pi} - m_{e\mu}$ invariant masses in the most signal-like BDT bin [8]. Fit result is shown with thick black/blue line, the thin black/purple line is the $D^0 \to \pi^+\pi^-$ component, and the dashed line corresponds to the $D^0 \to e^\mp\mu^\pm$.

2.3. The search for $\tau^+ \to \mu^+\mu^-\mu^+$ decay

Many BSM models predict large enhancements of lepton flavour violating tau decays like $\tau^+ \to \mu^+\mu^-\mu^+$. Hence, the choice of the searched decay. As the normalisation channel, the decay $D_s^- \to \phi\,(\to \mu^-\mu^+)\,\pi^-$ is chosen. The signal region is defined to be within 20 MeV/c^2 of the known τ^+ mass. The $\mu^+\mu^-\mu^+$ invariant mass range studied is extended to the 1600–1950 MeV/c^2 range to allow evaluation of possible background contributions. The signal–background separation is obtained using multivariate classifiers. The first classifier is based on the reconstructed mass of the $\mu^+\mu^-\mu^+$ system. The $\mathcal{M}_{\mathrm{3body}}$ geometric classifier is composed using the blending method. The classifier is used to distinguish signal candidates from N-body decays ($N > 3$) and from track combinations that do not have a common vertex. The blending method uses multiple classifiers and transforms them into a single more efficient classifier. As input of the blending method, classifiers based on methods such as Fisher discriminants, neural networks, function-discriminant analysis, and linear discriminant are used. All of them are trained using simulated $\tau^+ \to \mu^+\mu^-\mu^+$ signal sample, and $b\bar{b} \to X\mu\mu$ and $c\bar{c} \to X\mu\mu$ background samples. A multivariate classifier to reduce background from misidentification, referred to in the following as $\mathcal{M}_{\mathrm{PID}}$ is also trained on simulated samples. It is dedicated to check compatibility of the final-state particles with the muon hypothesis.

Possible background sources are decays with three muons in the final state, or misidentified decays like $D^{*+} \to D^0\,(\to K^-\pi^+\pi^0)\,\pi^+$ or $D^0 \to K^-\pi^+\pi^-$. Within the first group, only backgrounds originating from D_s^+ and D^+ are considered because of their higher production rate with respect to the B meson's. Those background sources are assumed to be negligible. The background decay including π^0 falls outside the signal region because the neutral pion is not reconstructed. The $D^0 \to K^-\pi^+\pi^-$ contribution is estimated in classifiers bins and it is negligible outside the lowest $\mathcal{M}_{\mathrm{PID}}$ bin. The bin is excluded from the fit to data sidebands. Other reflection decays that could fall into τ mass region are negligible outside the same $\mathcal{M}_{\mathrm{PID}}$ bin. The expected invariant mass shape of the $\mu^+\mu^-\mu^+$ system is taken from an invariant mass fit to the $D_s^- \to \phi\,(\to \mu^+\mu^-)\,\pi^-$ candidates from the data (see Fig. 4). The fit is performed in bins of each classifier responses.

The fit to the invariant mass shows no excess of events over expected background, thus a limit on the branching fraction $\mathcal{B}(\tau^+ \to \mu^+\mu^-\mu^+)$ at 90% (95%) C.L. is determined [9]

$$\mathcal{B}\left(\tau^+ \to \mu^+\mu^-\mu^+\right) < 4.6(5.6) \times 10^{-8}\,.$$

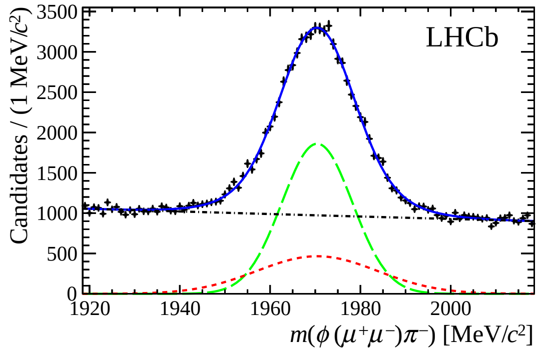

Fig. 4. (Colour on-line) The fit to the $D_s^- \rightarrow \phi\ (\rightarrow \mu^+\mu^-)\ \pi^-$ candidates [9]. The solid/blue line refers to the total model, the dash-dotted/black line correspond to the combinatorial background. Long-dashed/green and dashed/red lines correspond to two Gaussian components used to model the shape of the D_s^-.

3. Summary

These proceedings summarise recent searches for charged lepton flavour violation. All the presented analyses are performed using the proton–proton collision data, corresponding to 3 fb^{-1} of integrated luminosity. None of the presented searches resulted in an observation of signal and upper limits on the corresponding branching fractions are established. Recent hits of lepton universality violation motivate further searches for lepton flavour violating decays with the LHCb Run 2 data.

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