PROCEEDINGS OF SCIENCE

Lepton Flavour Violation at LHCb

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Charged Lepton Flavour Violation (cLFV) processes are highly suppressed in the Standard Model, even forbidden if neutrino mixing is not taken into account. Any observation of cLFV decay would be a clear hint of new Physics Beyond SM, since their expected branching fraction ($\mathcal{B}$) is well below any current experiment sensitivity. The LHCb collaboration has performed many searches of cLFV involving heavy hadrons in $b \to s l^+ l^-$, $b \to c l^- \nu_l$ and τ decays, setting upper limits to constrain BSM theories.

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1. Introduction

Lepton Flavour conservation is an accidental symmetry in the Standard Model (SM). The discovery of neutrino's oscillation due to their non-zero mass lead to Lepton Flavour Violation (LFV) transitions for neutral leptons. Charged Lepton Flavour Violating processes (cLFV) are allowed in the minimal extended SM with the inclusion of neutrino's mixing, but with branching fraction ($\mathcal{B}$) that are well below the current and future foreseen experiments. Beyond Standard Model (BSM) new particles can enhance processes such as $\tau \to \mu^+\gamma$ or $\tau^+ \to \mu^+\mu^-\mu^+$ up to $O(10^{-10} - 10^{-7})$ [1, 2]. The direct observation of cLFV would be a clear sign of New Physics (NP), while improving upper limits on $\mathcal{B}$ will improve constraints on different theories of NP. The LHCb experiment [3] at LHC is an excellent detector to study beauty and charm hadrons, and to search for indirect evidence of physics BSM. It is a forward spectrometer with an excellent vertex resolution, tracking, and Particle Identification capabilities.

These proceedings report on the most recent cLFV searches conducted at LHCb, including the searches for semileptonic B decays with electron and muon in the final state ($B^0 \to K^{*0}e^\pm\mu^\mp$, $B_s^0 \to \phi e^\pm\mu^\mp$ and $B^+ \to K^+mu^\pm e^\mp$) and with tau and muon in the final state ($B^0 \to K^{*0}\tau^\pm\mu^\mp$ and $B_s^0 \to \phi\mu^\mp\tau^\pm$) described in Sec. 3, and $\tau^- \to \mu^-\mu^+\mu^-$ decay in Sec. 4.1.

2. Lepton Flavour Universality

cLFV is intrinsically connected to Lepton Flavour Universality Violation (LFUV) [4]. In the SM the leptons of different flavour families couple identically to electroweak bosons, resulting in Lepton Flavour Universality (LFU). Some flavour observable as R_K, R_{K^*} measuring the electron-muon universality with $b \to sl^+l^-$ transitions (defined in Equation 1 as double ratios of efficiency corrected yields in the nonresonant and resonant modes, where $\frac{N}{\varepsilon}(X)$ represents the efficiency corrected yield for process X) are compatible with SM predictions [5], while ratios of branching fractions R_{D^*}, R_{D^0} (defined in Equation 2) measuring the tau-muon universality with $b \to cl^-\nu_l$ transitions show $\sim 3\sigma$ deviations with SM that could suggest LFV [6].

$$R_{(K,K^*)} \equiv \frac{\frac{N}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}\mu^+\mu^-)}{\frac{N}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\frac{N}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}e^+e^-)}{\frac{N}{\varepsilon}(B^{(+,0)} \to K^{(+,*0)}J/\psi(\to e^+e^-))} \tag{1}$$

$$R(D^*) \equiv \frac{\mathcal{B}(\bar{B} \to D^*\tau^-\nu_\tau)}{\mathcal{B}(\bar{B} \to D^*\mu^-\nu_\mu)}, \quad R(D^0) \equiv \frac{\mathcal{B}(B^- \to D^0\tau^-\nu_\tau)}{\mathcal{B}(B^- \to D^0\mu^-\nu_\mu)} \tag{2}$$

New physics mediators such as Z' or leptoquarks allow for additional tree-level contributions that enhance the $\mathcal{B}$ of the process involved, with amplitude contributions similar to the Standard Model one's [1]. At LHCb the measure of branching fraction of unobserved decays is generally normalized to a well measured control channel:

$$\mathcal{B}_{sig} = \frac{\mathcal{B}_{norm}}{N_{Norm}} \times \frac{\epsilon_{norm}}{\epsilon_{sig}} \times N_{sig} \tag{3}$$

Where N_{sig} (N_{norm}) is the number of signal (control) events and ϵ_{sig} (ϵ_{norm}) the corresponding efficiency.

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3. electron-muon final states

In the search for $B^0 \to K^{*0}e^{\pm}\mu^{\mp}$ the two possible charge combinations were studied separately since BSM physics could affect the charge combinations separately, while in the $B_s^0 \to \phi(K^+K^-)e^{\pm}\mu^{\mp}$ analysis the decay of B_s^0 and $\bar{B}_s^0$ are not distinguishable due to the decay of the scalar ϕ meson decaying into two opposite charge kaons [7]. The chosen normalization modes are $B^0 \to K^{*0}J/\psi(\mu^+\mu^-)$ and $B^0 \to \phi J/\psi(\mu^+\mu^-)$ respectively. The signal candidate selection is based on tight particle identification and K^{*0} and ϕ mesons mass window requirements. Background events coming from J/ψ and $\psi(2s)$ resonances, or semileptonic cascades with charm mesons are removed with vetoes. Remnant combinatorial background is tackled with two dedicated boosted decision tree (BDT) selections, while the main mis-identification (MisID) backgrounds (from $B_{(S)}$ and $D_{(S)}$) are included into the final fit, because they can escape vetoes due to their higher mass.

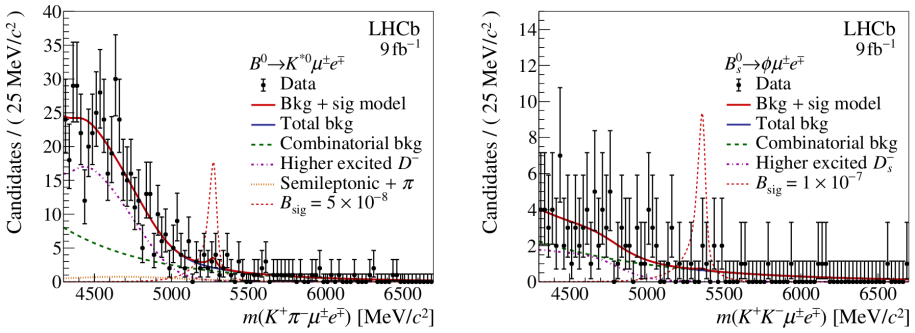

Figure 1: Mass distributions for $B^0 \to K^{*0}e^{\pm}\mu^{\mp}$ (left) and $B_s^0 \to \phi e^{\mp}\mu^{\pm}$ (right). The data are overlaid with the fit results. For illustration, the signal shape, scaled to a branching fraction of 5×10^{-8} for $B^0 \to K^{*0}e^{\pm}\mu^{\mp}$ and 1×10^{-7} for $B_s^0 \to \phi e^{\mp}\mu^{\pm}$, is drawn as red dashed line.

The final fits shown in Figure 1 are performed combining the two data sample, with signal shapes determined from simulation and their mass resolution corrected using factors evaluated on the normalization samples. No significant signals are observed in the 9 fb^{-1} data collected by LHCb, resulting in the world's most stringent upper limits to date at 90% (95%) confidence level:

$$\begin{aligned}
\mathcal{B}(B^0 \to K^{*0}e^-\mu^+) &< 5.7 \times 10^{-9} (6.9 \times 10^{-9}),\\
\mathcal{B}(B^0 \to K^{*0}e^+\mu^-) &< 6.8 \times 10^{-9} (7.9 \times 10^{-9}),\\
\mathcal{B}(B^0 \to K^{*0}e^{\pm}\mu^{\mp}) &< 10.1 \times 10^{-9} (11.7 \times 10^{-9}),\\
\mathcal{B}(B_s^0 \to \phi e^{\mp}\mu^{\pm}) &< 16.0 \times 10^{-9} (19.8 \times 10^{-9})
\end{aligned}$$

The search for $B^+ \to K^+\mu^{\pm}e^{\mp}$ [8] is performed on Run1 dataset, which corresponds to an integrated luminosity of 3 fb$^-$1, but improved the previous result [9] by one order of magnitude. As in the aforementioned analysis, the two final states are studied independently. The signal yields are normalized to those of $B^+ \to K^+J/\psi(\mu^+\mu^-)$. Different sources of backgrounds were studied in details: The combinatorial background is reduced with a BDT algorithm combining information about the B^+ kinematics and parameters with respect to the primary vertex, together with electron, muon and kaon candidate kinematics. Another BDT is tuned to remove partially reconstructed decays and decays involving charmonium resonances, together with mass vetoes.

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MisID backgrounds are reduced with cuts on PID variables: a correction is performed using high-purity calibration data samples because the performance of the PID algorithms is not perfectly simulated. The analysis is performed assuming a phase-space model for the signal decay and to allow for the interpretation of the result in different BSM scenarios, efficiency maps in bins of the invariant masses $m^2_{K^+e^\pm}$ and $m^2_{K^+\mu^\mp}$ are computed.

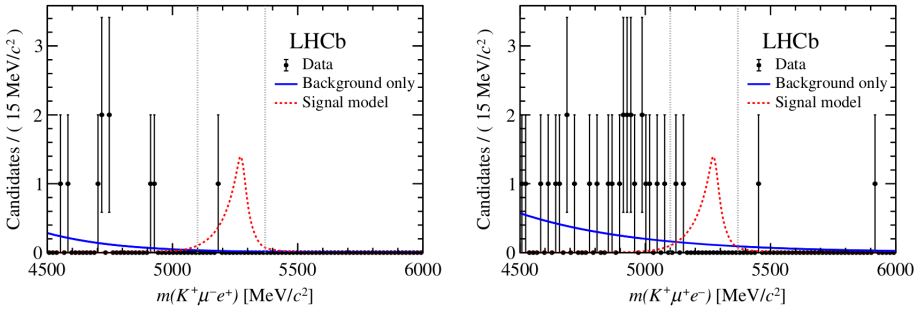

Figure 2: Invariant-mass distributions of the (left) $B^+ \to K^+\mu^+e^+$ and (right) $B^+ \to K^+\mu^+e^-$ candidates obtained on the combined datasets recorded in 2011 and 2012 with background only fit functions (blue continuous line) and the signal model normalized to 10 candidates (red dashed line) superimposed. The signal window is indicated with gray dotted lines.

In Figure 2 is shown the final fit to the invariant-mass distributions of $B^+ \to K^+\mu^\pm e^\mp$. The upper limits on the branching fractions are set with the CLs method [10], using the GammaCombo framework [11, 12] with a one-sided test statistic:

$$\mathcal{B}(B^+ \to K^+\mu^+e^-) < 6.4(8.8) \times 10^{-9} \text{ at } 90\% \ (95\%) \text{ C.L.}$$
$$\mathcal{B}(B^+ \to K^+\mu^+e^+) < 7.0(9.5) \times 10^{-9} \text{ at } 90\% \ (95\%) \text{ C.L.}$$

4. tau-muon final states

There are two main strategies that are used to reconstruct signal candidates in $b \to s\tau\mu$ transitions, where tau leptons are reconstructed as $\tau \to \pi\pi\pi\nu_\tau$ or $\tau \to \pi\pi\pi\pi^0\nu_\tau$. Since the neutral particles are not explicitly reconstructed, a corrected mass M_{corr} is used to recover part of the missing energy of the B meson [13]: considering M_{vis} the invariant mass of the set of vertex-associated tracks, and assuming the invariant mass of the missed neutral particles $M_0 = 0$ and considering only the components orthogonal to the B flight direction:

$$M_{corr} = \sqrt{M^2_{vis} + P^2_t} + |P_t|$$

The second strategy implies the use of a kinematic fit [14], which applies direction and mass constraints in a parametrization of the whole decay chain in terms of vertex positions, momenta, and decay times.

The first method is applied in the search for $B^0 \to K^{*0}\tau^\pm\mu^\mp$ [16], where the signal candidates are reconstructed with $K^{*0} \to K^\pm\pi^\mp$ and $\tau \to \pi\pi\pi\nu_\tau$ or $\tau \to \pi\pi\pi\pi^0\nu_\tau$. The chosen normalization

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mode is $B^0 \to D^-(K^+\pi^-\pi^-)D_s^+(K^+K^-\pi^+)$. Background candidates are rejected using a multi-stage selection approach based on BDT cut and mass vetoes: in the first stage, the same topological variables used in the selection of the signal channel are fed to a BDT which targets the combinatorial background. The remaining physics and misID backgrounds are removed with mass vetoes defined from the possible final state particle combinations.

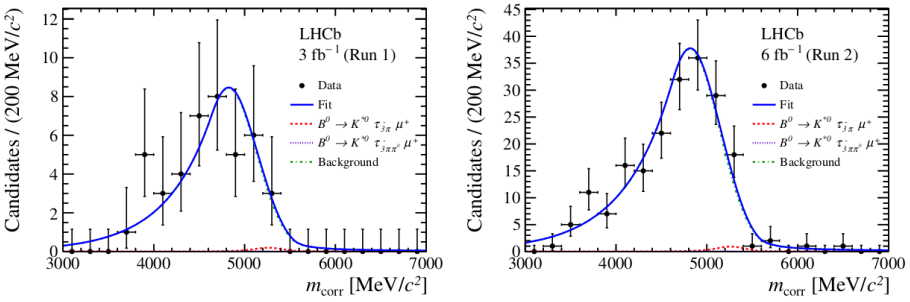

Figure 3: Distribution of the corrected mass m_{corr} of selected $B^0 \to K^{*0}\tau^-\mu^+$ candidates in (left) Run 1 and (right) Run 2 data, with the simultaneous fit overlaid (blue solid line). The red dashed line is the dominant signal component with $\tau \to \pi\pi\pi\nu_\tau$; the violet dotted line is the subdominant signal component with $\tau \to \pi\pi\pi\pi^0\nu_\tau$, extremely small and consequently barely visible; and the green dash-dotted line is the background.

An extended maximum likelihood fit (Figure 3) to M_{corr} is performed independently for the two possible charge combinations and results in the most stringent limits on $b \to s\tau\mu$:

$$\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0(1.2) \times 10^{-5} \text{ at } 90\% \ (95\%) \text{ C.L.}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+) < 8.2(9.8) \times 10^{-6} \text{ at } 90\% \ (95\%) \text{ C.L.}$$

In the search for $B_s^0 \to \phi(K^+K^-)\mu^\mp\tau^\pm$ [15] the kinematic fit method is used to compute the mass of the candidate. Figure 4 shows the constrained-mass distribution for simulated 3π and $3\pi\pi^0$ signals. The normalization mode $B_s^0 \to \phi\psi(2S)$ is reconstructed using $\phi \to K^+K^-$ and $\psi(2S) \to J/\psi(\mu^+\mu^-)\pi^+\pi^-$. Two different BDTs are used to fight combinatorial and partially reconstructed backgrounds, while the main misID$_{\pi\to\mu}$ contribution coming from $B \to \bar{D}K^+K^-\pi^+$ is estimated with exclusive $\bar{D} \to \pi^-\pi^+\pi^-X$, where X refers to any number of unreconstructed particles.

The upper limit set by LHCb using 9 fb^{-1} is the first limit on this decay:

$$\mathcal{B}(B_s^0 \to \phi\mu^\mp\tau^\pm) < 1.0(1.1) \times 10^{-5} \text{ at } 90\% \ (95\%) \text{ C.L.}$$

There is a third strategy to recover the missing energy of the B/B^* candidate, making use of its long lifetimes: having a decaying vertex well separated from any primary vertex allows not only to reduce the amount of background but by tagging the B produced by an excited state, its energy can be determined up to a quadratic ambiguity. The τ leptons are then selected inclusively, requiring just an additional charged track coming from the decaying vertex.

The search for $B^+ \to K^+\mu^-\tau^+$ [17] implements this technique, that allows to fit a peak in missing mass squared (m^2_{miss}). The $\mu^-\tau^+$ final state is preferred with respect to its charge conjugate

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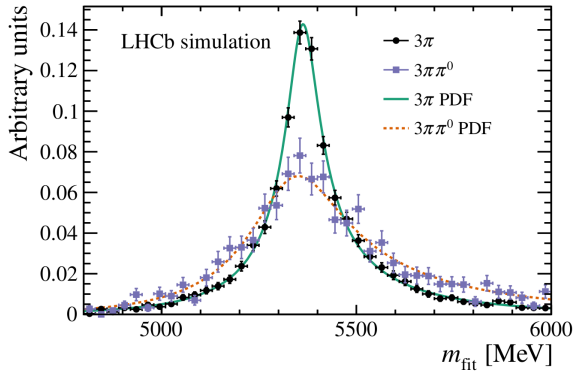

Figure 4: Distributions of the constrained mass for simulated 3π and $3\pi\pi^0$ decays. The probability density functions (PDFs) used to model the signal shapes in the final result, are overlaid.

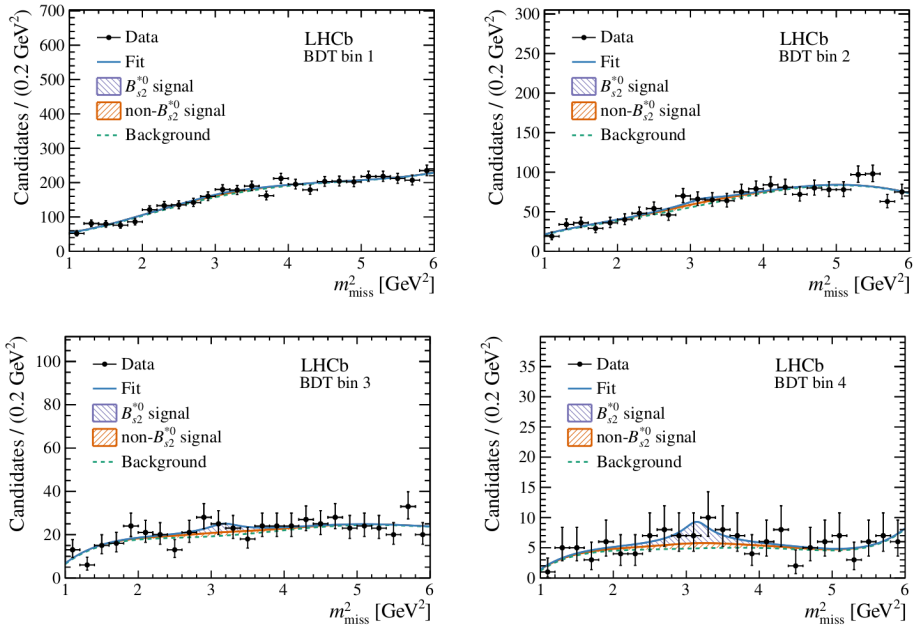

Figure 5: Fits to the missing-mass-squared distribution signal sample in each bin of BDT output included in the final fit. The best fit is overlaid. BDT bin 1 is the most background-like. The fit is performed using a fifth degree polynomial description of the background.

due to lower background from $B \to \bar{D}X\mu^+\nu_\mu$. The normalization mode used in this analysis is $B^+ \to K^+J/\psi(\mu^+\mu^-)$. Partially reconstructed b-hadron decays are the main source of background, but none of them produces a narrow peak in m^2_{miss}. Only B^+ mesons produced from B^*_{s2} decays have a resolution comparable to the signal, and thus all reduced by means of simple PID cuts. The signal selection is further improved by a BDT making use of different topological information computed on a triple made of K^+, μ^- and a third track t^+.

An unbinned maximum-likelihood fit is shown in Fig. 5: it is performed simultaneously in four bins of BDT output to the missing mass distribution, where the smooth signal shape is modelled as a polynomial. No significant excess is observed, setting the following first LHCb upper limits on

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this decay, assuming a phase space decay model:

$$\mathcal{B}(B^+ \to K^+\mu^-\tau^+) < 3.9(4.5) \times 10^{-5} \text{ at } 90\%(95\%) \text{ C.L.}$$

4.1 cLFV in tau decays

b-factories have studied radiative and three-lepton decays with all possible combinations [18], searching for signal of Lepton Flavour Violation decays using 719 million of produced $\tau^+\tau^-$ pairs in 782 fb^{-1} data sample. τ leptons are abundantly produced at LHCb, where are originated mainly from prompt or secondary decays of $b-$ and $c-$hadrons. Among $l \to l'l'l'$ decays the $\tau \to \mu\mu\mu$ offers a clear final state, with high reconstruction and identification efficiencies at LHCb.

In the search for $\tau^\pm \to \mu^\pm\mu^\mp\mu^\pm$ decay on 3 fb−1 Data [19] the $D_s^+ \to \phi(\mu^+\mu^-)\pi^+$ is chosen as normalization and control mode. The main misID backgrounds are the $D^+_{(s)} \to \pi^+\pi^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ decays, which are removed with a BDT trained on PID information, while the most important physical background (with three actual muons in the final state) is the $D_s^- \to \eta(\mu^+\mu^-\gamma)\,\mu^-\bar{\nu}_\mu$ about 90% of which is removed by requiring a dimuon mass above 450 MeV/c^2. The combinatorial background is fight with a BDT making use of geometric information and the remnant modelled as an exponential in the final unbinned maximum likelihood fit, which results in an upper limit of:

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

The current best experimental limit is from Belle II [20] at

$$\mathcal{B}(\tau^+ \to \mu^+\mu^-\mu^+) < 1.9 \times 10^{-8} \text{ at } 90\% \text{ C.L.}$$

5. Conclusion and Outlook

LHCb as a very rich program of charged lepton flavour violations searches. No signal observed so far with Run 1 and Run 2, but the improved limits on branching fractions helps to constrain the Beyond Standard Model theories on cLFV [21–23]. LHCb has started a new data-taking (Run 3) with an upgraded detector and an improved trigger system that allow to run at $(2 \times 10^{33} cm^{-2}s^{-}1)$, 5 times higher than the instantaneous luminosity of Run 2.

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