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# Flavour anomalies in $b \to s\ell^+\ell^-$ and $b \to c\ell\nu_\ell$ transitions

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Flavour anomalies observed in $b \to s\ell^+\ell^-$ and $b \to c\ell\nu_\ell$ transitions show tantalising tensions with the predictions of the Standard Model. Anomalies in absolute and relative branching fractions and angular observables measured by the LHCb, CMS and ATLAS collaborations are reviewed. Direct searches for leptoquarks, which could explain these anomalies are discussed.

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## 1. Flavour anomalies

In recent years, tensions with the Standard Model (SM) have been observed in the flavour sector. If confirmed, these so-called flavour anomalies would be a clear indication of physics beyond the SM. The processes where these tensions have been seen are $b \to c\ell\nu_\ell$ and $b \to s\ell^+\ell^-$ transitions. The former are flavour-changing charged currents mediated through a $W$-boson at tree-level, while the latter can only occur at loop-level in the SM. The ATLAS [1], CMS [2] and LHCb [3] experiments at the Large Hadron Collider (LHC) provide ideal testing grounds for studying $b$-hadron decays, given the large amount of different $b$-hadrons produced in proton-proton collisions. In particular, the LHCb experiment is designed to make precision measurements in the flavour sector, while the ATLAS and CMS experiments are well suited to directly search for new particles, which could contribute to these processes and modify the SM expectation through virtual diagrams.

In the SM, the leptons couple with gauge bosons independently of their generation and the only differences arise from their different masses. Testing this lepton flavour universality (LFU) provides powerful tests of the SM. By measuring the ratios of branching fractions

$$\mathcal{R}(H_s) = \frac{\mathcal{B}(H_b \to H_s\mu^+\mu^-)}{\mathcal{B}(H_b \to H_s e^+e^-)} \tag{1}$$

and

$$\mathcal{R}(H_c) = \frac{\mathcal{B}(H_b \to H_c\tau\overline{\nu}_\tau)}{\mathcal{B}(H_b \to H_c\ell\overline{\nu}_\ell)}, \tag{2}$$

where $H_b$, $H_s$ and $H_c$ indicates hadrons containing a $b$, $s$ or $c$ quark, respectively, LFU can be tested. Using ratios as observable improves the precision of the SM predictions and leads to the cancellation of some experimental uncertainties.

## 2. Flavour-changing neutral currents

Several observables involving $b \to s\ell^+\ell^-$ transitions have shown tensions with the SM. These include differential branching fractions (BFs), measurements of angular quantities and tests of LFU. The SM predictions of these observables are made more difficult from the uncertainty on the form factors describing the hadronic process, as well as the contribution from charm loops. Angular observables can be designed to reduce the impact of form factors [4] and the associated uncertainty cancel in LFU tests, improving the precision of the theory predictions.

The differential BFs of various $b \to s\ell^+\ell^-$ decays have been measured by the LHCb experiment, where the BF is determined in bins of the square of the muon-muon four-momentum $q^2$ and tensions with the SM predictions are seen in several bins for several decay modes [5][6][7]. One of the most recent measurements by the LHCb experiment is of the differential BF of the $\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$ decay, shown in Fig. 1. In this case, there are large discrepancies between different theory predictions over most of the $q^2$ range, which highlights the need for improved theory calculations for this decay.

Angular observables such as the forward-backward asymmetry $A_{FB}$ or $P_5'$, which are designed to reduce uncertainty on the SM prediction from the hadronic form factors, have been measured by the LHCb, CMS and ATLAS experiments. In the measurement of $P_5'$ tensions with the SM prediction are observed in several $q^2$ regions. As examples, Fig. 2 shows the measurement of

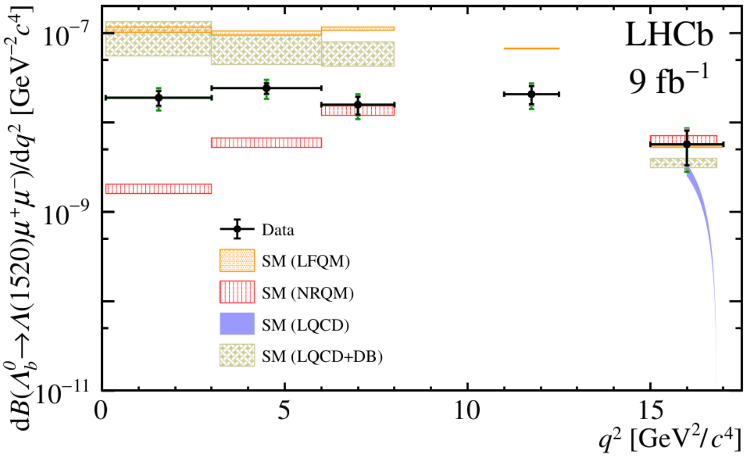


**Figure 1:** Differential branching fraction of the $\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$ decay in intervals of $q^2$ [8]. The error bars in black, gray, and green represent the measured results with statistical, systematic, and $\mathcal{B}(\Lambda_b^0) \to pK^-J/\psi$ uncertainties taken into account. Also shown are various SM predictions [9][10][11][12].

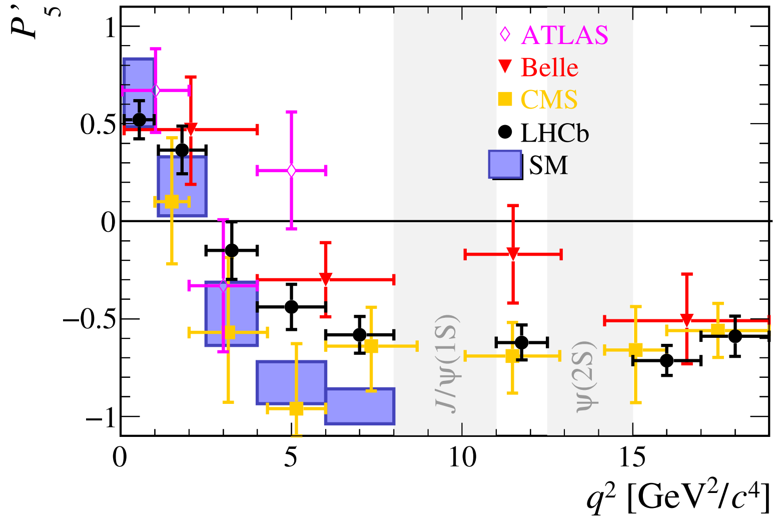


**Figure 2:** Measurements of $P'_5$ in bins of $q^2$ by ATLAS [13], CMS [14] and LHCb [15] using the $B^0 \to K^{*0}\mu^+\mu^-$ decay, as compiled in [16].

$P'_5$ using the $B^0 \to K^{*0}\mu^+\mu^-$ decay by the LHCb, ATLAS and CMS experiments and Fig. 3 the measurement of $F_L$ using the $B_s^0 \to \phi\mu^+\mu^-$ decay by the LHCb experiment.

Tests of lepton flavour universality are performed by the LHCb experiment by measuring the double-ratio

$$R_X = \frac{\mathcal{B}(B \to X\mu^+\mu^-)}{\mathcal{B}(B \to Xe^+e^-)} \times \underbrace{\frac{\mathcal{B}(B \to XJ/\psi\,(\to e^+e^-))}{\mathcal{B}(B \to XJ/\psi\,(\to \mu^+\mu^-))}}_{r(J/\psi)^{-1}}, X = K^+, K^{*0}, \ldots \tag{3}$$

which results in the cancellation of some systematic uncertainties and makes use of the fact that the

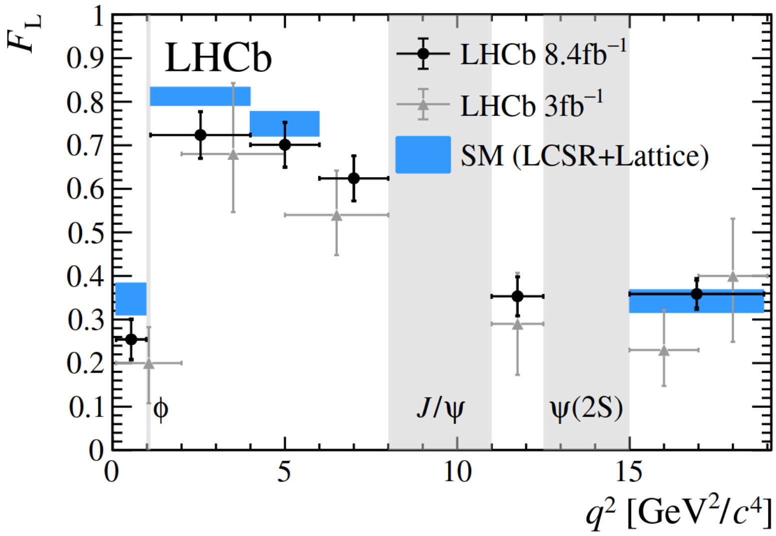


**Figure 3:** Results for the CP-averaged angular observable $F_L$ in bins of $q^2$ measured using the $B_s^0 \to \phi\mu^+\mu^-$ decay by LHCb [17].

ratio $r(J/\psi)$ is known to be one with good precision [18]. The latest measurement of the ratios $R(K)$ and $R(K^*)$ by LHCb is performed in two regions of $q^2$ [19][20]. The signal yields are extracted by fitting the $m(K^+\ell^+\ell^-)$ and $m(K^+\pi^-\ell^+\ell^-)$ invariant mass distributions. The signal shapes for the electron modes have long tails due the lost energy from Bremsstrahlung emission and they contain a significant contribution from mis-identified and partially reconstructed background. The measured values for $R(K)$ and $R(K^*)$ in both $q^2$ bins are summarised in Fig. 4 and are in agreement with the SM prediction. This analysis employs a tighter electron identification requirement and an improved modelling of the mis-identified hadronic background contributions to the $e^+e^-$ final state compared to previous publications [21].

Additionally, the LHCb experiment has measured the ratios $\mathcal{R}(K_S^0)$ and $\mathcal{R}(K^{*+})$ [22] and $\mathcal{R}(pK^-)$ [23], which were found to agree with the SM prediction.

## 3. Flavour-changing charged currents

Measurements of the relative branching fractions of flavour-changing charged currents have shown tensions with the SM predictions, as shown in Fig. 5, where LFU is tested by measuring the relative branching fraction

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau^+\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)}. \quad (4)$$

At LHCb, both the muonic $\tau^+ \to \mu^+\nu_\mu\overline{\nu}_\tau$ and hadronic $\tau^+ \to \pi^+\pi^+\pi^-(\pi^0)\overline{\nu}_\tau$ tauon decays are used and final states including muons are used for the denominator ($\ell = \mu$). As the neutrinos in the final state are not reconstructed, the kinematics of the $b$-hadron are approximately measured and the signal yields have to be extracted using multi-dimensional templates describing the signal and background contributions. The analysis techniques differ depending on the tauon decay used. In particular, measurements using the hadronic tauon decay rely on external input of relative branching

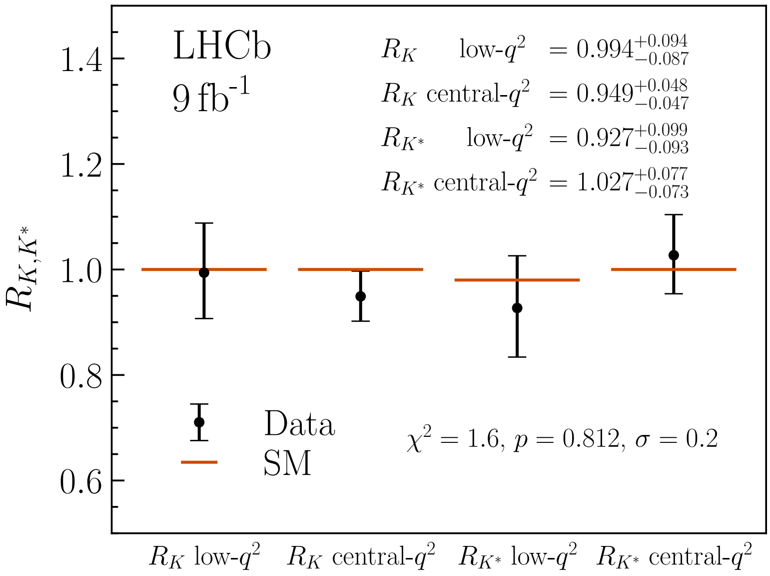


**Figure 4:** Measured values of $R(K)$ and $R(K^*)$ by LHCb [19].

fractions to extract the final result. The relative BFs $\mathcal{R}(D^0)$ and $\mathcal{R}(D^*)$ are measured simultaneously using the muonic decay mode of the tau lepton by LHCb [24] to be

$$\mathcal{R}(D^*) = 0.281 \pm 0.018\,(\text{stat}) \pm 0.024\,(\text{syst}),$$
$$\mathcal{R}(D^0) = 0.441 \pm 0.060\,(\text{stat}) \pm 0.066\,(\text{syst}),$$
$$\rho = -0.43,$$

where the first uncertainty is statistical and the second is systematic and $\rho$ is the correlation between the two measurements. In combination, the measured values for $\mathcal{R}(D^0)$ and $\mathcal{R}(D^*)$ are $1.9\sigma$ away from the SM prediction.

The relative BF $\mathcal{R}(D^{*-})$ is also measured by LHCb using the hadronic decay mode [25] to be

$$\mathcal{R}(D^{*-}) = 0.247 \pm 0.015\,(\text{stat}) \pm 0.015\,(\text{syst}) \pm 0.012\,(\text{ext}),$$

where the first uncertainty is statistical, the second is systematic and the third is due to the uncertainty of the external BF measurements used. This measurement is combined with the previous LHCb measurement [26][27], resulting in

$$\mathcal{R}(D^{*-})_{comb} = 0.257 \pm 0.012\,(\text{stat}) \pm 0.014\,(\text{syst}) \pm 0.012\,(\text{ext}).$$

In combination with measurements by the Belle and BaBar experiments, the experimental average is found to be in tension with the SM prediction by around $3.3\sigma$ [28]. In addition, the LHCb experiment has measured the ratios $\mathcal{R}(\Lambda_c^+)$ [29] and $\mathcal{R}(J/\psi)$ [30], which were found in agreement with the SM predictions.

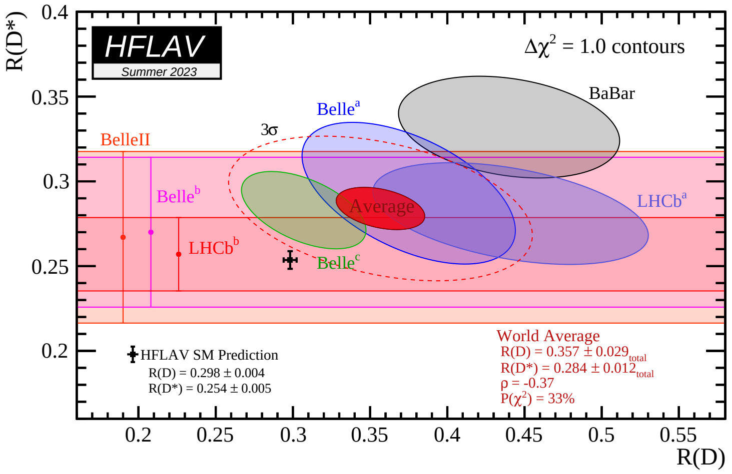


**Figure 5:** Summary of experimental measurements and SM predictions of the relative branching fractions $\mathcal{R}(D^{(*)})$ compiled by HFLAV [28].

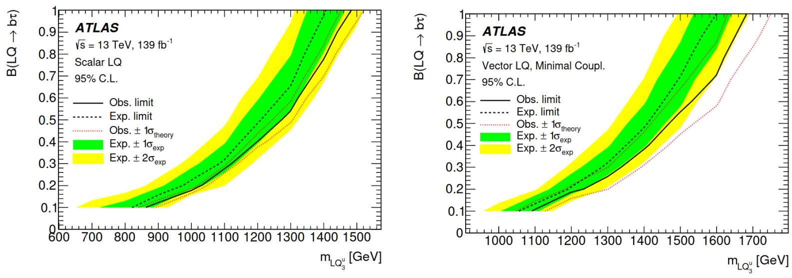


**Figure 6:** The observed (solid line) and expected (dashed line) 95% CL upper limits on the branching ratio into charged leptons as a function of $m_{LQ}$ for the scalar LQ case (left) and the vector LQ case in the minimal-coupling scenario (right) determined by ATLAS [34].

## 4. Interpretation & Outlook

To explain the flavour anomalies, various new physics models have been proposed, typically introducing new particles contributing to these processes. Several such models, e.g [31][32][33], have proposed the existence of leptoquarks (LQs), which directly couple quarks and leptons. In some models, their masses could be of the order of $O(\text{TeV})$, and thus they could be produced at the LHC. Based on the assumptions made for the leptoquark, such as spin structure and coupling strength, the direct searches performed by the ATLAS and CMS experiments, such as [34] and [35], can be translated into exclusion limits, as shown in Figs. 6 and 7. It can be seen that, depending on the interpretation, direct searches are starting to exclude parts of the parameter space for leptoquark masses and coupling strengths preferred by the flavour anomalies.

To further investigate the flavour anomalies and confirm the tensions seen with the SM, additional measurements and larger data samples are required. The current and upcoming runs of the LHC will enable the LHCb, ATLAS and CMS experiments to further probe these tensions by measuring the observables in tension more precisely and by directly searching for new particles.

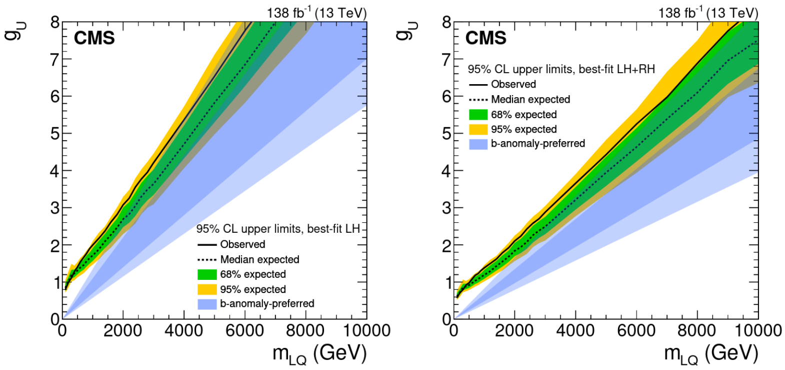


**Figure 7:** Expected and observed upper limits of the LQ coupling $g_U$ as a function of the mass in the LH (left) and LH+RH (right) scenarios determined by CMS [35]. The blue band shows the 68 and 95% regions of $g_U$ preferred by the fit to the $b$ anomalies data [36].

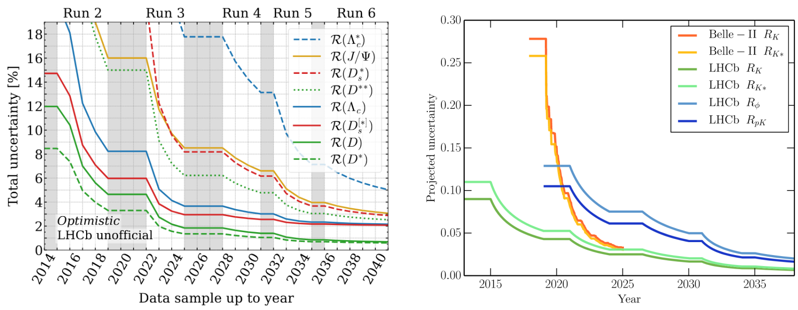


**Figure 8:** Projections for the expected precision on the measurement of selected $\mathcal{R}(H_c)$ ratios at LHCb as a function of the year in which the corresponding data sample becomes available (left) [37]. Projected uncertainty for various $\mathcal{R}(H_s)$ ratios from the Belle II and LHCb experiments (right) [38].

The expected sensitivities of LFU tests with different final states at LHCb are shown in Fig. 8. It is expected that LFU can be measured with percent-level precision for many final states.

## 5. Summary

Several tensions with the SM have been observed in the angular distributions and absolute and relative branching fractions of $b \to c\ell\nu_\ell$ and $b \to s\ell^+\ell^-$ transitions. If confirmed, these flavour anomalies would be a clear sign of contributions from physics beyond the SM. To complete the picture, additional measurements with larger datasets and in some cases advancements on the theory predictions are required.

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