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## Intriguing results at the LHCb experiment: the flavour anomalies strengthen

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## Intriguing results at the LHCb experiment: the flavour anomalies strengthen

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Measurements of decays of B-mesons at the LHCb experiment show an intriguing pattern of deviations with respect to Standard Model predictions. These measurements are consistent with the existence of a new fundamental interaction. The most recent of these measurements has provided the first evidence of lepton universality violation in a single decay, strengthening the New Physics interpretation of these so-called flavour anomalies. Here we discuss the history, status and future prospects of the anomalies.

### I. Anomalies in Rare Decays

In 2012 the last particle predicted by the Standard Model of particle physics (SM), the Higgs boson, was discovered by the experiments ATLAS [1] and CMS [2]. Merely 1 year later, in 2013, the first in a series of discrepancies with respect to SM predictions in $b \to s\ell^+\ell^-$ decays appeared in the angular distributions of the $B^0 \to K^{*0}\mu^+\mu^-$ decay [3]. It was immediately suggested that this *anomaly* could be interpreted as a sign of physics beyond the SM [4], often known as New Physics (NP). The $B^0 \to K^*\mu^+\mu^-$ anomaly was subsequently confirmed by other LHCb analyses [5, 6]. These measurements are consistent with the fact that branching ratios of $b \to s\mu^+\mu^-$ transitions are observed to be lower than the SM predictions [7–13].

However, it was pointed out that both the decay rate and angular deviations could be qualitatively explained by a larger-than-expected charm-loop contribution [14, 15]. The so-called charm-loop is a SM process, represented in the Feynman diagram of Fig. 1 (center), for which there is not yet a full consensus on the theory uncertainty. During intense and fruitful discussions on the nature of these discrepancies and the magnitude of the charm-loop contribution, an unexpected new result from LHCb shed a new light on these anomalies. The ratio of branching fraction

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} \qquad (1)$$

was measured with 3 fb$^{-1}$ of data by LHCb to be $0.745^{+0.090}_{-0.074}(stat) \pm 0.036(syst)$, deviating by 2.6 standard deviations from the SM prediction [16]. The deviation in $R_K$ is numerically consistent with the low branching fractions in $b \to s\mu^+\mu^-$ processes and with the original anomaly in the angular observables of the $B^0 \to K^*\mu^+\mu^-$ decay. The $R_K$ observable is predicted to be unity in the SM [17–20], due to Lepton Flavour Universality (LFU). LFU is an accidental symmetry of the SM, arising from how the lepton families are organized. LFU breaking cannot be explained by the charm-loop contribution or any other theoretical uncertainty, meaning that deviation from LFU would be a clear sign of NP. The numerical coherence of the anomalies is what makes them particularly interesting and is almost certainly the most compelling hint of NP that has arisen from the Large Hadron Collider (LHC) to date. The only way to understand the correlation between the various observables is to use the language of the effective Lagrangian, where the short-distance four-lepton interaction is encapsulated in so-called Wilson coefficients. This approach is analogous to Fermi's theory of beta decays [21], and allows to consider each observable in rare B-meson decays as a different measurement of the same $b \to s\ell^+\ell^-$ (where $\ell = e, \mu$) short-distance interaction. Since the same Wilson coefficients appear in different decays, we can combine various channels using this Effective Field Theory (EFT) approach, and also check the consistency between the value of Wilson coefficients measured in different processes. All these rare decays anomalies can be explained by the same numerical shift to the Wilson coefficients $C_9$ and $C_{10}$ with respect to their SM values.

Further evidence appeared in 2017 when the ratio $R_{K*}$ between the decays $B \to K^*\mu^+\mu^-$ and $B \to K^*e^+e^-$ was measured in two bins of di-lepton invariant mass squared ($q^2$), showing discrepancies of 2.1 – 2.5$\sigma$ in each bin.
These discrepancies were in the same direction as the existing rare decay anomalies, suggesting a deficit of muons with respect to electrons. More recently, in 2019 the measurement of $R_K$ at LHCb was updated with 5 fb$^{-1}$, finding a value of $0.846^{+0.060+0.016}_{-0.054-0.014}$ [22]. This measurement superseded the previous one performed in 2014 [16], leaving the situation unchanged, as while the total uncertainty decreased, the central value approached the SM. In that scenario, the

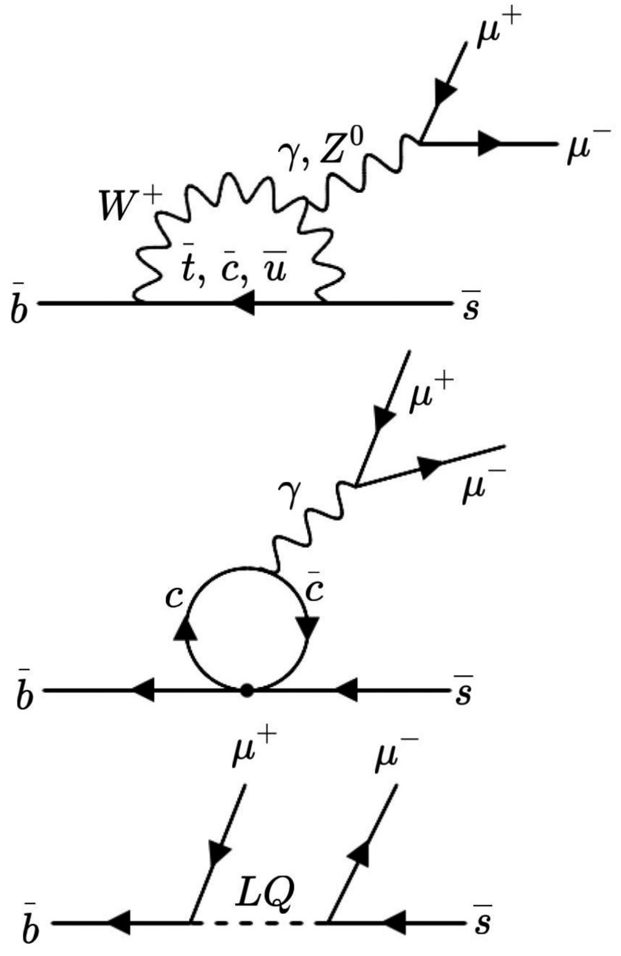

*FIG. 1. Possible Feynman diagrams for $b \to s\ell^+\ell^-$ ($\ell = \mu, e$) processes, for the SM (top), charm-loop (center) and for New Physics mediated by a Leptoquark (bottom).*

measurement of $R_K$ with the full Run1&2 data by LHCb was highly anticipated. The new measurement was released in March 2021.

## II. The new Measurement

The update of $R_K$ with the entire 9 fb$^{-1}$ of data was made public with a CERN press release, creating a great echo in the mainstream media. The result was $R_K = 0.846^{+0.044}_{-0.041}$ in the region 1.1 GeV$^2$ < q$^2$ < 6.0 GeV$^2$, which corresponds to 3.1$\sigma$ deviation from SM predictions, consisting of the first evidence for LFU violation in a single B-meson rare decay. The evolution of $R_K$ measurements, is shown in Fig 2. The main control channels for this analysis are the decays $B^+ \to J/\psi(\to \ell^+\ell^-)K^+$ and $B^+ \to \psi(2S)(\to \ell^+\ell^-)K^+$, which have the same experimental signature as the signal, differing only in the value of $q^2 = m_{\ell^+\ell^-}$, corresponding to the mass squared of the $J/\psi$ (~ 9.6 GeV$^2$) and of the $\psi$(2S) (~ 13.6 GeV$^2$), respectively. In order to reduce systematic uncertainties due to imperfect knowledge of the electron and muon efficiencies, the double ratio between $B^+ \to K^+\ell\ell$ and $B^+ \to J/\psi K^+$ defined as

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)}\frac{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \qquad (2)$$

is used. In addition, LFU tests of the control channels are used to cross-check the measurement. Notably, the measurement of the LFU single ratio $r(J/\psi) = 0.981 \pm 0.020$ and of the LFU double ratio (with respect to the $J/\psi$ mode) $R(\psi(2S)) = 0.997 \pm 0.011$ give strong confidence in the modeling of muon and electron reconstruction at LHCb.

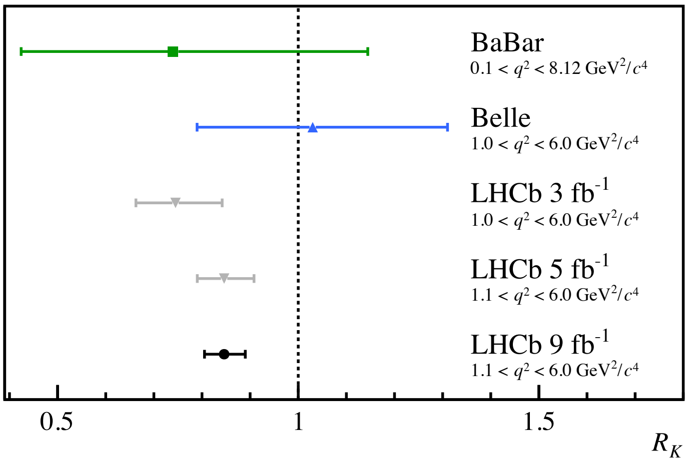

*FIG. 2. Evolution of the measurement of $R_K$ [23].*

## III. The Semileptonic Anomalies

In addition to the rare decays anomalies described in the previous sections, other deviations from SM predictions have been measured in semileptonic decays of B-mesons by the experiments BaBar [24, 25], Belle [26–29] and LHCb [30–32]. These semileptonic anomalies suffer from a large amount of background due to the presence of weakly interacting neutrinos in the final state. However, the coherence between experiments in vastly different environments provides confidence in the results. The analyses measure the LFU ratios, $R(D)$ and $R(D^*)$, defined as the decay probability of the decay $B \to D^{(*)}\tau\nu$ with respect to the lighter-lepton counterpart $B \to D^{(*)}\ell\nu_\ell$, where $\ell$ denotes either a muon or electron. The global significance of these LFU semileptonic tests is about 3$\sigma$ [33] from SM predictions.

While the rare decays and semileptonic anomalies cannot be linked model-independently, both can be interpreted as a new fundamental interaction that violates LFU by hierarchically coupling to the lepton and quark generations. The presence of third generation leptons in the semileptonic decays can explain the larger effect with respect to the rare decays anomalies. This fact has led theorists to propose NP models that naturally explain both sets of anomalies simultaneously (see for instance Refs [34–43]). Many of these models predict the existence of Leptoquarks, depicted in the bottom of Fig. 1, which are particles carrying both lepton and baryon numbers. As was pointed out in Refs [34, 36, 44], the semileptonic anomaly would indicate a NP scale of a few TeV, which would have experimental signatures that would be detected directly at the High-luminosity LHC. If all flavour anomalies persist, then, we will probably observe new particles at the ATLAS and CMS upgrades and certainly at the Future Circular Collider (FCC) [45]. Such a discovery could lead to answer some of the fundamental questions in particle physics. For example, the anomalies might be related to the problem of the origin of the masses [46], i.e. the lack of explanation for the very different values of the masses of the different generations of particles.

## IV. Future Prospects

The rare decays anomalies are particularly interesting because they consist of several measurements involving $b \to s\ell^+\ell^-$ processes that can be related using an EFT approach. While there is no single measurement yet that deviates more than 5$\sigma$ from the SM, which is considered the gold standard in particle physics to claim a discovery, several theory groups have combined these measurements by means of fitting Wilson coefficients, obtaining significances greater than 5$\sigma$ [37, 47–50]. In Ref. [51] it was shown that even adopting an hyper-conservative theory and a conservative statistical approach, a global significance of about 4$\sigma$ for NP is obtained in rare B-meson decays. The LHCb collaboration has not yet analyzed the full Run1&2 datasets for all related measurements. In particular, the measurement of $R_{K*}$ has only been performed with Run1 data, which is around 25% of the total dataset. The update of this measurement is crucial to increase our confidence in the anomalies. Especially interesting will be the value of $R_{K*}$ in the low-$q^2$ bin, which is expected to become more compatible with unity due to the large contribution of the photon diagram, depicted in Fig. 1 (top), in this region. Moreover it will be important to measure as precisely as possible all LFU R ratios. For instance, the measurement of $R_{pK} = \frac{\mathcal{B}(\Lambda_b \to pK\mu^+\mu^-)}{\mathcal{B}(\Lambda_b \to pKe^+e^-)}$ [22] has still large uncertainty, but it is consistent with the anomalies. Other LFU R ratios that may have good experimental sensitivities are $R_{K\pi\pi} = \frac{\mathcal{B}(B \to K\pi\pi\mu^+\mu^-)}{\mathcal{B}(B \to K\pi\pi e^+e^-)}$ and $R_{K\pi} = \frac{\mathcal{B}(B \to K\pi\mu^+\mu^-)}{\mathcal{B}(B \to K\pi e^+e^-)}$, where K$\pi$ refers to the region above the K$^{*0}$(892) resonance.

In addition, measurements of LFU ratios of angular observables in $B^0 \to K^{*0}\ell^+\ell^-$ decays, such as $Q_5$ [52], will add a fundamental piece to the flavour anomaly puzzle, also allowing discrimination between NP models.

Regarding the semileptonic anomalies, the LHCb measurement of $R(D^*)$ are performed only with Run1 data. Updates of these measurements with Run2 will have a significant increase in precision. In addition, more measurements of the non-excited state, i.e. $R(D)$, are important to clarify the anomalies. The current value of these observables favours a NP explanation consisting of a purely left-handed current, which is consistent with the best fit of the rare decays anomalies, thus suggesting a direct connection between the two sets of anomalies. The measurement of $R(\Lambda_c)$ with the decays $\Lambda_b \to \Lambda_c \tau\nu$ and $\Lambda_b \to \Lambda_c \mu\nu$ could not only increase the significance of the anomalies, but can also be related model-independently to $R(D)$ and $R(D^*)$ [53], providing an important consistency check of these measurements.

Most models explaining the anomalies predict the existence of SM forbidden decays that violate lepton flavour, such as $\tau \to 3\mu$ and $\mu \to 3e$ [54]. These decays could be observed in the near future. Therefore, searches for lepton flavour violating decays of taus at Belle II and LHCb Upgrades, and of muons at dedicated experiments such as Mu3e [55], are of paramount importance.

## V. Conclusions

In summary, several flavour anomalies manifesting in rare and semileptonic decays of B-mesons show an interesting pattern that is consistent with the existence of a new fundamental force that couples hierarchically to the three families of quarks and leptons. Analyses with LHCb Run2 data have the potential to clarify whether the anomalies are a genuine sign of physics beyond the SM. In addition, independent measurements of semileptonic anomalies by Belle II and CMS can be expected in the near future.

The unambiguous confirmation of the flavour anomalies would mark the beginning of a new era of discoveries in particle physics. The current and planned upgrades of the LHCb experiment would eventually shed light on the structure and coupling of NP. The possible connection between the anomalies and the violation of lepton flavour, places urgency on experiments such as Mu3e at PSI, which could test some crucial predictions of the most promising NP models explaining the anomalies. Finally, the direct detection of NP particles associated with the flavour anomalies could be possible at ATLAS and CMS or at future experiments at the FCC.

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