PROCEEDINGS OF SCIENCE

Recent results in $b \to s\ell\ell$ transitions at LHCb

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In the Standard Model the processes mediated by flavour changing neutral currents, such as $b \to s(d)\ell\ell$ transitions, are forbidden at tree level and can only happen through electroweak loop diagrams. Possible new Physics contributions could hence affect several observables related to these decays, such as branching fractions or angular distributions. The status of the LHCb measurements for different observables related to $b \to s\ell\ell$ transitions will be given in this proceedings.

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1. Introduction

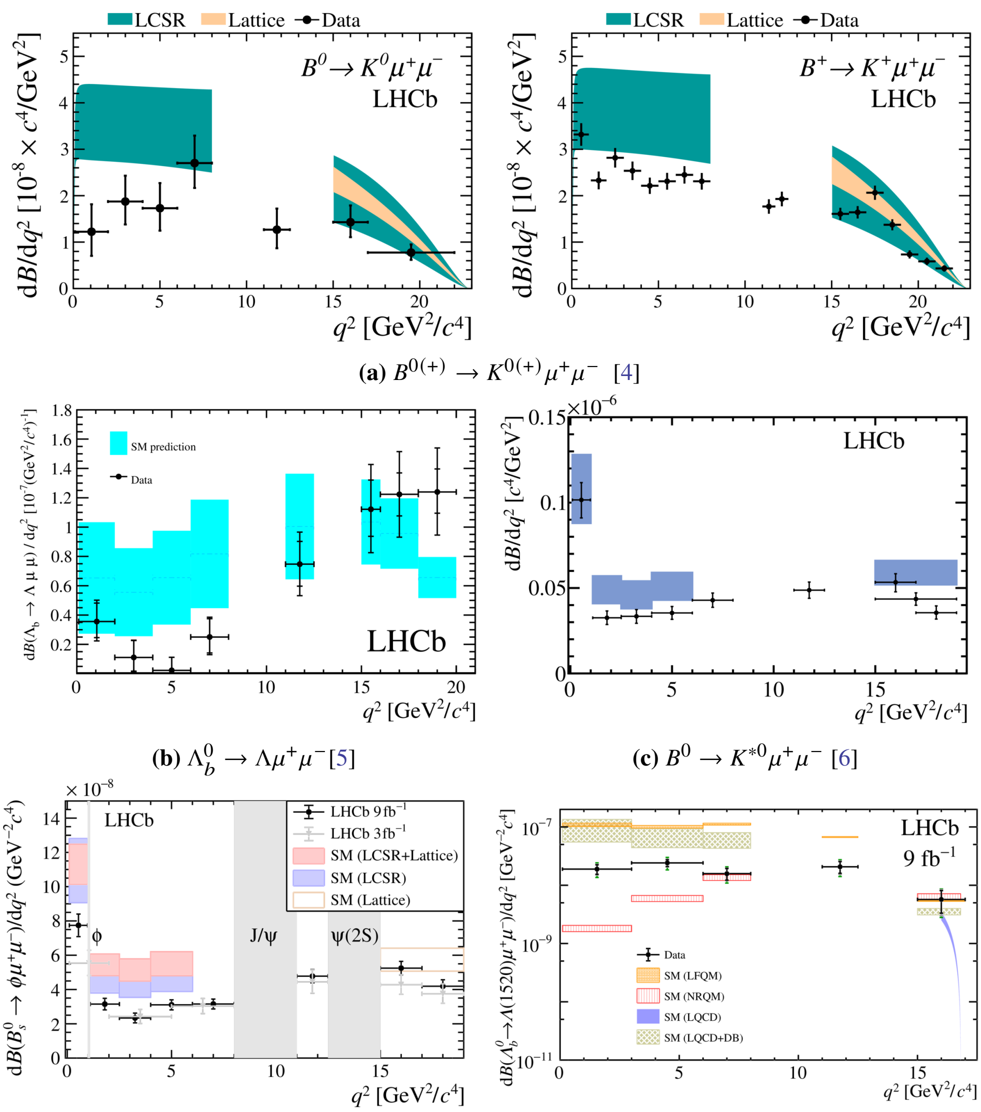
Physics processes mediated by $b \to s\ell\ell$ quark-level transitions have been widely studied in the past years, as they serve as excellent probes for possible New Physics (NP) scenarios. Such processes are in fact forbidden at the lowest perturbation order by the Standard Model, and thus they could receive comparable contributions from new heavy physics mediators (such as leptoquarks [1] or Z' [2]). The state of the art of the LHCb measurements for such decays, with most of them having the world best precision to date, are presented in this proceedings. The LHCb detector is in fact highly suited for this type of decays, being a forward spectrometer with an high acceptance of the many b hadrons produced by the LHC, good particles identification and trigger performances on displaced tracks and excellent tracking efficiency [3].

2. Differential branching fractions

Figure 1 shows the differential branching fractions measured by the LHCb collaboration for several $b \to s\mu\mu$ transitions as a function of the dilepton invariant mass squared $q^2 = m^2(\mu\mu)$. The branching fractions are shown for: $B^{0(+)} \to K^{0(+)}\mu^+\mu^-$ [4], $\Lambda_b^0 \to \Lambda\mu^+\mu^-$[5], $B^0 \to K^{*0}\mu^+\mu^-$ [6], $B_s^0 \to \phi\mu^+\mu^-$ [7], and $\Lambda_b^0 \to \Lambda(1520)(\to pK^-)\mu^+\mu^-$ [8], the latest being a very recent result published in 2023. The branching fractions appear to be consistently lower than the SM predictions, with the largest discrepancy of $\sim 3.6\sigma$ observed in $B_s^0 \to \phi\mu^+\mu^-$ decays. However, as it can be seen from the figure, these observables are affected by large theory uncertainties, mainly coming from the form factors descriptions.

3. Angular distributions

The QCD uncertainties can be reduced at leading order by looking at the angular distributions of the final state particles. The decay rate of physics processes such as $B^0 \to K^{*0}\mu^+\mu^-$ can in fact be fully described by three angles: $cos(\theta_\ell)$, $cos(\theta_K)$ and ϕ, as defined in Ref. [9], by means of angular parameters sensitive to possible NP contributions. These parameters are usually optimised in angular observables which are less sensitive to the uncertainties coming from the form factor descriptions. Figure 2 shows one of the most famous angular observable, namely P_5', measured by the LHCb collaboration in $B^0 \to K^{*0}\mu^+\mu^-$ decays [10] (using 4.7fb^{-1} of integrated luminosity) and in $B^+ \to K^{*+}\mu^+\mu^-$ decays [11] (using the full dataset collected). A local tensions of $2.4 - 2.7\sigma$ with respect to the SM predictions is observed, depending on the q^2 intervals and the hadronic uncertainties considered. It is worth to mention here the long-standing debate within the theory community about whether non-perturbative QCD contributions from charm-loop could mimic NP contributions and thus explain these discrepancies. Figure 2 also shows the angular observable $F_{\rm L}$ measured in $B_s^0 \to \phi\mu^+\mu^-$ decays where, given the presence of a flavour symmetric final state, not all the observables are accessible ($e.g. P_5'$). Here the results are found to be compatible with the Standard Model predictions.



(a) $B^{0(+)} \to K^{0(+)}\mu^+\mu^-$ [4]

(b) $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [5]

(c) $B^0 \to K^{*0}\mu^+\mu^-$ [6]

(d) $B_s^0 \to \phi\mu^+\mu^-$ [7]

(e) $\Lambda_b^0 \to \Lambda(1520)\mu^+\mu^-$ [8]

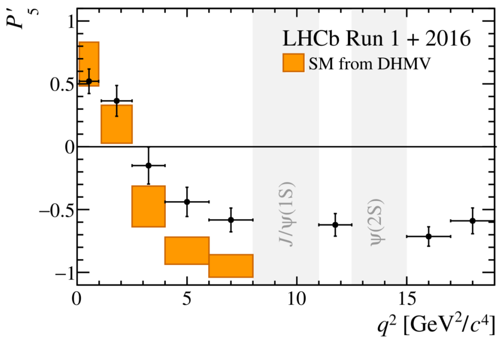
Figure 1: Differential branching fractions extracted as a function of the di-muon invariant mass square (q^2), published by the LHCb collaboration. SM predictions are also shown for each decay mode.

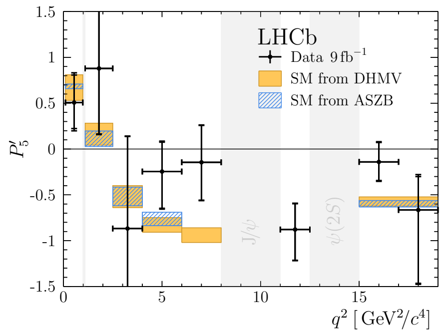
4. Lepton Flavour Universality ratios

Relative rates of the form

$$R_{H_s} = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}(H_b \to H_s ee) dq^2}{dq^2}}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathcal{B}(H_b \to H_s \mu\mu) dq^2}{dq^2}}, \quad (1)$$

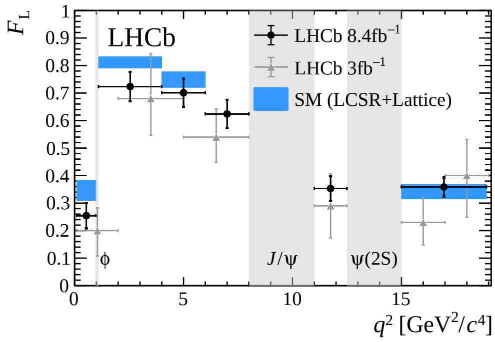
where $H_{b(s)}$ is a generic hadronic system containing a $b(s)$ quark, are expected to be equal to one due to the Lepton flavour universality (LFU) of the Standard Model (where gauge interactions have the same amplitudes for all the lepton families). Such observables are particularly clean and predicted with very high accuracy, with the theoretical uncertainties coming from the QCD





(a) $B^0 \to K^{*0}\mu^+\mu^-$ [10]

(b) $B^+ \to K^{*+}\mu^+\mu^-$ [11]



(c) $B_s^0 \to \phi\mu^+\mu^-$ [12]

Figure 2: Angular observables measured by the LHCb collaboration for different decays, in bins of the di-lepton invariant mass. Standard Model predictions are also shown.

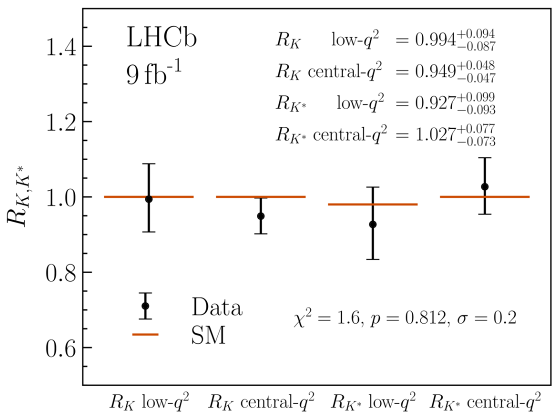


Figure 3: The most precise values up to date for R_K and R_K^*. The label low$-q^2$ stands for a range of $0.1 < q^2 < 1.1$ GeV$^2/c^4$ and central$-q^2$ for $1.1 < q^2 < 6.0$ GeV$^2/c^4$ [17].

part of the decay cancelling out in the ratio. In the past years LHCb measured several lepton flavour universality ratios by looking at different decays: $B^+ \to K^+\ell^+\ell^-$ [13], $B^0 \to K^{*0}\ell^+\ell^-$ [14], $B^0 \to K^0_s\ell^+\ell^-$ and $B^+ \to K^{*+}\ell^+\ell^-$ [15], $\Lambda_b \to pK\ell^+\ell^-$ [16]. The results seemed to point to a coherent pattern of deviations from one, but none of the measurements was significant enough to firmly conclude presence of NP contributions. In 2023 LHCb published the most precise lepton flavour test up to date, which was performed by analysing simultaneously the high-yields decay channels $B^{+(0)} \to K^{+(*0)}\ell^+\ell^-$, and using the full dataset collected by the LHCb detector [17] (and thus updating the former $R_{K^{*0}}$ measurement which used only 3fb^{-1}). The results, shown in Figure 3, are found to be compatible with the SM predictions, with the discrepancies with respect to the previous results due partly to the use of a tighter electron identification selection and partly to an additional modelling of the background coming from misidentification of hadrons to electrons.

5. Lepton flavour violation

NP scenarios that could explain possible LFU violation usually also predict sizable contributions to lepton flavour violating (LFV) decays. The LHCb collaboration very recently set the best limits on the $B^0 \to K^{*0}\mu^\pm e^\mp$ and the $B^0_s \to \phi\mu^\pm e^\mp$ LFV decays, providing constraints for scalar and left-handed NP scenarios. The results are available also separately for $b \to s\mu^+e^-$ and $b \to s\mu^-e^+$, since possible NP could contribute differently with respect to the charge combinations. The limits on the branching fractions at 90% (95%) confidence level were found to be [19]:

$$
\begin{aligned}
\mathcal{B}(B^0 \to K^{*0}\mu^+e^-) &< 5.7\times10^{-9}\ (6.9\times10^{-9}),\\
\mathcal{B}(B^0 \to K^{*0}\mu^-e^+) &< 6.8\times10^{-9}\ (7.9\times10^{-9}),\\
\mathcal{B}(B^0 \to K^{*0}\mu^\pm e^\mp) &< 10.1\times10^{-9}\ (11.7\times10^{-9}),\\
\mathcal{B}(B^0_s \to \phi\mu^\pm e^\mp) &< 16.0\times10^{-9}\ (19.8\times10^{-9}),
\end{aligned}
$$

where the main systematic uncertainties come from the branching fraction of the normalisation channel and, for the $B^0_s \to \phi\mu^\pm e^\mp$ decays, the unknown a-priori effective lifetime of the final state. In addition, the LHCb collaboration recently published the most stringent limits on $b \to s\tau\mu$ transitions by looking at $B^0 \to K^{*0}\tau^\pm\mu^\mp$, where the τ is reconstructed via *e.g.* $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$. The limits at 90%(95%) confidence level were found to be: $\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0\ (1.2) \times 10^{-5}$ and $\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+) < 8.2\ (9.8) \times 10^{-6}$ [20].

6. Conclusions

In order to understand the remaining angular and differential decay rates anomalies, several measurements are currently being performed at LHCb, aiming at updating with the full dataset collected the former measurements, and at studying many more decay channels (*e.g.*$R_{K\pi\pi}$, R_ϕ or angular analysis with electrons in the final state). In addition, the higher yields we will collect in the future (with an upgraded LHCb detector) and the synergy with other experiments will allow to reach unprecedented precision in the study of those rare transitions.

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