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# New results in LU/LFV tests with LHCb

**Jessica Prisciandaro***
*Universidade de Santiago de Compostela (ES)*
*E-mail:* jessica.prisciandaro@cern.ch

During the Run 1 of the LHC, the LHCb experiment has collected a large sample of beauty-hadrons that corresponds to an integrated luminosity of $3.0\,\mathrm{fb}^{-1}$ at $pp$ centre-of-mass energy of 7 and 8 TeV. In the following, an overview of the rare decay measurements the LHCb collaboration performed during Run 1 is presented. In particular, recent tests of lepton flavour universality, with deviations also observed in semileptonic decays, and searches for lepton flavour violation decays will be presented.

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## 1. Introduction

Searches for lepton flavour violation (LFV) and tests of lepton flavour universality (LFU) are among the most powerful probes of the Standard Model (SM) and of possible New Physics (NP) effects.

The discover of the neutrino oscillation indicates that lepton-flavour symmetry is not exact in nature. Neutrino oscillation, and therefore lepton flavour violating processes, are therefore allowed in the SM. On the other hand, such processes are only induced by the tiny neutrino masses, and their branching fractions, of the order of $10^{-40}$ or less, are beyond the reach of any experiment. Observation of any LFV process would be therefore a clear and unambiguous sign of NP.

The SM also requires lepton universality, *i.e* equal couplings between the gauge bosons and the three family of leptons. As a consequence, branching fraction differences of semileptonic decays in $e$, $\mu$ and $\tau$, are only caused by phase space and helicity-suppressed contributions. However, several NP models predict non-SM bosons that do not couple equally to the different lepton families. Deviations from the SM prediction would be again signature of physics beyond the SM.

The LHCb experiment [1] at the Large Hadron Collider is mainly dedicated to flavour physics studies, and is perfect place where to look for rare decays, and perform precise measurements of $b$ and $c$ mesons decays. Hereafter three searches for lepton flavour violation and two tests of lepton flavour universality performed at LHCb will be presented.

## 2. Search for the Lepton-Flavor-Violating Decays $B_s^0 \to e^\pm\mu^\mp$ and $B \to e^\pm\mu^\mp$

The $B_s^0 \to e^\pm\mu^\mp$ and $B \to e^\pm\mu^\mp$ decays violate lepton flavour conservation, and are therefore forbidden within the SM. However, they are predicted in several NP scenarios, as for example in the Pati-Salam model [2], which allows leptons and quarks transitions mediated by spin-1 gauge bosons that carry both color and lepton quantum numbers, called Pati-Salam leptoquarks (LQ). This analysis [4] presents a search of the $B_s^0 \to e^\pm\mu^\mp$ and $B \to e^\pm\mu^\mp$ decays based on 1.0 $\text{fb}^{-1}$ of $pp$ collisions at $\sqrt{s} = 7$ TeV collected by the LHCb experiment in 2011. Given the same event topology as that of the signal, the $B^+ \to K^+\pi^-$ decay is chosen as reference channel for the branching fraction measurement, while $B^0_{(s)} \to h^+h'^-$ decays are used as control channels.

Background reduction is based on a two-stage boosted decision tree (BDT) selection, where the same requirement on the first discriminant is applied to both signal and normalization channels. The candidates surviving the selection are divided in bins of a second classifier and a fit to the invariant mass distribution is performed simultaneously for the different bins. The expected and observed distribution as a function of the branching fraction is computed with the $\text{CL}_s$ method [3], and are found to be compatible within $1\sigma$ (see Fig. 1). At 90 (95)% CL, the following limits are set on the branching fraction:

$$\mathscr{B}(B_s^0 \to e^\pm\mu^\mp) < 1.1(1.4)\times 10^{-8}\,, \tag{2.1}$$

$$\mathscr{B}(B \to e^\pm\mu^\mp) < 2.8(3.7)\times 10^{-9}\,. \tag{2.2}$$

These limits can be translated into lower bounds to the leptoquark masses in the Pati-Salam model, assuming that the leptoquark links the $\tau$ lepton to the first and second quark generation:

$$M_{\text{LQ}}(B_s^0 \to e^\pm\mu^\mp) > 107(101)\,\text{TeV/c}^2\,, \tag{2.3}$$

$$M_{\mathrm{LQ}}(B \to e^{\pm}\mu^{\mp}) > 135(126)\,\mathrm{TeV/c^2}, \tag{2.4}$$

at 90 (95)% CL respectively.

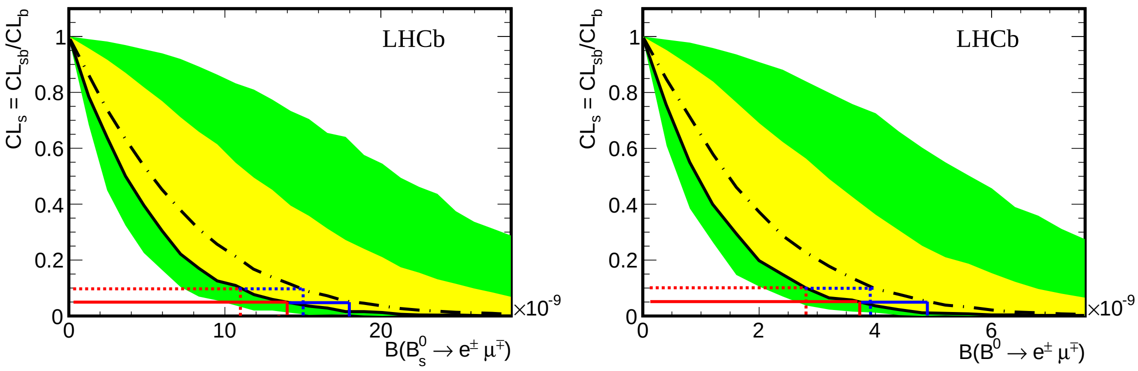


**Figure 1:** $\mathrm{CL}_s$ as a function of the assumed branching fraction for (left) $B^0_s \to e^{\pm}\mu^{\mp}$ and (right) $B \to e^{\pm}\mu^{\mp}$ decays. The dashed lines are the medians of the expected $\mathrm{CL}_s$ distributions if background only was observed. The yellow (green) area covers, at a given branching fraction, 34%(47.5%) of the expected $\mathrm{CL}_s$ distribution on each side of its median. The solid black curves are the observed $\mathrm{CL}_s$. The upper limits at 90 % (95 %) C.L. are indicated by the dotted (solid) vertical lines in blue for the expectation and in red for the observation.

## 3. Search for the lepton-flavour violating decay $D^0 \to e^{\pm}\mu^{\mp}$

As the $B_{(s)}$ decays presented in the previous section, another lepton flavour violating process studied at the LHCb experiment is the $D^0 \to e^{\pm}\mu^{\mp}$ decay [5]. Not allowed in the SM, it is instead predicted in various BSM theories [6], such as theory with multiple Higgs doublets, SM extensions with extra fermions, and minimal supersymmetric (SUSY) SM with R-parity violation. In the latter, a branching fraction as large as $\mathcal{O}(10^{-7})$ [7] is estimated.

Events are selected from the decay chain $D^{*+} \to D^0(\to e^{\pm}\mu^{\mp})\pi^+$ and the well-measured $D^{*+} \to D^0(\to e^{\pm}\mu^{\mp})\pi^+$ decay is used as normalization channel for the branching fraction measurement. A multivariate classifier based on a BDT is used to split the events in three different sub-samples, and a two dimensional unbinned ML fit to the $m(D^0)$ and $\Delta m = m(D^{*+}) - m(D^0)$ distributions is performed to extract the number of signal candidates. The fit is made simultaneously in three categories according to how the candidate was triggered. Figure 2 shows the fit superimposed to data in the two most-signal like bins. No evidence for the $D^0 \to e^{\pm}\mu^{\mp}$ signal is seen, and the CLs method is used to se an upper limit on the branching fraction, $\mathcal{B}(D^0 \to e^{\pm}\mu^{\mp}) < 1.3 \times 10^{-8}$ at 90% CL. Such limit supersede the previous limit measured by Belle, by an order of magnitude. The $CL_s$ as a function of $\mathcal{B}(D^0 \to e^{\pm}\mu^{\mp})$ is shown in Fig. 3.

## 4. Search for the lepton flavour violating decay $\tau^- \to \mu^-\mu^+\mu^-$

The $\tau^- \to \mu^-\mu^+\mu^-$ decay is a lepton flavour violating decay. The SM prediction is of the order of $10^{-40}$ [17, 18], much below the sensitivity of any experiment. However, LFV is predicted in

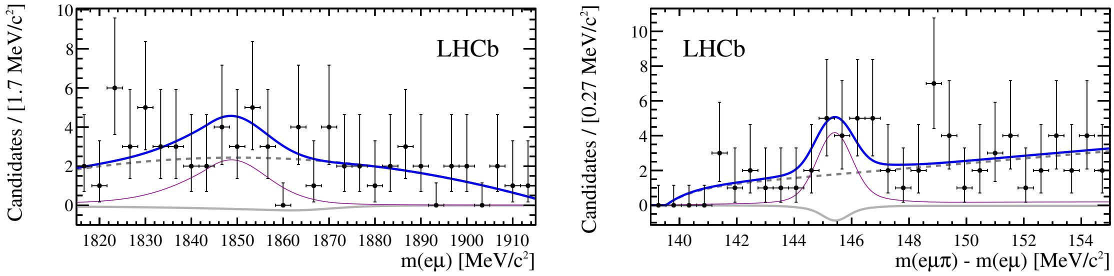


**Figure 2:** Distributions of (left) $m(D^0)$ and $\Delta m$ for $D^0 \to e^{\pm}\mu^{\mp}$ candidates reconstructed in the combined 7 TeV and 8 TeV data, with fit functions overlaid in the most signal-like bin. The solid (blue) lines show the total fit results, while the thick (grey) lines show the total $D^0 \to e^{\pm}\mu\mp$ component, the thin (purple) lines show the total misidentified $D^0 \to \pi^+\pi^-$ and the dashed (grey) lines indicate the combinatorial background.

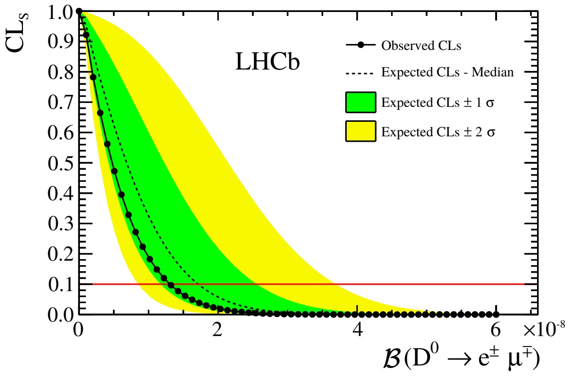


**Figure 3:** Distribution of $CL_s$ as a function of $\mathcal{B}(D^0 \to e^{\pm}\mu^{\mp})$. The expected distribution is shown by the dashed line, with the $\pm 1\sigma$ and $\pm 2\sigma$ region shaded. The observed distribution is shown by the solid line connecting the data points. The horizontal line indicates the 90% confidence level.

many extension of the SM, enhancing the predicted branching fraction to values within experimental reach [19], especially in $\tau$ decays, because of the large difference in mass between the tau and muon leptons. This analysis [8] aims at searching for the decay, using the 3 fb$^{-1}$ of $pp$ collisions collected by LHCb during Run1 and exploiting the large inclusive $\tau^-$ production cross-section at the LHC, estimated to be 85 µb at 7 TeV. Because of the similar topology to that of the signal, the measurement is performed with respect to the $D_s^- \to \phi(\mu^+\mu^-)\pi^-$. Figure 4 shows the fit to the normalisation channel. The data selection is based on two multivariate classifiers. The first involves kinematic and geometrical properties of the signal, while a particle identification classifier is used to select the muon candidates in the final state. The data sample containing signal candidates is split in bins of the classifier responses, and the expected and observed numbers of candidates in the signal region is extracted from a fit to the sidebands. No significant excess is found, and the observed limit to the branching fraction obtained with the CLs method is $\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 4.6(5.6) \times 10^{-8}$. The expected and observed limits are shown in Fig. 5.

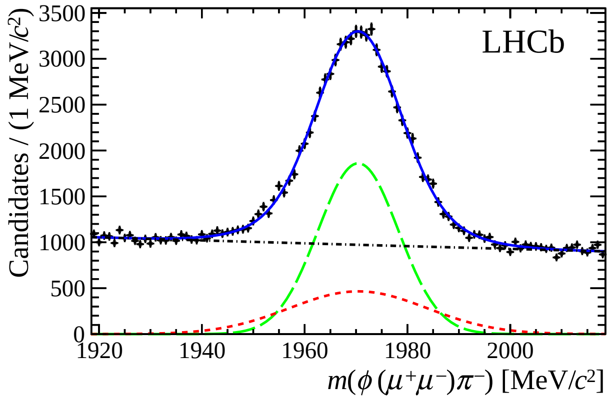


**Figure 4:** Invariant mass distribution of $\phi(\mu^+\mu^-)\pi^-$ candidates in 8 TeV data. The solid (blue) line shows the overall fit, the long-dashed (green) and short-dashed (red) lines show the two Gaussian components of the $D_s^+$ signal and the dot-dashed (black) line shows the combinatorial background contribution.

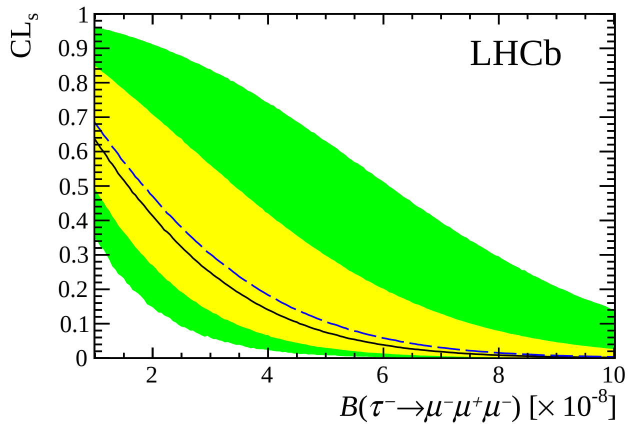


**Figure 5:** Distribution of $\mathrm{CL}_s$ values as a function of the assumed branching fraction for $\tau^- \to \mu^-\mu^+\mu^-$, under the hypothesis to observe background events only. The dashed line indicates the expected limit and the solid line the observed one. The light (yellow) and dark (green) bands cover the regions of 68% and 95% confidence for the expected limit.

## 5. Lepton flavour universality in $\bar{B}^0 \to D^{*+} l \nu_l$

Within the SM, the ratio $R(D^*) = \mathscr{B}(\bar{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)/\mathscr{B}(\bar{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)$ is precisely predicted, $R(D^*) = 0.252 \pm 0.003$ [13]. However, the presence of a charge Higgs boson, present in many extension of the SM might affect the branching fraction of the $\bar{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ decay, leading to significant deviation from the SM prediction. The BaBar experiment published recently the results of the measurement of $R(D^*)$ and $R(D) = \mathscr{B}(\bar{B}^0 \to D^+\tau^-\overline{\nu}_\tau)/\mathscr{B}(\bar{B}^0 \to D^+\mu^-\overline{\nu}_\mu)$ [15, 16], which show a deviation from the SM of $2.7\sigma$ and $2.0\sigma$ respectively [14, 13]. This analysis [9] shows the first measurement of $R(D^*)$ performed by the LHCb experiment and uses the $3\,\mathrm{fb}^{-1}$ of data collected during the Run1. The $\tau^-$ and the $D^{*+}$ are reconstructed through the decay chain $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$ and $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$. Given the same visible final state of the $\bar{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ (signal) and $\bar{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu$ (normalization) channels, the same selection is applied to both channels. In order to separate the signal, normalization and the background processes a three-dimensional maximum likelihood template fit is performed. Two significant background sources have to be taken in account in the fit in addition to the combinatorial background: $B$ decays to charmed hadrons followed by a semileptonic decay, $\bar{B} \to D^{*+}(\to \mu\nu_{\mu}X)H_cX$, and semileptonic decays to heavier charmed hadrons, $\bar{B} \to D^{**}(\to D^{*+}\pi\pi)\mu\nu_{\mu}$. The kinematic variables used in the fit are: the missing mass squared, $m^2_{miss} = (p^{\mu}_B - p^{\mu}_D - p^{\mu}_{\mu})^2$, the muon energy, $E^*_{\mu}$, and the squared four-momentum of the lepton system. All uncertainties on the template shapes, which constitute the major source of uncertainty, are incorporated in the fit. Figure 6 shows the fit to the $m^2_{miss}$ and $E^*_{\mu}$ variables in bins of $q^2$.

The yields ratio extracted from the fit is $N(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_{\tau})/N(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_{\mu}) = (4.54 \pm 0.46) \times 10^{-2}$, which lead to the ratio of branching fractions $R(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$. This measurement is in good agreement with the BaBar and Belle results and is 2.1 $\sigma$ larger than the SM predictions.

## 6. Test of Lepton Universality Using $B^+ \to K^+\ell^+\ell^-$ Decays

$B^+ \to K^+\ell^+\ell^-$, with $= \mu, e$ decays are $b \to s$ flavours-changing processes, and are therefore highly suppressed in the SM. Assuming lepton universality the ratio of the $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+e^+e^-$ branching fractions is predicted to be unity with an accuracy of the order of $10^{-3}$ [12, 11]. This analysis [10] explores lepton universality through the ratio

$$R_K = \mathscr{B}(B^+ \to K^+\mu^+\mu^-)/\mathscr{B}(B^+ \to K^+e^+e^-). \tag{6.1}$$

The measurement is performed in the range of the dilepton mass squared $1 < q^2 < 6\,\text{GeV}^2/c^4$. In order to remove potential sources of systematic uncertainties, $R_K$ is measured from the double ratio of branching fractions of $B^+ \to K^+\ell^+\ell^-$ decays and the well known $\mathscr{B}(B^+ \to J/\psi(\to \ell^+\ell^-)K^+)$. In the latter, lepton universality is assumed.

Background reduction is based on two multivariate algorithms based on a BDT selection, trained separately to enhance dielectron and dimuon signal decays. Figure 7 shows the reconstructed $B^+$ and dilepton mass of the selected candidates. From the plot, the $J/\psi$ and $\psi(2S)$ peaks along with their radiative tail can be clearly seen.

Signal yields are extracted using an extended maximum likelihood fit to the $K^+\ell^+\ell^-$ invariant mass distributions. The fit model is composed by the signal and combinatorial background. In the case of the di-electron a further component to describe partially reconstructed decays is included. A careful parametrization of the signal shape is required for the electron modes, where the mass distribution depends on the number of bremsstrahlung photons associated with the electrons. In order to do that, the sample of $B^+ \to K^+e^+e^-$ candidates is split into three samples according to the trigger selection, using a different shape according to the number of bremsstrahlung photons. Such parametrisation also corresponds to the dominant source of systematic uncertainty. The combination of the three $R_K$ measurements from the different categories gives $R_K = 0.745^{+0.090}_{0.074}(\text{stat}) \pm 0.036(\text{syst})$. This is the most precise measurement of $R_K$ and is consistent with the SM expectation within 2.6 $\sigma$. Figure 8 compares the LHCb, Belle and Babar measurement with the SM theoretical expectation. This analysis also determines the most precise measurement

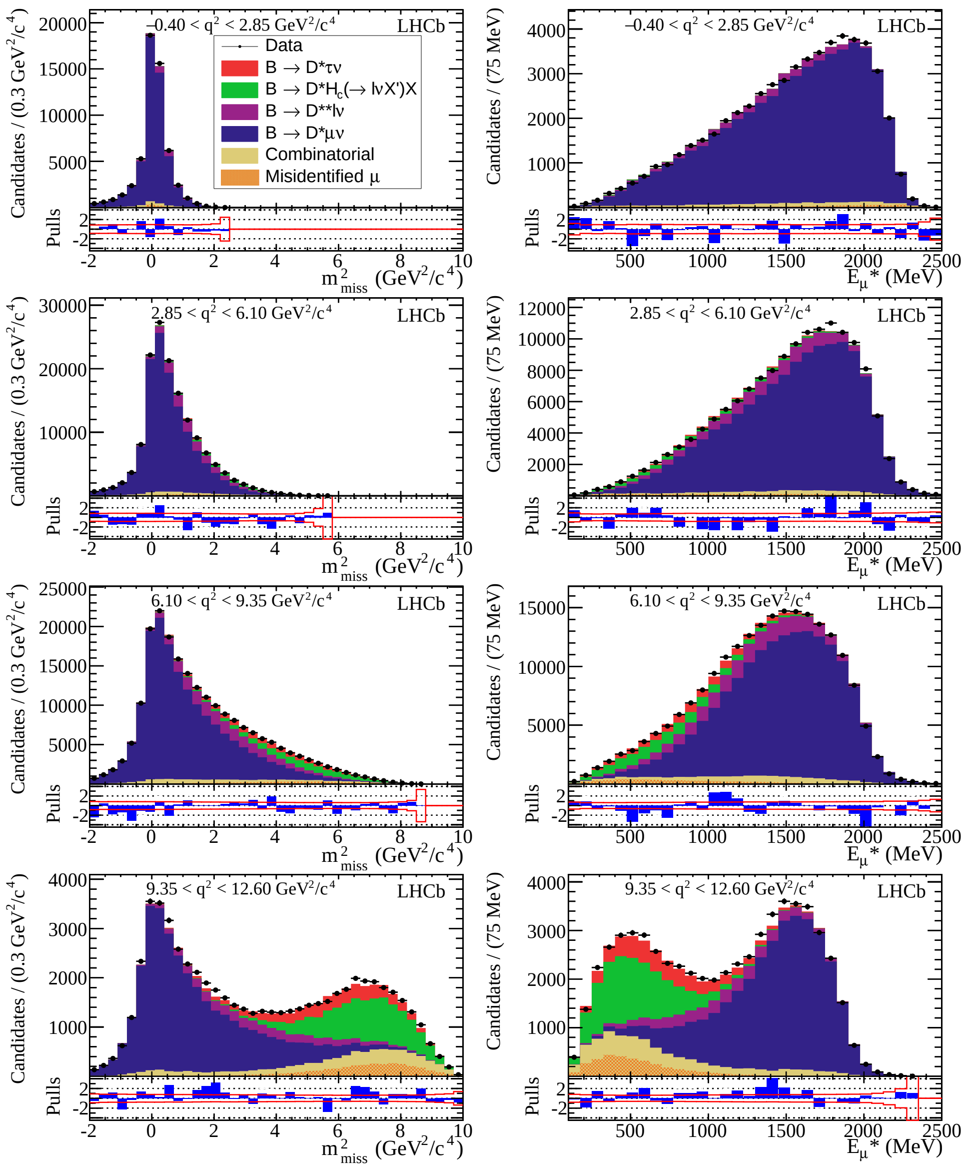


**Figure 6:** Distributions of $m^2_{miss}$ (left) and $E^*_\mu$ (right) of the four $q^2$ bins of the signal data, overlaid with projections of the fit model with all normalization and shape parameters at their best-fit values. Below each panel differences between the data and fit are shown, normalized by the Poisson uncertainty in the data. The bands give the $1\sigma$ template uncertainties.

to date of the $B^+ \to K^+e^+e^-$ branching fraction, measured using the $B^+ \to J/\psi(\to e^+e^-)K^+$ decay as reference channel. The value obtained is $\mathscr{B}(B^+ \to K^+e^+e^-) = 1.56^{+0.19}_{-0.15}(\text{stat})^{+0.06}_{-0.04}(\text{syst})$, compatible with the SM prediction.

## 7. Conclusion

With the Run 1 data the LHCb experiment demonstrated its excellence in searching for rare decays and in performing very precise tests of the SM. Analyses dedicated to the search for lepton

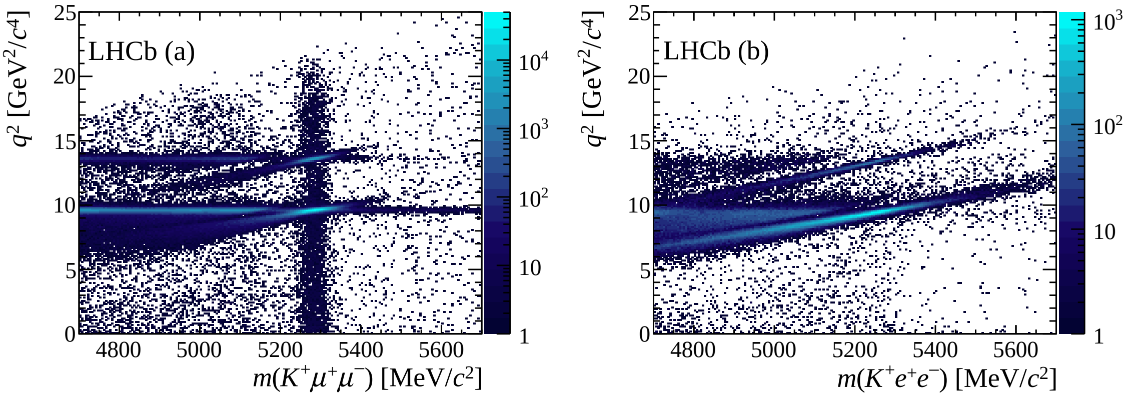


**Figure 7:** Dilepton invariant mass squared, $q^2$, as a function of the $K^+\ell^+\ell^-$ invariant mass, $m(K^+\ell^+\ell^-)$, for selected (a) $K^+\mu^+\mu^-$ and (b) $K^+e^+e^-$ candidates. The radiative tail of the $J/\psi$ and $\psi(2S)$ mesons is most pronounced in the electron mode due to the larger bremsstrahlung and because the energy resolution of the ECAL is lower compared to the momentum resolution of the tracking system.

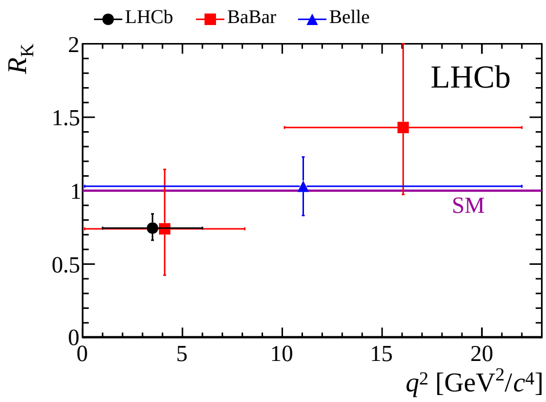


**Figure 8:** Summary of results on $R_K$ determined by LHCb, BaBar and Belle experiments. The SM prediction is also shown as a continuous function of $q^2$. The theoretical uncertainty on $R_K$ is expected to be O($10^3$).

flavour and lepton universality violations led to some of the most precise measurements in the flavour sector of particle physics. Moreover, the recent measurements of $R(K)$ and $R(D^*)$ showed hint of deviations from the SM. The larger statistics that will be collected during the Run 2 will allow further studies which will help to clarify the still open questions.

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