TEST OF LEPTON FLAVOUR UNIVERSALITY AT LHCb

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This contribution presents the $R_{D^*}$ and $R_K$ measurements, which are a clean probe of lepton flavour universality, and the angular analyses of the $B^0 \rightarrow K^{*0}\mu^+\mu^-$ and $B^0 \rightarrow K^{*0}e^+e^-$ decays, which allow to search for New Physics in rare decays proceeding through a $b \rightarrow s\ell^+\ell^-$ transition. All measurements have been performed by the LHCb collaboration using the full statistics of LHC Run I. An overview of the ongoing and future measurements is given in the conclusions.

1 Motivation

Lepton flavour universality, which states that the electroweak couplings of the three generations of leptons are the same, is a valid symmetry in the Standard Model (SM), but can be violated in many New Physics (NP) scenarios.\textsuperscript{1,2,3,4} Two semileptonic transitions that can serve as a probe of this symmetry are examined in this contribution. The first is the $b \rightarrow c\tau^-\nu_\tau$ transition, which is a charged-current tree-level transition in the SM. Since semileptonic decays of $b$-hadrons to third-generation leptons are measured to a precision of the order of 20\%, such processes are particularly sensitive to NP preferentially coupling to third-generation leptons, such as Higgs-like charged scalars or $W'$ bosons.\textsuperscript{5} A complementary approach to search for NP is to study rare decays, like those involving the $b \rightarrow s\ell^+\ell^-$ transition. Due to the absence of flavour-changing neutral currents at tree level, these decays are only allowed at loop level in the SM and are hence highly sensitive to virtual particles and interactions, such as charged Higgs or $Z'$ bosons mediating the transition from the quark $b$ to the quark $s$. In particular, by comparing decays with different leptons in the final state, one can probe NP involving lepton flavour universality violation among different generations.

All measurements presented here are based on the whole LHC Run I data sample recorded by the LHCb experiment. The data consists of proton-proton collisions at center-of-mass energies of 7 and 8 TeV and corresponds to an integrated luminosity of $3.0 \text{ fb}^{-1}$.

2 The $R_{D^*}$ measurement

$R_{D^*}$ is the ratio of the branching fractions $\overline{B}^0 \rightarrow D^{*+}\tau^-\nu_\tau$ to $\overline{B}^0 \rightarrow D^{*+}\mu^-\nu_\mu$, where the numerator and denominator are referred to as signal and normalisation channel, respectively. The SM prediction for $R_{D^*}$ is $0.252 \pm 0.03$ and differs from unity mainly because of phase-space effects due to the $\tau - \mu$ mass difference.\textsuperscript{6,7}

Previous measurements performed by BaBar and Belle reported an excess with respect to the SM prediction, with a significance between 1.6 and 2.7 standard deviations.\textsuperscript{8,9,10,11} At LHCb, the $D^{*+}$ has been reconstructed in the $D^0(\rightarrow K^-\pi^+)\pi^+$ final state, while the charged $\tau$ lepton
Figure 1 – Distribution of $m_{\text{miss}}^2$ (left) and $E_{\mu}^*$ (right) for candidates in the $q^2$ bin between 9.35 and 12.60 GeV$^2$/c$^4$. The data points are shown in black, while the different colors refer to the different components in the template distribution, according to the legend.

has been reconstructed in its purely leptonic decay mode $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$.\textsuperscript{12} One and three neutrinos are present in the final state of the signal and normalisation channel, respectively. Since the two channels share the same visible final-state topology, the candidates belonging to both are selected by a common procedure. The separation between signal and normalisation channel is then achieved by exploiting the difference in the charged-lepton masses and the presence of two extra neutrinos in the signal channel. These two properties affect the distributions of three kinematic variables: the muon energy, $E_{\mu}^*$, the squared missing mass, $m_{\text{miss}}^2$, and the squared four-momentum transfer to the lepton system, $q^2$, which are all evaluated in an approximated $B^0$ rest frame. The distributions of these kinematic variables are then fitted in a multidimensional maximum likelihood fit, using template distributions derived from control samples and from simulation validated against data. Several sources of background are taken into account, including partially reconstructed decays (i.e., decays to higher $D^*$ and $D^{**}$ resonances, and decays to pairs of charm hadrons) and combinatorial (that is, candidates from combinations of unrelated particles from different decays). The $m_{\text{miss}}^2$ and $E_{\mu}^*$ distributions for the candidates passing the full selection are shown in Fig. 1 for one specific $q^2$ bin. The yields extracted by the fit are used to determine the value of $R_{D^*}$, which is found to be $0.336 \pm 0.027 \pm 0.030$, where the first uncertainty is statistical and the second systematic. This result, which represents the first measurement of $b$-hadron decays to charged $\tau$ leptons at a hadron collider, is compatible with the SM prediction at 2.1 standard deviations.

By combining the LHCb result with those obtained by BaBar and Belle, an excess in the tau mode with respect to the SM prediction is observed, corresponding to a nearly 4 standard deviation discrepancy, as reported by the latest HFAG average.\textsuperscript{13} This is shown in Fig. 2 and could be an indication of lepton flavour non-universality involving the second and third generations of leptons.

Figure 2 – $R_D$ and $R_{D^*}$ combined results compared to SM predictions.\textsuperscript{13}
A similar measurement can be performed in $b \to s \ell^+\ell^-$ transitions, by measuring the ratio of the branching fractions of the $B^0 \to K^+\mu^+\mu^-$ and $B^0 \to K^+e^+e^-$ decays, hereafter referred to as $R_{K}$. Such ratio is predicted to be unity in the SM, with an uncertainty of $\mathcal{O}(10^{-3})$. However, deviations are expected in several extensions of the SM, such as those involving new scalar or pseudoscalar interactions or $Z'$ bosons coupling differently to electrons and muons.

The value of $R_{K}$ has been measured by LHCb in the $q^2$ region between 1.0 and 6.0 GeV$^2$/c$^4$. The measurement has been performed as a double ratio with respect to the $B^0 \to K^+J/\psi(\to \ell^+\ell^-)$ resonant mode. This approach allows to reduce systematic uncertainties and simplify the extraction of the efficiencies. The number of signal events has been obtained from an unbinned extended maximum likelihood fit of the invariant $m_{K^+\ell^+\ell^-}$ distribution. Since the distribution of the signal candidates in the electron mode depends on the nature of the particle that has triggered the event (lepton or hadron) and on the number of bremsstrahlung photons emitted by the electron pair, the data sample is split in distinct trigger categories and a simultaneous fit model consists of tree contributions: signal, combinatorial background (dark shaded area), and background due to the partially reconstructed decays (light shaded area).

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3 The $R_{K}$ measurement

Due to the presence of a vector meson in the final state, the $B^+ \to K^+\mu^+\mu^-$ decay provides a richer phenomenology than the $B^+ \to K^+\pi^-$ decay. In the former case, in fact, the differential decay width can be expressed in terms of $q^2$ and three decay angles ($\theta_1, \theta_k$, and $\phi$) and depends on several angular observables, which are functions of the $C_7$, $C_9$, and $C_{10}$ Wilson coefficients (and their chirality-flipped versions).

At LHCb, the value of the angular observables has been determined in 8 bins of $q^2$ from 0.1 to 19 GeV$^2$, reconstructing the $K^{*0}$ in the $K^+\pi^-$ final state. While most of the angular observables are found to be compatible with the SM predictions, a discrepancy is observed in $P_{1\ell}$, corresponding to 3.4 standard deviations. The fit results for $P_{1\ell}$ are shown in Fig. 4. They are in agreement with previous measurements and suggest an excess with respect to the SM predictions. It is worth noticing that recent measurements performed at Belle confirm such anomaly. Such excess might be explained in terms of SM charm-loop effects, but could also be a hint of contributions from NP, with several models involving lepton flavour universality.

4 The angular analysis of the $B^0 \to K^{*0}\mu^+\mu^-$ decay

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violation available in literature.\textsuperscript{23,1,2,3,4} It is interesting to note here that SM charm-loop effects cannot account for the deviation observed in $R_K$. On the other hand, an interpretation in terms of NP involving $C_9$ alone or a combination of $C_9$ and $C_{10}$ would succeed in explaining both the $B^0 \to K^{*0} \mu^+ \mu^-$ and $R_K$ anomalies.\textsuperscript{24}

5 The angular analysis of the $B^0 \to K^{*0} e^+ e^-$ decay

A similar angular analysis has been performed on the $B^0 \to K^{*0} e^+ e^-$ decay. Compared to the $B^0 \to K^{*0} \mu^+ \mu^-$ measurement, this angular analysis has the advantage of a simplified formalism, since the lepton masses are negligible. The differential decay width can be written in terms of four angular observables: $F_L$, the longitudinal polarisation fraction of the $K^{*0}$, $A_{T}^{(2)}$ and $A_{T}^{Im}$, related to the polarisation of the photon, and $A_{T}^{Re}$, related to the lepton forward-backward asymmetry.\textsuperscript{25} The measurement has been performed by the LHCb experiment in the low $q^2$ region, from $0.0020 \pm 0.0008$ to $1.120 \pm 0.060 \text{ GeV}^2/c^4$.\textsuperscript{25} This region is dominated by the $b \to s \gamma$ transition and is hence particularly suitable to measure the photon polarisation and the $C_7$ and $C_7'$ Wilson coefficients. Like the $R_K$ measurement, the electrons in the final state require to consider different trigger and bremsstrahlung categories. The angular observables have been obtained by fitting the $B^0$ invariant mass distribution and the three decay angles, as shown in Fig. 5. The measured values are:

\begin{align*}
F_L &= +0.16 \pm 0.06 \pm 0.03, \\
A_{T}^{(2)} &= -0.23 \pm 0.23 \pm 0.05, \\
A_{T}^{Im} &= +0.14 \pm 0.22 \pm 0.05, \\
A_{T}^{Re} &= +0.10 \pm 0.18 \pm 0.05,
\end{align*}

where the first uncertainty is statistical and the second systematic. All the results are dominated by the statistical uncertainty and are found to be compatible with the SM predictions.\textsuperscript{26,27}

6 Conclusions

The $R_D$ and $R_{D^*}$ measurements performed by LHCb, BaBar, and Belle show a 4 standard deviation discrepancy with respect to the SM predictions. In addition, two measurements involving the $b \to s \ell^+ \ell^-$ transition, namely the $R_K$ measurement performed at LHCb and the angular analysis of the $B^0 \to K^{*0} \mu^+ \mu^-$ decay performed at both LHCb and Belle, suggest a tension with respect to the values predicted by the SM. This fits in a coherent pattern of possible NP involving the $C_9$ and $C_{10}$ Wilson coefficients.

Since most of the results are dominated by the statistical uncertainty, it is compelling to provide an update based on more statistics. Additional measurements of $b \to c \tau^- \bar{\nu}_\tau$ and $b \to s \ell^+ \ell^-$...
transitions are also of great interest. Such measurements include ratios of branching fractions, like $R_D$, which is the ratio of $\overline{B^0} \to D^+ \tau^- \overline{\nu}_\tau$ to $\overline{B^0} \to D^+ \mu^- \overline{\nu}_\mu$; $R_K^*$, which is the ratio of $B^0 \to K^{*0} \mu^+ \mu^-$ to $B^0 \to K^{*0} e^+ e^-$; $R_\phi$, which is the ratio of $B^0_s \to \phi \mu^+ \mu^-$ to $B^0_s \to \phi e^+ e^-$, as well as angular analyses, like that of the non-resonant $B^0 \to K^\pm \ell^\mp \ell^-$ decay to muons and electrons. This wide physics program will allow to extend our knowledge on potential NP that violates lepton flavour universality.

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