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Lepton-flavour universality tests at LHCb

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Summary. — The Standard Model predictions about the universality of the gauge boson couplings to charged leptons have been tested in B meson semileptonic decays. Several measurements of charged-current and neutral current processes were performed with a data sample collected with the LHCb detector in proton-proton collisions at centre-of-mass energies of 7 and 8 TeV, corresponding to an integrated luminosity of 3 fb^{-1}. This review presents recent results that manifest some anomalies challenging the SM paradigm. Prospects for future measurements to elucidate the origin of these anomalies are also discussed.

1. – Introduction

The lepton flavour universality (LFU) of the electroweak couplings of the gauge boson to the charged leptons is an accidental symmetry of the Standard Model (SM) that is broken only by the Yukawa interaction. Differences among the semileptonic decays to electrons, muons or tau leptons should come only from their different masses. On the contrary, New Physics (NP) might couple differently to different lepton families. Hints of deviations from the SM predictions of LFU, emerging from measurements at the $\Upsilon(4S)$ and from LHCb, as will be discussed in this report, have triggered a series of thoretical speculations about possible NP interpretation [1].

The measurements presented here employ a data sample collected in Run 1 with the LHCb detector, in proton-proton (pp) collisions at centre-of-mass energies of 7 and 8 TeV corresponding to an integrated luminosity of 3 fb^{-1}. The LHCb detector is a forward spectrometer in the pseudorapidity range 2–5 that is described in detail elsewhere [2]. Relevant to these measurements are its excellent performance in the reconstruction of the primary vertices of the pp interaction (PV) and of secondary vertices of heavy-hadron and tau decays, the resolution on the track momentum determination and the capability to identify electron and muon leptons, pion, kaon and proton hadrons.

2. – Charged current transitions

Semileptonic decays are an ideal laboratory to test the LFU ansatz. The decays are precisely described in the SM and the visible branching ratios are high. The test variable, called $\mathcal{R}(\mathrm{H_c})$, is defined as the ratio of the branching ratios,

$$\mathcal{R}(\mathrm{H_c}) \equiv \frac{\mathcal{B}(\overline{\mathrm{B}}^0 \to \mathrm{H_c}^+\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{\mathrm{B}}^0 \to \mathrm{H_c}^+\ell^-\overline{\nu}_\ell)},$$

where $\mathrm{H_c}$ is a charmed hadron and ℓ represents a light lepton. Only muons are used in the current LHCb measurements. Experimental uncertainty related to selection efficiencies and theoretical uncertainty cancel in the ratio to a large extent.

BaBar and Belle experiments have measured both $\mathcal{R}(\mathrm{D}^*)$ and $\mathcal{R}(\mathrm{D})$ [3, 4], the averages of their results show a deviation from the SM expectation which assumes lepton universality [5], of about 3 and 2 sigmas, respectively.

A first measurement of $\mathcal{R}(\mathrm{D}^*)$ at an hadron collider was performed by LHCb, reconstructing the tau in its muonic decay $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$ [6]. In this case the signal $\overline{\mathrm{B}}^0 \to \mathrm{D}^{*+}\tau^-\overline{\nu}_\tau$and the normalization $\overline{\mathrm{B}}^0 \to \mathrm{D}^{*+}\mu^-\overline{\nu}_\mu$modes have the same visible final-state particles. A good separation between the two modes is achieved by considering three key kinematic observables, computed in the B rest frame: the muon energy, E^*_μ, the missing mass squared, calculated as $m^2_{miss} = (p^\mu_B - p^\mu_{D^*} - p^\mu_\mu)^2$, and the squared four-momentum transfer to the lepton system $q^2 = (p^\mu_B - p^\mu_{D^*})^2$, where p^μ_B, $p^\mu_{D^*}$ and p^μ_μ are the four-momenta of the $\overline{\mathrm{B}}^0$ meson, the D^{*+} meson and the muon. The momentum of B mesons produced in hadronic collisions is unknown, and the exact determination of the B momentum in the laboratory frame from the reconstructed final-state particles is not possible when one or more neutrinos are present in the decay. However, the momentum direction is well determined from the unit vector to the B decay vertex from the associated PV. The Lorentz boost of the B meson along the beam direction is approximated by the boost of the visible $(\mathrm{D}^{*+}\mu^-)$ system with a resulting resolution on the rest-frame variables of approximately 15–20%, that is sufficient to preserve the differences among the two decay modes. A binned maximum likelihood fit is performed to data, simultaneous on the three observables, with templates for signal, normalization and background channels derived from simulation and control data samples. The distributions of the three observables are shown in fig. 1. The result

$$\mathcal{R}(\mathrm{D}^*) = 0.336 \pm 0.027(\mathrm{stat.}) \pm 0.030(\mathrm{syst.})$$

is in good agreement with previous measurements [3,4] and 2.1 standard deviations above the SM expectation.

A second measurement of $\mathcal{R}(\mathrm{D}^*)$ is performed with an independent and complementary data sample, with the tau lepton reconstructed in the three-prong hadronic decay $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$ [7]. The large background from hadronic B decays is highly suppressed exploiting the significant separation between the B and the tau decay vertices, measured along the beam direction, and the structure of the tau decay, which includes kinematic and geometrical variables and the presence of intermediate resonances. In order to reduce experimental systematic uncertainties a normalization decay mode with a

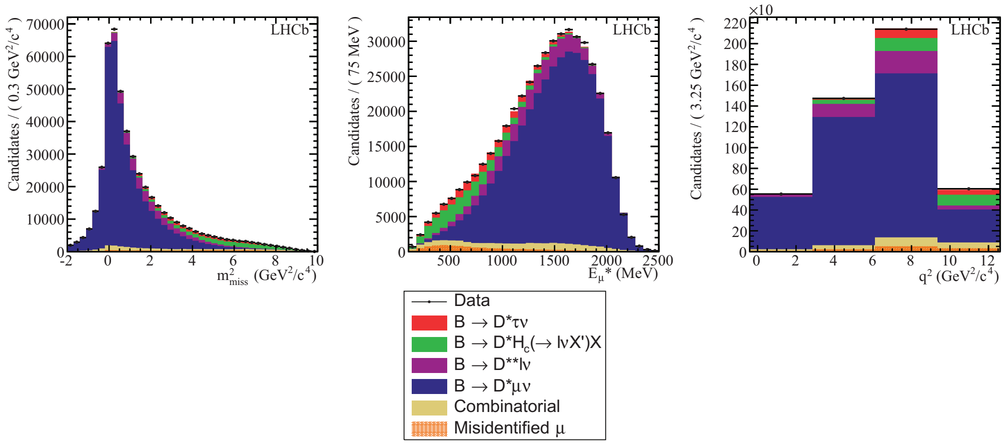

Fig. 1. – Distributions of m^2_{miss} (left), E^*_μ (middle) and q^2 (right) of the selected candidates, overlaid with projections of the fit model with all normalization and shape parameters at their best-fit values.

similar final state is chosen, measuring $\mathcal{R}(\mathrm{D}^*)$ from

$$\mathcal{K}(\mathrm{D}^*) \equiv \frac{\mathcal{B}(\overline{\mathrm{B}}^0 \to \mathrm{D}^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{\mathrm{B}}^0 \to \mathrm{D}^{*+}3\pi)} = \frac{N_{sig}}{N_{norm}} \frac{\epsilon_{norm}}{\epsilon_{sig}} \frac{1}{\mathcal{B}(\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu_\tau)}$$

and

$$\mathcal{R}(\mathrm{D}^*) = \mathcal{K}(\mathrm{D}^*) \times \frac{\mathcal{B}(\overline{\mathrm{B}}^0 \to \mathrm{D}^{*+}3\pi)}{\mathcal{B}(\overline{\mathrm{B}}^0 \to \mathrm{D}^{*+}\mu^-\overline{\nu}_\mu)},$$

where N_{sig} and ϵ_{sig} are the number of signal candidates and the total signal selection efficiency, and N_{norm} and ϵ_{norm} are the number of $\overline{\mathrm{B}}^0 \to \mathrm{D}^{*+}3\pi$candidates measured in the normalization sample and the corresponding selection efficiency. The values of the branching fractions for $\overline{\mathrm{B}}^0 \to \mathrm{D}^{*+}3\pi$and $\overline{\mathrm{B}}^0 \to \mathrm{D}^{*+}\tau^-\overline{\nu}_\tau$are taken from refs. [8] and [9], respectively. More details on this measurement are presented in another contribution to this conference [10]. The result is

$$\mathcal{R}(\mathrm{D}^*) = 0.291 \pm 0.019(\mathrm{stat.}) \pm 0.026(\mathrm{syst.}) \pm 0.013(\mathrm{syst.}),$$

where the third uncertainty originates from the uncertainties on the external branching fractions. The value is compatible with the measurement in the muonic mode and with previous measurements. The average among the two LHCb measurements gives

$$\mathcal{R}(\mathrm{D}^*) = 0.31 \pm 0.016(\mathrm{stat.}) \pm 0.021(\mathrm{syst.})$$

which is 2.2 standard deviations above the SM predictions.

The combination of all available measurements of $\mathcal{R}(\mathrm{D}^*)$ and $\mathcal{R}(\mathrm{D})$ which takes into account the correlation among the two observables, deviates from the SM prediction by 4.1 sigmas.

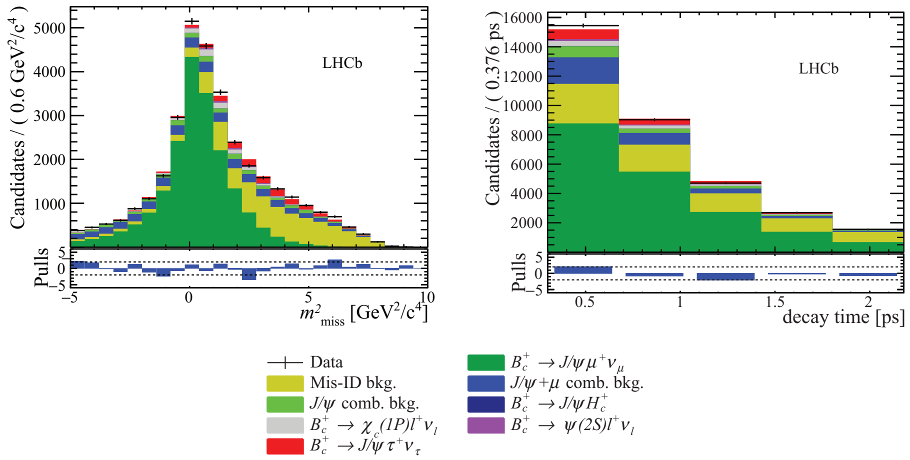

Fig. 2. – Distributions of m^2_{miss} (left) and decay time (right) of the selected candidates, overlaid with projections of the fit model with all normalization and shape parameters at their best-fit values. Below each panel differences between the data and fit are shown, normalized by the Poisson uncertainty in the data; the dashed lines are at the values ±2.

It is important to understand the origin of this deviation with further measurements. Since all the available results refer to B meson decays, one direction to go is the test of LFU on decays of other types of b-hadrons. LHCb can take advantage of the copious $\mathrm{B_c^-}$ production in pp collisions to study the $\mathrm{B_c^-}$ counterpart of $\overline{\mathrm{B}}^0 \to \mathrm{D}^{*+}\tau^-\overline{\nu}_\tau$that is $\mathrm{B_c^-} \to \mathrm{J}/\psi\tau^-\overline{\nu}_\tau$ [11]. Theoretical predictions for

$$\mathcal{R}(\mathrm{J}/\psi) \equiv \frac{\mathcal{B}(\mathrm{B_c^-} \to \mathrm{J}/\psi\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\mathrm{B_c^-} \to \mathrm{J}/\psi\mu^-\overline{\nu}_\mu)}$$

are in the range 0.25–0.28 [12], the spread being due to uncertainties in the form factors, that have not been constrained experimentally yet. The tau lepton is reconstructed from its muonic decay, and the J/ψ is reconstructed in J/$\psi \to \mu\mu$, yielding a three-muon final state for both the signal and the normalization mode. A similar strategy as for the muonic $\mathcal{R}(\mathrm{D}^*)$ measurement is followed, adding the tau decay time as a fourth fit observable. The time provides good separation of signal from background of semileptonic decays of lighter b-hadrons that have much longer lifetimes. The distributions of the missing mass squared and of the τ decay time are shown in fig. 2. The measured value

$$\mathcal{R}(\mathrm{J}/\psi) = 0.71 \pm 0.17(\mathrm{stat.}) \pm 0.18(\mathrm{syst.})$$

is within 2 sigmas from the SM, again on the higher side.

Semileptonic decays of Λ_b baryons are under study at LHCb for a measurement of $\mathcal{R}(\Lambda_\mathrm{c}^+) = \mathcal{B}(\Lambda_\mathrm{b} \to \Lambda_\mathrm{c}^+\tau^-\overline{\nu}_\tau)/\mathcal{B}(\Lambda_\mathrm{b} \to \Lambda_\mathrm{c}^+\mu^-\overline{\nu}_\mu)$, that will test a decay with a different spin structure. The ratio $\mathcal{R}(\Lambda_\mathrm{c}^{*+})$, with $\Lambda_\mathrm{c}^{*+} \to \Lambda_\mathrm{c}^+\pi^+\pi^-$, is another option, characterized by an additional secondary vertex in the experimental reconstruction and smaller feed-down from excited states, but miss the determination of the form factors. Other ongoing tests include the measurements of $\mathcal{R}(\mathrm{H_c})$ in $\overline{\mathrm{B}}^0 \to \mathrm{D}^-\mu^-\overline{\nu}_\mu$or $\overline{\mathrm{B}}{}^0_\mathrm{s} \to \mathrm{D_s^+}\mu^-\overline{\nu}_\mu$decays.

Another direction for future measurement is the test of LFU in $\mathrm{b} \to \mathrm{u}\ell^- \nu$transitions, instead of $\mathrm{b} \to \mathrm{c}\ell^- \nu$, to study the coupling of NP to a different quark family.

3. – Neutral current transitions

Flavour changing neutral currents are possible in the SM only at loop level, therefore $\mathrm{b} \to \mathrm{s}\ell^+\ell^-$ decays are suitable processes to unveil contributions of NP that can alter the rate of the process or change the angular distribution of final-state particles. For a test of LFU between the first and the second lepton families the ratio of branching ratios

$$\mathcal{R}_{\mathrm{K}^{(*)}} = \frac{\mathcal{B}(\mathrm{B}^0 \to \mathrm{K}^{(*)}\mu^+\mu^-)}{\mathcal{B}(\mathrm{B}^0 \to \mathrm{K}^{(*)}\mathrm{e}^+\mathrm{e}^-)}$$

is used. This is predicted in the SM to be unit with a per mille precision, as hadronic effects largely cancel. The measurement of the decay rates is performed in different regions of the dilepton invariant mass squared, q^2, that are sensitive to different types of NP contributions, outside charmonium resonances regions. Previous measurements of $\mathcal{R}_{\mathrm{K}^{(*)}}$ performed at the $\Upsilon(4S)$ are consistent with the SM predictions, with a precision of 20–50% [13, 14]. Larger data samples are available at LHCb, with excellent efficiency and momentum resolution in the muon decay mode, but lower efficiency and momentum resolution in the electron one, due to bremsstrahlung.

A measurement is performed using the 3 fb^{-1}data sample of pp collisions [15]. The K^{*0} meson is reconstructed in the $\mathrm{K}^+\pi^-$ final state, that is required to have an invariant mass within 100 MeV/c^2 of the known $\mathrm{K}^*(892)^0$ mass. Systematic uncertainties due to the different experimental efficiencies in the reconstruction of muons and electrons are reduced by measuring a double ratio, that normalize to the charmonium resonance

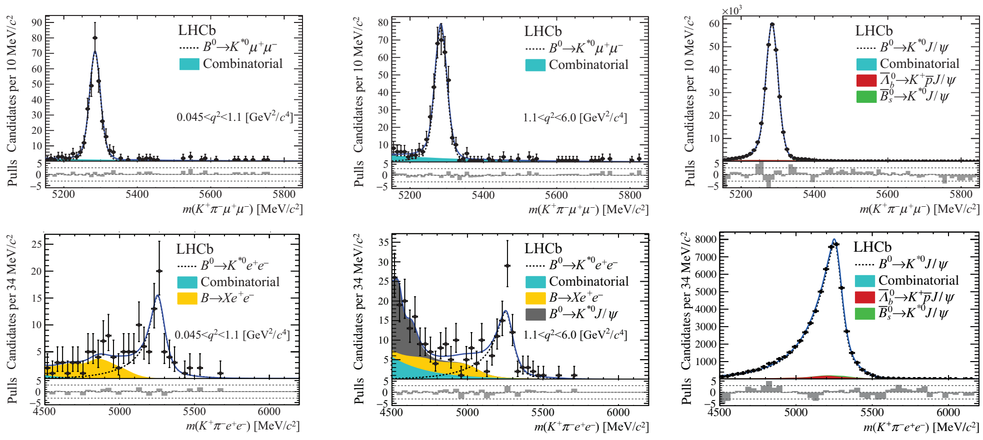

Fig. 3. – Top panel: fit to the $m(\mathrm{K}^+\pi^-\mu^+\mu^-)$ invariant mass of $\mathrm{B}^0 \to \mathrm{K}^{*0}\mu^+\mu^-$in the low- (left) and central- q^2 bins (middle) and of $\mathrm{B}^0 \to \mathrm{K}^{*0}\mathrm{J}/\psi(\mu\mu)$candidates (right). Bottom panel: fit to the $m(\mathrm{K}^+\pi^-\mathrm{e}^+\mathrm{e}^-)$ invariant mass of $\mathrm{B}^0 \to \mathrm{K}^{*0}\mathrm{e}^+\mathrm{e}^-$in the low- (left) and central- q^2 bins (middle) and of $\mathrm{B}^0 \to \mathrm{K}^{*0}\mathrm{J}/\psi(\mathrm{ee})$candidates (right). The dashed line is the signal PDF, the shaded shapes are the background PDFs and the solid line is the total PDF. The fit residuals normalized to the data uncertainty are shown at the bottom of each distribution.

mode

$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\mu\mu))} \times \frac{\mathcal{B}(B^0 \to K^{*0}J/\psi(ee))}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}.$$

A stringent test on the efficiencies is the check that the ratio of branching ratios in the resonance region is indeed consistent with unit, within one sigma, with a 4.5% precision. The invariant-mass distributions of the selected candidates are shown in fig. 3.

$\mathcal{R}_{K^{*0}}$ is measured to be $\mathcal{R}_{K^{*0}} = 0.66^{+0.11}_{-0.07}(\text{stat.}) \pm 0.03(\text{syst.})$ in the region $0.045 < q^2 < 1.1\ \text{GeV}^2/c^4$ and $\mathcal{R}_{K^{*0}} = 0.69^{+0.11}_{-0.07}(\text{stat.}) \pm 0.05(\text{syst.})$ in the region $1.1 < q^2 < 6\ \text{GeV}^2/c^4$. These results are the most precise measurement of these quantities to date, statistically limited by the size of the electron sample. They are compatible with the SM expectations at the level of about 2.2 (2.4) sigmas in the low (high) q^2 region.

A similar measurement performed in the charged kaon decay modes $B^+ \to K^+\mu^+\mu^-$, $B^+ \to K^+e^+e^-$ [16] provided a similar result $\mathcal{R}_K = 0.745^{+0.090}_{-0.074}(\text{stat.}) \pm 0.036(\text{syst.})$ in the region $1.1 < q^2 < 6\ \text{GeV}^2/c^4$, 2.6 sigmas lower than the SM prediction that is of unit with $O(10^{-3})$ precision.

In conclusion LHCb is completing the analysis of Run 1 data on semileptonic B decays observing some deviations from the SM predictions that assume LFU. Other decay modes are under study and updates of current measurements exploiting Run 2 are foreseen in order to test the consistency of the anomalies and to allow the test of NP models.

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