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Semileptonic B decays at LHCb

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Summary. — In the Standard Model of particle physics, the coupling of the gauge bosons to leptons is independent of their flavour. This property is called lepton flavour universality and it has been well tested. Any violation of lepton flavour universality would be a clear sign of physics beyond the Standard Model. Semileptonic decays of b hadrons to final states with a charmed meson and a charmed lepton are copiously produced at the LHC and provide a powerful tool to search for New Physics particles which preferentially couple to the 2nd and 3rd generations of leptons. In these proceedings, an overview of the recent searches of lepton flavour universality violation in $b \to cl\nu$ transitions at the LHCb experiment will be given. The results here presented are based on an integrated luminosity of 3 fb^{-1} collected in proton-proton collision at centre-of-mass energies of 7 and 8 TeV by the LHCb experiment.

1. – Introduction

In the Standard Model of particle physics (SM), the three leptons have the same coupling to the electroweak gauge bosons Z and $W^{\pm}$. This property goes under the name of lepton flavour universality (LFU). An immediate consequence of LFU is that the branching frations of decays that differ only for the final-state leptons are equal, apart from different phase space and helicity-suppressed contributions. A violation of LFU would be a clear sign of New Physics (NP). Many NP scenarios predict the existence of leptoquarks [1-3] or Z' [4,5] particles that would allow to accomodate for the violation of LFU.

Semileptonic $b \to cl\nu$ transitions represent an excellent probe to test LFU violation, since all three lepton generations can be accessed. Moreover, the large $b\bar{b}$ production cross-section in proton-proton collisions at the LHC [6] allowed the LHCb experiment to collect very large datasets, necessary to perform high-precision measurements in this

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field. Some interesting observables used to test LFU are the so-called $R(D^*)$ and $R(J/\psi)$, defined as

$$R(D^*) \equiv \frac{\mathcal{B}(B^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(B^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}, \qquad R(J/\psi) \equiv \frac{\mathcal{B}(B_c^+ \to J/\psi\tau^-\overline{\nu}_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\mu^-\overline{\nu}_\mu)}, \tag{1}$$

where the symbol $\mathcal{B}$ stands for the branching fraction of the decay indicated in the brackets.

These proceedings report about recent searches for LFU violation in $b \to cl\nu$ transitions by the LHCb Collaboration. All the measurement described are based on an integrated luminosity of $3\,\mathrm{fb}^{-1}$ of proton-proton collisions collected by the LHCb experiment at centre-of-mass energies of 7 and 8 TeV.

2. – Measurement of $R(D^*)$

A precise determination of the branching fraction of a b hadron decaying semileptonically to τ leptons is experimentally challenging at a hadron collider due to the presence of at least one undetected neutrino. Moreover, the presence of partially reconstructed B-decays into final states containing charmed mesons represents an abundant source of background for this kind of measurements. The tau lepton can be reconstructed in its muonic ($\tau^- \to \mu^-\nu_\mu\overline{\nu}_\tau$) or hadronic $\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$ final states, thus providing complementary experimental challenges in the two decay modes.

The muonic decay of the tau lepton has the advantage that both the signal and the reference channel in the $R(D^*)$ ratio contain the same visible final state. This helps in reducing the experimental systematic uncertainties. In order to separate the signal from the backgrounds, a three-dimensional fit is performed. The variables used are sensitive to the mass difference between the muon and the tau, as well as the presence of additional neutrinos in the tau decay. These quantities are: the energy of the muon in the B^0 rest frame (E^*_μ), the squared missing mass, defined as $m^2_{miss} \equiv (p(B^0) - p(D^*) - p(\mu))^2$, where p is the four-momentum of a given particle, and the squared four-momentum transfer to the lepton system, $q^2 \equiv (p(B^0) - p(D^*))^2$. The fit projections are shown in fig. 1. The number of $B^0 \to D^{*+}\mu^-\overline{\nu}_\mu$ decays found by the fit is 363000 ± 1600 and the ratio of the number of signal decays with a tau to those with a muon is equal to $(4.54 \pm 0.16) \times 10^{-2}$. Taking $\mathcal{B}(\tau^- \to \mu^-\nu_\mu\overline{\mu}_\tau)$ as input [11] and measuring the ratio of the efficiencies, one obtains $R(D^*) = 0.336 \pm 0.027$.

Several sources of systematic uncertainty have been investigated. The dominant one is due to the finite size of the simulated samples used to build the three-dimensional templates. In conclusion, the ratio $R(D^*)$ is measured to be

$$R(D^*) = 0.336 \pm 0.027 \pm 0.030,$$

where the first uncertainty is statistical and the second systematic. This value is in agreement with previous measurements at BaBar and Belle [7-9] and it is 2.1 standard deviations greater than the SM expectation [10].

Concerning the hadronic measurement of $R(D^*)$, in this analysis the $\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$ decay mode is exploited and the $B^0 \to D^{*+}\pi^+\pi^-\pi^-$ decay is used as reference channel, allowing to measure the ratio

$$K(D^*) \equiv \frac{\mathcal{B}(B^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(B^0 \to D^{*+}\pi^+\pi^-\pi^-)}. \tag{2}$$

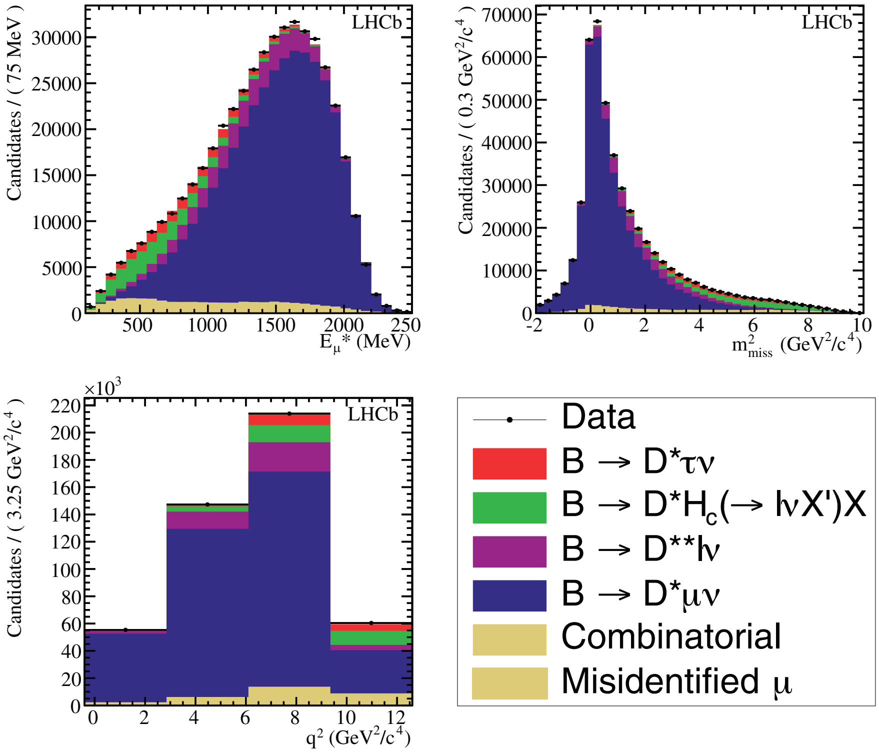

Fig. 1. – Distributions of (top-left) E^*_μ, (top-right) m^2_{miss} and (bottom-left) q^2 with fit projections overlaid. The legend explaining the various fit components is reported in the bottom-right panel.

As for the muonic $R(D^*)$, both decays have the same visible final state to better control experimental systematic uncertainties. By taking as input $\mathcal{B}(B^0 \to D^{*+}\pi^+\pi^-\pi^-)$ and $\mathcal{B}(B^0 \to D^{*+}\mu^-\overline{\nu}_\mu)$ [11] one can measure

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

The presence of three visible tracks coming from the tau lepton allows for a precise measurement of its decay vertex. This is fundamental in order to reject the main background contribution, represented by $B^0 \to D^{*+}\pi^+\pi^-\pi^- X$ decays, where X stands for unreconstrcuted particles. This background is about 100 times more abundant than the signal channel and its largely rejected by requiring the tau decay vertex to be downstream of the B meson one with a 4σ significance, as sketched in the left part of fig. 2. The effect of this requirement on the signal and background modes is studied on simulated events, as can be seen in right part of fig. 2. The remaining backgrounds are due to doubly charmed B-meson decays and are rejected by means of a multivariate classifier, namely a boosted decision tree (BDT).

In order to determine the signal yields, a three-dimensional extended maximum-likelihood fit is performed. The used variables are the BDT output, the tau decay time (t_τ) and the transferred four-momentum (q^2) is performed. The fit projections are shown in fig. 3. The yields of the reference channel are determined by a fit to the

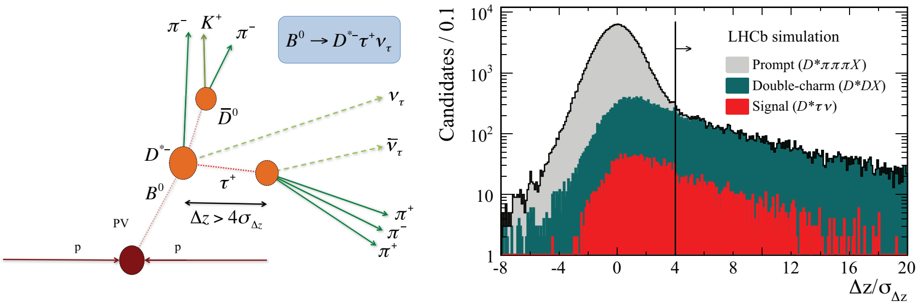

Fig. 2. – The left figure represents the topology of the $B^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ signal decay together with the tau decay vertex requirement applied to reject the $B^0 \to D^{*+}\pi^+\pi^-\pi^- X$ background, while the right figure shows the tau decay vertex significance for signal and background simulated events.

invariant-mass distribution of the $D3\pi$ system. The value of $K(D^*)$ is found to be $K(D^*) = 1.97 \pm 0.13 \pm 0.18$, where the first uncertainty is statistical and the second systematic. The calculated value of $R(D^*)$ is then

$$R(D^*) = 0.291 \pm 0.019 \pm 0.026 \pm 0.013,$$

where the first uncertainty is statistical, the second systematic and the third due to the external inputs. This measurement is one of the most precise to date and it is found to be in agreement with the SM prediction [10] within 1 standard deviation.

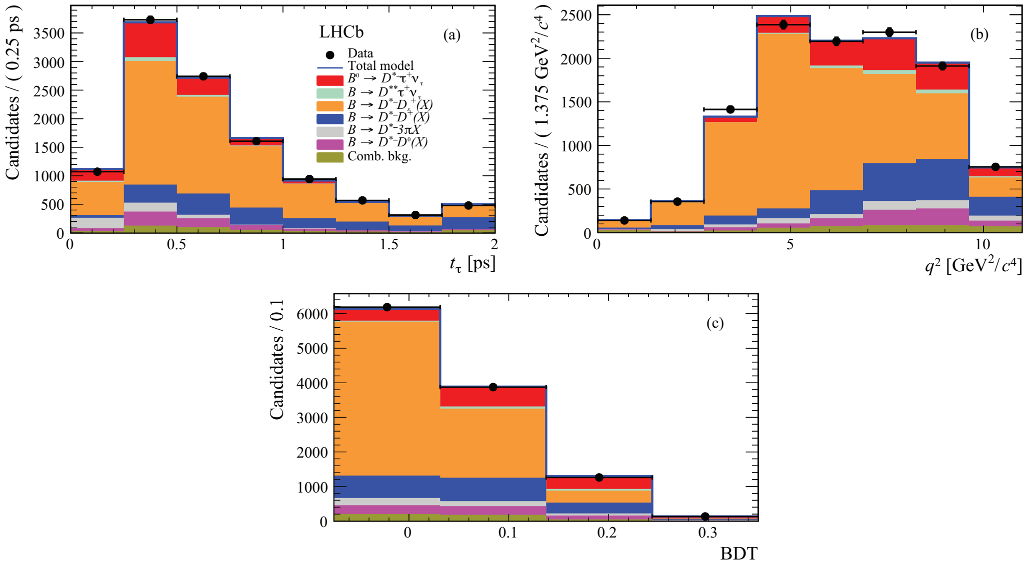

Fig. 3. – Distributions of (top-left) t_τ, (top-right) q^2 and (bottom) output of the BDT classifier with fit projections overlaid.

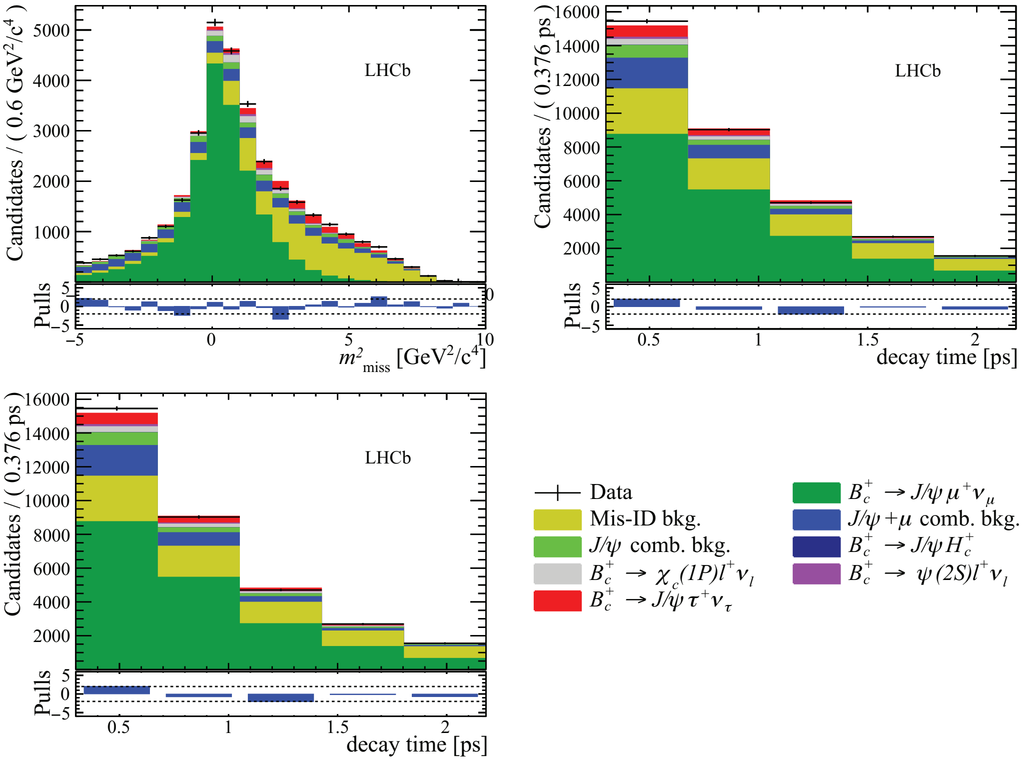

Fig. 4. – Distributions of (top-left) m^2_{miss}, (top-right) B_c^+ decay time and (bottom-left) the category Z with fit projections overlaid. The legend explaining the various fit components is reported in the bottom-right panel.

3. – Measurement of $R(J/\psi)$

This measurement probes LFU in a similar way with respect to the $R(D^*)$ measurement, but with a different spectator quark involved. The tau lepton is reconstructed in his fully leptonic and the J/ψ in the di-muon decay channel, as to have an identical visible final state with respect to the $B^0 \to J/\psi \mu^- \overline{\nu}_\mu$ reference channel.

The B_c^+ meson has a small production rate if compared to B^0 mesons, but the key advantage is that this decay channel does not suffer from the large backgrounds due to D mesons decays. The most relevant background is due to $H_b \to J/\psi h^+$ decays, where H_b stands for a generic b-hadron and h^+ is a charged hadron misidentified as a muon. This contribution is suppressed to a negligible level by imposing stringent particle-identification criteria on the muon coming from the B_c^+ decay.

A three-dimensional fit to the missing-mass squared, $m^2_{miss} = (p_{B_c^+} - p_{J/\psi} - p_\mu)^2$, the B_c^+ decay time, and a categorical quantity Z, representing 8 bins of (E^*_μ, q^2), is performed in order to disentangle the various signal and background contributions. The fit projections are shown in fig. 4. The yields of the signal and reference channels are 1400 ± 300 and 19140 ± 340, respectively.

Several sources of systematic uncertainties are investigated. The dominant ones are due to the poor knowledge of the $B_c^+ \to J/\psi$ form factors and to the size of the simulated samples used to build the fit templates.

Accounting for the $\tau^- \to \mu^- \nu_\mu \overline{\mu}_\tau$ branching fraction [11] and for signal-to-reference channel efficiency ratio, one obtains

$$R(J/\psi) = 0.71 \pm 0.17 \pm 0.18,$$

where the first uncertainty is statistical and the second systematic. This result lies within two standard deviations of the range of central values predicted from the SM, 0.25 to 0.28 [12-15].

4. – Conclusions

The study of $b \to c l \nu$ transitions represents a powerful tool to test LFU in the SM. If LFU is violated, this would be a clear sign of NP and several beyond the SM theories predict the existence of new particles to explain this discrepancy. In these proceedings, the measurements of $R(D^*)$ and $R(J/\psi)$ performed by the LHCb Collaboration using an integrated luminosity of $3\,\mathrm{fb}^{-1}$ of proton-proton collisions collected at centre-of-mass energies of 7 and 8 TeV have been presented. The LHCb experiment has already collected a dataset twice as large with respect to the one employed to perform these analyses and this will allow in the near future to greatly improve the precision of these key tests of the SM.

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