Tests of lepton universality with semitauonic b-quark decays

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Tests of Lepton Flavor Universality are presented using ratios of branching fractions $\mathcal{B}(B \to X_c \tau^+\nu_\tau)/\mathcal{B}(B \to X_c \mu^+\nu_\mu)$, with $X_c = D^{*-}$ or $J/\psi$, using the data collected by the LHCb experiment during 2011 and 2012. When combined with the results from the BaBar and Belle experiments, the Standard Model is challenged at the 3.8σ level. We also give implications and prospects of these key measurements.
The Standard Model (SM) features Lepton Flavor Universality (LFU), which means that the electroweak couplings to all charged leptons are the same. Hence, the branching ratios to electron, muon and tau leptons should only differ due to their mass. However, a $2.8\sigma$ tension has been measured already at LEP [1], when comparing the cross-section of $W \to \tau \nu_\tau$ with respect to the one of $\sigma(W \to e \nu_e) + \sigma(W \to \mu \nu_\mu)$. This article presented tests of LFU in semitauonic decays using the following ratios:

$$R(X_e) = \frac{\mathcal{B}(B \to X_e \tau^+ \nu_\tau)}{\mathcal{B}(B \to X_\mu \mu^+ \nu_\mu)},$$

with $X_e$ being a $D^{*-}$ or a $J/\psi$ meson and $B$ and a $B^0$ or a $B^{*-}$ meson\(^1\). The Standard Model prediction for these ratios are respectively: $R(D^*) = 0.258 \pm 0.005$ [2] and $R(J/\psi) \in [0.25, 0.28]$ [3]. These ratios are sensitive to possible New Physics (NP) coupling mainly to the third generation. Feynman diagrams corresponding to $B \to X_e \tau^+ \nu_\tau$ are respectively:

$$R$$

with $X_e$ to variables evaluated in the final state as the signal. Signal and normalization are separated by means of a 3D template fit of the analysis.

For the $R(D^*)$ muonic measurement [7], the normalization mode has the same visible final state as the signal. Signal and normalization are separated by means of a 3D template fit to variables evaluated in the $B$ rest frame: missing mass squared ($m^2_{\text{miss}}$), muon energy ($E_{\mu}$) and squared 4-momentum transfer to the di-lepton system ($q^2$). The background and signal shapes are extracted from control samples and simulations validated against data. The result is $R(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$, $1.9\sigma$ above the Standard Model expectation. The dominant systematic uncertainty is the size of the signal samples and it will be improved in the next iteration of the analysis.

For the $R(D^*)$ hadronic [8, 9], we measure:

$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \to D^{-} 3\pi)} = \frac{N^{D^{*-} \tau \nu_\tau}_{X_e}}{N^{D^{-} 3\pi}} \times \frac{\epsilon_{D^{*-} \tau \nu_\tau}}{\epsilon_{D^{-} 3\pi}} \times \frac{1}{\mathcal{B}(\tau^+ \to 3\pi(0)\bar{\nu}_\tau)},$$

where $N_{X_e}$ is the number of events of category $X$ and $\epsilon_{X_e}$, the efficiency to select those. The $\tau^+$ is reconstructed into $\pi^+ \pi^- \pi^+ \bar{\nu}_\tau$, which allows for the $\tau^+$ vertex to be reconstructed. The normal-

\(^1\)Though only $R(D^*)$ has been measured so far in LHCb, we use the notation “$R(D^*)$” instead in the rest of this article, assuming, as the b-factories did, that $R(D^{*-}) = R(D^*) \equiv R(D^*)$
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The ratio $R(J/\psi)$ is analogous of $R(D^*)$, using $B_{c}^{+}$ meson $[10]$. It is defined by: $R(J/\psi) = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)}$, $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$. The $B_{c}^{+}$ has a low production rate and a short lifetime, but the $B_{c}^{+} \rightarrow J/\psi \tau^+ \nu_\tau$ mode benefit from a clear $J/\psi$ peak that facilitates the reconstruction. Similarly to the $R(D^*)$ analysis, $m_{miss}^2$, $E_{miss}^2$, and $q^2$ are used in a template fit. The information from the $B_{c}^{+}$ decay time is added to help. The shapes of various components are represented by a template distribution derived from control samples or simulations validated against data. The main background is $b \rightarrow J/\psi$ accompanied by a mis-identified hadron. The first evidence for the decay $B_{c}^{+} \rightarrow J/\psi \tau^+ \nu_\tau$ is obtained at 3$\sigma$ level and we measured: $R(J/\psi) = 0.71 \pm 0.17$ (stat) $\pm 0.18$ (syst). The main systematics are due to the form factor and the size of simulation samples.

Three $b \rightarrow c(\mu/\tau)\nu$ tests of LFU have been performed so far in LHCb: $R(D^*)$ muonic, $R(D^*)$ hadronic and $R(J/\psi)$ muonic. The LHCb average is: $R(D^*) = 0.310 \pm 0.0155$ (stat) $\pm 0.0219$ (syst). It is 1.9$\sigma$ above the SM prediction. When combining with the results from the BaBar and Belle experiments, as well as using the $R(D)$ measurement, the tension with respect to the Standard Model is 3.8$\sigma$ [2], as indicated on Fig. 2, one the highest nowadays in High Energy Physics. The 2$\sigma$ discrepancy observed in $B_{c}^{+} \rightarrow J/\psi \tau^+ \nu_\tau$ goes in the same direction. The measurements presented were performed using only data collected during the Run 1 period. The Run 2 will bring a factor 5 in statistics. The Run 3 and followings will improve even more these results. Many systematics will be reduced with larger samples. Others will benefit from BESIII and Belle II measurements. Many more analyses will be performed using $b \rightarrow c\tau\nu$ transitions: $R(D^+)$, $R(D^0)$, $R(D^{(*)0})$, $R(\Lambda_b^{(*)+})$, ... and $b \rightarrow u\tau\nu$ transitions: $R(\Lambda_b \rightarrow p\tau\nu)$, $R(B \rightarrow p\tau\nu)$, ... Interest will then shift towards new observables beyond the branching fraction ratios, for example angular analysis to determine spin structure of potential New Physics. We have a truly exciting work-plan in the coming years, with crucial interplay between experiments and theory.

References

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Figure 2: $R(D)$ and $R(D^*)$ measured by the BaBar, Belle and LHCb experiments. The world average value is indicated by the red ellipse while blue ellipse shows the Standard Model expectation [2].


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[10] R. Aaij et al. [LHCb Collaboration], “Measurement of the ratio of branching fractions $\mathcal{B}(B_s^+ \to J/\psi \tau^- \nu_{\tau})/\mathcal{B}(B_s^+ \to J/\psi \mu^+ \nu_{\mu})$,” Phys. Rev. Lett. 120 (2018) no.12, 121801.