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Recent results in semileptonic B decays at LHCb

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The Standard Model (SM) predicts the universality of lepton couplings with the electroweak gauge bosons. Three measurements performed by the LHCb collaboration using semitauonic B decays are reported in this work: a combined measurement of $R(D^0)$ and $R(D^*)$ using muonic τ decays, a measurement of $R(D^*)$ using hadronic τ decays and the first measurement of the longitudinal D^* polarization fraction ($F_L^{D^*}$) in the same τ decay channel. Including these latest LHCb results, the updated world average of the $R(D) - R(D^*)$ combination shows a discrepancy of 3.3 standard deviations with respect to the SM prediction. The value of $F_L^{D^*}$ is found to be compatible with the SM.

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1. Introduction

The Standard Model (SM) predicts that different charged leptons have identical electroweak interaction strength, with any discrepancy being solely due to the different masses of the e, μ and τ leptons. The measurement of the branching fraction ratio

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)}, \quad (1)$$

with $l = e, \mu$, can be used as a test of the lepton flavour universality (LFU) in $b \to c\ell\nu_\ell$ charged-current transitions. The advantage of measuring ratios instead of direct branching fractions is related to the cancellation of many uncertainties related to the form factor normalization. Over the last few decades, this ratio has been extensively studied by Belle [1, 2], Babar [3] and LHCb [4–6] collaborations. The $R(D) - R(D^*)$ combination measurement shows a discrepancy of 3.3 standard deviations [7] with respect to the SM prediction. Possible New Physics (NP) explanations take into account leptoquark models [8–10].

Another interesting probe of possible NP contributions is represented by the longitudinal D^* polarization fraction ($F_L^{D^*}$) in $B^0 \to D^{*-}(\to \bar{D}^0\pi^-)\tau^+\nu_\tau$ decays. This quantity is computed as:

$$F_L^{D^*}(q^2) = \frac{a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}{3a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}, \quad (2)$$

where the $a_{\theta_D}(q^2)$ and $c_{\theta_D}(q^2)$ coefficients describes the 2° polynomial dependence of the differential decay rate on the $\cos\theta_D$ quantity:

$$\frac{\mathrm{d}^2\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_D} = a_{\theta_D}(q^2) + c_{\theta_D}(q^2)\cos^2\theta_D. \quad (3)$$

In this formalism, q^2 is the squared invariant mass of the $\tau\nu_\tau$ system and θ_D is the angle between the $\bar{D}^0$ meson direction and the direction opposite to the B^0 in the D^* rest frame. This measurement is complementary and independent from the $R(D^*)$ providing additional sensitivity to possible NP scenarios even if the $R(D^*)$ value is found to be compatible with the SM prediction [11, 12]. At present, only the Belle experiment performed a measure of $F_L^{D^*}$ [13] obtaining a value of $0.60 \pm 0.08(\text{stat}) \pm 0.04(\text{syst})$, compatible with the SM prediction, the most precise theoretical prediction being 0.441 ± 0.006 [14].

2. Combined $R(D)$-$R(D^*)$ measurement with muonic τ^+ decays

The LHCb collaboration performed a combined measurement of $R(D)$-$R(D^*)$, using data collected at $\sqrt{s}$ of 7-8 TeV and corresponding to a integrated luminosity of 3 fb^{-1} [15]. The candidates are reconstructed from $D^{*+}\mu^-$ and $D^0\mu^-$ combinations, where the D^{*+} decays into a $D^0\pi^+$ pair and the D^0 decays into $K^-\pi^+$. The candidate selection is optimized to reduce the dominant systematic uncertainties found in the previous $R(D^*)$ measurement [4]. In particular, a tight selection is applied to the μ lepton, which is flatter in kinematic acceptance, and the trigger selection is based only on the D^0 meson in order to not alter the μ acceptance in the low momentum region. Another important role in the candidate selection is covered by the request of not having

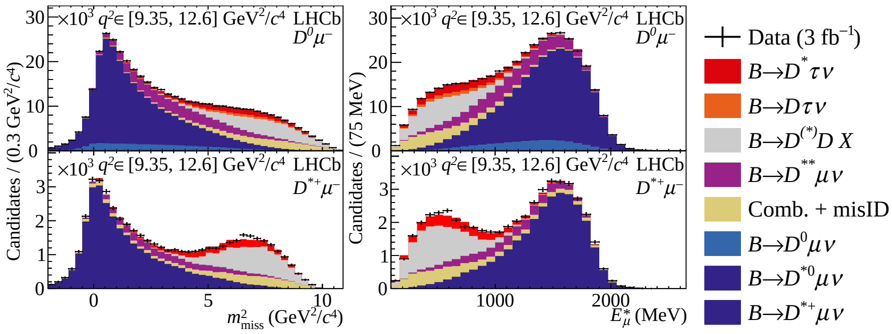

Figure 1: Distributions of (left) missing mass m_{miss} and (right) muon energy $E^{*}_{\mu^+}$ in the high q^2 region. The distributions are depicted for the (top) $D^0\mu^-$ and (bottom) $D^{*+}\mu^-$ signal data with the fit model projections.

additional charged particles compatible with the B^0 and $D^{(*)}$ vertices, used to reject most of the partially reconstructed backgrounds. The signal and normalization modes are represented by the $B \to D^{*+,0}\tau^-\nu_\tau$ and $B \to D^{(*+,0)}\mu^-\nu_\mu$, respectively. Their yields are extracted by means of a three-dimensional binned template fit to the variables: $q^2 \equiv (p_B - p_{D^{(*)}})^2$ and $m^2_{miss} \equiv (p_B - p_{D^{(*)}} - p_\mu)^2$, where p_X stands for the four-momentum of the X particle; and E^*_μ, the muon energy in the B rest frame. The fit projections in the high q^2 region are shown in Figure 1. The final results are:

$$R(D) = 0.441 \pm 0.060 \pm 0.066, \qquad R(D^*) = 0.281 \pm 0.018 \pm 0.023, \tag{4}$$

where the first uncertainty is statistical and the second is systematic. The results are found to be compatible with the SM prediction at 1.9 standard deviation.

3. LHCb measurements using hadronic τ^+ decays

Signal $B^0 \to D^{*-}\tau^+\nu_\tau$ candidates are selected reconstructing $D^{*-}\tau^+$ pairs, with the D^{*-} meson decaying in $D^0\pi^-$, and the D^0 meson decaying into $K^+\pi^-$. The τ lepton is reconstructed from three charged pions associated with the same origin vertex. The dominant background is represented by the $B \to D^{*-}3\pi^\pm X$ decays, where the three pions come directly from the B meson. These background events are suppressed up to less than 0.01% requiring the τ vertex to be downstream with respect to the B vertex along the beam direction and by means of a dedicated multivariate classifier trained with more vertex separation features. Other important sources of background are double-charm $B \to D^*DX$ decays, where the D meson can be a D^0, D^+ or a D^+_s. Due to their signal-like topology and non-negligible D lifetime these background events are rejected through multivariate algorithms, based on Boost Decision Tree (BDT), trained to distinguish these charmed modes from the signal.

The remaining background events are dominated by the $B \to D^{*-}D^+_s X$ mode that is studied by means of two dedicated control samples enriched in D_s decays: the first for studying the $D_s \to 3\pi X$ decays and the second to determine the abundance of the various $B \to D^* D_s X$ modes.

3.1 $R(D^*)$ measurement

The updated $R(D^*)$ measurement using hadronic τ decays performed by the LHCb experiment exploits data collected at $\sqrt{s}$ of 13 TeV and corresponding to an integrated luminosity of 2 fb^{-1} [16].

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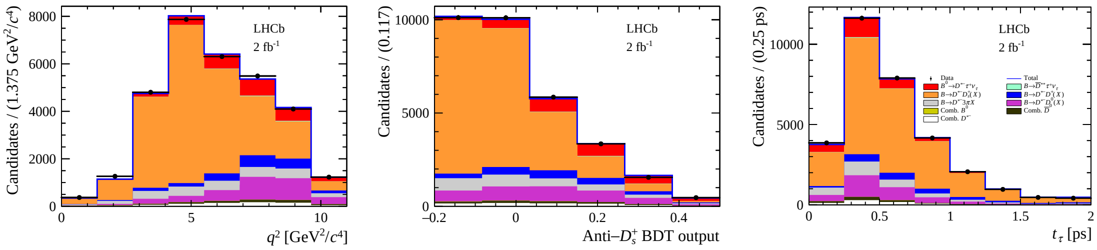

Figure 2: Distributions of (left) q^2, (middle) anti-D_s BDT output and (right) τ decay time of the signal data with the fit projections overlaid.

A binned maximum-likelihood fit is performed on three variables: q^2, the anti-D_s BDT output and the τ decay time. The corresponding projections are depicted in Figure 2. The signal $B^0 \to D^{*-}\tau^+\nu_\tau$ yield results to be 2419 ± 154 candidates, 40% higher than in the Run1 measurement due to the increased $b\bar{b}$ production cross-section. The $B^0 \to D^{*-}3\pi^\pm$ decays are used as normalization mode, for the similarity with the signal visible final state.The $R(D^*)$ value is computed as:

$$R(D^*) = \mathcal{K}(D^*)\frac{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}, \qquad \mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)}, \tag{5}$$

where the ratio of the two branching ratios in the first equation is used as external input. The observed normalization yield is around 30 000 candidates, leading to a value $\mathcal{K}(D^*)$ equal to $1.70 \pm 0.10(\text{stat})^{+0.11}_{-0.10}(\text{syst})$. The final $R(D^*)$ is finally computed using the most recent measurement of the $B^0 \to D^{*-}3\pi^\pm$ and $B^0 \to D^{*-}\mu^+\nu_\mu$ branching fractions, $(7.21 \pm 0.29) \times 10^{-3}$ and $(4.97 \pm 0.12)\%$ [17], respectively. The obtained results are:

$$\begin{aligned} R(D^*) &= 0.247 \pm 0.015(\text{stat}) \pm 0.015(\text{syst}) \pm 0.012(\text{ext}), \\ R(D^*)_{\text{comb}} &= 0.257 \pm 0.012(\text{stat}) \pm 0.014(\text{syst}) \pm 0.012(\text{ext}), \end{aligned} \tag{6}$$

where the last uncertainty is related to the external branching fractions used in the computation. The $R(D^*)_{\text{comb}}$ represents the combination with the $R(D^*)$ obtained in the Run1 measurement [5] and turns out to be the most precise $R(D^*)$ measurement to date. When included, the $R(D) - R(D^*)$ combination maintains a tension of more than 3σ significance with the SM prediction.

3.2 $F_L^{D^*}$ measurement

The longitudinal D^* polarization measurement is performed including the data collected by the LHCb experiment during the 2011-2012 at $\sqrt{s}$ equal to 7 and 8 TeV (Run1) and during the 2015-2016 at $\sqrt{s}$ equal to 13 TeV (Run2), corresponding to an integrated luminosity of 3 and 2 fb^{-1}, respectively. The $F_L^{D^*}$ value is determined in two different q^2 regions, below and above 7 GeV^2/c^4, by means of a four-dimensional binned maximum-likelihood fit to the following variables: $\cos\theta_D$, q^2, the anti-D_s BDT and the τ decay time. The simulated signal template is splitted in two components: one is completely unpolarized while the other is fully polarized. This separation makes the $a_{\theta_D}(q^2)$ and $c_{\theta_D}(q^2)$ parameters, needed for the $F_L^{D^*}$ computation, directly proportional to the yields of the unpolarized and polarized components, respectively. Two sets of weights are assigned to each simulated signal event: the first for correcting the decay kinematics according to

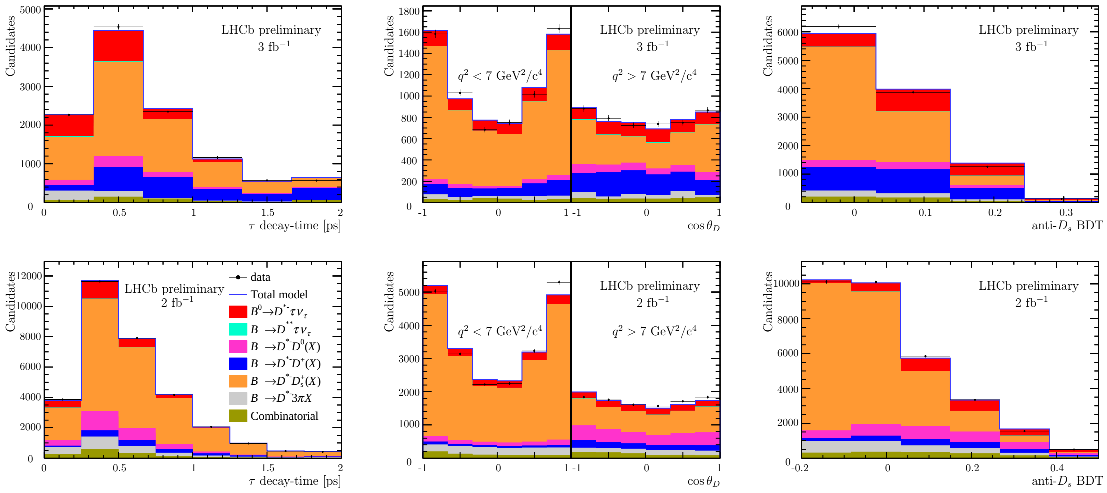

Figure 3: Distributions of (left) τ decay time, (middle) $\cos\theta_D$ and (right) anti-D_s BDT output of the signal (top) Run1 and (bottom) Run2 data with the fit projections overlaid.

the form-factors CLN parameterization [18] and the second to take into account possible effects due to the reconstruction of the signal decays and retrieve the correct $F_L^{D^*}$ value.

After the full candidate selection the residual background is mainly due to the $D^*D^{0,+}_{(s)}X$ components. Specific control samples are used to validate and correct the simulated templates and in particular their $\cos\theta_D$ distribution.

The fit projections are reported in Figure 3 and the resulting $F_L^{D^*}$ values are:

$$\begin{aligned} F_L^{D^*}(q^2 < 7\ \mathrm{GeV}^2/\mathrm{c}^4) &= 0.51 \pm 0.07 \pm 0.03, \\ F_L^{D^*}(q^2 > 7\ \mathrm{GeV}^2/\mathrm{c}^4) &= 0.35 \pm 0.08 \pm 0.02, \\ F_L^{D^*}(q^2 \mathrm{integrated}) &= 0.43 \pm 0.06 \pm 0.03, \end{aligned} \tag{7}$$

where the last result is obtained from the average of the binned $F_L^{D^*}$ values, corrected by efficiency.

4. Conclusions

This paper reports the results of the three most recent LHCb measurements using semi-tauonic B decays. The global picture of the $R(D) - R(D^*)$ combination remains largely unchanged, with a tension of more than 3σ compared to the SM prediction. The result on $F_L^{D^*}$ is the most precise single measurement to date and is found to be compatible with the SM prediction.

The new LHCb data taking has started with the aim to collect data corresponding to an integrated luminosity of 25 fb^{-1}. This new dataset, along with improved trigger and reconstruction techniques, will allow to make more precise measurements giving new insights on the nature of the leptons couplings within the SM and beyond.

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