PROCEEDINGS OF SCIENCE

LHCb measurements on semileptonic decays of b-hadrons

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Semileptonic b-hadron decays provide various opportunities for the searches of the New Physics (NP) beyond the Standard Model (SM). This proceeding covers three recent relevant studies at the LHCb experiment. There are two new contributions to $R(D^{(*)})$, including the simultaneous measurements of $R(D)$ and $R(D^*)$ with the muonic τ^+ decay using the LHCb Run 1 data, and the $R(D^*)$ measurement based on the hadronic τ^+ decays using the 2015-2016 data. With these latest results included, the combination of $R(D)$ and $R(D^*)$ shows a tension over three standard deviations from the SM predictions. The first LHCb result of the D^* longitudinal polarisation in the $B^0 \to D^{*-}\tau^+\nu_\tau$ decay is also presented, where the result is consistent with the SM prediction.

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1. Introduction

Semileptonic decays of b-hadrons offer a crucial platform for the searches of New Physics (NP) beyond the Standard Model (SM). Particles that are not included in the SM , *e.g.* charged Higgs and leptoquarks [1], could contribute to the $b \to cl\overline{\nu}$ and $b \to ul\overline{\nu}$ transitions in addition to the W boson in the SM, causing relevant physics observables deviating from the SM predictions. Precise measurements of these observables in experiment provide crucial tests of the SM and probes of NP.

This proceeding presents three latest LHCb measurements related to NP searches in semileptonic b-hadron decays, covering the topics of the Lepton Flavour Universality (LFU) tests and the D^{*-} longitudinal polarisation measurement. These analyses benefit from the dedicated design and the excellent performance of the LHCb detector for reconstructions of b-hadron decays.

2. Lepton Flavour Universality tests

The LFU is tested in $B \to D^{(*)}l^+\nu$ decays ($l \in \{\mu, \tau\}$) via the branching-fraction ratios

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau^+\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\mu^+\nu_\mu)} . \tag{1}$$

The SM states that the couplings between the electroweak gauge bosons and the different lepton generations are universal, and thus the deviation of $R(D^{(*)})$ from unity is only due to the different masses of the charged leptons. The $R(D^{(*)})$ quantity is an ideal experimental probe to NP because the hadronic uncertainties largely cancel in the ratio and the NP effect could be enhanced in the decay involving the τ^+ lepton.

There is a longstanding tension of $R(D^{(*)})$ from the SM predictions at the level of three standard deviations (σ) [2], attracting great interests in the particle physics community to explore if this tension is from the NP. The LHCb experiment recently contributed to this effort by improving the $R(D^{(*)})$ measurements using two different kinds of τ^+ decays, *i.e.* the muonic mode $\tau^+ \to \mu^+\nu_\mu\overline{\nu}_\tau$ and the hadronic modes $\tau^+ \to 3\pi(\pi^0)\overline{\nu}_\tau$ where $3\pi \equiv \pi^+\pi^-\pi^+$.

2.1 $R(D^{(*)})$ with the muonic τ^+ mode

Using pp collision data collected in the LHC Run 1 operating period, the combined measurement of $R(D)$ and $R(D^*)$ is performed [3]. The $D^0\mu^-$ and $D^{*+}\mu^-$ candidates are reconstructed. Trigger independent of the muon candidate is required to preserve the low-momentum muons that are mainly from τ^- decays. The identification of muons is improved using a dedicated multivariate selector to reduce the misidentified background from hadrons which contributed to the dominant systematic uncertainty in the previous $R(D^*)$ measurement [4].

The $B \to D^{(*)}\tau^-\overline{\nu}_\tau$ and $B \to D^{(*)}\mu^-\overline{\nu}_\mu$ signal yields are determined from a three-dimensional binned template fit to the variables $q^2 \equiv (p_B - p_{D^{(*)}})$, $m^2_{\rm miss} \equiv (p_B - p_{D^{(*)}} - p_\mu)^2$ and the muon energy E^*_μ, where p_X is the four-momentum of the particle X that is estimated with the topological and kinematic constraints taken into account. The fit is performed simultaneously in eight distinct subsets of $D^{(*)}\mu^-$ samples, and in each subset the candidates from dedicated signal or background contributions are enhanced. The modelling of the various backgrounds are well constrained in this way.

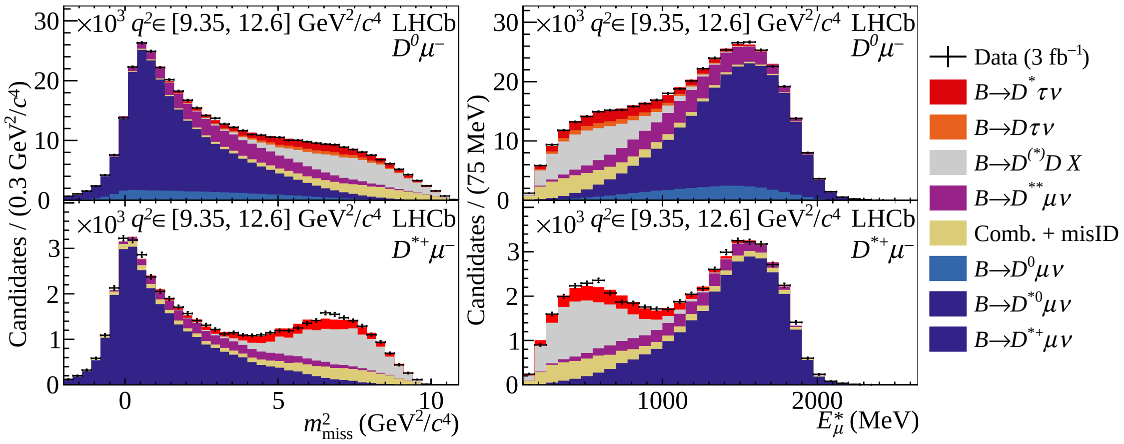

Figure 1: Distributions of (left) m^2_{miss} and (right) E^*_μ in the specified q^2 bin of the (top) D^0 µm and (bottom) D^{*+} µm signal data, overlaid with projections of the fit model.

The results of the fit to the fully isolated (signal) sub-samples are shown in Fig. 1. The $R(D^{(*)})$ values are determined to be

$$R(D) = 0.441 \pm 0.060 \pm 0.066, \quad R(D^*) = 0.281 \pm 0.018 \pm 0.023, \tag{2}$$

with a correlation of $\rho = -0.43$. Here, the first uncertainty is statistical and the second systematic. These results are consistent with the current average of these quantities and agree with the SM predictions within 2σ. [2]

2.2 $R(D^*)$ with the hadronic τ^+ modes

With pp collision data collected in the LHC operation years of 2015–2016, the $R(D^*)$ value is updated following the similar strategy of that in the Run 1 analysis. [5–7] The $B^0 \to D^{*-}\tau^+\nu_\tau$ branching fraction is measured relative to that of the control mode $B^0 \to D^{*-}3\pi$ as $\mathcal{K}(D^*) \equiv \mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)/\mathcal{B}(B^0 \to D^{*-}3\pi)$. The $R(D^*)$ value can then be extracted using the external inputs of the $B^0 \to D^{*-}\mu^+\nu_\mu$ and $B^0 \to D^{*-}3\pi$ branching fractions [8], *i.e.*

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

The selection is improved by employing four multivariate classifiers for background suppression compared with that in the Run 1 study [5, 6]. The dominant background $B \to D^{*-}3\pi X$ decays with X being unreconstructed objects are significantly suppressed by a classifier which mainly benefits from the detachment feature of the B^0 and τ^+ vertices. Two additional classifiers are designed to suppress the combinatorial and partially reconstructed backgrounds. A dedicated boosted decision tree (BDT) classifier is employed to discriminate the dominant double charm backgrounds $B \to D^{*-}D_s^+X, D_s^+ \to 3\pi X'$ from signal decays. It takes advantage of the different resonant structures in the $\tau^+ \to 3\pi\overline{\nu}_\tau$ and $D_s^+ \to 3\pi X'$ decays.

The $B^0 \to D^{*-}\tau^+\nu_\tau$ signal yield is determined from a three-dimensional binned template fit to the variables $q^2 \equiv (p_{B^0} - p_{D^*})^2$, the τ^+ proper lifetime t_τ and anti-D_s^+ BDT output. The

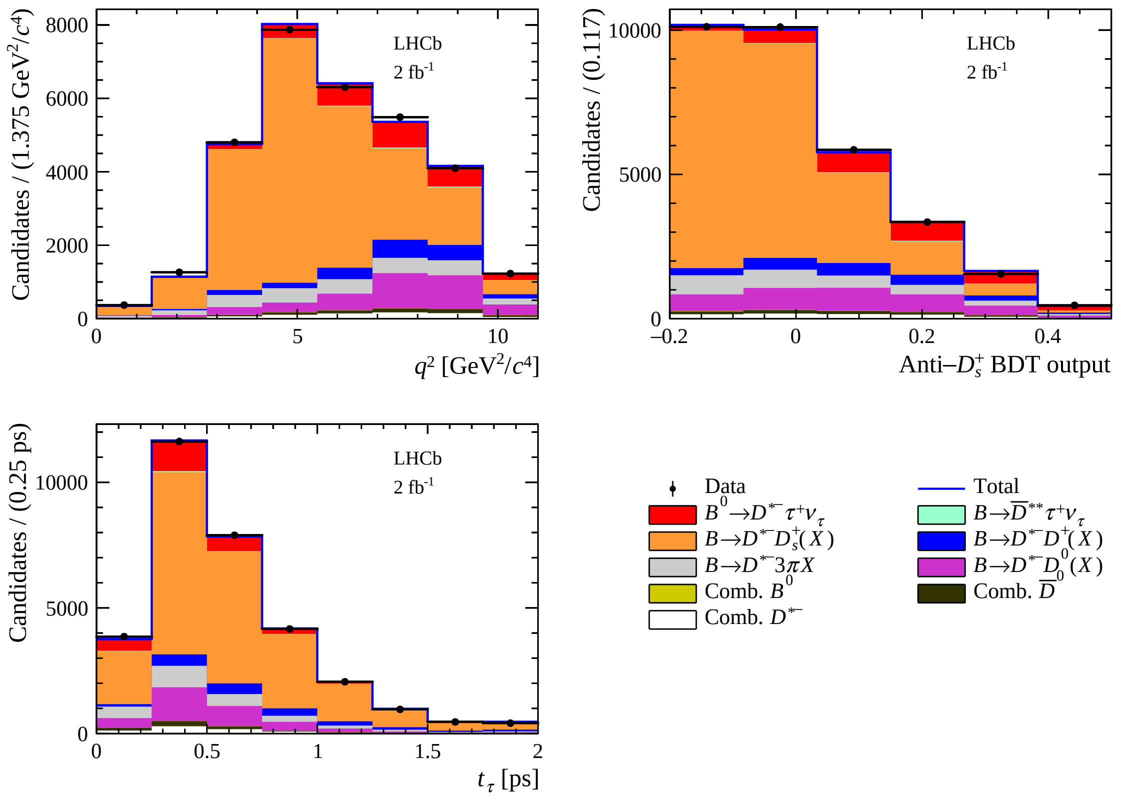

Figure 2: Distributions of (top left) q^2, (top right) anti-D_s^+ BDT out and (bottom left) t_τ in the $B^0 \to D^{*-}\tau^+\nu_\tau$ data sample with the fit result overlaid.

momenta used to determine related quantities are from approximations with kinematic and topological constraints applied. The template shapes are obtained from simulation samples for partially reconstructed backgrounds, and from data for combinatorial backgrounds. To improve the background templates involving the $D_s^+ \to 3\pi X'$ decays, the $D_s^+ \to 3\pi X'$ branching fractions in the simulation samples are aligned to those expected in data. The improvement is also applied to the $B \to D^{*-}D_s^+X$ background templates, where relative branching fractions of double charm decays are constrained using data.

The fit results are shown in Fig. 2. With the $B^0 \to D^{*-}3\pi$ yield determined from the fit to the $D^{*-}3\pi$ invariant mass, the efficiencies obtained from simulation samples and the external inputs of the relevant branching fractions, $R(D^*)$ is determined to be

$$R(D^*) = 0.247 \pm 0.015 \pm 0.015 \pm 0.012\,, \tag{4}$$

where the first uncertainty is statistical, the second systematic and the third is due to the uncertainties on the external inputs. Combining this result with the Run 1 measurement [6], the $R(D^*)$ value is

$$R(D^*)_{\text{comb}} = 0.257 \pm 0.012 \pm 0.014 \pm 0.012\,, \tag{5}$$

which is one of the most precise measurements of $R(D^*)$ to date. With these results included, the $R(D)$–$R(D^{*-})$ combination is still in tension from the SM prediction over 3σ. [2]

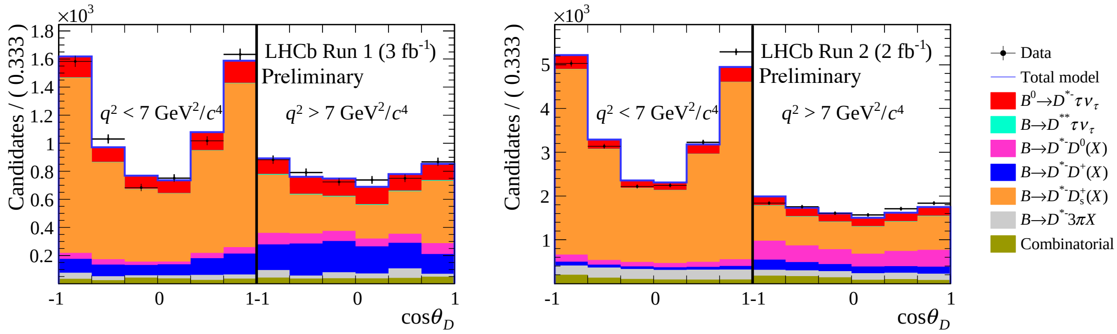

Figure 3: The $\cos\theta_D$ distributions in two q^2 regions for the (left) Run 1 and (right) Run 2 $B^0 \to D^{*-}\tau^+\nu_\tau$ data samples with the fit results overlaid.

3. D^{*-} longitudinal polarisation

Using the same dataset as that in the $R(D^*)$ measurements with the hadronic τ^+ modes, [5–7] the D^{*-} longitudinal polarisation is measured. The D^{*-} longitudinal polarisation fraction $F_L^{D^*}$ is extracted from the angular distribution

$$\frac{d^2\Gamma}{dq^2 d\cos\theta_D} = a_{\theta_D}(q^2) + c_{\theta_D}(q^2)\cos^2\theta_D, \quad F_L^{D^*} = \frac{a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}{3a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}, \tag{6}$$

where θ_D is the angle between the $\overline{D}^0$ momentum and the opposite of the B^0 momentum in the D^{*-} rest frame, and the coefficients $a_\theta(q^2)$ and $c_\theta(q^2)$ contain information of hadronic effects and fundamental couplings.

The coefficients $a_\theta(q^2)$ and $c_\theta(q^2)$ are determined from a four-dimensional binned template fit to q^2, t_τ, $\cos\theta_D$ and anti-D_s^+ BDT output. In addition to the corrections introduced in Sec. 2.2, an extra correction is also applied to the $\cos\theta_D$ distributions for the template shapes of double charm backgrounds. The fit projections for the $\cos\theta_D$ distribution are shown in Fig. 3. Using the determined coefficients, $F_L^{D^*}$ is extracted in the two q^2 bins and also with q^2 integrated out:

$$\begin{aligned} q^2 < 7\text{GeV}^2/c^4 &: 0.51 \pm 0.07 \pm 0.03, \\ q^2 > 7\text{GeV}^2/c^4 &: 0.35 \pm 0.08 \pm 0.02, \\ q^2 \text{ integrated} &: 0.43 \pm 0.06 \pm 0.03, \end{aligned} \tag{7}$$

where the first uncertainty is statistical and the second systematic. These results are most precise to date. They are consistent with the SM predictions within 1σ. [9, 10]

4. Conclusion and prospects

Two recent LHCb results of $R(D^{(*)})$, measured using the muonic and hadronic τ^+ decay modes, respectively, are presented. The global picture of $R(D)$-$R(D^*)$ combination is largely unchanged and the tension with the SM is still at the 3σ level. The first LHCb measurement of the D^{*-} longitudinal polarisation in the $B^0 \to D^{*-}\tau^+\nu_\tau$ decay is introduced. The most precise result to date is obtained, and is found to be consistent with the SM prediction. These measurements contribute to the continuous effort of searching for NP in semileptonic decays of b-hadron.

There are a lot physics topics to be studied with the ongoing experiments. The $R(D)$-$R(D^*)$ tension is expected to be better understood with more precise measurements using larger dataset in the future. Full angular analyses of the semileptonic decays can be performed where different angular coefficients are sensitive to different NP scenarios. With the increase of the accessible dataset, the decays with low statistics can be explored, *e.g.* those involving excited charm and charmless hadrons, providing new insights for the NP searches in semileptonic b-hadron decays.

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